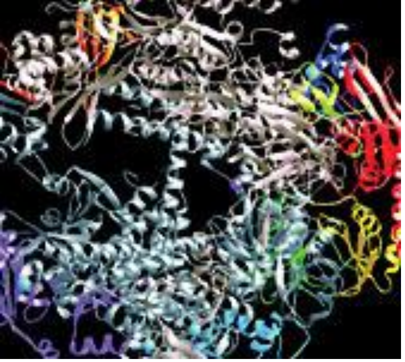

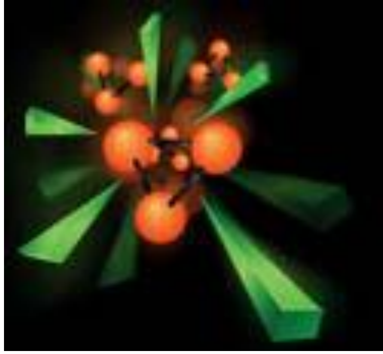

US Particle Accelerator School

Northern Illinois University: Lisle, Illinois

Accelerator Power System Engineering

June 2017

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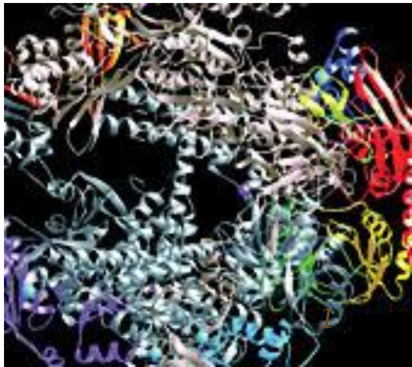
SLAC National Accelerator Laboratory (SLAC)



Sections

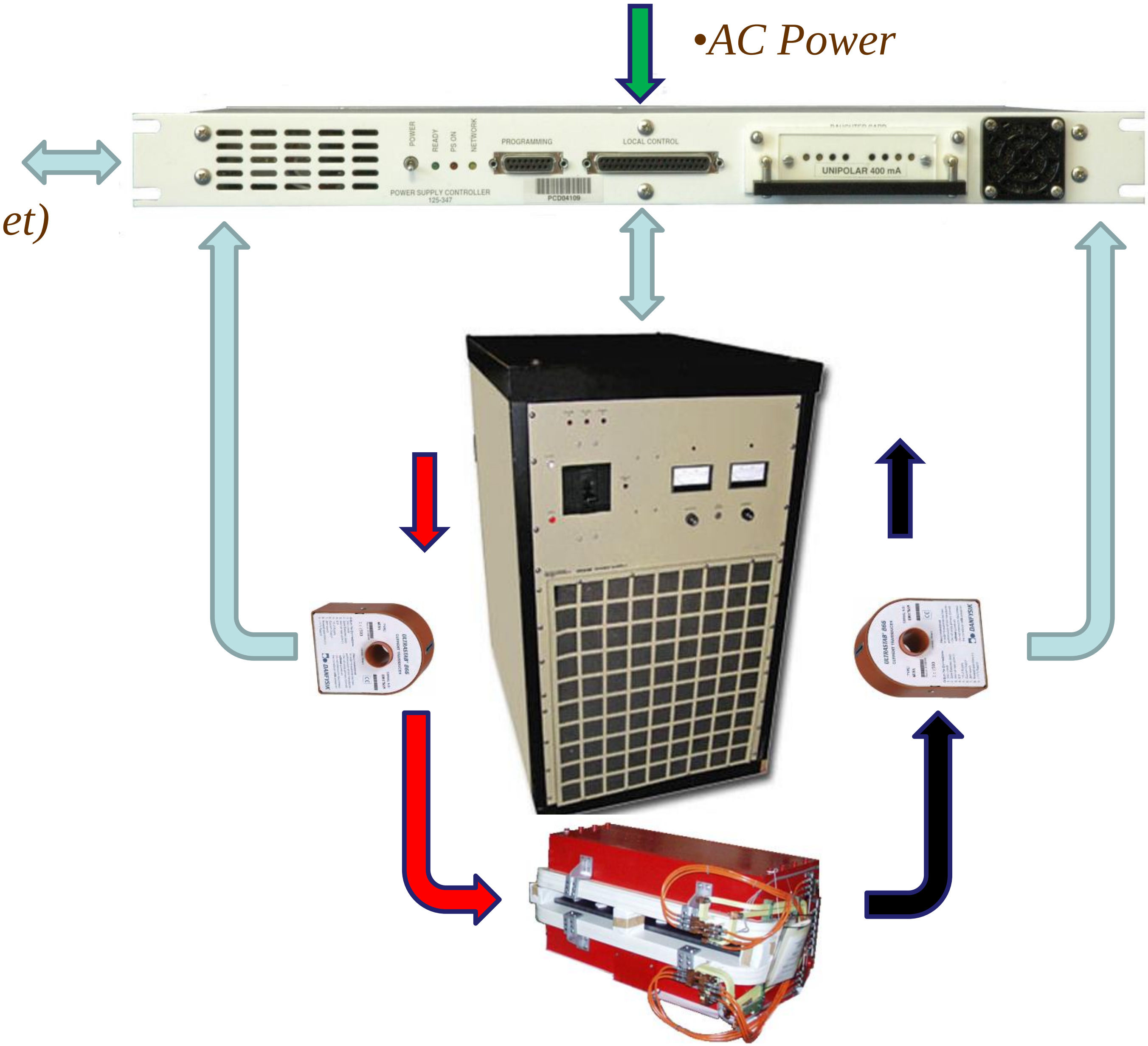
Section 1

- Introduction

A Typical DC Magnet Power System

- AC Power

- EPICS
- (Ethernet)



- Power Supply Controller
- Power Supply
- Feedback and Monitor Transducers
- Magnet

Section 2

- Purpose
- Goals
- Intended Audience
  - Civil, Mechanical Designers
  - Control Engineers
  - Electrical Distribution System Designers
  - Maintenance Personnel
  - Magnet Designers
  - Operators
  - Physicists
  - Power Conversion / Power Supply Designers
  - Project Engineers / Managers
  - Safety Engineers / Designers

Purpose

- *Provide an overview of Accelerator Power Electronics Engineering with an emphasis on DC and an overview of pulsed power supplies*

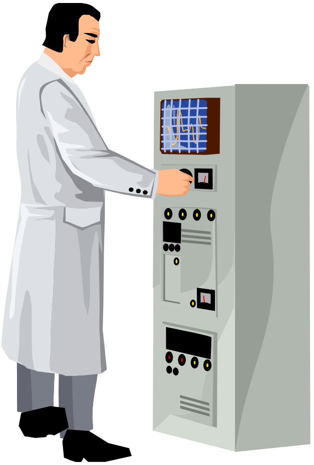
Goals

- *Provide a historical overview of Accelerator Power Supplies from early designs, to presently employed technology, to some promising future developments now in incubation*
- *Survey the most pertinent power supply topologies from the perspectives of accelerators, load type and rating*
- *Give other, non-power conversion disciplines a glimpse of, and a better understanding of, Power Electronics Engineering*
- *Define the information needed for the power supply designer, or user, to make appropriate choices for power supply type, design, and rating*

Intended Audience

- ***Civil, Mechanical Designers*** *– interest in facility space, mounting, cooling*

- ***Control Engineers*** *– an insight into some interface requirements*



Intended Audience

- ***Electrical Distribution System Designers*** – *AC distribution requirements, address and reduce harmonics and EMI*

- ***Maintenance Personnel*** – *power system reliability and maintainability*

- ***Magnet Designers*** – *tradeoffs between power supply output voltage, current and stability limitations and the magnet design. The power supply role in magnet protection via cooling interlocks and ground fault detection and protection*

Intended Audience

- ***Accelerator Operators*** *– Power supply control and operating characteristics*

- ***Physicists*** *– Power system rating limitations, magnet configuration options vs. physics tradeoffs, long and short-term current stability limitations*

Intended Audience

- ***Power Conversion / Power Supply Designers*** *– power systems from another point of view*

- ***Project Engineers and Managers*** *– Power conversion system costs*

- ***Safety Engineers / Designers*** *– Personnel and equipment safety in an electrical power environment. General power safety provisions*

Section 3

- *Mathematical Preliminaries*
  - *Why Mathematical Preliminaries*
  - *Average and RMS Values*
  - *Complex Exponentials*
  - *Differential Equations*
  - *Linear Systems*
  - *Impulse and Step Functions*
  - *System Transfer Function*
  - *Fourier Series and Transforms*
  - *Laplace Transforms*

Why Mathematical Preliminaries?

- *We need to use circuits and understand their behavior*
  - *Power supply loads*
  - *Filter circuits*
  - *Pulse shaping circuits*
  - *Feedback and control circuits*

- *Many important circuits are passive, consisting of*
  - *Resistors*
  - *Capacitors*
  - *Inductors*

- *For these circuits we the voltage-current relations for each element*
  - $v_R = Ri_R$
  - $v_L = L\frac{di_L}{dt}$
  - $i_C = C\frac{dv_C}{dt}$

- *And*

  Kirchoff's Voltage Law for each loop:

  $$\sum_{n=1}^{N} v_n = 0$$

  Kirchoff's Current Law for each node

  $$\sum_{n=1}^{N} i_n = 0$$

Why Mathematical Preliminaries?

- *Solving circuit equations therefore involves solving differential equations, which includes calculus, integration, and convolution*

- *Fortunately circuits containing only passive elements can be well-approximated by linear systems*

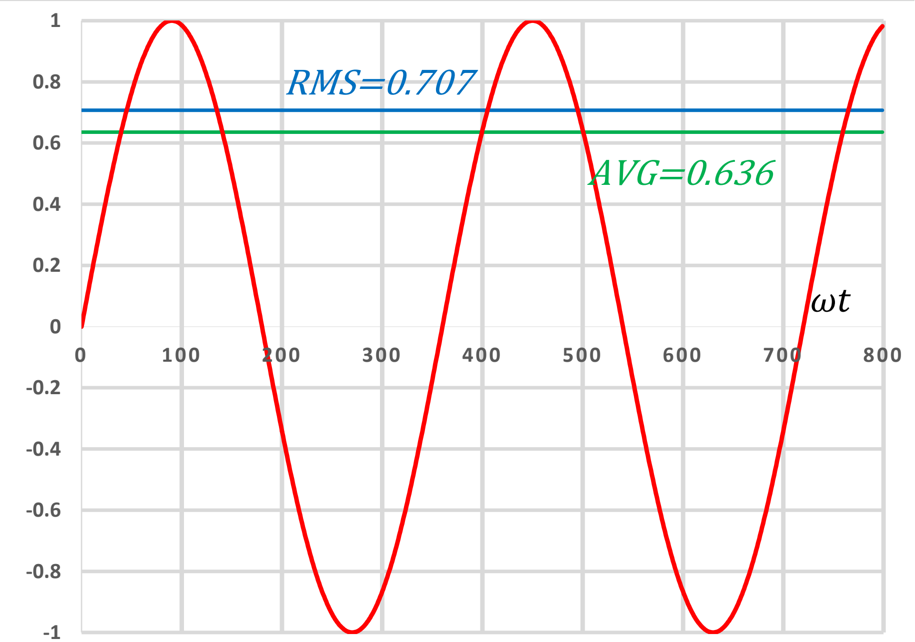
- *If we learn the mathematics behind linear systems*
  - *Fourier and Laplace transforms and their inverses*
  - *Impulse and step functions*

- *We can trade*
  - *Calculus for algebra*
  - *Convolution for multiplication*

Mathematical Preliminaries – Average and RMS Values – Sine Waves

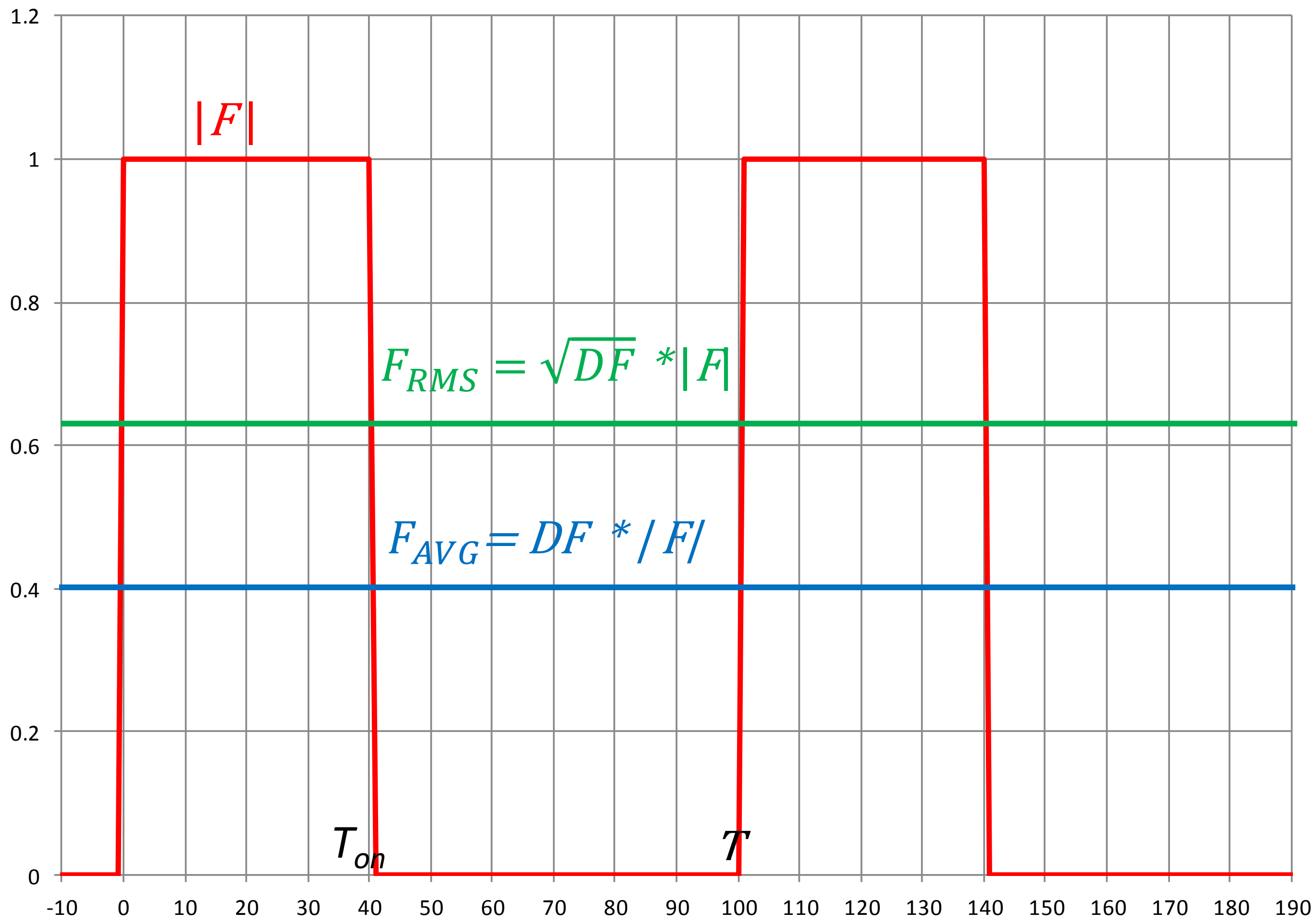
$$F_{ave} = \frac{1}{T}\int_{t=0}^{t=T} f(t)dt, \quad if \quad f(t) = F_m \sin(\omega t), \quad F_{ave} = \frac{1}{\omega T}\int_{\omega t=0}^{\omega t=T} F_m \sin(\omega t)\, d\omega t = 0.636 * F_m$$

$$F_{rms} = \sqrt{\frac{1}{T}\int_{t=0}^{t=T} f(t)^2 dt}\ , \ if \quad f(t) = F_m \sin(\omega t), \ F_{rms} = \sqrt{\frac{1}{\omega T}\int_{\omega t=0}^{\omega t=T} (F_m \sin(\omega t))^2 d\omega t} = \frac{F_m}{\sqrt{2}} = 0.707 * F_m$$



Mathematical Preliminaries – Average and RMS Values – Rectangular Pulses

$$Duty\ Factor = DF = \frac{T_{on}}{T}$$



$$Duty\ Factor = DF = \frac{T_{on}}{T_{on} + T_{off}} = \frac{T_{on}}{T}$$

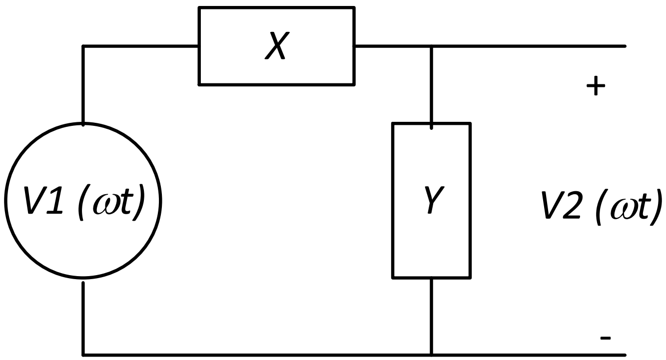
$$F_{ave} = \frac{1}{T}\int_{t=0}^{t=T} f(t)dt, \quad if \quad f(t) = F_m \ during \ T_{on}$$

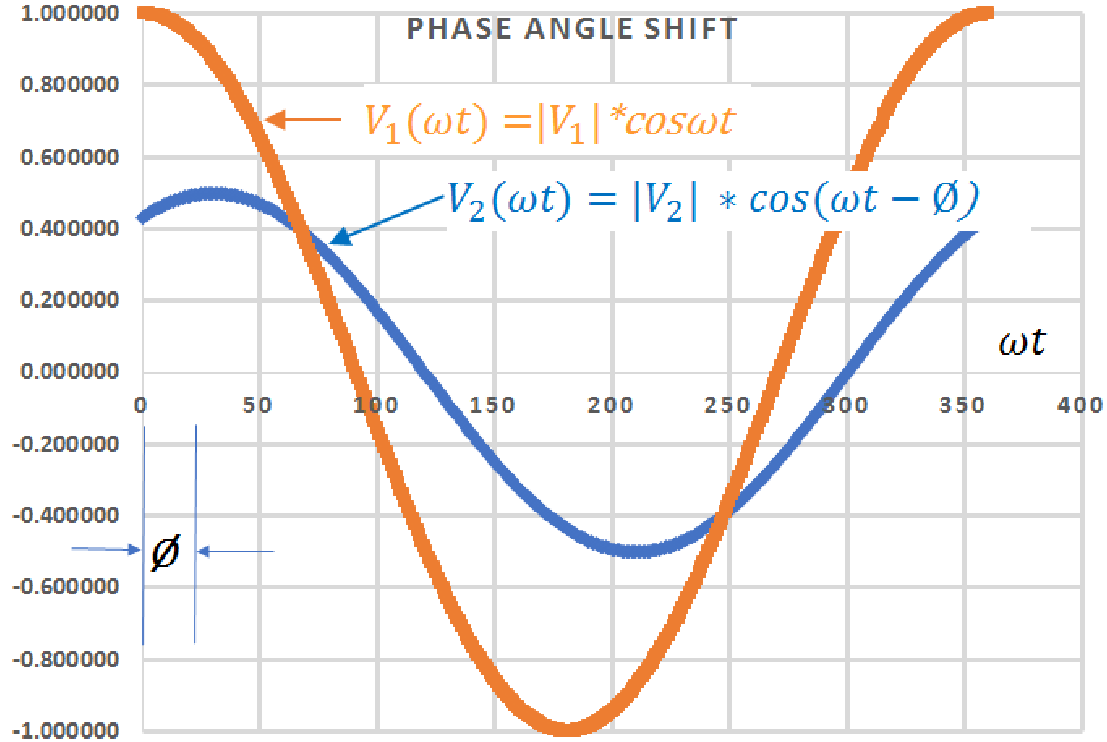
$$F_{ave} = \frac{1}{T}\int_{t=0}^{t=T_{on}} F_m \ dt = \frac{T_{on}}{T} * F_m = DF * F_m$$

$$F_{rms} = \sqrt{\frac{1}{T}\int_{t=0}^{t=T} f(t)^2 dt} \ , \quad if \quad f(t) = F_m \ during \ T_{on}$$

$$F_{rms} = \sqrt{\frac{1}{T}\int_{t=0}^{t=T_{on}} {F_m}^2 dt} = \sqrt{\frac{T_{on}}{T}} * F_m = \sqrt{DF} * F_m$$

Given $\omega = 2\pi f\ (\frac{rad}{sec})$, t= time (sec), $V = |V| * \angle(\omega t\ \pm\ \emptyset)$





$V_1(\omega t) = |V_1| * \cos \omega t$, *Real, in-phase component only*

$V_1(\omega t) = |V_1| * \angle(\omega t + 0) = |V_1| * \angle 0$ *phasor form*

$V_2(\omega t) = |V_2| * \cos(\omega t - \emptyset)$, *in-phase and out-of-phase components*

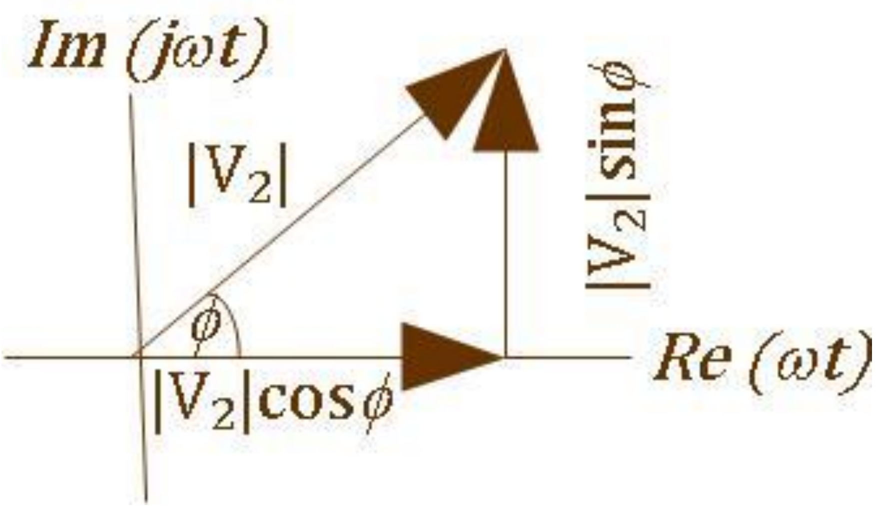
$V_2(\omega t) = |V_2| * \angle(\omega t - \emptyset)$, *or* $V_2 = |V_2| * \angle - \emptyset$ *phasor form*

Euler's Identity: $Ae^{jX} = \mathrm{A}(\cos X + j \sin X)$

Use the trigonometric identity

$cos(U \pm V) = cos\, U * cos\, V \mp sin\, U * sin\, V$

$V_2(\omega t) = |V_2| * cos(\omega t - \emptyset) = |V_2| * [cos\, \omega t * cos\, \emptyset + sin\, \omega t * sin\, \emptyset]$



$Re\, V_2 = |V_2| \cos \emptyset$

$Im\, V_2 = |V_2|\, sin\, \emptyset$

$V_2 = |V_2| \cos \emptyset + j\, |V_2| \sin \emptyset$

$V_2 = |V_2| e^{j\emptyset}$

$$V_2(\omega t) = |V_2| e^{j(\omega t \pm \phi)} = |V_2| e^{\pm j \phi} \textit{ exponential form}$$

$$|V_2| = |V_2| * \sqrt{\cos \emptyset^2 + \sin \emptyset^2} = |V_2| * 1$$

•*This has to move*

- *Lastly, since the magnitude of the complex exponential is always 1, this function gives us a steady state eigenfunction of the constant, differential and integral operators we will need to analyze circuits*

Eigenfunction = any function that satisfies a differential equation

Mathematical Preliminaries - Complex Exponentials

- *The phasor amplitude is the eigenvalue of that frequency*
- *For example if the behavior of a system is determined by the equation*

  $ax^2 + bx + c = 0$ *, the roots given by the quadratic formula* $x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$ *are the eigenvalues or the roots of the system.*

Eigenvalue = proper value or characteristic roots

- *If the input to a system consists of a single frequency, the output will consist of just that same frequency, although with a different amplitude and phase than the input*

Differential equations describe systems that change with time

For a system with time varying quantities, u(t), y(t), that satisfy

the differential equation $$\frac{dy(t)}{dt} = a\,u(t)$$

y(t) depends on its past values as well as those of u(t)

$$\frac{dy(t)}{dt} \equiv \lim_{\Delta t \to 0} \frac{y(t_0 + \Delta t) - y(t_0)}{\Delta t} = au(t)$$

$$y(t_0 + \Delta t) \cong y(t_0) + \Delta t\, a\, u(t_0)$$

Continuing this to construct y(t) at later times

$$y(t_0 + 2\Delta t) \cong y(t_0 + \Delta t) + \Delta t\, a\, u(t_0 + \Delta t) \cong y(t_0) + \Delta t\, a\, u(t_0) + \Delta t\, a\, u(t_0 + \Delta t)$$

$$y(t_0 + N\Delta t) \cong y(t_0) + a\sum_{n=0}^{N-1} \Delta t\, u(t_0 + n\,\Delta t)$$

Resulting in the integral equation

$$y(t) = y(t_0) + a\int_{t_0}^{t} u(\tau)\,d\tau$$

Differential equations describe systems that evolve with time

In general, given a driving term $u(t)$ and a driven term $y(t)$, one can define a differential equation for the evolution of $y(t)$

$$\frac{dy(t)}{dt} + ay(t) = bu(t)$$

$y(t)$ depends on the past and current values of itself and $u(t)$

The derivative is defined as

$$\frac{dy(t)}{dt} = \lim_{\Delta t \to 0} \frac{y(t) - y(t - \Delta t)}{\Delta t} = -ay(t) + bu(t)$$

so that

$$y(t) \approx y(t - \Delta t) + \Delta t[-ay(t) + bu(t)]$$

$$\approx \frac{1}{1 + a\Delta t} y(t - \Delta t) + \frac{b\Delta t}{1 + a\Delta t} u(t)$$

If we continue this construction

$$y(t+\Delta t) \approx y(t) + \Delta t[-ay(t+\Delta t) + bu(t+\Delta t)]$$

$$\approx \frac{1}{1+a\Delta t} y(t-\Delta t) + \frac{b\Delta t}{1+a\Delta t} u(t) + \Delta t[-ay(t+\Delta t) + bu(t+\Delta t)]$$

$$y(t+\Delta t) \approx \frac{1}{(1+a\Delta t)^2} y(t-\Delta t) + b\left[\frac{u(t)}{(1+a\Delta t)^2} + \frac{u(t+\Delta t)}{1+a\Delta t}\right]$$

$$y(t+(N+1)\Delta \mathrm{t}) \approx \frac{1}{(1+a\Delta t)^N} y(t-\Delta t) + b\sum_{n=0}^{N+1} \frac{u(t+\mathrm{n}\Delta t)}{(1+a\Delta t)^{N-n}}$$

From this we can continue on to obtain the exact solution

$$y(t) = e^{-at}[y(t_0) + \int_{t_0}^{t} e^{a\tau} u(\tau) d\tau]$$

which can be obtained by, for example, the method of variation of parameters.

Note that the ay term in the differential equation gives rise to a term

$$e^{-at}$$

that acts to damp out initial conditions and past inputs.

A linear system, $h[x]$ is defined such that for inputs x_1 and x_2, if
$y_1 = h[x_1]$ and $y_2 = h[x_2]$
then

$$ay_1 + by_2 = h[ax_1 + bx_2]$$

This is the principle of linear superposition.

Examples of linear systems:

Constant gain system	$h_1[x] = A_1 x$	$V = R_1 I$
Sum of two constant gains	$h_2[x] = A_2 x + A_3 x$	$V = R_2 I + R_3 I$
Derivatives	$h_3[x] = A_4 \frac{dx}{dt}$	$V = L_4 \frac{dI}{dt}$
Integrals	$h_4[x] = A_5 \int x\, dt$	$V = \frac{1}{C_5} \int I\, dt$

We are interested in linear systems because there are many mathematical tools available for use on linear systems and because many common physical systems and components are linear: Resistors, Inductors, Capacitors

$h[x] = e^x$ *This is a nonlinear system*

Proof:

$$e^{(ax+bx)} = e^{ax} e^{bx} \neq a e^x + b e^x$$

We note that non-linear systems can often be approximated by linear systems

- *The problems we investigate involve a control signal acting on a system*
- *We simplify the solution by representing the control signal as a sequence of elementary functions*
- *Then we need to characterize the response of our system to these elementary functions*
- *Finally, we use the properties of linear systems to obtain the response of the system with the control signal acting on it*
- *Two such commonly used elementary functions are the impulse function and the step function*

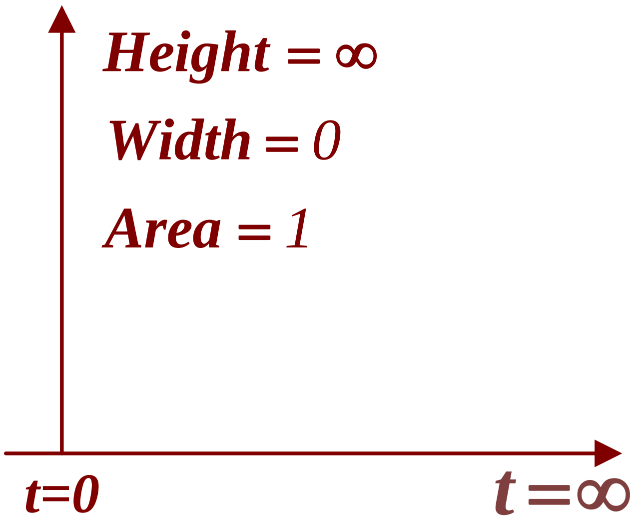
Continuous Dirac delta function, $\delta(t)$ *properties*

$$\delta(t) = 0, \quad t \neq 0 \qquad \delta(t) = \infty, \quad t = 0$$

$$\int_{-\infty}^{\infty} \delta(t)\,dt = 1$$

Functional representation

$$f(t_0) = \int_{-\infty}^{\infty} f(t)\,\delta(t - t_0)\,dt$$

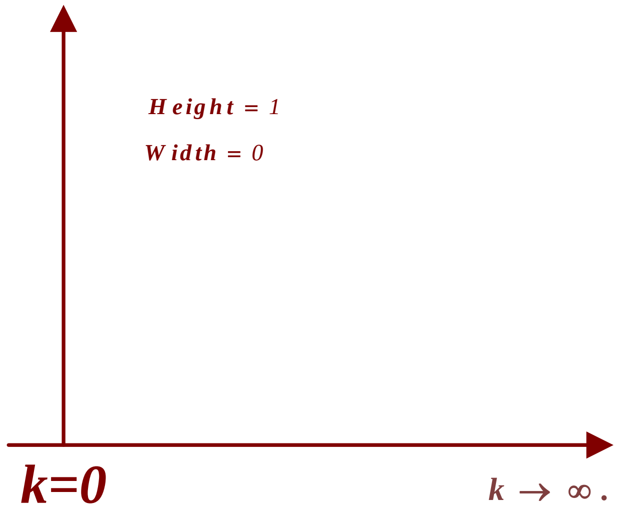


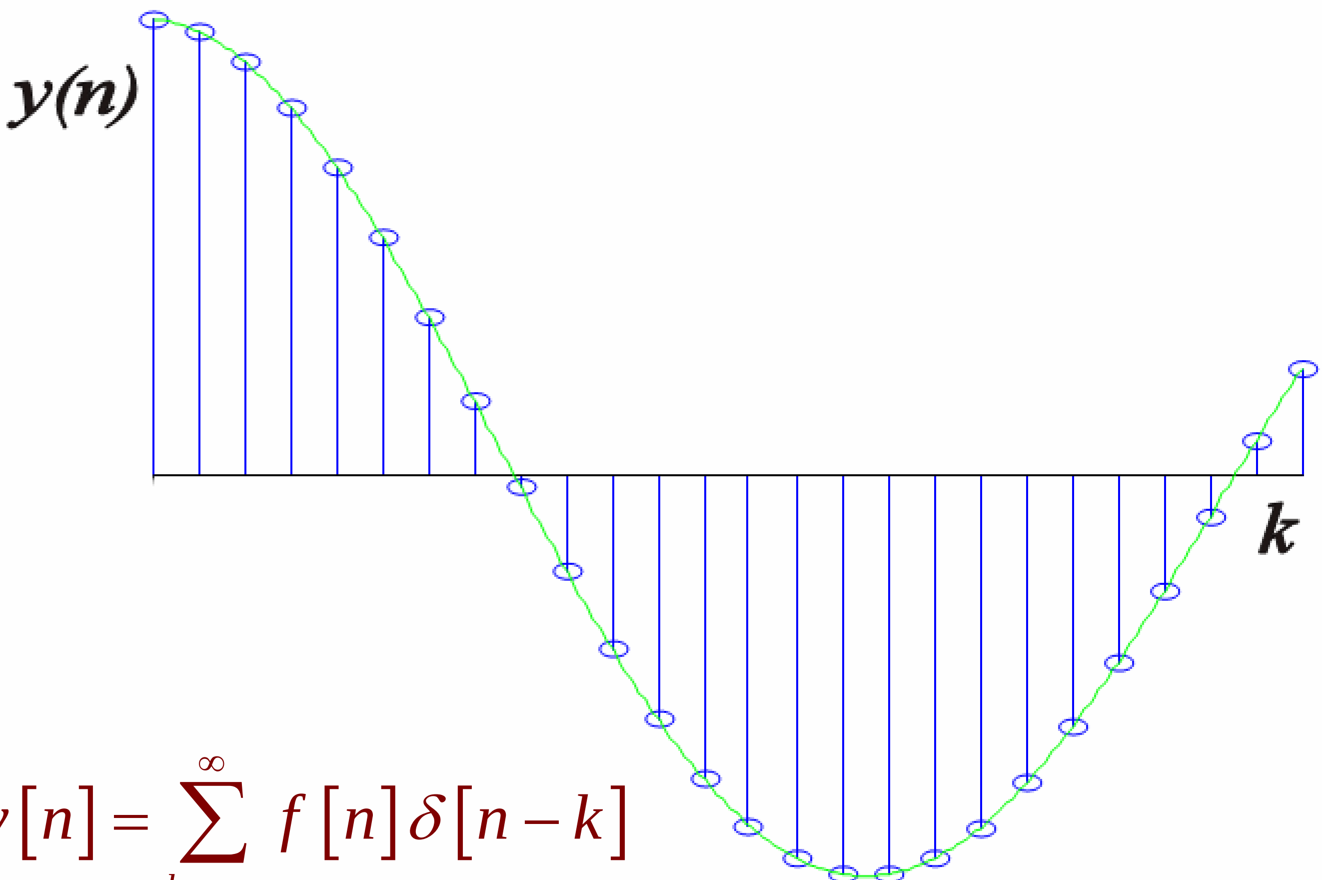
Discrete impulse function properties

$$\delta[n] = 0, \quad n \neq 0 \qquad \delta[n] = 1, \quad n = 0$$

Functional representation

$$f[n] = \sum_{k=-\infty}^{\infty} f[k]\,\delta[k - n]$$



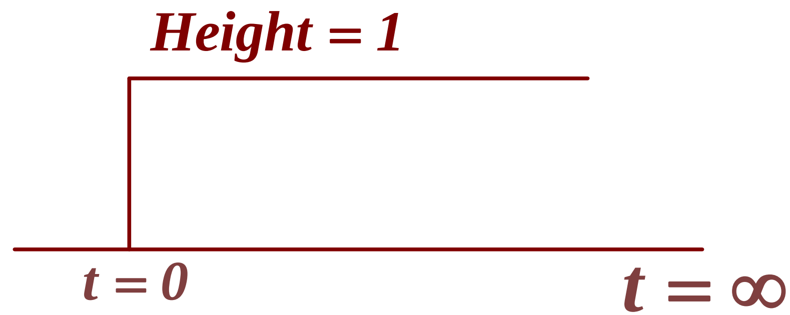


$$y[n]=\sum_{k=-\infty}^{\infty} f[n]\delta[n-k]$$

Mathematical Preliminaries - Continuous Step Function

Properties

$$U(t) = 0, \qquad t < 0$$
$$U(t) = 1, \qquad t \geq 0$$



Relation to Impulse

$$\delta(t) = \frac{d}{dt} U(t)$$

Functional Representation

$$f(t_0) = \int_{-\infty}^{\infty} f(t)\delta(t - t_0)\, dt$$

$$= \int_{-\infty}^{\infty} f(t)\left(\frac{d}{dt} U(t - t_0)\right) dt$$

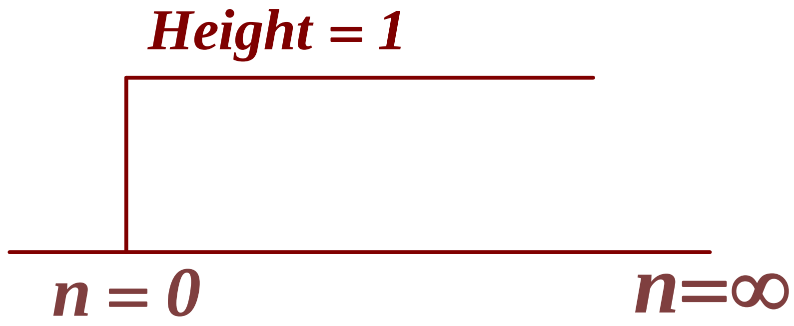
$$= f(t)U(t - t_0)\Big|_{-\infty}^{\infty} - \int_{-\infty}^{\infty} U(t - t_0)\frac{df(t)}{dt}\, dt$$

$$= f(\infty) - \int_{t_0}^{\infty} \frac{df(t)}{dt}\, dt = f(\infty) - \big(f(\infty) - f(t_0)\big) = f(t_0)$$

Heaviside step function

$U[n] = 0, \qquad n < 0$

$U[n] = 1, \qquad n \geq 0$



Relation to impulse

$\delta[n] = U[n] - U[n-1]$

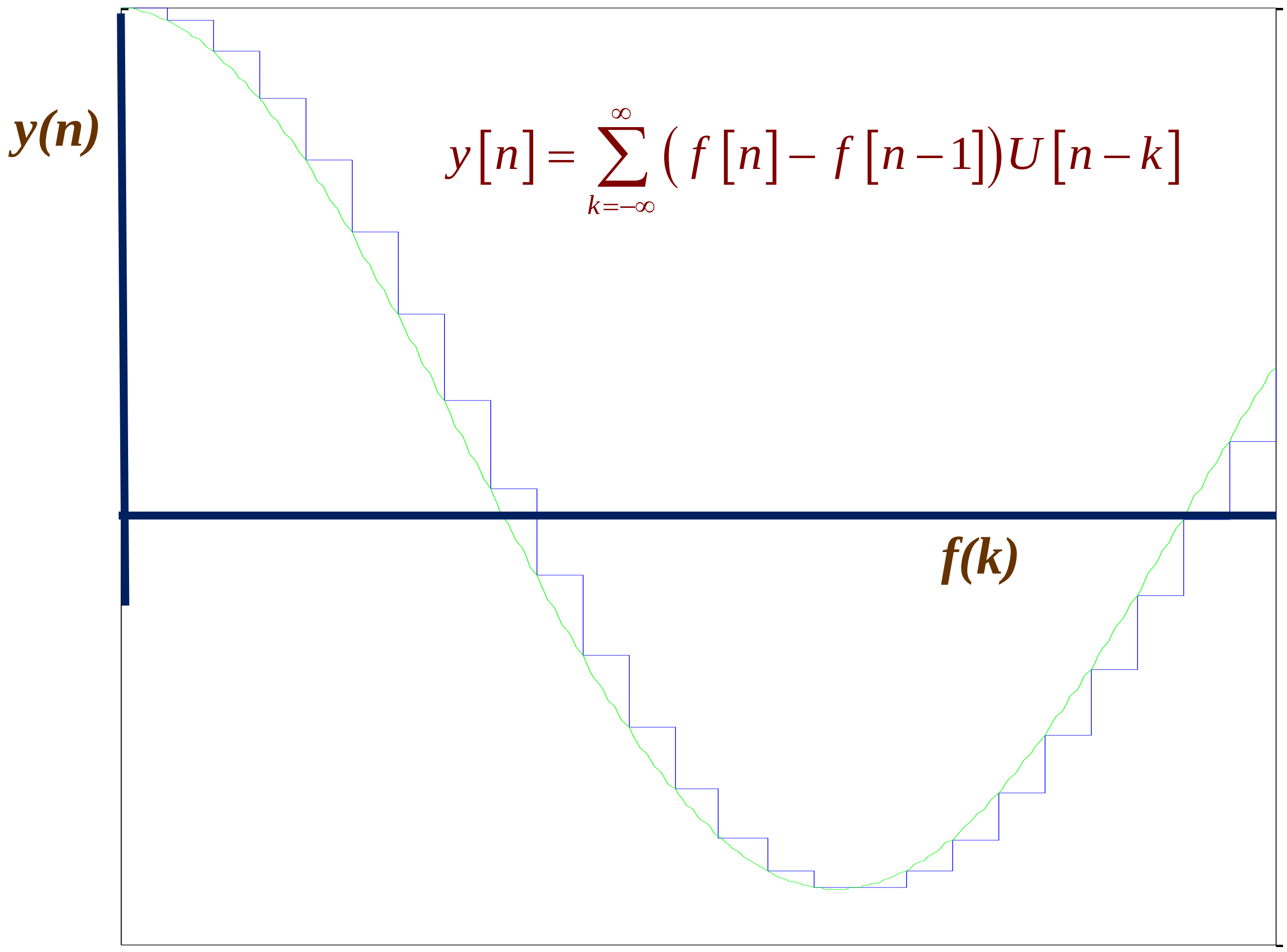
Functional representation

$$f[n] = \sum_{k=-\infty}^{\infty} f[k]\delta[k-n]$$

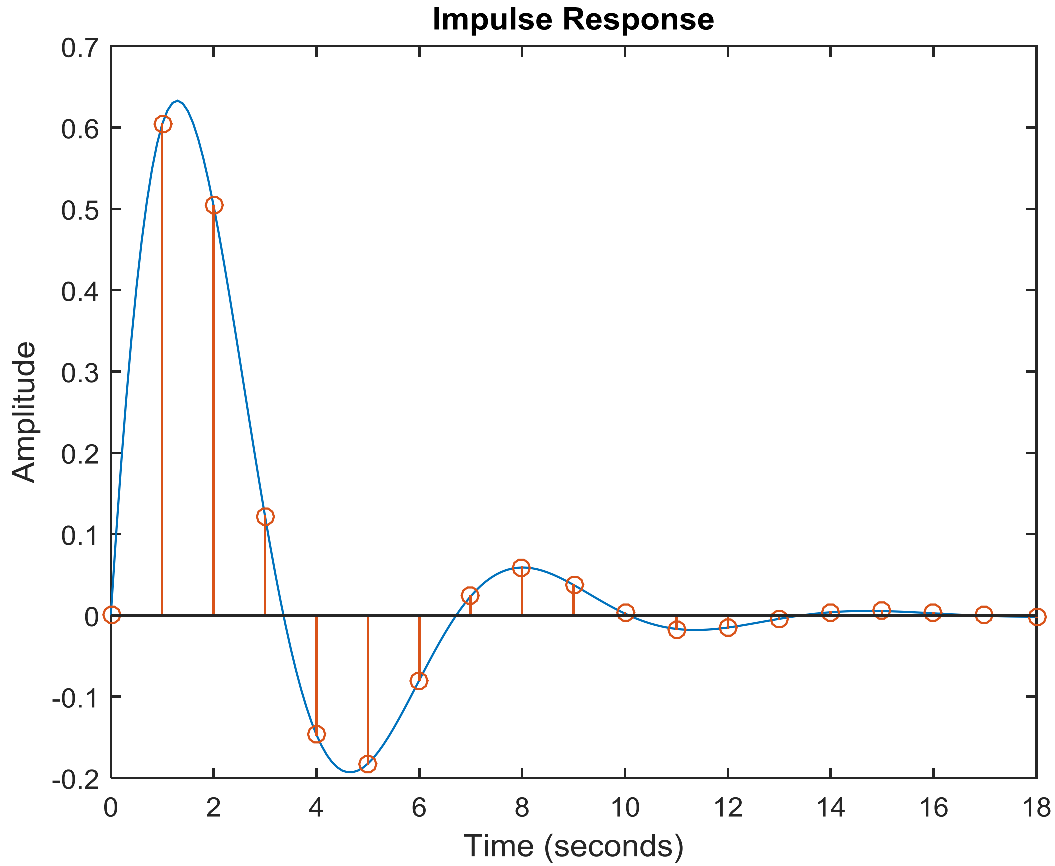
$$= \sum_{k=-\infty}^{\infty} f[k]\left(U[k-n] - U[k-n-1]\right)$$

$$= \sum_{k=-\infty}^{\infty} \left(f[k] - f[k+1]\right) U[k-n]$$

$$= \sum_{k=n}^{\infty} \left(f[k] - f[k+1]\right) = f[n]$$



$$y[n] = \sum_{k=-\infty}^{\infty} \left(f[n] - f[n-1] \right) U[n-k]$$



The impulse response of a general system is causal

There is no response before the impulse occurs

The impulse response, in general, also lasts after the impulse ends

The input to the system can be represented as a series of impulses, $x[k]$.
For each impulse, the output at any later time is the system response to that impulse

$$y[n] = h[n-k]x[k]$$

The total system output for the total system input is

$$y[n] = \sum_{k=-\infty}^{\infty} h[n-k]x[k]$$

where $h[n]$ *is causal, so vanishes for* $n < 0$.

For continuous systems, this is

$$y(t) = \int_{-\infty}^{\infty} h(t-u)x(u)du$$

These are convolution integrals and sums.
If one Fourier-transforms this integral relationship, the convolution integral in the time domain becomes a product in the frequency domain

$$Y(\omega) = H(\omega)X(\omega)$$

We want to convert the convolution integral of the input with the impulse response into the frequency domain.

We first need to define, and then use, a representation of the delta function

$$\delta(\omega - \omega_0) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{j(\omega-\omega_0)t}\,dt$$

Intuition:

For $\omega \neq \omega_0$, the integrand oscillates, so the average value vanishes

For $\omega = \omega_0$, the integrand is unity, and the integral is infinite

We now return to the convolution integral

$$y(t) = \int_{-\infty}^{\infty} h(t-u)x(u)du$$

and insert the transforms for $h(t-u)$ *and* $x(u)$

$$y(t) = \frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} H(\omega)e^{j\omega(t-u)}X(\omega_1)e^{j\omega_1 u}du\, d\omega_1 d\omega$$

$$= \frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} H(\omega)X(\omega_1)e^{j\omega t}e^{j(\omega_1-\omega)u}du\, d\omega_1 d\omega$$

$$= \frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} H(\omega)X(\omega_1)e^{j\omega t}\delta(\omega_1-\omega)d\omega_1 d\omega$$

$$= \frac{1}{2\pi}\int_{-\infty}^{\infty} H(\omega)X(\omega)e^{j\omega t}d\omega = \frac{1}{2\pi}\int_{-\infty}^{\infty} Y(\omega)e^{j\omega t}\, d\omega$$

Therefore $\quad Y(\omega) = H(\omega)X(\omega)$

The transform of the output equals the product of the transform of the input multiplied by the transform of the impulse response.

Given an input, $x(t)$, a system, $h(t)$, and an output, $y(t)$, the Transfer Function is the Fourier Transform of $h(t)$

$$H(\omega) = \int_{-\infty}^{\infty} h(t) e^{-j\omega t}\, dt$$

$$H(\omega) = \frac{Y(\omega)}{X(\omega)}$$

where

$$Y(\omega) = \int_{-\infty}^{\infty} y(t) e^{-j\omega t}\, dt$$

$$X(\omega) = \int_{-\infty}^{\infty} x(t) e^{-j\omega t}\, dt$$

- *Fourier transforms represent some of the Eigen functions as combinations (sums/integrals) of complex exponentials.*
- *The standard Fourier transform pair for continuous functions is*

$$F(\omega) = \int_{-\infty}^{\infty} f(t)\, e^{-j\omega t} dt \qquad f(t) = \int_{-\infty}^{\infty} F(\omega)\, e^{j\omega t} \frac{d\omega}{2\pi}$$

- *For periodic systems, with a period,* T, *the only complex eigenvectors that can be used to represent the signals are those whose frequencies are multiples of the "fundamental harmonic",* $\omega = 2\pi/T$.

- *Periodic functions are represented by the infinite sums of the appropriately weighted harmonics. In this case the Fourier transform pairs are*

$$F_n = \frac{1}{T} \int_{-T/2}^{T/2} f(t)\, e^{-j\frac{2\pi n}{T}t} dt \qquad f(t) = \sum_{n=-\infty}^{\infty} F_n e^{j\frac{2\pi n}{T}t}$$

Using Euler's formula, we can also represent these relations as

$$f(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos\frac{2\pi n}{T}t + \sum_{n=1}^{\infty} b_n \sin\frac{2\pi n}{T}t$$

The series is complete, that is, it can represent any continuous function

The terms of the series are orthogonal

$$a_0 = \frac{1}{T}\int_0^T f(t)\,dt$$

$$a_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\cos\frac{2\pi n}{T}t\,dt$$

$$b_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\sin\frac{2\pi n}{T}t\,dt$$

- *The DC term is orthogonal to all others*

$$\int_{-T/2}^{T/2} \cos\frac{2\pi nt}{T}dt \;=\; \int_{-T/2}^{T/2} \sin\frac{2\pi nt}{T}dt = 0$$

- *The sinusoidal terms are periodic, so the integral over one period vanishes.*

- *All cosine terms are orthogonal to all sine terms. Using* $\sin A \cos B = 1/2[\sin(A+B) + \sin(A-B)]$

$$\int_{-T/2}^{T/2} \cos\frac{2\pi nt}{T}\sin\frac{2\pi mt}{T}dt$$

$$= \frac{1}{2}[\int_{-T/2}^{T/2} \sin\frac{2\pi(m+n)t}{T}dt + \int_{-T/2}^{T/2} \sin\frac{2\pi(m-n)t}{T}dt] = 0$$

- *Cosine terms are orthogonal to other cosine terms. Using* $\cos A \cos B = 1/2[\cos(A+B) + \cos(A-B)]$ *we get*

$$\int_{-T/2}^{T/2} \cos\frac{2\pi nt}{T} \cos\frac{2\pi mt}{T} dt$$

$$= \frac{1}{2}\left[\int_{-T/2}^{T/2} \cos\frac{2\pi(n+m)t}{T} dt + \int_{-T/2}^{T/2} \cos\frac{2\pi(n-m)t}{T} dt\right]$$

$$= \begin{cases} 1/2 & n = m \\ 0 & n \neq m \end{cases}$$

- *Using* $\sin A \sin B = 1/2[\cos(A-B) - \cos(A+B)]$, *we find the same relationship for products of sine terms.*

- *Using the calculations above, we represent the Fourier series of the periodic function* $f(t)$

$$f(t) = a_0 + \sum_{n=1}^{\infty}\left(a_n \cos\frac{2\pi nt}{T} + b_n \sin\frac{2\pi nt}{T}\right)$$

where

$$a_0 = \frac{1}{T}\int_{-T/2}^{T/2} f(t)\,dt$$

$$a_n = \frac{2}{T}\int_{T/2}^{T/2} f(t)\cos\frac{2\pi nt}{T}\,dT$$

$$b_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\sin\frac{2\pi nt}{T}\,dT$$

$$f(t) = \begin{cases} 0 & -T/2 \le t < 0 \\ 1 & 0 \le t < T/2 \end{cases}$$

$$a_0 = \frac{1}{T}\int_0^{T/2} dt = \frac{1}{2}$$

$$a_n = \frac{2}{T}\int_0^{T/2} \cos\frac{2\pi n t}{T}\,dt = \frac{2}{T}\frac{T}{2\pi n}\sin\frac{2\pi n t}{T}\Big|_0^{T/2} = \frac{1}{\pi n}\sin n\pi = 0$$

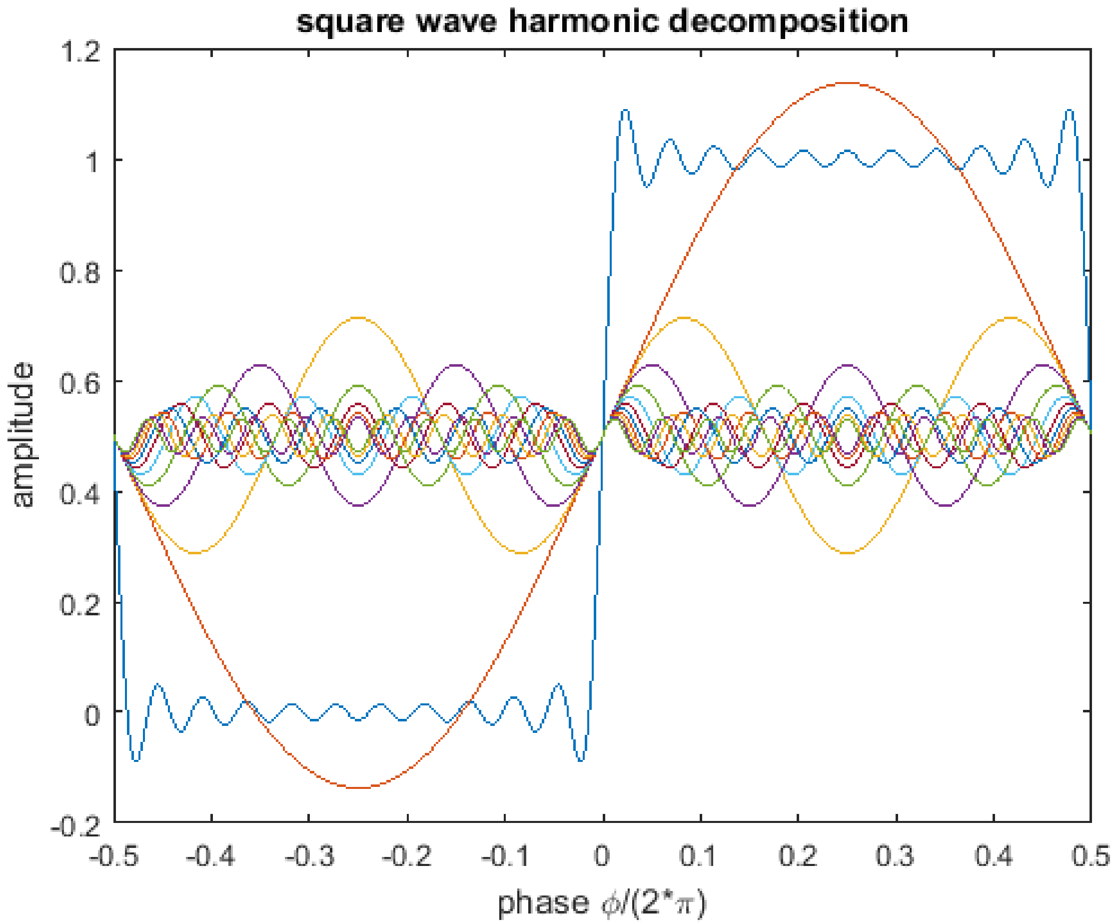
$$b_n = \frac{2}{T}\int_0^{T/2} \sin\frac{2\pi n t}{T}\,dt = -\frac{1}{\pi n}\cos\frac{2\pi n t}{T}\Big|_0^{T/2} = \frac{1}{\pi n}(1-\cos n\pi)$$

$$= \frac{1}{\pi n}(1-(-1)^n)$$

$$f(t) = \frac{1}{2} + \sum_{n=1}^{\infty}\frac{1}{\pi n}(1-(-1)^n)\sin\frac{2\pi n t}{T}$$

$$f(t) = \frac{1}{2} + \frac{2}{\pi}\sum_{n=0}^{\infty}\frac{1}{2n+1}\sin\frac{2\pi(2n+1)t}{T}$$

- *Fundamental term dominates*
- *Harmonic terms mainly contribute to sharp transition at edge*
- *Since the square wave function is discontinuous, the edges have "Gibbs ears"*



Mathematical Preliminaries – Fourier Triangle Wave Expansion

$$f(t) = \begin{cases} 1 + 2t/T & -T/2 \le t < 0 \\ 1 - 2t/T & 0 \le t < \mathrm{T}/2 \end{cases}$$

$$a_0 = \frac{1}{T}\left[\int_{-T/2}^{0} (1 + 2t/T)\, dt + \int_{0}^{T/2} (1 - 2t/T)\, dt\right]$$

$$= \frac{1}{T}\left[\left(t + \frac{2}{T}\frac{t^2}{2}\right)\Big|_{-T/2}^{0} + \left(t - \frac{2}{T}\frac{t^2}{2}\right)\Big|_{0}^{T/2}\right]$$

$$= \frac{1}{T}\left[\left(\frac{T}{2} - \frac{1}{T}\left(\frac{T}{2}\right)^2\right) + \left(\frac{T}{2} - \frac{1}{T}\left(\frac{T}{2}\right)^2\right)\right] = \frac{1}{2}$$

Mathematical Preliminaries – Fourier Triangle Wave Expansion

$$a_n = \frac{2}{T}[\int_{-T/2}^{0}\left(1+\frac{2t}{T}\right)\cos\frac{2\pi nt}{T}dt + \int_{0}^{T/2}\left(1-\frac{2t}{T}\right)\cos\frac{2\pi nt}{T}dt]$$

$$= \frac{2}{T}\left[\int_{-T/2}^{T/2}\cos\frac{2\pi nt}{T}dt + \frac{2}{T}\int_{-T/2}^{0}t\cos\frac{2\pi nt}{T}dt - \frac{2}{T}\int_{0}^{T/2}t\cos\frac{2\pi nt}{T}dt\right]$$

$$= \left(\frac{2}{T}\right)^2\left[\int_{-T/2}^{0}t\cos\frac{2\pi nt}{T}dt - \int_{0}^{T/2}t\cos\frac{2\pi nt}{T}dt\right]$$

$$= -2\left(\frac{2}{T}\right)^2\int_{0}^{T/2}t\cos\frac{2\pi nt}{T}dt$$

$$= -2\left(\frac{2}{\mathrm{T}}\right)^2[\frac{\mathrm{T}}{2\pi n}\mathrm{t}\sin\frac{2\pi nt}{T}\Big|_0^{T/2} - \frac{T}{2\pi n}\int_{0}^{T/2}\sin\frac{2\pi nt}{T}dt]$$

$$= 2\left(\frac{2}{T}\right)^2\left(\frac{T}{2\pi n}\right)^2(1-\cos n\pi) = \frac{2}{(\pi n)^2}(1-(-1)^n)$$

$$\mathrm{b_n} = \frac{2}{T}\left[\int_{-T/2}^{T/2} \sin\frac{2\pi nt}{T}dt + \frac{2}{T}\int_{-T/2}^{0} t\sin\frac{2\pi nt}{T}dt - \frac{2}{T}\int_{0}^{T/2} t\sin\frac{2\pi nt}{T}dt\right]$$

$$= \left(\frac{2}{T}\right)^2 [-\frac{T}{2\pi n}t\cos\frac{2\pi nt}{T}\Big|_{-T/2}^{0} + \frac{T}{2\pi n}\int_{-T/2}^{0}\cos\frac{2\pi nt}{T}dt$$

$$+ \frac{T}{2\pi n}t\cos\frac{2\pi nt}{T}\Big|_{0}^{T/2} - \frac{T}{2\pi n}\int_{0}^{T/2}\cos\frac{2\pi nt}{T}dt]$$

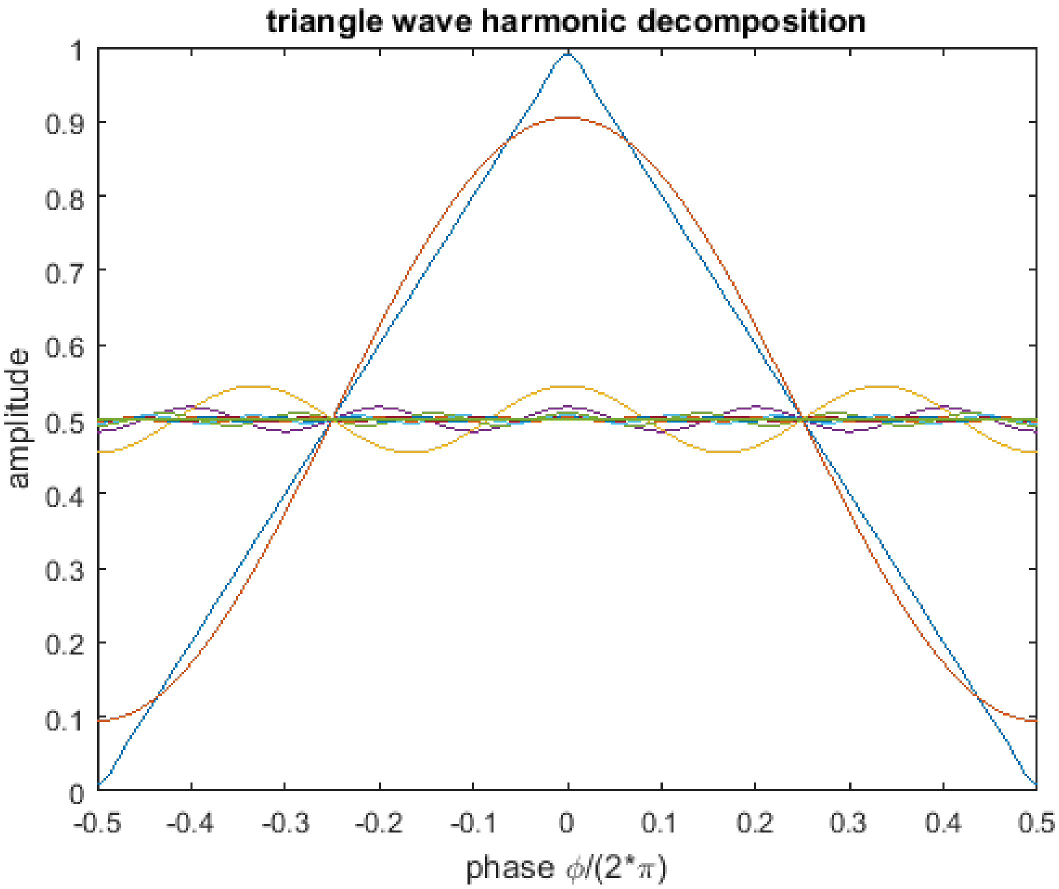
$$= \left(\frac{2}{T}\right)^2 \left[-\frac{T}{2\pi n}\frac{T}{2}\cos(-n\pi) - \left(\frac{T}{2\pi n}\right)^2 \sin\left(-\mathrm{n}\pi\right) + \frac{\mathrm{T}}{2\pi n}\frac{\mathrm{T}}{2}\cos\left(n\pi\right)\right.$$

$$\left. - \left(\frac{T}{2\pi n}\right)^2 \sin n\pi\right] = 0$$

$$f(t) = \frac{T}{2} + \sum_{n=1}^{\infty}\frac{2}{(n\pi)^2}\left(1 - (-1)^n\right)\cos\frac{2\pi nt}{T}$$

$$f(t) = \frac{T}{2} + \left(\frac{2}{\pi}\right)^2 \sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\cos\frac{2\pi(2n+1)t}{T}$$

- *Fundamental term again dominates*
- *Now harmonics mainly contribute to peaks*
- *Sharp corners require high harmonics*
- *Triangle wave is continuous so expansion approaches waveform everywhere*



- *When working with linear, time-invariant systems, there are several advantages to moving from the time domain to the frequency domain.*
- *If* $x_1 \rightarrow y_1$ *and* $x_2 \rightarrow y_2$ *and if* $ax_1 + bx_2 \rightarrow ay_1 + by_2$
then the system is ***linear****.*
- *If* $x(t) \rightarrow y(t)$ *and if* $x(t - t_0) \rightarrow y(t - t_0)$
then the system is ***time-invariant****.*
- *Each frequency corresponds to a unique eigenfunction of the system and the system response for each frequency can be calculated independently.*

- There is another transform often used in system analysis, the Laplace transform.
- It is closely related to the Fourier transform in that it is also based on system eigenfunctions.
- In addition to "real" frequencies, it also uses complex frequencies that allow it to also study decaying solutions.
- As with Fourier transform, integral must converge in order for transform to exist.
- It is convenient to use Laplace transforms for the study of solutions to problems with initial conditions.
- The variable used in Laplace transforms is often $s = j\omega$

- *The Laplace transform is used for analysis of systems with given initial conditions*

- *For a given function of time, $f(t)$, its Laplace transform, F(s), is defined as*

$$\mathcal{L}\big(f(t)\big) = F(s) = \int_0^\infty f(t)e^{-st}dt$$

- $f(t)$ *has to grow less quickly than* e^{-st} *descreases as* $t \to \infty$

- *When working in the frequency* (s) *domain, we express transfer functions in terms of known Laplace transforms and take the inverse transform,* $\mathcal{L}^{-1}(F(s))$, *to obtain the time domain solution.*

- ***Delta function:*** $f(t) = \delta(t)$

$$F(s) = \int_0^\infty \delta(t)e^{-st}dt = 1$$

- ***Delta function with delay:*** $f(t) = \delta(t - t_0), t \geq 0$

$$F(s) = e^{-st_0}$$

- ***Step function:*** $f(t) = U(t)$

$$F(s) = \int_0^\infty U(t)e^{-st}dt = \int_0^\infty e^{-st}dt = -\frac{1}{s}e^{-st}\Big|_0^\infty = \frac{1}{s}$$

- ***Step function with delay:*** $f(t) = U(t - t_0), t \geq 0$

$$F(s) = \frac{e^{-st_0}}{s}$$

- ***Ramp function:*** $f(t) = t$

  Use integration by parts (IBP)

  $$\int_a^b u dv = uv\Big|_a^b - \int_a^b v du$$

  $$u = t; du = dt; dv = e^{-st}dt; v = -e^{-st}/s$$

  $$F(s) = \int_0^\infty te^{-st}dt = -\frac{t}{s}e^{-st}\Big|_0^\infty + \frac{1}{s}\int_0^\infty e^{-st}dt = \frac{1}{s^2}$$

- ***Exponential function:*** $f(t) = e^{at}$ *with a an arbitrary complex number*

  $$F(s) = \int_0^\infty e^{at}e^{-st}dt = \int_0^\infty e^{-(s-a)t}dt$$

  $$F(s) = -\frac{1}{s-a}e^{-(s-a)t}\Big|_0^\infty = \frac{1}{s-a}$$

  Only if $\lim_{t\to\infty} e^{-(s-a)t}$ *exists does F(s) exist. Therefore* $Re(a) \leq 0$. *Note that a can be imaginary.*

- ***Sinusoidal functions:*** $f(t) = \cos\omega t \qquad f(t) = \sin\omega t$

  We could do this from the definition and IBP, but instead we use Euler's formula, exponential transforms, and the linearity of the Laplace transform

$$F(s) = \int_0^\infty \cos\omega t\, e^{-st} dt = \frac{1}{2}\int_0^\infty \left(e^{j\omega t} + e^{-j\omega t}\right) e^{-st} dt$$

$$= \frac{1}{2}\left(\int_0^\infty e^{-(s-j\omega)t} dt + \int_0^\infty e^{-(s+j\omega)t} dt\right) = \frac{1}{2}\left(\frac{1}{s-j\omega} + \frac{1}{s+j\omega}\right)$$

$$F(s) = \frac{s}{s^2+\omega^2}$$

$$F(s) = \int_0^\infty \sin\omega t e^{-st} dt = \frac{\omega}{s^2+\omega^2}$$

- ***Transform of a derivative:*** $f(t) = \frac{dg(t)}{dt}$

$$F(s) = \int_0^\infty \frac{dg(t)}{dt} e^{-st} dt$$

$$= g(t)e^{-st}\Big|_0^\infty + \int_0^\infty sg(t)e^{-st} dt$$

$$= g(t)e^{-st}\Big|_0^\infty + s\int_0^\infty g(t)e^{-st} dt$$

$$F(s) = sG(s) - g(0)$$

where we have used integration by parts and $G(s) = \int_0^\infty g(t)e^{-st} dt$

$\boldsymbol{f(t)} = \mathcal{L}^{-1}(F(s))$	$F(s) = \mathcal{L}(f(t))$
$\delta(t)$	1
$U(t)$	$\frac{1}{s}$
t	$\frac{1}{s^2}$
e^{-at}	$\frac{1}{s+a}$
$\cos\omega t$	$\frac{s}{s^2+\omega^2}$
$\sin\omega t$	$\frac{\omega}{s^2+\omega^2}$
$e^{-at}\cos\omega t$	$\frac{s+a}{(s+a)^2+\omega^2}$
$e^{-at}\sin\omega t$	$\frac{\omega}{(s+a)^2+\omega^2}$
$\frac{dg(t)}{dt}$	$sG(s) - g(0)$
$f(t-t_0)$	$e^{-st_0}F(s)$

Mathematical Preliminaries - Inverting Laplace Transforms

- *Laplace Transforms simplify the calculations of system behavior, but these calculations are performed in the complex frequency (s) domain.*
- *In order to return to a time domain function, the s domain function must be inverted.*
- *Inversion of these functions can be performed via complex variable techniques.*
- *Much more commonly, one uses readily available tables of functions and their Laplace transform pairs*
- *There also exist such transform tables for Fourier transforms.*

http://www.vibrationdata.com/Laplace.htm
http://en.wikipedia.org/wiki/Laplace_transform
http://mathworld.wolfram.com/FourierTransform.html
http://en.wikipedia.org/wiki/Fourier_transform

- ***Response of a single pole low pass filter to an impulse***

$$H(s) = \frac{a}{s+a}$$

$$(H(j\omega) = \frac{a}{j\omega + a})$$

$$(H(0) = 1;\ \ 3 \text{ dB rolloff at } \omega = a)$$

$$X(s) = 1$$

$$Y(s) = H(s)X(s) = \frac{a}{s+a}$$

$$y(t) = \mathcal{L}^{-1}\big(Y(s)\big) = \mathcal{L}^{-1}\left(\frac{a}{s+a}\right)$$

$$y(t) = e^{-at}$$

- ***Response to a step:***

$$Y(s) = H(s)X(s) = \frac{a}{s+a}\frac{1}{s}$$

$$y(t) = \mathcal{L}^{-1}\left(\frac{a}{s+a}\frac{1}{s}\right)$$

Use partial fractions to expand argument and then linearity of $\mathcal{L}$

$$\frac{a}{s(s+a)} = \frac{A}{s} + \frac{B}{s+a} \qquad\qquad a = (s+a)A + sB$$

$$s = 0 \Rightarrow A = 1$$

$$s = -a \Rightarrow B = -1$$

$$y(t) = \mathcal{L}^{-1}\left(\frac{a}{s+a}\frac{1}{s}\right) = \mathcal{L}^{-1}\left(\frac{1}{s} - \frac{1}{s+a}\right) = \mathcal{L}^{-1}\left(\frac{1}{s}\right) - \mathcal{L}^{-1}\left(\frac{1}{s+a}\right)$$

$$= 1 - e^{-at}$$

- ***Response to an exponential:***

$$x(t) = e^{-bt}$$

$$X(s) = \mathcal{L}\left(e^{-bt}\right) = \frac{1}{s+b}$$

$$Y(s) = H(s)X(s) = \frac{a}{s+a}\frac{1}{s+b}$$

$$y(t) = \mathcal{L}^{-1}\left(\frac{\mathrm{a}}{\mathrm{s+a}}\frac{1}{\mathrm{s+b}}\right) = \frac{a}{b-a}\mathcal{L}^{-1}\left(\frac{1}{s+a} - \frac{1}{s+b}\right)$$

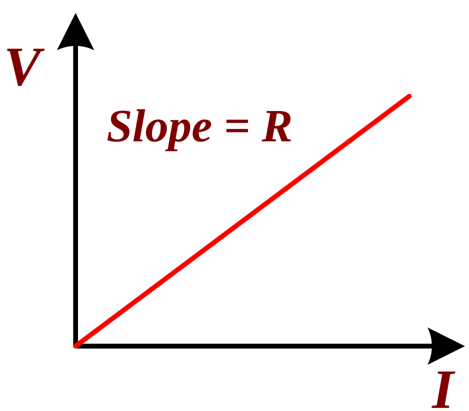
$$= \frac{a}{b-a}\left(e^{-at} - e^{-bt}\right)$$

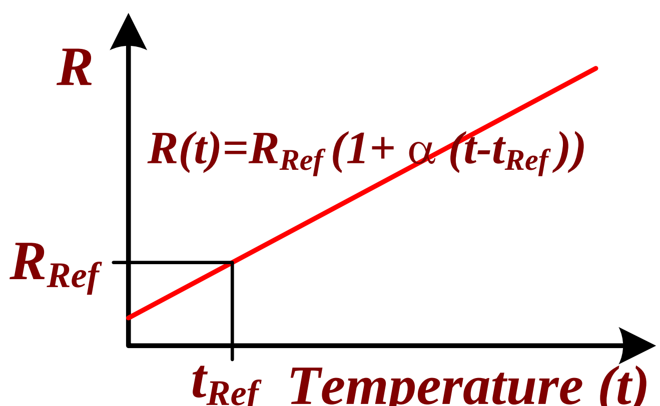
Section 4

- *Typical Load Types*
  - *Resistive – Electron Beam Filament*
  - *Resistive - Titanium Sublimation Pumps (TSPs)*
  - *DC Magnets*
  - *Klystrons*
  - *Electron Beam Gun*
  - *Pulsed Magnets*

Electron Beam Guns (Filament) / Titanium Sublimation Pump Heaters

- High temperature – 1,500 ^{O} C not uncommon
- High current – 10 to 100s of amperes, low voltage, typically < 50 V
- Short thermal time-constants - 100s of milliseconds, power stability needed to keep temperature constant
- Resistive with (+) metal or (-) carbon temperature coefficient of resistance
- Power with constant voltage, current or power. Might have to avoid DC (more later in AC Controllers) depending upon circumstances
- Heat gradually to avoid thermally shocking and breaking brittle loads
- Usually linear V-I and R-T characteristics, but sometimes non-linear





Resistive Load Characteristics

Electron Beam Gun Filaments / Titanium Sublimation Pump Heaters

Ideal Characteristics

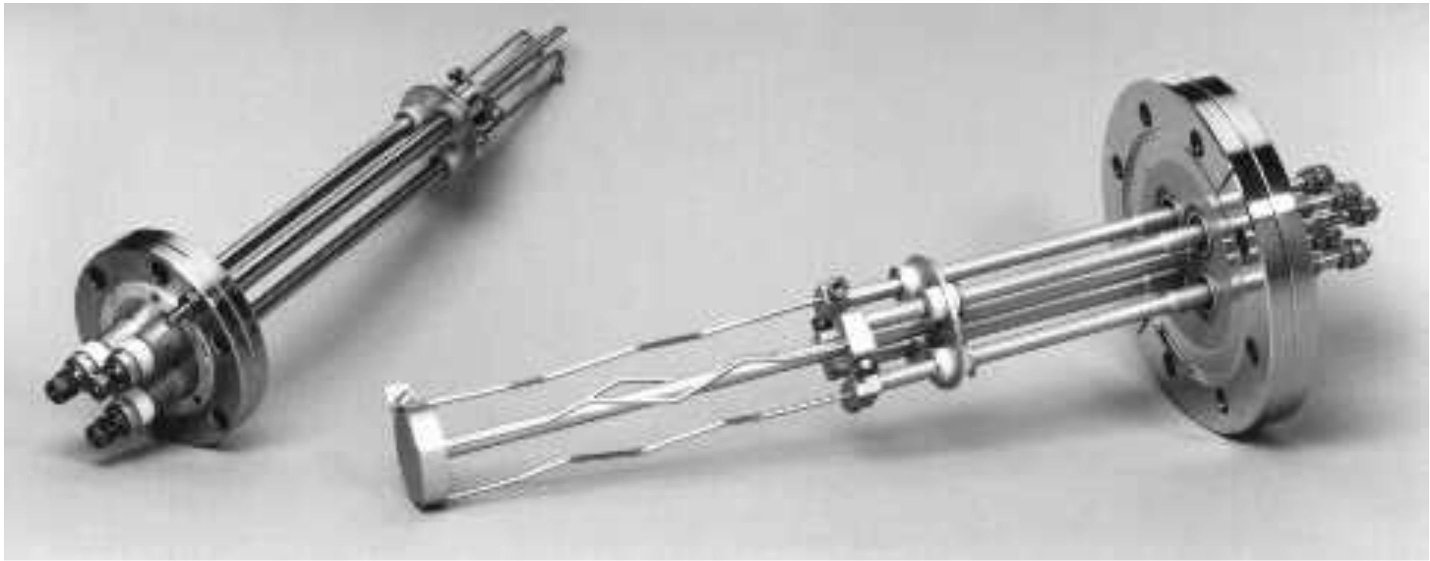
- *Low potential barrier (work function)*
- *High melting point*
- *Chemical stability at high temperatures*
- *Long life*

Work function *- the minimum energy which must be supplied to extract an electron from a solid; symbol ϕ, units J (joule), or more often eV (electron-volt). It is a measure of how tightly electrons are bound to a material. The work function of several metals is given below:*

Material	***Work function (eV)***
Sodium	*2.75*
Silver	*4.26*
Titanium	*4.33*
Silicon	*4.60*
Gold	*5.31*
Graphite	*5.37*
Tungsten	*5.40*

Titanium Sublimation Pumps (TSPs)

- Titanium Sublimation Pumps (TSPs) are used to pump chemically reactive, getterable gases, such as H_2, H_2O, CO, N_2, O_2, CO_2 from vacuum vessels. Titanium is effective, easily sublimed, and inexpensive.
- TSPs filaments are 85% titanium and 15% molybdenum, a combination which prevents premature filament "burnout" and have high pumping speeds, typically 10 l / sec / cm^2

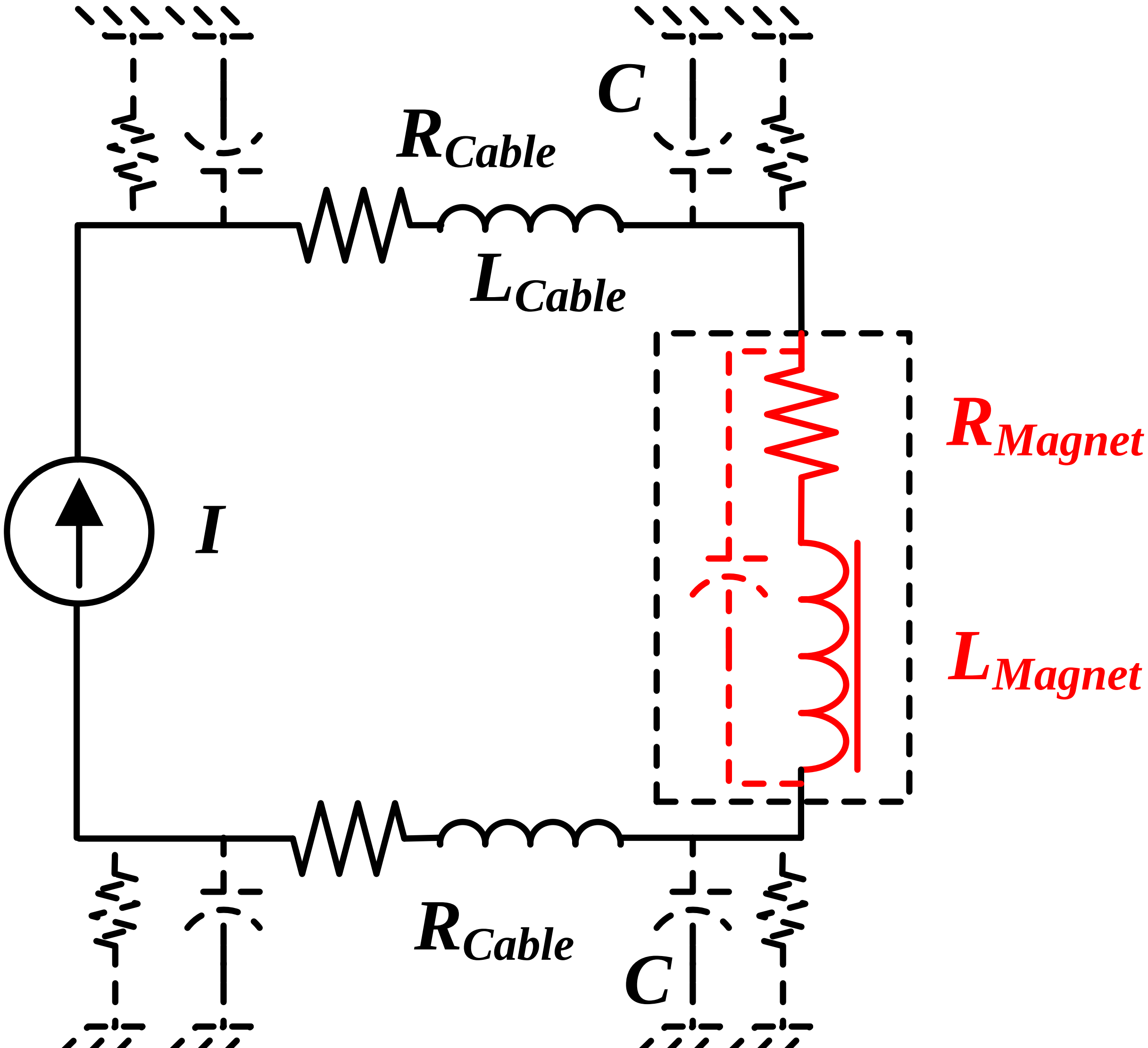


Sublimate - To transform directly from the solid to the gaseous state. Deposition is the passing from the gaseous to the solid state without becoming a liquid.

DC Magnet Loads – Characteristics

- *Linear and inductive with long (mS to sec) electrical time-constants (τ = L/R)*
- *Families include dipole steering, quadrupole and sextupole focusing / defocusing, corrector / trims*
- *Driven by constant current and require high current stability (Δ I in PPM)*
- *Correctors / trims frequently require current modulation for beam-based alignment / diagnostic systems, orbit correction and stabilization*
- *Air-cooled or water-cooled (temperature or flow interlocks to power supply)*
- *Occasionally series-connected in strings and powered from a common power supply to reduce power system cost*

DC Magnet Loads – Characteristics



Ampere's Law

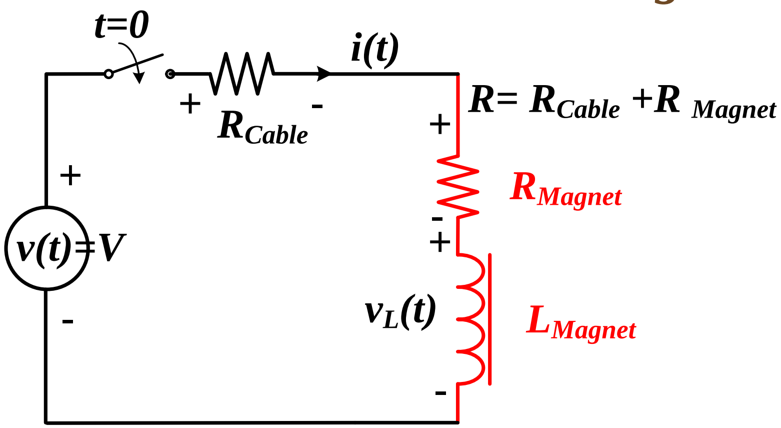
$$B = \mu H = \frac{\mu_r \mu_0 N I}{l}$$

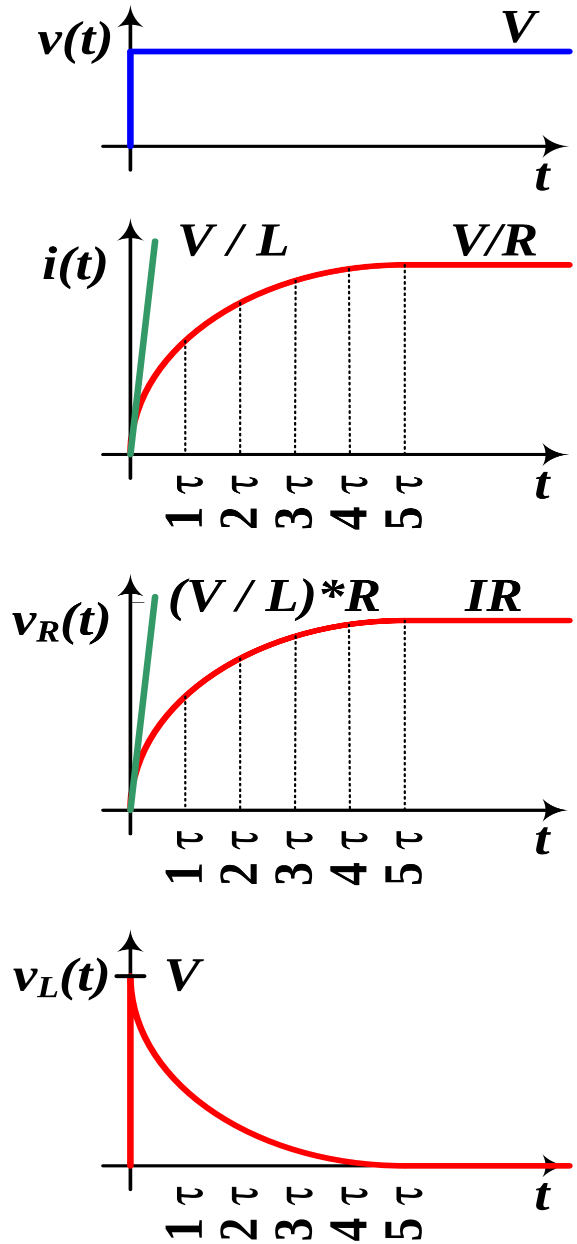
Lorentz Force Law

$$F = q(E + (v \times B))$$

Representation

DC Magnet Loads – Characteristics





Using Kirchoff's voltage law (KVL):

$$-v(t) + (R_{cable} + R_{magnet})\, i(t) + L\frac{di(t)}{dt} = 0$$

$$R\, i(t) + L\frac{di(t)}{dt} = v(t)$$

Converting to the s domain

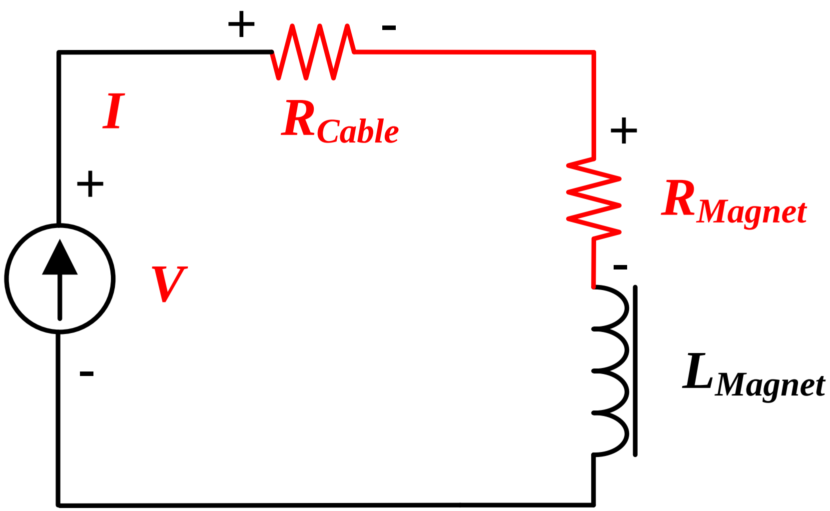
$$R\, I(s) + LsI(s) - L\, i(0) = V(s), \qquad \text{But } i(0) = 0 \text{ and } V(s) = \frac{V}{s}$$

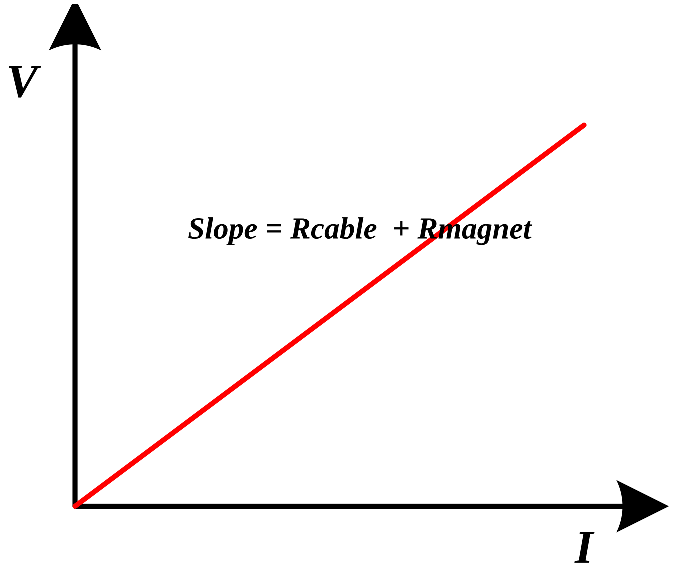
Rearranging gives

$$I(s)\frac{L}{R}\left(s + \frac{R}{L}\right) = \frac{V}{R}\frac{1}{s} \qquad \text{let } \frac{R}{L} = \alpha \text{ and } \frac{L}{R} = \frac{1}{\alpha} = \tau$$

$$I(s) = \frac{V}{R}\,\frac{\alpha}{s(s+\alpha)} \qquad i(t) = \frac{V}{R}\left(1 - e^{-\frac{t}{\tau}}\right)$$

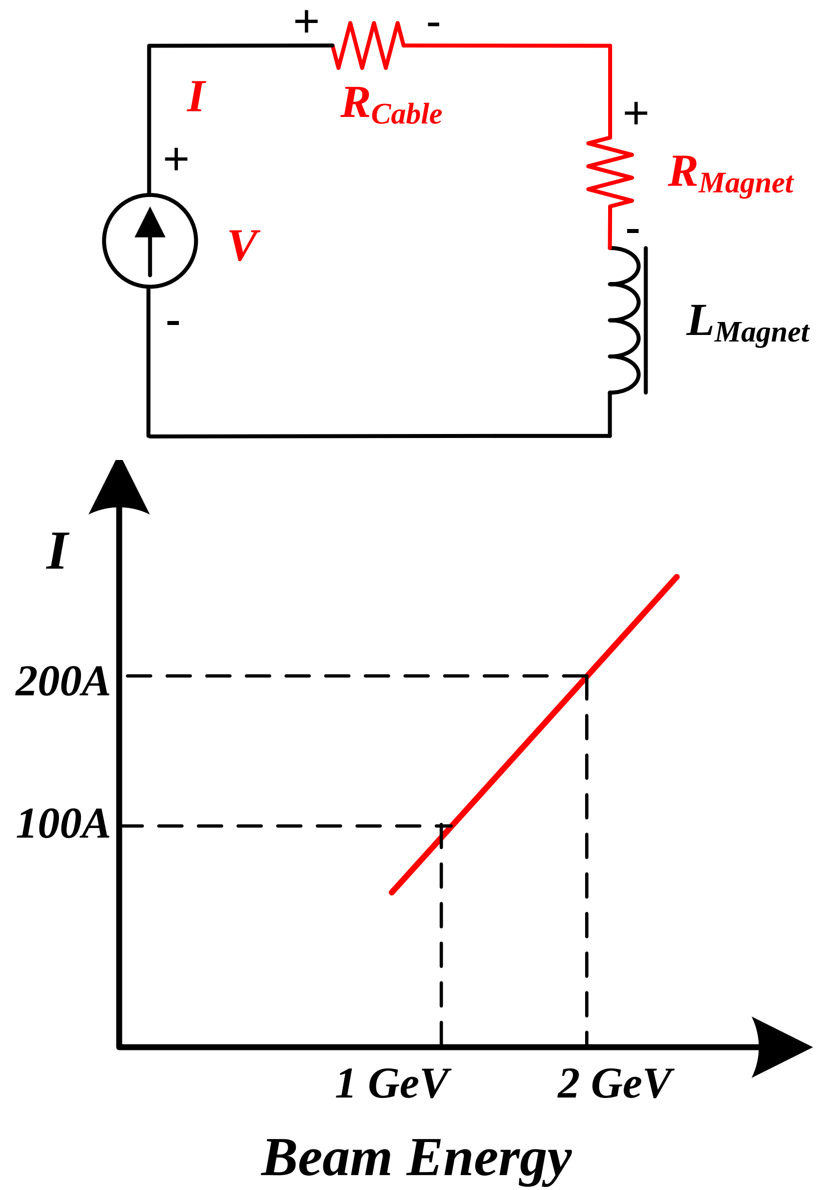
$$v_L(t) = Ve^{-t/\tau}$$



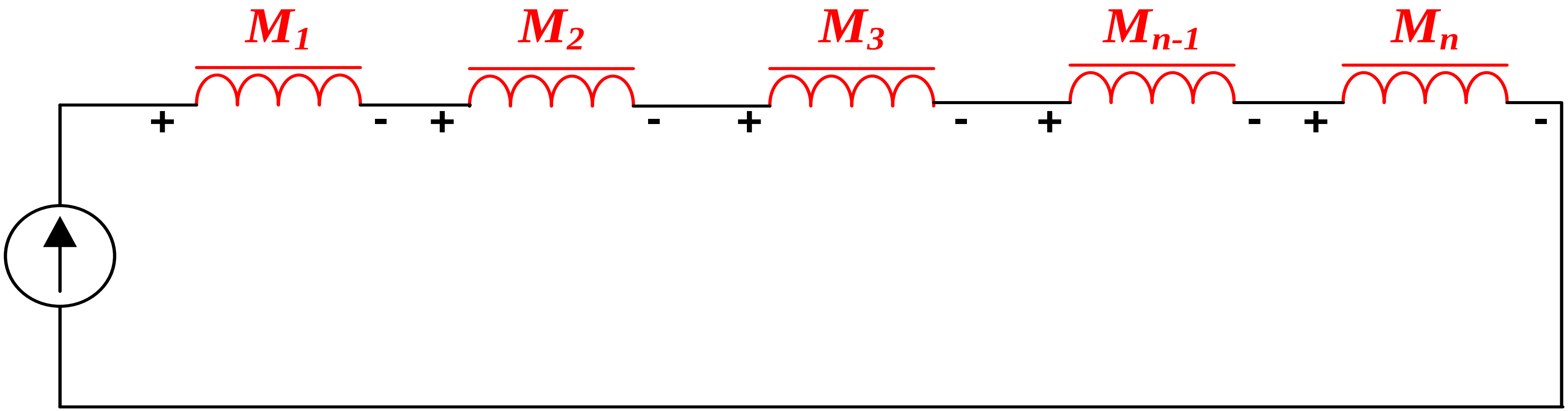


DC V-I Characteristic

DC Magnet Loads – Characteristics



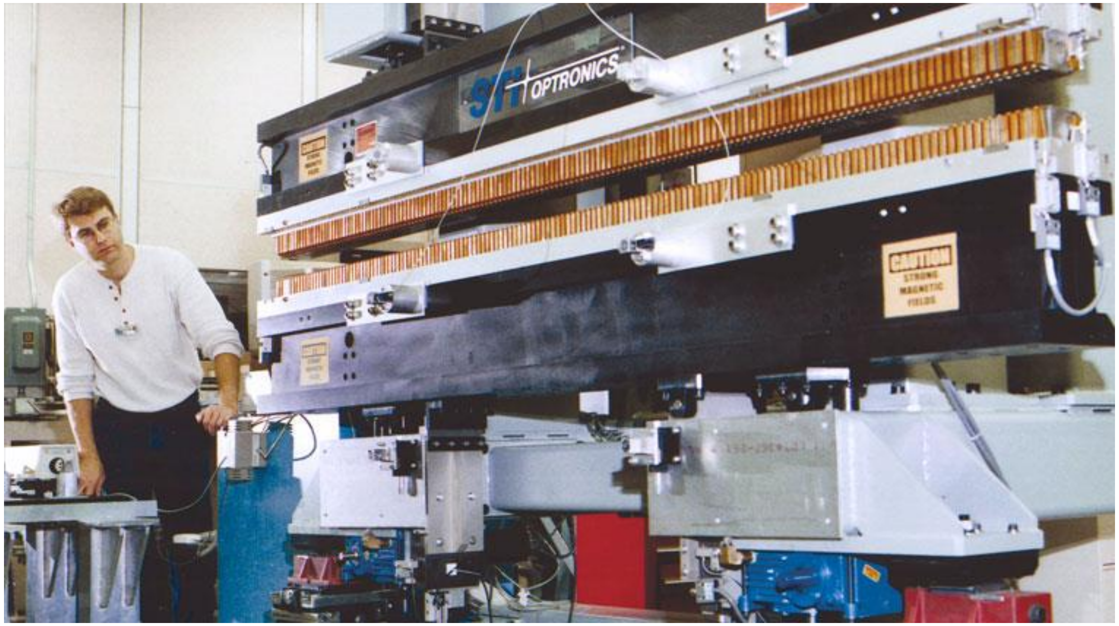
DC Magnet Loads – Characteristics

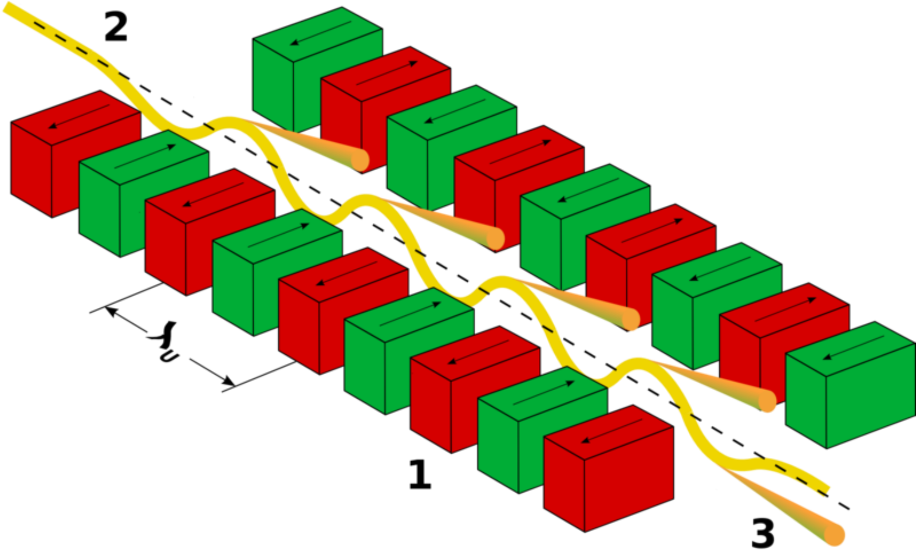


String (series-connect) magnets for economy when there are no special optics requirements. The current in each series-connected magnet is the same.

An insertion device (ID) *is a component in modern synchrotron light sources. They are periodic magnetic structures that stimulate highly brilliant, forward-directed synchrotron radiation emission by forcing a stored charged particle beam to perform wiggles, or undulations, as they pass through the device. This motion is caused by the Lorentz force, and it is from this oscillatory motion that we get the names for the two classes of device, which are known as wigglers and undulators*

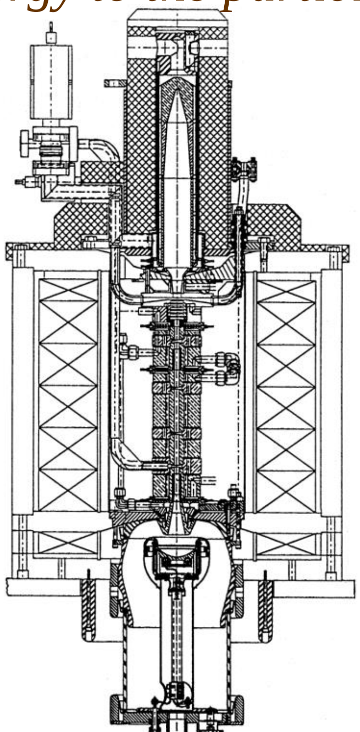
Photograph of an Insertion Device at the APS

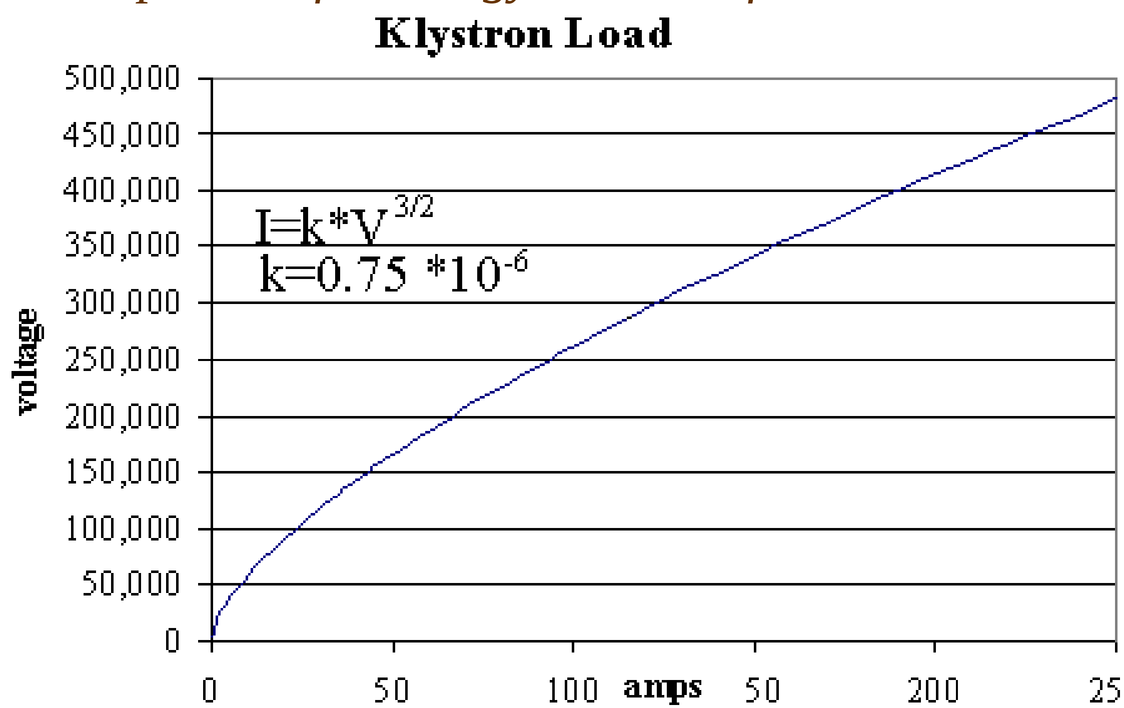




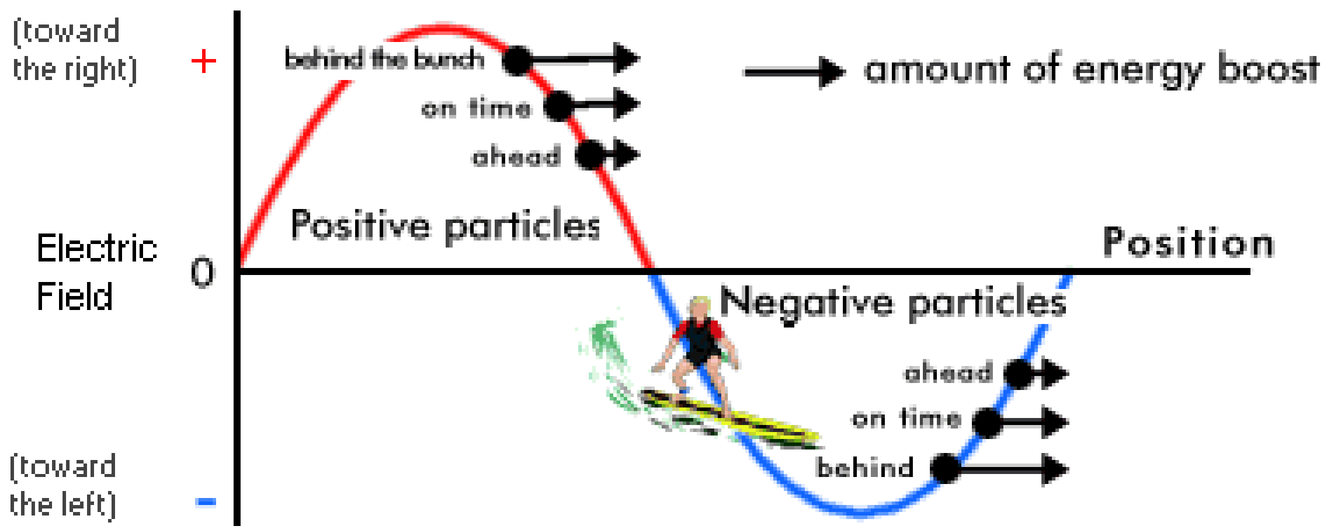
Klystron Load

- *Klystrons in RF and microwave systems accelerate particle beams. They need a power supply and an RF source.*
- *Their transfer function is called perveance (k) which expresses the beam current and accelerating voltage relation. It is usually expressed as µp.*
- *In LINACs they operate in a pulsed mode to accelerate particle beams*
- *In boosters and storage rings they operate in continuous-mode to supply make-up energy to the particle beam to compensate for energy losses or for beam bunching*



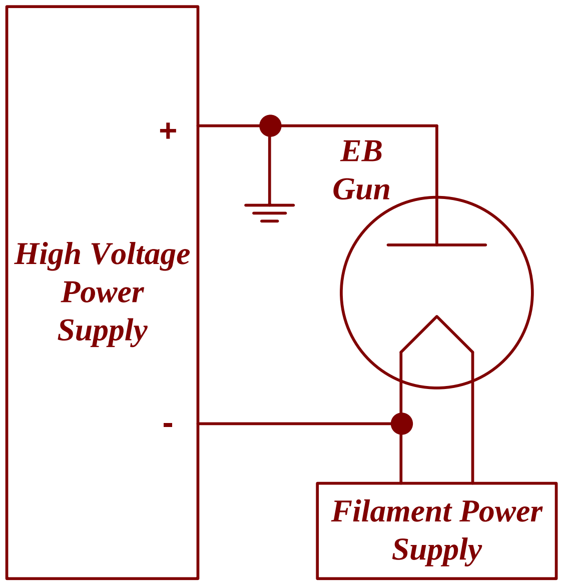


- *Electrons and positrons may be accelerated by injecting them into structures with traveling electromagnetic waves*
- *The microwaves from klystrons are fed into the accelerator structure via waveguides. This creates a pattern of electric and magnetic fields, which form an electromagnetic wave traveling down the accelerator. The beam energy is a function of the energy boost per klystron and the total number of klystrons.*

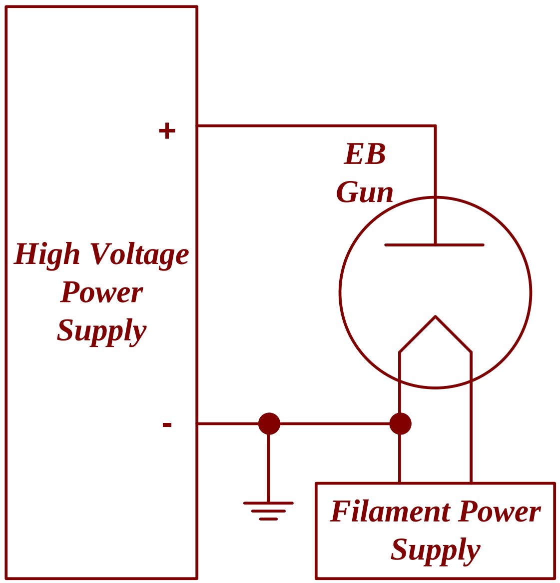


DC Electron Beam Gun Electrical Load Characteristics

- Electron gun exhibits non-linear V-I characteristics
- Capacitive loading
- High voltage, low DC current
- High peak pulsed current
- Subject to arcing
- Limited fault energy capability - arc protection (crowbar) needed



If work surface (anode) is difficult to insulate - put at ground potential. Float filament at HV.



If work surface (anode) is easy to insulate - float at HV. Put filament at ground potential.

Characteristics

- *Capacitive loading*
- *High voltage, low DC current*
- *High peak pulsed current*
- *Subject to arcing*
- *Limited energy capability - arc protection (crowbar) needed*

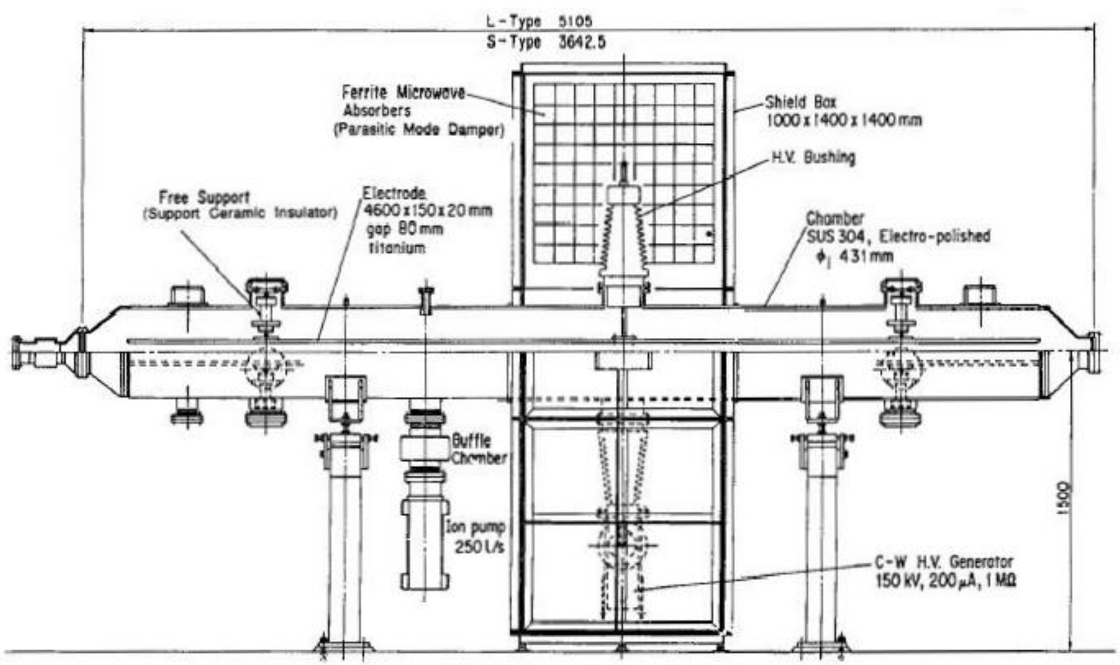


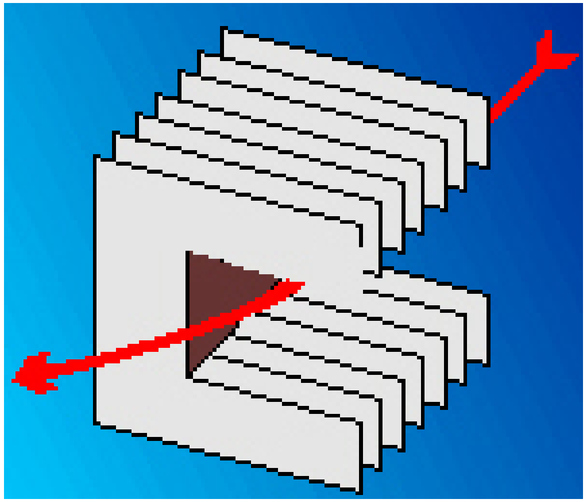
Fig.2 Separator chamber.

Pulsed Magnet Loads - Kickers, Pulsed Deflectors, Etc.

- *Kicker magnets interact with positively or negatively charged particle beams which, in most cases, are grouped into bunches*

- *The purpose of an injection kicker is to fully deflect (kick) bunches, without disturbance to the preceding or following bunches, from a beamline into a storage ring*

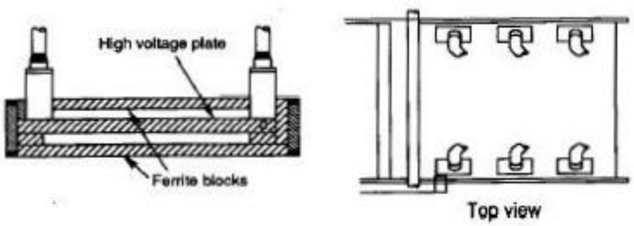
- *An ejection kicker will do the inverse, that is, kick a particle beam from a storage ring into a working beamline.*



Pulsed Magnet Loads – Kickers, Pulsed Deflectors

- *Short time constants ($\tau = L/R$) << 1 mS*
- *Characteristic impedance is like a transmission line*
- *High voltage, low impedance*
- *Fast pulse, match or terminating resistors*
- *Subject to reflection and breakdown*

Fig. 5. SLAC-designed kicker magnet.



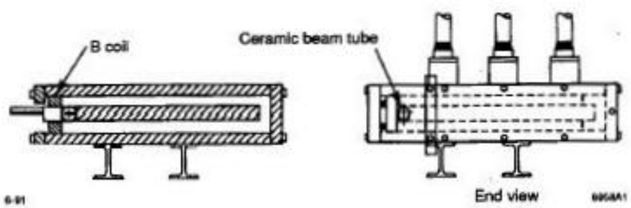
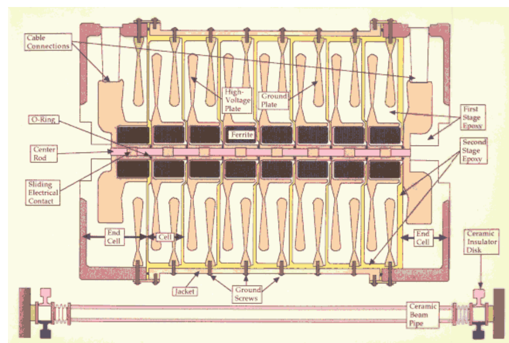
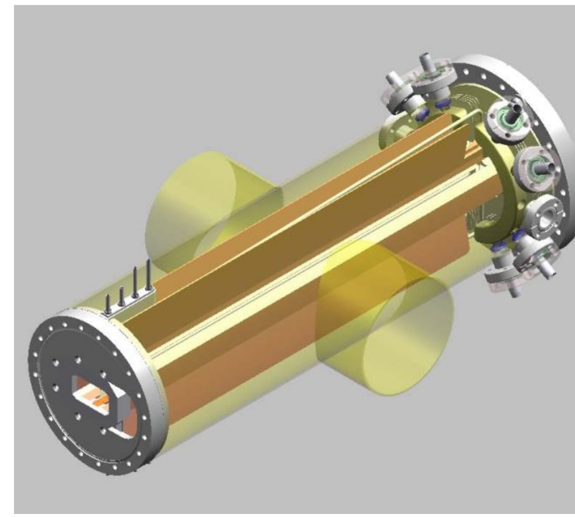
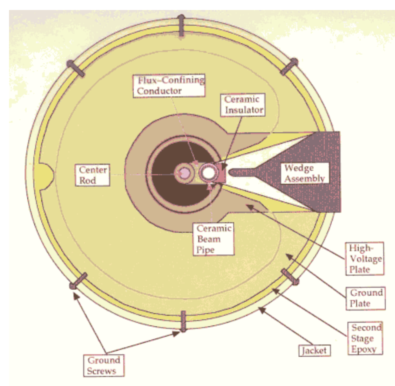
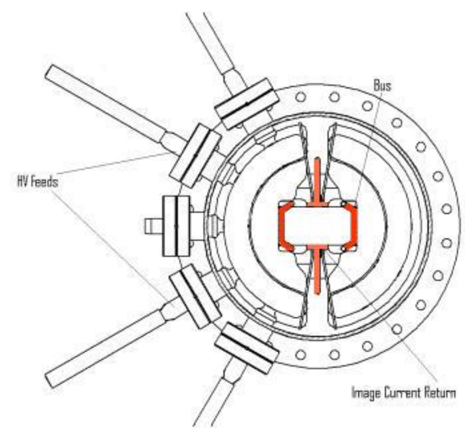


Fig. 6. SLAC-style kicker magnet.





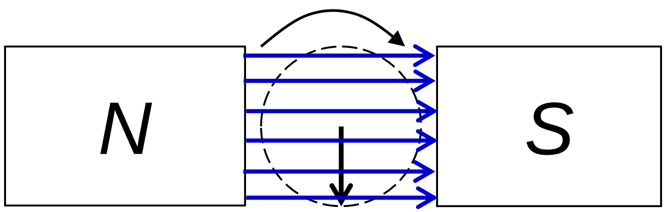




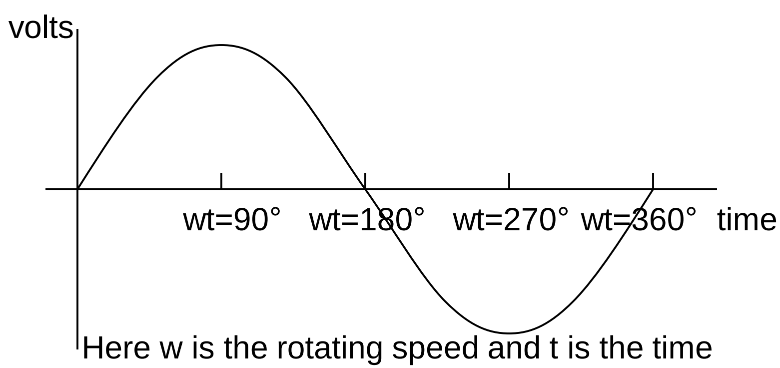
Section 5

- *Power Line and Other Considerations*
  - *Fundamental Quantities*
  - *Single Phase Systems*
  - *Three Phase Systems*
  - *Transformer Primer*
  - *The Per Unit Calculation System*
  - *Harmonics, Complex Waveforms and Fourier Series*
  - *SCR Commutation as Distortion Cause*
  - *Electromagnetic Compatibility and Interference (EMC/EMI)*
  - *Power Factor*

- *Generation of sine waves*



- *Plotting of sine waves*



- *Expression of sine waves*

$$v(t) = V_{max} \sin(\omega t)$$
$$\omega = 2\pi f$$

- *Average value:*

$$V_{ave} = \frac{1}{T}\int_0^T v(t)dt$$

for AC sine system

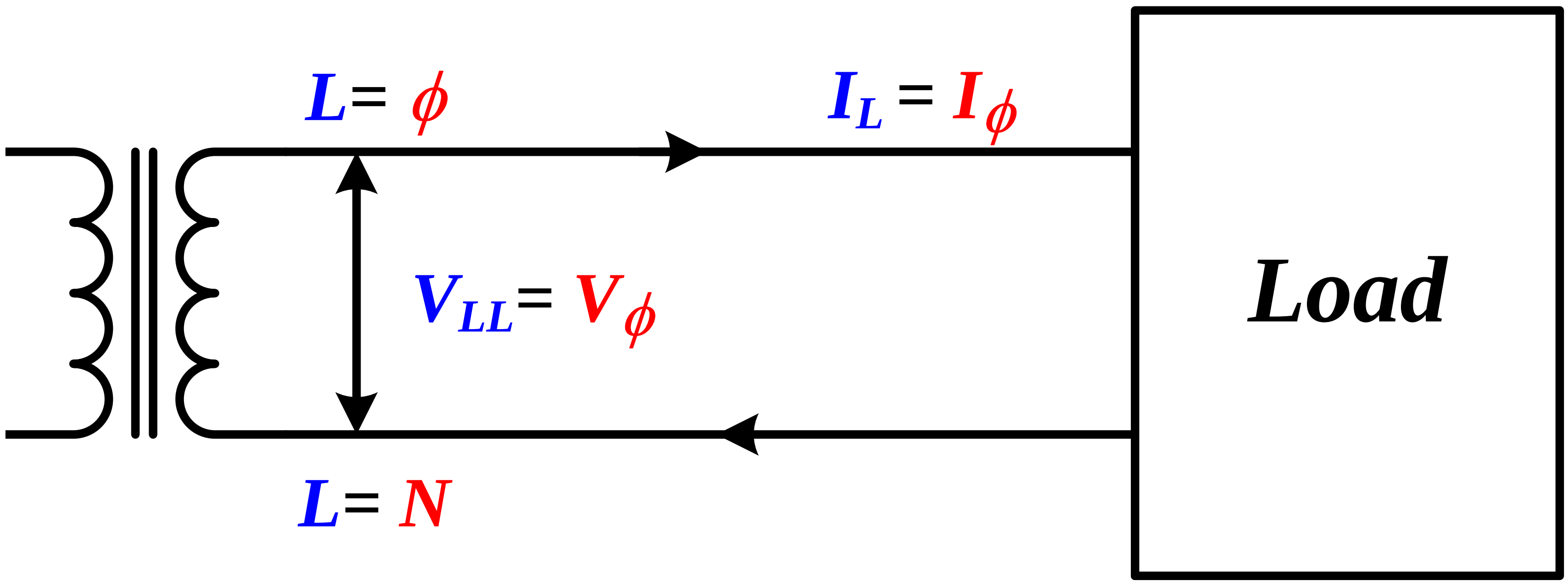
$$v(t) = V_m\,sin(\omega t),\ \ then \quad V_{ave} = \frac{2}{\omega T}\int_0^{\frac{T}{2}} V_m\,sin(\omega t)\,d\omega t = 0.636V_m$$

- *RMS value:*

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T v(t)^2\,dt}$$

for AC sine system

$$V_{rms} = \sqrt{\frac{1}{\omega T}\int_0^T (V_m\,sin(\omega t))^2\,d\omega t} = \frac{V_m}{\sqrt{2}} = 0.707 * V_m$$

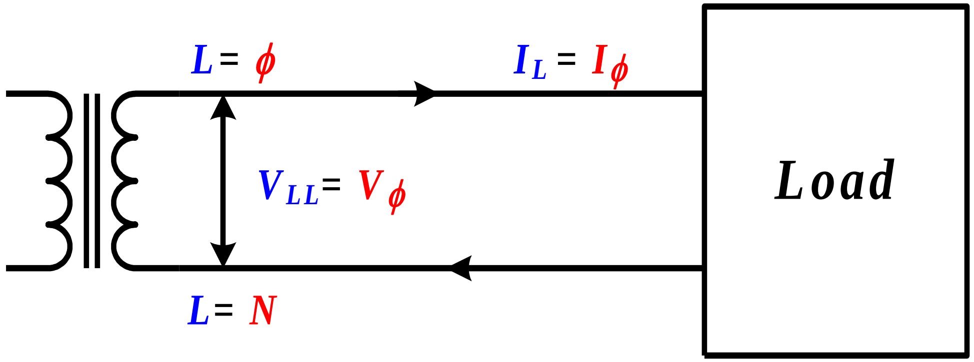


For 1ϕ AC input

$$V_\phi = V_{LL}$$

$$I_\phi = I_L \qquad \text{where } V_\phi \text{ and } I_\phi \text{ are RMS values}$$

Single Phase Systems



The Apparent, Real and Reactive "powers" are:

Apparent $\quad S_{1\phi} = V_{LL}\ I_L = P_{1\phi} + j\ Q_{1\phi} \quad$ VA

Real (active) $\quad P_{1\phi} = V_{LL}\ I_L \cos(\alpha) \quad$ Watt,

Reactive $\quad Q_{1\phi} = V_{LL}\ I_L \sin(\alpha) \quad$ VAR

$\alpha =$ phase angle between line current
and line-line voltage with current as the reference.

All "powers" are average "powers"

$$S_{1\phi} = \sqrt{\frac{1}{T}\int_0^T v_{LL}^2(t)dt} * \sqrt{\frac{1}{T}\int_0^T i_L^2(t)dt} = \frac{1}{T}\int_0^T v_{LL}(t)i_L(t)dt$$

Instantaneous power p(t) is the product of the instantaneous voltage v(t) and the instantaneous current i(t)

Derivation

$$p(t) = v(t)i(t)$$

let $\quad v(t) = \sqrt{2}V\sin(\omega t + \phi)$

$$i(t) = \sqrt{2}I\sin(\omega t)$$

and $\quad p(t) = \sqrt{2}V\sin(\omega t + \phi)\sqrt{2}I\sin(\omega t) = 2VI\sin(\omega t + \phi)\sin(\omega t)$

Identity

$$\sin(a)\sin(b) = \frac{1}{2}(\cos(a - b) - \cos(a + b))$$

Substituting

$$p(t) = VI[\cos(\omega t - \omega t + \phi) - \cos(\omega t + \omega t + \phi)]$$

$$p(t) = VI[\cos(\phi) - \cos(2\omega t + \phi)]$$

$$p(t) = VI\cos(\phi) - VI\cos(2\omega t + \phi)$$

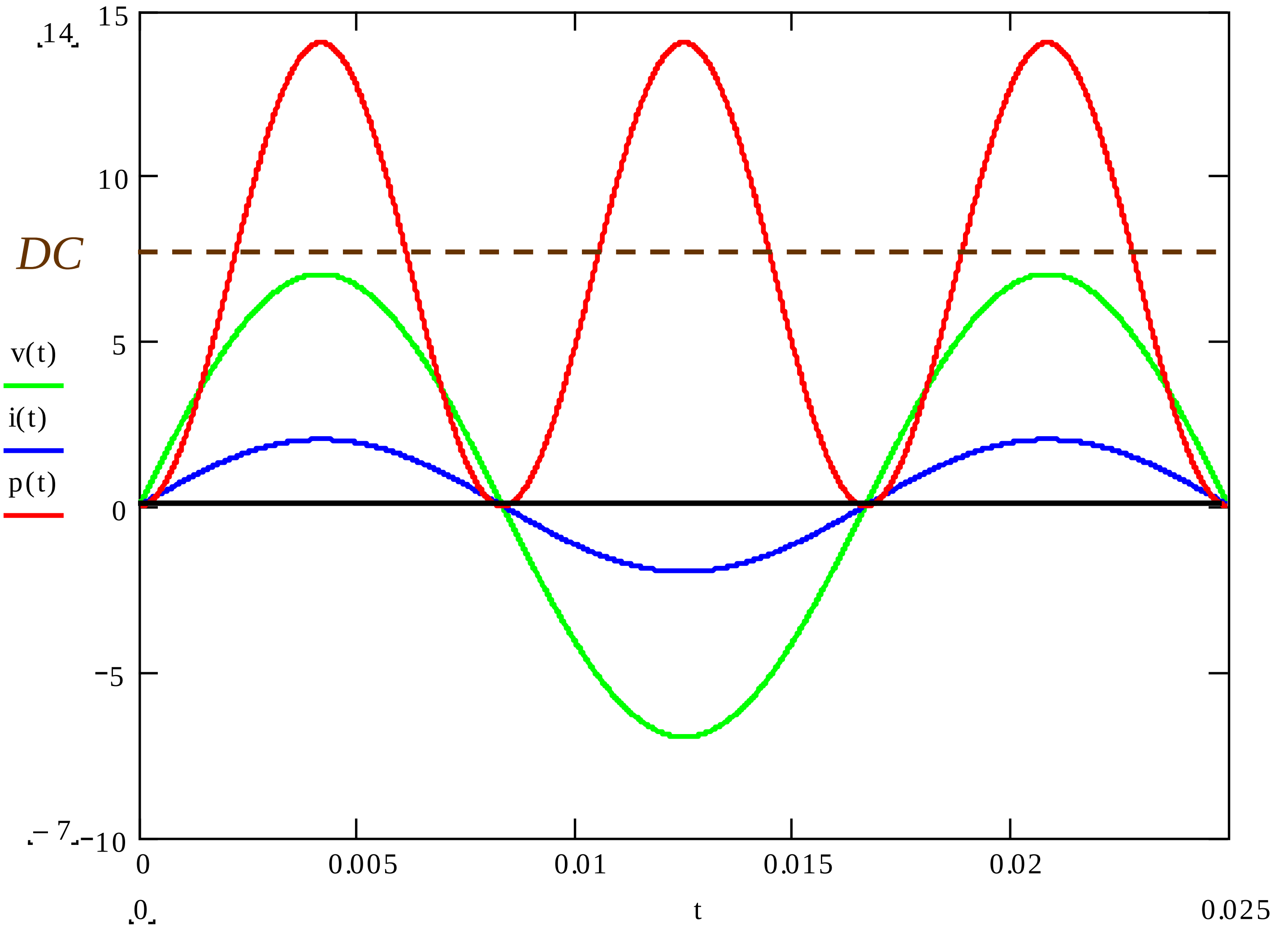
It is seen that

$p(t) =$ *DC component + AC component with twice the frequency of the voltage or current*

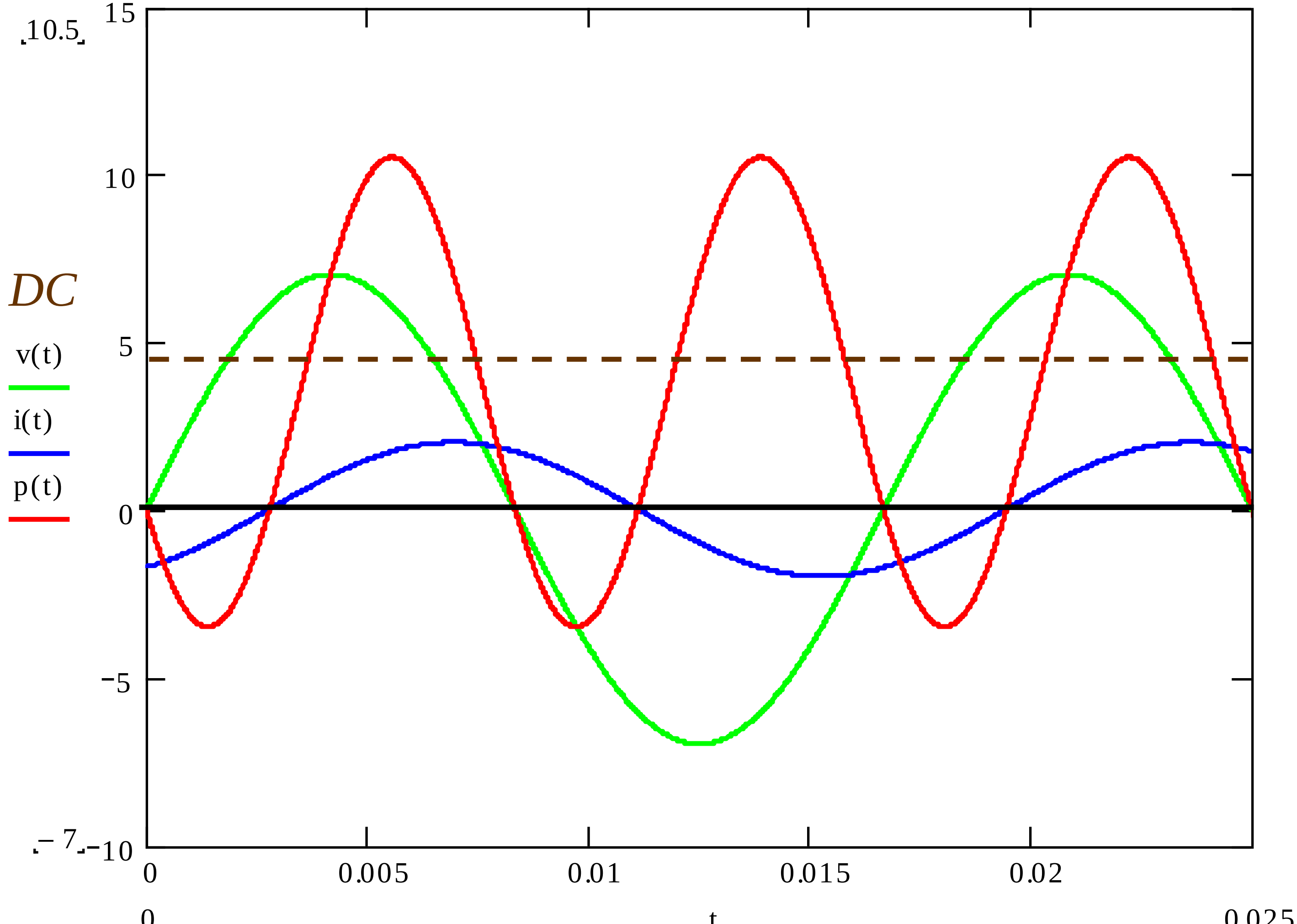
The DC component is a maximum when the voltage and current are in phase

The power is the product of the RMS values of the line – line voltage and line current

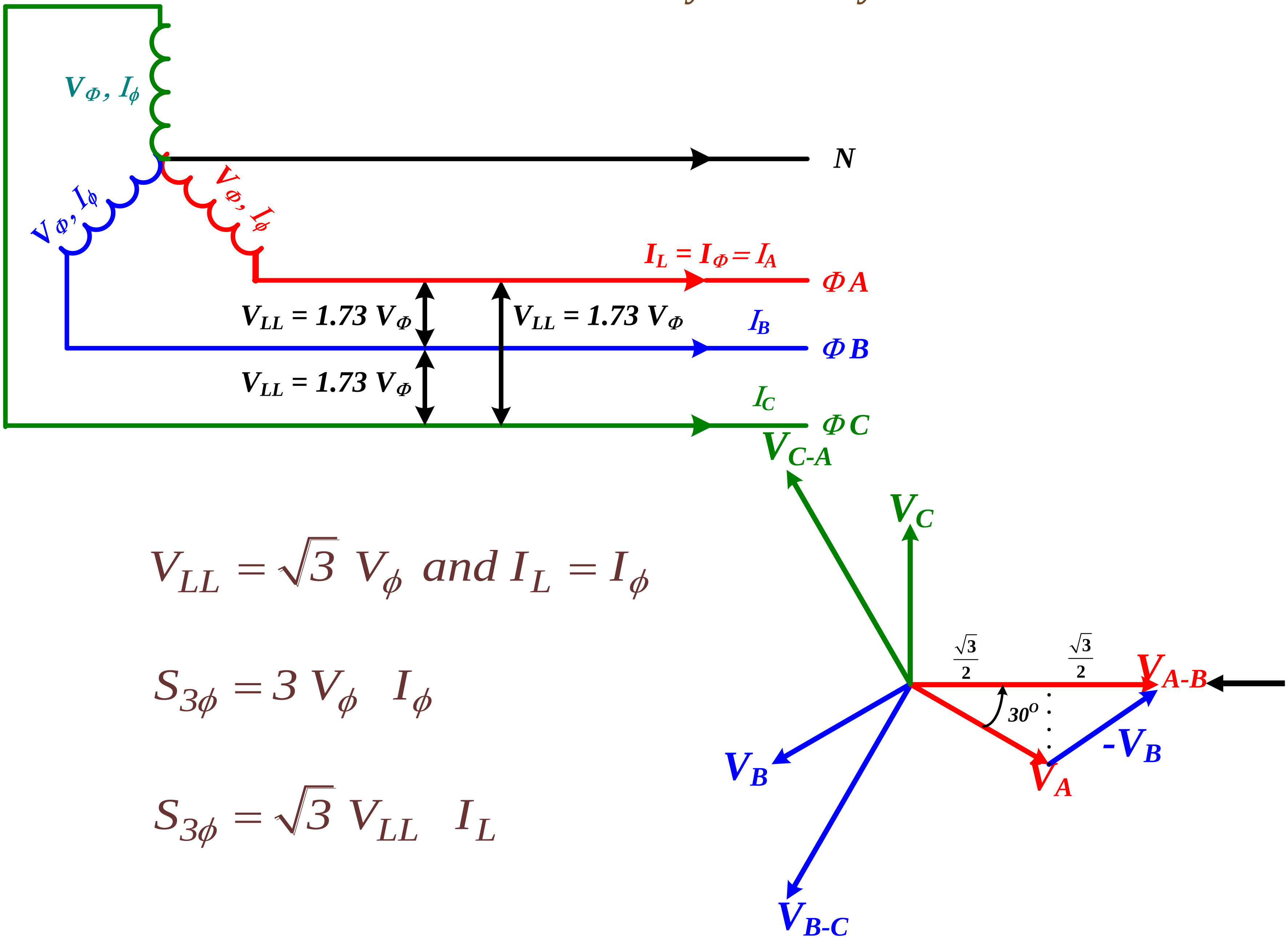
Single Phase Systems



- *Voltage and current are in phase at 60 Hz*
- *Power = DC + 120Hz terms, both equal in amplitude*



- *Voltage leads current by 60^{O} at 60 Hz*
- *Power = DC + 120Hz terms, but now unequal in amplitude*
- *Power is + (delivered to load) and – (returned to the AC line) and 120 Hz*
- *+ and – power are equal when current – voltage are 90^{0} out of phase*

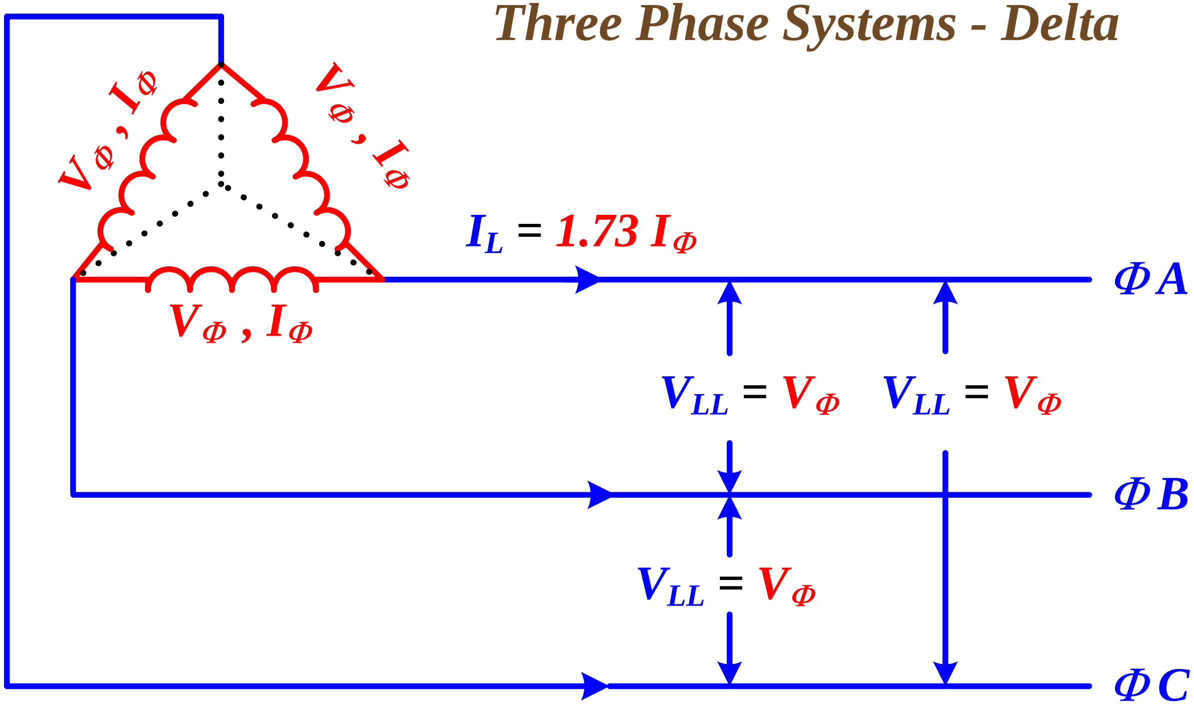


$$V_{LL} = \sqrt{3}\ V_\phi \text{ and } I_L = I_\phi$$

$$S_{3\phi} = 3\ V_\phi\ \ I_\phi$$

$$S_{3\phi} = \sqrt{3}\ V_{LL}\ \ I_L$$

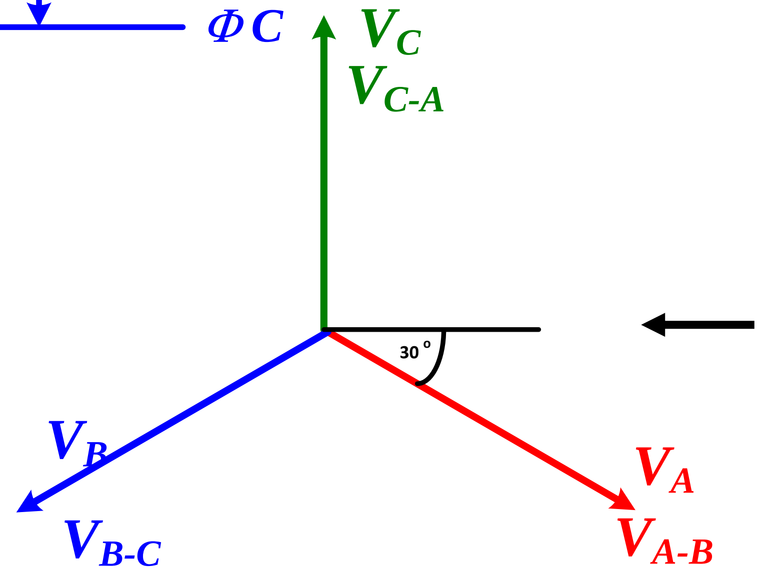
Three Phase Systems - Delta

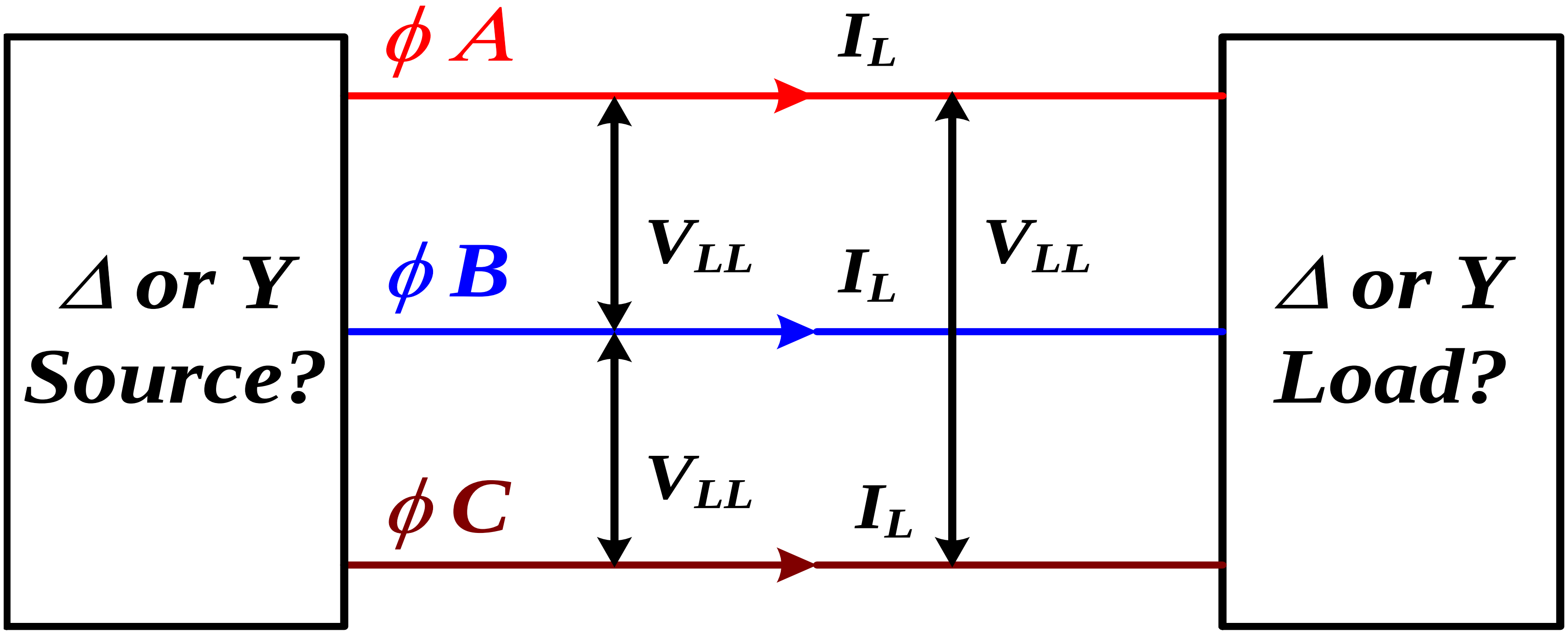


$$V_{LL} = V_{\phi} \quad and\ I_L = \sqrt{3}\, I_{\phi}$$

$$S_{3\phi} = 3\, V_{\phi} \quad I_{\phi}$$

$$S_{3\phi} = \sqrt{3}\, V_{LL} \quad I_L$$





For Wye

$$S_{3\phi} = \sqrt{3}\, V_{LL} \quad I_L$$

For Delta

$$S_{3\phi} = \sqrt{3}\, V_{LL} \quad I_L$$

$$V_{A-B} = |V_{A-B}|\, e^{j0} \quad V_{B-C} = |V_{B-C}|\, e^{-j120} \quad V_{C-A} = |V_{C-A}|\, e^{-j240}$$

This will show that three phase power is constant

$$s(t)=v_{ab}(t)i_a(t)+v_{bc}(t)i_b(t)+v_{ca}(t)i_c(t)$$

$$s(t)=\frac{|V_{ab}|}{\sqrt{2}}sin(\omega t)\frac{|I_a|}{\sqrt{2}}sin(\omega t-\phi)$$

$$+\frac{|V_{bc}|}{\sqrt{2}}sin(\omega t-120^o)\frac{|I_b|}{\sqrt{2}}sin(\omega t-120^o-\phi)$$

$$+\frac{|V_{ca}|}{\sqrt{2}}sin(\omega t-240^o)\frac{|I_c|}{\sqrt{2}}sin(\omega t-240^o-\phi)$$

But $\frac{|V_{ab}|}{\sqrt{2}}=\frac{|V_{bc}|}{\sqrt{2}}=\frac{|V_{ca}|}{\sqrt{2}}=V$ *and* $\frac{|I_a|}{\sqrt{2}}=\frac{|I_b|}{\sqrt{2}}=\frac{|I_c|}{\sqrt{2}}=I$ *(if load is balanced)*

Identity

$$sin(\alpha)sin(\beta)=\frac{1}{2}(cos(\alpha-\beta)-cos(\alpha+\beta))$$

Making the substitutions we have

$$s(t)=VI[cos(\omega t-\omega t+\phi)-cos(\omega t+\omega t-\phi)]$$

$$+VI[cos(\omega t-120^o-\omega t+120^o+\phi)-cos(\omega t-120^o+\omega t-120^o-\phi)]$$

$$+VI[cos(\omega t-240^o-\omega t+240^o+\phi)-cos(\omega t-240^o+\omega t-240^o-\phi)]$$

$$s(t)=VI[cos(\phi)-cos(2\omega t-\phi)+cos(\phi)-cos(2\omega t-240^o-\phi)+cos(\phi)-cos(2\omega t-480^o-\phi)]$$

Recognizing that $cos(-480^o)=cos(-120^o)$ *the following is obtained*

$$s(t)=VI[cos(\phi)-cos(2\omega t-\phi)+cos(\phi)-cos(2\omega t-240^o-\phi)+cos(\phi)-cos(2\omega t-120^o-\phi)]$$

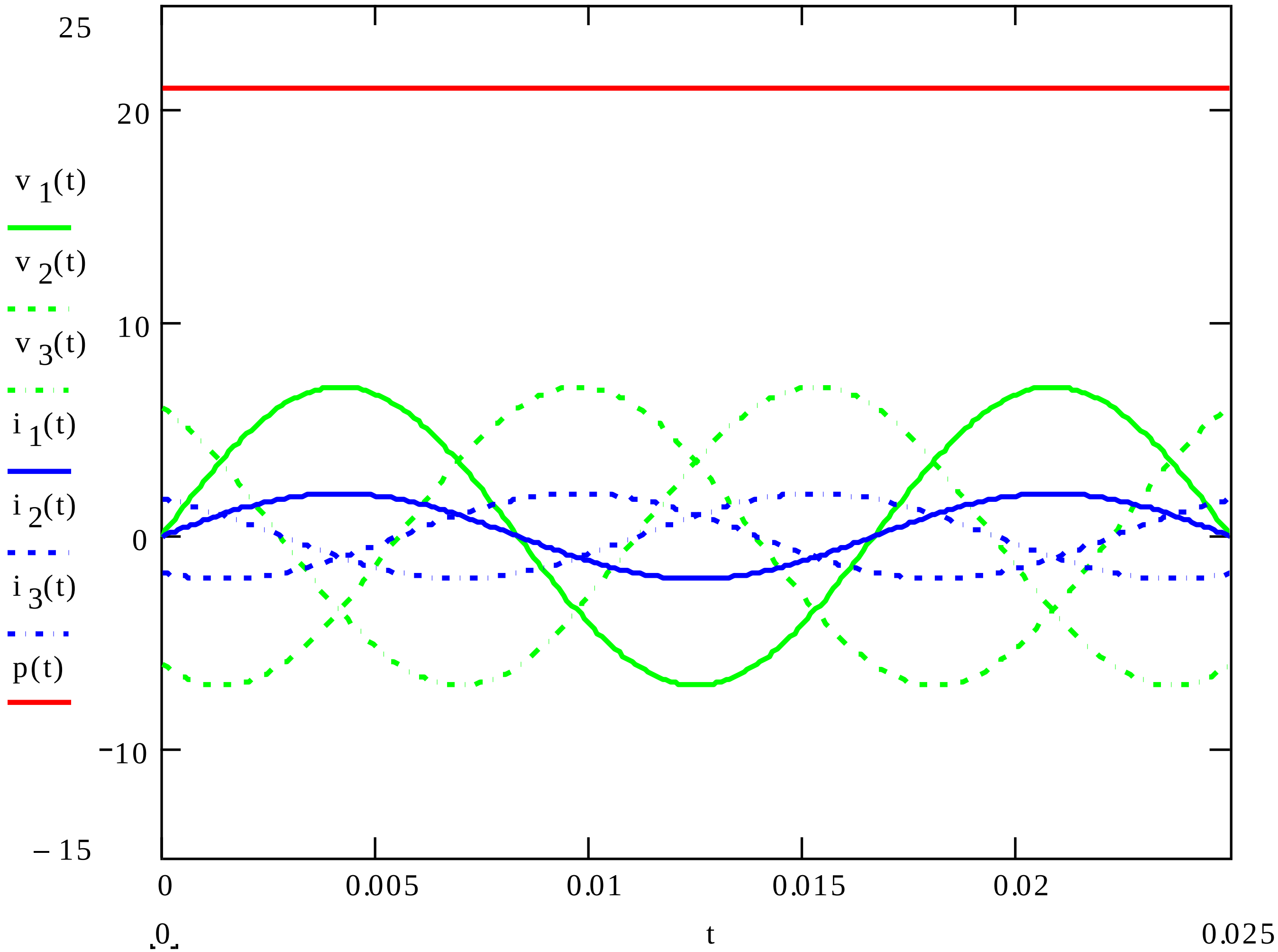
$$s(t)=VI[3cos(\phi)-(cos(2\omega t-\phi)+cos(2\omega t-120^o-\phi)+cos(2\omega t-240^o-\phi))]$$

Acknowledging that $cos(2\omega t-\phi)+cos(2\omega t-120^o-\phi)+cos(2\omega t-240^o-\phi)=0$ *yields*

$$s(t)=3VI\,cos(\phi)$$

A constant power, with a maximum when $\phi=0^o$ *and where V and I are RMS values*

Three Phase Systems



- *$p(t) = v_A(t) * i_A(t) + v_B(t) * i_B(t) + v_C(t) * i_C(t)$*
- *3 times the single phase power with only 3 conductors, not 6*
- *For balanced load, p (t) is constant*

Transformer Primer - Why Needed

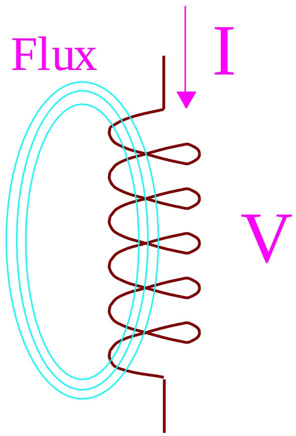
- *Needed to transform the load voltage to the line voltage*
- *Needed to isolate the load from the line for better ground fault immunity and to reduce the magnitude of fault currents*

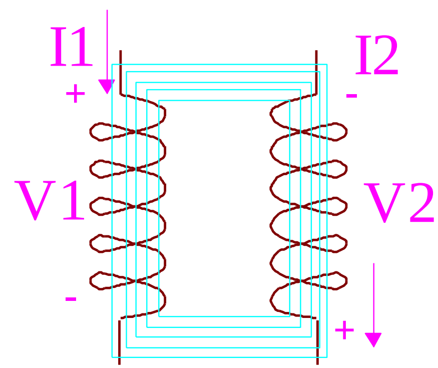
Transformer Primer

- *Transformers are inductors with linked flux φ:*

*Volts = # of turns * time rate of change of flux in the coil* **$V = N * d\varphi / dt$** *or*

*Volts = (inductance) * (rate of change of current)* **$V = L_m * di / dt$**





- *Iron core transformers are used at frequencies below 1 kHz*

- *L_m results from the number of turns, the area of turn path, length of flux path and μ of the iron. It is normally referred to as the magnetizing inductance*

- *Magnetizing inductance for a low frequency transformer is large, typically requiring about 1% of the rated primary current to produce the desired excitation*

Equivalent Transformer Circuit

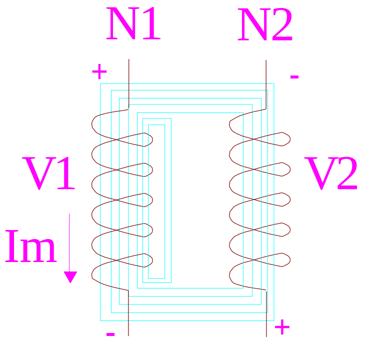
- The current required to magnetize the core with flux is called the magnetizing current and is made up of two parts:

  1. A component out of phase with the induced voltage due to the magnetizing inductance.

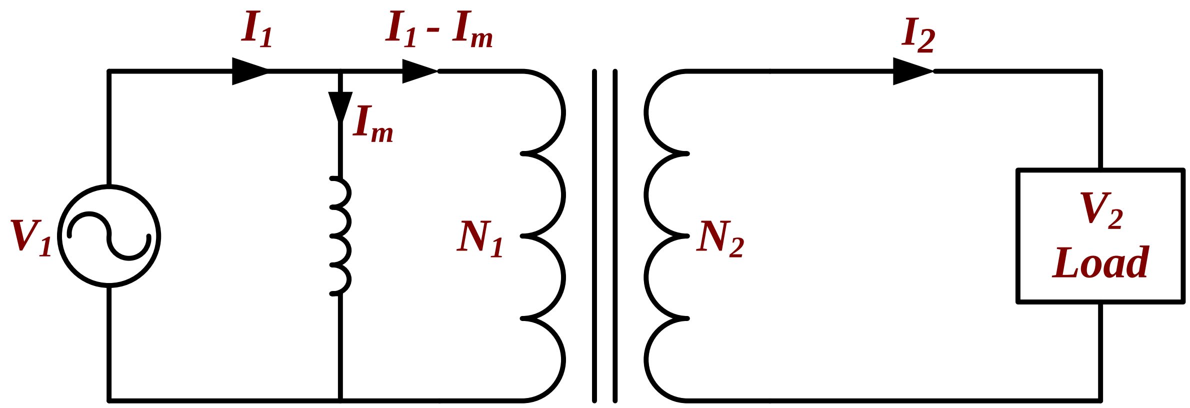
  2. A component in phase with the induced voltage from losses due to eddy current and hysteresis losses.

- The magnetizing inductance is obtained by driving the transformer with the secondary open circuited $I_2=0$ and measuring the Primary voltage and current.

$$L_m = (V_1 / I_1) / (2 * \pi * f)$$



Transformer Primer – Turns / Voltage / Current Ratios



Secondary winding turns cut by the common flux produce a voltage with the same volts per turn as the driving primary turns

$$\frac{V_1}{N_1} = \frac{d\phi}{dt} = \frac{V_2}{N_2} \qquad \text{or} \qquad \frac{V_1}{V_2} = \frac{N_1}{N_2}$$

Where N_1 and N_2 are the number of turns cut by the same flux

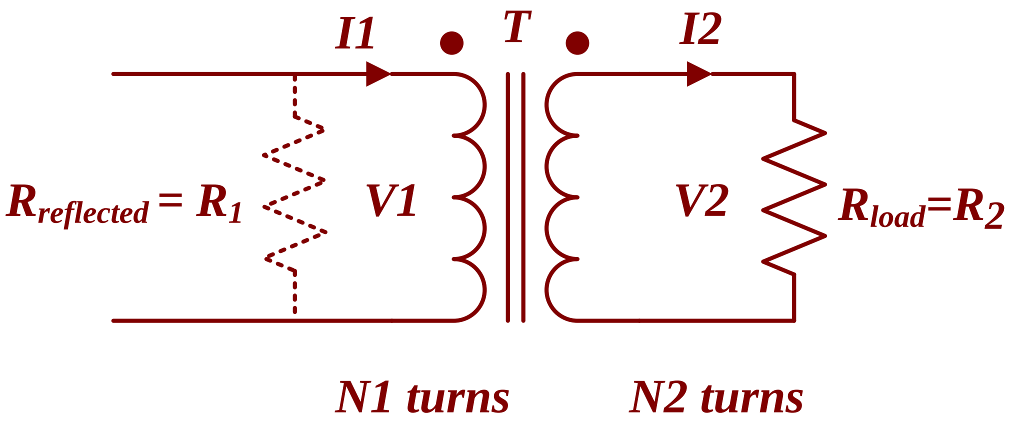
With a source and a load, the primary current equals the source current minus the magnetizing current. Ampere-turns in the primary and secondary must equate

$$N_1(I_1 - I_m) = I_2 N_2 \qquad \text{or} \qquad \frac{N_1}{N_2} = \frac{I_2}{I_1 - I_m}$$

If $I_m << I_1$ then

$$\frac{I_1}{I_2} = \frac{N_2}{N_1}$$

Transformer Primer - Impedance Ratios and Reflected Impedances



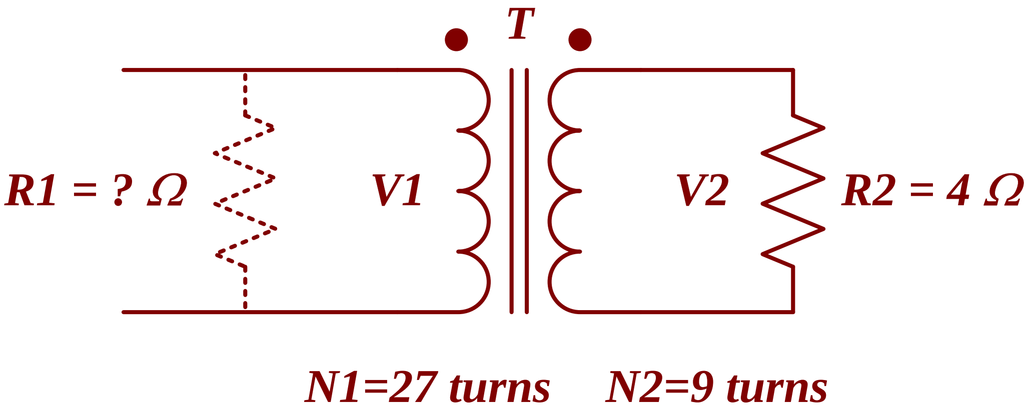
$$R_1 = \frac{V_1}{I_1} = \frac{\frac{N_1}{N_2} V_2}{\frac{N_2}{N_1} I_2} = \frac{N_1 V_2}{N_2} * \frac{N_1}{N_2 I_2}$$

$$R_1 = \frac{N_1^2}{N_2^2} * \frac{V_2}{I_2} = \frac{N_1^2}{N_2^2} * R_2$$

$$\frac{R_1}{R_2} = \left(\frac{N_1}{N_2}\right)^2$$

Example

$R_2 = 4\Omega$, ***what is the value of the reflected resistance as seen on the primary side?***

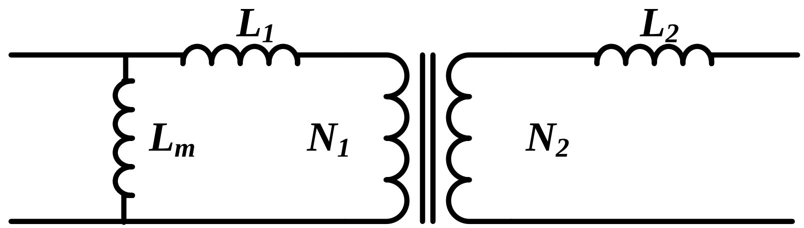


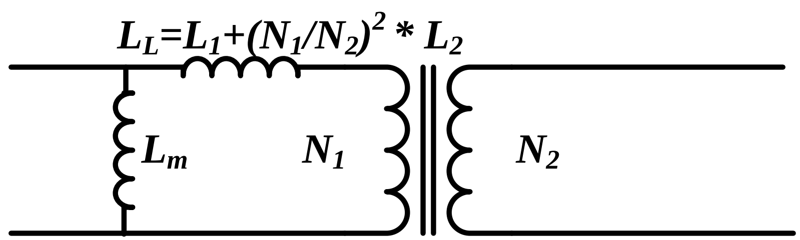
$$R_1 = \frac{N_1^2}{N_2^2} * R_2 = \frac{27^2}{9^2} * 4\Omega$$

$$R_1 = 9 * 4\Omega = 36\Omega$$

Transformer Primer - Leakage Inductance - Equivalent Circuit

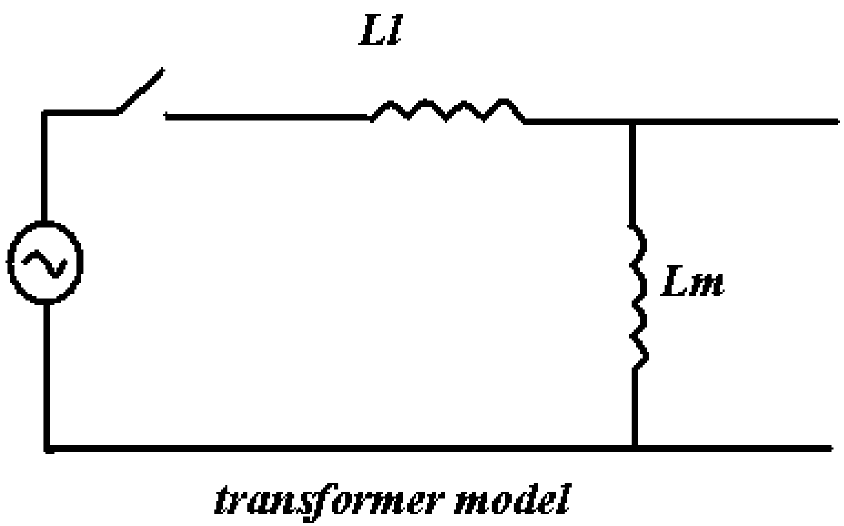
- *Flux that does not couple both windings is called the leakage flux and acts like a series inductor called the leakage inductance*
- *If the secondary is shorted and the magnetizing current is small ($I_m << I_1$), then the leakage inductance is proportional to the primary voltage divided by the primary current (or secondary current referred to the primary side)*





- *If the secondary is shorted the "percent impedance" is the drive voltage divided by the rated input voltage with rated load current flowing*

$$\frac{V_1}{V_{rated}} \text{ with } I_{rated} \;\; X \; 100\% = \% \text{ impedance}$$

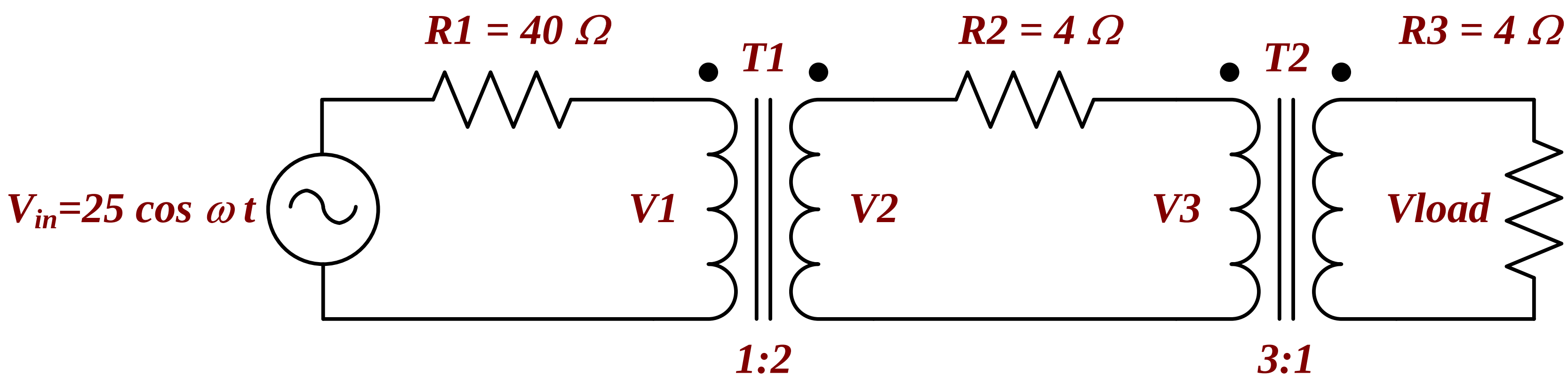


An air gap is undesirable in a transformer because:

• *It reduces L_m , and a large L_m is desired to reduce the magnetizing and inrush current*

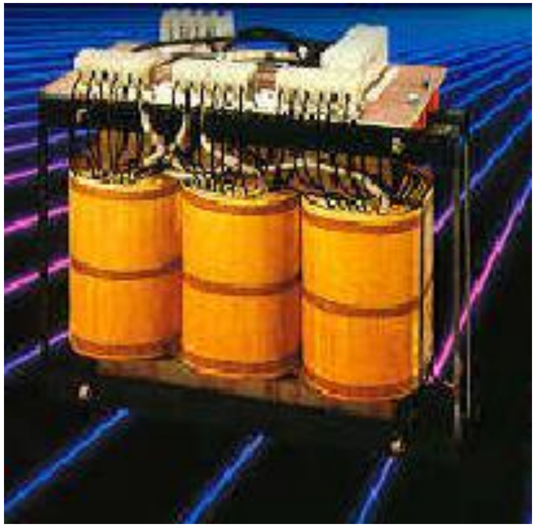
• *It increases L_l , and a small L_l is desired to lower energy and other losses*

Calculate the output voltage in the circuit shown below.



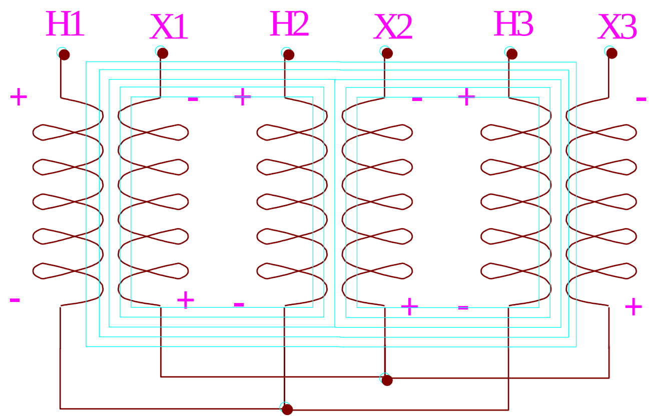
Transformer Primer - Configuration

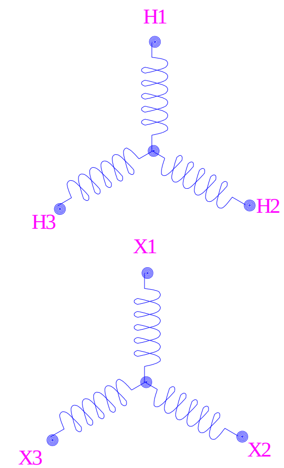
- Low frequency, 60 Hz, transformers almost always use laminated iron cores to reduce Eddy Current and hysteresis losses
- For low power applications < 2.5 kW single phase transformers are used to eliminate the need for costly 3 phase input power lines.
- 3 phase lines and transformers are used to reduce the cost of higher power systems (usually >2.5 kW)
- 3 phase lines allow the use of phase shifting transformers to generate any number of output phases

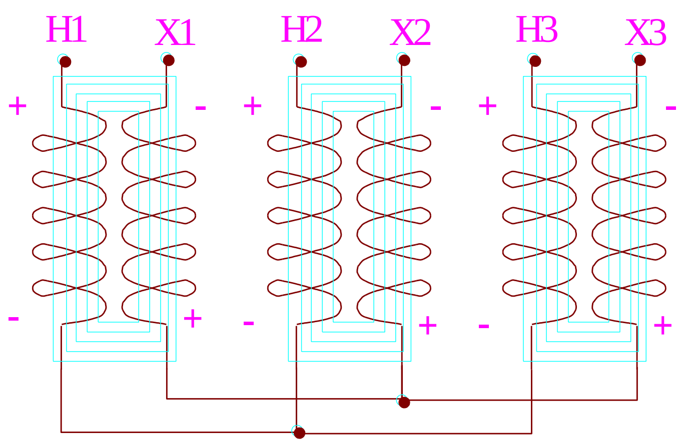


Transformer Primer - Three Phase Most Common Types

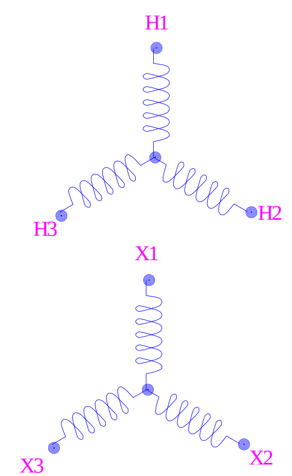
Single core and 3 core three phase transformers





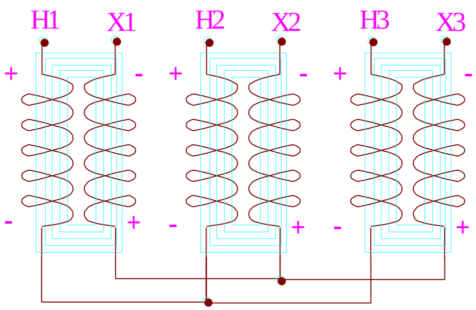


Wye-Wye Transformer

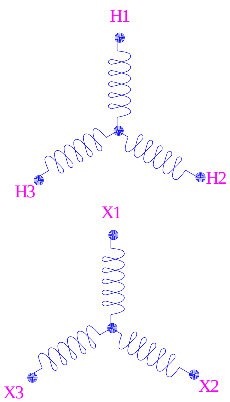


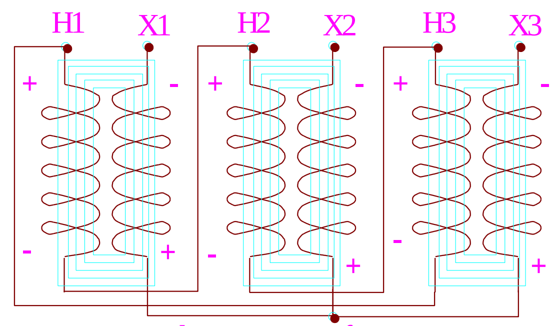
Three phase Transformers

- *A three phase transformer can be constructed with 1 core or 2 or 3 independent cores*
- *Independent core transformers are more expensive (use more steel) and can result in line imbalances*

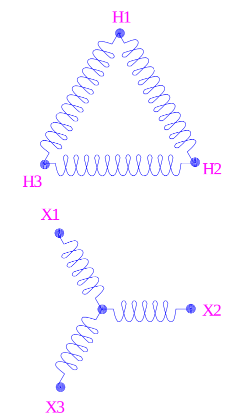


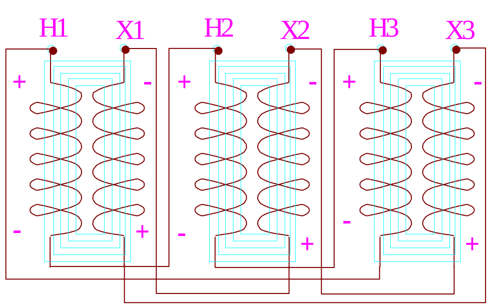
Wye-Wye Transformer



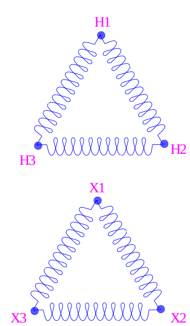


Delta -Wye Transformer



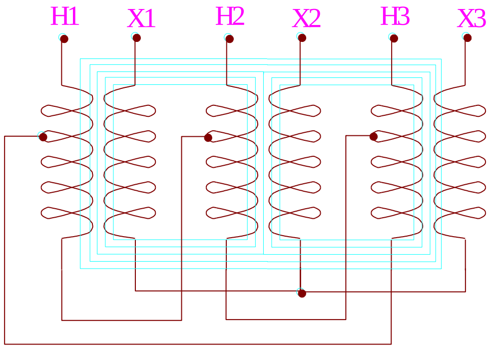


Delta - Delta Transformer

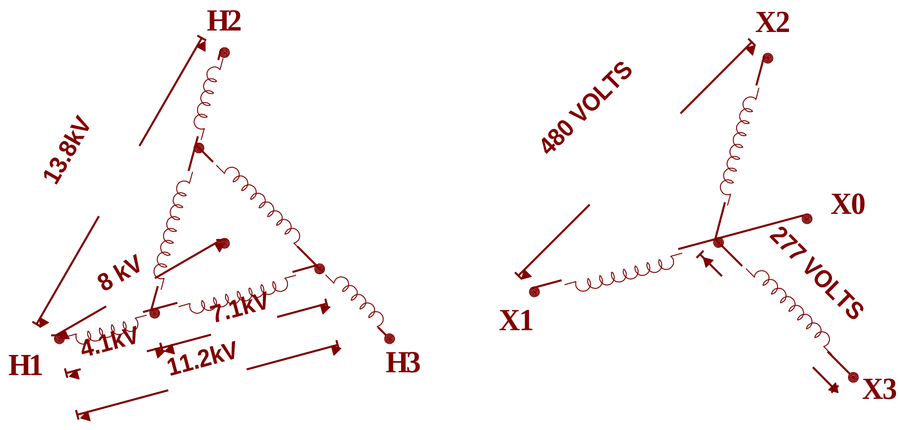


Extended Delta Phase shifting transformer

EXTENDED DELTA 13.8kV to 480 V 7.5 ^{0}



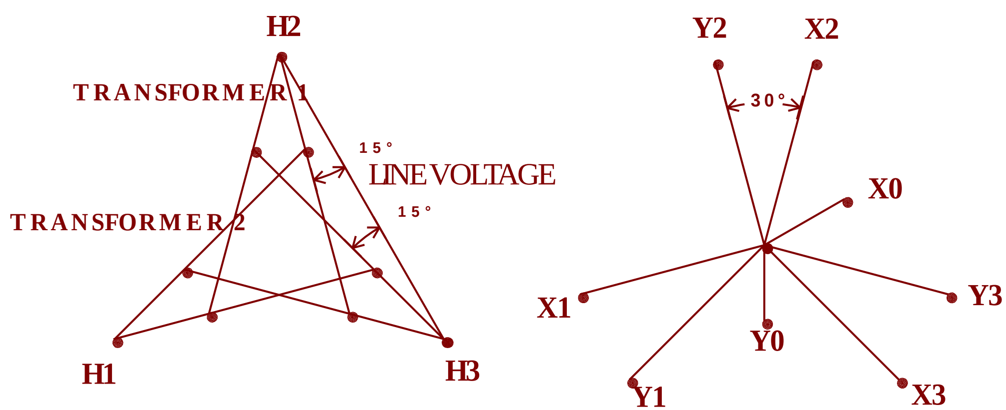
Extended Delta-Wye Transformer 3 core



PRIMARY VOLTAGE RELATIONSHIP

SECONDARY VOLTAGE RELATIONSHIP

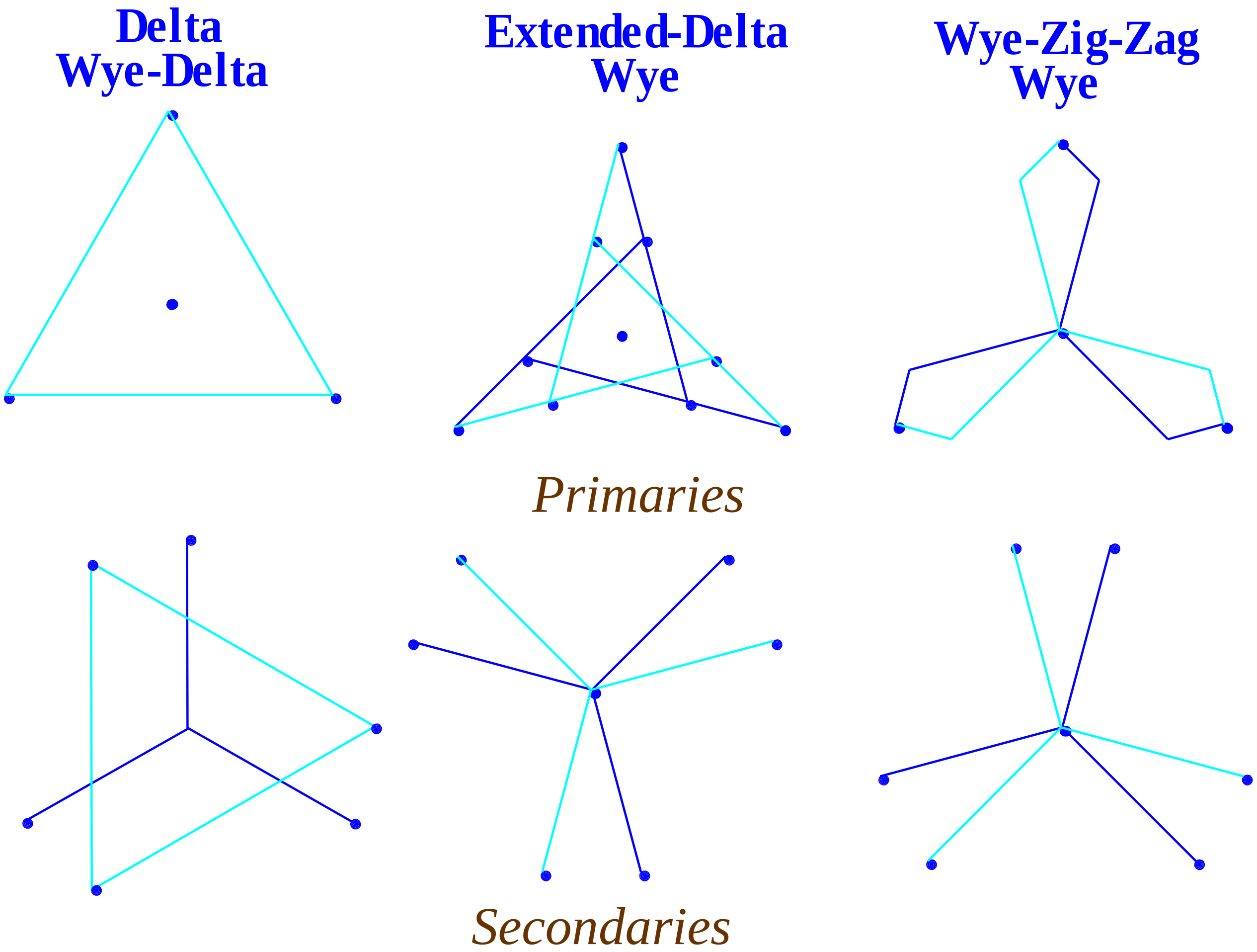
PHASE RELATIONSHIP



PRIMARY PHASE RELATIONSHIP

SECONDARY PHASE RELATIONSHIP

Phase shifting transformer for 12 Pulse operation



Standards for Power Rectifier Transformers

1) Practice for Semiconductor Power Rectifiers ANSI C34.2-1973
2) IEEE standards for Transformer and Inductors for Electronic power conversion Equipment ANSI/IEEE std 388-1992

Insulation Class Recommendations for Rectifier Transformers

1) Oil filled, 65 ℃ rise over ambient (paper oil insulation)

2) Dry type, Class B 80°C rise over ambient, (paper, varnish)

3) Dry type, Class H 150°C over ambient (fiberglass, epoxy)

Phase Relationship and labeling

1) General requirements for distribution power and regulating transformers ANSI C57.12.00-1973

*Transformer Primer - **Problems***

Low Frequency Transformers have been around a long time and designs are well established. There are a few problems related to rectifier operation that should be considered when using transformers;

*1) **Harmonic currents** in the core and coils can result in excessive losses.*

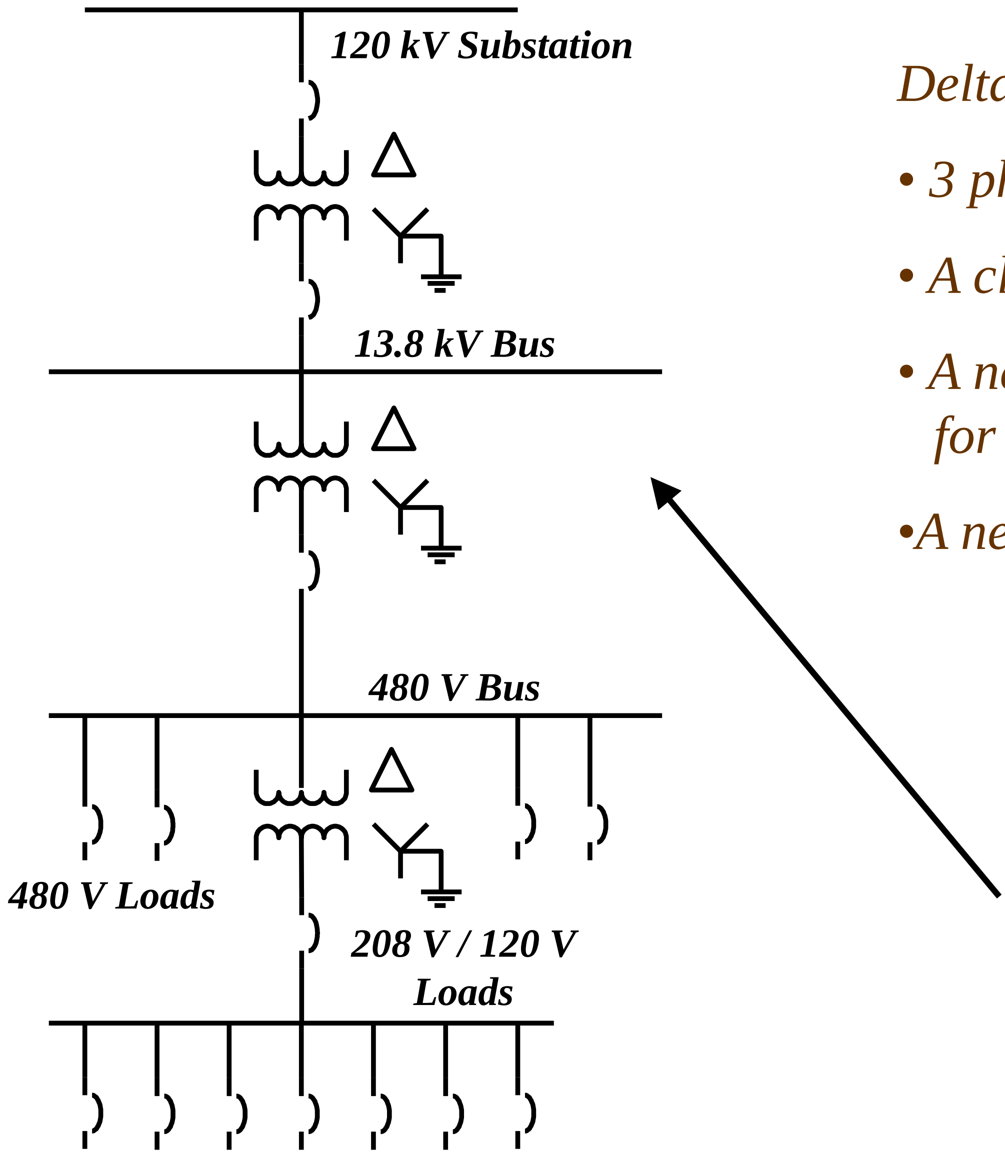
*2) Presence of DC and/or **second harmonic** currents/ voltage can saturate the core resulting in more harmonics and excessive core hysteresis loss.*

*3) **Short circuits** are common in rectifiers resulting in high forces on the coils and the coil bracing resulting in coil faults.*

*4) Connection to the center of a wye can generate excessive **third harmonic** current resulting in voltage distortion and overheating.*

*5) The **fast switching voltages** of rectifiers under commutation can produce non-uniform voltage distribution on coil windings resulting in insulation failure.*

Three Phase Systems - Delta - Wye Configuration – The Preferred Choice

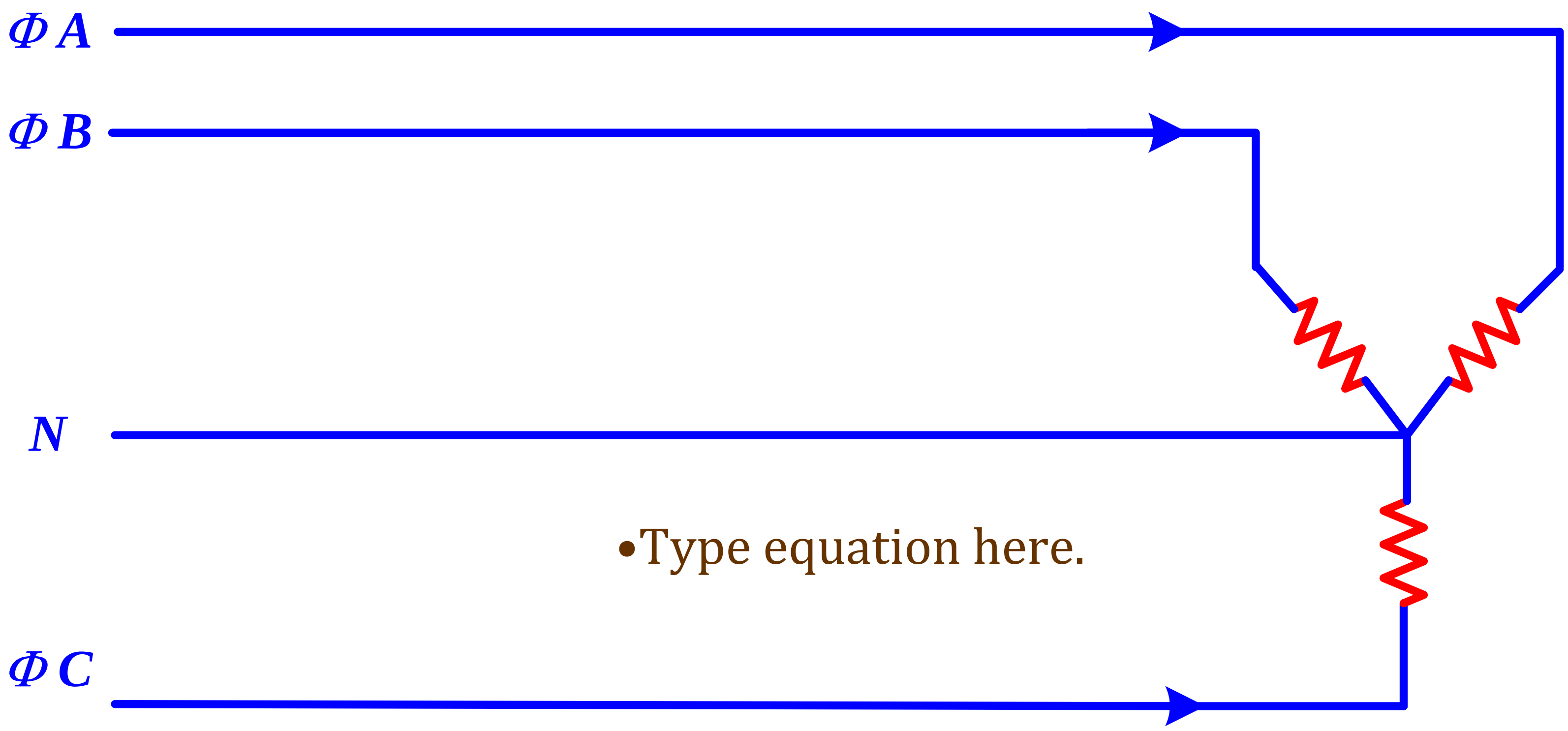


Delta - Wye Provides

- *3 phase output*
- *A closed path for harmonic currents*
- *A neutral for connection to ground for safety*
- *A neutral for single phase loads*

Single or One-Line Diagram

Three Phase Systems - Neutral Wire Size – Balanced, Linear Load



•Type equation here.

$I_A = |I_A|e^{-j30}$ $I_B = |I_B|e^{-j150}$ $I_C = |I_C|e^{-j270}$

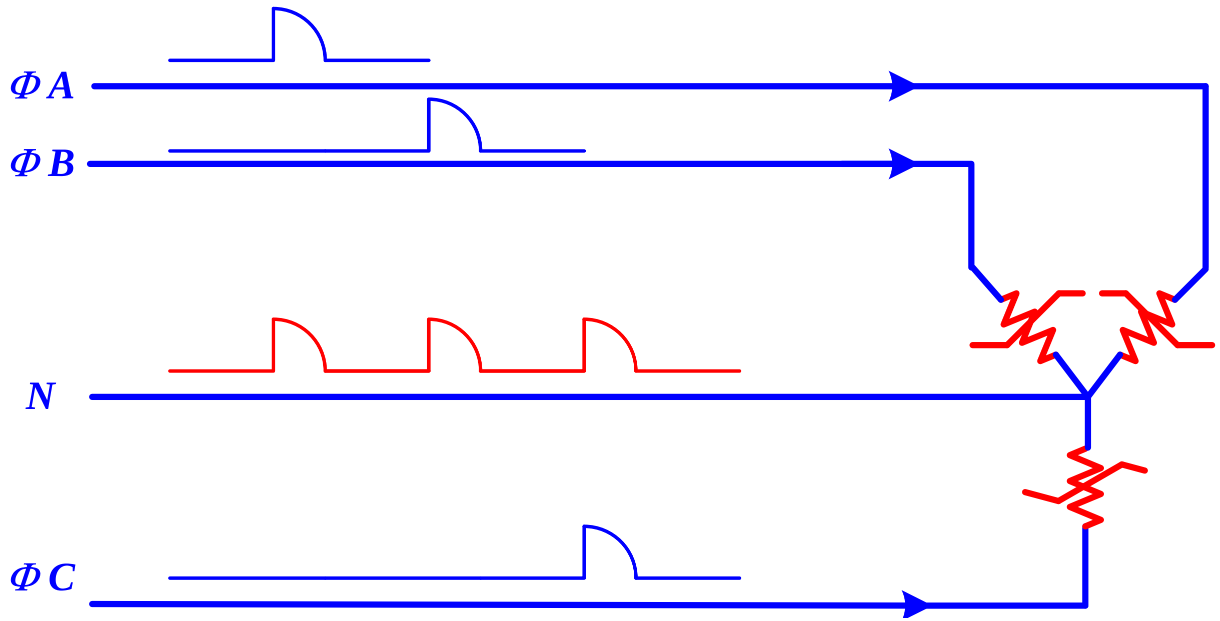
$|I_A| = |I_B| = |I_C|$

$I_N = I_A + I_B + I_C$

$I_N = |I_A|[(0.87 - j0.5) + (-0.87 - j0.5) + (0 + j1)] = 0$

There is no neutral current flow if load is balanced and linear

Three Phase Systems - Neutral Wire Size – Unbalanced and/or Non-linear Loads



For balanced non-linear loads $|I_A| = |I_B| = |I_C| = |I_L|$

$$|I_N| = \sqrt{|I_A|^2 + |I_B|^2 + |I_C|^2} = \sqrt{3}\, I_L$$

For unbalanced linear or non-linear loads $|I_A| \neq |I_B| \neq |I_C|$

$$|I_N| = \sqrt{|I_A|^2 + |I_B|^2 + |I_C|^2}$$

The neutral conductor can safely be sized for $\sqrt{3} * MAX(I_A, I_B, I_C)$

Fundamental Quantities American Commercial and Residential AC Voltages

Class	Voltage	Type	Derivatives
High Voltage	138 kV	3ϕ	None
	69 kV	3ϕ	None
Medium Voltage	13.8 kV	3ϕ	None
	12.47 kV	3ϕ	None
	4.16 kV	3ϕ	None
Low Voltage	480 V	3ϕ	277 V, 1ϕ
	240V	1ϕ	120 V, 1ϕ
	208 V	3ϕ	120 V, 1ϕ
	120 V	1ϕ	None

$$V_{LL}(RMS) = \sqrt{\frac{1}{T}\int_0^T v_{LL}^2(t)dt}$$

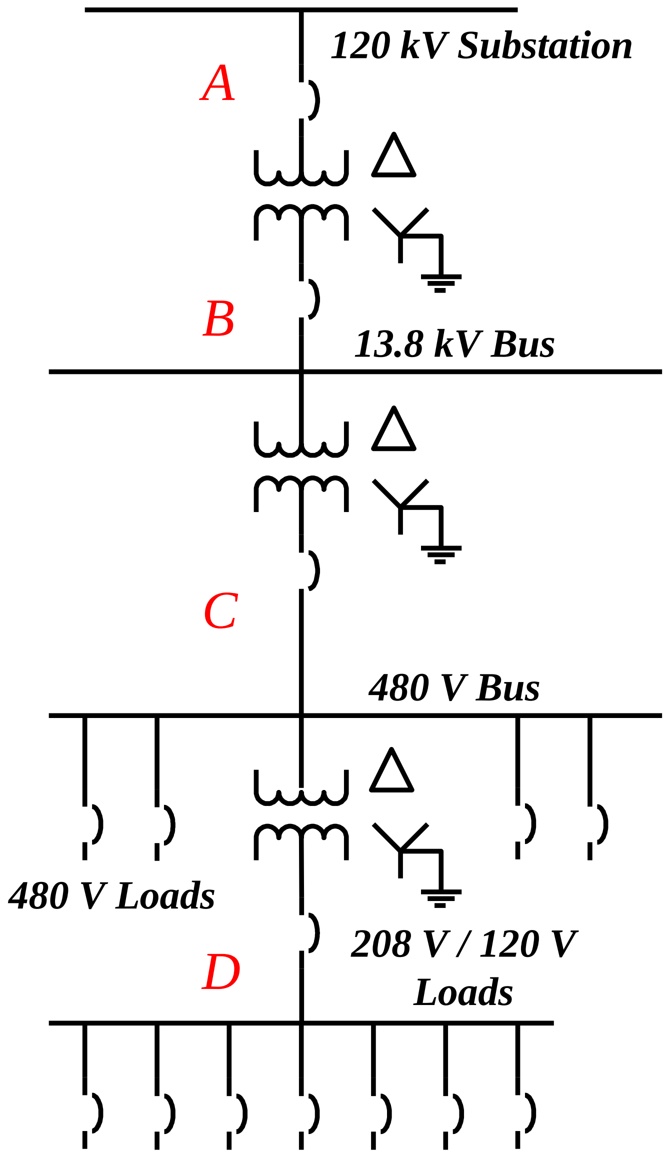
Why Mentioned Here

- Because the power supplies will interface to the AC line
- Because all AC power equipment (generators, motors, transformers and chokes) impedances are expressed in %
- Because line limitations (short-circuit currents, arc flash, V droop, transients, harmonics) must be considered. These effects are usually calculated in the per unit system

Why Used

- To make quantities and values convenient and manageable
- To put quantities on a single per phase or 3-phase basis
- To avoid having to remember to correct for transformer turns ratios, reflected voltages, current and impedances
- No worries about delta or wye configurations

Establish Configuration, then Power, Voltage, Current and Impedance Bases			
Base	**Per ϕ Phase**	**3 Phase**	**Notes**
S,P,Q	= Base kVA	= Base kVA = 3* per ϕ Base kVA	One power base must be used throughout
V	= Base kV (L-N)	= Base kV (L-L)	V Base location dependent
I	= Base kVA / Base kV	= Base kVA / $\sqrt{3}$Base kV	I Base location dependent
Z	= (Base kV) ^{2} / Base kVA	= (Base kV) ^{2} / Base kVA	Z Base location dependent Z Base phase independent perϕ Z Base = 3ϕ Z Base



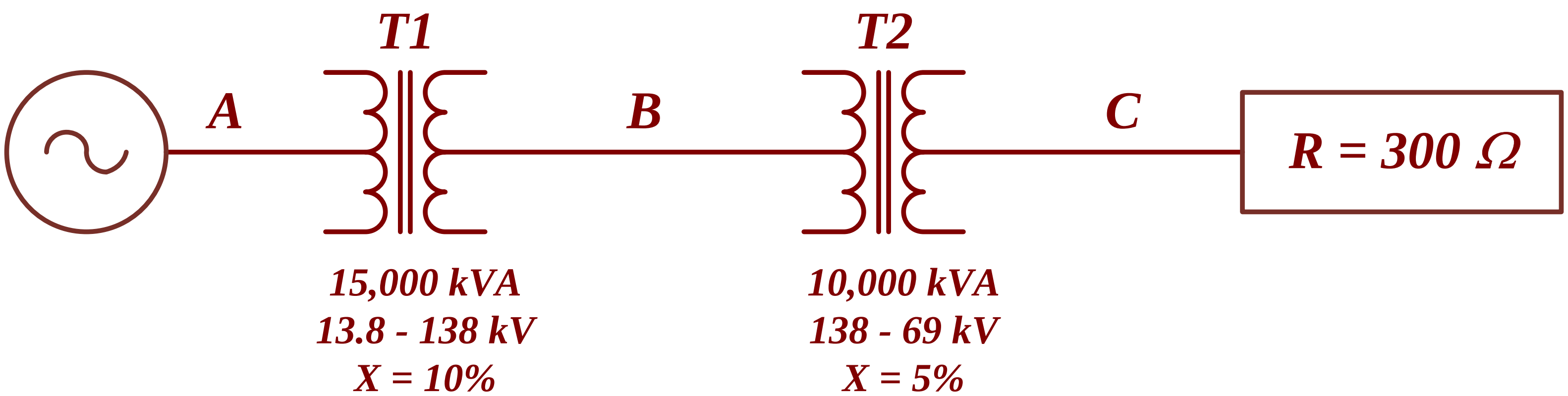
Example - various locations on one-line diagram

• p.u. = actual value / Base value

• $$p.u._{new} = p.u._{given} \left(\frac{Base\, kV_{given}}{Base\, kV_{new}} \right)^2 * \left(\frac{Base\ kVA_{new}}{Base\ kVA_{given}} \right)$$

• % = p.u. * 100 %

• Choose the system and base that yield the most convenient numbers and calculations!



Establish Bases

In Section A

$$\text{Base } S = 10{,}000 \text{ kVA}$$

$$\text{Base } V = 13.8 \text{ kV}$$

$$\text{Base } I = \frac{S}{V} = \frac{10{,}000\,\text{kVA}}{13.8\,\text{kV}} = 725\,A$$

$$\text{Base } Z = \frac{V^2}{S} = \frac{(13.8\,\text{kV})^2}{10{,}000\,\text{kVA}} = 19\,\Omega$$

Section B

$$S = 10{,}000 \text{ kVA}$$

$$V = 138\,\text{kV}$$

$$I = \frac{10{,}000\,\text{kVA}}{138\,\text{kV}} = 72.5\,A$$

$$Z = \frac{(138\,\text{kV})^2}{10{,}000\,\text{kVA}} = 1900\,\Omega$$

Section C

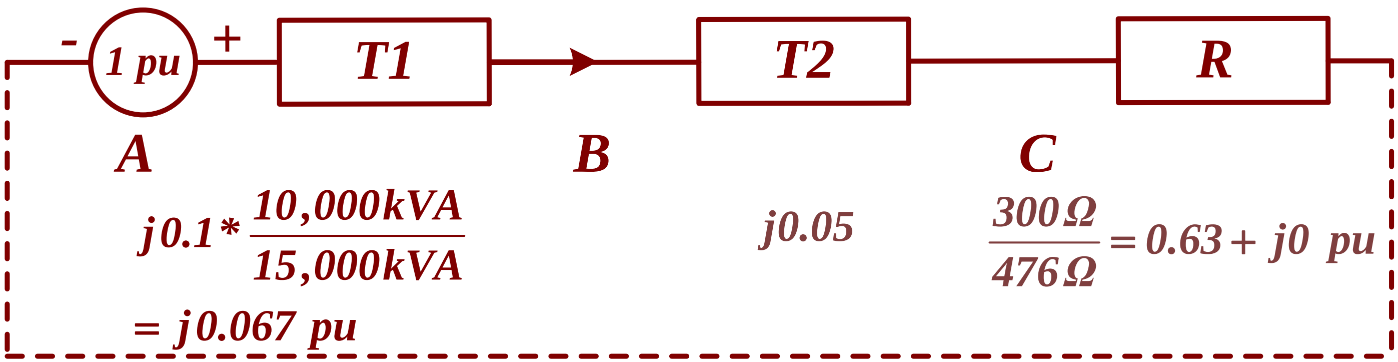
$$S = 10{,}000\,\text{kVA}$$

$$V = 69\,\text{kV}$$

$$I = \frac{10{,}000\,\text{kVA}}{69\,\text{kV}} = 145\,A$$

$$Z = \frac{(69\,\text{kV})^2}{10{,}000\,\text{kVA}} = 476\,\Omega$$

Obtain pu values

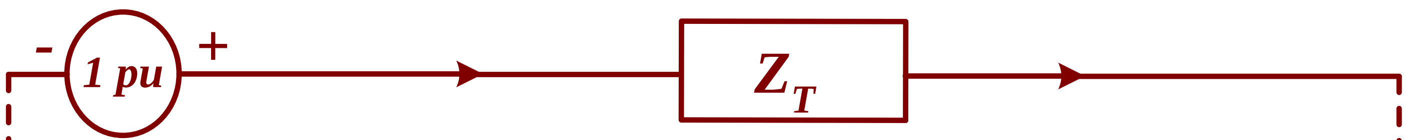


$$j0.1*\frac{10,000kVA}{15,000kVA} = j0.067\ pu$$

$$j0.05$$

$$\frac{300\,\Omega}{476\,\Omega} = 0.63 + j0\ \ pu$$

Combine impedances – Solve for I



$$|I| = \frac{1}{0.64} = 1.56\ pu$$

$$Z_T = 0.63 + j0.117\ pu$$

$$|Z_T| = 0.64\ pu$$

$$|I| = 1.56\ pu$$

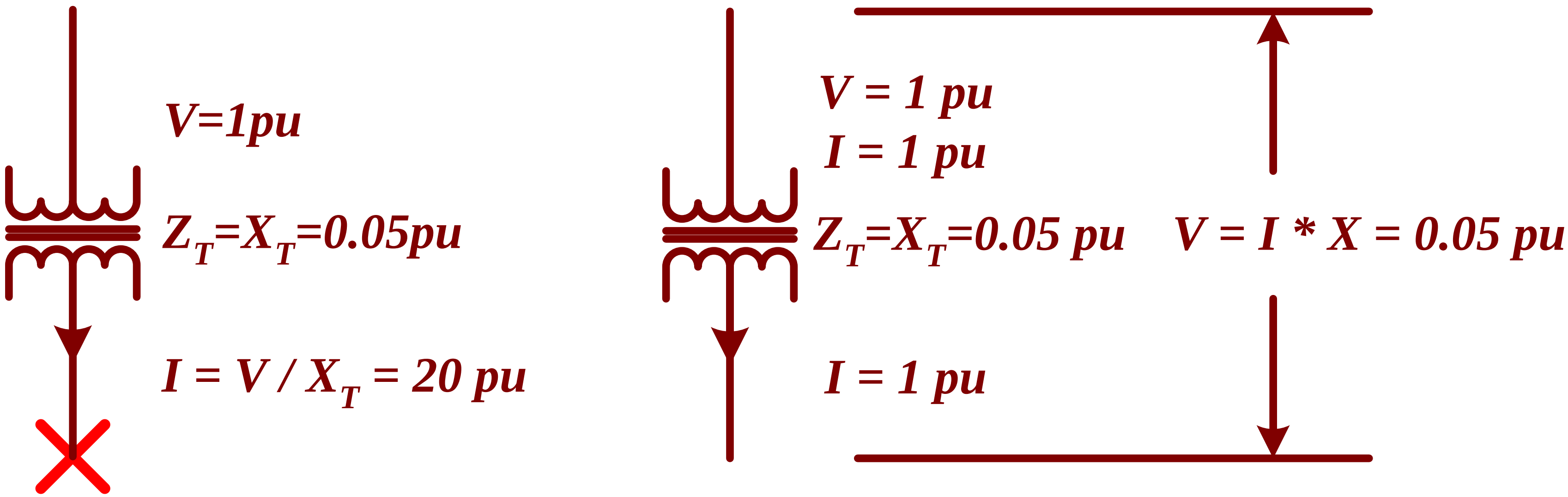
$$|I_A| = 1.56\ pu*725\,A = 1,131\,A$$

$$|I_B| = 1.56\ pu*72.5\,A = 113\,A$$

$$|I_C| = 1.56\ pu*145\,A = 226\,A$$

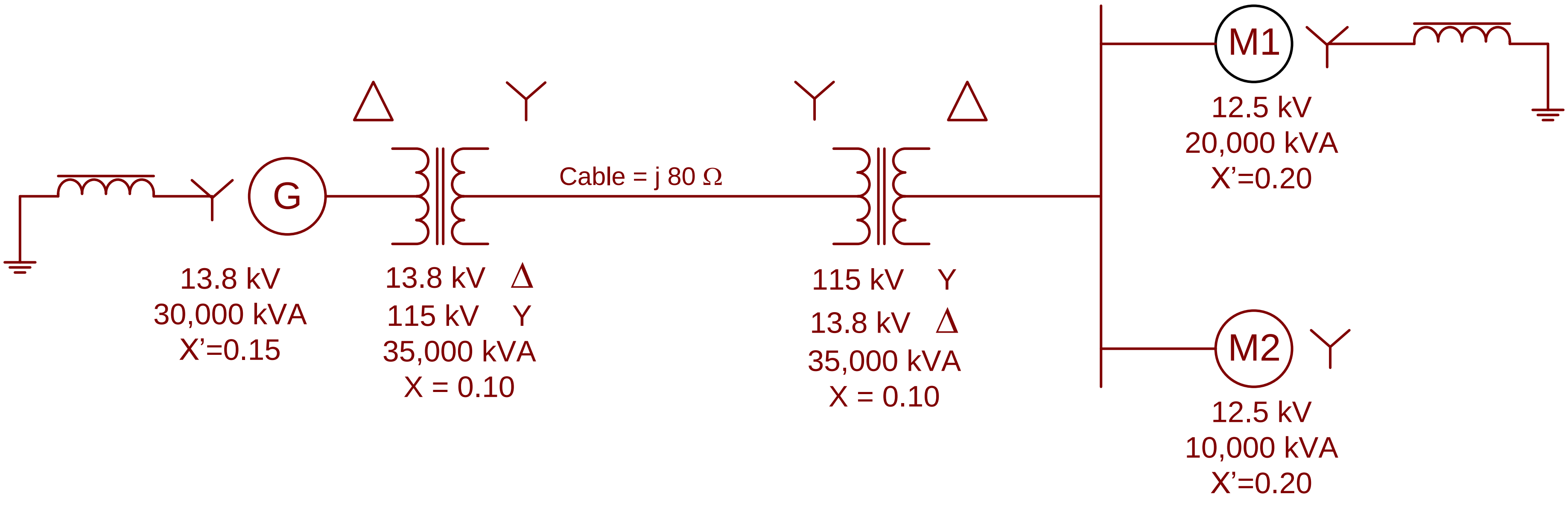
A transformer impedance of 5% means:

- *The short circuit current is 20X rated full load input / output*
- *The voltage drop across the transformer at full load is 5% of rated*



Referring to the one-line diagram below, determine the line currents in the:

A. Generator B. Transmission Line C. M1 D. M2



Per Unit System - Homework Problem #3

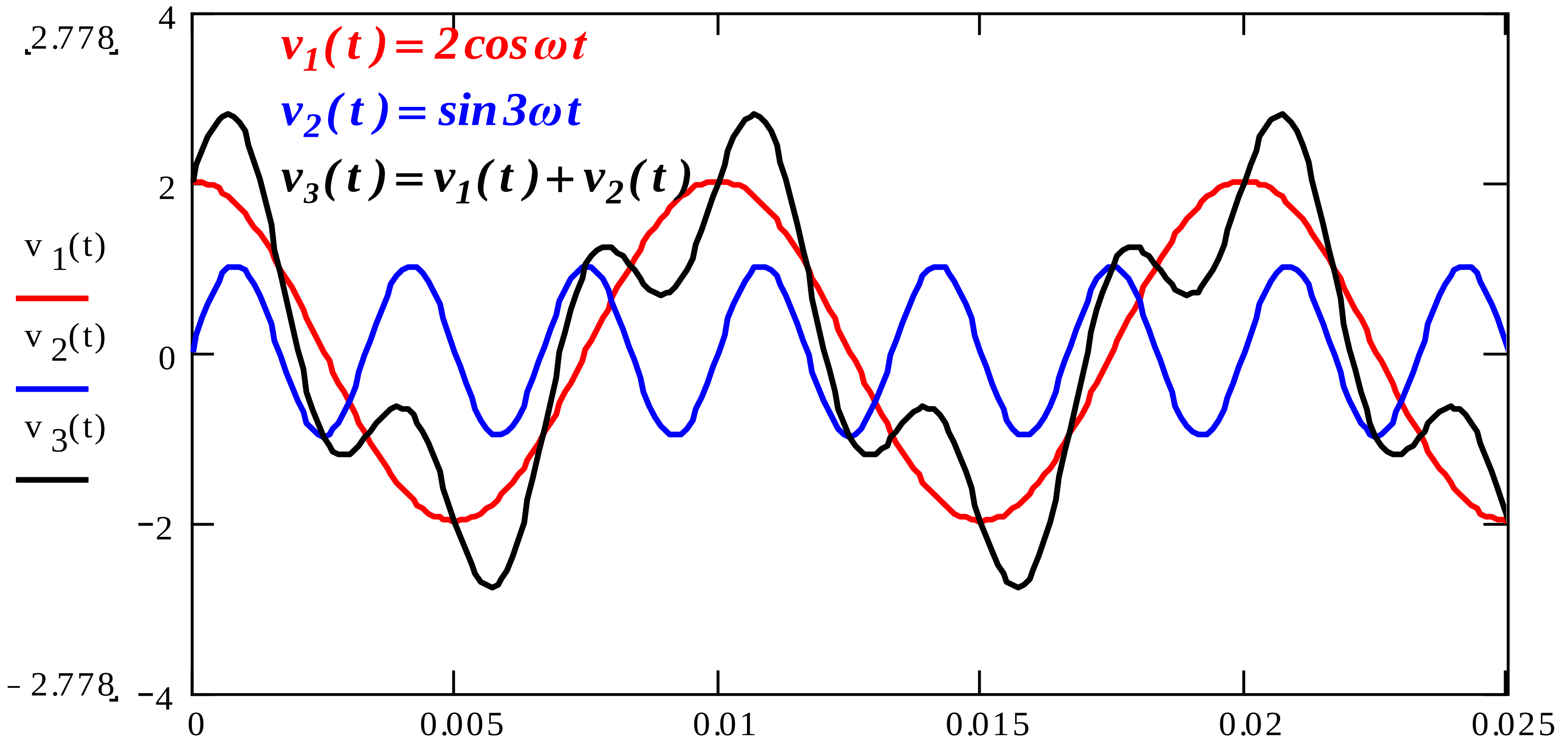
A 1000kVA, 12.47kV to 480V, 60Hz three-phase transformer has an impedance of 5%. Calculate:

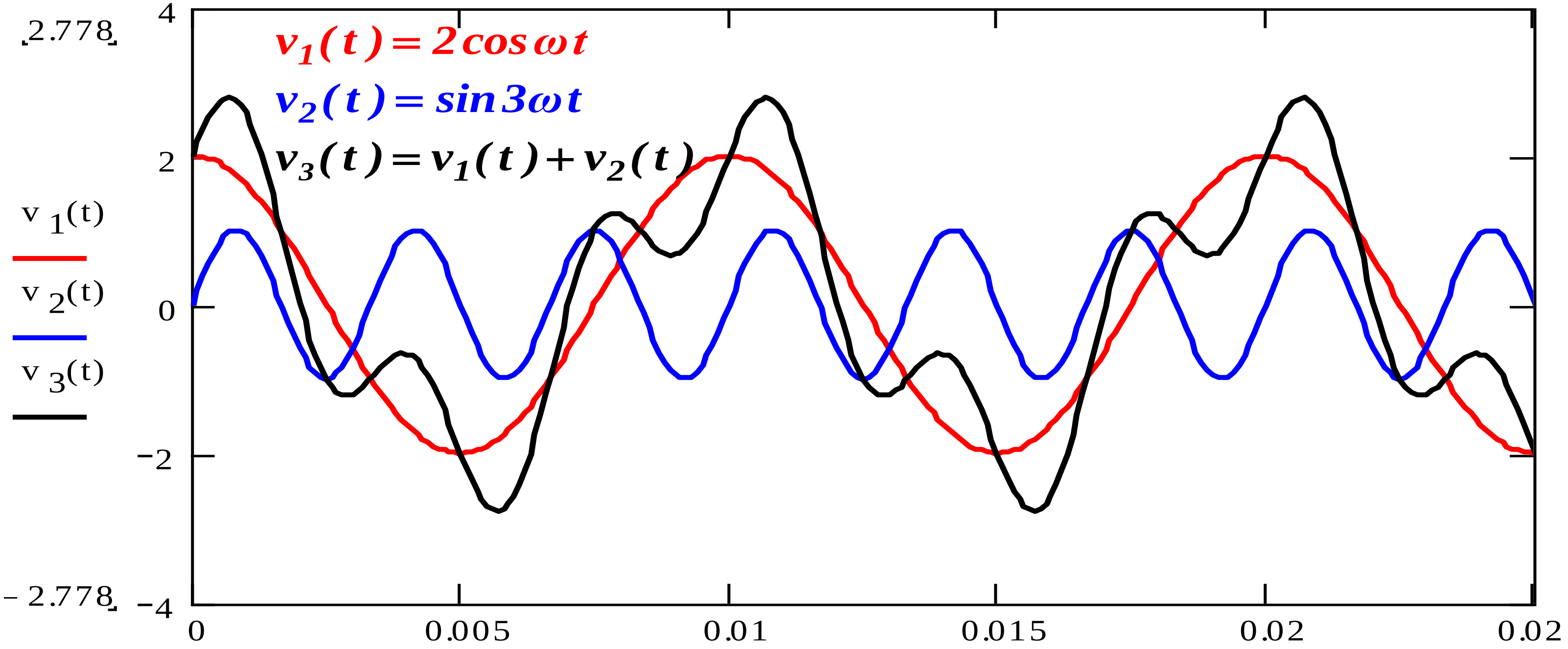
a. The actual impedance and leakage inductance referred to the primary winding

b. The actual impedance and leakage inductance referred to the secondary winding

c. The magnetizing inductance referred to the primary winding

- *Non-sinusoidal waves are complex and are composed of sine and cosine harmonics*
- *The harmonics are integral multiples of the fundamental frequency (1st harmonic) of the wave. The second harmonic is twice the fundamental frequency, the third harmonic is 3 X the fundamental frequency, etc.*



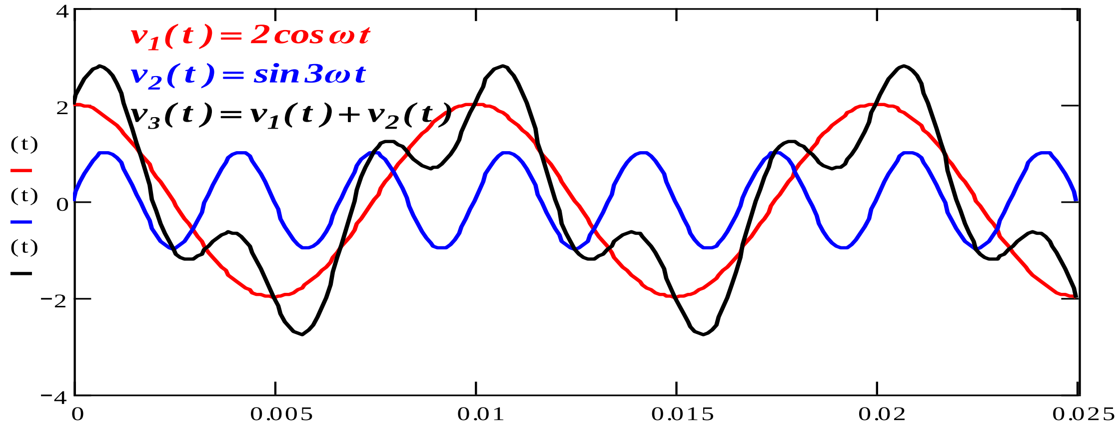


Trigonometric forms of the Fourier Series

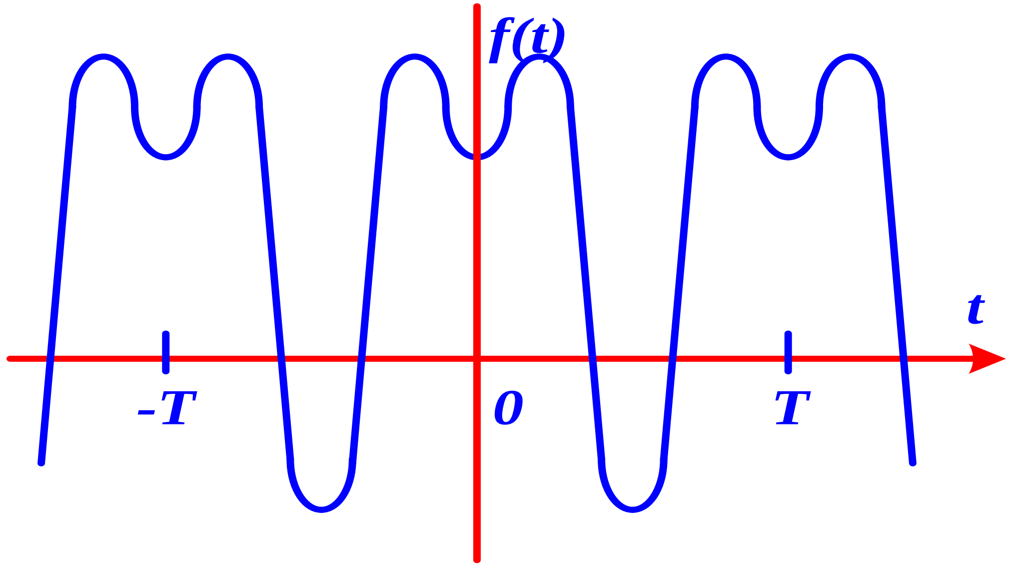
$$a_0 = \frac{1}{T}\int_0^T f(t)\,dt \qquad a_k = \frac{2}{T}\int_0^T f(t)\cos k\omega t\,dt \qquad b_k = \frac{2}{T}\int_0^T f(t)\sin k\omega t\,dt$$

$$f(t) = a_0 + \sum_{k=1}^{\infty} a_k \cos\frac{2\pi kt}{T} + b_k \sin\frac{2\pi kt}{T}$$

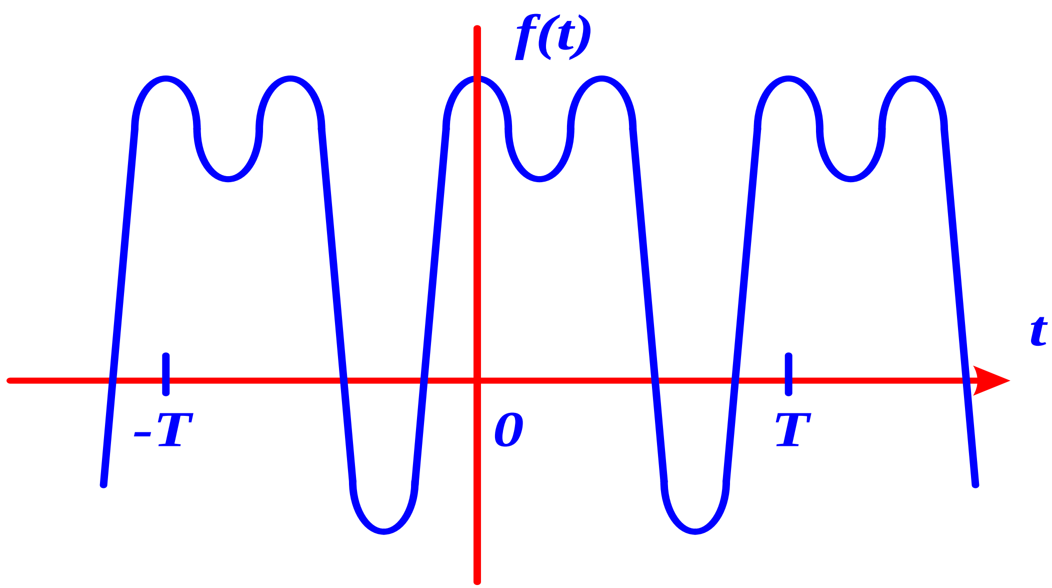
Harmonics, Complex Waveforms and Fourier Series - Coefficient Facilitators



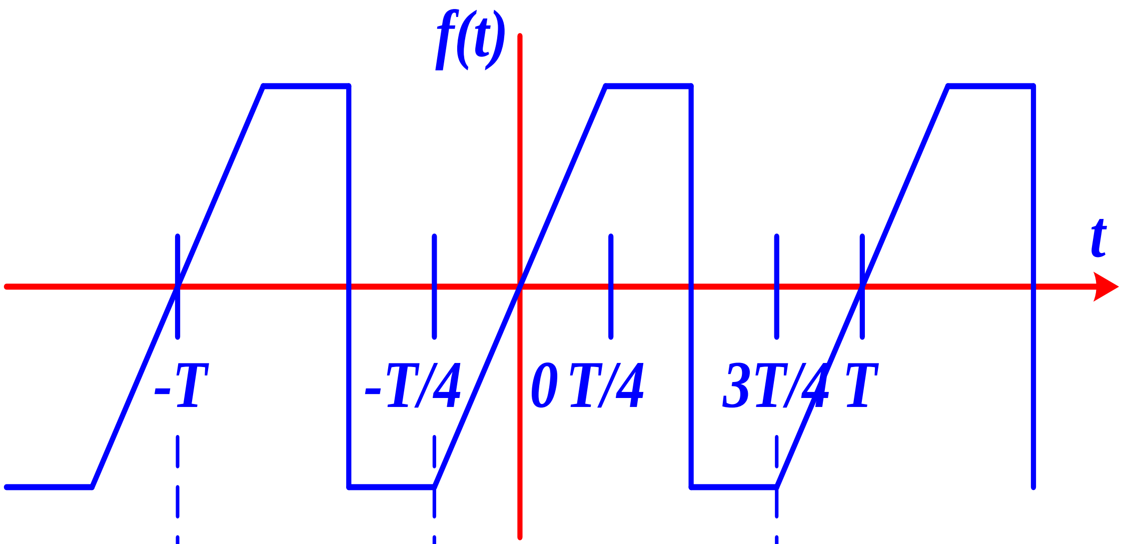
No symmetries		a_k cosines, b_k sines, for all k	*May or may not have DC component*
Even function symmetry	$f(t) = f(-t)$	Only a_k cosines for all k ($b_k = 0$)	*Has DC component if no half-wave symmetry*
Odd function symmetry	$f(t) = -f(-t)$	Only b_k sines for all k ($a_k = 0$)	*No DC component*
Half-wave symmetry	$f(t) = -f\left(t - \frac{T}{2}\right)$	a_k cosines, b_k sines, for odd k	*No DC component*
Half-wave, even function symmetry	$f(t) = -f\left(t - \frac{T}{2}\right)$ $f(t) = f(-t)$	Only a_k cosines for odd k ($b_k = 0$)	*No DC component*
Half-wave, odd function symmetry	$f(t) = -f\left(t - \frac{T}{2}\right)$ $f(t) = -f(-t)$	Only b_k sines for odd k ($a_k = 0$)	*No DC component*



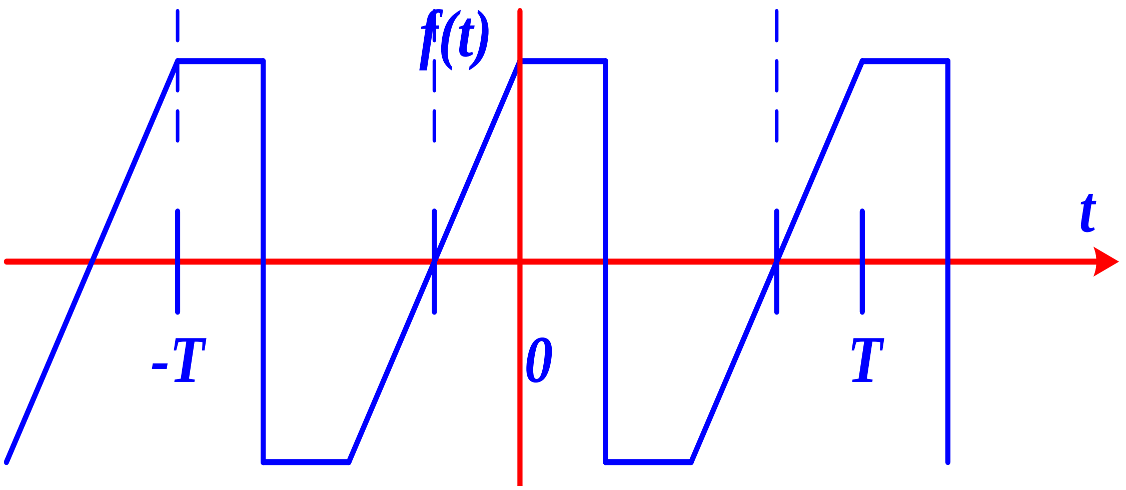
- $f(t) = f(-t)$ even function
- $f(t) \neq -f(t-T/2)$
- No half-wave symmetry
- DC component, a_o
- No sine terms, only cosines, all ks
- $a_k = \frac{2}{T}\int_0^T f(t)\cos k\omega_o t\,dt$



- No even or odd function symmetry
- No half-wave symmetry
- Have sine and cosine terms, all k
- DC component, a_o
- a_o, a_k , b_k terms

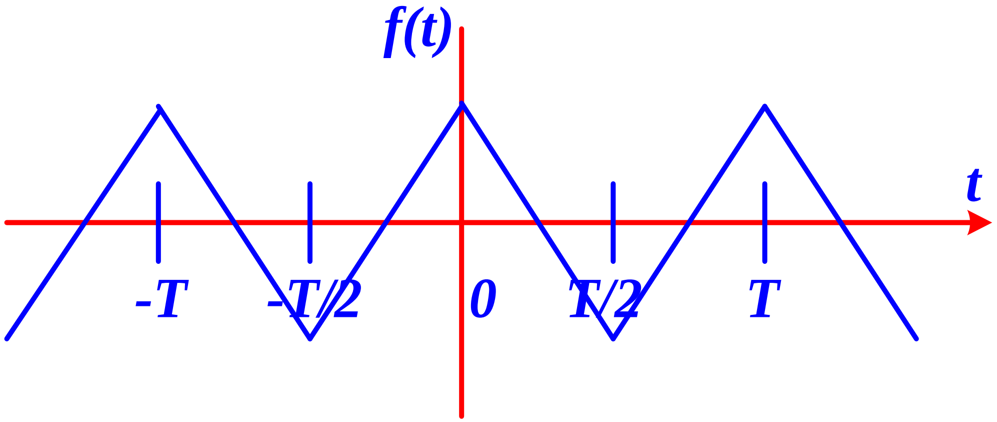


- $f(t)=-f(-t)$ odd function
- No half-wave symmetry
- No DC component
- Just b_k sines, all k
- $b_k = \frac{2}{T}\int_0^T f(t) \sin k\omega_o t \, dt$

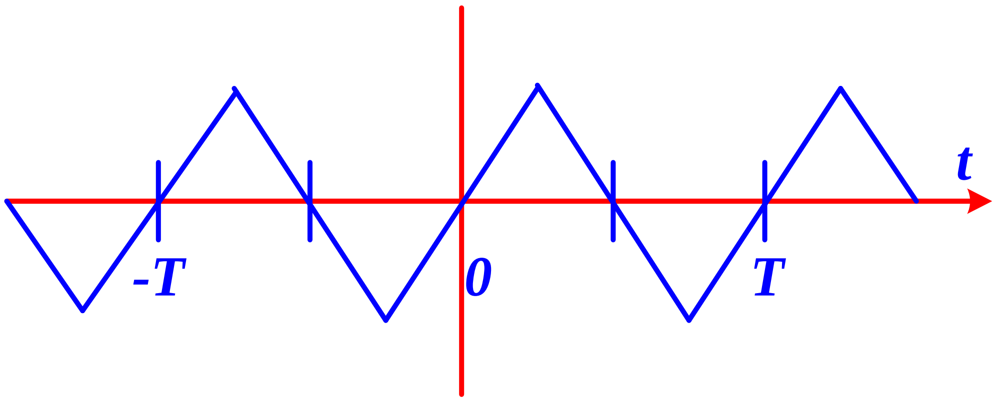


- No symmetries
- No DC component
- Have a_k cosine and b_k sine terms, all k

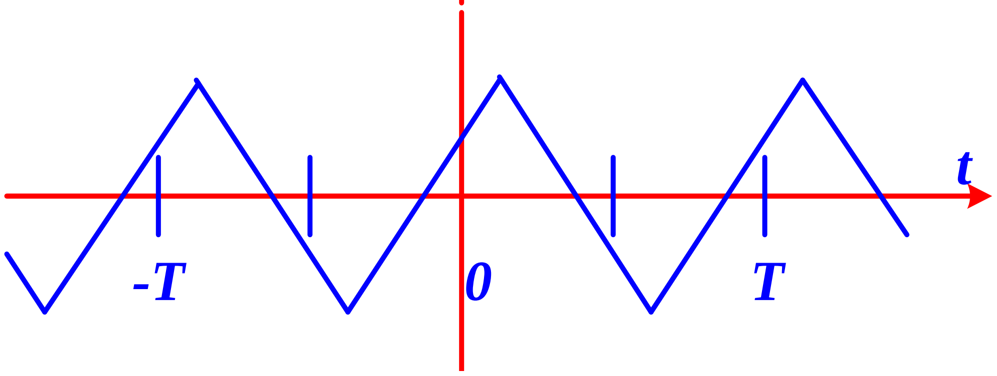
Fourier Series - Examples of Periodic Waveforms



- $f(t)=f(-t)$ even function
- Half-wave symmetry
- No DC component
- Have a_k for odd ks

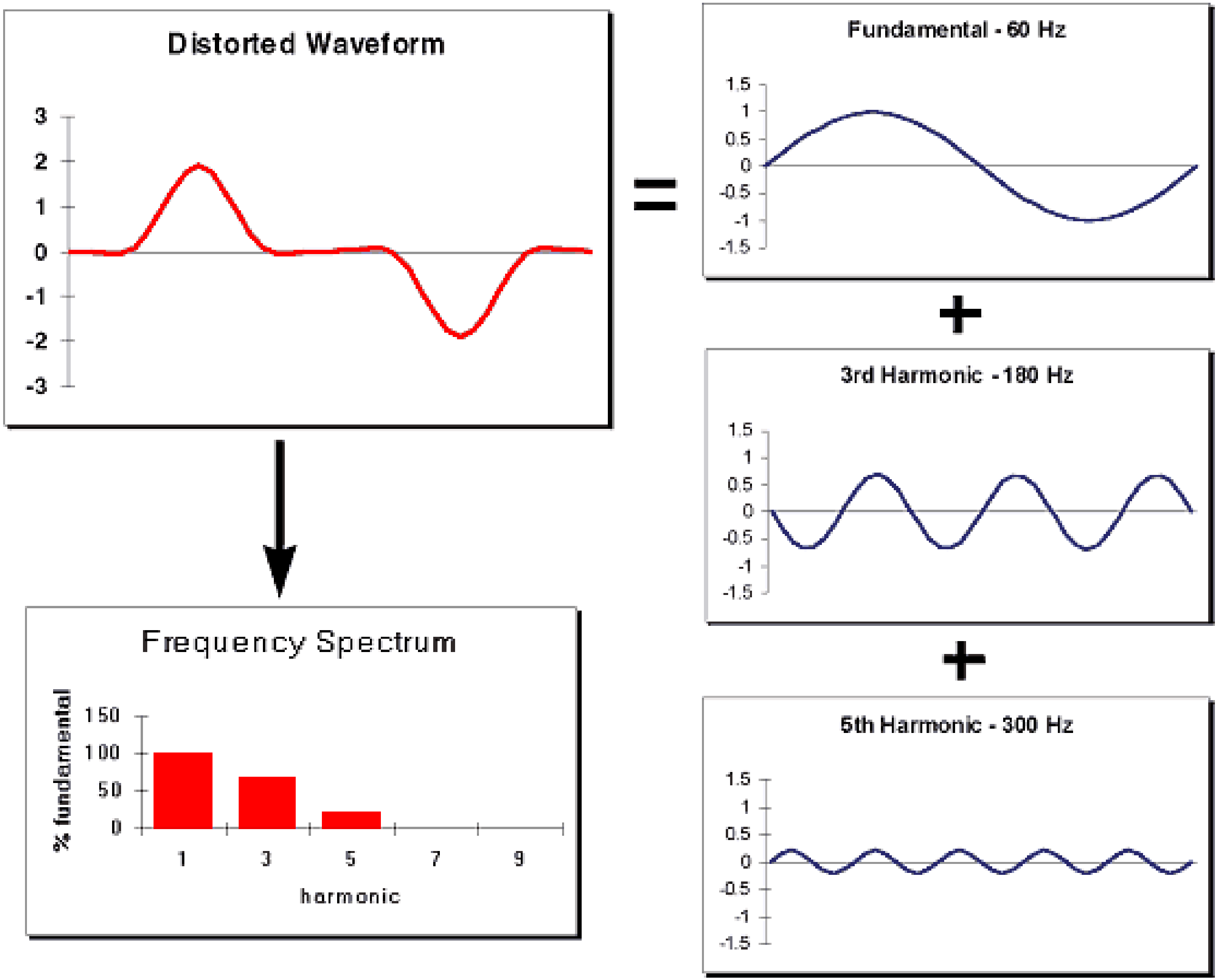


- $f(t)=-f(-t)$
- Half wave symmetry
- No DC component
- Have b_k for odd ks

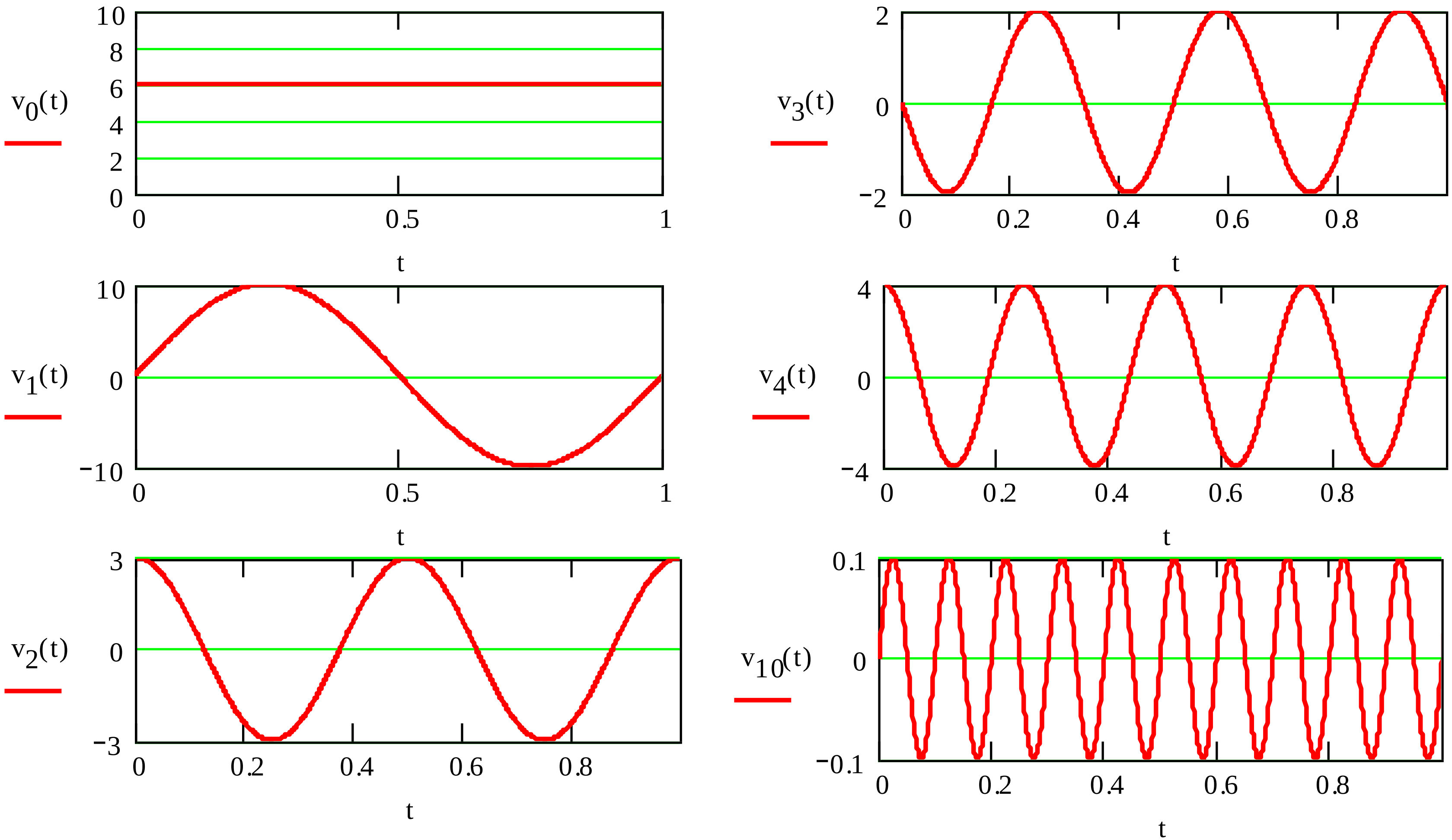


- No even or odd symmetry
- Half wave symmetry
- No DC component
- Have a_k , b_k for odd ks

Fourier Series - Distorted (Complex) Waveforms



A waveform v(t) was analyzed and found to consist of 6 components as shown here.



a. Write the mathematical expression for each component in terms of $\omega=(2*\pi)/T$

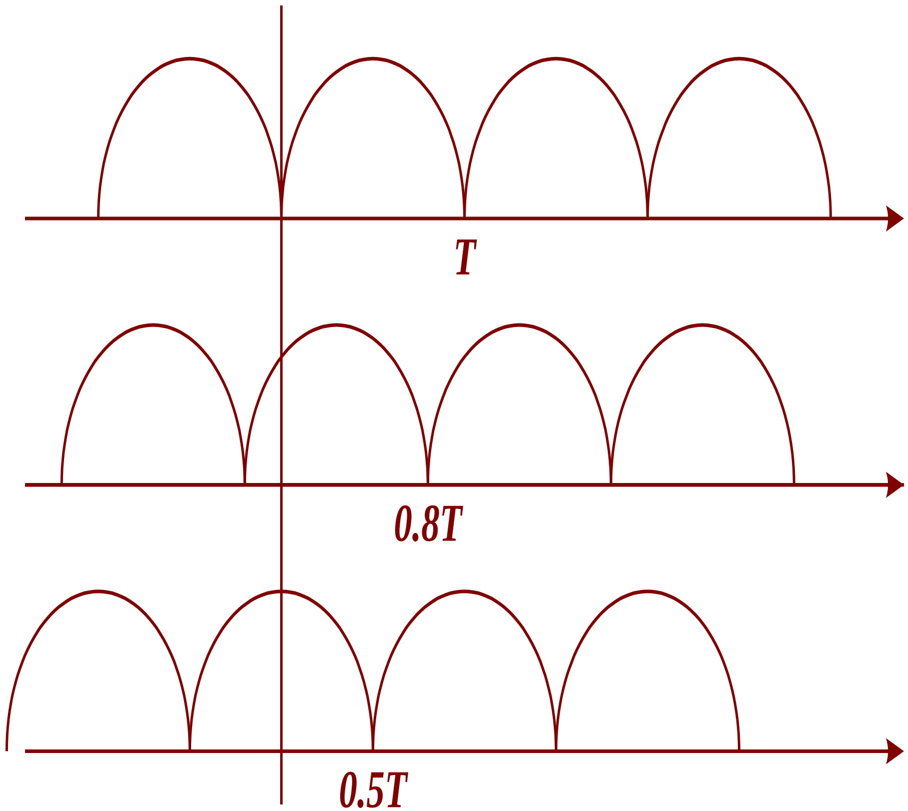
b. Show the harmonic content graphically by plotting the frequency spectrum

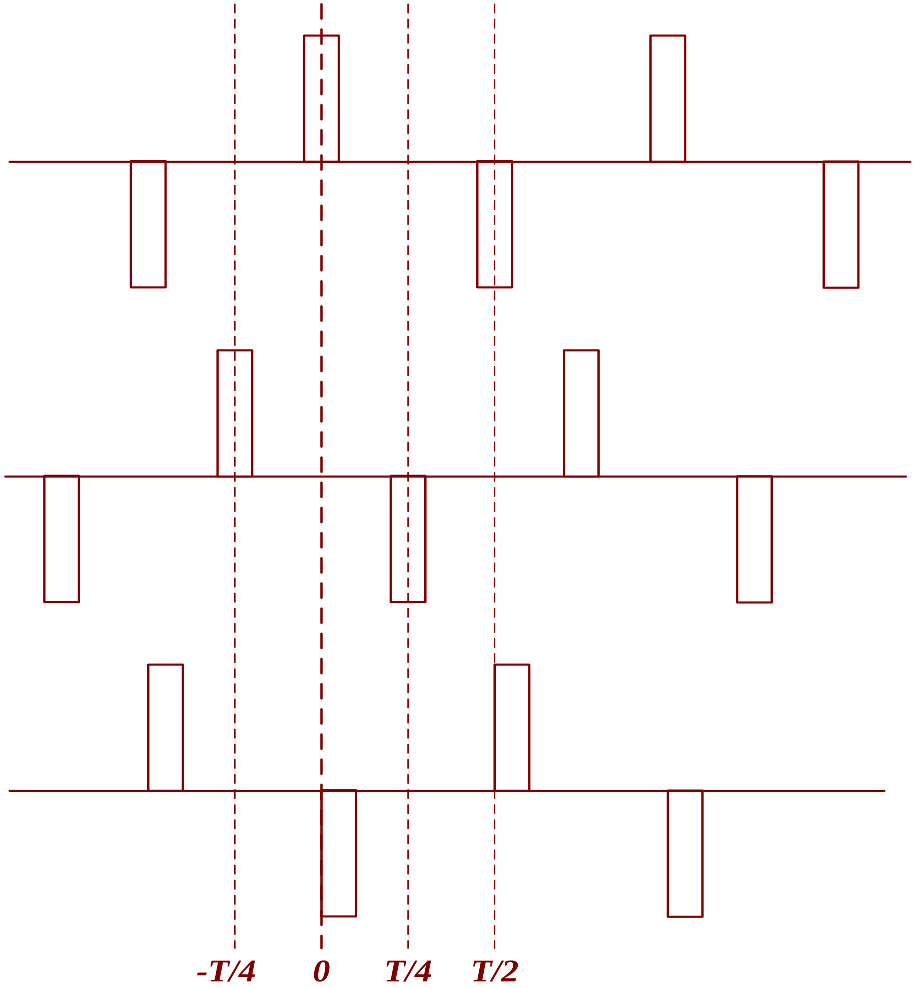
c. Give the numerical result of

$$b_3 = \frac{2}{T}\int_0^T v(t)\sin 3\omega t\, dt \qquad Help: \int \sin^2(3\omega t)\, dt = \frac{t}{2} - \frac{\sin 6\omega t}{12\omega}$$

$$b_4 = \frac{2}{T}\int_0^T v(t)\sin 4\omega t\, dt \qquad Help: \int \cos(4\omega t)\sin(4\omega t)\, dt = \frac{\sin(4\omega t)^2}{8\omega}$$

Each waveform below can be written as a Fourier series. The result depends upon the choice of origin. For each of the 6 cases, state the type of symmetry present, non-zero coefficients and the expected harmonics.





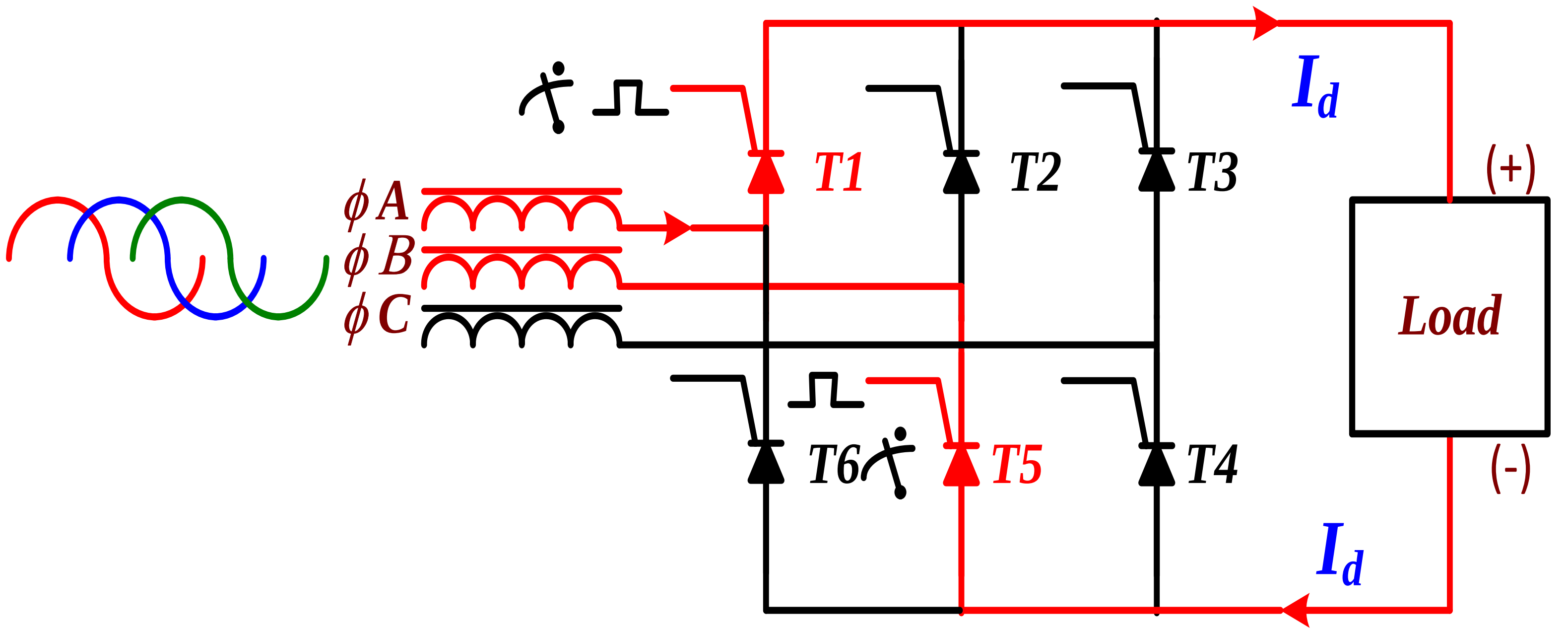
Signal Total Harmonic Distortion (THD): *The ratio of the square root of the summed squares of the amplitudes of all harmonic frequencies above the fundamental frequency to the fundamental frequency*

$$THD_V = \frac{\left[\sum_{i=2}^{N} V_i^2\right]^{1/2}}{V_1} * 100\%$$

$$THD_I = \frac{\left[\sum_{i=2}^{N} I_i^2\right]^{1/2}}{I_1} * 100\%$$

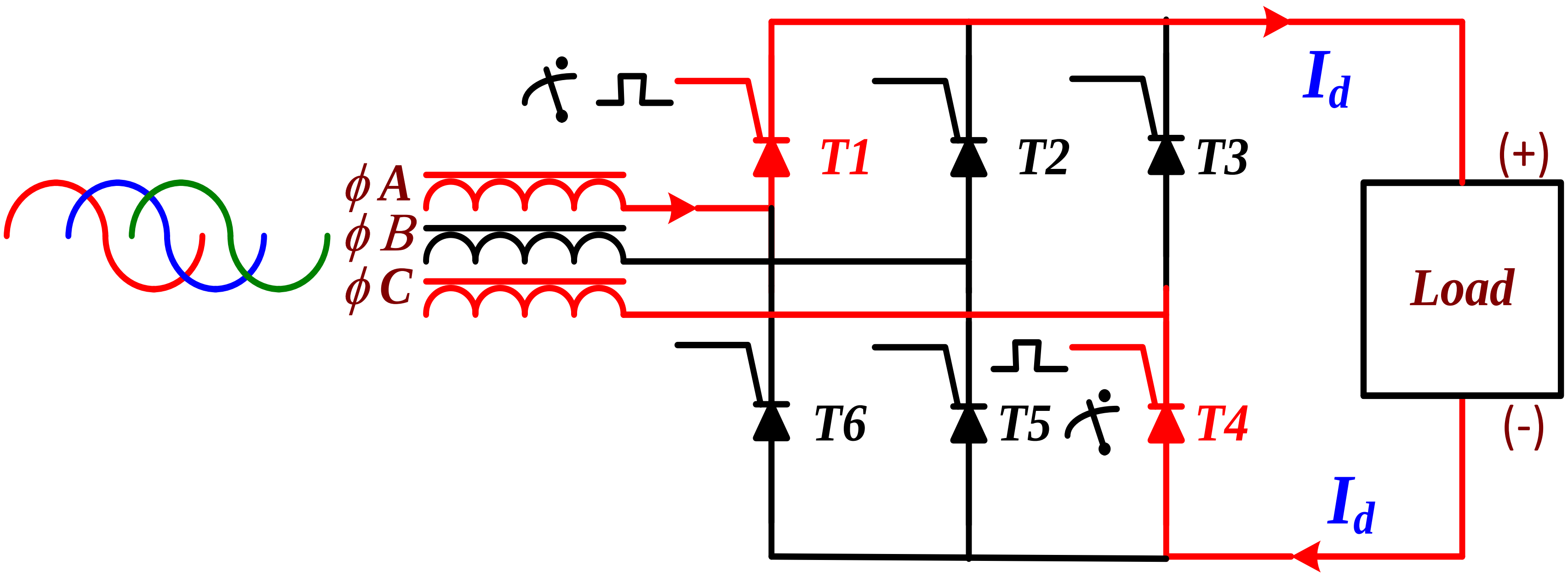
- *SCR or diode commutation*
- *Unbalanced 3-phase, non-linear loads*

SCR Commutation as Distortion Cause



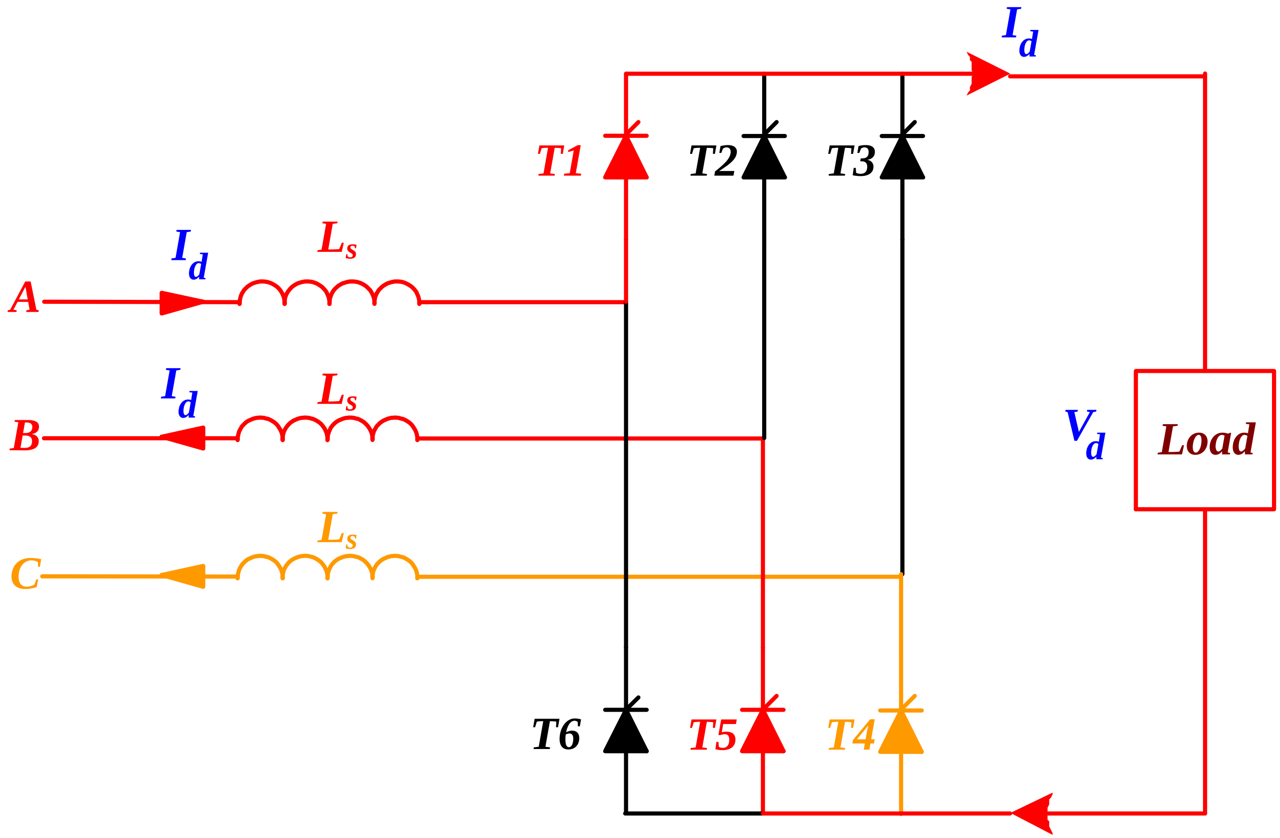
State 1: A-B (+) SCR s 1 – 5 On

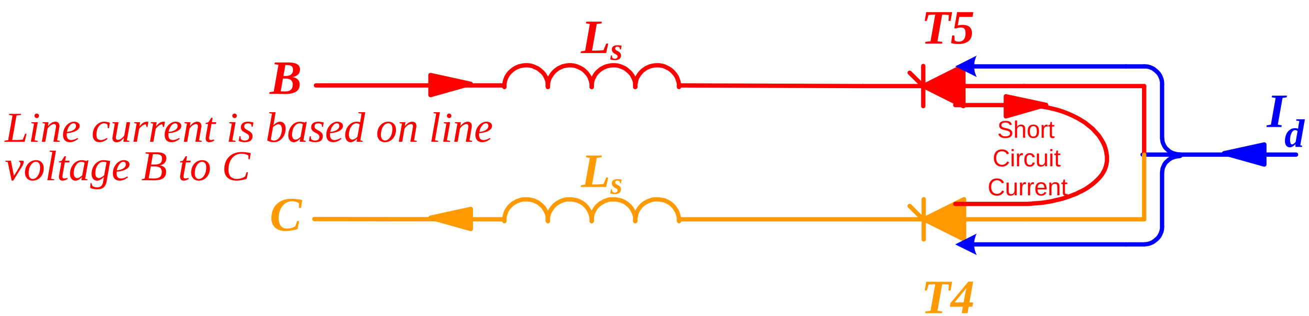
SCR Commutation as Distortion Cause



State 2 : A-C (+), 5 off, 4 on, SCR s 1 – 4 On

SCR Commutation as Distortion Cause





SCR Commutation Voltage Drop

$$V_d = V_{do} - V_u$$

$$V_{Ls} = L_s \frac{di}{dt}$$

$$V_u = \frac{q}{\omega T}\int_{\alpha}^{\alpha+\mu} V_{Ls}\, d(\omega t) = \frac{q}{2\pi}\omega L_s \int_0^{I_d} di = \frac{q}{2\pi}\omega L_s I_d = q\, f\, L_s I_d$$

Commutation voltage drop

$$V_d = \frac{q\sqrt{2}}{2\pi} V_{LL}\cos\alpha - q\, f\, L_s I_d$$

$V_d =$ reduced output, $V_{do} =$ Theoretical output, $V_u =$ commutation drop

$V_{Ls} =$ Voltage drop due to line impedance, $i =$ phase current

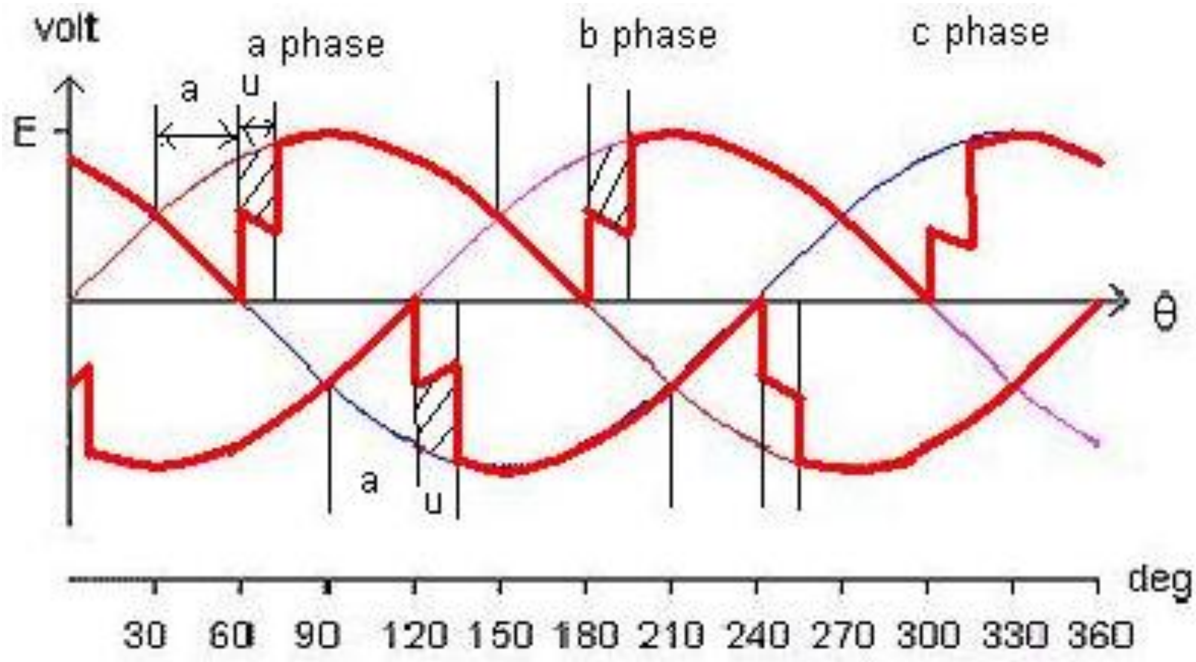
$q =$ number of rectifier states, $\alpha =$ SCR gate trigger retard angle, $\mu =$ commutation overlap angle

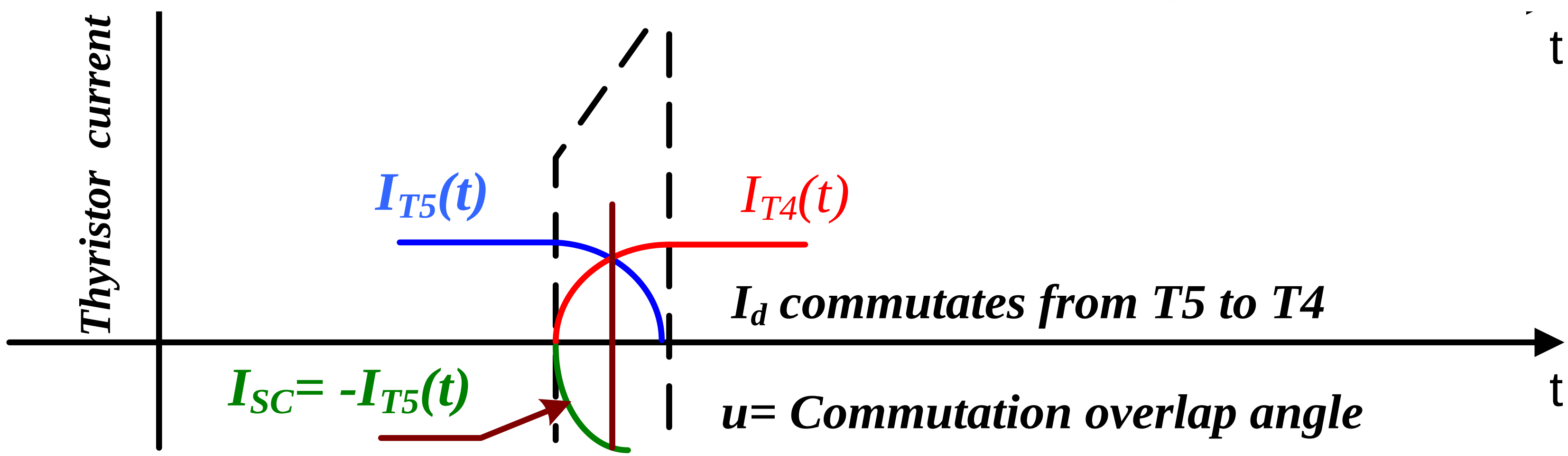
$\omega =$ operating frequency in radians, $f =$ frequency in Hz, $I_d =$ Load current

Conclusions

- The current commutation takes a finite commutation interval u.
- During the commutation interval, three SCRs conduct.
- Vu (and line voltage distortion) is directly proportional to the inductance of the input AC line or transformer and the DC current flowing in the load

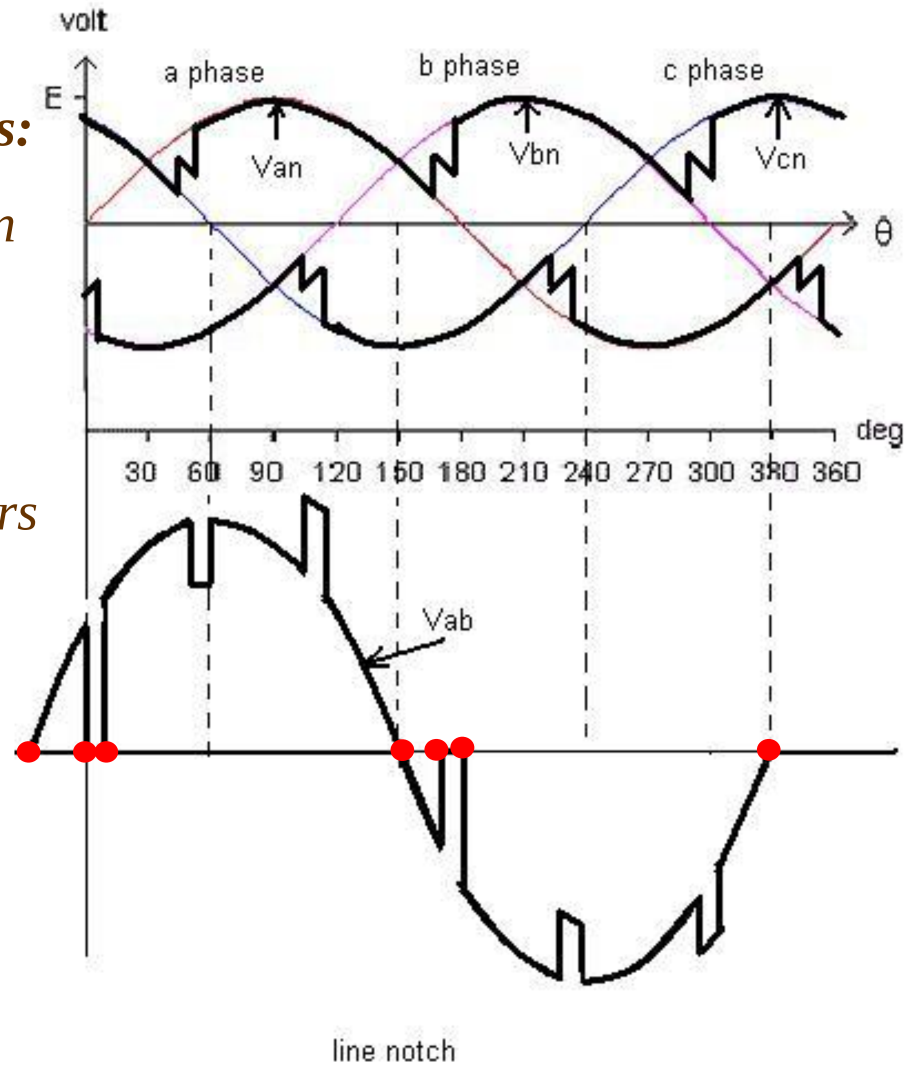
SCR Commutation as Distortion Cause





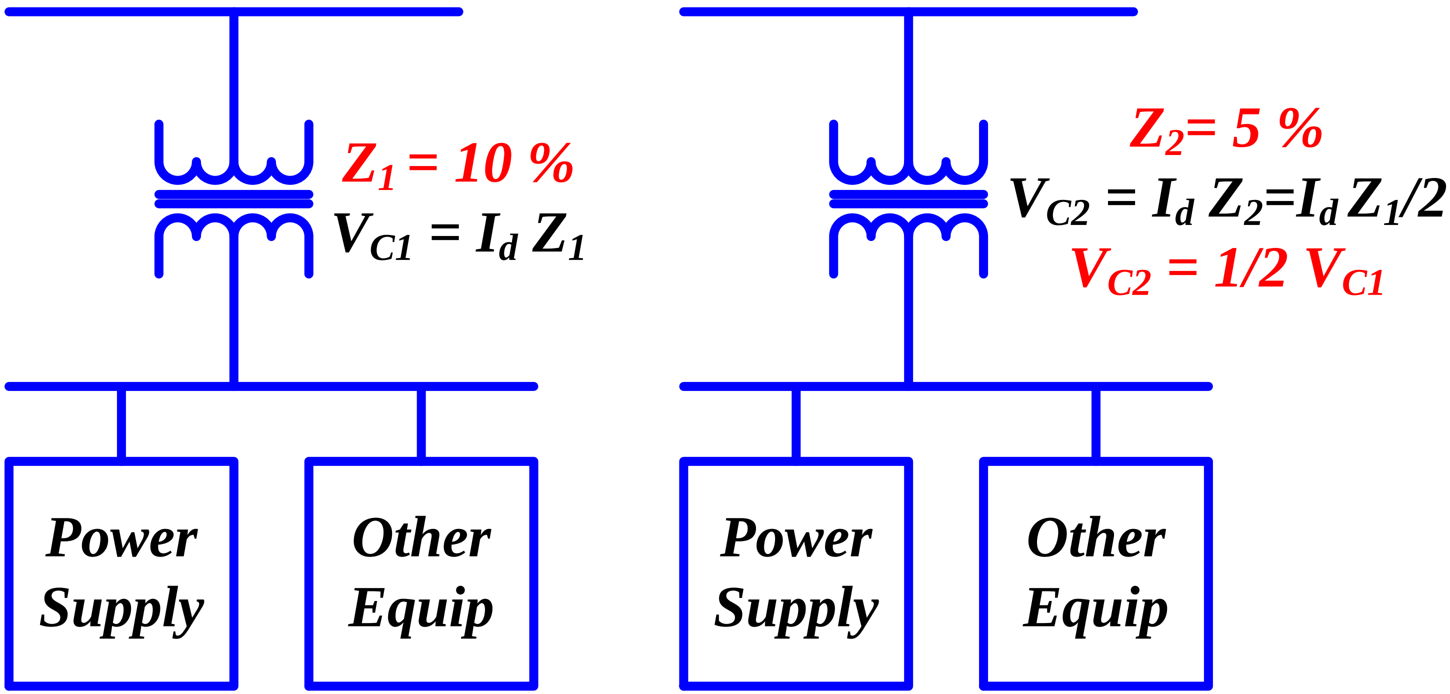
SCR / diode commutation line notches:

- Are a source of line voltage distortion
- If deep enough, they cause extra zero crossovers in the line voltage. In 3 phase systems, instead of 2 zero crossovers per cycle, 6 zero crossovers can be experienced
- The extra zero crossovers can upset equipment timing. This can cause SCRs to trigger at the wrong time, damaging the power supply or cause false turn-on and damage to other equipment.



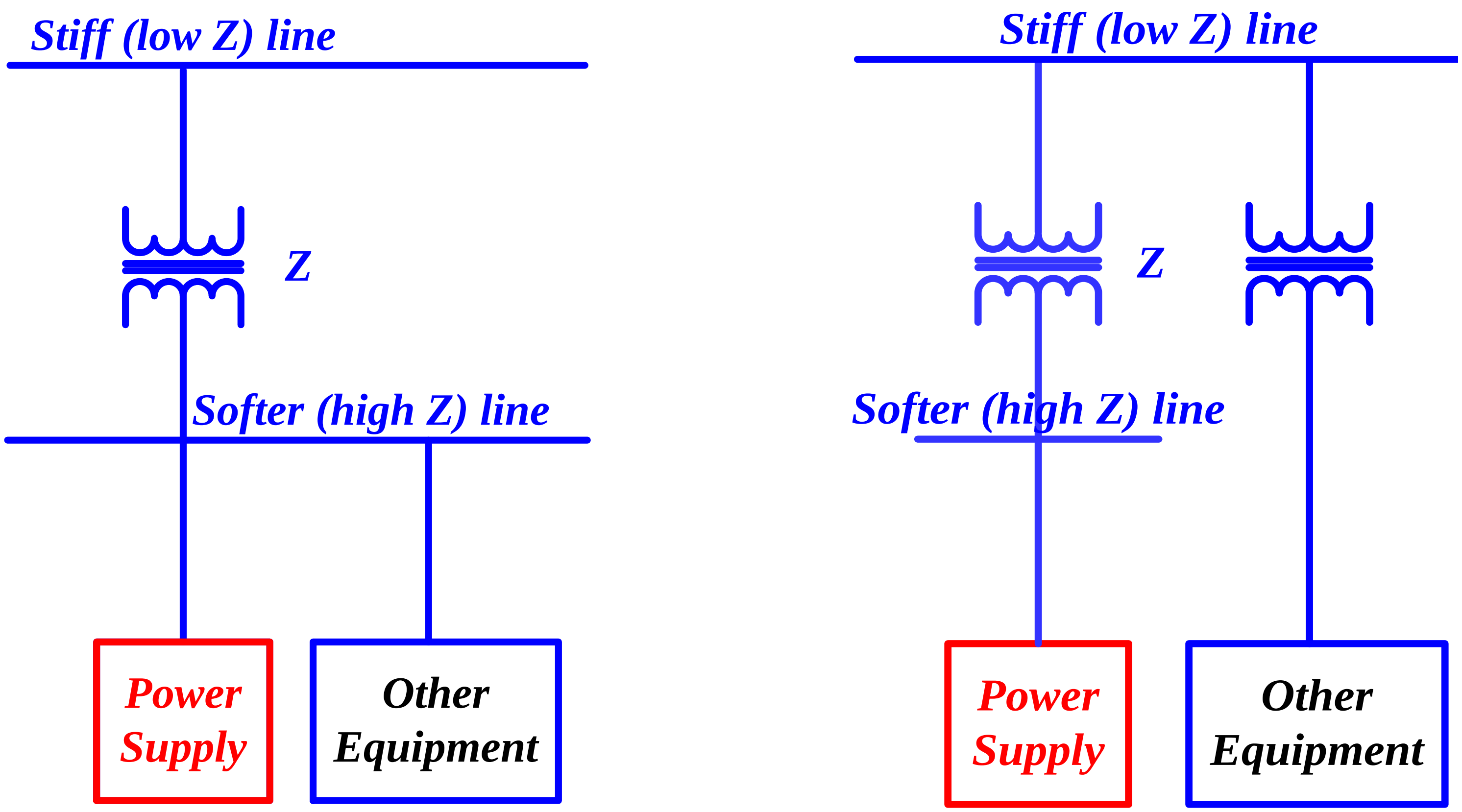
Reducing SCR commutation effects

- *Commutation notches (voltage drops) are directly proportional to system Z and DC load current. To reduce commutation notch depth, use a stiff (large, low Z) line.*



Reducing SCR commutation effects on other equipment

- Isolate other equipment by placing them on another line



Australia	*AS/NZS 61000.3.6 , replaces AS 2279 - "Disturbances in Mains Supply Networks" and is compatible with IEEE 519 recommendations*
Britain	*G5/4 – 1 "Standard for Harmonic Control in Power Systems" which is compatible with IEEE 519 – 1992*
Europe	*International Electrotechnical Commission* *IEC 555 Series for harmonic current distortion limits for small devices (extended by IEC 1000 standards)* *Larger devices IEC61000-3-2, EN61000-3-2*
United States	*IEEE 519 – 1992 "Standard Practices and Requirements for Harmonic Control in Electrical Power Systems" .*

SCR Commutation Effects - IEEE 519- 1992 Voltage Distortion Limits

Table 10.2 Low Voltage System Classification And Distortion Limits			
	Special Applications [1]	General Systems	Dedicated Systems [2]
THD (Voltage)	3%	5%	10%
Notch Depth	10%	20%	50%
Notch Area [3]	16,400 $V - \mu S$	22,800 $V - \mu S$	36,500 $V - \mu S$

1. Airports and hospitals
2. Exclusive use converters
3. Multiply by V / 480 for other than 480 V systems

$$\text{Example}: 480V * \sqrt{2} = 678.8V \qquad 20\% \text{ notch depth} = 135.8V$$

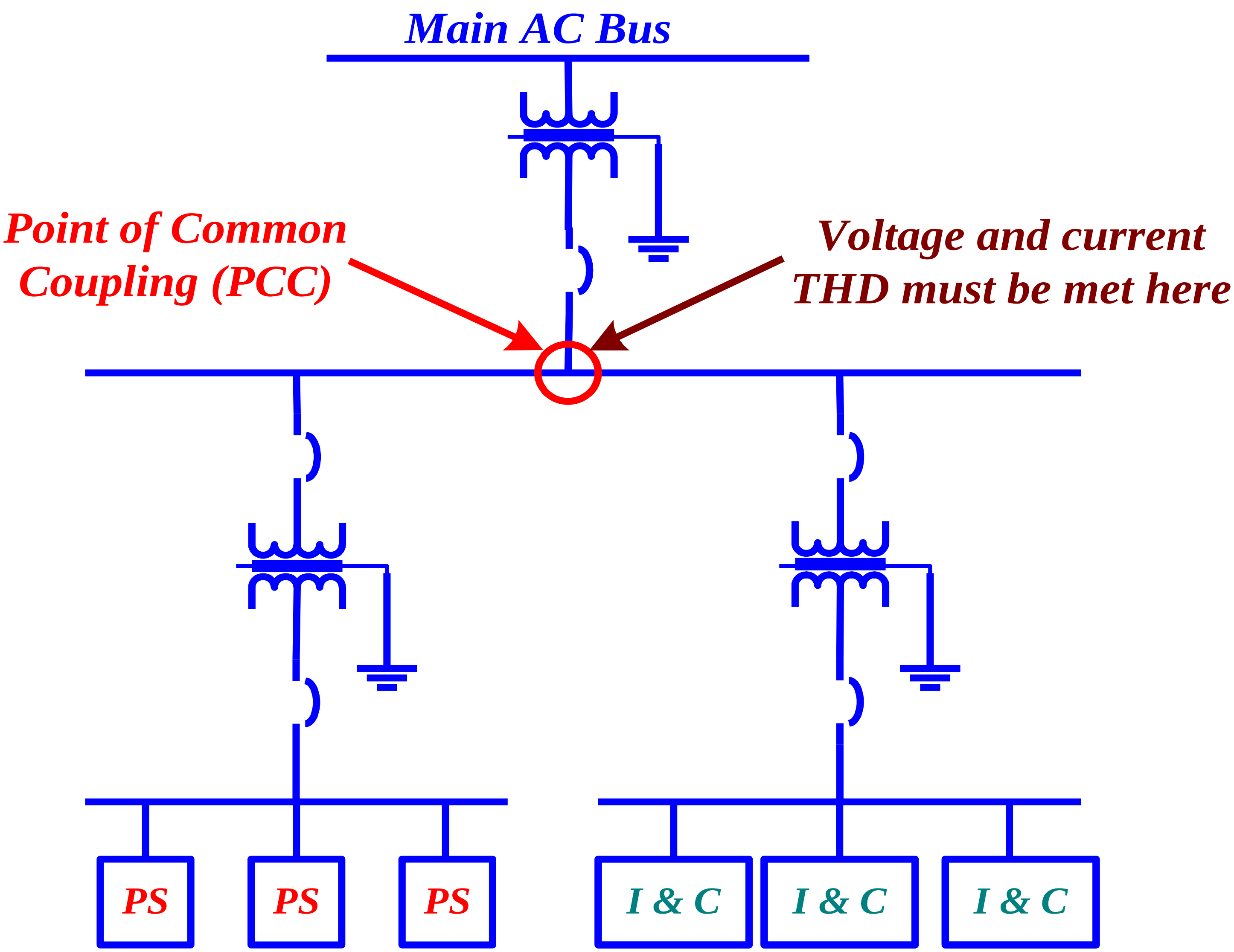
$$\frac{22{,}800V * \mu S}{135.8V} = 168\mu S \qquad \frac{168\mu S}{16.6mS} \sim 1\% \text{ of } 60Hz \text{ period}$$

SCR Commutation Effects - IEEE 519- 1992 Load Current Distortion Limits

General Distribution Systems – 120 V Through 69 kV	
I_{SC} / I_L	Maximum THD
< 20	5
20 < 50	8
50 < 100	12
100 < 1,000	15
> 1,000	20

1. I_{SC} = maximum short-circuit current at Point of Common Coupling (PCC)
2. I_L = maximum load current at PCC
3. I_{SC} / I_L = system short-circuit current capability to load current ratio

SCR Commutation Effects - Point of Common Coupling Illustrated



Electromagnetic Interference (EMI) *is any electromagnetic disturbance that interrupts, obstructs, or otherwise degrades or limits the effective performance of electronics/electrical devices, equipment or systems. Sometimes also referred to as radio frequency interference (RFI)*

Electromagnetic Compatibility (EMC) *describes how an electronic device will behave in a "real world" setting of EMI*

Broadband Interference *This type of interference usually exhibits energy over a wide frequency range and is generally a result of sudden changes in voltage or current. It is normally measured in decibels above one micro-volt (or micro-ampere) per megahertz* $dB\,\mu V / MHz$ *or* $dB\,\mu A / MHz$

Narrowband Interference *has its spectral energy confined to a specific frequency or frequencies. This type of interference is usually produced by a circuit which contains energy only at the frequency of oscillation and harmonics of that frequency. It is normally measured in "decibels above one micro-volt (or micro-ampere)", e.g.,* $dB\,\mu V$ *or* $dB\,\mu A$.

Five Types of EMI

- Conducted Emissions (CE) - the EMI emitted into lines and connections by an electronic device. Of particular interest is the EMI conducted onto the AC input power lines
- Conducted Susceptibility (CS) - the EMI present on lines and connections (e.g. power lines) and its effect on a connected electronic device.
- Radiated Emissions (RE) - the EMI radiated by an electronic device
- Radiated Susceptibility (RS) - radiated EMI effect on an electronic device
- Electromagnetic Pulse (EMP) – radiated EMI by lightning or atomic blast

Culprits and Victims

- Culprits are devices, equipment or systems that emit EMI
- Victims are devices, equipment or systems that are susceptible to EMI

USA

- ***MIL-STD-461E Emissions & Susceptibility Standard for Defense Electronics*** *This standard sets the Emissions & Susceptibility (Immunity) noise limits and test levels for electrical / electronic and electromechanical equipment*

- ***MIL-STD-462E*** *is the companion standard that describes the methods and test procedures for certification under MIL-STD-461.*

- *The object of the standards is to maximize safety and reliability and to minimize downtime and breakdowns of equipment essential for defense.*

- *The worldwide defense electronics and aerospace community recognizes and generally accepts MIL-STD-461.*

USA

Federal Communications Commission (FCC) under the Code of Federal Regulations CFR, Part 15, Sub-Part J, for Class A and B devices and equipment.

Germany

Verband Deutscher Elektrotechniker (VDE) has developed VDE 0871 for Level A and Level B.

European Community

EMC Directives of 1996

The FCC and VDE specifications are similar in that Class A and Level A describe industrial equipment, while Class B and Level B are applicable to consumer equipment.

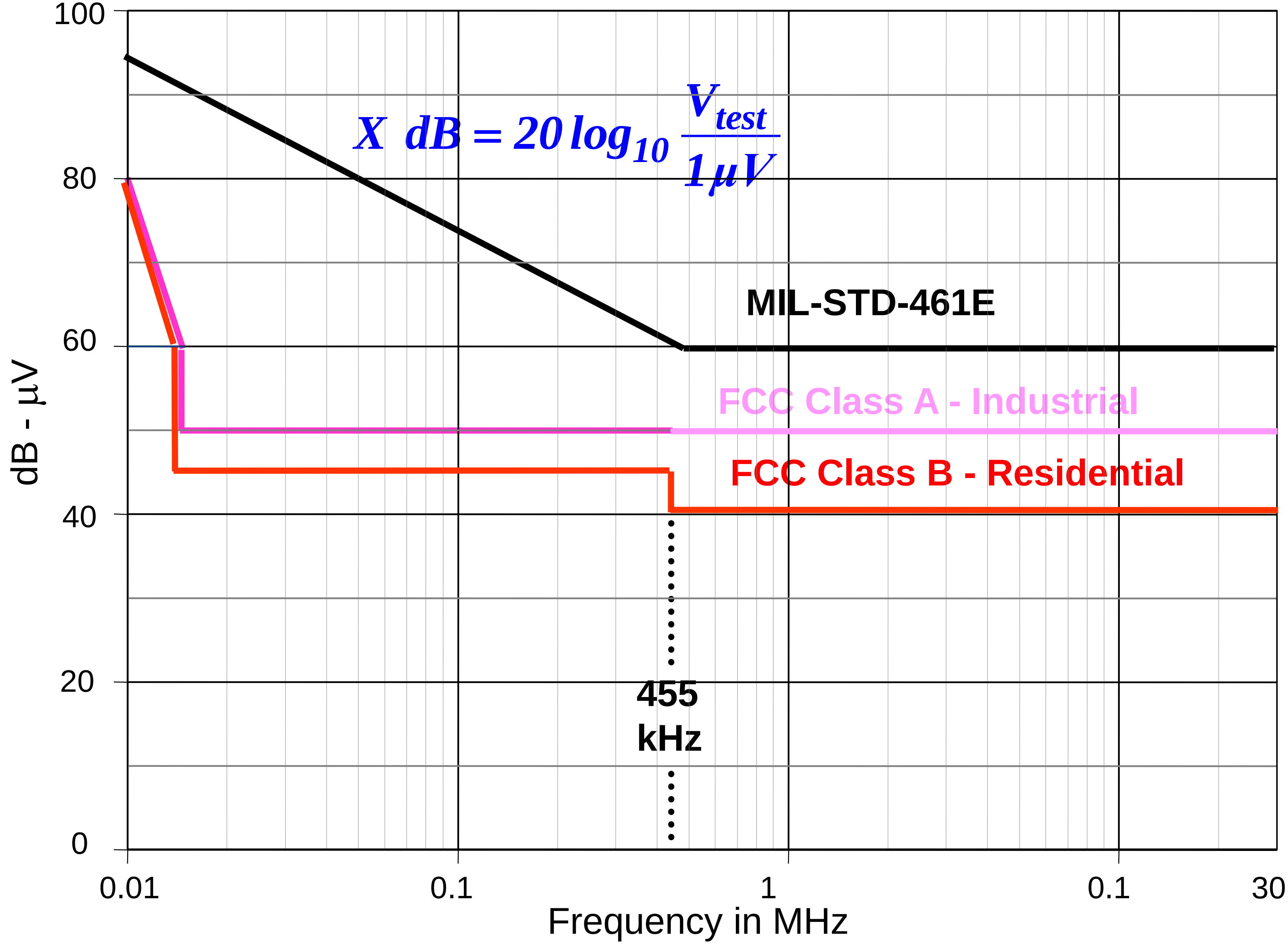
Conducted emissions

- *EMI conducted onto AC Lines by the power supply.*
- *Typically 10 kHz to 30 MHz*
- *Measured in μV or dB - μV (Reference: 1 $\mu V = 0$ dB)*

$$dB = 20 * \log_{10} \frac{measured\ \mu V}{1\,\mu V}$$

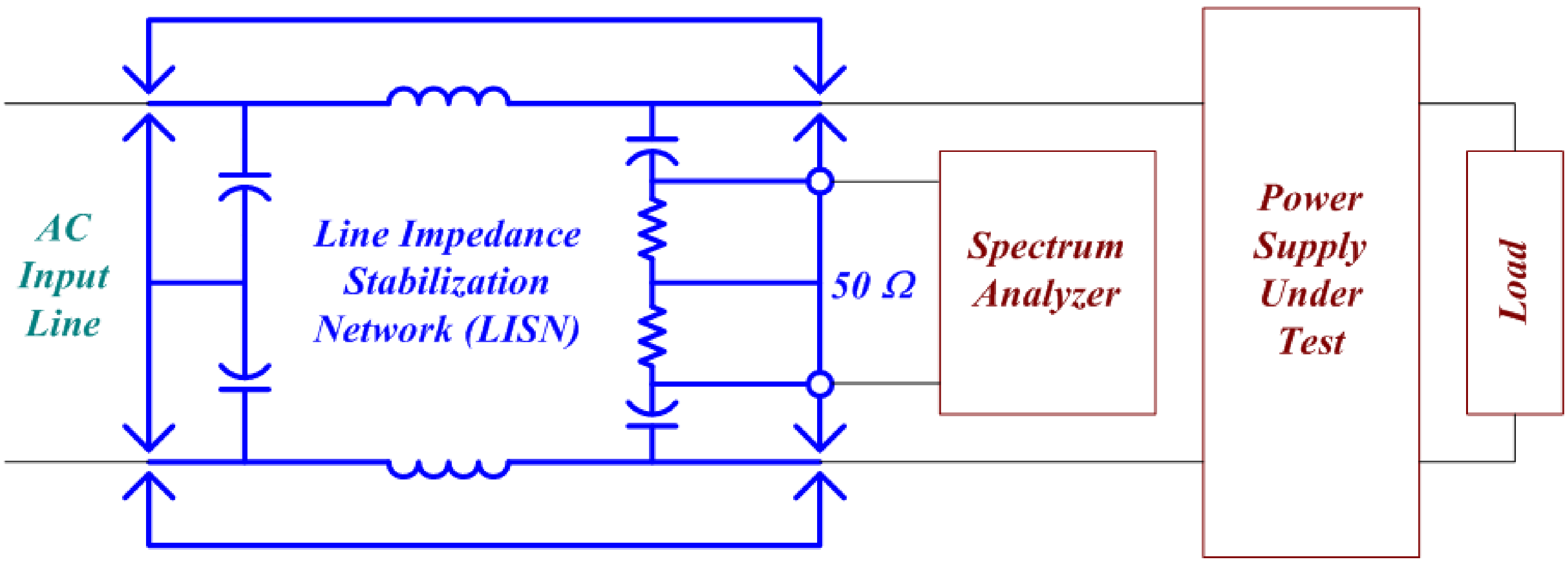
Example: Measured noise = $100\,\mu V$

$$dB = 20 * \log_{10} \frac{100\,\mu V}{1\,\mu V} = 40 dB$$


100
80
60
40
20
0
dB - μV
$X\ dB = 20 \log_{10} \frac{V_{test}}{1\mu V}$
MIL-STD-461E
FCC Class A - Industrial
FCC Class B - Residential
455
kHz
0.01
0.1
1
0.1
30
Frequency in MHz

Test equipment used – *Spectrum analyzers with Line Impedance Stabilization Networks (LISNs) that*

- *Filter and divert external AC line intrinsic noise from the EMI measurements*
- *Isolate and decouple the AC line high voltage and prevent line transients from damaging spectrum analyzers and other sensitive test equipment*
- *Present a known, fixed impedance at RF frequencies to the power supply undergoing test*



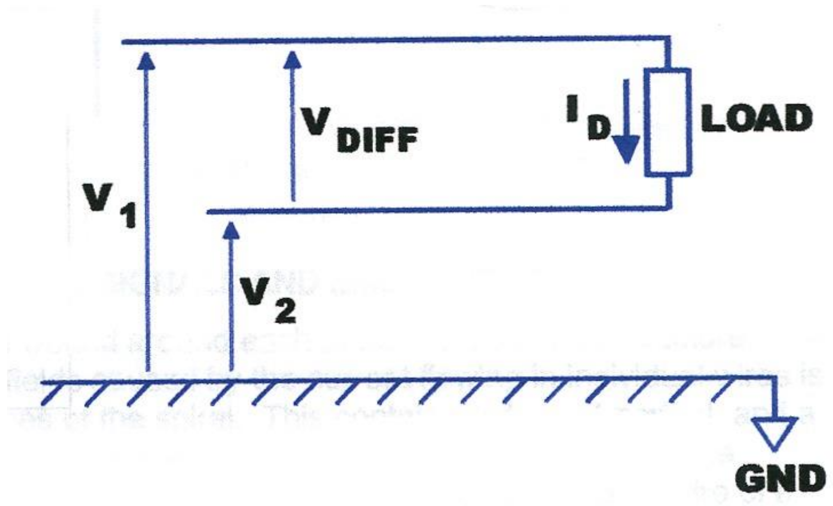
LISN considerations:

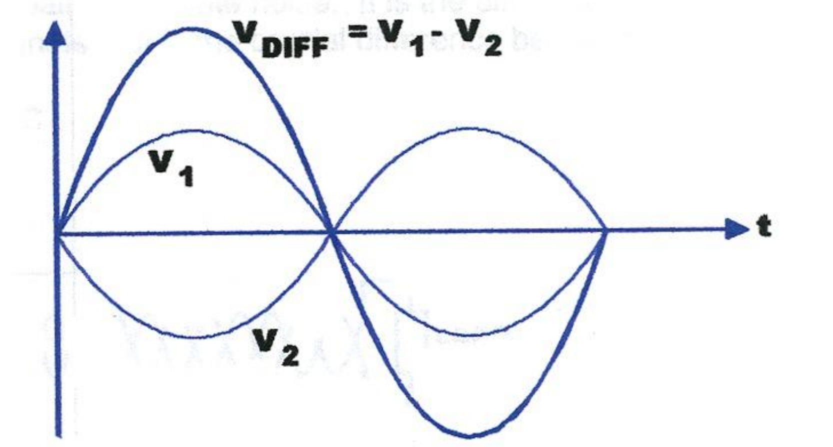
- Desired impedance (typically 50 Ω)
- Bandwidth (typically victims are susceptible to 10 kHz to 30 MHz)
- Line type (DC, Single phase, 3 ϕ delta, 3 phase wye)
- Line voltage (120 V, 208 V, 480 V, etc)
- Power supply input current when under load

Spectrum Analyzers

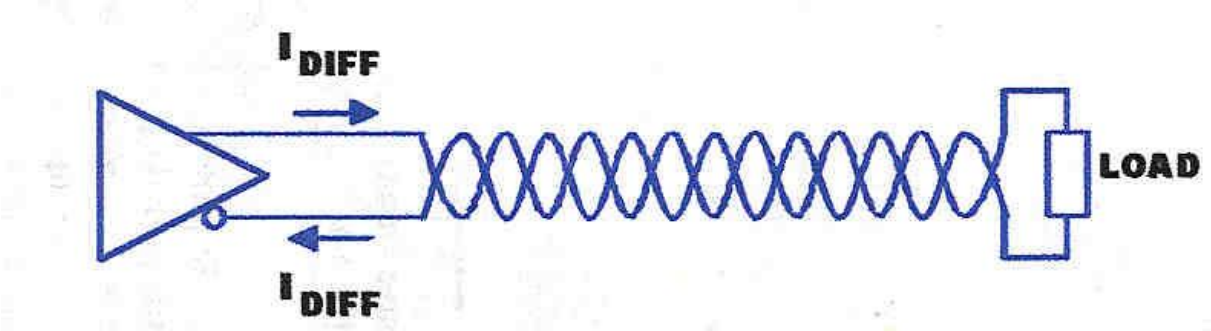
Anritsu, Keysight, Rigol,

Rohde and Schwarz

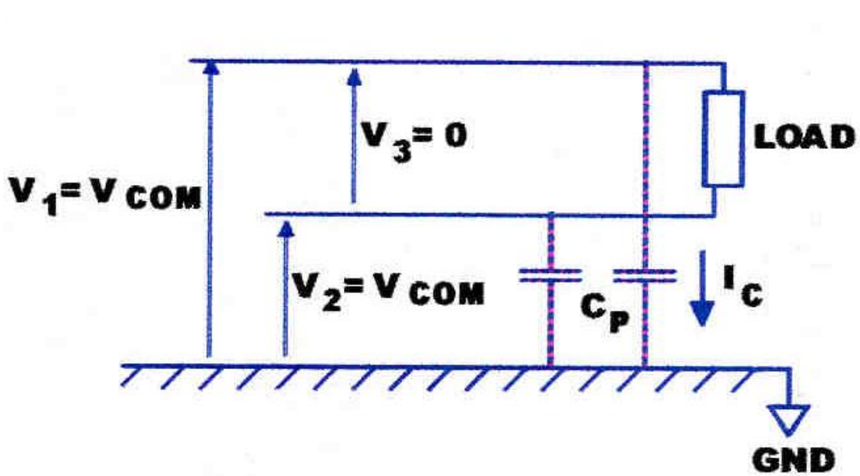


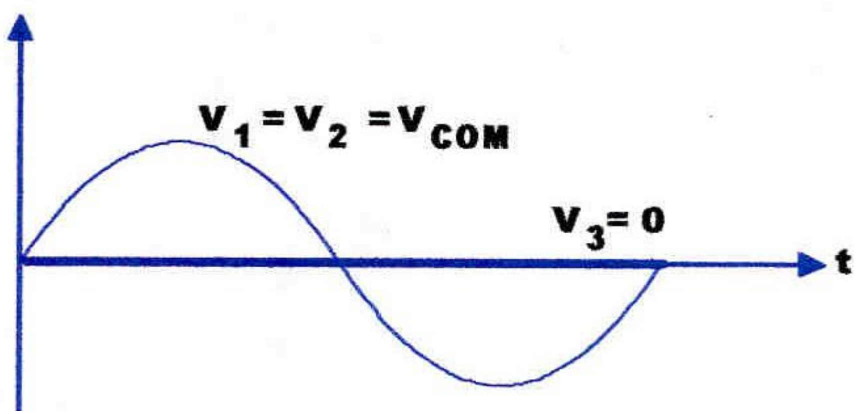


- *Produced as a natural result of complex, high frequency switching V and I*
- $V_1 = - V_2$
- *Magnitudes are equal*
- *Phase difference is* 180^O
- $V_{Load} = V_1 – V_2 =$ *KVL unwanted signal*
- $I_D = |V_1| + |V_2| / R_{Load}$



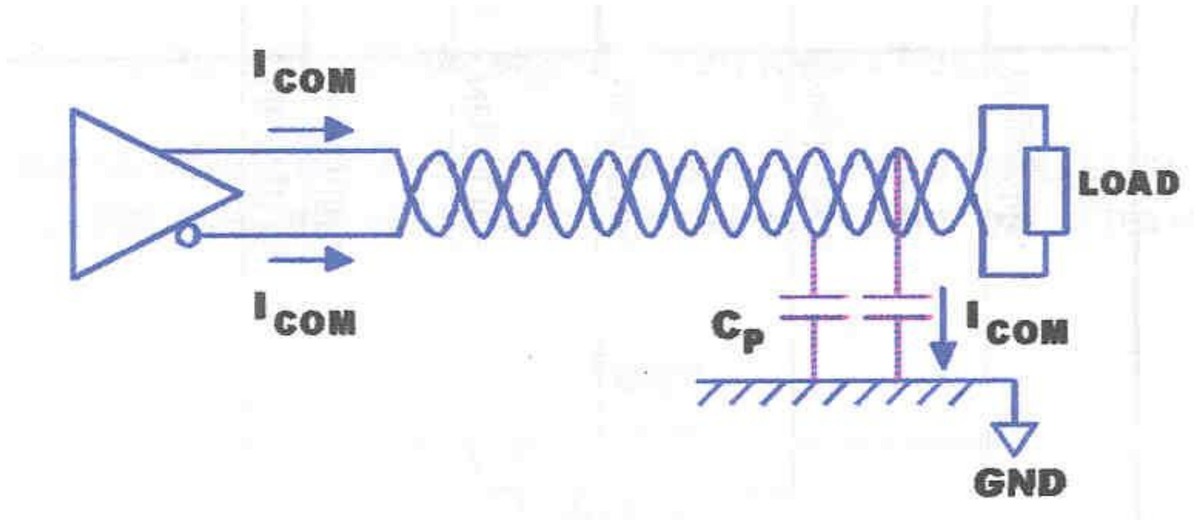
- *Current flow in opposite directions so that the magnetic field is contained within the spirals*
- *The tighter the cable twist the greater the containment and noise attenuation*
- *Shielding the pair (and tying the shield to ground in one or more places) will also increase noise attenuation*





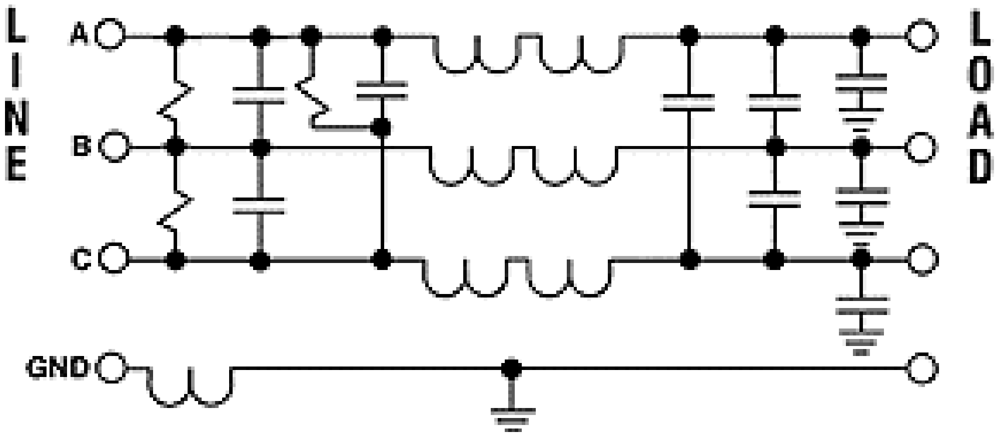
- *Produced as a result of circuit imbalances, currents produced by simultaneous high frequency voltages on (+) and (-) lines capacitively coupled to ground*
- $V_1 = V_2 = V_{COM}$
- *Magnitudes are equal*
- *Phase difference is* 0^O
- $I_{Load} = (V_1 - V_2) / R_{Load}$
- $V_{SUM} = V_1 + V_2 = 0$

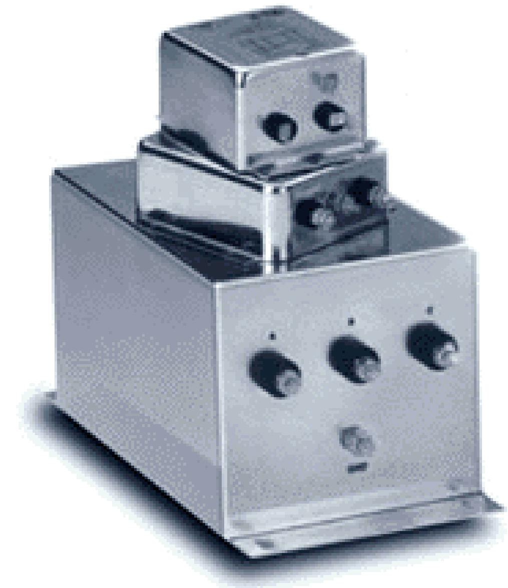
EMC/EMI - Common Mode Compatibility



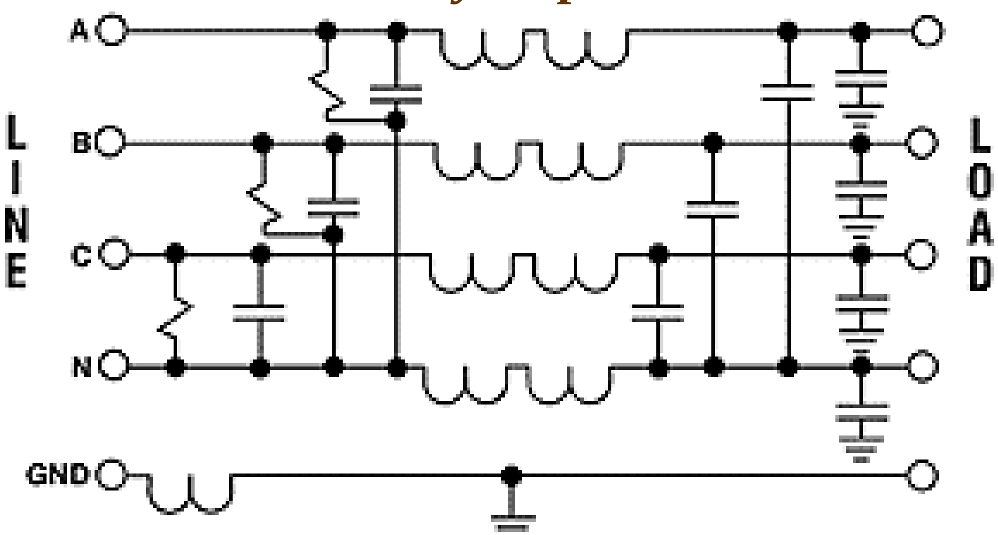
- Common mode current generated by common mode voltages impressed across parasitic capacitances to ground
- Current flows are the same magnitude and in the same direction so that the spirals have no effect on containing the magnetic fields
- The pair must be shielded and the shield tied to ground in one or more places for noise attenuation

Delta input



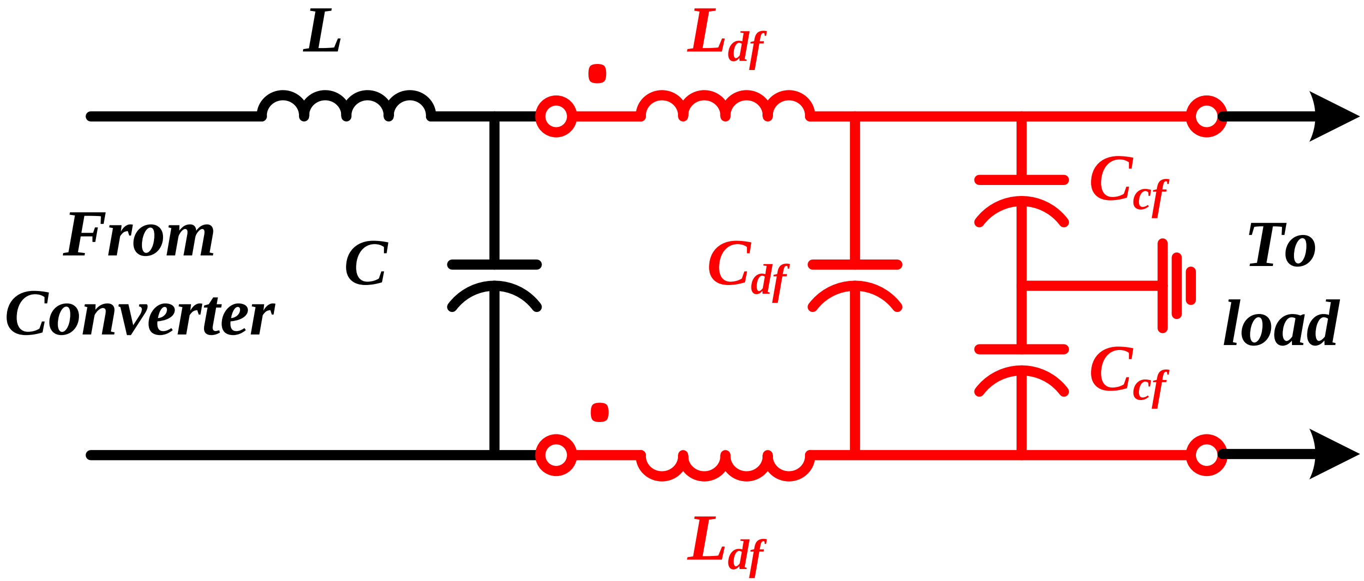


Wye input



- *Configurations C, L, Pi, T*
- *Attenuation 20 to 70dB*
- *Filters both differential and common mode noise*

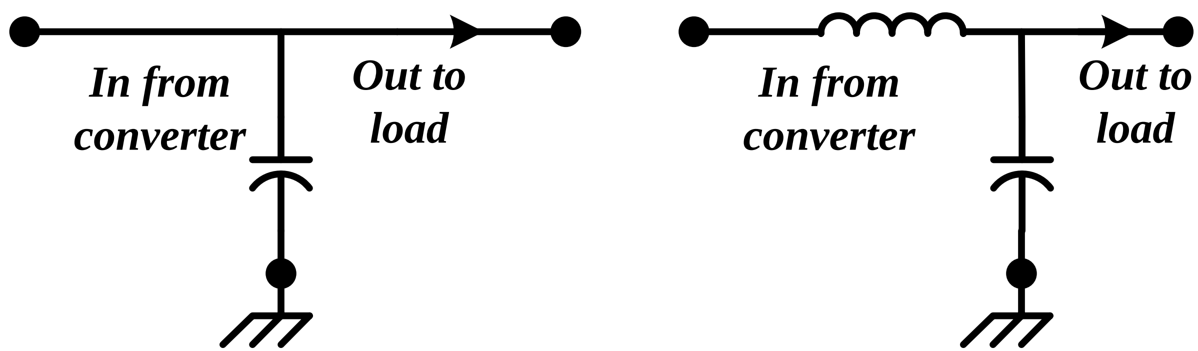
http://www.filterconcepts.com/three_phase/3v_series.html



- L and C are not good noise ($f > f_{sw}$) filters
- L looks capacitive at $f > f_{sw}$, C looks inductive at $f > f_{sw}$
- $L_{d\,f}$ is a differential / common mode noise filter inductor and might be a real inductance or the intrinsic inductance of the bus
- $C_{d\,f}$ is a differential mode noise filter capacitor
- $C_{c\,f}$ are common mode noise filter capacitors

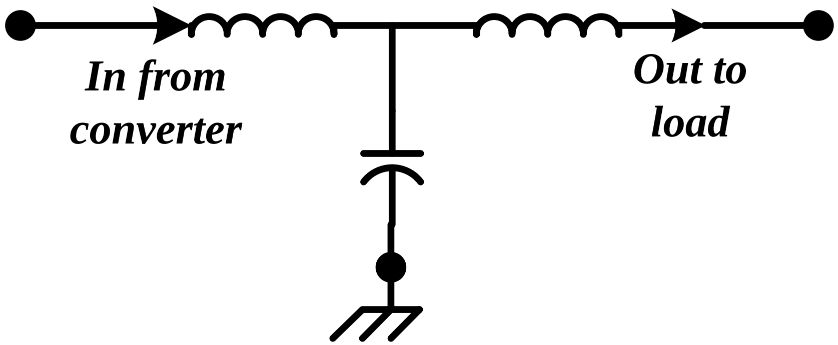
EMC/EMI - Output Line Feed-through Noise Filters

• ***C filters*** *are the most common EMI filter, consisting of a 3 terminal feed-thru capacitor, used to attenuate high frequency signals*

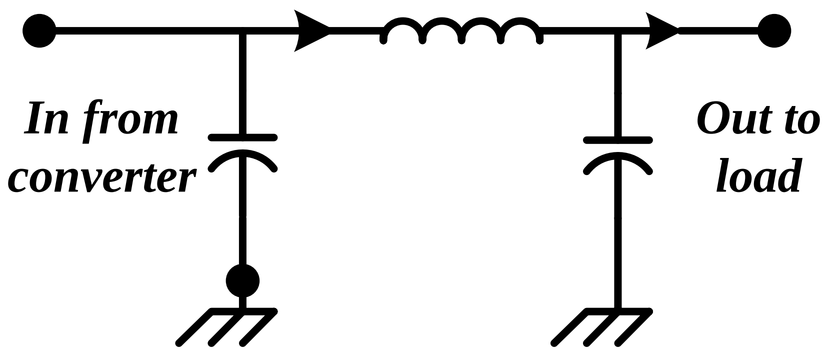


• ***L filters*** *consist of one inductive element and one capacitor. One disadvantage is that the inductor element in smaller filters consists of a ferrite bead that will saturate and lose effectiveness at larger load currents*

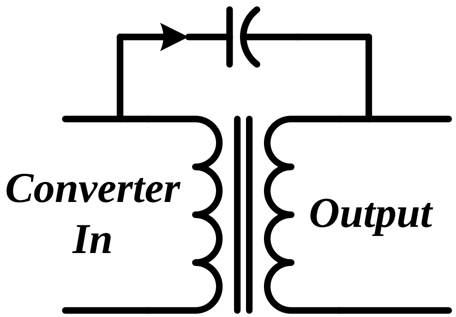
- ***T filters*** *consist of two inductive elements and one capacitor. This filter presents a high impedance to both the source and load of the circuit*



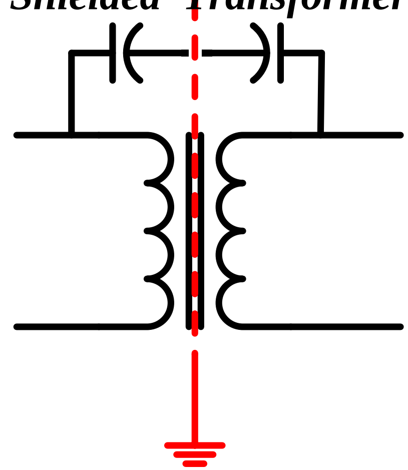
- ***Pi*** *filters consist of two capacitors and one inductor. They present a low impedance to both source and load. The additional capacitor element, provides better high frequency attenuation than the C or L filters*



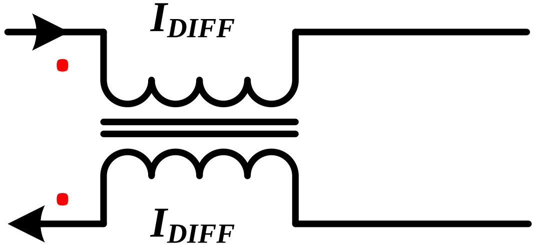
Plain Transformer

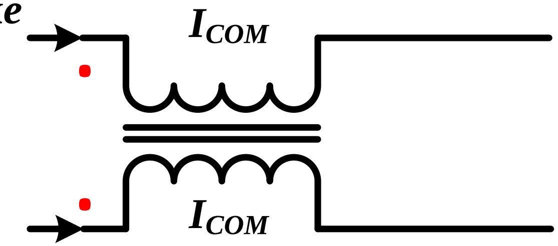


Electrostatic (Faraday) Shielded Transformer



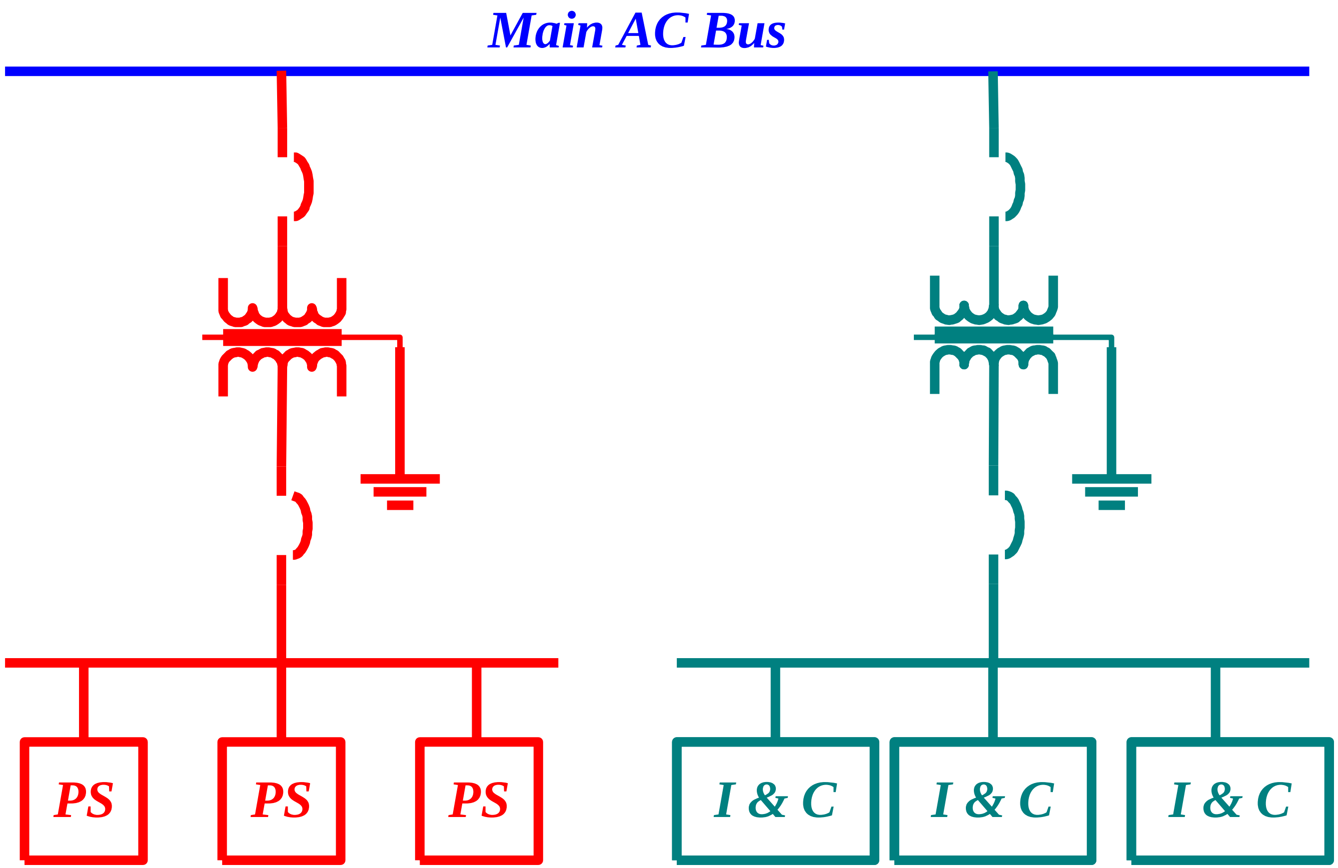
Common Mode Choke





Differential mode currents flow in opposite directions. Magnetic fields cancel, choke presents low impedance, low attenuation to noise

Common mode currents flow in same direction. Magnetic fields add, choke presents high impedance, high attenuation to noise



- *Separate noisy power supplies from sensitive I & C loads by Faraday-shielded transformers to attenuate common mode noise*

Radiated emissions

- EMI radiated from cables, transformers, other components.
- Typically 30 MHz to > 1GHz. 30 MHz start because cables and other equipment are effective radiators of frequencies above 30 MHz
- Measured in $\mu V/m$ or dB - $\mu V/m$ (Reference: 1 $\mu V/m$ = 0 dB)
- Measured 3 m (residential) or 30 m (industrial) from the emitting equipment. TVs located within 3 m of computers in the home and within 30 m in the industrial setting. Limits 100 to 200 $\mu V/m$ are 1/10 of TV reception signal
- Industrial FCC Class A limits of 200 $\mu V/m$ are higher (less severe) than residential Class B because it is assumed that there will be an intervening wall between culprit and victim that will provide some shielding

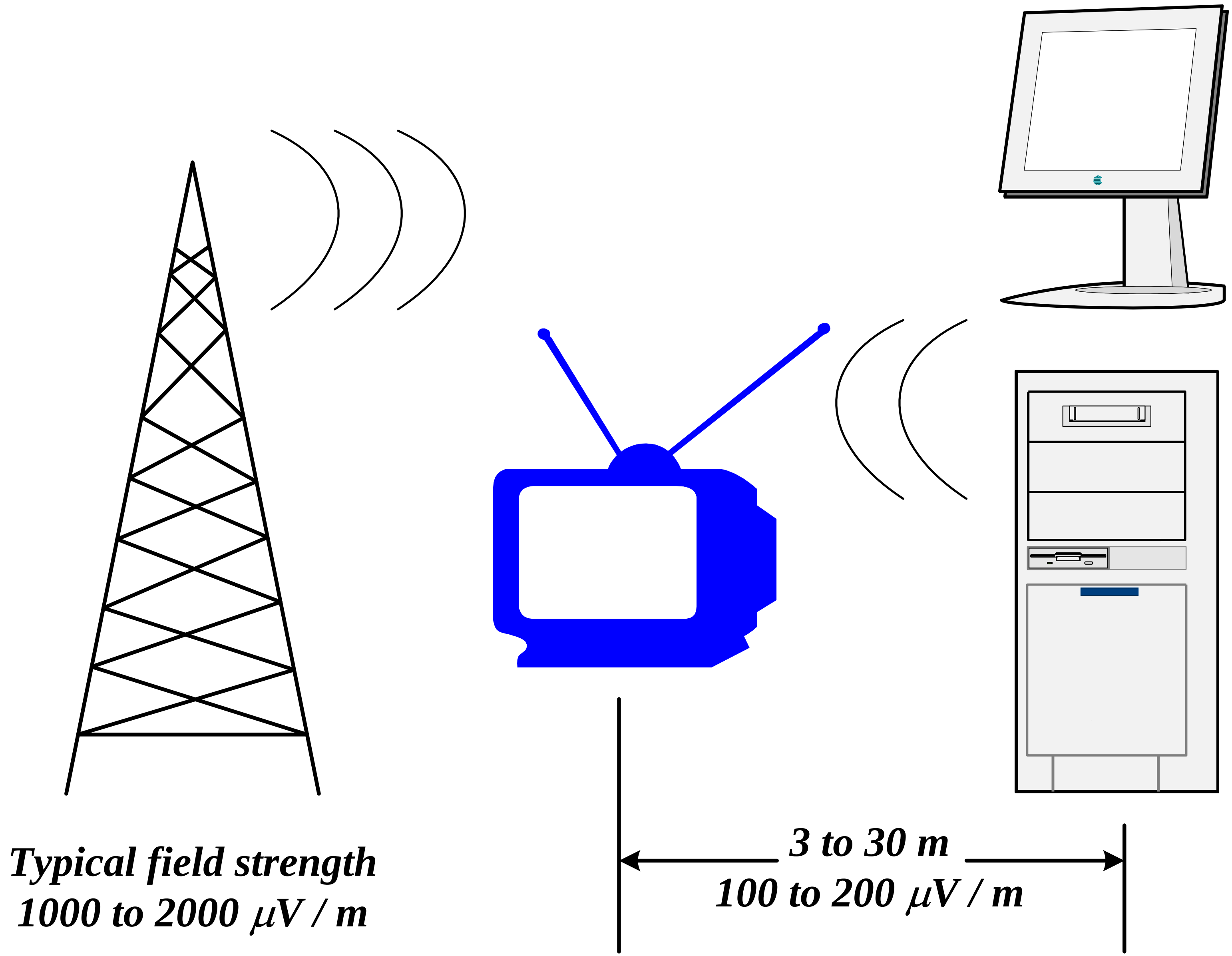
Test equipment used

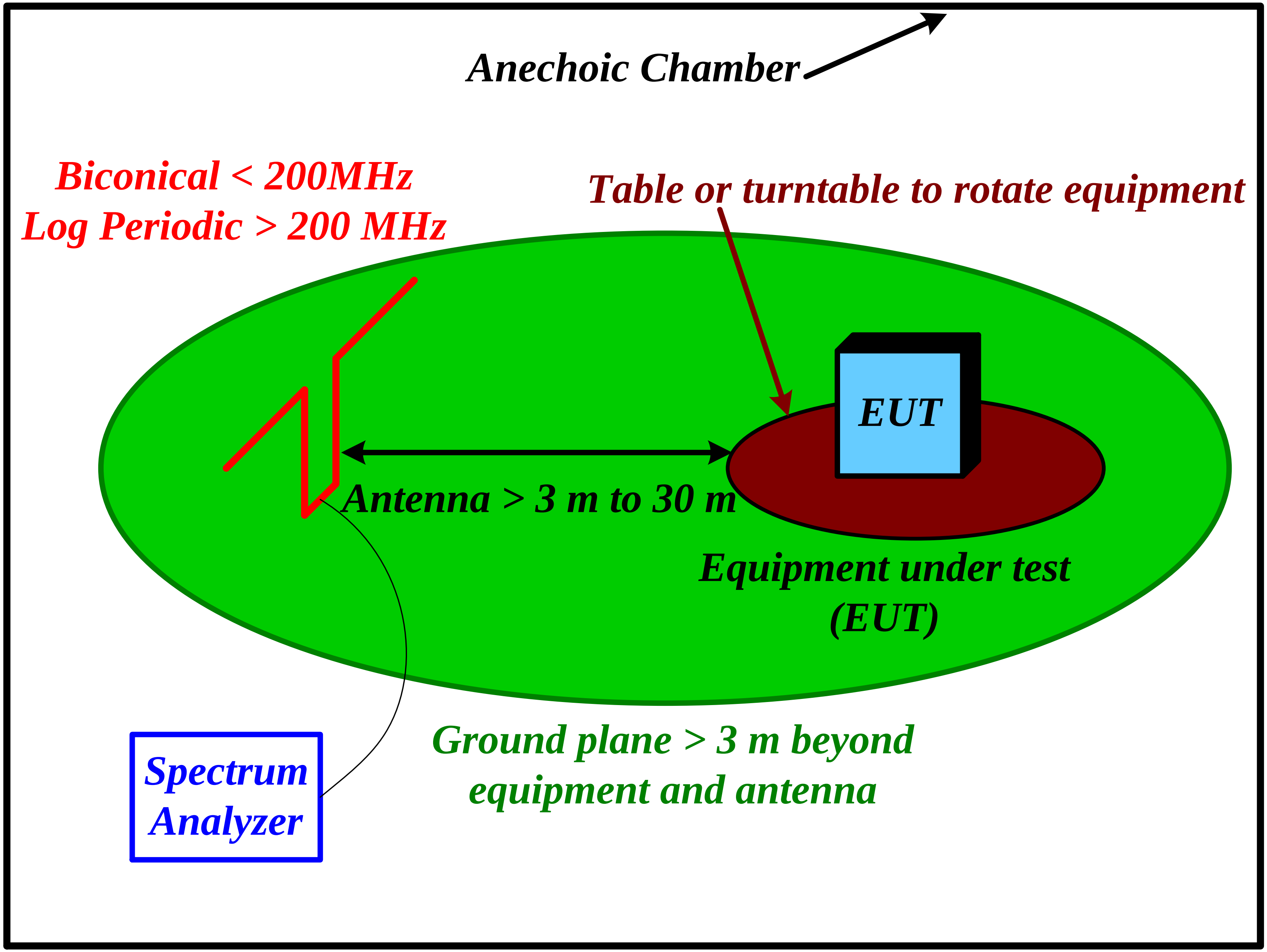
- Spectrum Analyzers, rotating tables, conical and/or log periodic antennas and anechoic chambers designed to minimize reflections and absorb external EMI

Any component or cable > 1/2 wavelength (λ) will be an efficient radiating or receiving antenna

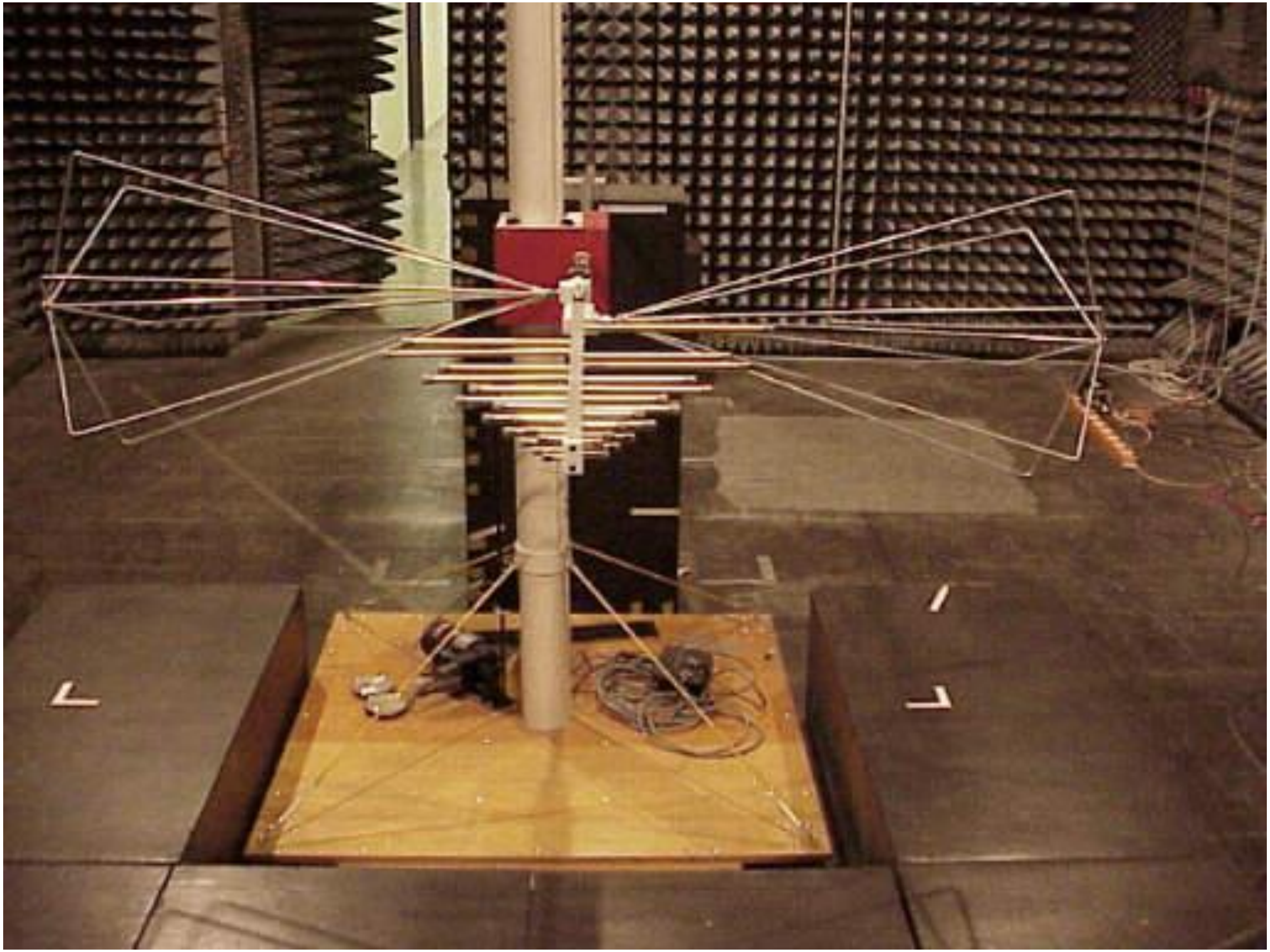
Cable Lengths Vs Wavelength			
Frequency	λ	**1/2** λ	**1/4** λ
10 kHz	30 km	15000 m	7500 m
100 kHz	3 km	1500 m	750 m
1 MHz	300 m	150 m	75 m
10 MHz	30 m	15 m = 50 ft	7.5 m = 25 ft
30 MHz	10 m	500 cm = 16 ft	2.5 m = 8 ft
100 MHz	3 m	150 cm = 5 ft	75 cm = 2.5 ft
1 GHz	30 cm	15 cm = 6 in	7.5 cm = 3 in

EMC/EMI - Basis For Industrial – Residential Emission Limits




Anechoic Chamber
Biconical < 200MHz
Log Periodic > 200 MHz
Table or turntable to rotate equipment
EUT
Antenna > 3 m to 30 m
Equipment under test
(EUT)
Ground plane > 3 m beyond
equipment and antenna
Spectrum
Analyzer

EMC/EMI - Bi-Conical Antenna



EMC/EMI - Log-Periodic Antenna

- $B = T = 10{,}000$ gauss
- $A = m^2$
- $(T/s)*m^2 = V$

Faraday's Induced Voltage Law

$$V = \oint E \bullet dl = -\frac{d\varphi}{dt} = -\frac{dB}{dt}A$$

Hint: Homework problem

$$V \propto \frac{dB}{dt}$$ *the magnitude and rate of change of flux density with time*

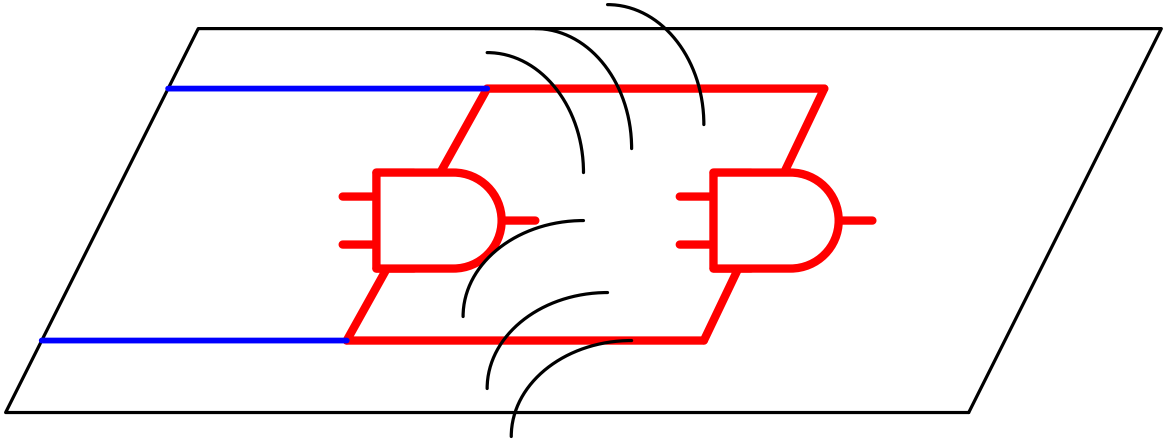
$$V \propto A$$ *the area of the loop cut by flux*

Moral - minimize loop areas by:

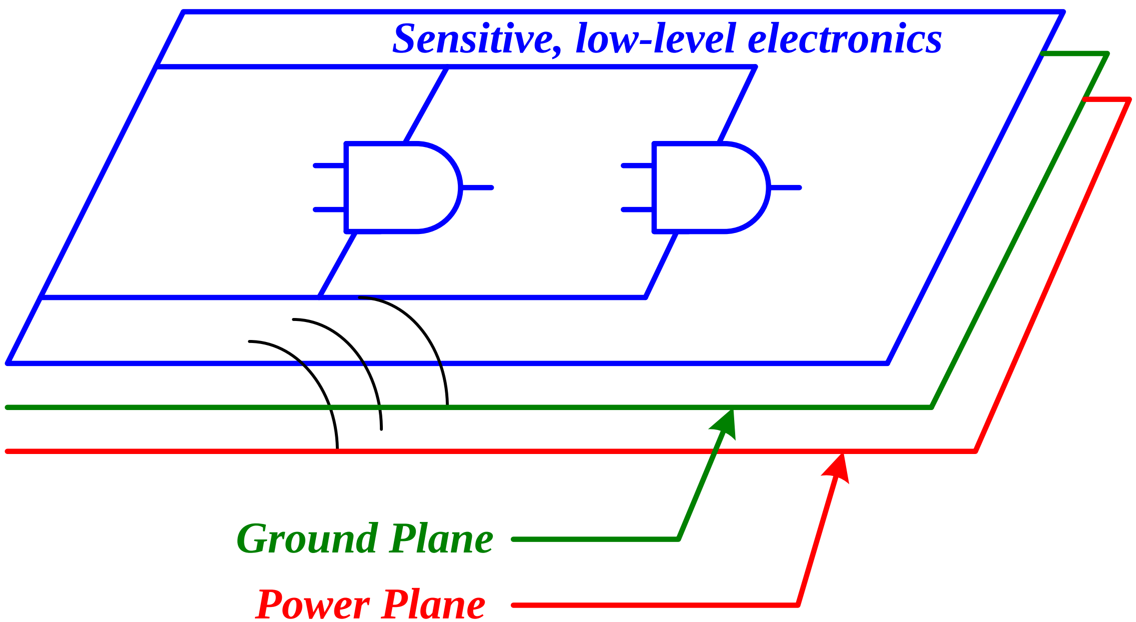
running supply and return bus or cable conductors together

twisting cables whenever possible

EMC/EMI - Radiated Noise Reduction By PCB Small Loops

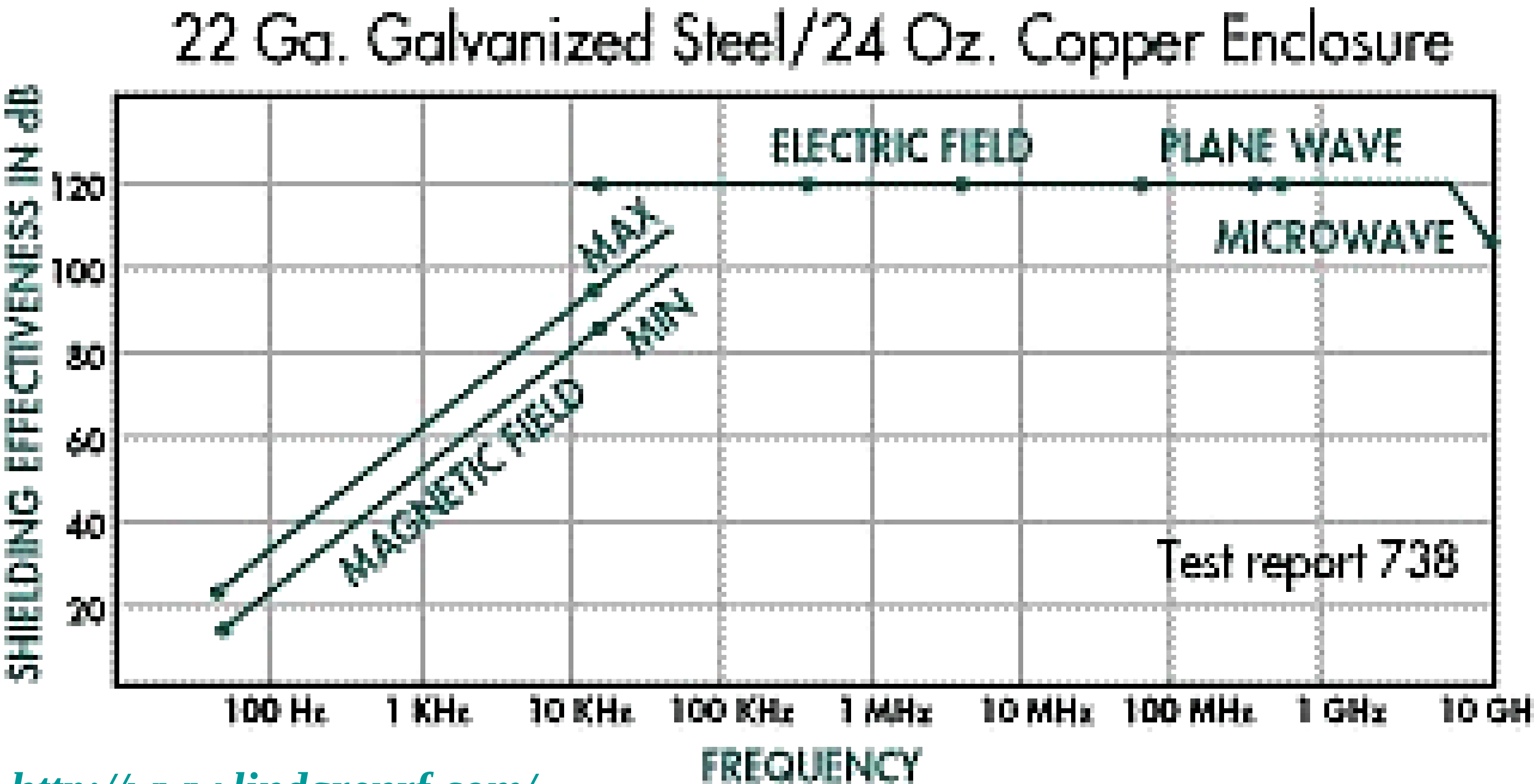


Radiated Noise Reduction By PCB Ground Planes



Use shielded cables

Use shielded enclosures (if necessary for interior controls)



http://www.lindgrenrf.com/

note – link no longer valid

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

Shielding

- Use ground planes extensively to minimize E and H fields
- If ribbon cable is used, employ and spread ground conductors throughout to minimize loop areas
- Avoid air gaps in transformer/inductor cores.
- Use toroid windings for air core inductors
- If shielding is impractical, then filter

Filtering

- Use common mode chokes whenever practical
- Use EMI ferrites, not low-loss ferrites – useful frequency range 50 to 500 MHz. Be careful of DC or low-frequency current saturation
- Use capacitors and feed-through capacitors, separately or in conjunction with chokes/ferrites. Be mindful of capacitor ESR and inductance

Homework Problem # 6

A uniform magnetic field B is normal to the plane of a circular ring 10 cm in diameter made of #10 AWG copper wire having a diameter of 0.10 inches. At what rate must B change with time if an induced current of 10 A is to appear in the ring? The resistivity of copper is about 1.67 $\mu\,\Omega * cm$.

Hint: $R = \frac{\rho * L}{A}$

Single Phase System

$$S_{1\phi} = V_{\phi}\, I^{*}_{\phi} = P_{1\phi} + j\, Q_{1\phi}$$

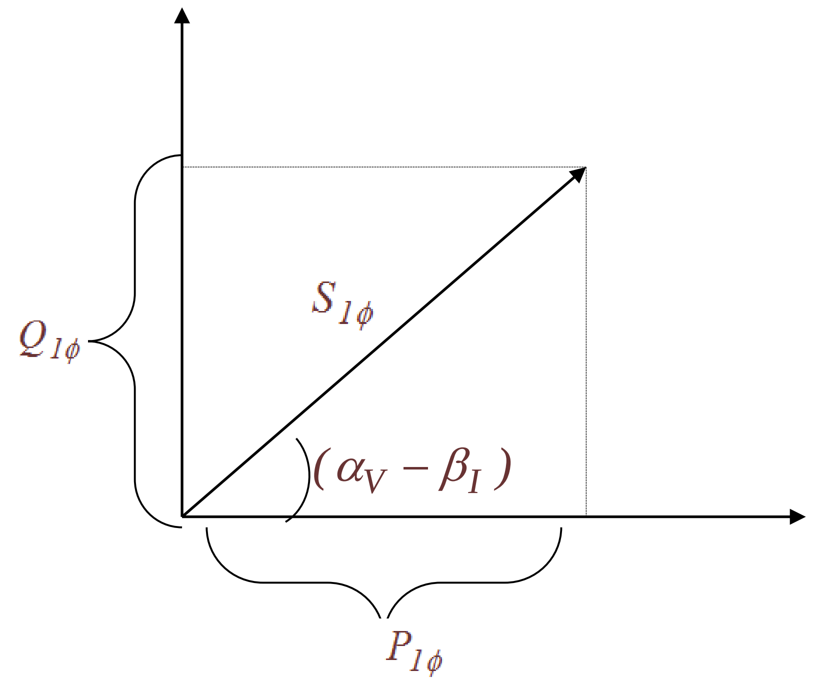
$$|S_{1\phi}| = |V_{\phi}|\,|I_{\phi}|\, e^{j\alpha_V} e^{-j\beta_I}$$

$$|S_{1\phi}| = |V_{\phi}|\,|I_{\phi}|\,[\cos(\alpha_V - \beta_I) + j\sin(\alpha_V - \beta_I)]$$

$$P_{1\phi} = |V_{\phi}|\,|I_{\phi}|\cos(\alpha_V - \beta_I)$$

$$Q_{1\phi} = |V_{\phi}|\,|I_{\phi}|\sin(\alpha_V - \beta_I)$$

$$PF = \frac{|P_{1\phi}|}{|S_{1\phi}|} = \cos(\alpha_V - \beta_I)$$



$0 \le PF \le 1$, *leading or lagging, current is reference*

PF is not efficiency $\quad Eff = \dfrac{P_o}{P_i}$

Balanced three Phase

$$S_{3\phi} = 3V_{\phi} I_{\phi} = \sqrt{3}\, V_{LL}\ I_{L}$$

$$P_{3\phi} = 3V_{\phi}\ I_{\phi} cos(\alpha_{I\phi} - \beta_{V_{\phi}})$$

$$PF_{3\phi} = \frac{P_{3\phi}}{S_{3\phi}} = cos(\alpha_{I_{\phi}} - \beta_{V_{\phi}})$$

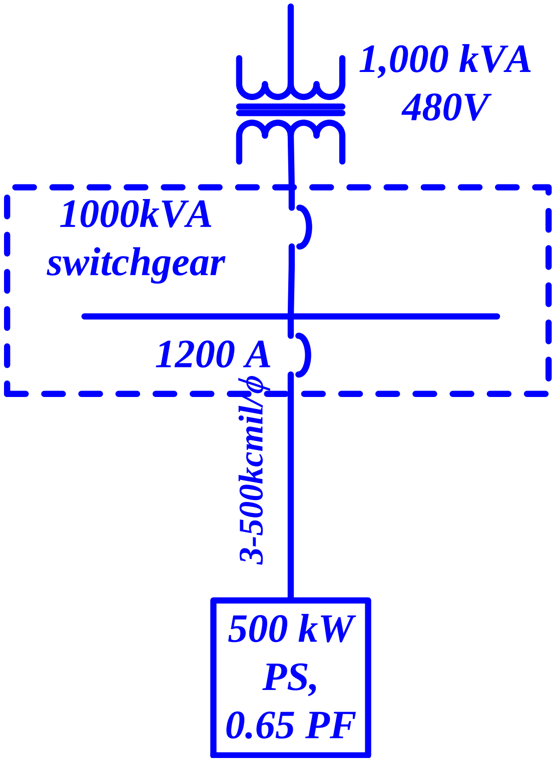
Unbalanced three phase power

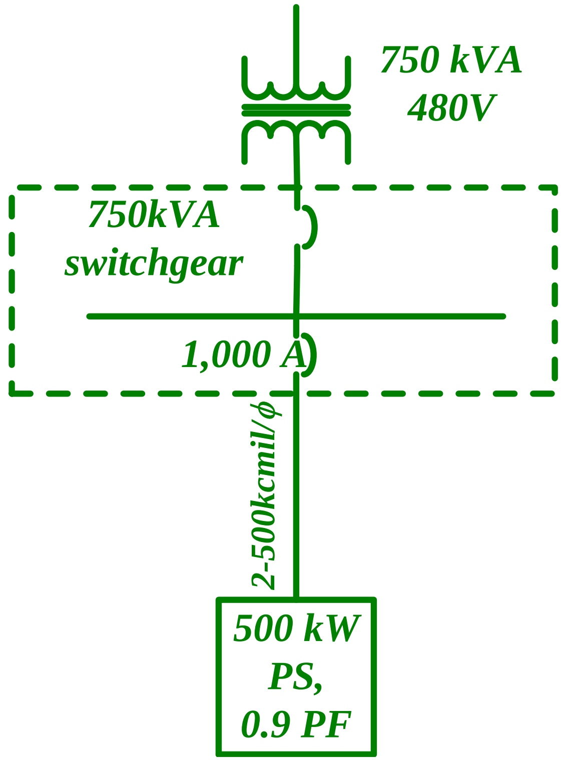
$$S_{3\phi} = V_{\phi A} I_{\phi A} + V_{\phi B} I_{\phi B} + V_{\phi C} I_{\phi C}$$

$$P_{3\phi} = V_{\phi A} I_{\phi A} cos(\alpha_{I_{\phi A}} - \beta_{V_{\phi} A}) + V_{\phi B} I_{\phi B}(\alpha_{I_{\phi B}} - \beta_{V_{\phi} B}) + V_{\phi C} I_{\phi C}(\alpha_{I_{\phi} C} - \beta_{V_{\phi} C})$$

$$PF_{3\phi} = \frac{P_{3\phi}}{S_{3\phi}}$$

Power Factor is Important - Capital Equipment Cost





$$S = \frac{P}{PF} = \frac{500kW}{0.65} = 769kVA$$

$$I = \frac{769kVA}{\sqrt{3} * 480V} = 925A$$

$$I_{CB} = 925A * 1.25 = 1{,}156A, \text{ buy } 1200A$$

Buy 1000kVA switchgear/transformer

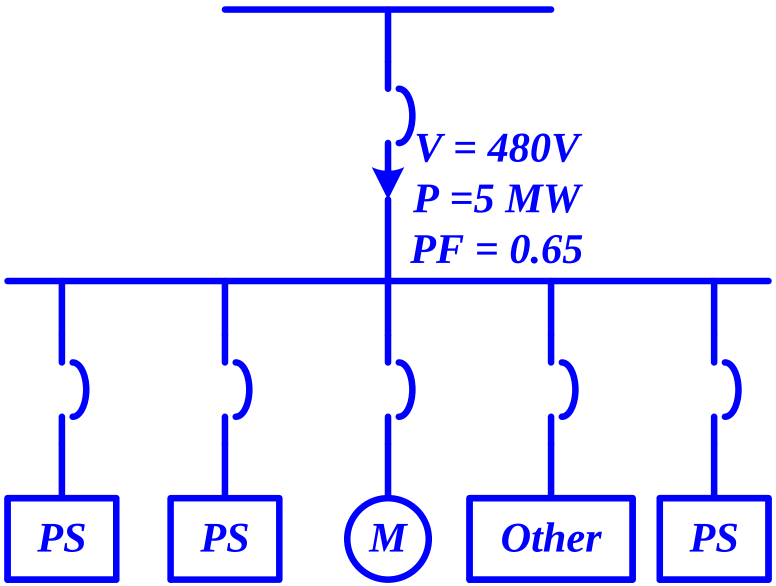
$$S = \frac{P}{PF} = \frac{500kW}{0.9} = 555kVA$$

$$I = \frac{555kVA}{\sqrt{3} * 480V} = 667A$$

$$I_{CB} = 667A * 1.25 = 834A, \text{ buy } 1000A$$

Buy 750kVA switchgear/transformer

Power Factor is Important – Energy Cost



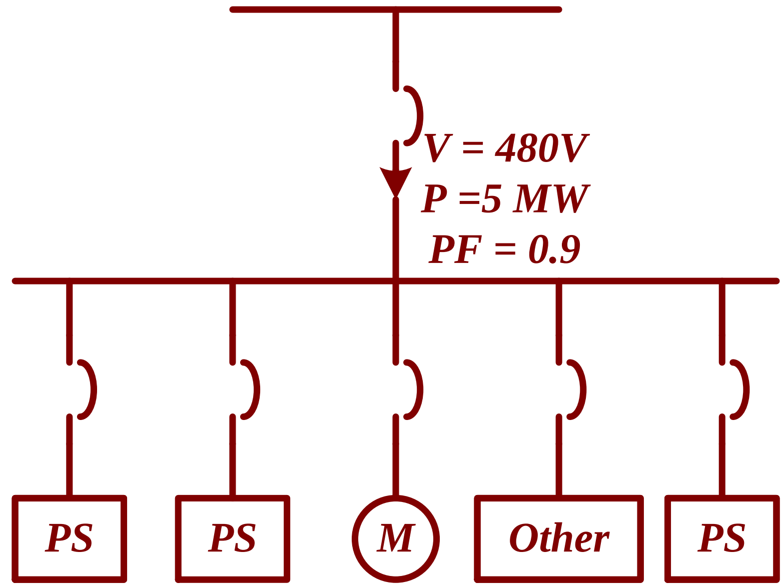
$$S = \frac{P}{PF} = \frac{5MW}{0.65} = 7.7MVA$$

$$Electric\ rate = \frac{\$0.06}{kW - Hr}$$

$$9\,months * \frac{30days}{month} * \frac{24hr}{day} = \frac{6480hr}{yr}$$

$$7.7MVA * \frac{\$0.06}{kW - Hr} * \frac{6480hr}{yr} = \frac{\$3.0M}{yr}$$

$$\frac{\$3M}{yr} * 20\,yr = \$60M$$



$$S = \frac{P}{PF} = \frac{5MW}{0.9} = 5.6MVA$$

$$Electric\ rate = \frac{\$0.06}{kW - Hr}$$

$$9\,months * \frac{30days}{month} * \frac{24hr}{day} = \frac{6480hr}{yr}$$

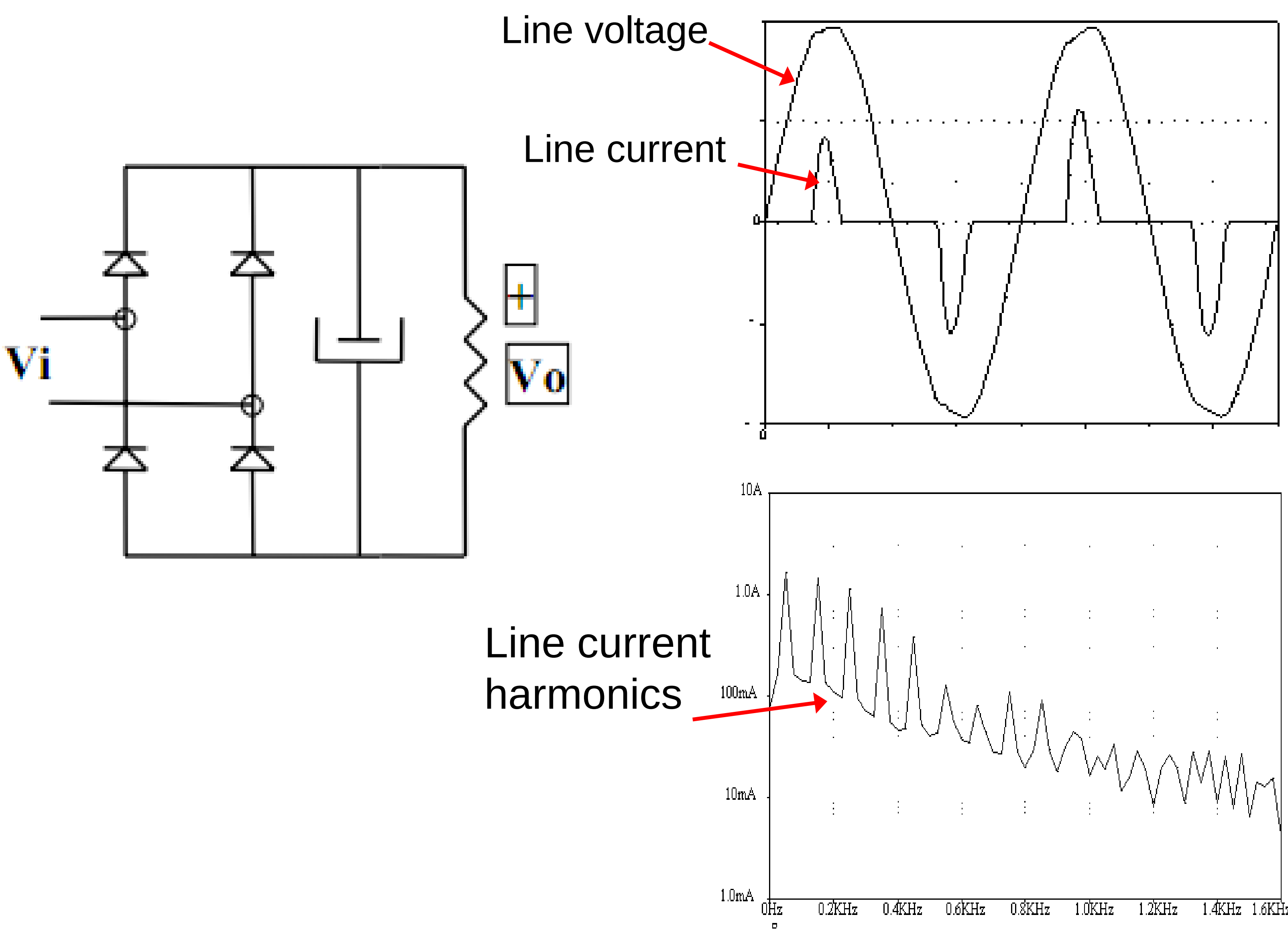
$$5.6MVA * \frac{\$0.06}{kW - Hr} * \frac{6480hr}{yr} = \frac{\$2.2M}{yr}$$

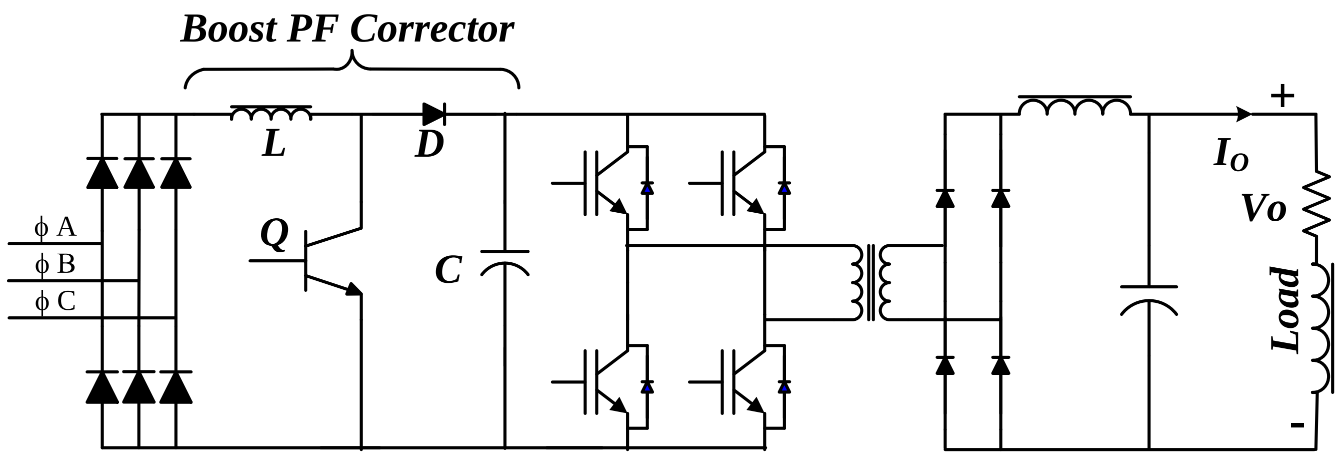
$$\frac{\$2.2M}{yr} * 20\,yr = \$44M$$

Power Factor Improvement

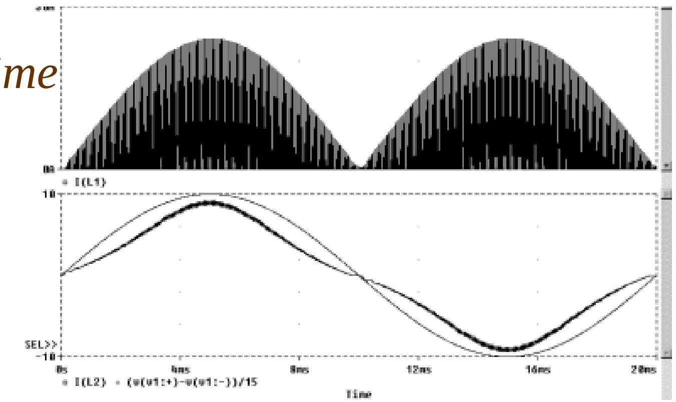
Higher Power Factor Translates to:

- Lower apparent power consumption
- Lower equipment electrical losses
- Electrically/physically smaller equipment
- Less expensive equipment
- Lower electric bill
- Implies lower distortion of the line voltage and current

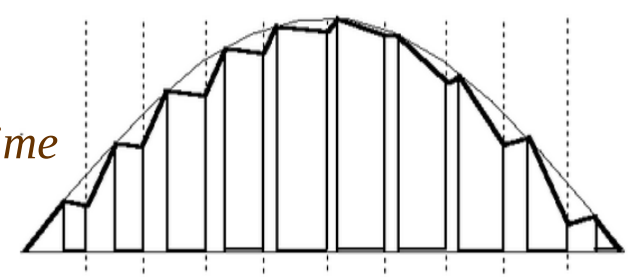

Vi
+
Vo
Line voltage
Line current
Line current harmonics
10A
1.0A
100mA
10mA
1.0mA
0Hz
0.2KHz
0.4KHz
0.6KHz
0.8KHz
1.0KHz
1.2KHz
1.4KHz
1.6KHz



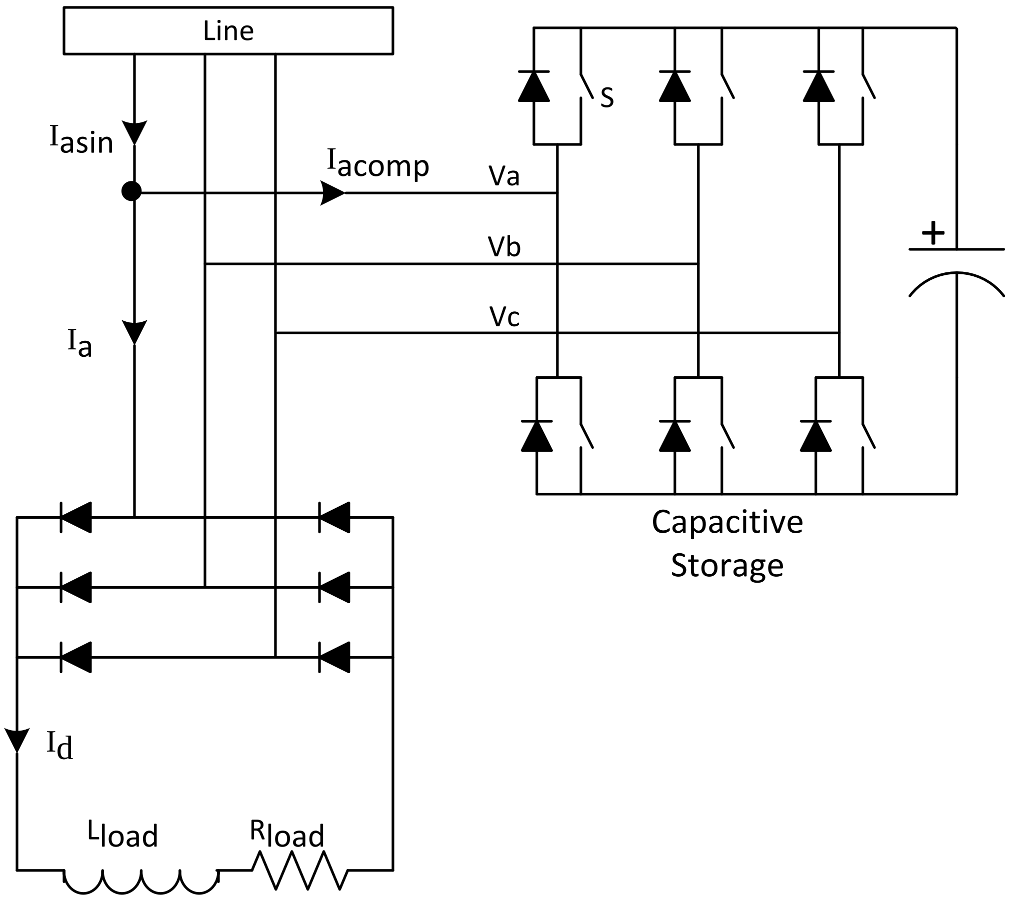
I_c v. time

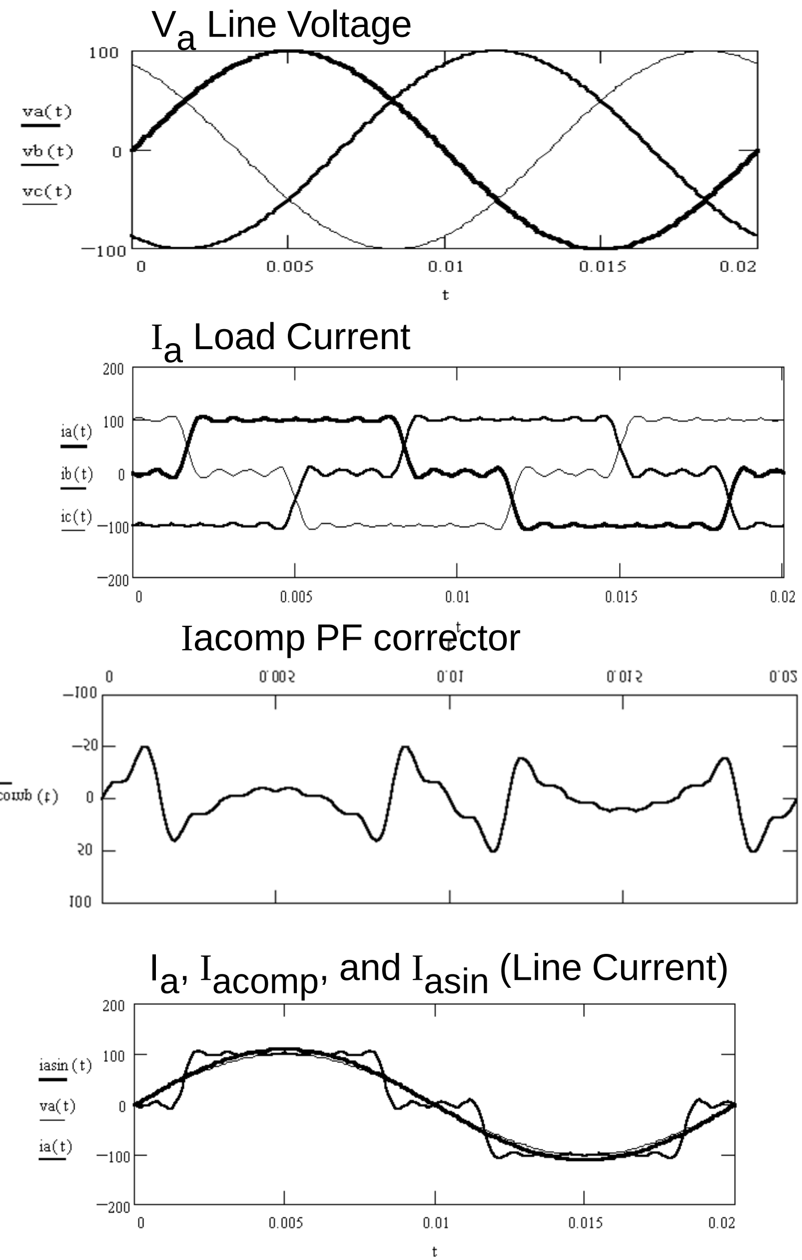


V_{ab}, I_L, I_Q v. time



Active Power Factor Correction - 3 Phase Systems

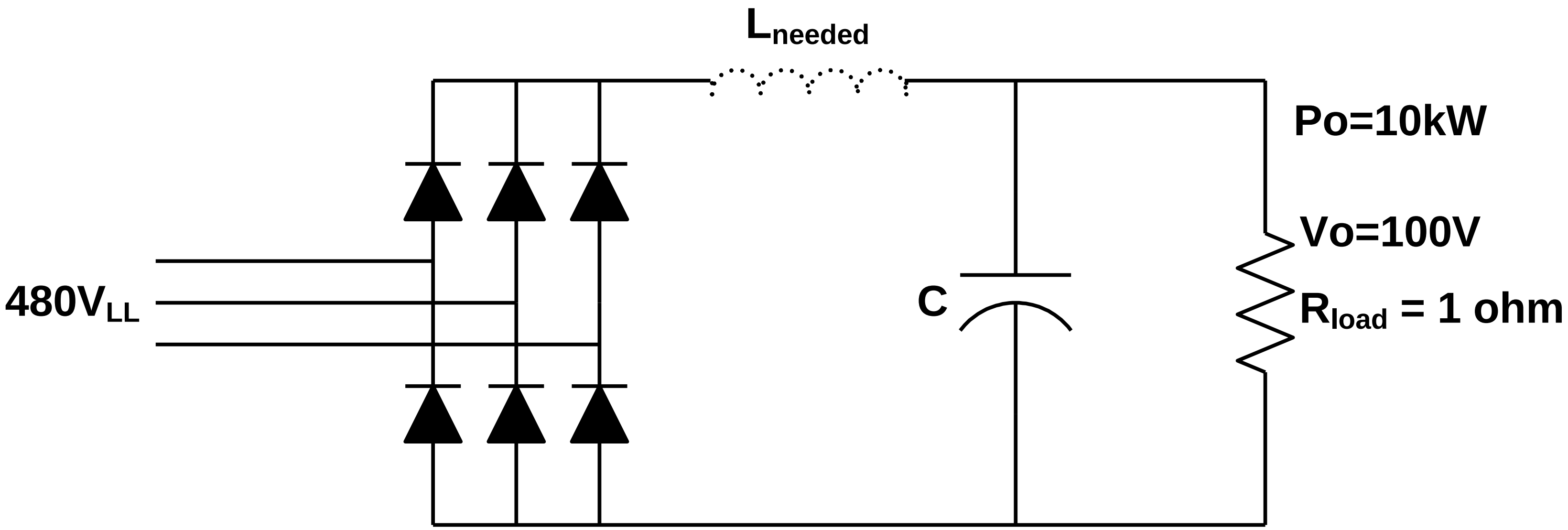




- *Appropriate switches (s) are rapidly opened and closed to control charging and discharging of the capacitor (I_{acomp})*
- *From KCL, $I_{asin}=I_a + I_{acomp}$*

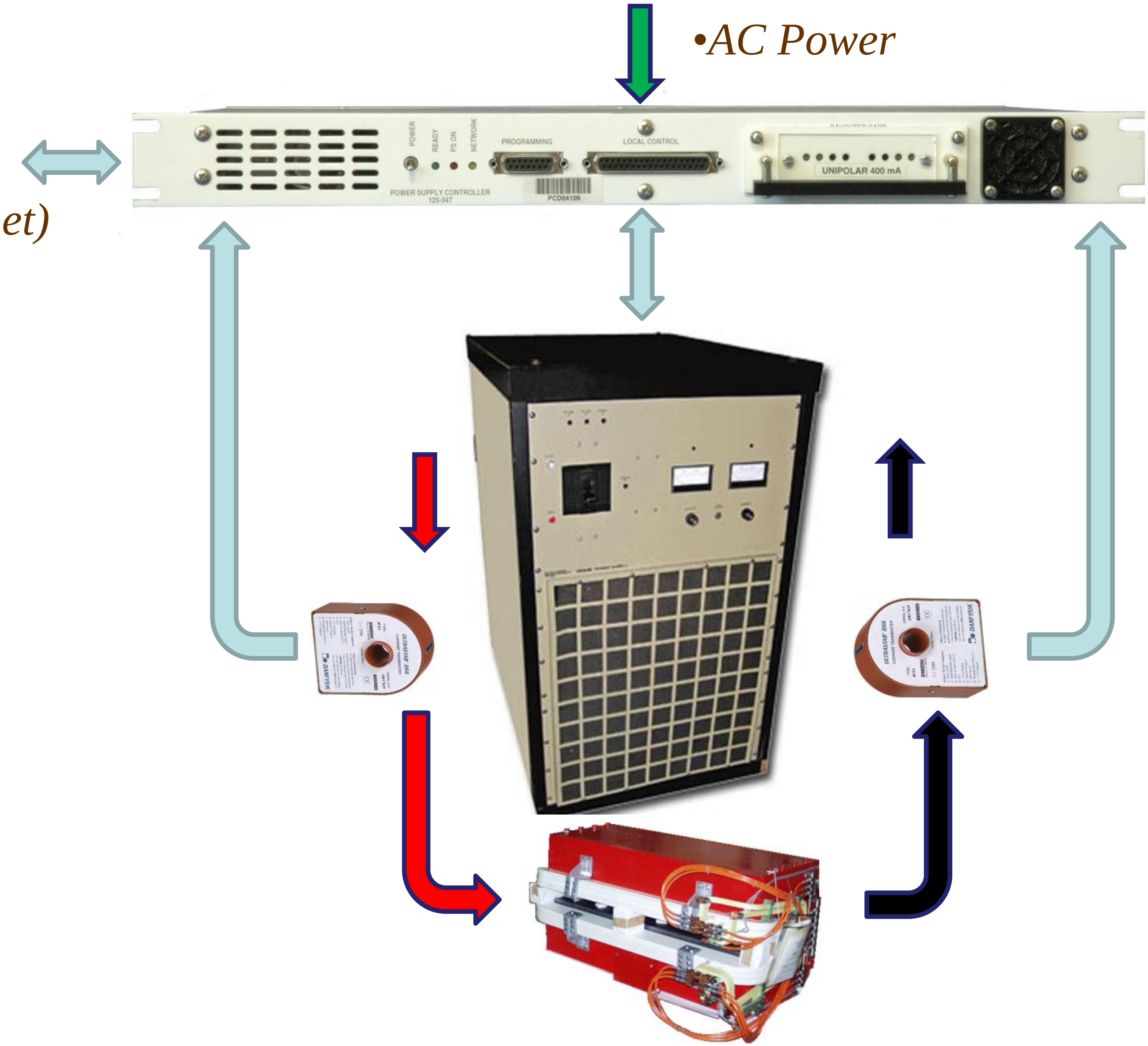
Homework Problem # 7

A 10kW, 3 phase power supply has an efficiency of 90% and operates with a leading power factor of 0.8. Determine the size of the inductor needed to improve the power factor to 1.0. Hint: the ripple frequency of the rectifier output is 360Hz.



Section 6 – DC Power Supplies

A Typical DC Magnet Power System



- AC Power
- EPICS
- (Ethernet)
- Power Supply Controller
- Power Supply
- Feedback and Monitor Transducers
- Magnet

Definition

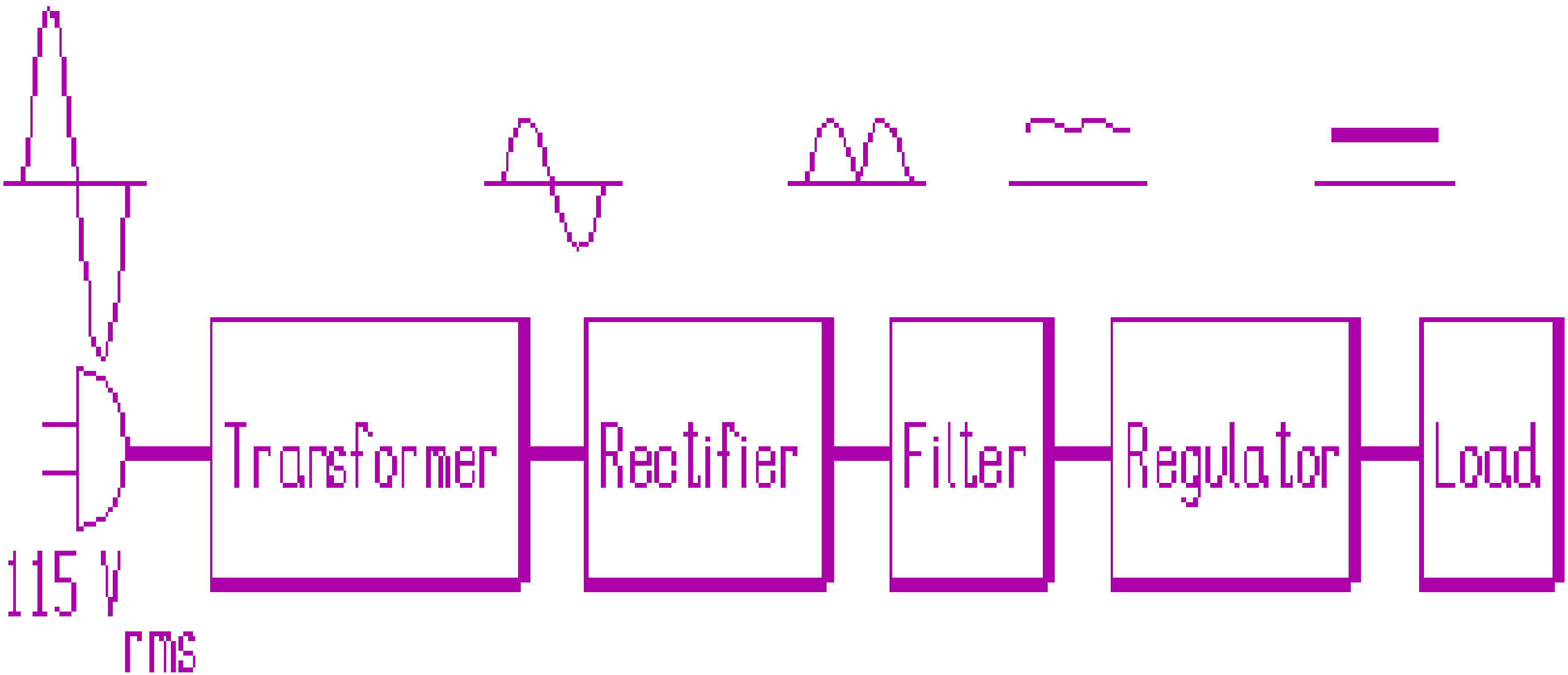
- *A "DC power supply" is a device or system that draws uncontrolled, unregulated input AC or DC power at one voltage level and converts it to controlled and precisely regulated DC power at its output in a form required by the load*

Purpose

- *Change the output to a different level from the input (step-up or step-down)*
- *Rectify AC to DC*
- *Isolate the output from the input*
- *Provide for a means to vary the output*
- *Stabilize the output against input line, load, temperature and time (aging) changes*

Example

- *120 VAC is available. The load is a logic circuit in a personal computer that requires regulated 5V DC power. The power supply makes the 120 V AC power source and 5V DC load compatible*



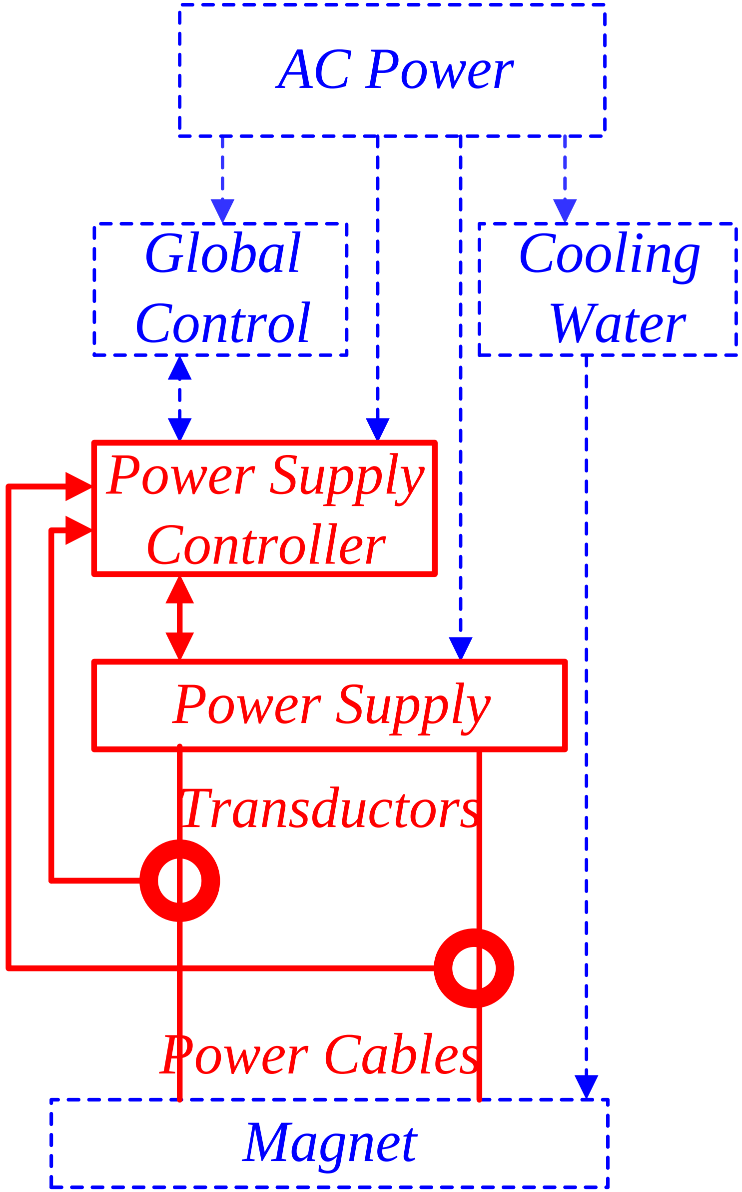
Power Line EMI/EMC

Controls

Interlocks

Reliability

Power Supply Definition, Purpose, and Scope – A DC Magnet Power System



Power Supply Definition, Purpose, and Scope – A DC Magnet Power System

Power Supply Definition, Purpose, and Scope – Characteristics

Some characteristics of the power supplies most often used in particle or synchrotron accelerators are:

• They are voltage or current sources that use the AC mains (off-line) as their source of energy.

•They can be DC-DC converters

•They are not AC controllers.

• They are <u>not</u> computer power supplies or printed circuit board converters

•They have a single output.

• The output voltage or current is not fixed (such as those used by the telephone and communications industry), but are adjustable from zero to the full rating

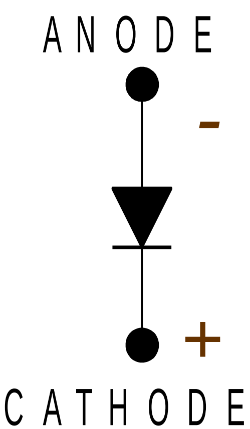
•The DC output power ratings range from a few watts to several megawatts

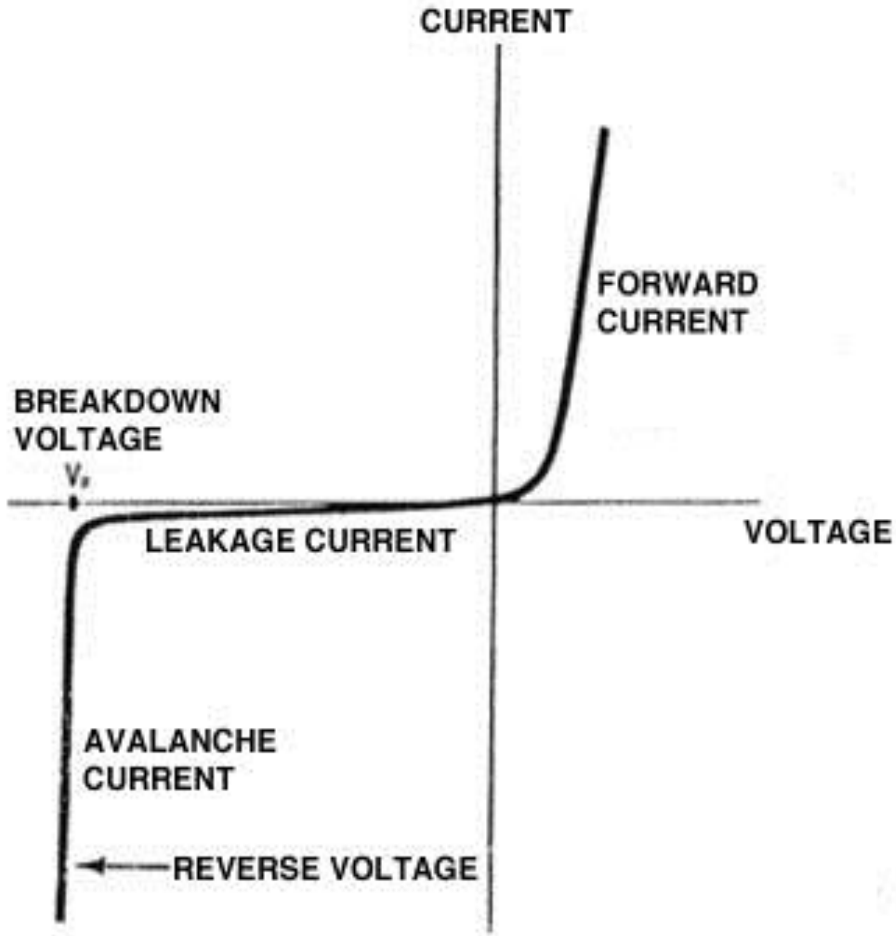
•Typical loads are magnets or capacitor banks

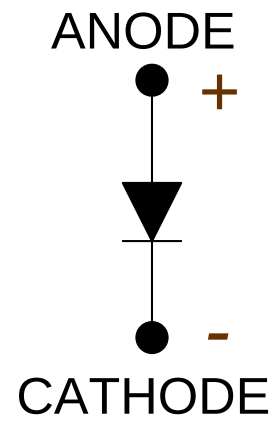
•The bipolar power supplies discussed later are typically used for small corrector magnets are DC-DC converters fed from a common off-line power supply

• They can have pulsed outputs as discussed later

Rectifiers - Diode Characteristics



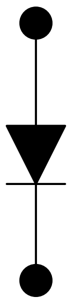




In the reverse direction, there is a small leakage current up until the reverse breakdown voltage is reached

Forward voltage drop, V_f : a small current conducts in forward direction up to a threshold voltage, 0.3V for germanium and 0.7V for silicon

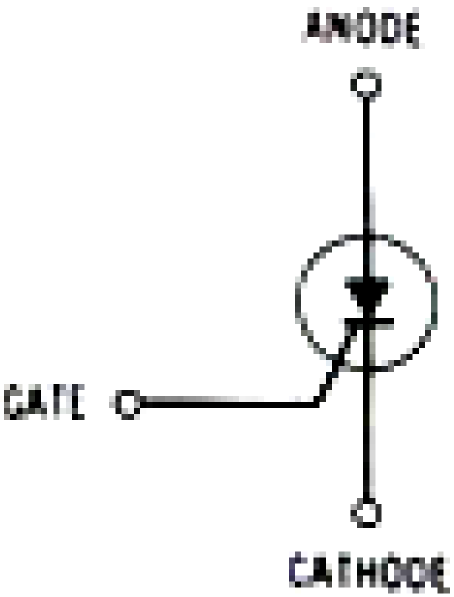
Rectifiers - Diode Considerations



Schematic representation

- *Forward voltage drop,* V_F or $V_{F(AV)}$
- *Forward current,* I_F or $I_{F(AV)}$
- *Maximum reverse (blocking) voltage,* V_R
- *Average reverse (leakage) current,* $I_{R(AV)}$
- *Forward recovery time,* t_{fr}
- *Reverse recovery time,* t_{rr} *, usually much less than* t_{fr}
- *Peak surge current,* I_{surge}
- *Cooling (air, water, oil, other)*
- *Package style*
- $I = I_o\left(e^{\frac{qV}{nkT}} - 1\right)$ *Shockley equation*

Rectifiers - Thyristors - Silicon Controlled Rectifier (SCR)

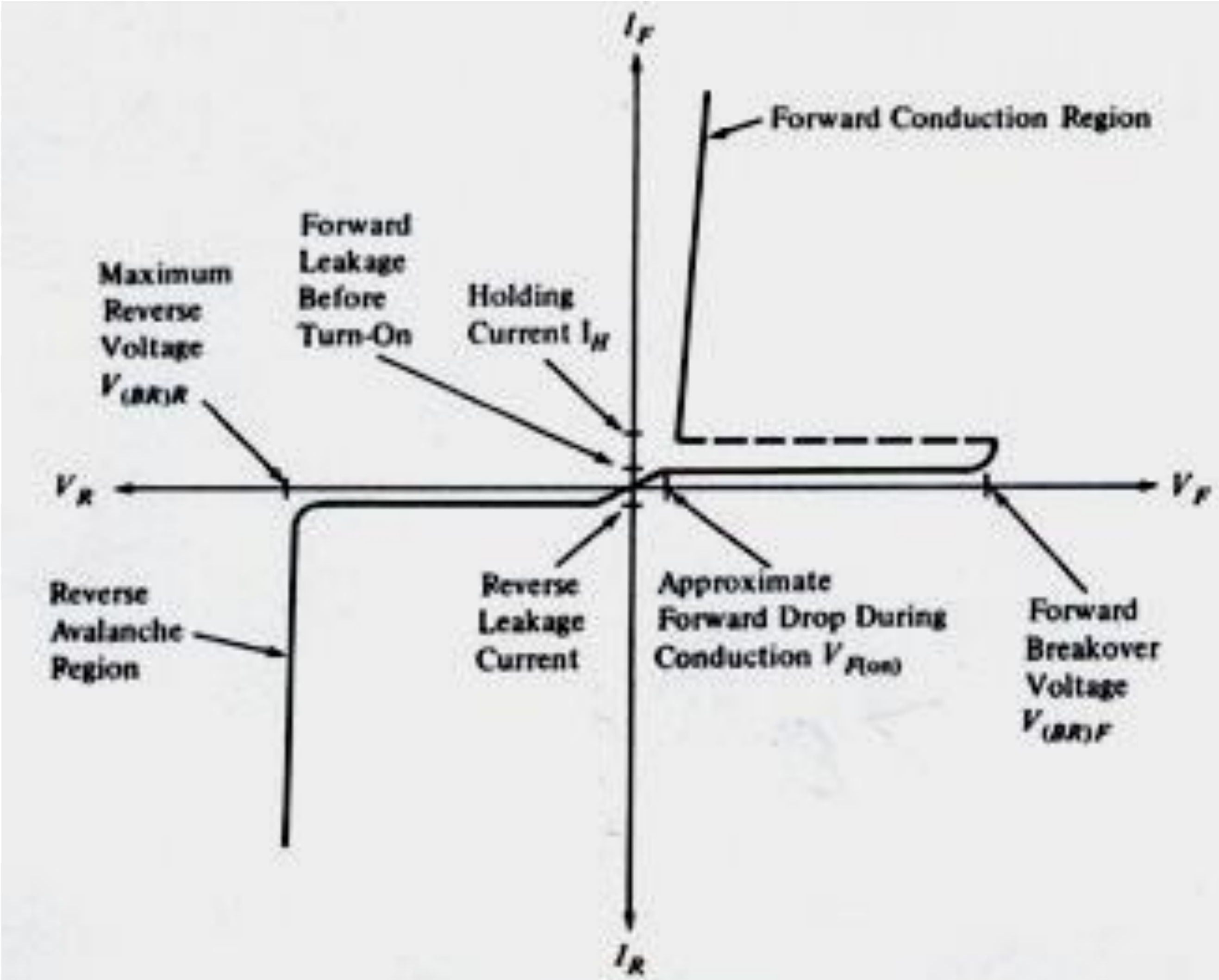


Schematic representation

SCR properties

- *It is simply a conventional rectifier with turn on controlled by a gate signal*
- *It is controlled from the off to on states by a signal applied to the gate-cathode*
- *It has a low forward resistance and a high reverse resistance*
- *It remains on once it is turned on even after removal of the gate signal*
- *The anode-cathode current must drop below the "holding" value in order to turn it off*

Rectifiers - SCR Characteristics



V–I characteristics of the SCR with gate open.

Rectifiers - SCR Considerations

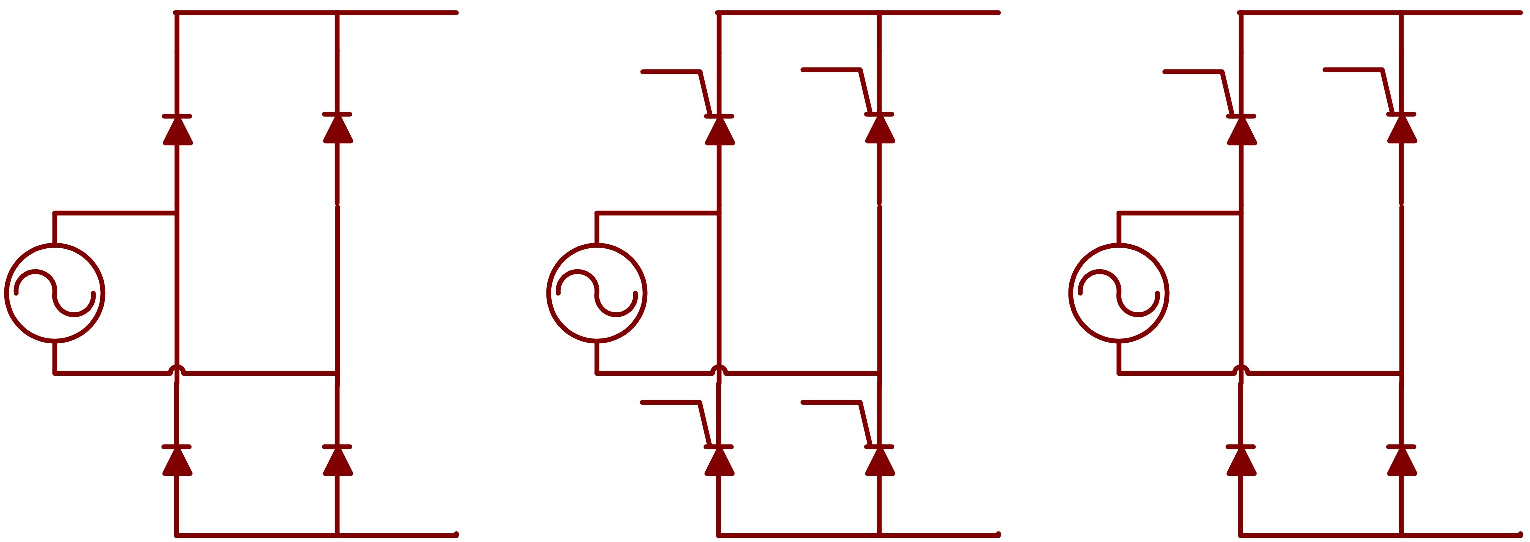
- *Maximum forward current*
- *Reverse breakdown voltage*
- *Gate trigger voltage and current*
- *Minimum holding current, I_h*
- *Power dissipation*
- *Peak forward voltage*
- *Maximum reverse dv/dt*

- *A rectifier converts ac voltage to dc voltage*
  - *Classifications*

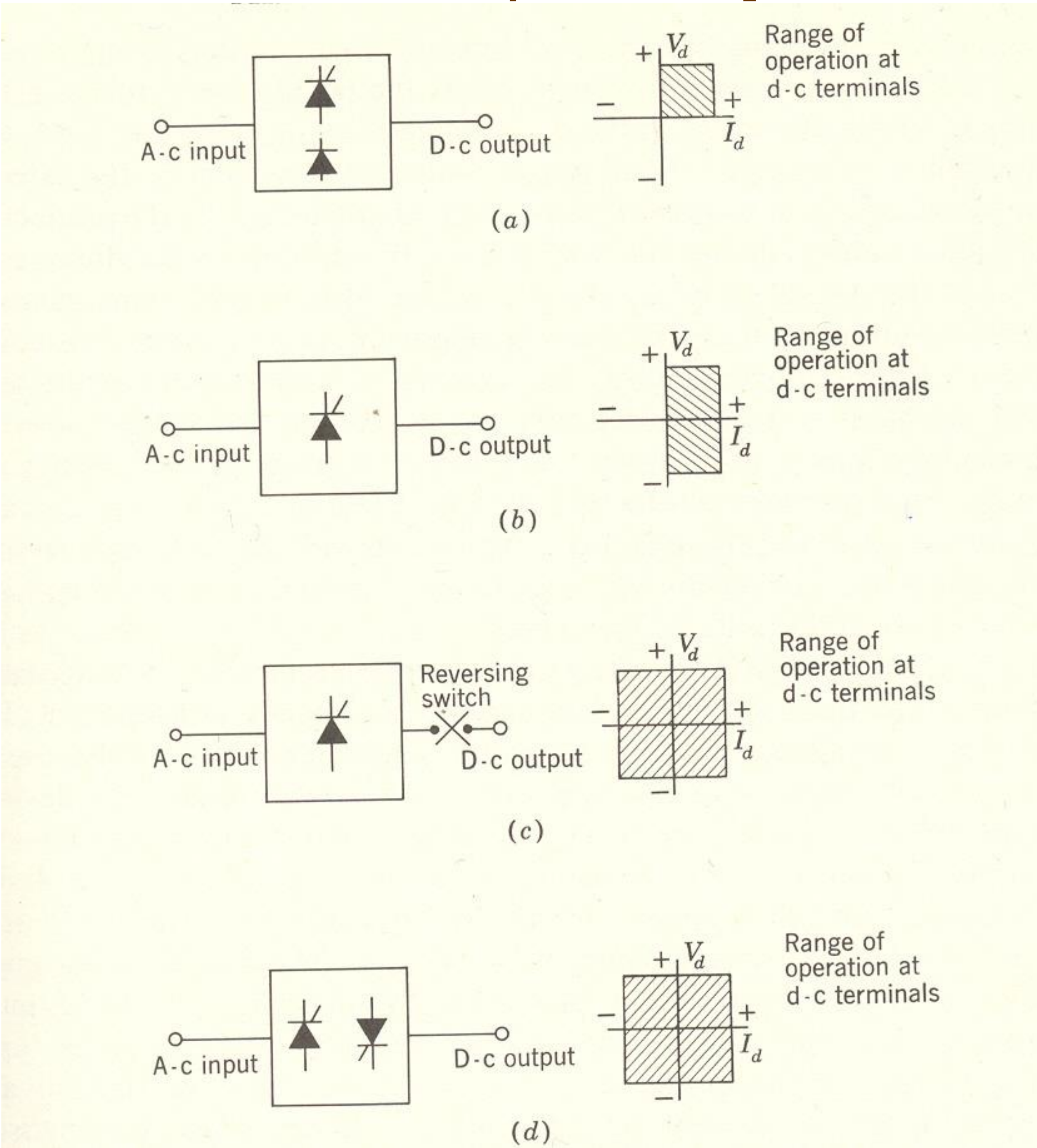
    Uncontrolled rectifiers (diodes)

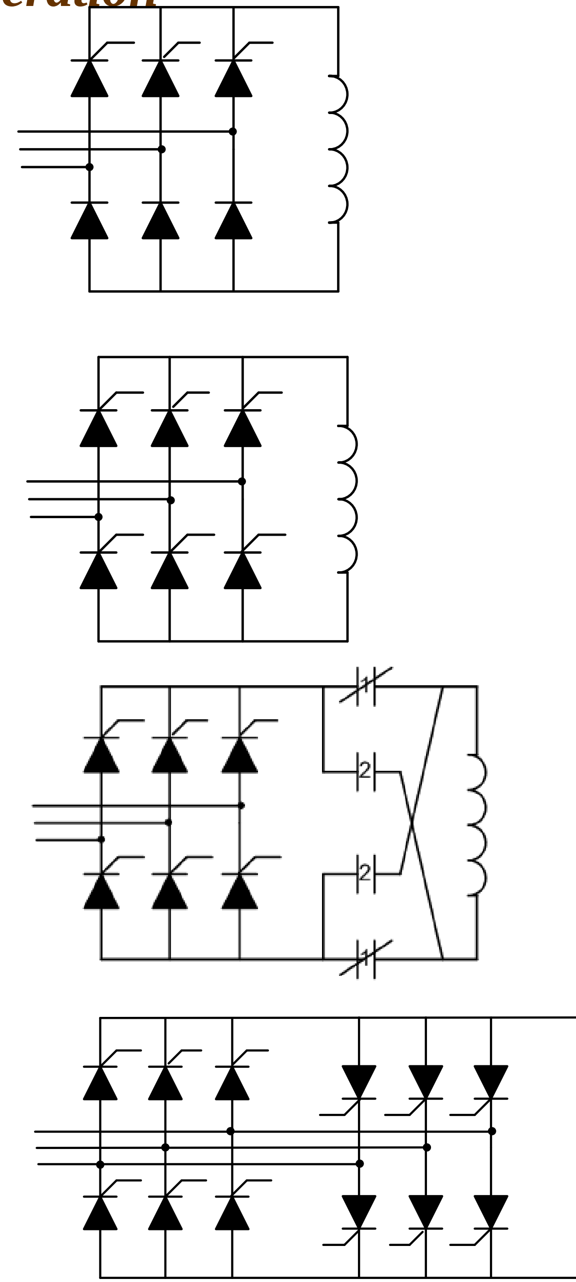
    Controlled rectifiers (all SCRs)

    Semi-controlled rectifiers (SCRs and diodes)

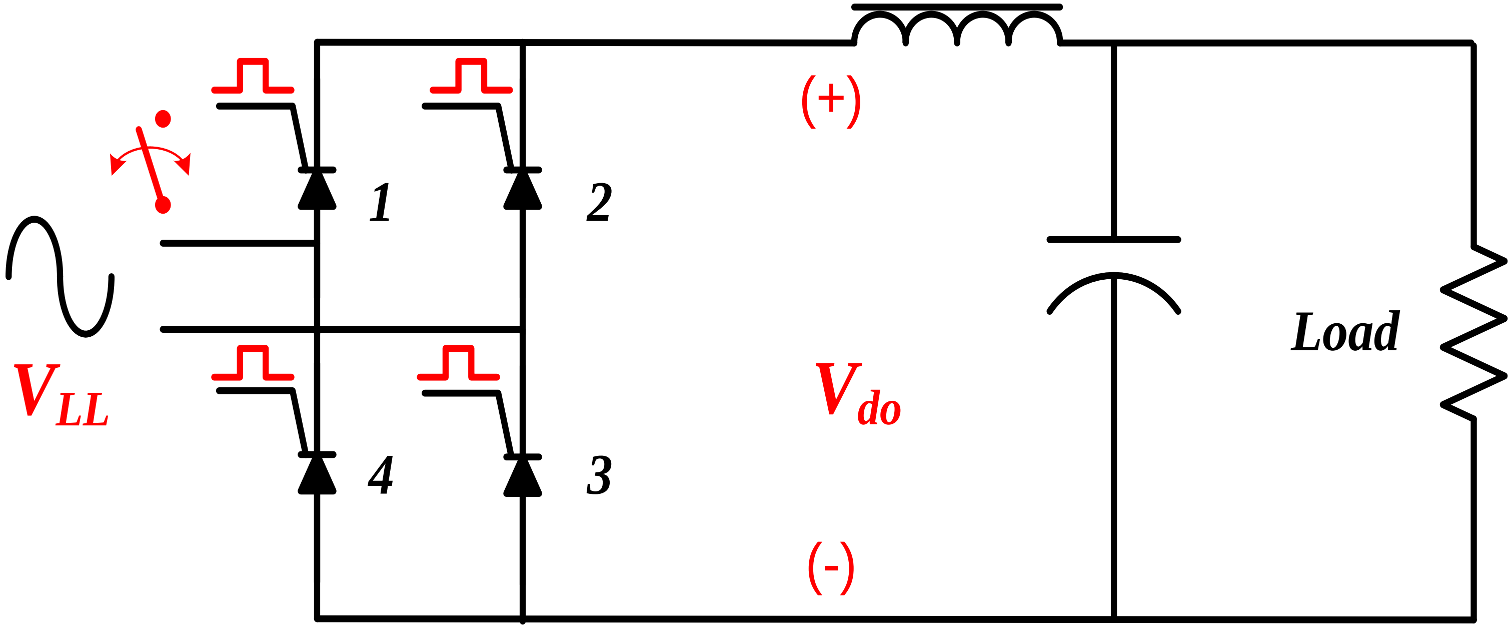


Rectifiers - Multiple Quadrant Operation



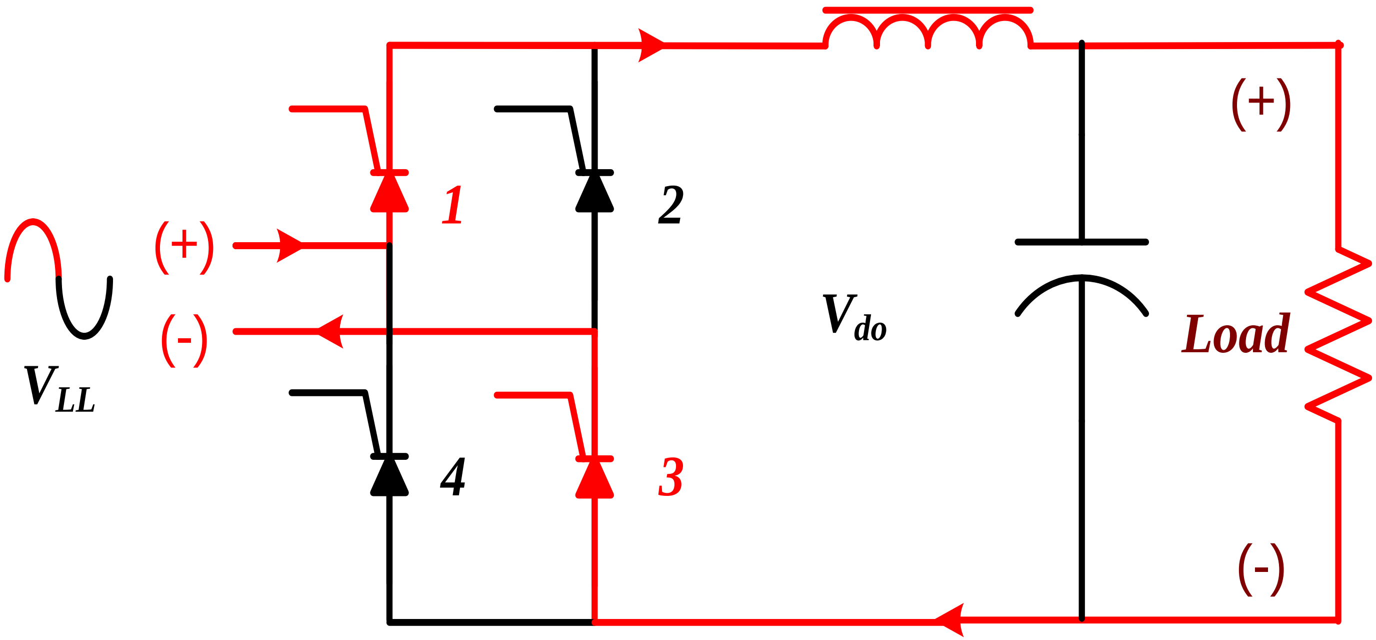


Rectifiers - 1 ϕ Full Wave (q = 2 Pulse)

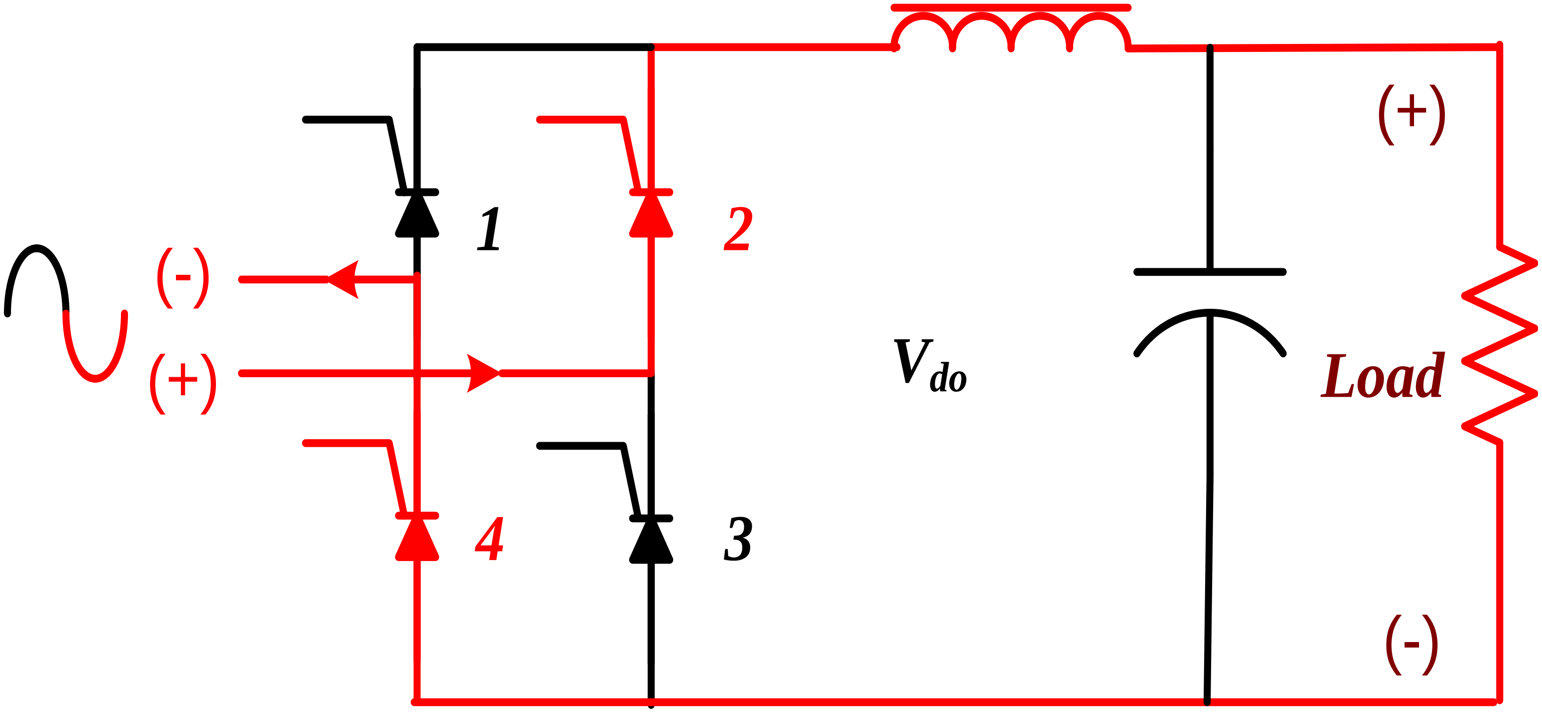


- *q ≡ the number of possible rectifier states*
- *SCR s are electronic switches*

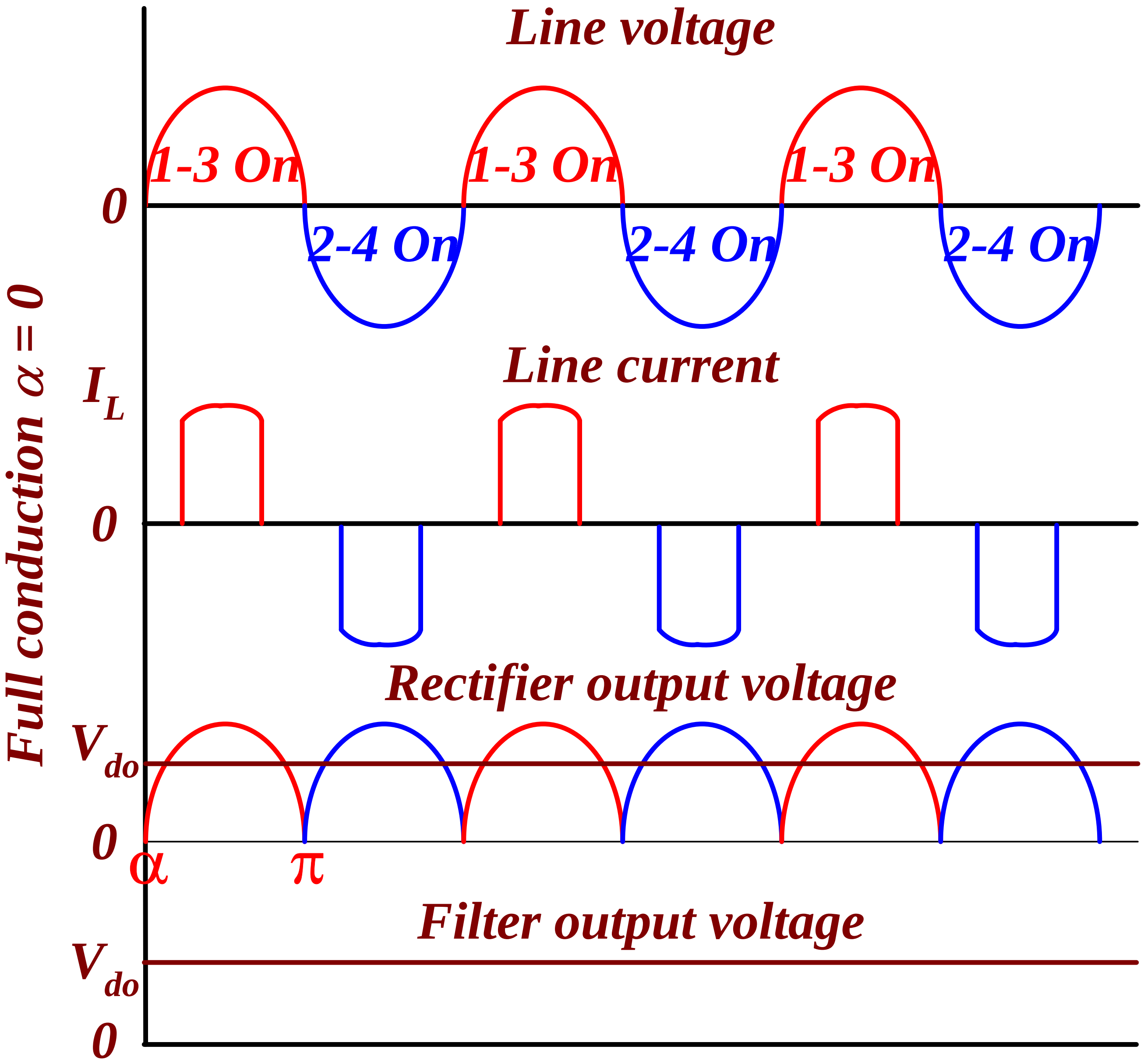
Rectifiers - 1 ϕ Full Wave (q = 2 Pulse)

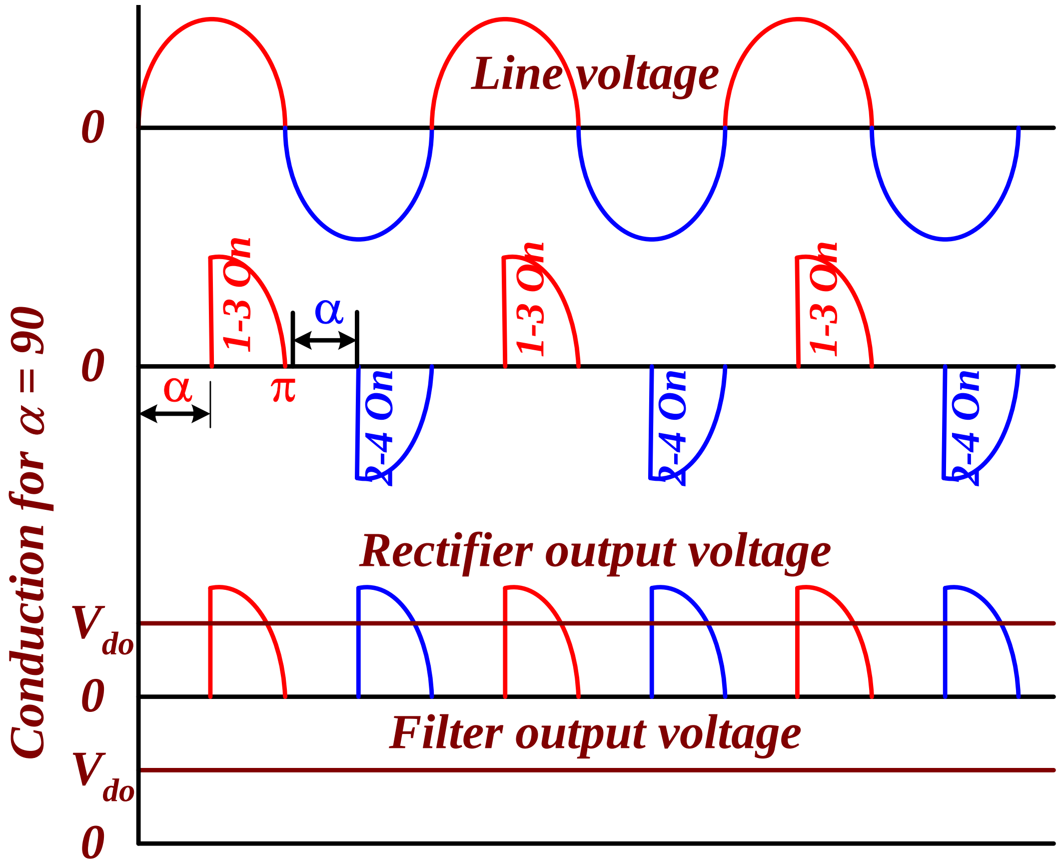


State 1 : SCR s 1 – 3 On



State 2 : SCR s 2 – 4 On


Line voltage
1-3 On
1-3 On
1-3 On
0
2-4 On
2-4 On
2-4 On
Full conduction α = 0
Line current
I_L
0
Rectifier output voltage
V_do
0
α
π
Filter output voltage
V_do
0



$$V_{do} = \frac{1}{T}\int_{t}^{T} v_{LL}(t)dt = \frac{1}{T}\int_{t}^{T}\sqrt{2}\,V_{LL}\,\sin\omega t\;dt = \frac{1}{\omega T}\int_{\alpha}^{\omega T}\sqrt{2}\,V_{LL}\,\sin\omega t\;d\omega t$$

the SCR gate trigger retard angle range is $0 \le \alpha \le \pi$

$$V_{do} = \frac{\sqrt{2}\,V_{LL}}{\pi}(1+\cos\alpha)\quad \text{for resistive load}$$

Rectifiers - 1 ϕ, Full Wave (q = 2 Pulse) Summary

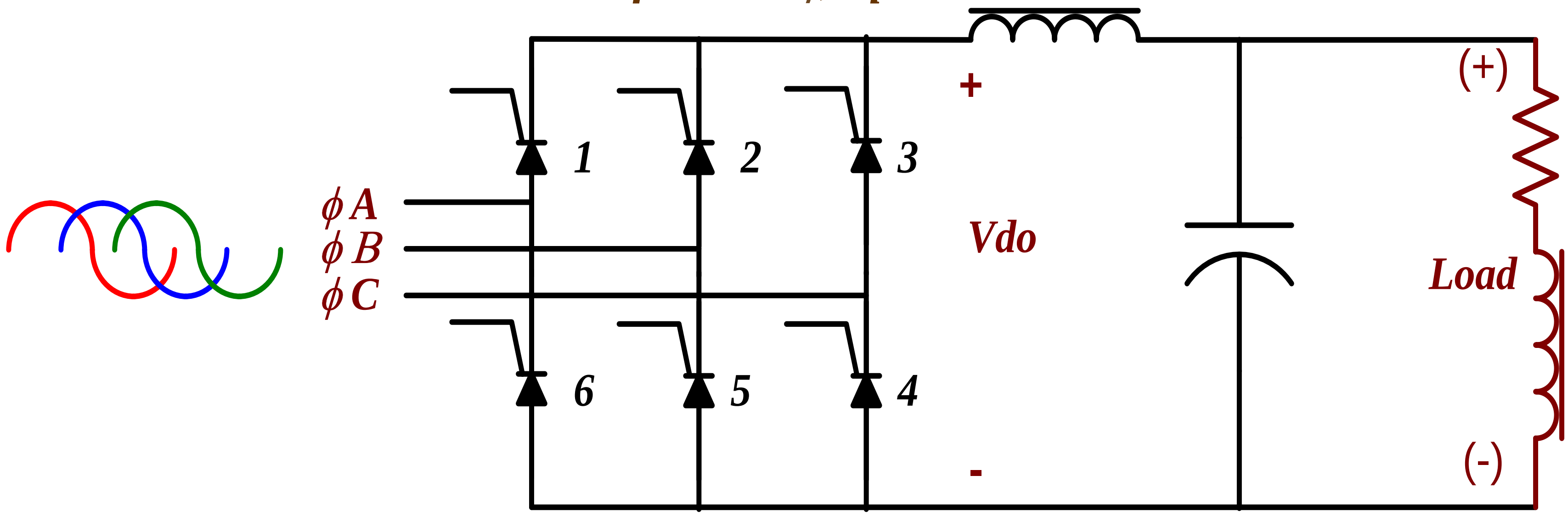
- *2 pulse rectifier – low input power factor, high output ripple*
- *Ripple frequency is 120 Hz (if input is 60 Hz)*
- *Large filter needed*
- *Limited in use to power supplies < 2.5 kW*

$$V_{do} = \frac{1}{T}\int_{t}^{T} v_{LL}(t)dt = \frac{1}{T}\int_{t}^{T} \sqrt{2}\, V_{LL} \sin\omega t \; dt = \frac{1}{\omega T}\int_{\alpha}^{\omega T} \sqrt{2}\, V_{LL} \sin\omega t \; d\omega t$$

the SCR gate trigger retard angle range is $0 \le \alpha \le \pi$

$$V_{do} = \frac{\sqrt{2}\, V_{LL}}{\pi}(1 + \cos\alpha) \quad \textit{for resistive load}$$

Rectifiers - 3 ϕ, q = 6 Pulse

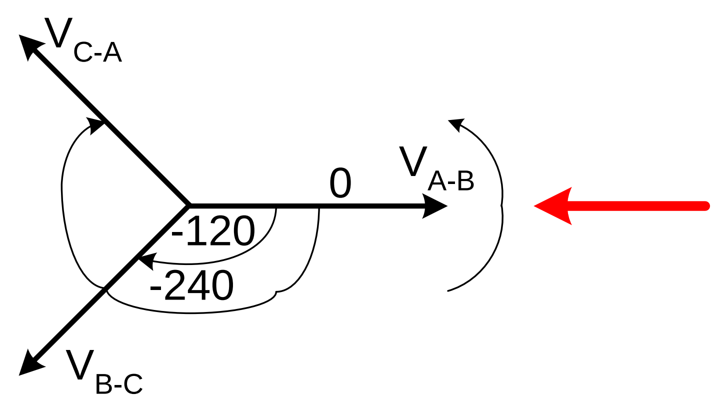


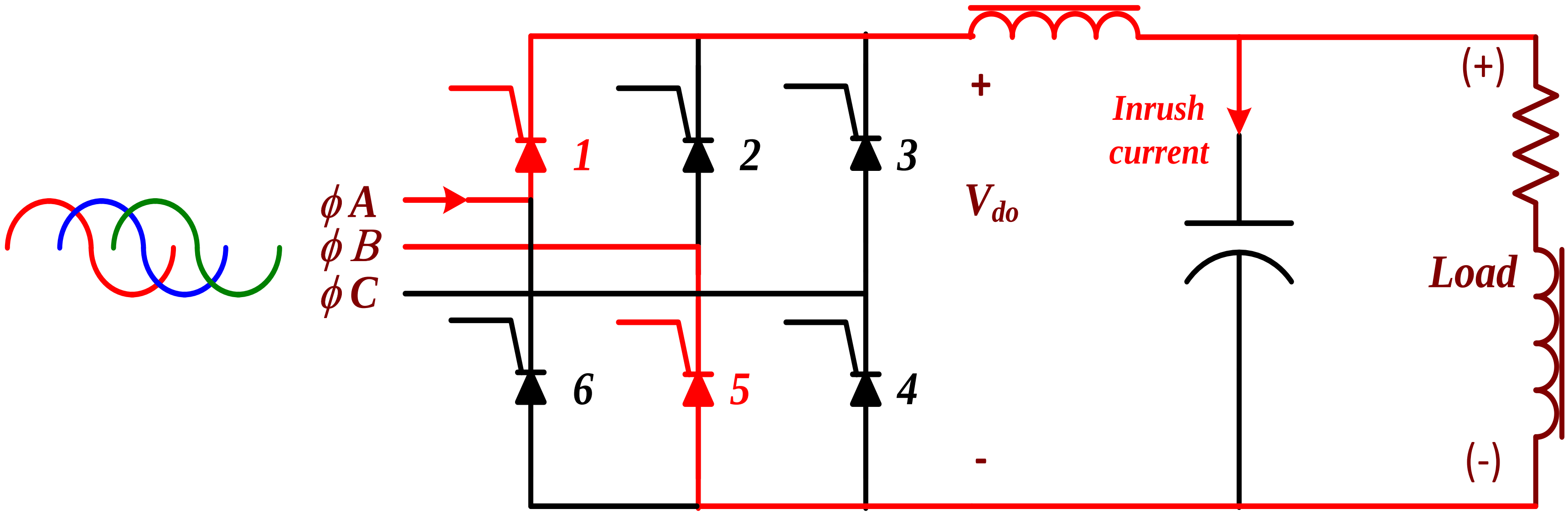
Assuming the American standard phase rotation of

$$V_{A-B} = |V|\, e^{j0} \qquad V_{B-C} = |V|\, e^{-j120} \qquad V_{C-A} = |V|\, e^{-j240}$$

The thyristor firing sequence is:

1-5, 1-4, 2-4, 2-6, 3-6, 3-5

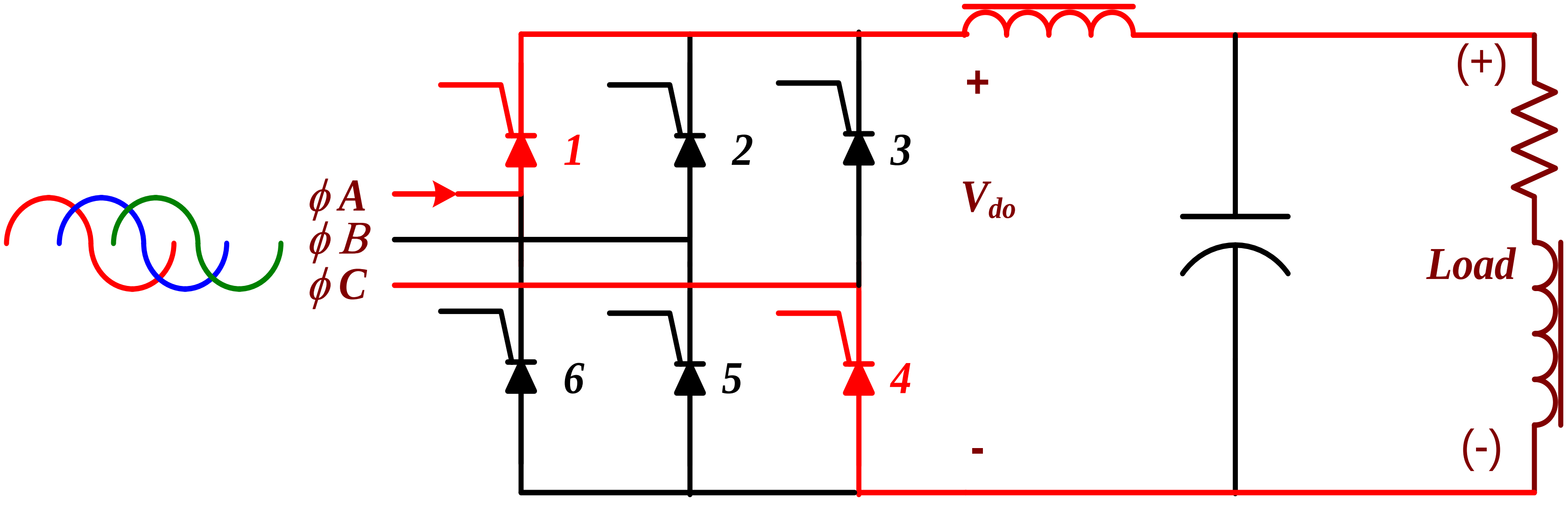




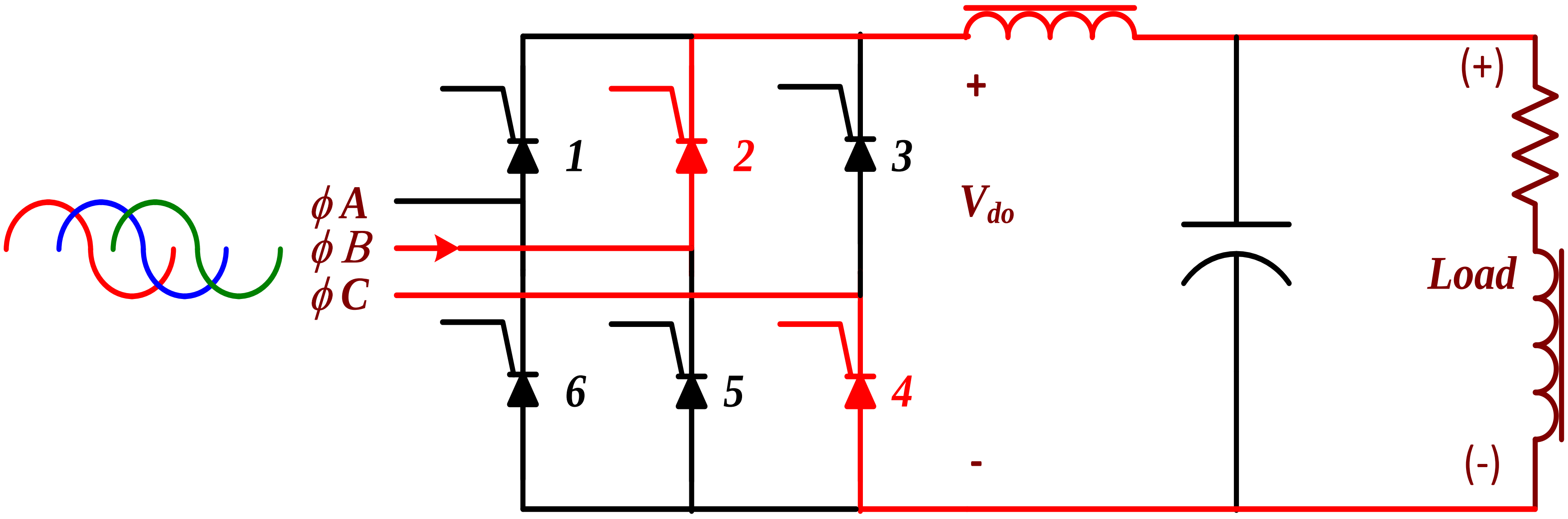
State 1: A-B (+) SCR s 1 – 5 On

Note: Phase SCRs from full retard to full forward slowly to bring the rectifier output voltage up slowly and reduce the capacitor inrush current

Rectifiers - 3 ϕ, q = 6 Pulse

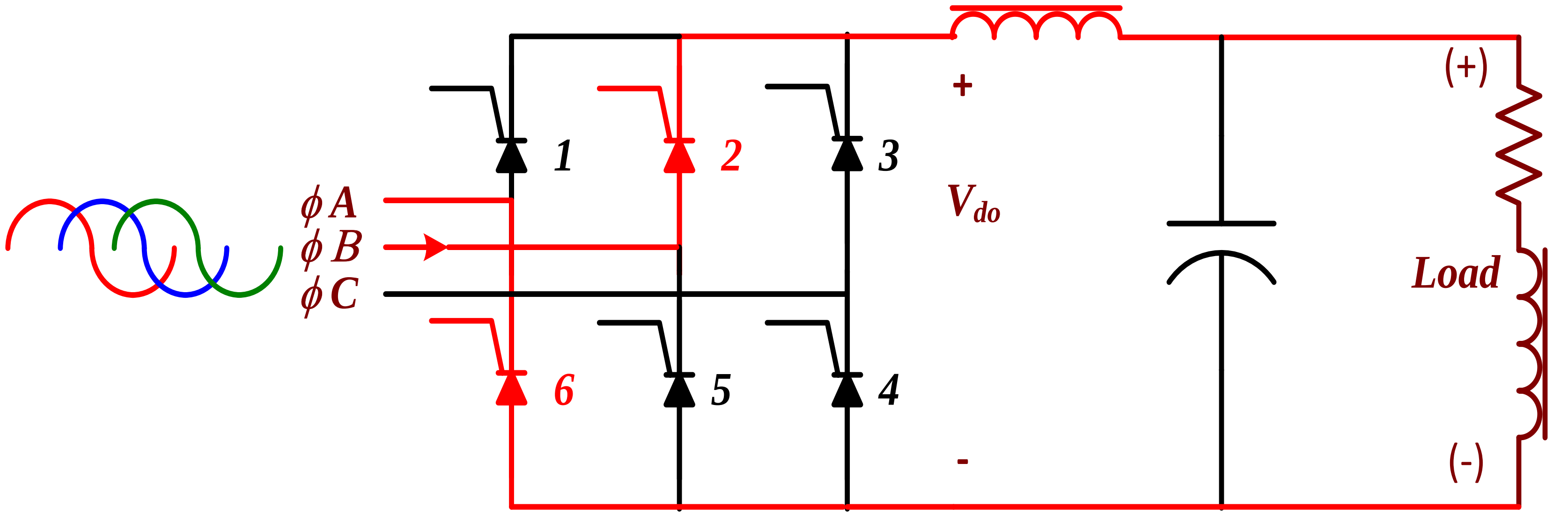


State 2 : A-C (+), 5 off, SCR s 1 – 4 On



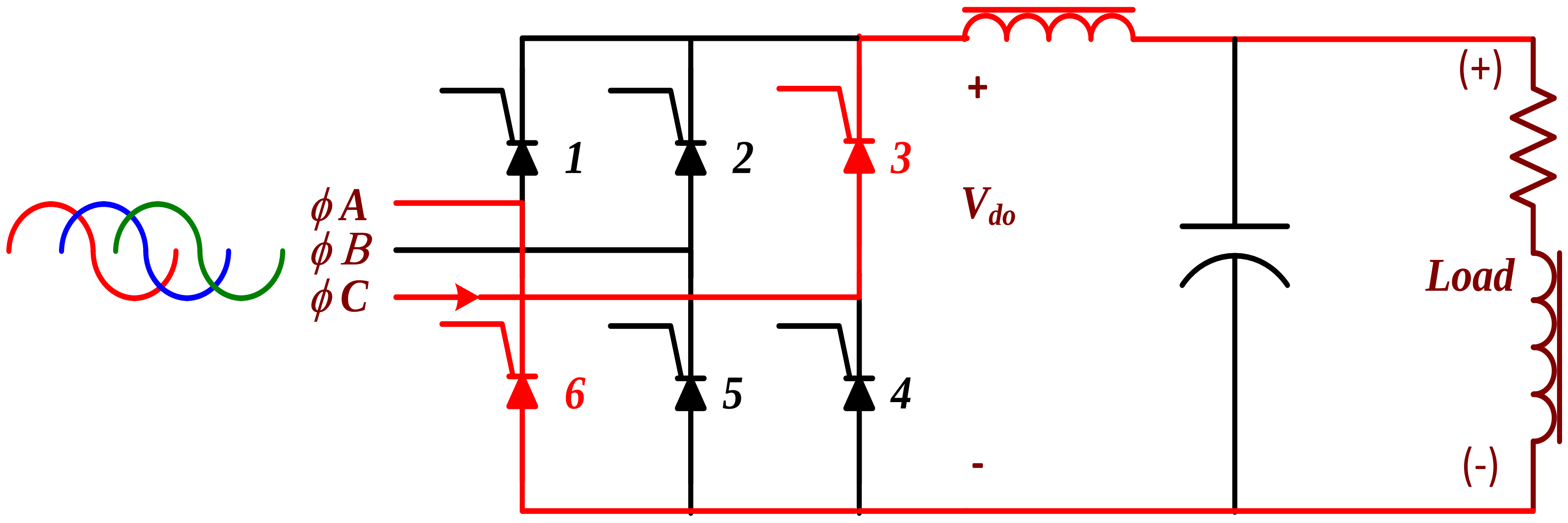
State 3 : B-C (+), 1 off, SCR s 2 – 4 On

3 ϕ, q = 6 Pulse Rectifier

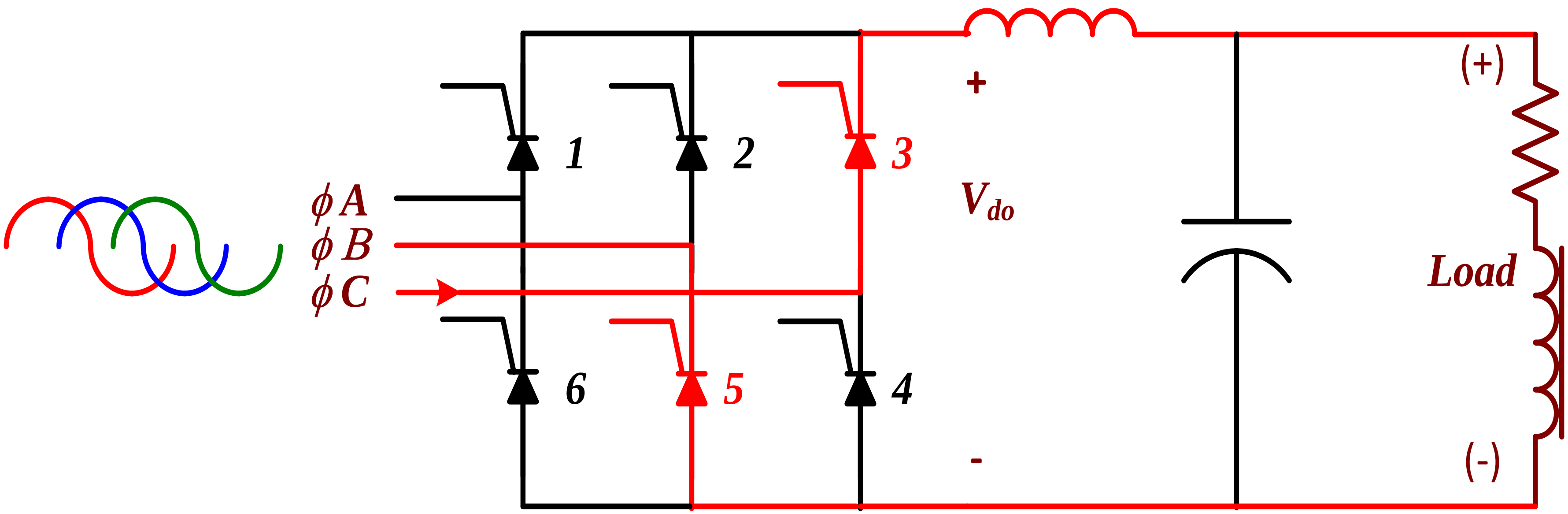


State 4 : B-A (+), 4 off, SCR s 2 – 6 On

3 ϕ, q = 6 Pulse Rectifier

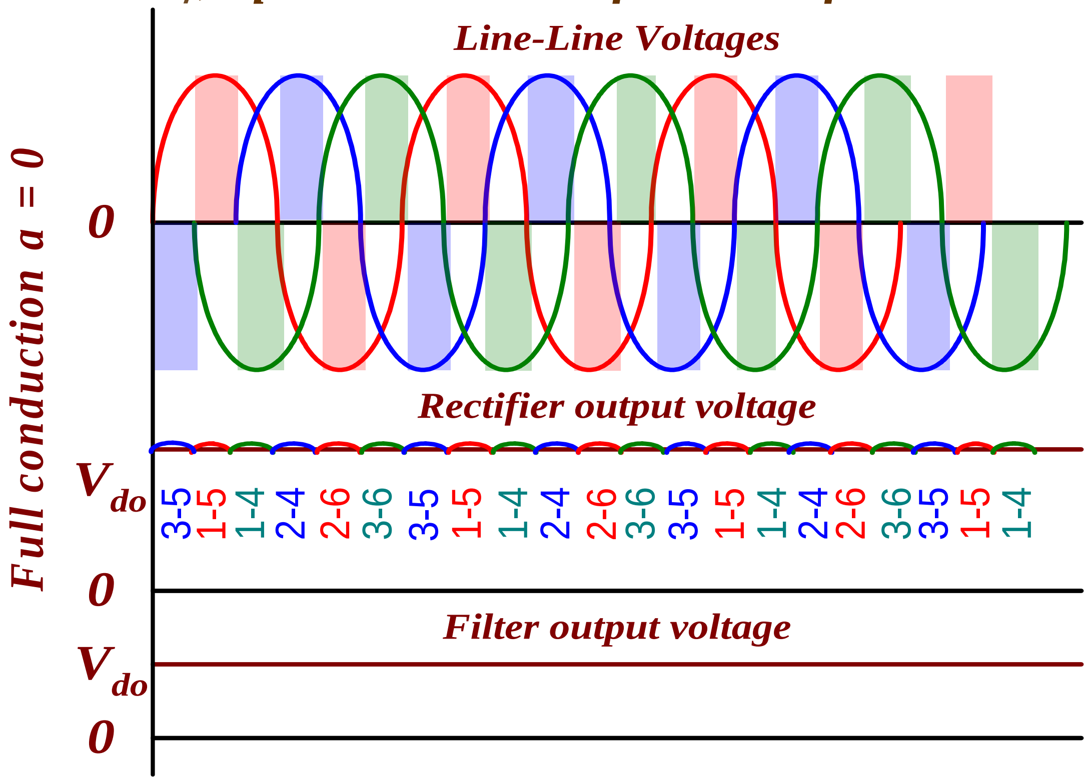


State 5 : C-A (+), 2 off, SCR s 3 – 6 On



State 6 : C-B (+), 6 off, SCR s 3 – 5 On

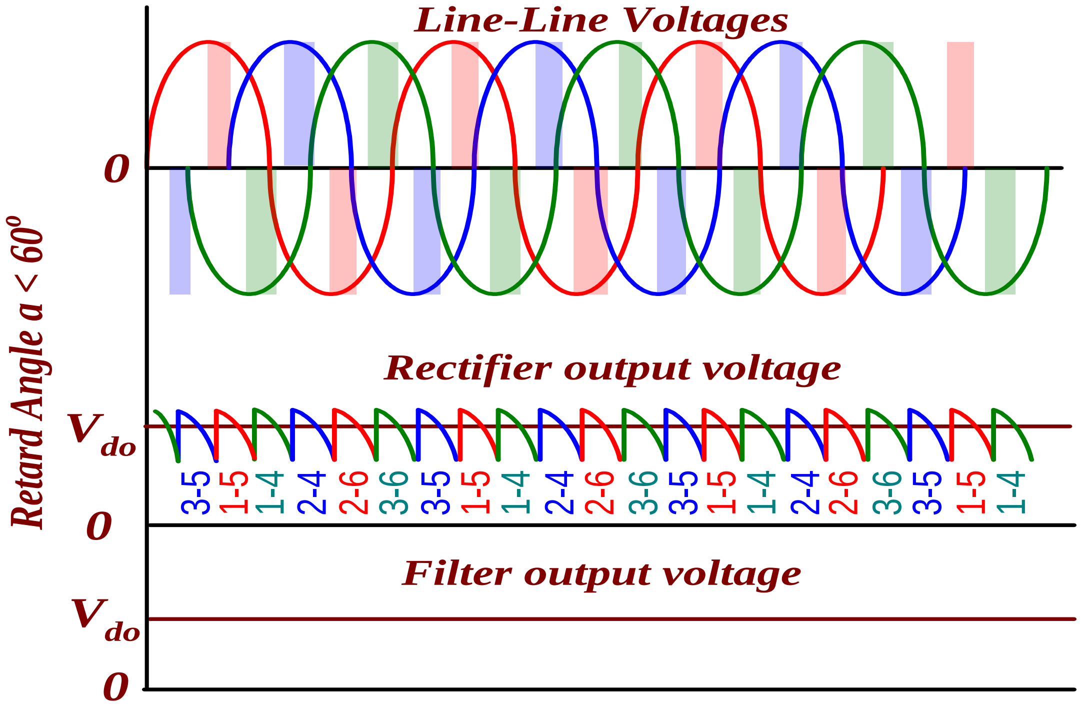
3 ϕ, q = 6 Pulse Rectifier Waveforms



$$V_{do} = \frac{3\sqrt{2}}{\pi} V_{LL} \cos\alpha$$

where α is the gate trigger retard angle and conduction is continuous

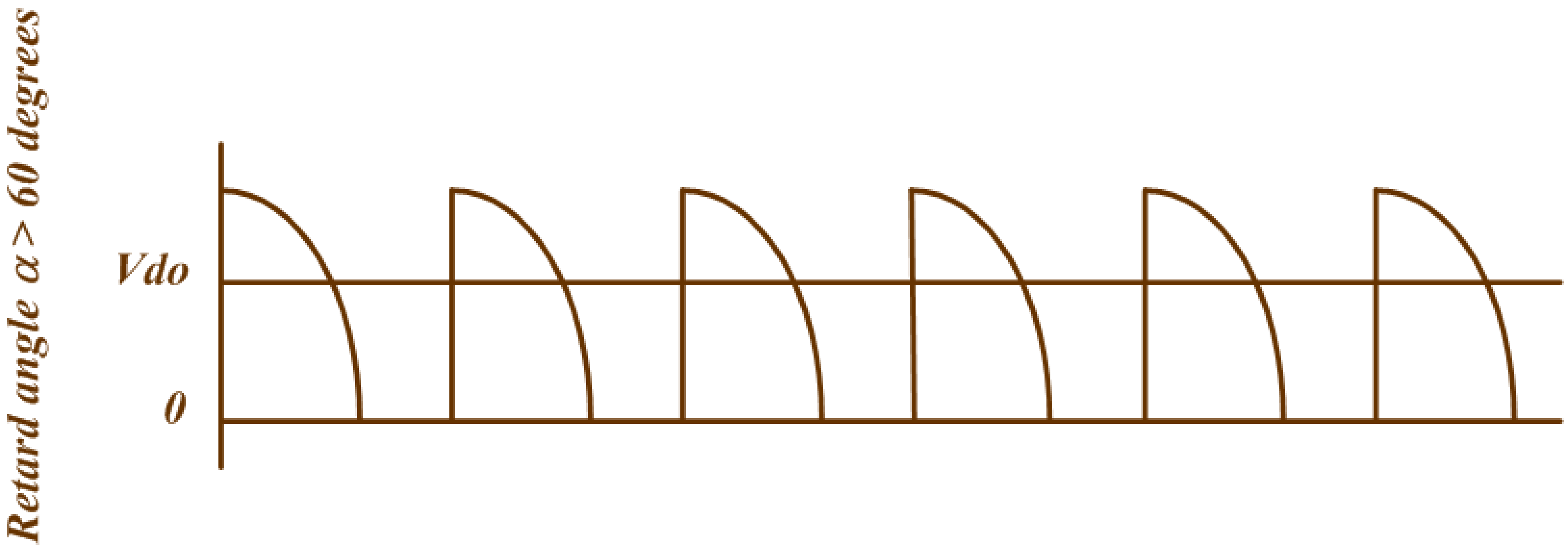
$3\ \phi,\ q = 6$ Pulse Rectifier Waveforms



For $0 \le \alpha \le \dfrac{\pi}{3}$ where α is the gate trigger retard angle and conduction is continuous

$$V_{do} = \frac{3\sqrt{2}}{\pi} V_{LL} \cos\alpha$$

3 ϕ, q = 6 Pulse Rectifier Waveforms



$$For\ \frac{\pi}{3} < \alpha \le \frac{2\pi}{3}\ \ where\ conduction\ can\ be\ discontinuous$$

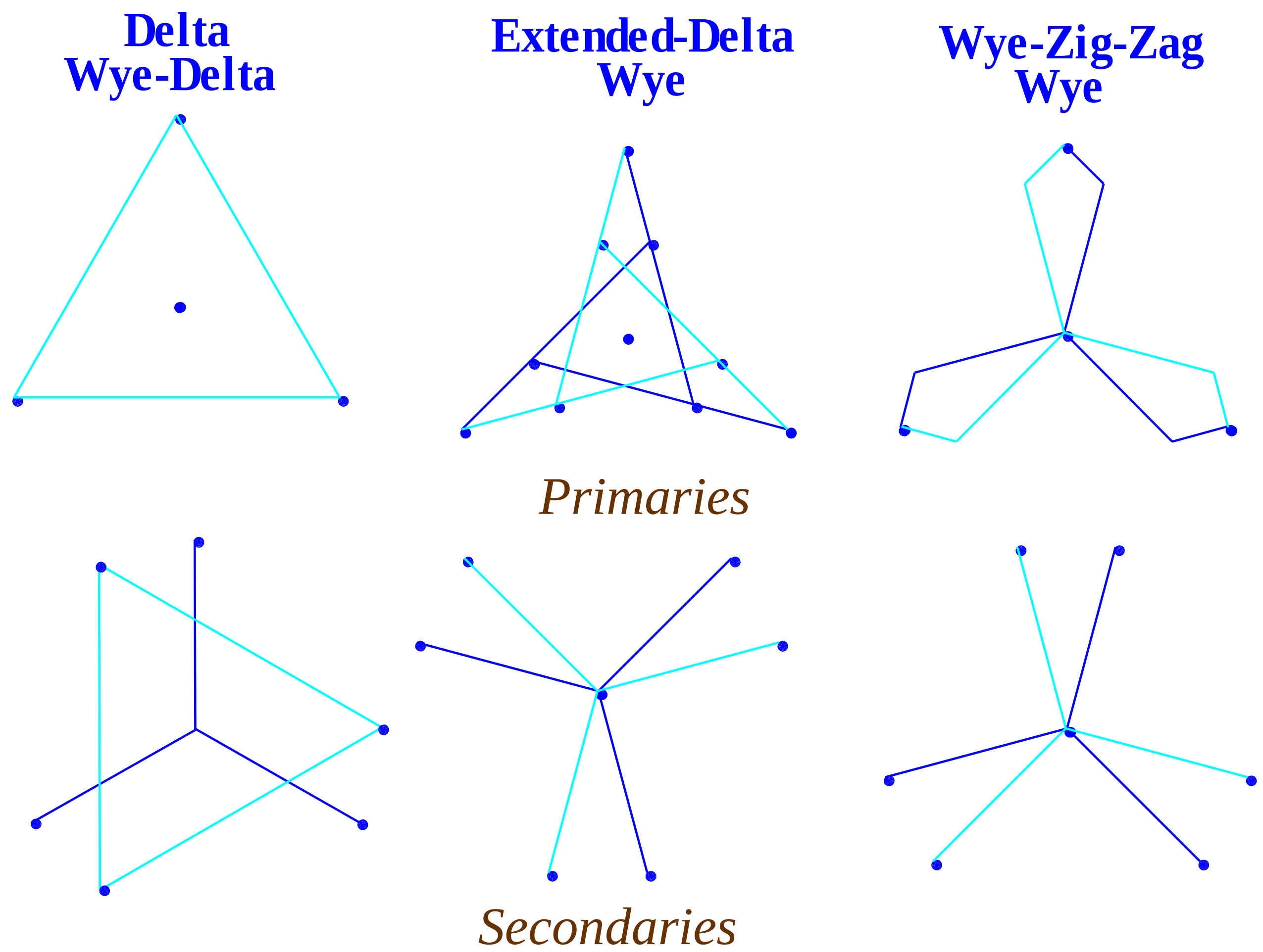
$$V_{do} = \frac{3\sqrt{2}}{\pi} V_{LL}(1 + \cos(\alpha + \frac{\pi}{3}))\ \ for\ resistive\ load$$

3 ϕ, q = 6 Pulse Rectifier Summary

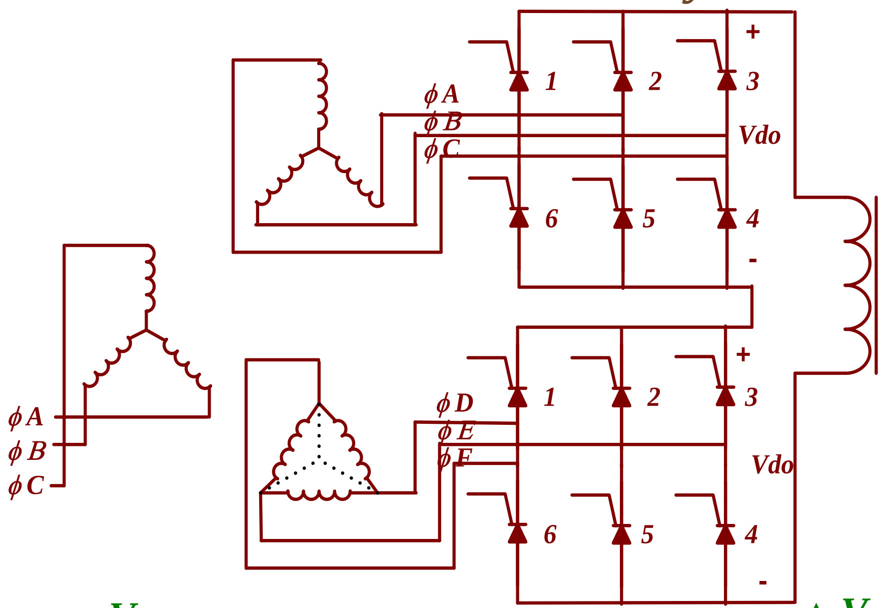
- *6 pulse – high input PF $\rightarrow$ 0.95*
- *Use soft-start to limit filter capacitor inrush current.*
- *Output ripple frequency is 360 Hz for 60 Hz input*
- *Relatively low output ripple and easy to filter with small LC*
- *Limited to loads < 350 kW*
- *Diodes or SCRs are air or water-cooled depending upon load current*

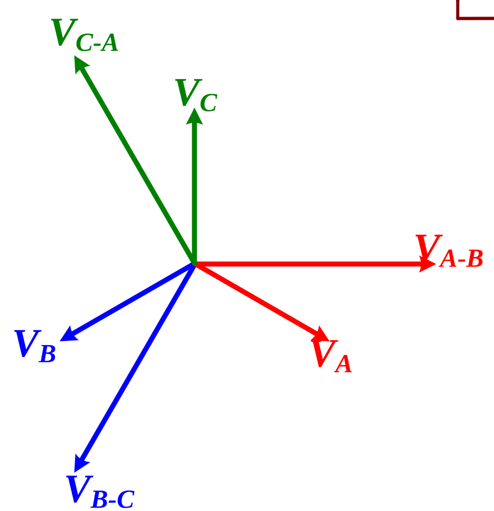
Three Phase, Phase Shifting Transformer

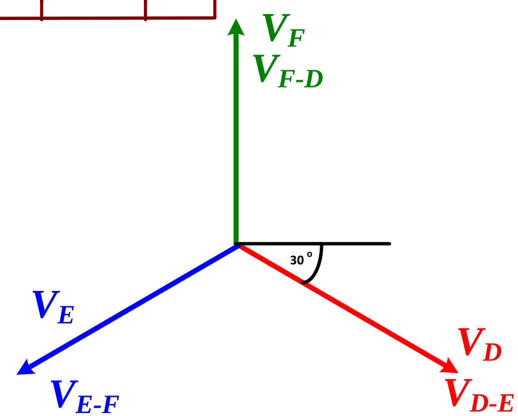
Phase shifting transformer for 12 Pulse operation



Total Primary Current in Wye-Wye-Delta

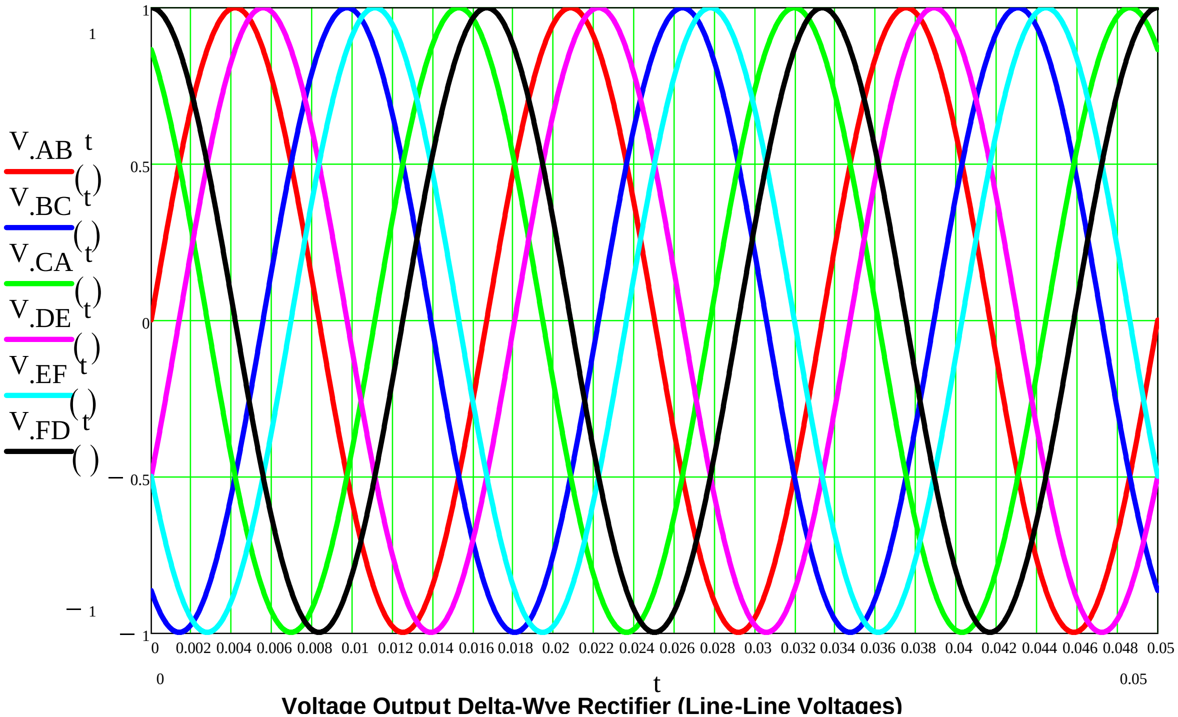




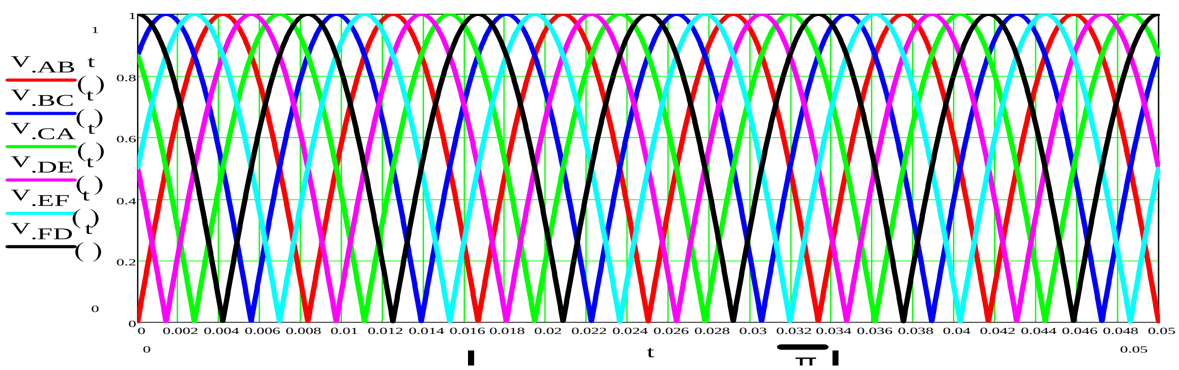


Line	Phase (°)
VA-B	0
VD-E	-30
VB-C	-120
VE-F	-150
VC-A	-240
VF-D	-270

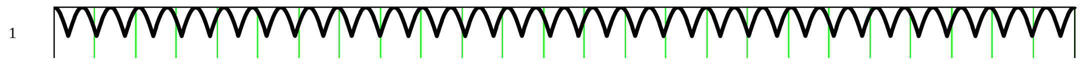
Total Primary Current in Wye-Wye-Delta



6 cycles (phases) in T=16.67ms

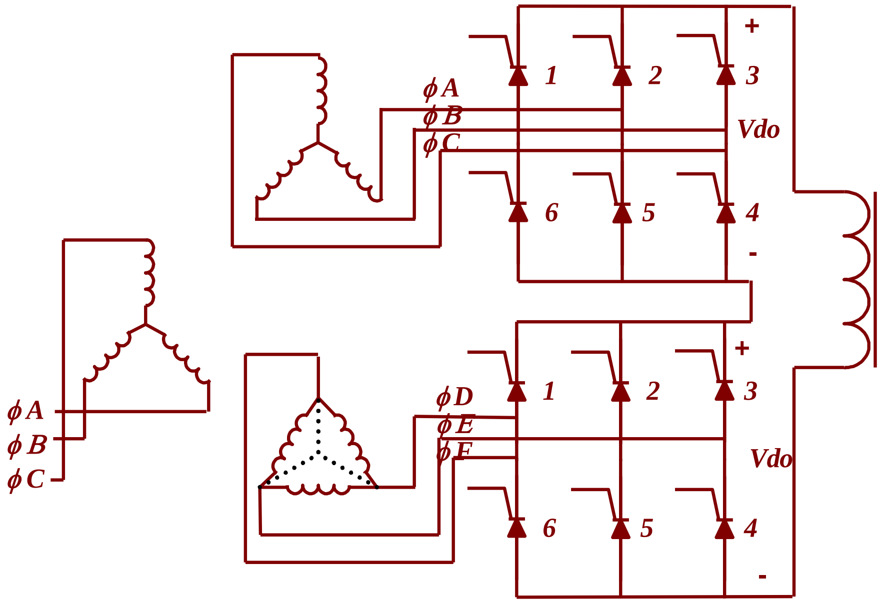


12 cycles in T=16.67ms

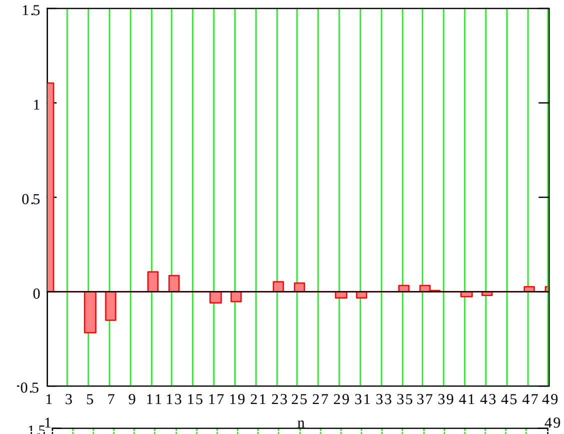


12 pulses in T=16.67ms

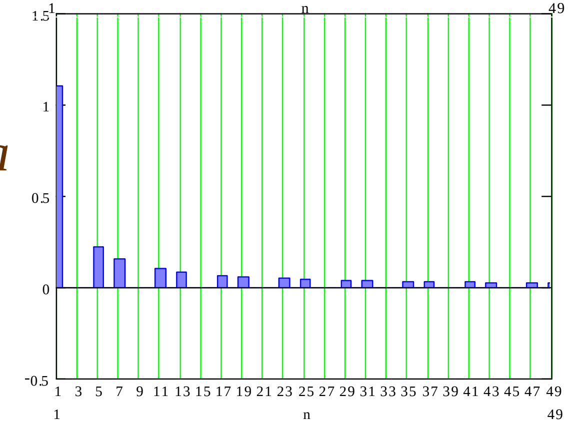
Total Primary Current in Wye-Wye-Delta

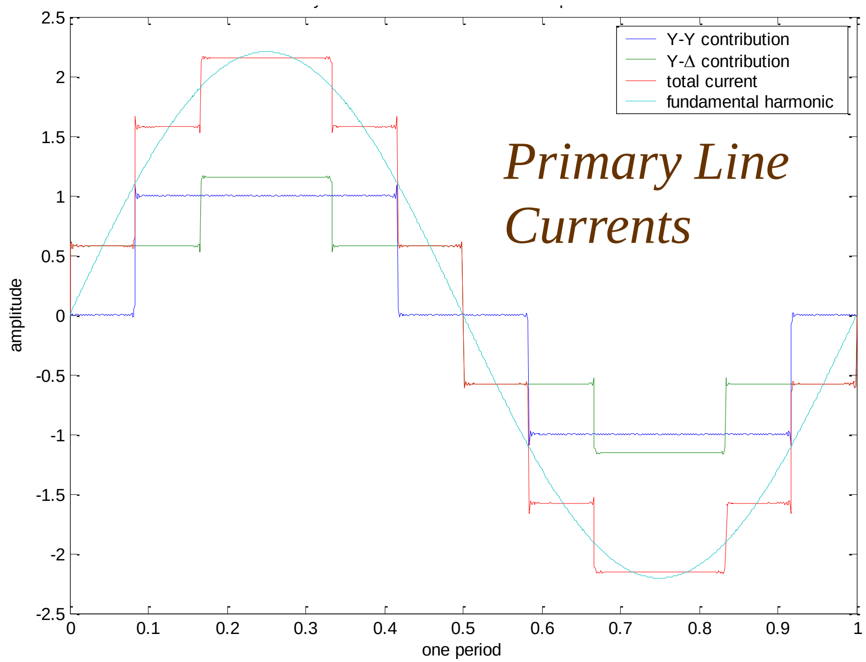


Wye-Wye



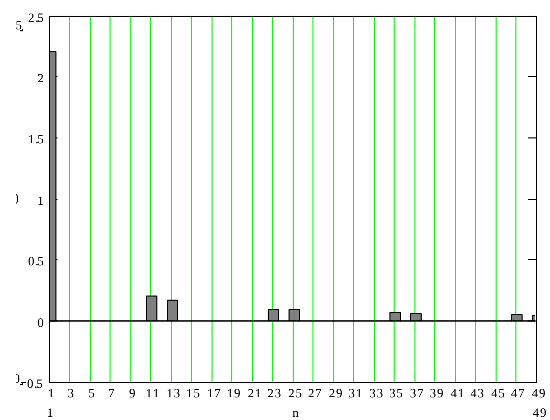
Wye-Delta





Primary Line Currents

Wye-Wye-Delta



Balanced Bridge Harmonics - Trigonometric Identities

Addition formulae

$$\sin(A+B) = \sin A\cos B + \sin B\cos A$$

$$\sin(A-B) = \sin A\cos B - \sin B\cos A$$

Therefore

$$\sin(A+B) + \sin(A-B) = 2\sin A\cos B$$

$$\sin(A+B) - \sin(A-B) = 2\sin B\cos A$$

and

$$\sin A + \sin B = 2\sin\frac{A+B}{2}\cos\frac{A-B}{2}$$

$$\sin A - \sin B = 2\sin\frac{A-B}{2}\cos\frac{A+B}{2}$$

Similarly

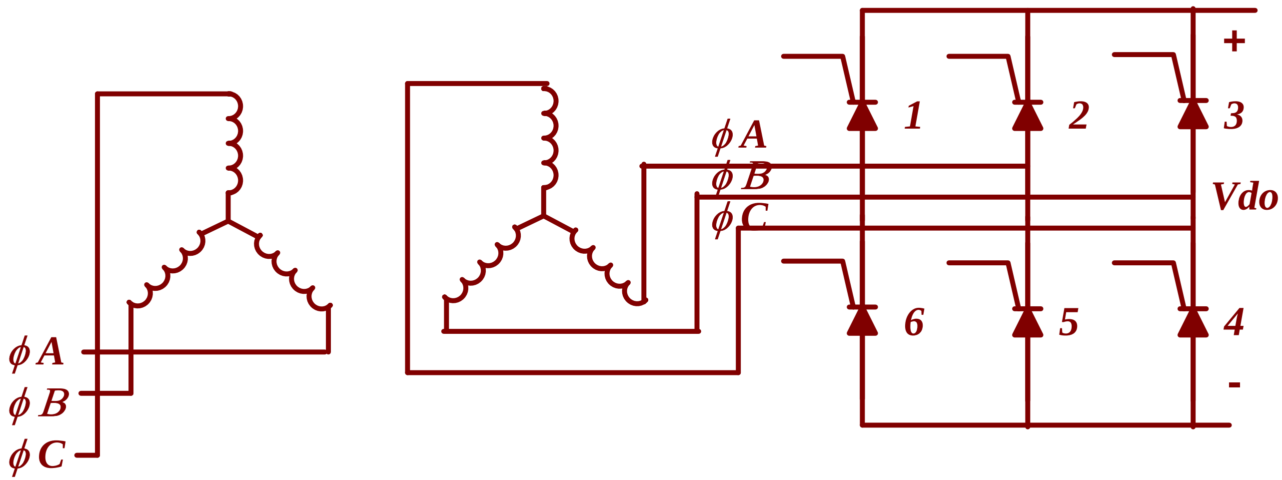
$$\cos(A+B) = \cos A\cos B - \sin A\sin B$$

$$\cos(A-B) = \cos A\cos B + \sin A\sin B$$

$$\cos A + \cos B = 2\cos\frac{A+B}{2}\cos\frac{A-B}{2}$$

$$\cos A - \cos B = -2\sin\frac{A+B}{2}\sin\frac{A-B}{2}$$

Three Phase Wye-Wye



$$V_{Ap} = V_{LNp} \sin \omega t$$

$$V_{Bp} = V_{LNp} \sin\left(\omega t - 2\pi/3\right)$$

$$V_{Cp} = V_{LNp} \sin\left(\omega t - 4\pi/3\right)$$

$$\begin{aligned} V_{ABp} &= V_{Ap} - V_{Bp} \\ &= V_{LNp}\left[\sin \omega t - \sin\left(\omega t - 2\pi/3\right)\right] \\ &= 2V_{LNp} \sin \pi/3 \cos\left(\omega t - \pi/3\right) \\ &= \sqrt{3} V_{LNp} \sin\left(\omega t - \pi/3 + \pi/2\right) \\ &= \sqrt{3} V_{LNp} \sin\left(\omega t + \pi/6\right) \end{aligned}$$

$$V_{BCp} = \sqrt{3} V_{LNp} \sin\left(\omega t - \pi/2\right)$$

$$V_{CAp} = \sqrt{3} V_{LNp} \sin\left(\omega t - 7\pi/6\right)$$

For a transformer ratio, N_{YY}

$$V_s = N_{YY} V_p \,;\; I_s = I_p / N_{YY}$$

$$V_{ABYs} = \sqrt{3} N_{YY} V_{LNp} \sin\left(\omega t + \pi/6\right)$$

$$V_{BCYs} = \sqrt{3} N_{YY} V_{LNp} \sin\left(\omega t - \pi/2\right)$$

$$V_{CAYs} = \sqrt{3} N_{YY} V_{LNp} \sin\left(\omega t - 7\pi/6\right)$$

$$I_{ABYs} = \left(\sqrt{3} I_{LNp} / N_{YY}\right) \sin\left(\omega t + \pi/6 + \phi_Z\right)$$

$$I_{BCYs} = \left(\sqrt{3} I_{LNp} / N_{YY}\right) \sin\left(\omega t - \pi/2 + \phi_Z\right)$$

$$I_{CAYs} = \left(\sqrt{3} I_{LNp} / N_{YY}\right) \sin\left(\omega t - 7\pi/6 + \phi_Z\right)$$

Spectrum of Wye-Wye

Assume full conduction into a large inductive load

The load current, I_L, is then constant

The current out of the A leg of the transformer is

$$
\begin{aligned}
I_{ANYs}(t) &= 0 \qquad 0 \le t \le T/12 \\
&= I_L \qquad T/12 \le t \le 5T/12 \\
&= 0 \qquad 5T/12 \le t \le 7T/12 \\
&= -I_L \quad 7T/12 \le t \le 11T/12 \\
&= 0 \qquad 11T/12 \le t \le T
\end{aligned}
$$

The Fourier series expansion is

$$I_{ANYs}(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos\frac{2\pi nt}{T} + b_n \sin\frac{2\pi nt}{T}$$

From the symmetry of the waveform,

$$a_0 = a_n = 0$$

$$b_n = \frac{2}{T}\int_0^T I_{ANYs}(t)\sin\frac{2\pi nt}{T}\,dt$$

$$= \frac{2I_L}{T}\left[\int_{T/12}^{5T/12} \sin\frac{2\pi nt}{T}\,dt - \int_{7T/12}^{11T/12} \sin\frac{2\pi nt}{T}\,dt\right]$$

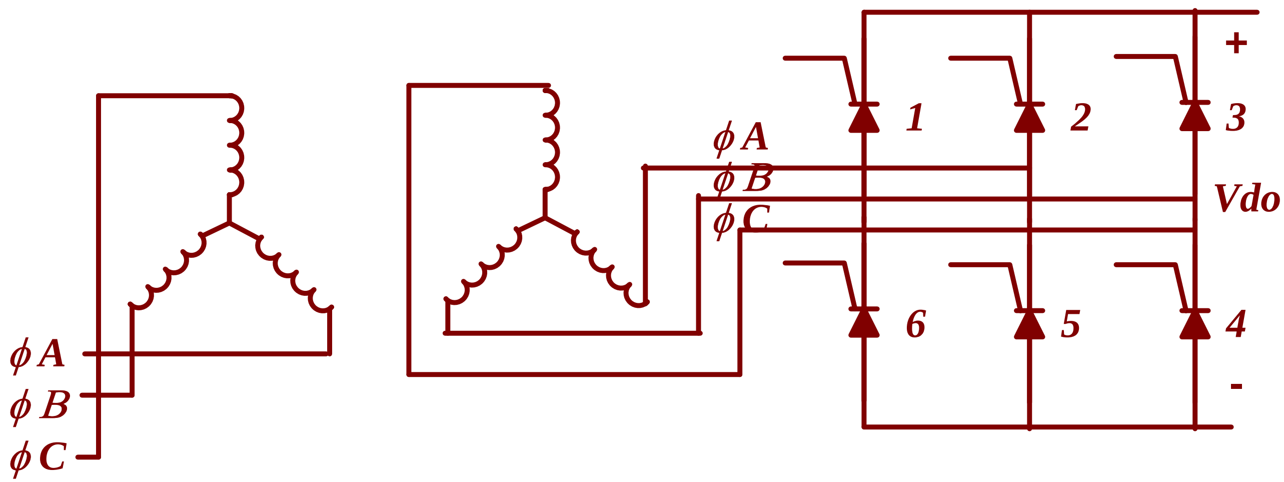
$$= \frac{4I_L}{T}\int_{T/12}^{5T/12} \sin\frac{2\pi nt}{T}\,dt$$

$$= -\frac{2I_L}{n\pi}\cos\frac{2\pi nt}{T}\Big|_{T/12}^{5T/12}$$

$$= -\frac{2I_L}{n\pi}\left[\cos(5n\pi/6) - \cos(n\pi/6)\right]$$

$$b_n = \frac{4I_L}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}$$

Wye-Wye Primary Current

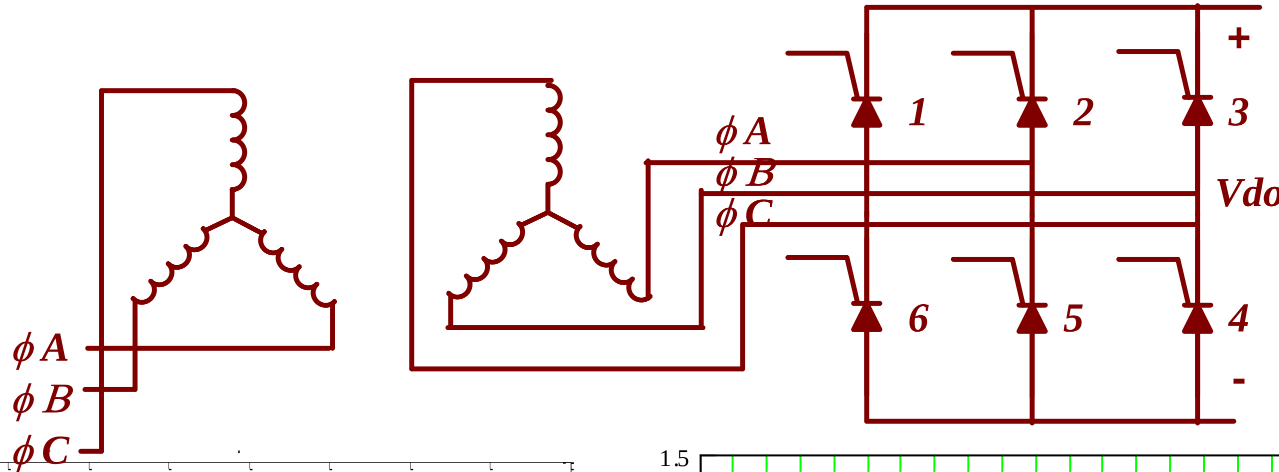


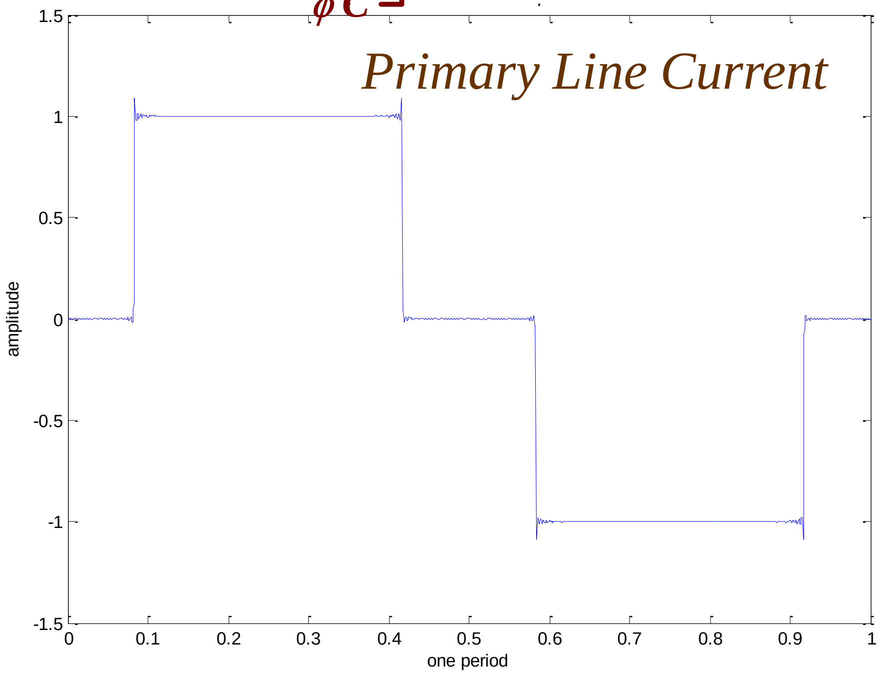
The current on the primary leg of the transformer, due to the YY winding is

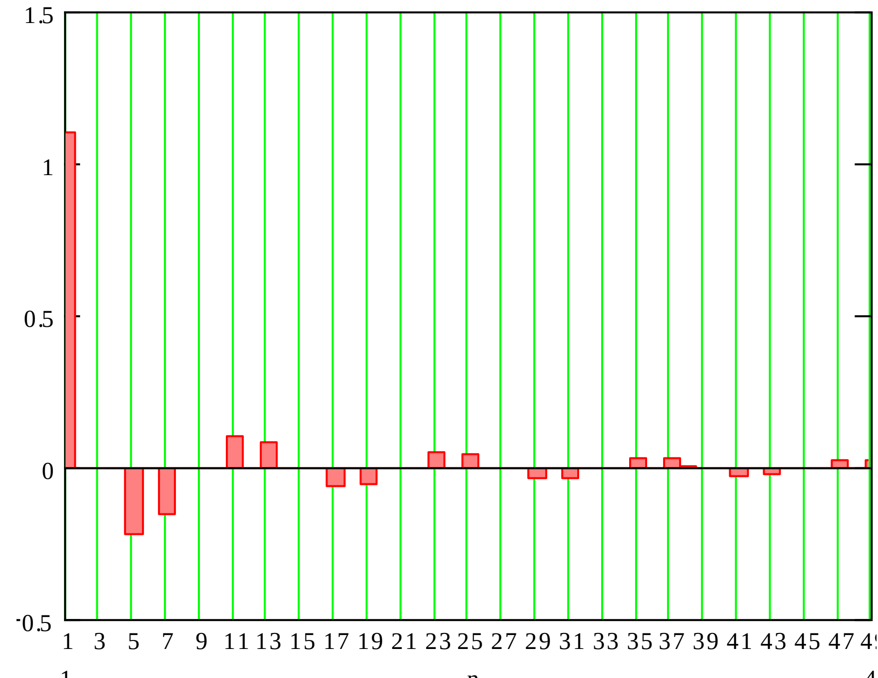
$$I_{ANYp}(t) = N_{YY}\frac{4I_L}{n\pi}\sum_{n=1}^{\infty} \sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\frac{2\pi nt}{T}$$

Note that the first term eliminates all of the even harmonics and the second eliminates all multiples of the third harmonic.

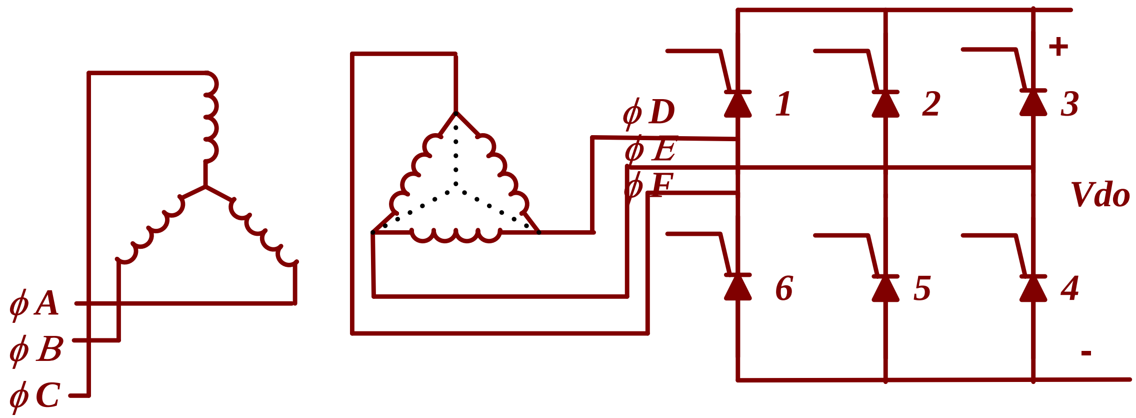
Wye-Wye Primary Current







Harmonic	1	5	7	11	13	15	17	19
Frequency	60	300	420	660	780	900	1020	1140
Amplitude	1.103	-0.221	-0.158	0.100	0.085	0	-0.065	-0.058



In order to have balanced current on the primary

$$I_{A\Delta s} + I_{B\Delta s} + I_{C\Delta s} = 0$$

When two delta leg A switches conduct

$$I_{B\Delta s} = I_{C\Delta s}$$

so that

$$I_{A\Delta s} + 2I_{B\Delta s} = 0$$

The current through the switch is then

$$I_L = I_{A\Delta s} - I_{B\Delta s}$$

$$I_L = I_{A\Delta s} + \frac{1}{2} I_{A\Delta s}$$

$$I_L = \frac{3}{2} I_{A\Delta s}$$

$$I_{A\Delta s} = \frac{2}{3} I_L$$

For a transformer ratio $N_{Y\Delta}$

$$V_{AB\Delta s} = N_{Y\Delta} V_{LNp} \sin(\omega t)$$

$$V_{BC\Delta s} = N_{Y\Delta} V_{LNp} \sin(\omega t - 2\pi/3)$$

$$V_{CA\Delta s} = N_{Y\Delta} V_{LNp} \sin(\omega t - 4\pi/3)$$

$$I_{AB\Delta s} = \left(V_{LNp} / N_{Y\Delta}\right) \sin(\omega t + \phi_Z)$$

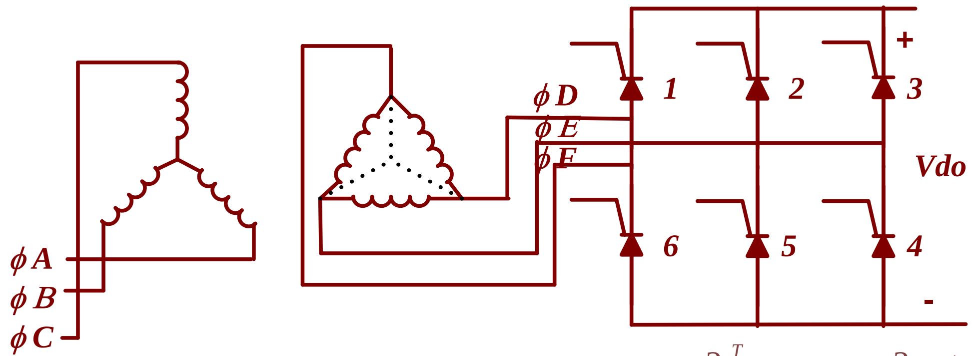
$$I_{BC\Delta s} = \left(V_{LNp} / N_{Y\Delta}\right) \sin(\omega t - 2\pi/3 + \phi_Z)$$

$$I_{CA\Delta s} = \left(V_{LNp} / N_{Y\Delta}\right) \sin(\omega t - 4\pi/3 + \phi_Z)$$

For equal secondary voltages

$$N_{Y\Delta} = \sqrt{3} N_{YY}$$

Wye-Delta Spectrum



The current through the A winding is

$$
\begin{aligned}
I_{A\Delta s}(t) &= I_L/3 && 0 \le t \le T/6 \\
&= 2I_L/3 && T/6 \le t \le T/3 \\
&= I_L/3 && T/3 \le t \le T/2 \\
&= -I_L/3 && T/2 \le t \le 2T/3 \\
&= -2I_L/3 && 2T/3 \le t \le 5T/6 \\
&= -I_L/3 && 5T/6 \le t \le T
\end{aligned}
$$

$$a_0 = a_n = 0$$

Again, by symmetry, only the b_n terms are non-zero

$$b_n = \frac{2}{T}\int_0^T I_{A\Delta s}(t)\sin\frac{2\pi nt}{T}dt$$

$$= \frac{4I_L}{3T}\left[\int_0^{T/6}\sin\frac{2\pi nt}{T}dt + 2\int_{T/6}^{T/3}\sin\frac{2\pi nt}{T}dt + \int_{T/3}^{T/2}\sin\frac{2\pi nt}{T}dt\right]$$

$$= -\frac{2I_L}{3n\pi}\left[\cos\frac{2\pi nt}{T}\bigg|_0^{T/6} + 2\cos\frac{2\pi nt}{T}\bigg|_{T/6}^{T/3} + \cos\frac{2\pi nt}{T}\bigg|_{T/3}^{T/2}\right]$$

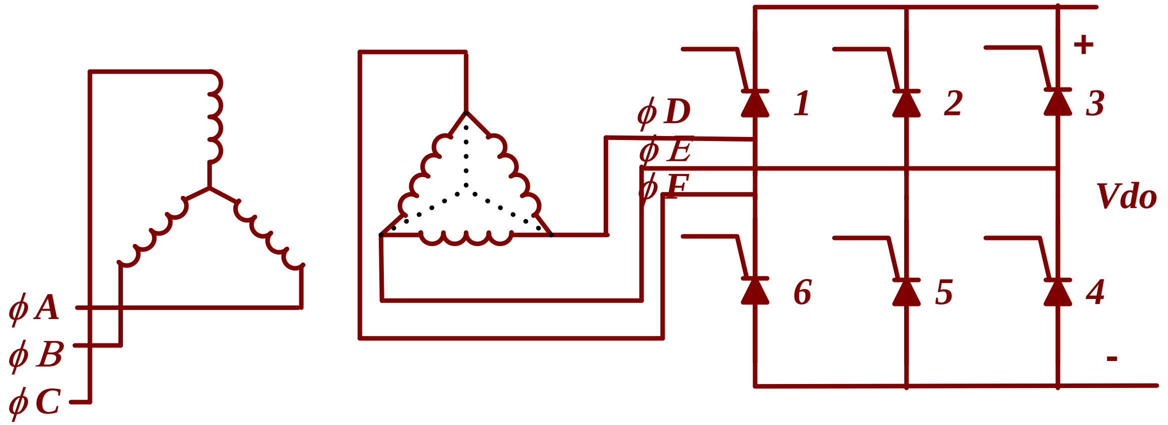
$$= \frac{2I_L}{3n\pi}\left[\left(\cos 0 + \cos\frac{\pi n}{3}\right) - \left(\cos\frac{2\pi n}{3} + \cos\pi n\right)\right]$$

$$= \frac{4I_L}{3n\pi}\left(\cos\frac{n\pi}{6}\cos\frac{n\pi}{6} - \cos\frac{5n\pi}{6}\cos\frac{n\pi}{6}\right)$$

$$= \frac{4I_L}{3n\pi}\cos\frac{n\pi}{6}\left(\cos\frac{n\pi}{6} - \cos\frac{5n\pi}{6}\right)$$

$$= \frac{8I_L}{3n\pi}\cos\frac{n\pi}{6}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}$$

Primary Current in the Wye-Delta



$$I_{A\Delta s}(t)=\frac{8I_L}{3n\pi}\sum_{n=1}^{\infty}\cos\frac{n\pi}{6}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\frac{2\pi nt}{T}$$

Note that multiples of the 2^{nd} and 3^{rd} harmonics are also suppressed.

The $\cos\frac{n\pi}{6}$ *term does not introduce any extra zeros, but it does contribute to the sign of the terms.*

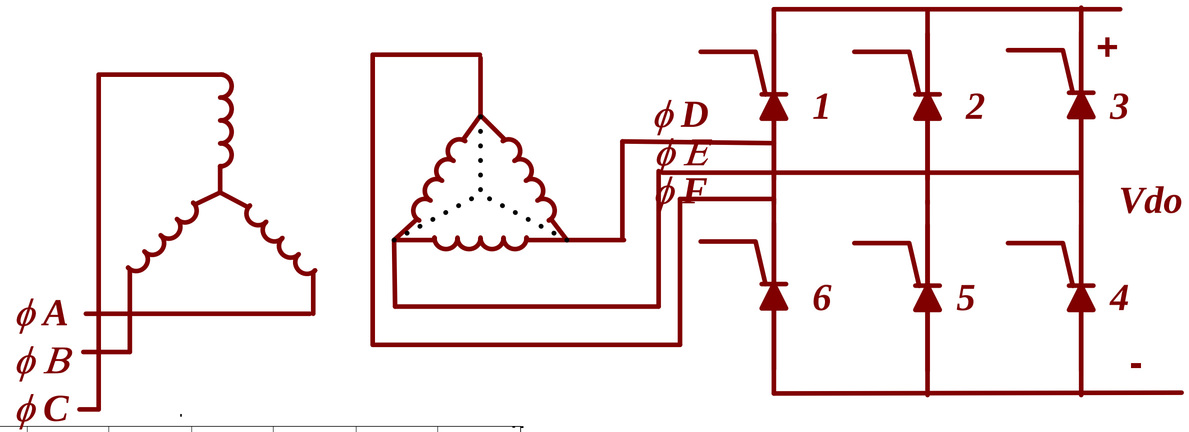
The non-vanishing terms are $n=1,5,7,11,\cdots$, *for which the magnitude is* $\sqrt{3}/2$.

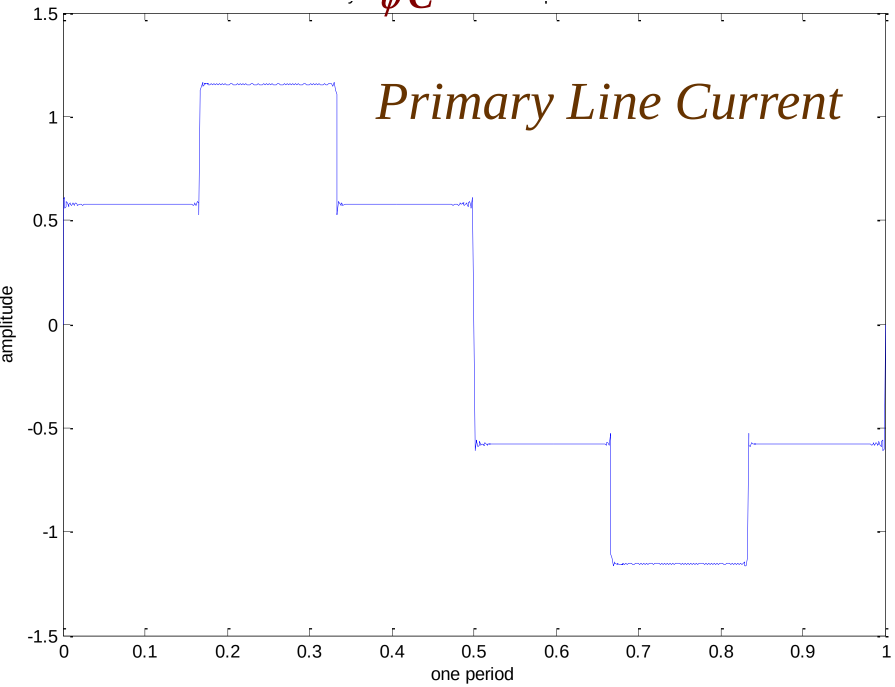
Referred back to the primary, the current is

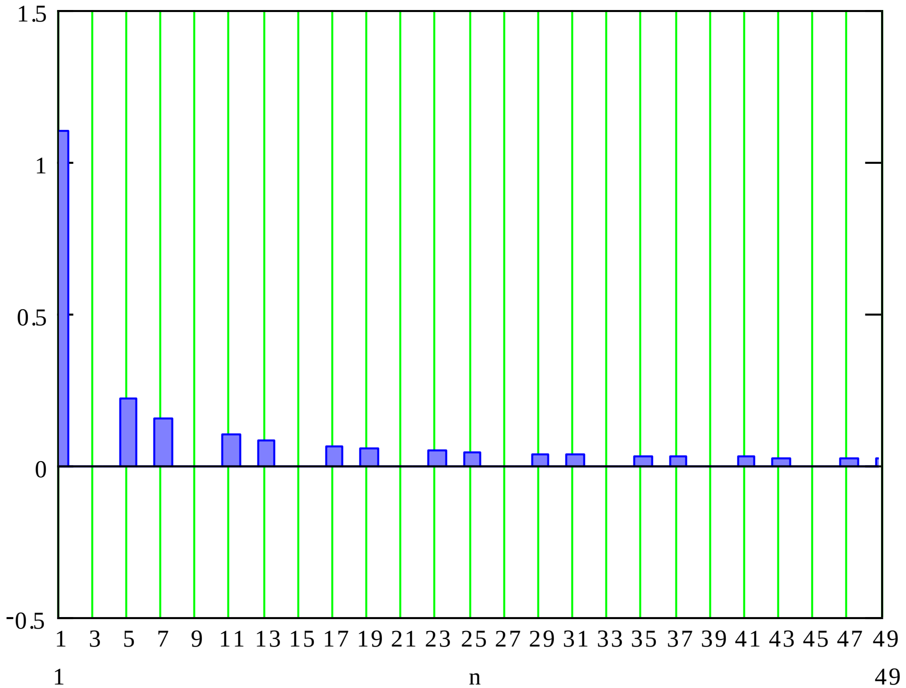
$$I_{A\Delta p}(t)=N_{Y\Delta}\frac{8I_L}{3n\pi}\sum_{n=1}^{\infty}\cos\frac{n\pi}{6}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\frac{2\pi nt}{T}$$

$$I_{A\Delta p}(t)=N_{YY}\frac{8\sqrt{3}I_L}{3n\pi}\sum_{n=1}^{\infty}\cos\frac{n\pi}{6}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\frac{2\pi nt}{T}$$

Primary Current in the Wye-Delta

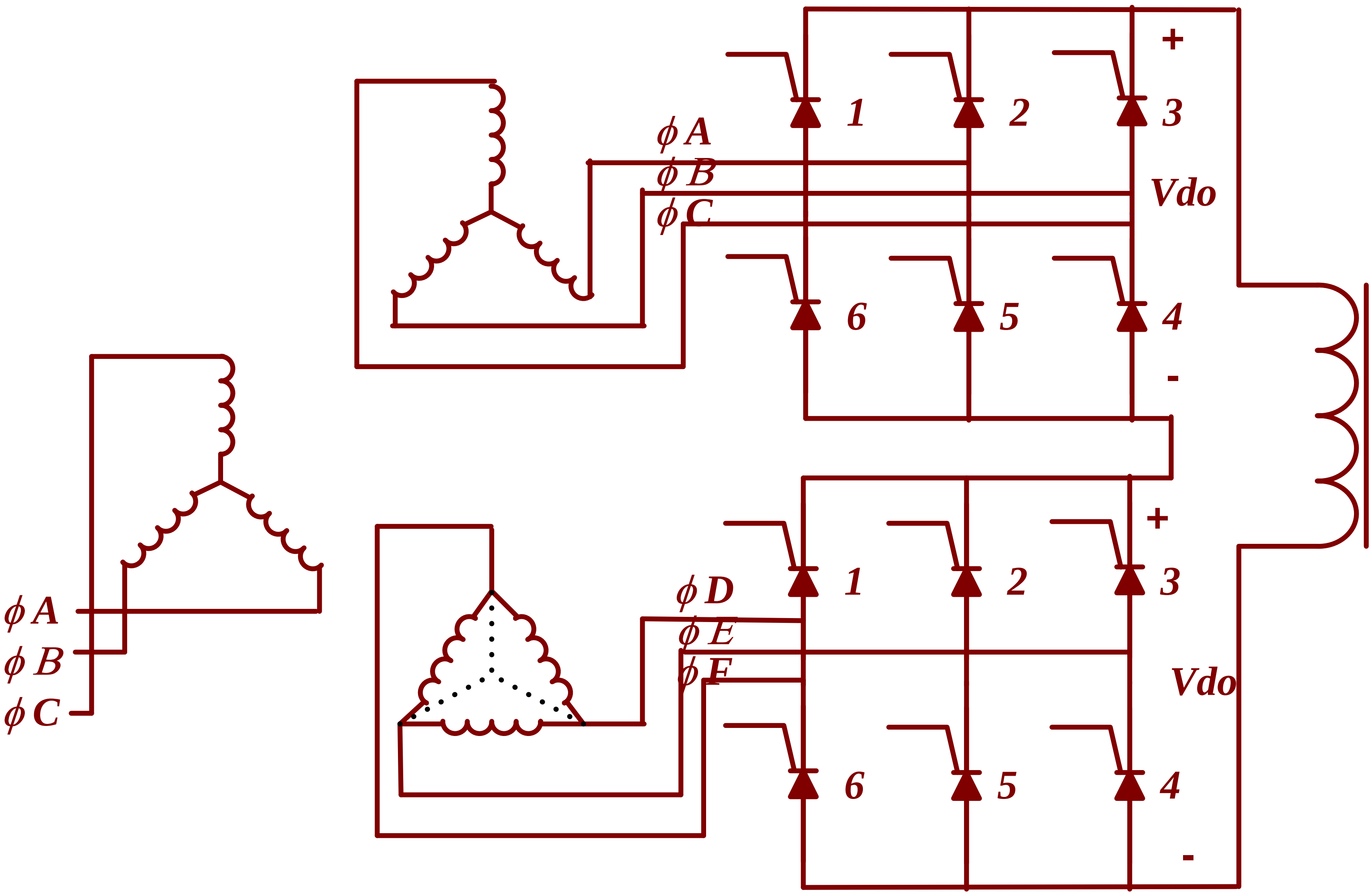






Harmonic	1	5	7	11	13	15	17	19
Frequency	60	300	420	660	780	900	1020	1140
Amplitude	1.103	0.221	0.158	0.100	0.085	0	0.065	0.058

Total Current (Primary Wye Current) in Wye-Wye-Delta



Total Primary Current in Wye-Wye-Delta

The total current in the A leg of the primary is the sum of these two terms.

$$I_{Ap}\left(t\right) = I_{ANYp}\left(t\right) + I_{A\Delta p}\left(t\right)$$

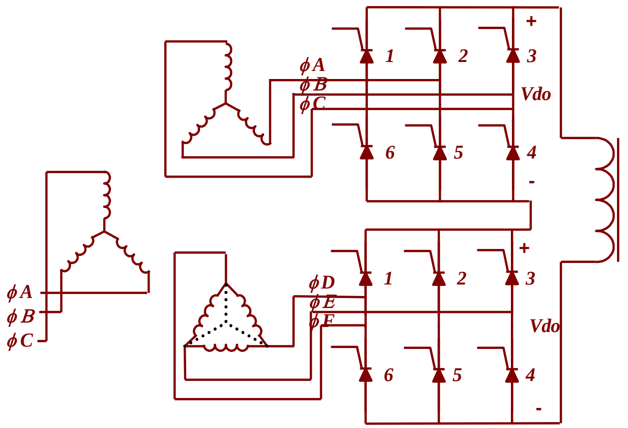
The only non-vanishing terms in both of these series are $n = 1,5,7,11$

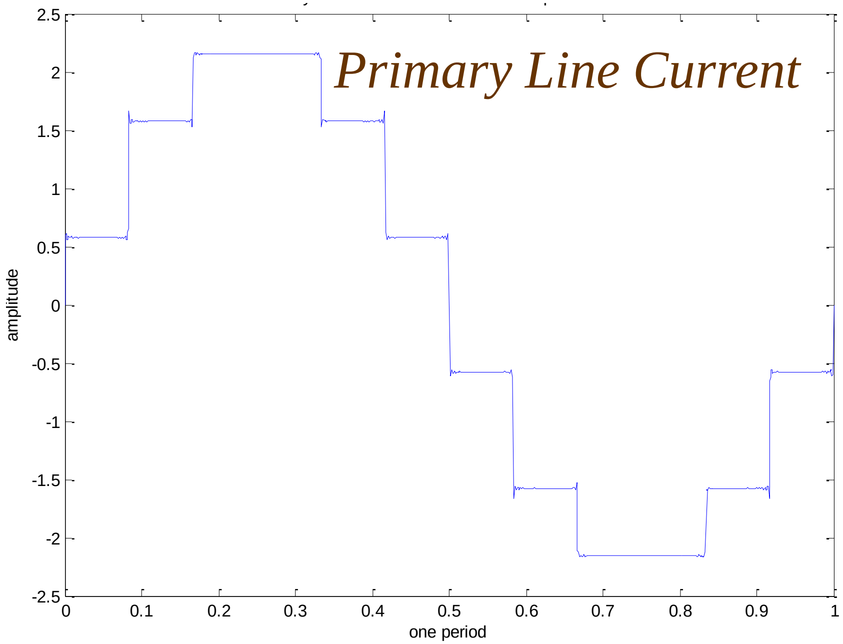
and all other values of n which have the same phase

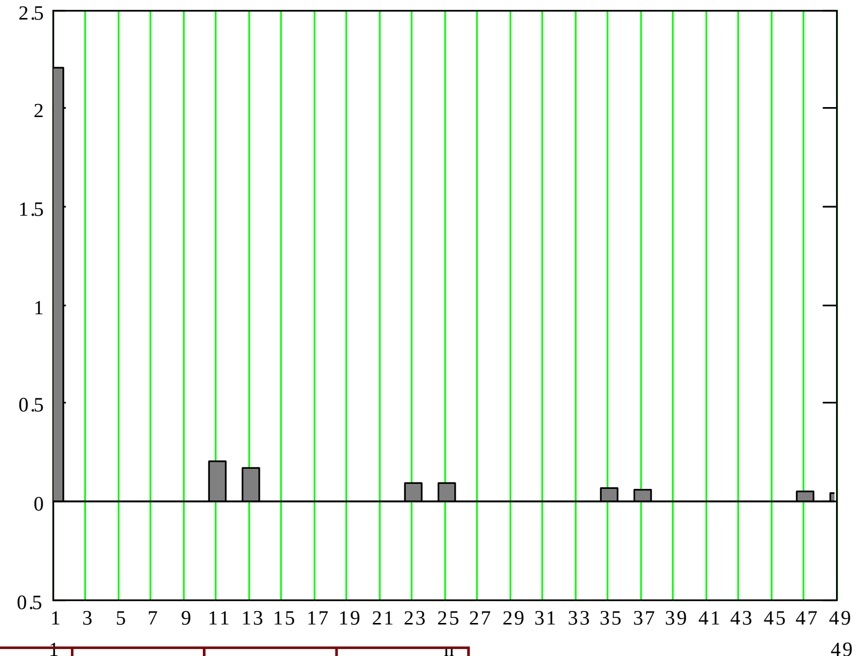
The values of $\cos\frac{n\pi}{6}$ *for these n are* $\frac{\sqrt{3}}{2},-\frac{\sqrt{3}}{2},-\frac{\sqrt{3}}{2},\frac{\sqrt{3}}{2}$

The surviving terms in each series have the same magnitude, but half have different signs so that the only remaining harmonics in the total balanced 12 pulse bridge are $n = 1,11,13,23,25,35,\cdots$ *with coefficient* $N_{YY}\frac{4I_L}{n\pi}$

Total Primary Current in Wye-Wye-Delta

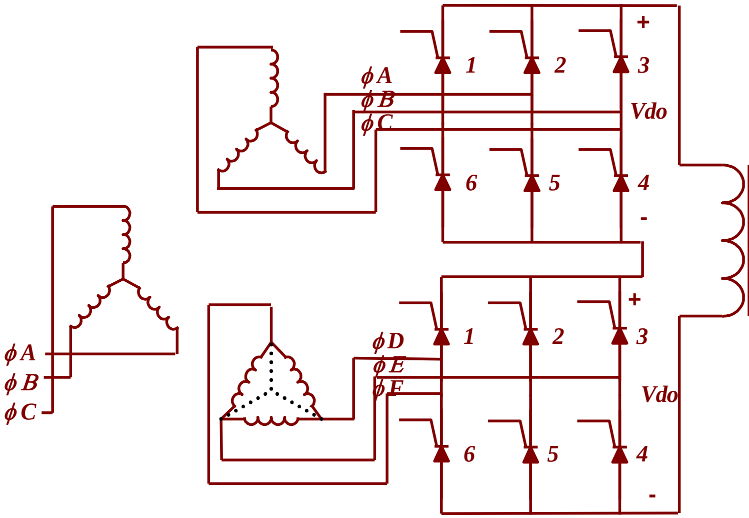


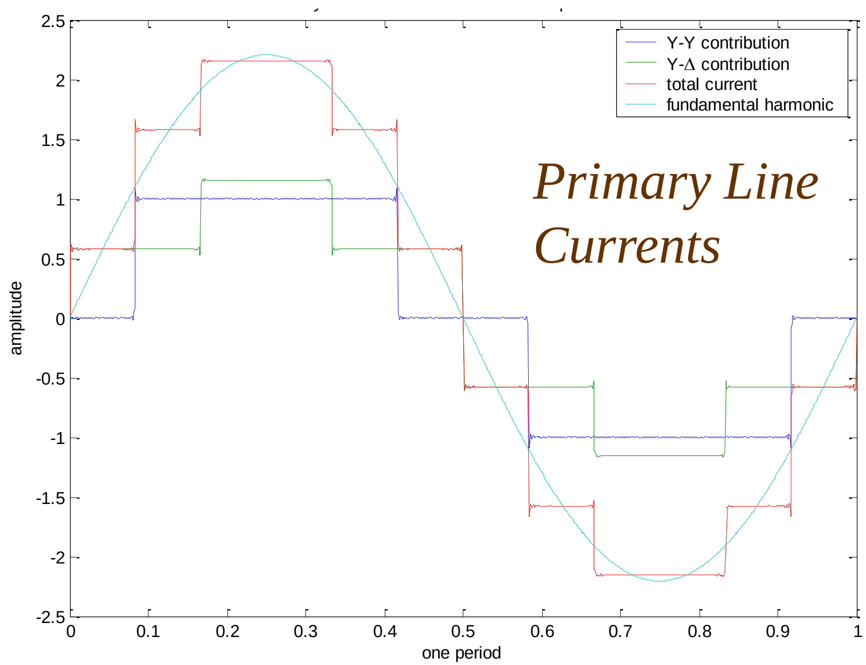




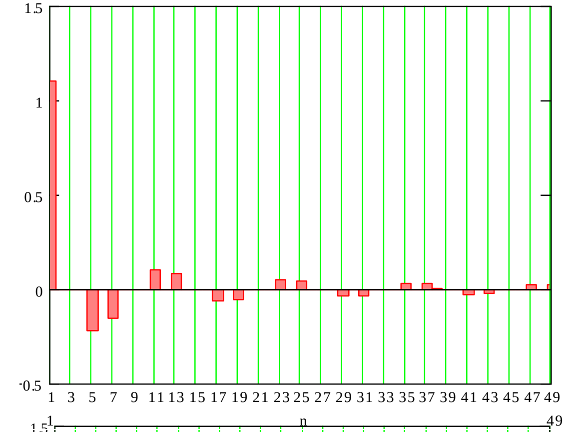
Harmonic	1	5	7	11	13	15	17	19
Frequency	60	300	420	660	780	900	1020	1140
Amplitude	2.205	0	0	0.200	0.085	0.170	0	0

Total Primary Current in Wye-Wye-Delta

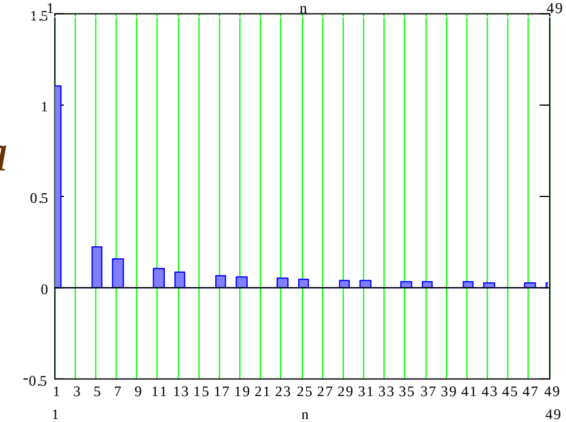




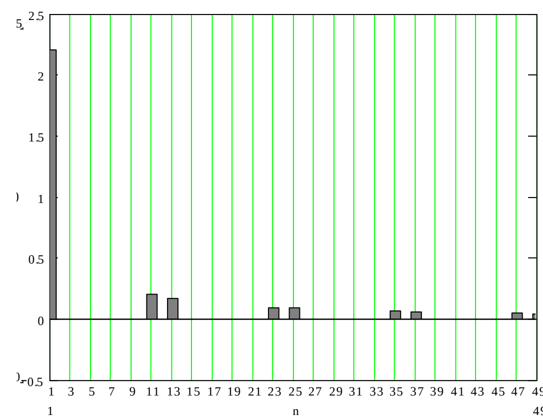
Wye-Wye



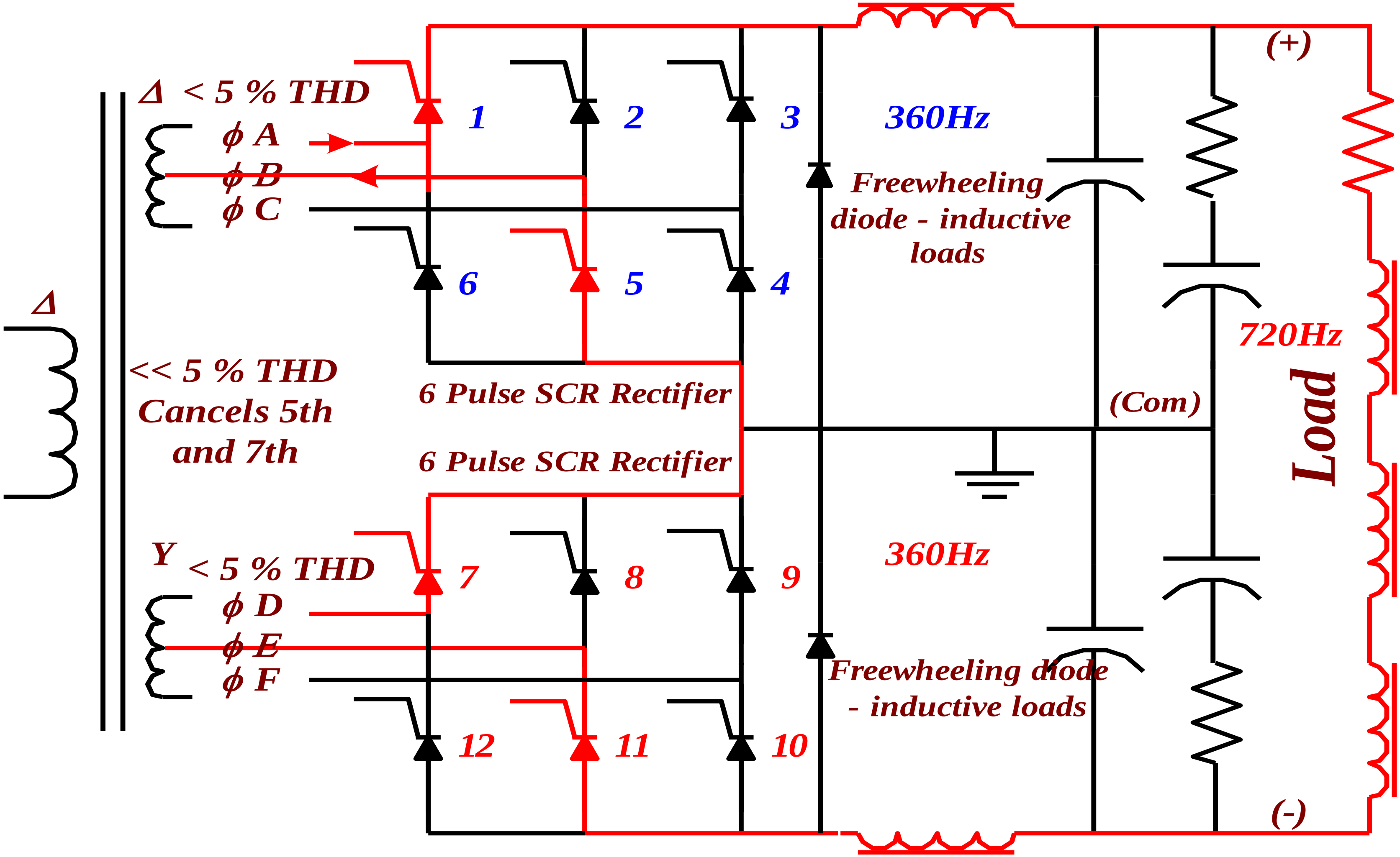
Wye-Delta



Wye-Wye-Delta



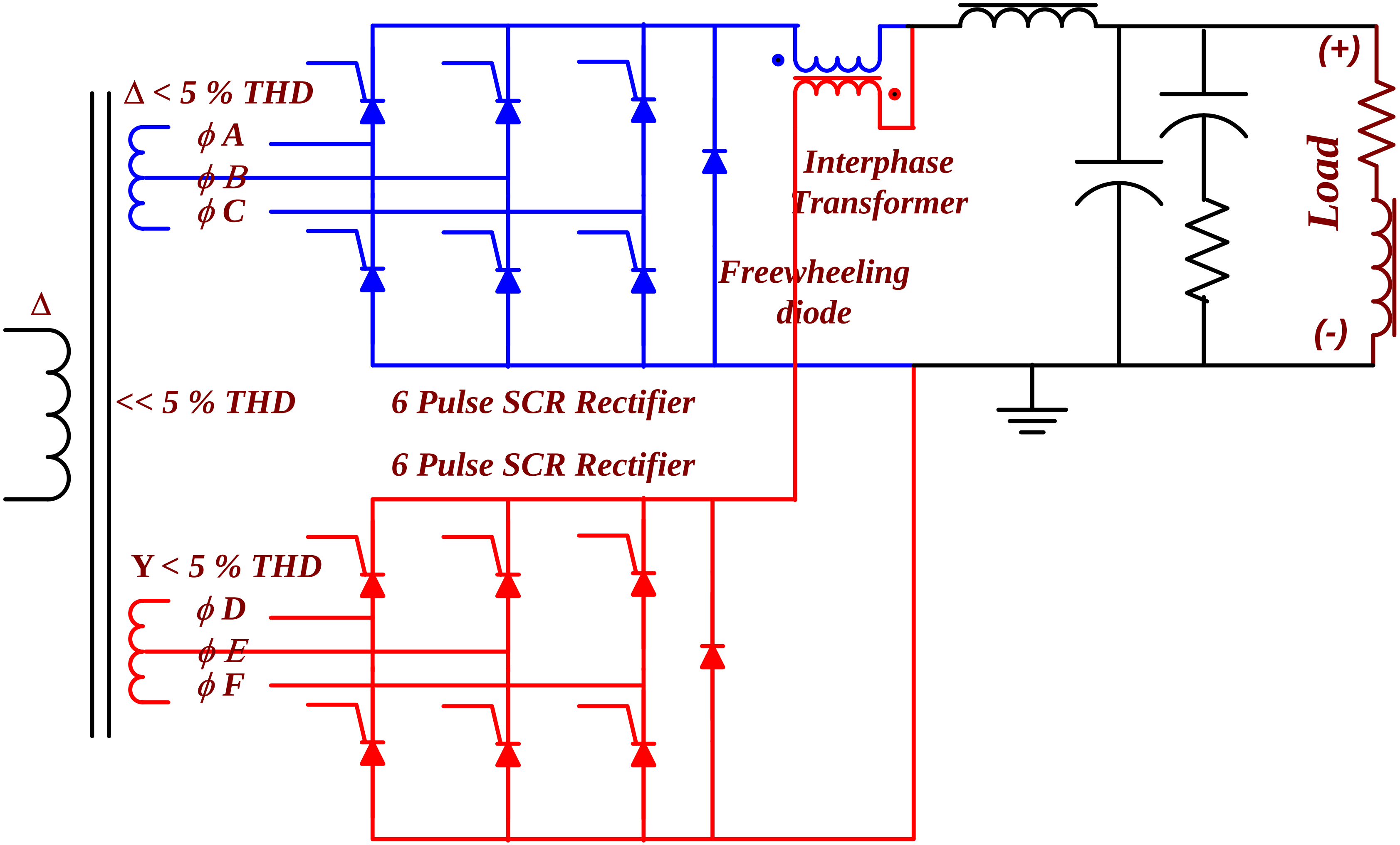
6 ϕ, q = 12 Pulse By Series Bridges



SCR sequence for 30^O lagging wye secondary

1-5, 7-11, 1-4, 7-10, 2-4, 8-10, 2-6, 8-12, 3-6, 9-12, 3-5, 9-11

6 ϕ, q = 12 Pulse By Parallel Bridges



Transformer phases and SCR firing sequence are the same as shown for the series-connected bridges

$6\ \phi$, q = 12 Pulse Rectifiers - Summary

For Both Series And Parallel-Connected Bridges

- *Input transformer Δ primary, $\Delta - Y$ secondaries for 6 AC phases*
- *Δ - Y secondaries are phase shifted 30^O*
- *5^{th} and 7^{th} harmonics virtually non-existent in input line, << 5 % THD of line voltage < 20 % THD of line current*
- *Very high input PF to 0.97*
- *Output ripple frequency is 720 Hz for 60 Hz input*
- *Use soft-start to limit filter capacitor inrush current*
- *Freewheeling diode for to allow lagging bridge to conduct*
- *For loads $\geq$ 350 kW*

6 ϕ, q = 12 Pulse Rectifiers - Summary

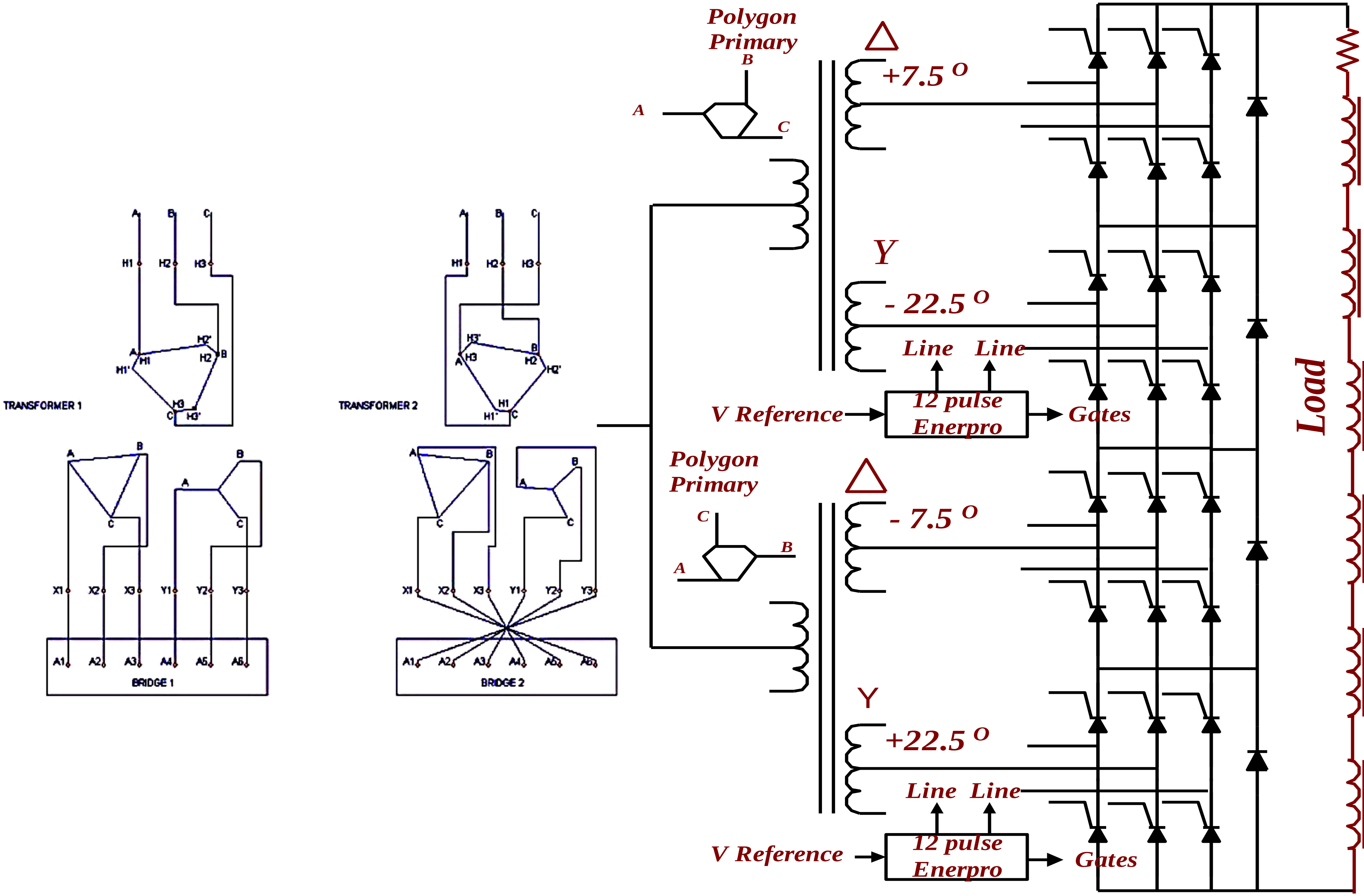
Series-connected bridges

- *For high-voltage, low-current loads*

Parallel-connected bridges

- *For high-current, low-voltage loads $\geq$ 350 kW.*
- *Inter-phase transformer needed for current sharing*

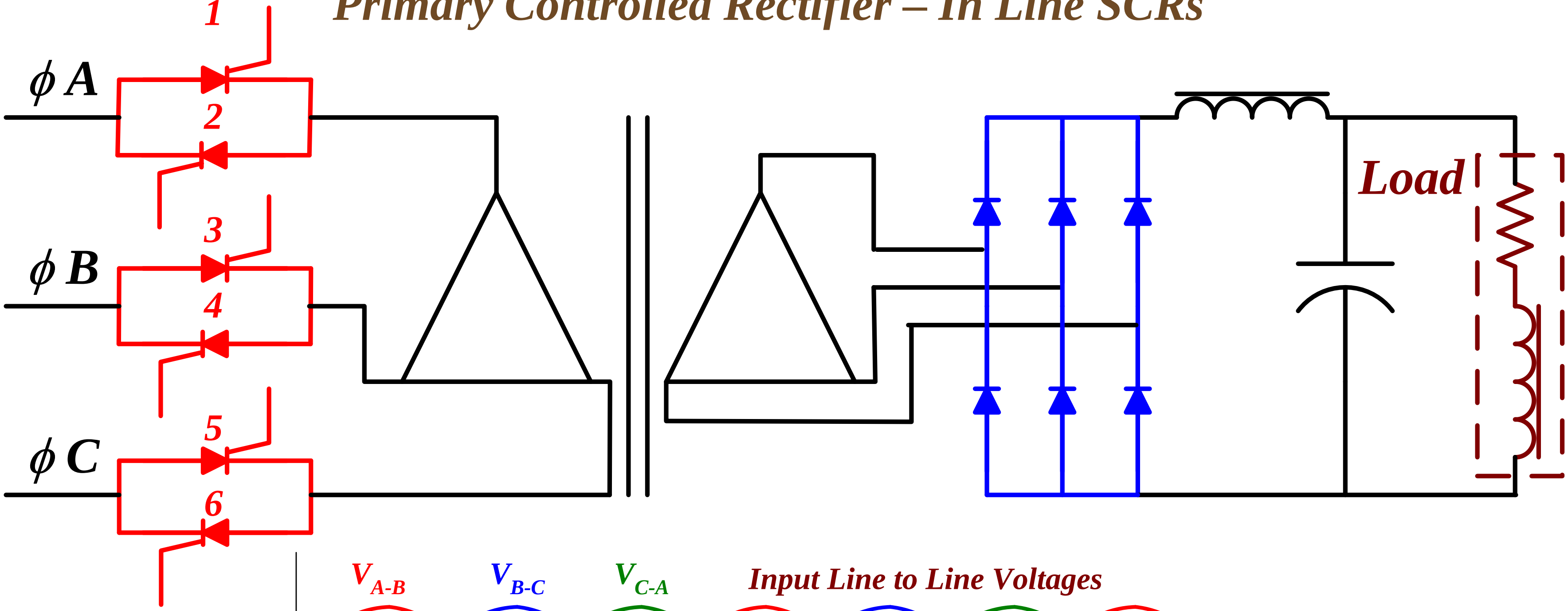
12 ϕ, q = 24 Pulse Rectifier

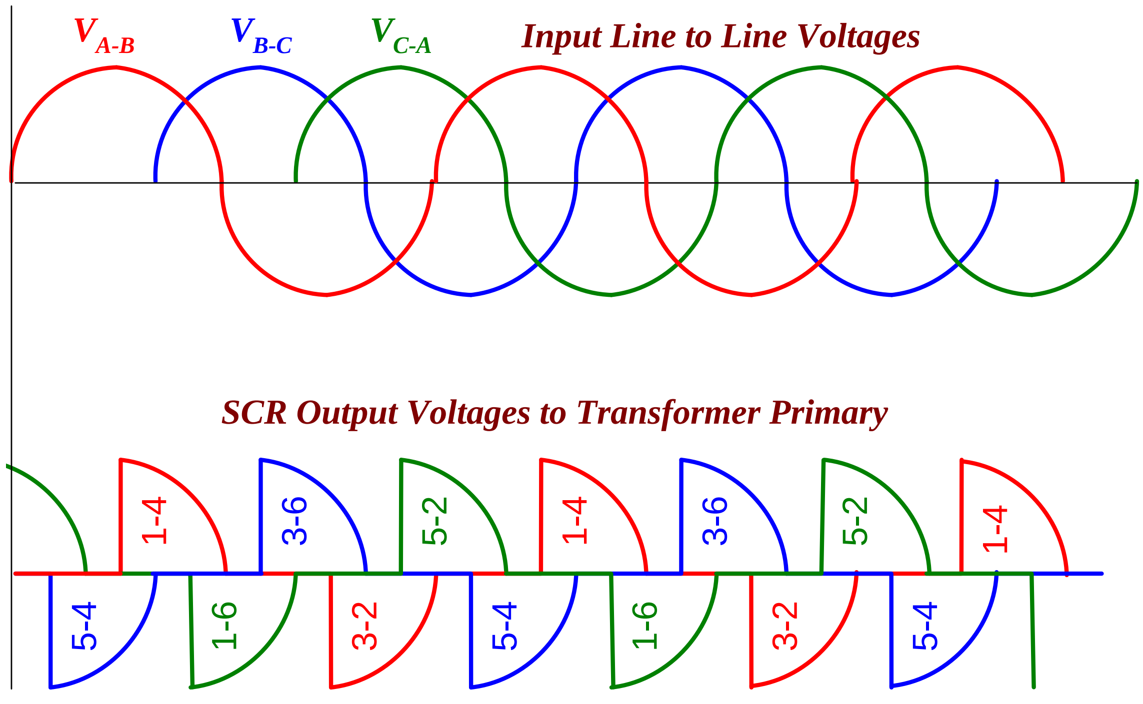


12 ϕ, q = 24 Pulse Rectifier Summary

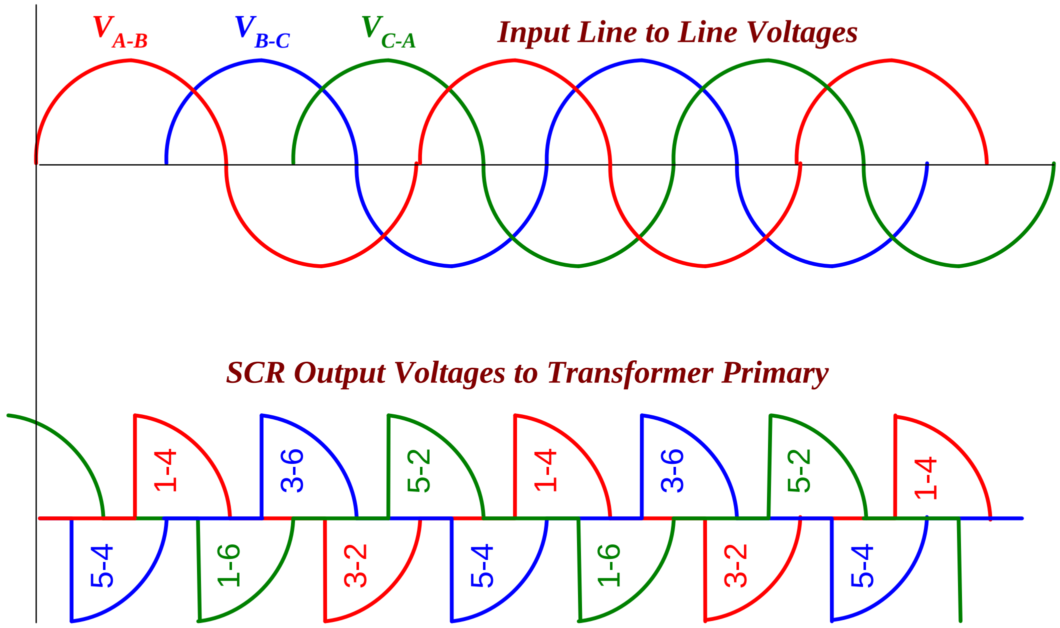
- *Input transformer polygon primary to + 7.5^{O} Δ – Y secondaries for -30^{O} shift*
- *Input transformer polygon primary to - 7.5^{O} Δ – Y secondaries for +30^{O} shift*
- *15^{O} shift between the 4 sets of bridges*
- *For loads $\geq$ 1 MW DC or Pulsed*

Primary Controlled Rectifier – In Line SCRs





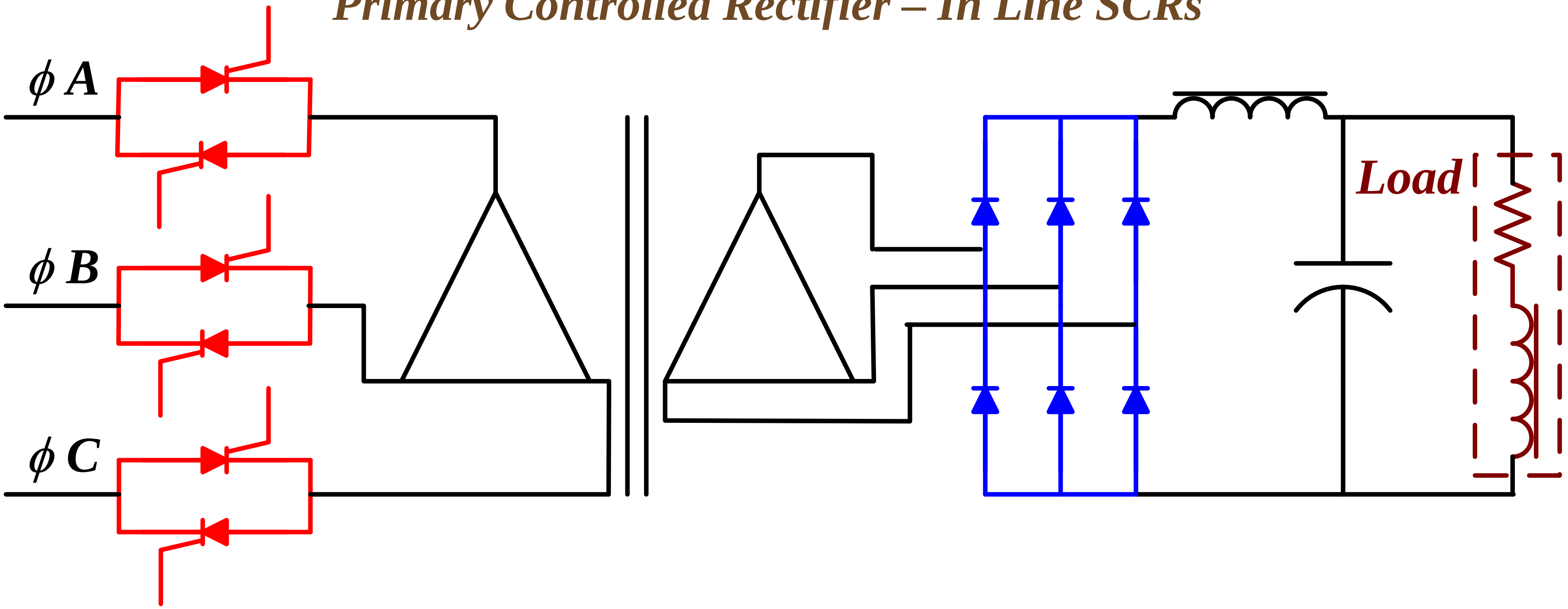
Primary Controlled Rectifier – In Line SCRs



$$V_{RMS} = \sqrt{\frac{1}{\omega T}\int_{\alpha}^{\omega T} \sqrt{2}\, V_{LL} \sin^2 \omega t \; d\omega t}$$

$$V_{do} = \frac{3\sqrt{2}\, V_{RMS}}{\pi} * N$$ *where N is the transformer secondary to primary voltage ratio*

Primary Controlled Rectifier – In Line SCRs



Advantage Compared To Secondary Control

- *Keep SCR controls out of the HV and HV oil*

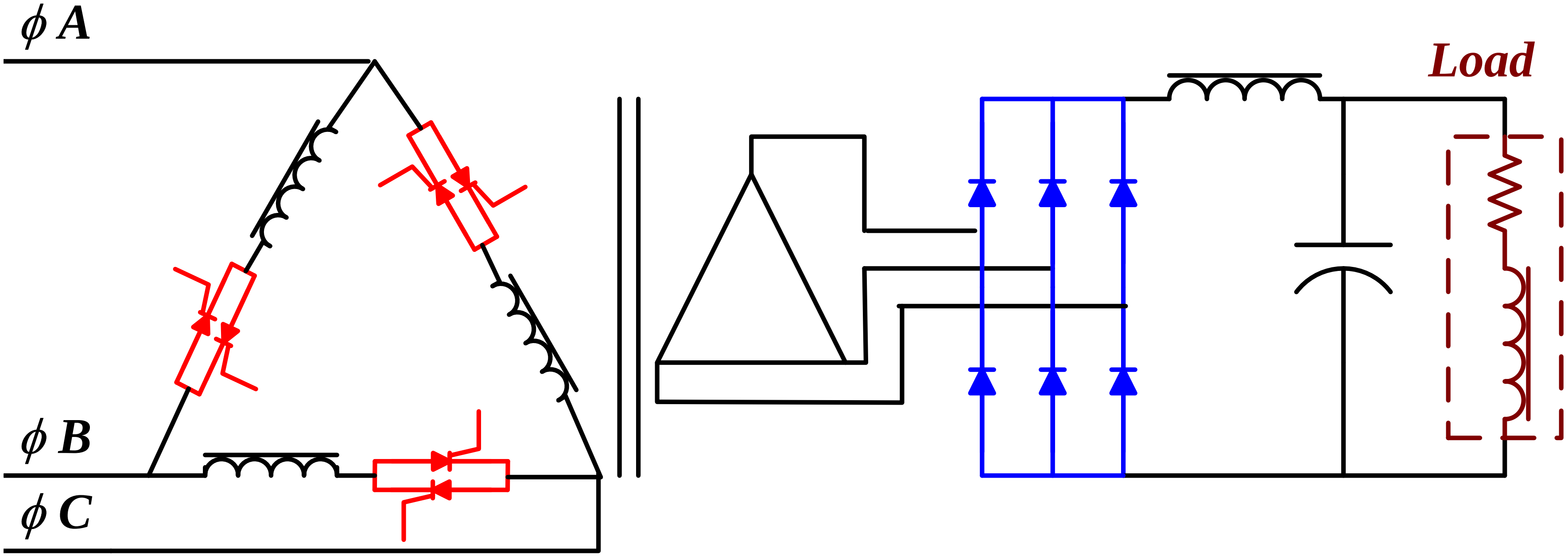
Disadvantage Compared To secondary Control

- *Twice the semiconductors mean higher losses and lower efficiency*

Similarities

- *PF*
- *Input / output harmonics*
- *Output ripple frequency*

Primary Controlled Rectifier – In Delta SCRs



Advantage Compared To In Line SCRs

- $\frac{1}{\sqrt{3}}$ *lower SCR current and power (SCR on-voltage is constant)*

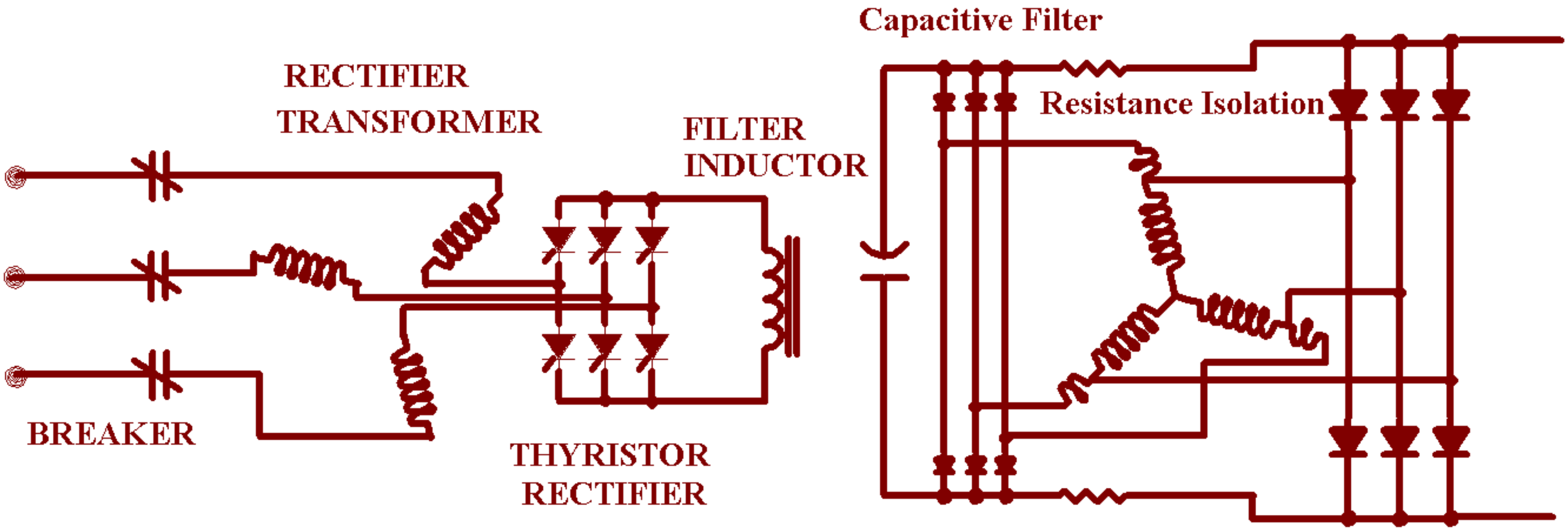
Disadvantage

- *Transformer wiring more complex*

Similarities

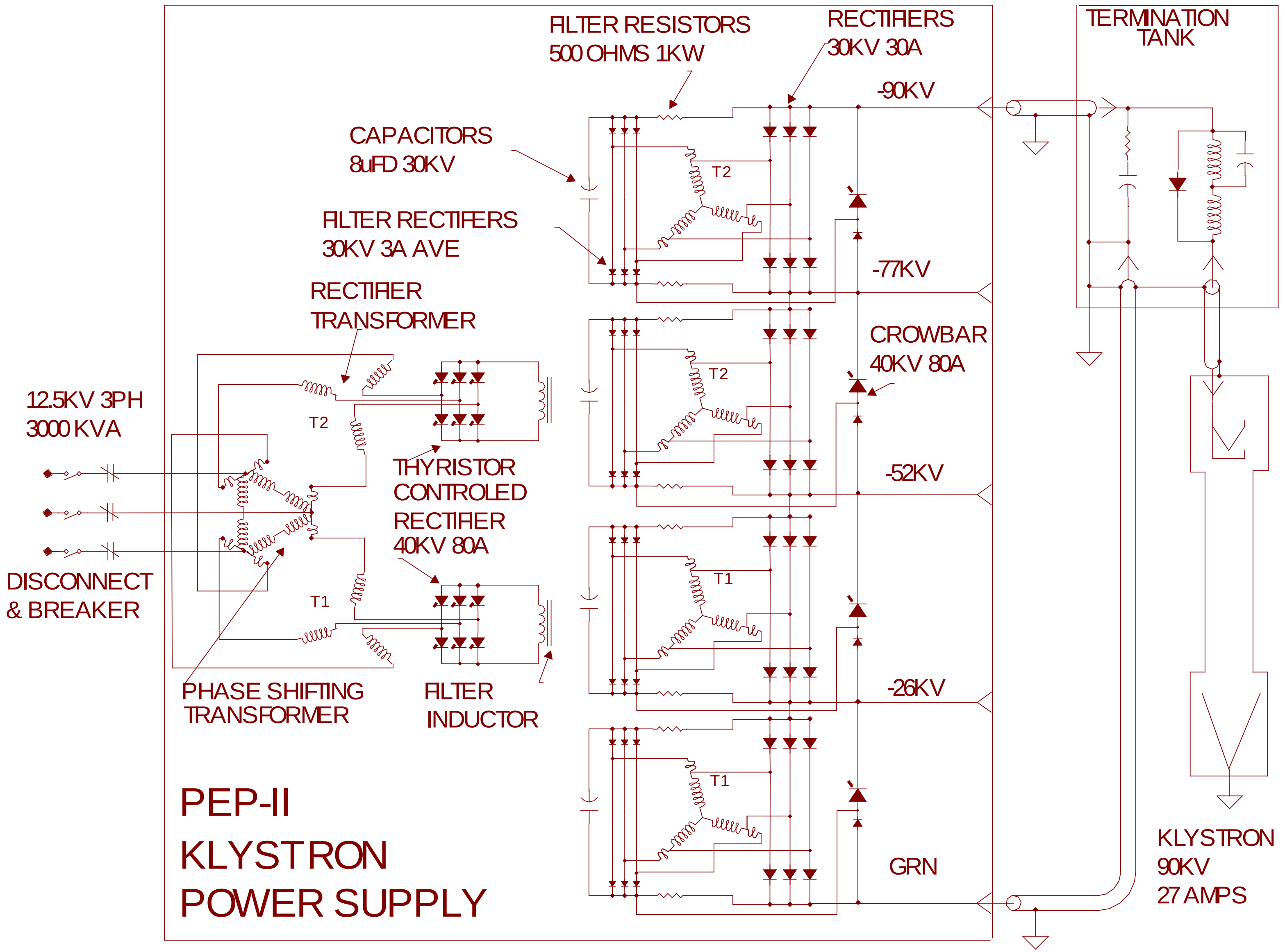
- *Other characteristics similar to In Line SCR controller*

6 Pulse SCR Star Point Rectifier



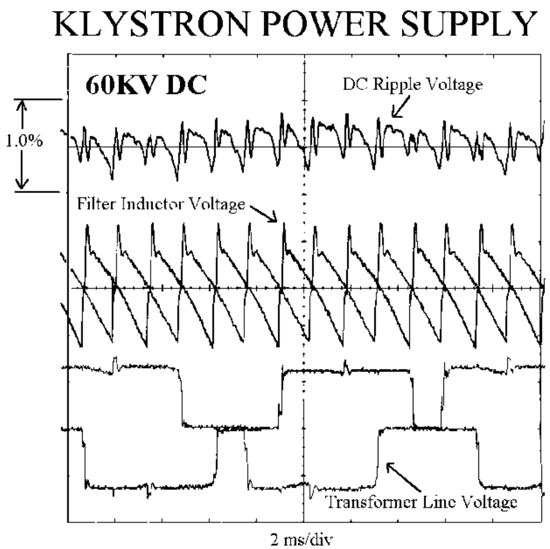
- *Primary SCR in open wye with filter inductor in lower voltage primary*
- *High voltage secondary with diodes and filter capacitor isolated from main load*
- *Protected against secondary faults. High output impedance, capacitor bank isolated from load*
- *Secondary uses diodes only.*

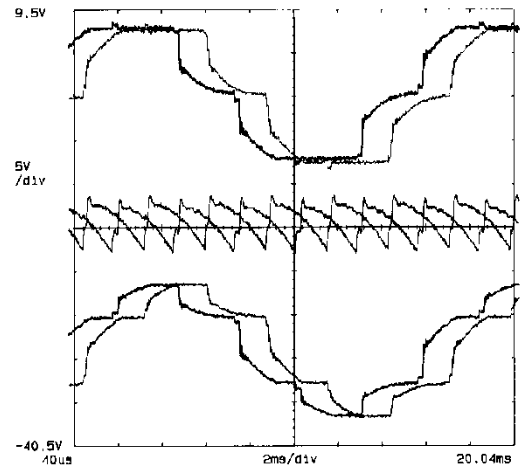
Multi-Phase SCR Star Point Rectifier with Isolated filter



6 Phase SCR Star Point Rectifier

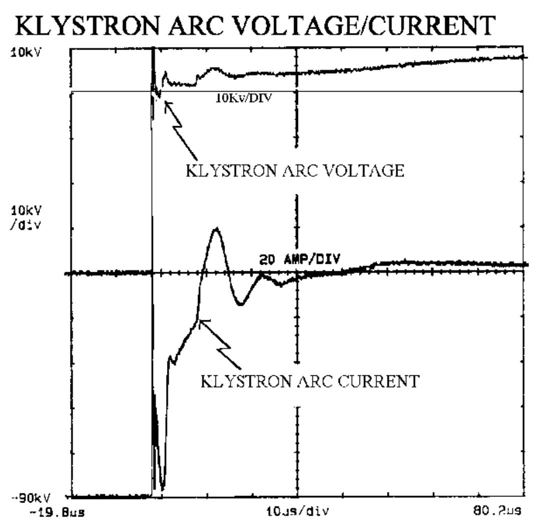
- *Large Joules under Load with Fault from filter Capacitor and Inductor*

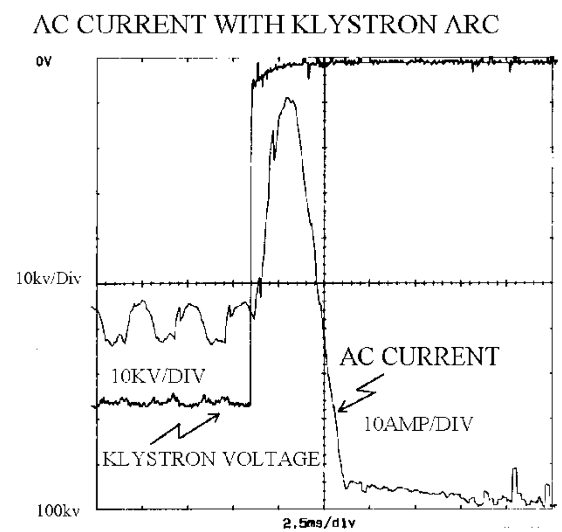




- *Large Joules under Load Fault from filter Capacitor*

- *Low Joules under Fault*
- *Filter Loss V_{max}* I_{ripple} or ~ 5% of Load*





- *Low Joules under Fault*
- *Filter Loss 5% Vmax* Iripple or ~0.03% of Load*

Rectifiers - SCR Gate Firing Boards

Enerpro FCOP-1200

- 12 pulse operation
- 900 VAC L-L
- Soft start and stop
- Phase loss detection
- Instant gate inhibit
- Phase reference sense

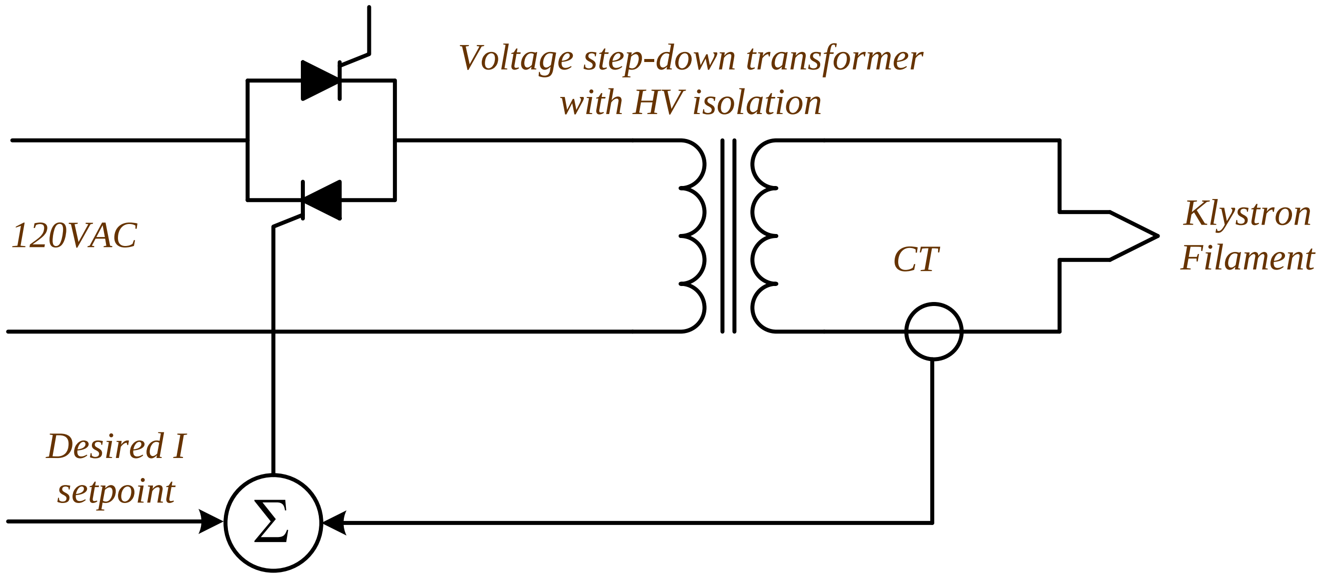
http://www.enerpro-inc.com

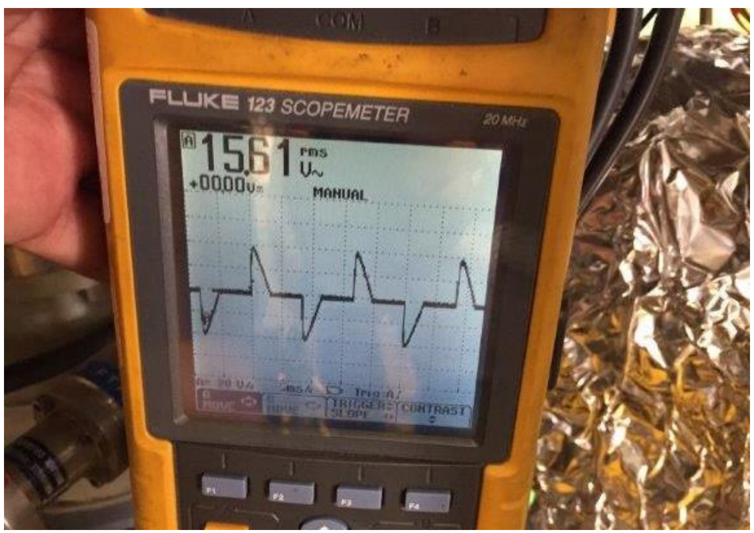
AC Controllers for Filament Power

- *Klystron filaments need power. In some situations, DC power is undesirable. SLAC experience is that DC power can cause certain electrolysis effects that erode the filaments. Hence we sometimes avoid DC and use AC controllers*

- *So we also briefly discuss AC controllers (Variacs and electronic types), their waveforms, and their suitability to power klystron filaments*

- *We must also be aware that in certain situations AC powered filaments surrounded by a DC magnetic field (such as in an electron bean gun) can cause filament flexing and early filament failure from mechanical stress. We need to use DC power for these filaments.*





$$I(\omega t) = I_{pk} \sin \omega t$$

$$I_{RMS} = \sqrt{\frac{1}{\omega T} \int_{\alpha}^{\pi} \left(I_{pk} \sin \omega t\right)^2 d\omega t}$$

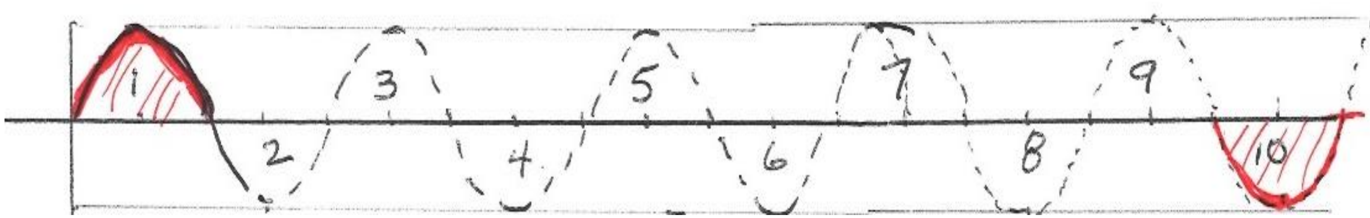
$$I_{RMS} = \frac{I_{pk}}{\sqrt{\pi}} \sqrt{\frac{\pi}{2} - \frac{\alpha}{2} + \frac{1}{4} \sin 2\alpha}$$

•For duty cycles < 50% firing time is two half cycles

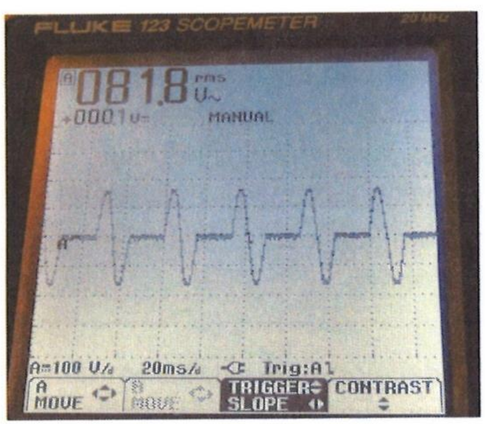
• 50% firing and non-firing time are equal at 2 halves on, 2 halves off

• > 50% non-firing time is one-half cycle

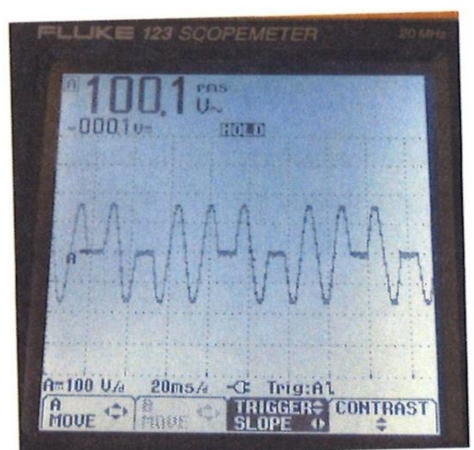
$$I_{RMS} = \frac{\sqrt{\frac{1}{\omega T}\int_0^{\omega T}\left(I_{pk}\sin\omega t\right)^2 d\omega t}}{T_{on}/T_{cycle}}$$



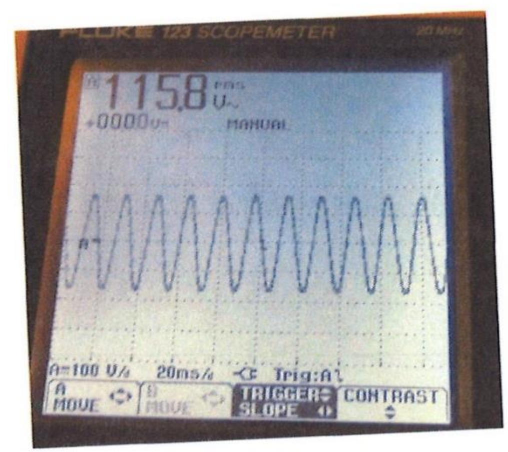
2 on, 8 off, =20% duty cycle   8*8.3ms = 66.4ms off



50%



80%

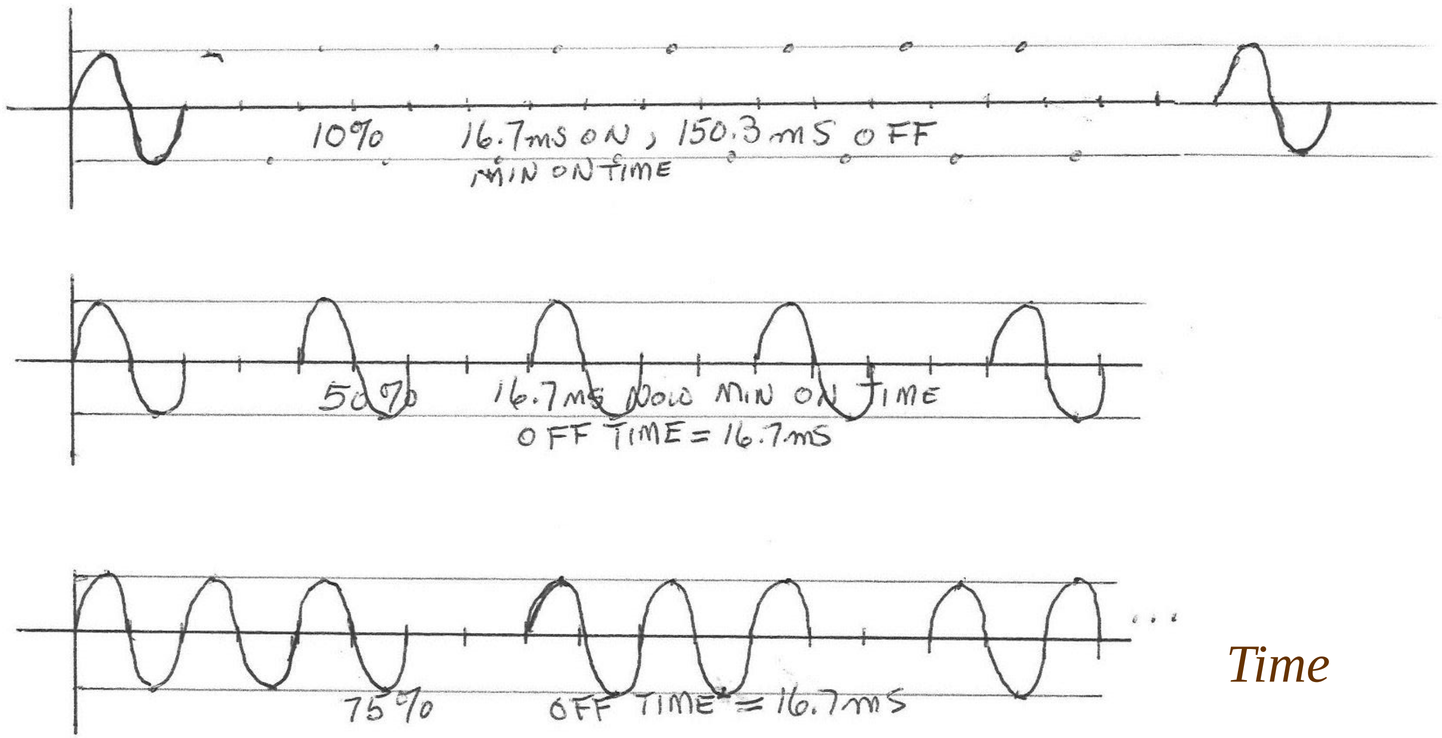


100%

Fixed Amplitude AC Controllers – Variable Burst Firing

- *0 to 50% of set-point, on time is 16.7ms. O**ff time** is varied to achieve control*
- *51% to 100%, **off time** is 16.7ms. Power is controlled by varying the on cycles*

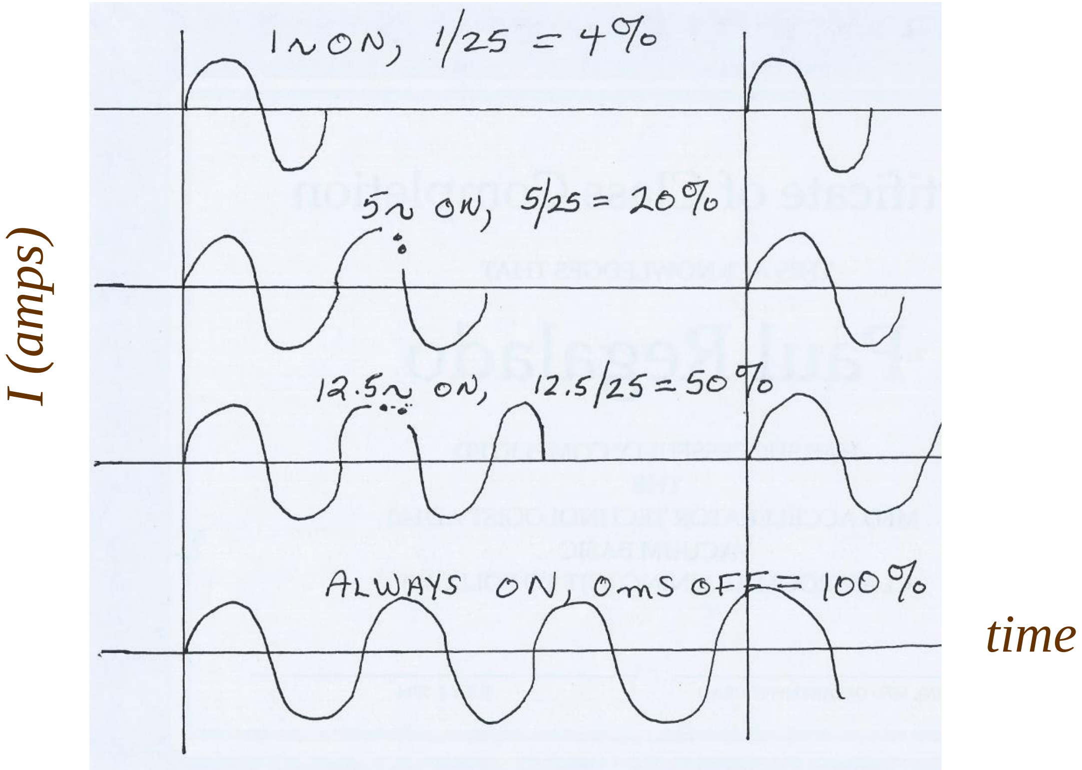
I (amps)



Time

$$I_{RMS} = \frac{\sqrt{\frac{1}{\omega T}\int_0^{\omega T}\left(I_{pk}\sin\omega t\right)^2 d\omega t}}{T_{on}/T_{cycle}}$$

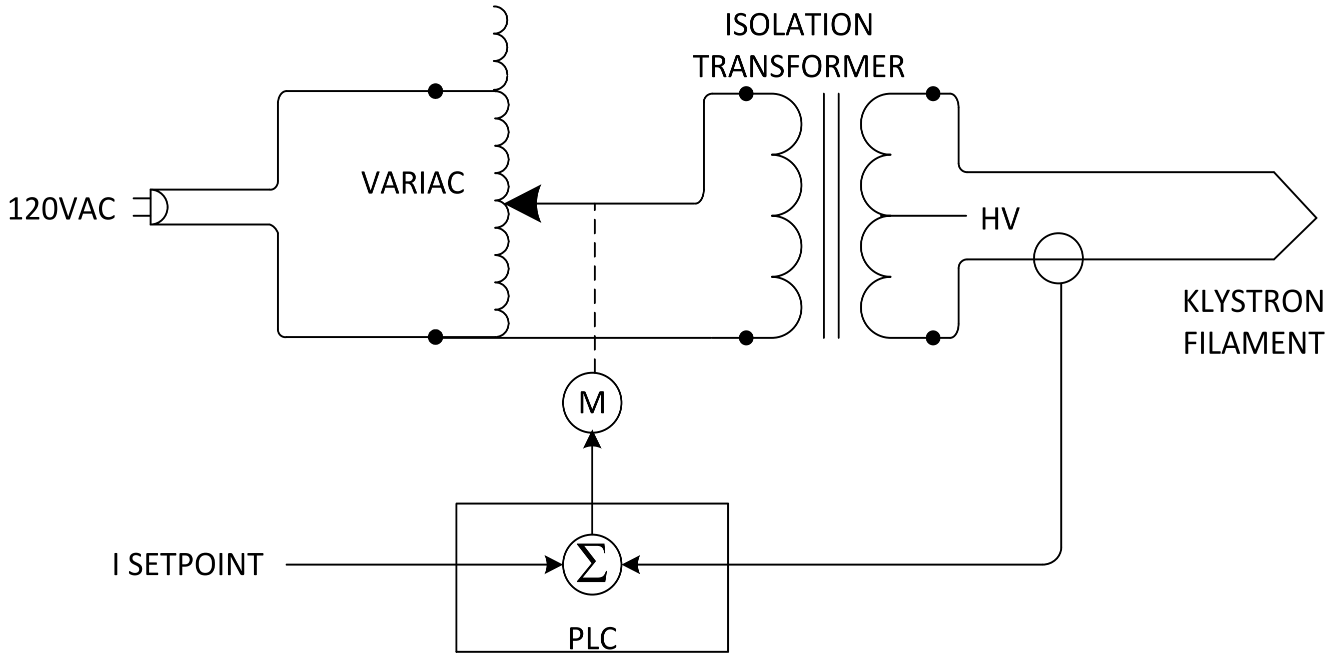
Fixed Cycle Time 25 periods to 1000 periods – Use 25 periods here



$$I_{RMS} = \frac{\sqrt{\frac{1}{\omega T}\int_0^{\omega T}\left(I_{pk}\sin\omega t\right)^2 d\omega t}}{T_{on}/T_{cycle}}$$

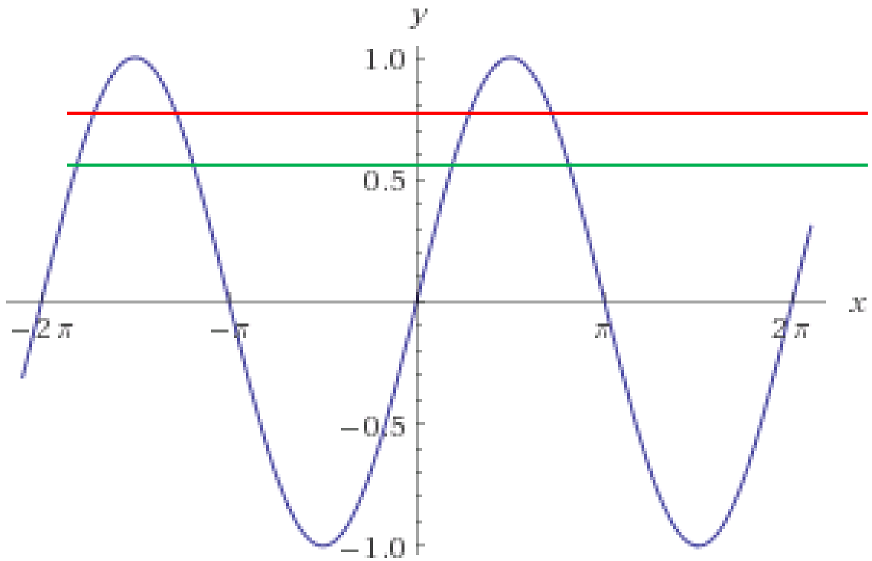
$$T_{cycle} = 25\ periods = 417.5ms$$

Variable Amplitude AC – Variac Controller



Requires motor driven Variac. More maintenance than solid-state, few manufacturers, difficult to obtain spare parts in future

Variable Amplitude AC Waveform



$$I_{AVG}(DC) = \frac{1}{\omega T}\int_0^{\omega T} I_{pk} \sin \omega t \, d\omega t$$

$$I_{AVG} = 0.636 * I_{pk}$$

$$I_{pk} = 1.57 * I_{AVG}$$

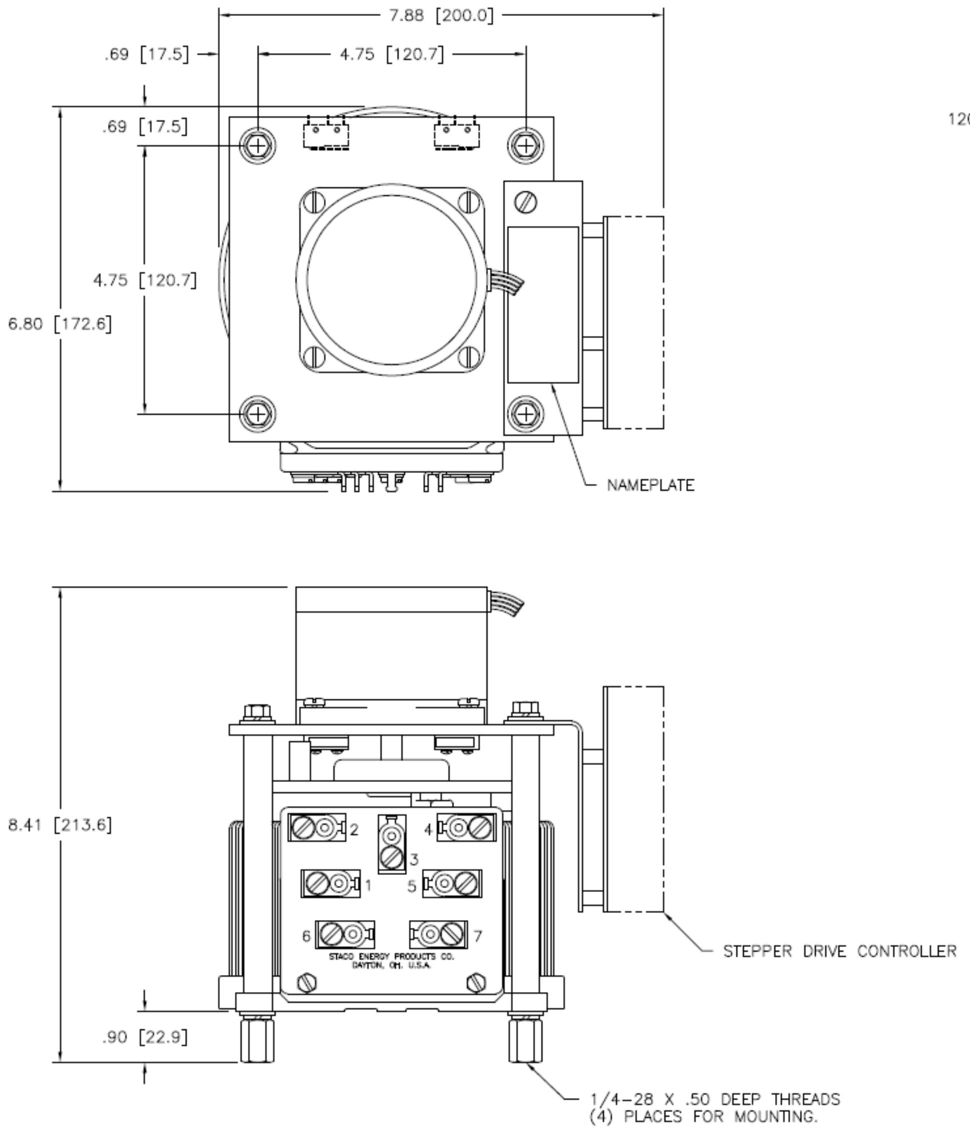
$$I_{RMS} = \sqrt{\frac{1}{\omega T}\int_0^{\omega T} \left(I_{pk} \sin \omega t\right)^2 d\omega t}$$

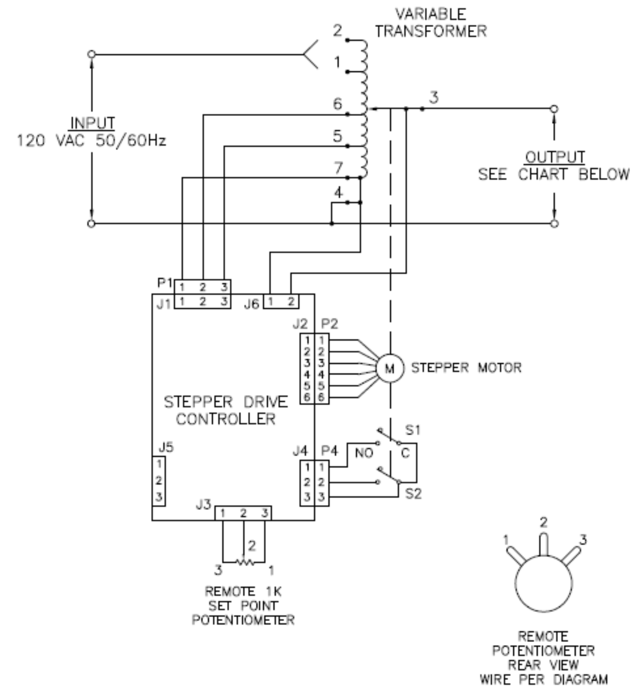
$$I_{RMS} = \frac{I_{pk}}{\sqrt{2}}$$

$$I_{pk} = 1.41 * I_{RMS}$$

- *Sinusoidal varying current –mechanical and thermal stress on filament*
- *I and V peaks only as large as needed*

REVISIONS			
SYM.	E.C.N.	DATE	APVD.
A	24028	8/18/99	
	CLARIFIED 5VDC NOTE		





SET POINT ADJUSTMENT:
THE OUTPUT SET POINT MAY BE ADJUSTED WITH THE REMOTE 1K POTENTIOMETER PROVIDED OR WITH A 0–5 VDC SIGNAL TO THE J3 CONNECTOR ON THE STEPPER DRIVE CONTROL. MAKE CONNECTIONS TO J3–2(+) & J3–3(–). A NOMINAL +5 VDC SETPOINT SUPPLY IS AVAILABLE AT J3–1 (ADJUSTABLE AT TRIMPOT R22).

SPECIFICATIONS									
WIRING	INPUT		OUTPUT					TERMINAL CONNECTIONS	
	VOLTS	HERTZ	VOLTS	CONSTANT CURRENT LOAD		CONSTANT IMPEDANCE LOAD			
				MAX. AMPS	MAX. KVA	MAX. AMPS	MAX. KVA	INPUT	OUTPUT
SINGLE PHASE	120	50/60	0–120	15	1.80	20	2.40	2–4	4–3
			0–140	15	2.10	–	–	1–4	4–3

TITLE: SPEC. CONTROL DRAWING STEPPER DRIVEN VARIABLE TRANSFORMER MODEL SD1510

STACO ENERGY PRODUCTS CO.
DAYTON, OHIO U.S.A.

DRAWN BY: S.A. SMITH DATE: 12/7/95
SCALE: 1=1 SHEET 1 OF 1
DWG. SIZE: D DWG. NO. 095–1804

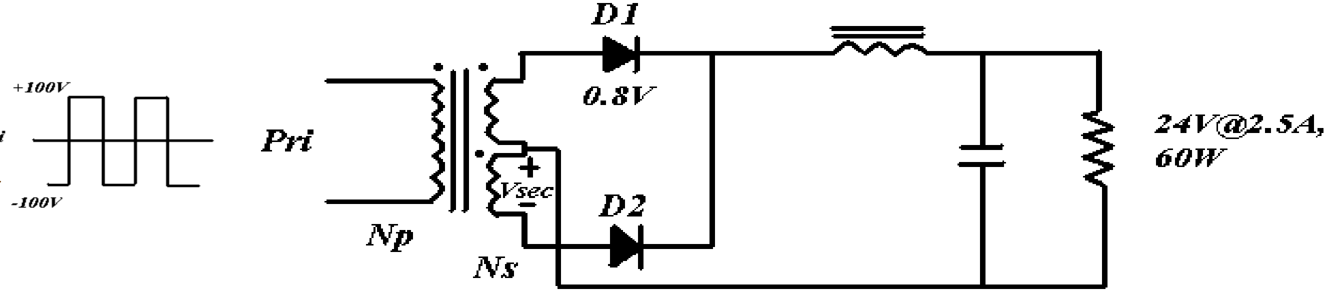
AC Controllers for Filaments

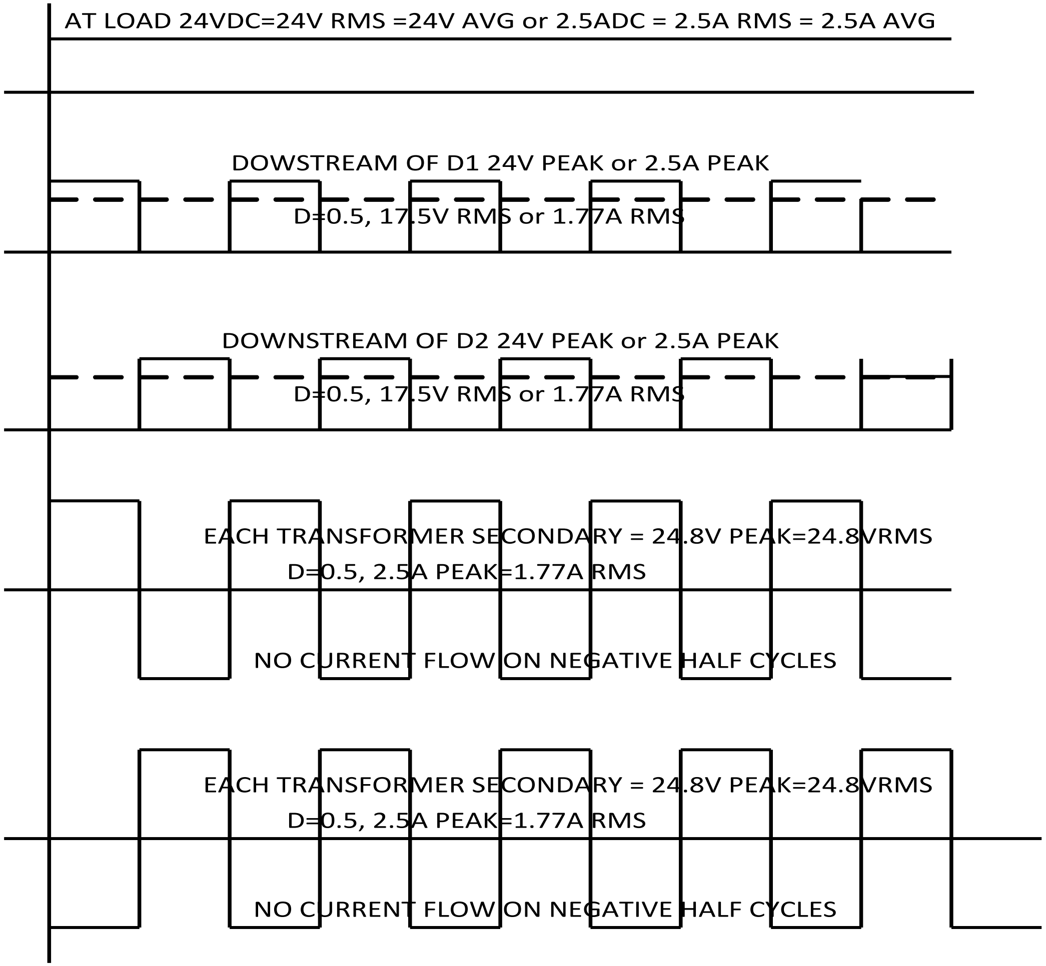
Controller Type	*Type*	*Stress Types*
Variac	*Variable Amplitude AC*	*Least thermal stress from AC current – no off time*
Intelligent half-cycle	*Fixed Amplitude AC*	*Thermal stress from AC current – short off time*
Burst Variable	*Fixed Amplitude AC*	*Thermal stress from AC current – long off time*
Burst Fixed	*Fixed Amplitude AC*	*Thermal stress from AC current – longest off time*
Phase Angle Triggered	*Fixed Amplitude AC*	*Thermal and mechanical stresses from chopped AC current*

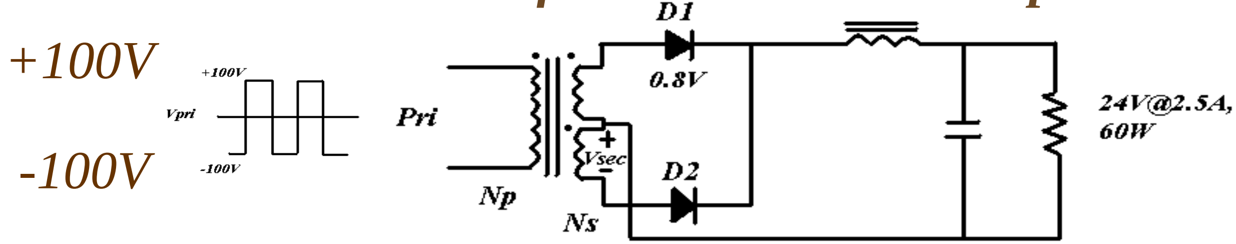
Transformer Primer - Example

+100V

-100V







$$V_{load} = 24VDC = V_{peak} = V_{rms} \quad I_{load} = 2.5A = I_{peak} = I_{rms}$$

$$P_{load} = 24V * 2.5A = 60W$$

$$V_{secrms} = V_{secpeak} * \sqrt{D} = 24.8V * \sqrt{0.5} = 17.5V \; each\; winding$$

$$V_{secrms} = \sqrt{17.5V^2 + 17.5V^2} = 24.8V \; both\; windings$$

$$I_{secrms} = \sqrt{1.77A^2 + 1.77A^2} = 2.5A \; total\; from\; both\; windings$$

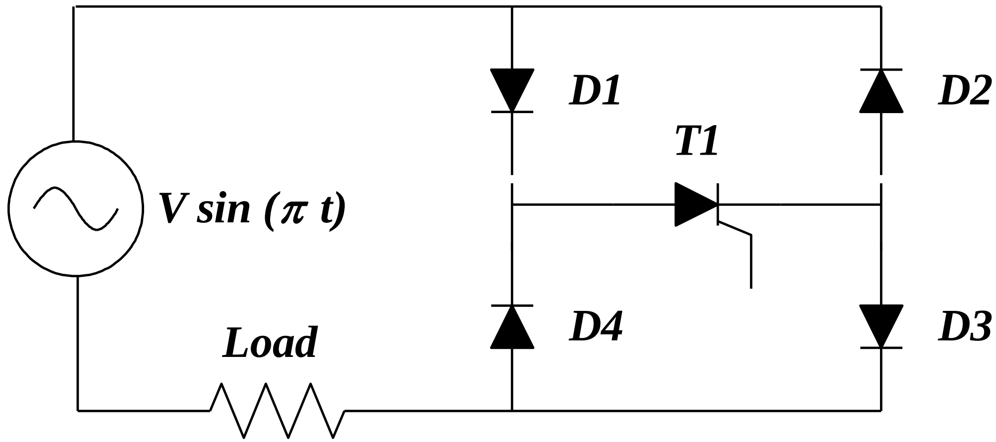
$$P_{sec} = V_{secrms} * I_{secrms} \text{=24.8V*2.5A=62W both secondaries}$$

$$V_{prirms} = V_{pripeak} * \sqrt{D} = 100V * \sqrt{1} = 100V$$

$$I_{prirms} = \frac{V_{rmssec}}{V_{rmspri}} * I_{secrms} = \frac{24.8V}{100V} * 2.5A\text{=0.62A}$$

$$P_{pri} \text{ =100V*0.62A=62W}$$

$$Eff = \frac{P_{load}}{Psec} * 100\% = \frac{60W}{62W} * 100\% \text{ =96.8\%}$$



Assume ideal components in the phase-controlled circuit above. For a purely resistive load:

A. Explain how the circuit operates

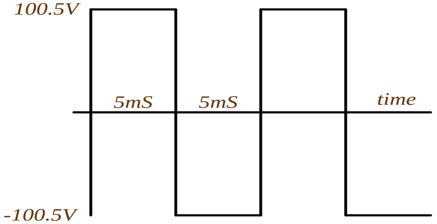
B. Draw the load voltage waveform and determine the boundary conditions of the delay angle α

C. Calculate the average load voltage and average load current as a function of α

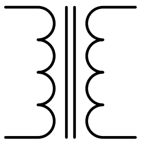
D. Find the RMS value of the load current. Help: $\int \sin^2 ax\,dx = \frac{x}{2} - \frac{\sin 2ax}{4a}$

Rectifiers - Homework Problem # 9

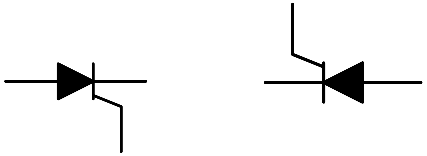
Given the following:



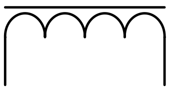
- *Input voltage waveform*

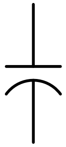


- *Lossless transformer*



- *Two SCRs, each with conducting voltage drop of 1V.*





- *Inductor, lossless, with very large inductance. Capacitor, large and lossless*

- *Resistor, 10 ohms, capable of very large power dissipation*
- *Circuit operating under steady-state conditions (i.e. all transients have subsided)*

Rectifiers - Homework Problem # 9 Continued

Problem

A. With the SCRs triggering retard angle at zero degrees, arrange the circuit to provide a full-wave, rectified, and properly low-pass filtered DC output of 200V into the 10ohm load resistor.

B. Calculate the load current and power

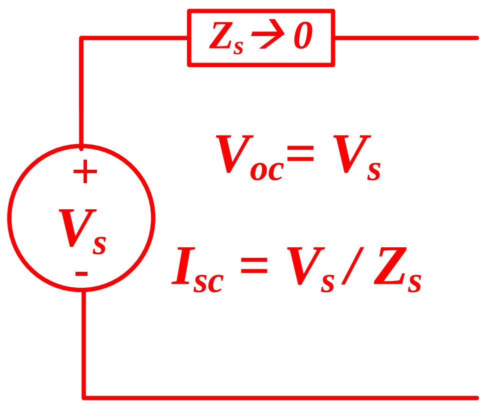
C. Determine the needed transformer turns ratio.

D. Calculate the circuit efficiency

Increase the SCRs trigger retard angle to 90 degrees and
F. Calculate the new output voltage, current, and power

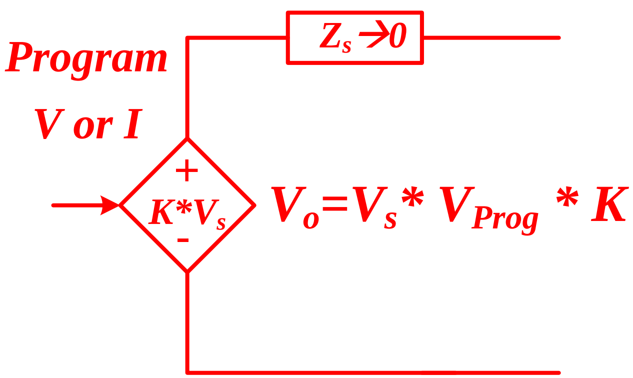
G. Determine the new circuit efficiency

Independent



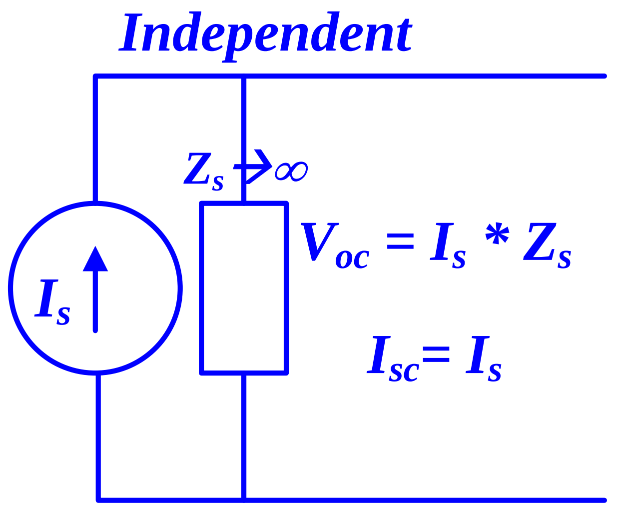
- A way to analyze any complex source and load network
- Provides a constant output voltage regardless of the output current
- Fixed DC output voltage

Dependent

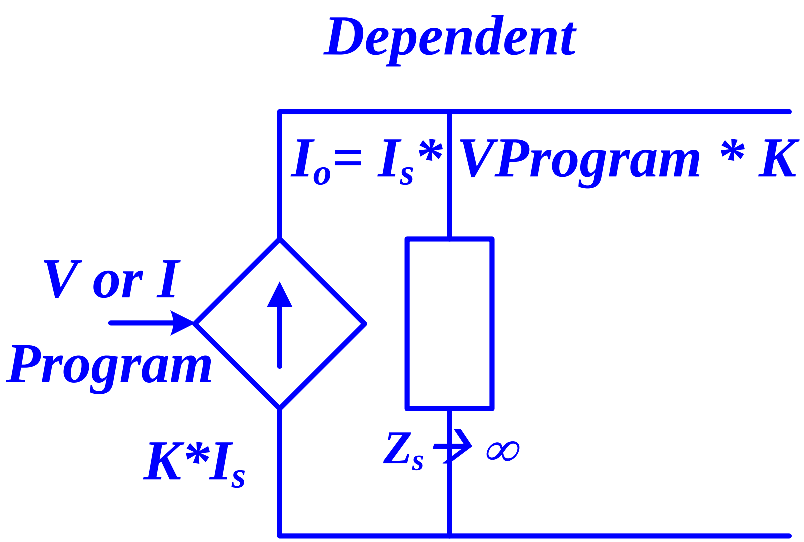


- Provides a constant output voltage regardless of the output current
- Continuously adjustable
- V_o dependent on V_{Prog} (V_{Ref})

Norton Current Sources



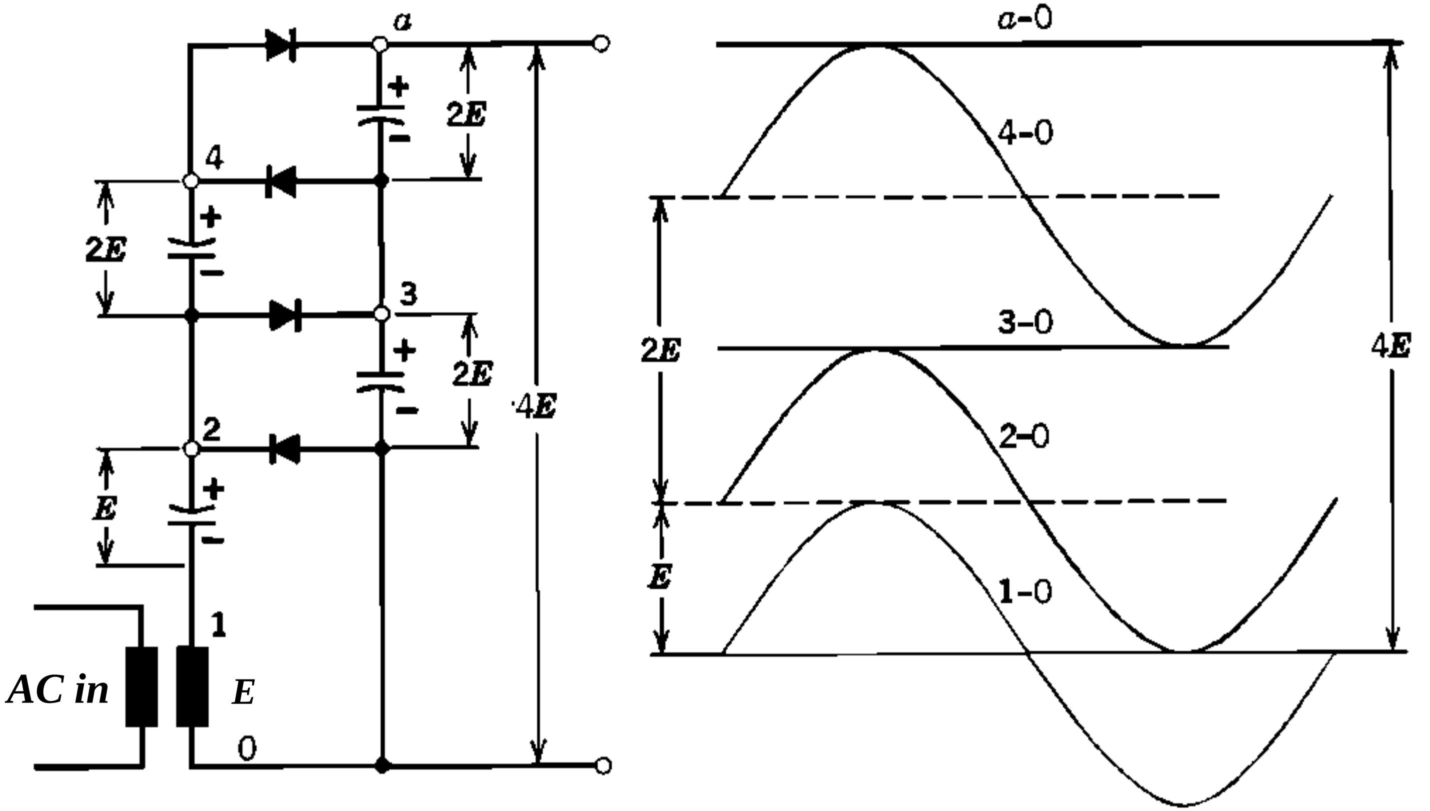
- Provides a constant output current regardless of the output voltage
- Fixed DC output current

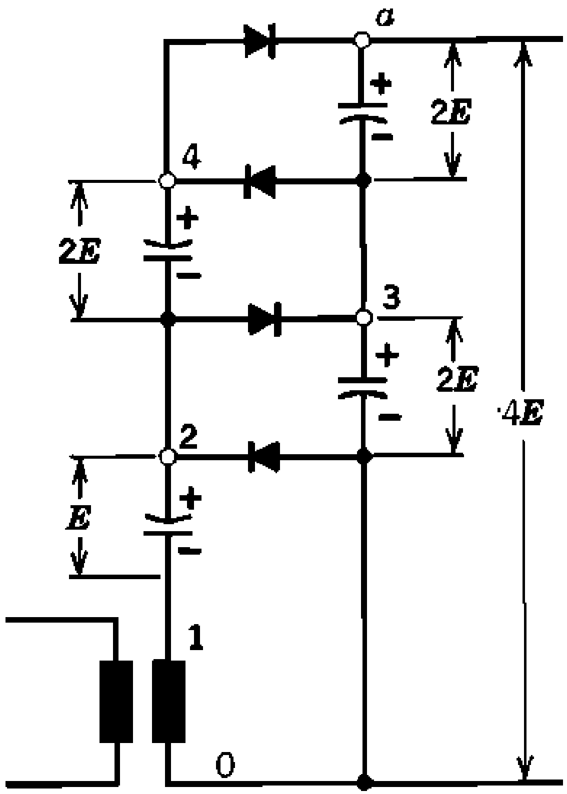


- Provides a constant output current regardless of the output voltage
- Continuously adjustable
- I_o dependent on V_{Prog} (V_{Ref})

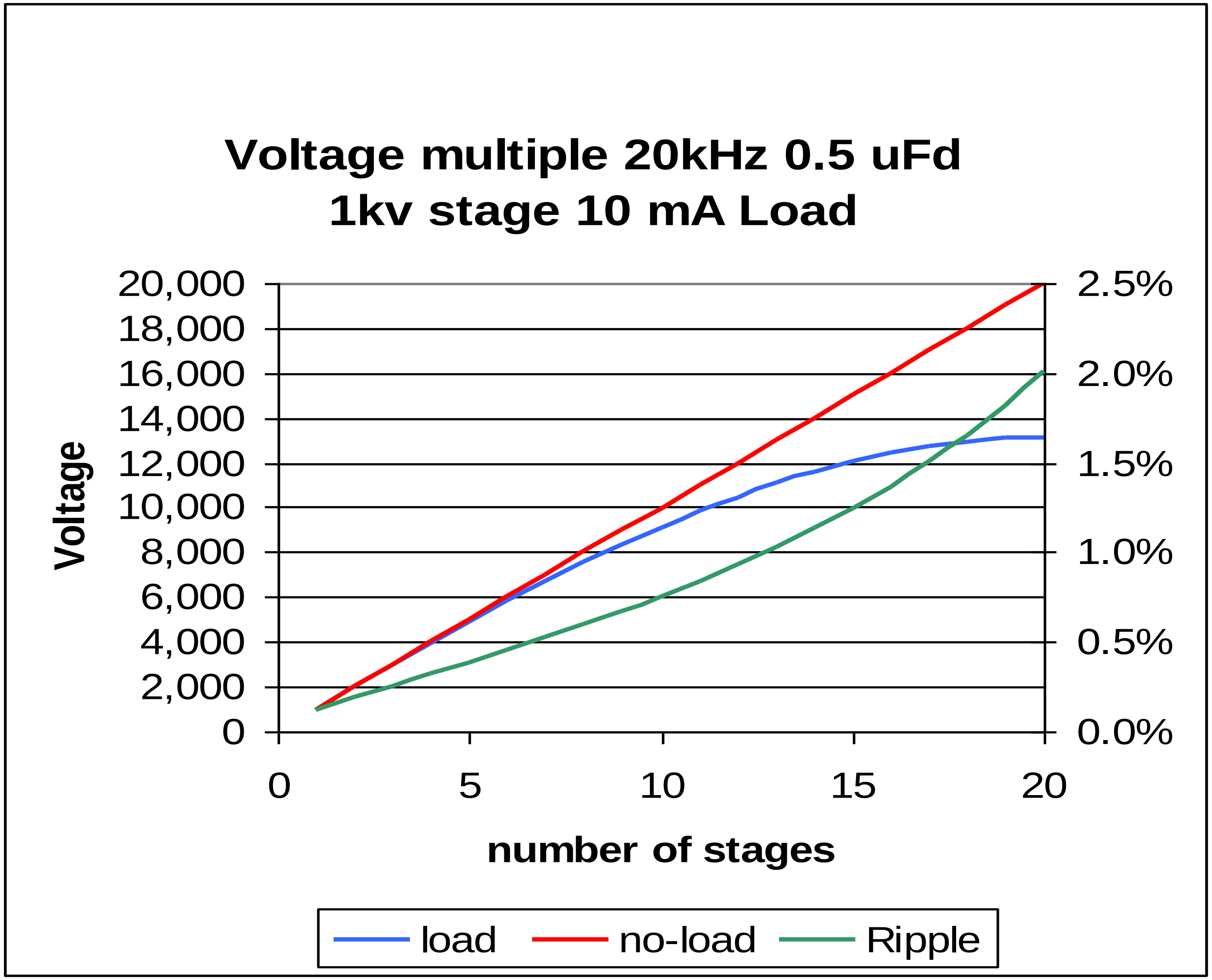
High Voltage Low Current DC supplies

Voltage Multipliers, Cockroft Walton or Cascade Supplies





- *Voltage multipliers or cascaded supplies*
- *Electron beam gun supplies and deflector supplies*
- *Half-wave, full-wave, three-phase, or six phase*
- *20kV to 1,000 kV, 0 to 10 mA DC*
- *Requires high frequency input drive ~ 5 kHz to 50 kHz, but at low instantaneous power*
- *Provides low frequency, but high instantaneous power output*
- *Advantages – simple, reliable, inexpensive*
- *Disadvantages- low output power, poor regulation high output ripple, high output Z, 1st stage draws high current*

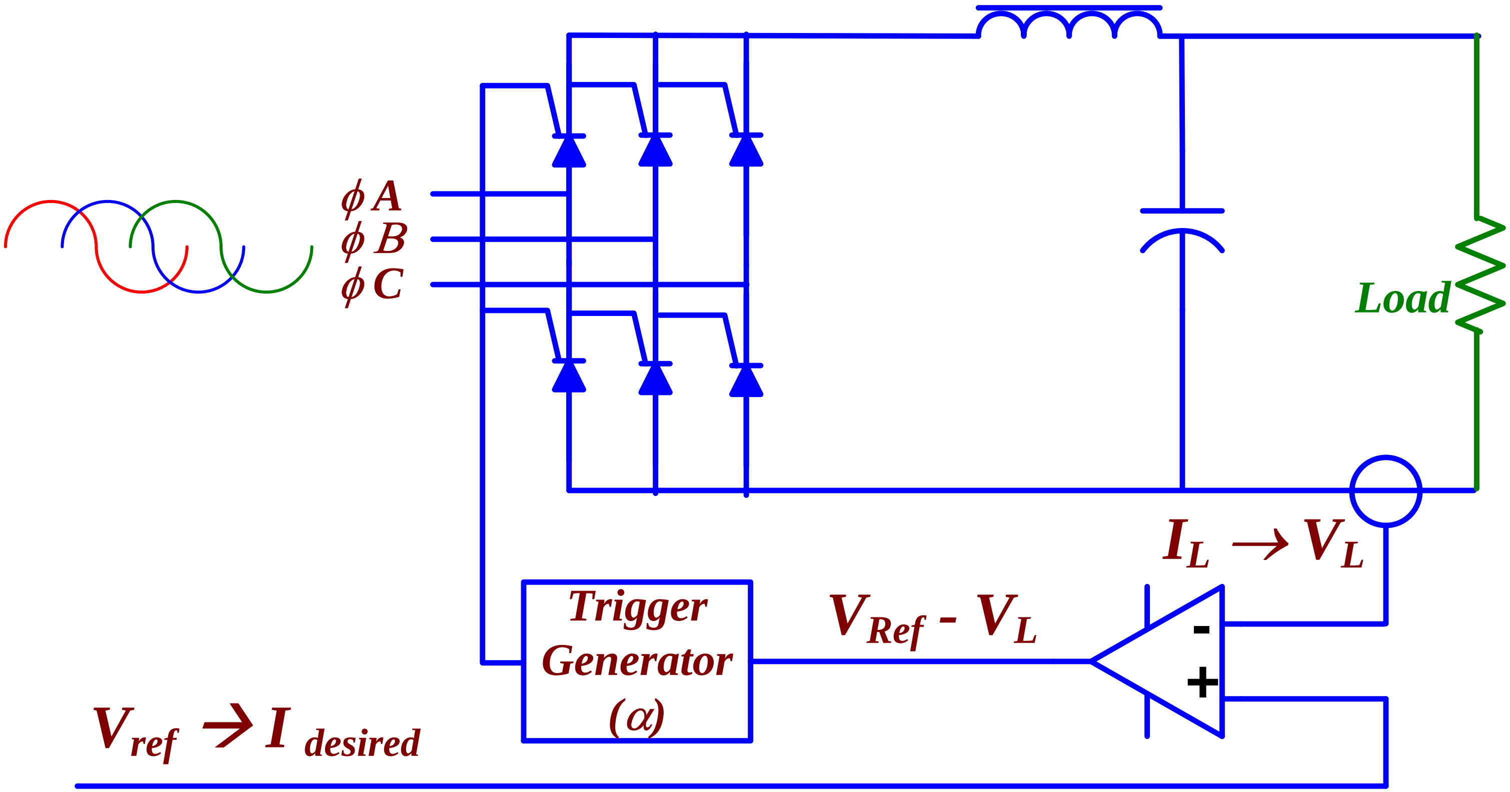


- *Disadvantages:*

  Poor regulation $E_{drop} = (I_{load} / (f*C)) * (2/3*n^3 + n^2/2 - n/6)$

  Large ripple $E_{ripple} = (I_{load}/(f * C))*n*(n+1)/2$

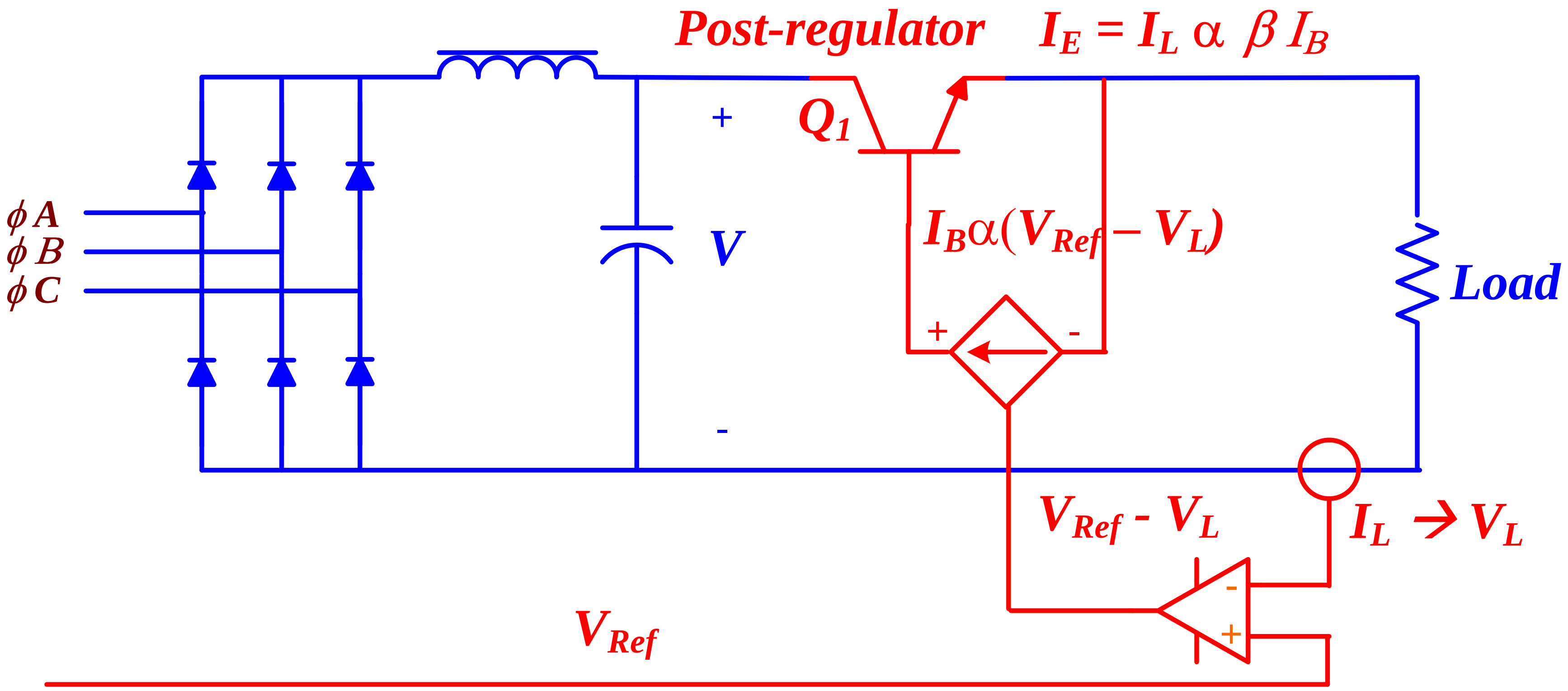
SCR Rectifier / Regulator Current Source



Reference Change	$V_{Ref}\uparrow$	$V_{Ref} - V_L \uparrow$	$\alpha\downarrow,\ I_L \uparrow$
Reference Change	$V_{Ref}\downarrow$	$V_{Ref} - V_L \downarrow$	$\alpha\uparrow,\ I_L \downarrow$
Load I Correction	$I_L \uparrow$	$V_{Ref} - V_L \downarrow$	$\alpha\uparrow,\ I_L \downarrow$
Load I Correction	$I_L \downarrow$	$V_{Ref} - V_L \uparrow$	$\alpha\downarrow,\ I_L \uparrow$

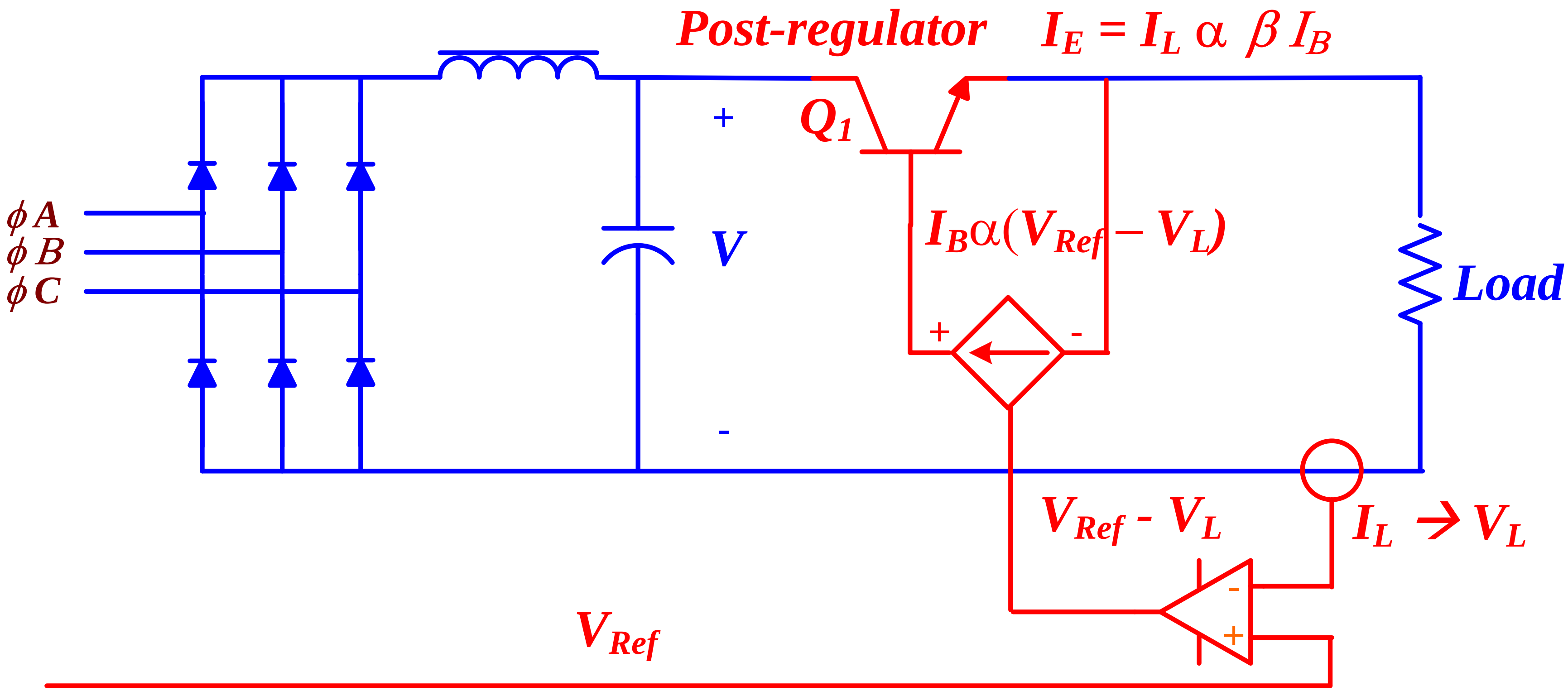
Disadvantage: *Line commutated, low bandwidth, some fast changes not regulated*

Diode Rectifier With Linear Post-Regulator To Improve Response



Reference Change	$V_{Ref} \uparrow$	$I_B \alpha V_{Ref} - V_L \uparrow$	$I_E = I_L \uparrow$
Reference Change	$V_{Ref} \downarrow$	$I_B \alpha V_{Ref} - V_L \downarrow$	$I_E = I_L \downarrow$
Load I Correction	$I_L \uparrow$	$I_B \alpha V_{Ref} - V_L \downarrow$	$I_E = I_L \downarrow$
Load I Correction	$I_L \downarrow$	$I_B \alpha V_{Ref} - V_L \uparrow$	$I_E = I_L \uparrow$

Diode Rectifier With Linear Post-Regulator To Improve Response



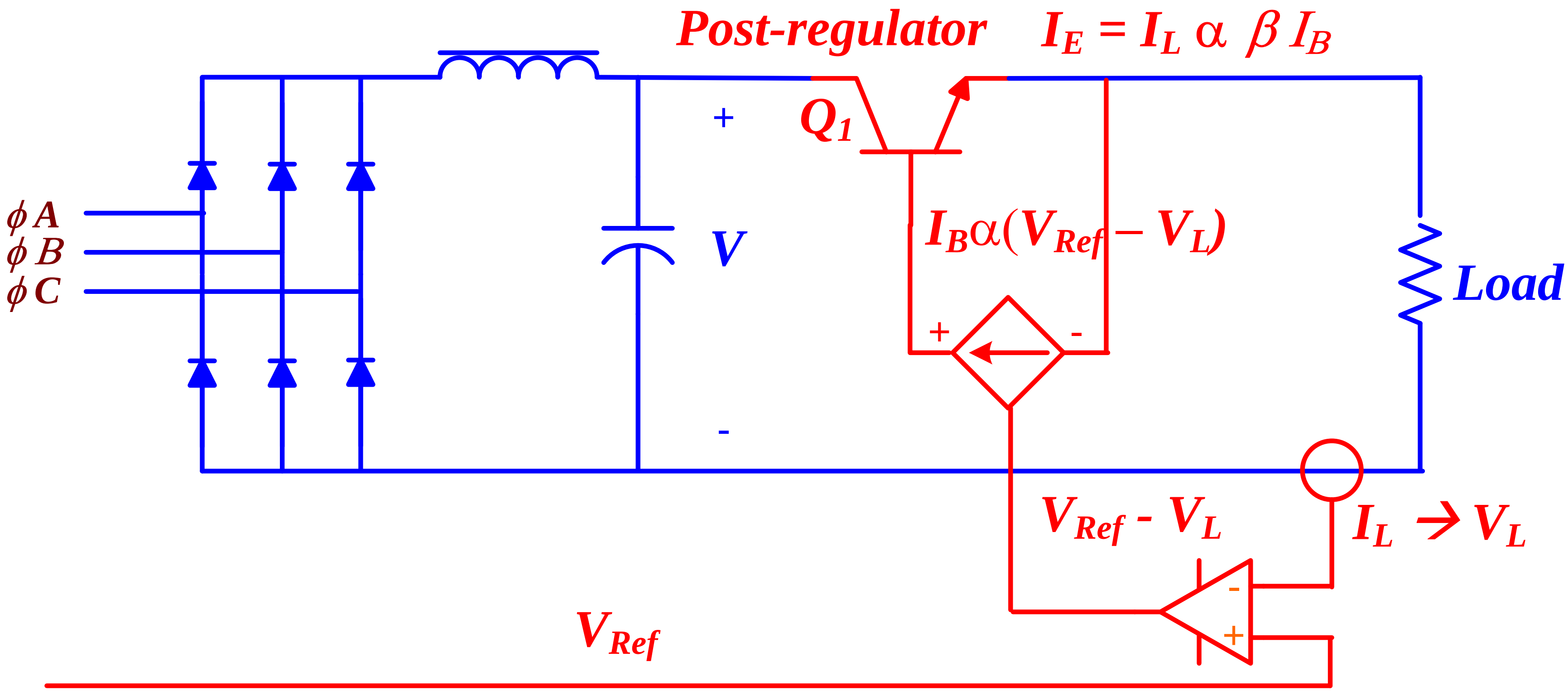
Regulation occurs by changing the transistor Q1 resistance

$$R_{Q1} = \frac{V_{CE}}{I_E} = \frac{V - V_L}{I_L}$$

V *is constant, so* $\quad$ *if* $I_L \uparrow, V_L \uparrow, V - V_L \downarrow, R_{Q1} \downarrow$

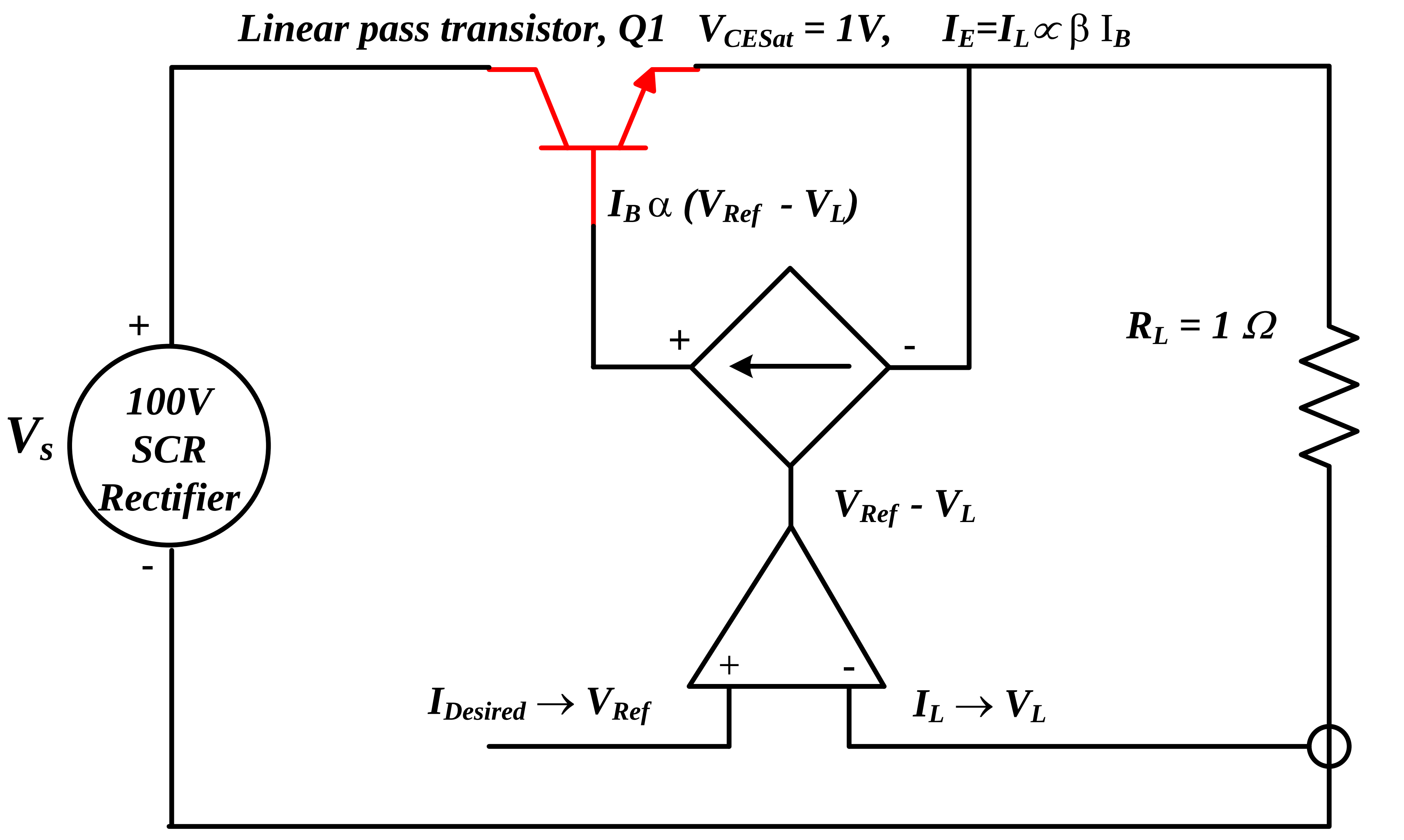
if $I_L \downarrow, V_L \downarrow, V - V_L \uparrow, R_{Q1} \uparrow$

Diode Rectifier With Linear Post-Regulator To Improve Response

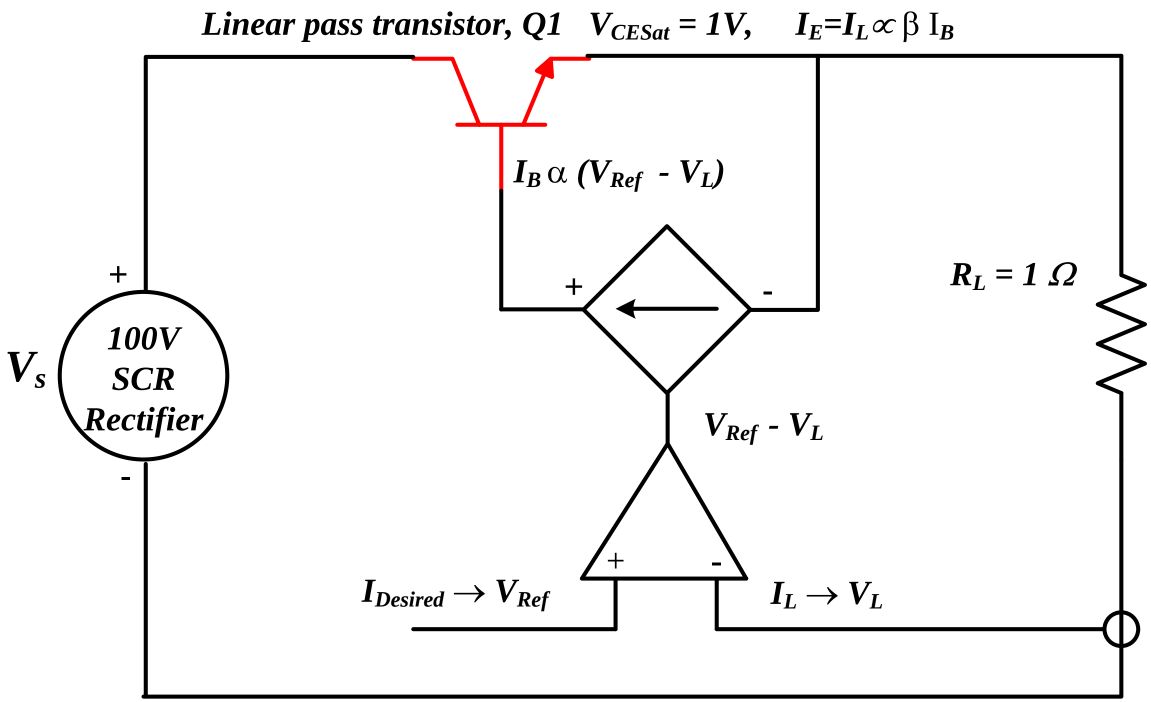


- *Output I sensed and deviations due to programming, load or other changes are corrected by changing the resistance of the post-regulator.*
- *Broader bandwidth than line-commutated type*
- *Very inefficient topology, except when full output is required*

Linear Regulator Disadvantage



Linear Regulator Disadvantage



$$V_S = 100V \qquad I_L = 0 \rightarrow 99A \qquad V_{Q1} = V_S - V_L$$

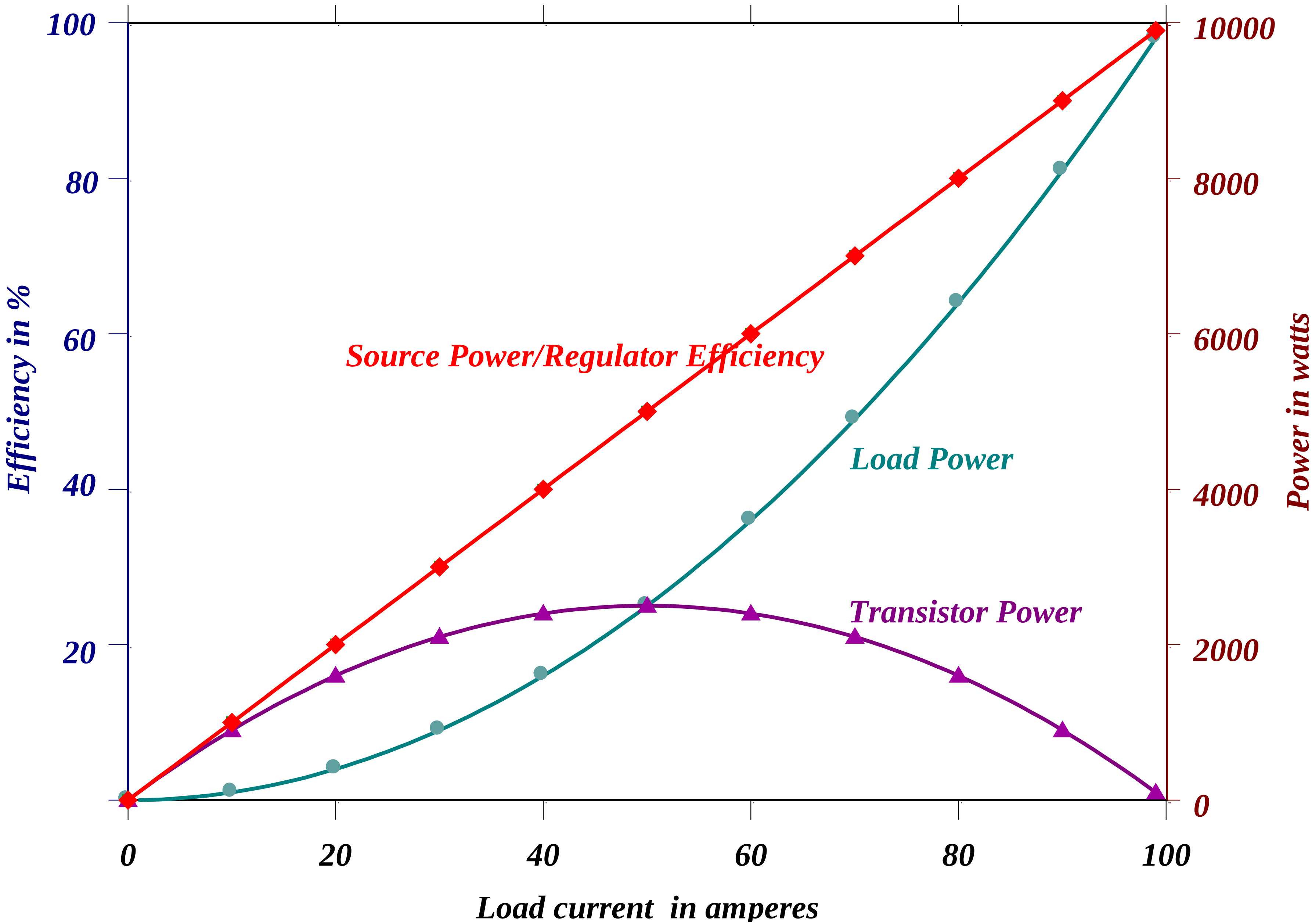
$$I_S = I_L \qquad V_L = I_L * R_L \qquad P_{Q1} = V_{Q1} * I_{Q1}$$

$$P_S = V_S * I_S \qquad P_L = V_L * I_L \qquad Eff = \frac{P_L}{P_S}$$

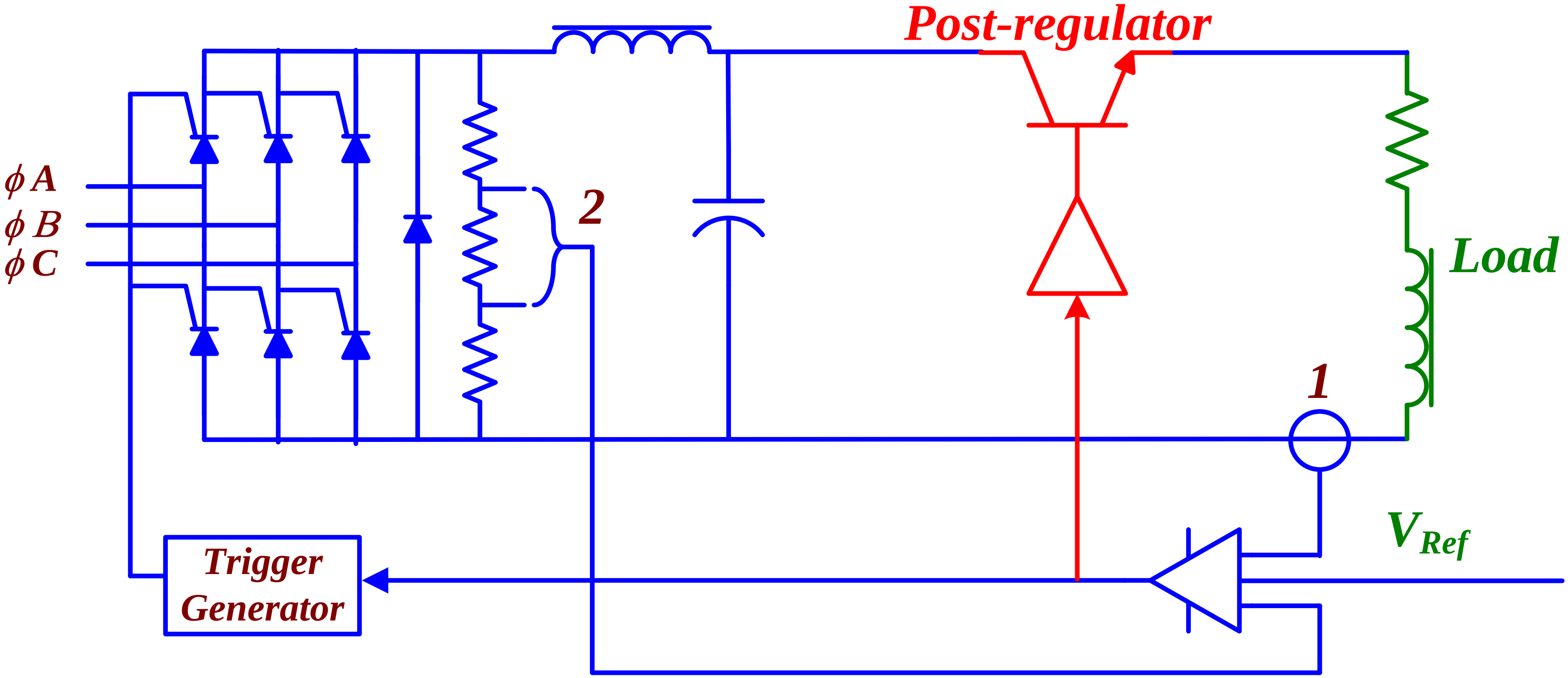
Linear Regulator Disadvantage

Load Amperes I_L = I Desired	Load Volts $V_L = I_L * R_L$	Load Watts $P_L = V_L * I_L$	Q1 Volts $V_{Q1}=V_S - V_L$	Q1 Amperes $I_{Q1}=I_L$	Q1 Watts $P_{Q1}=V_{Q1}*I_{Q1}$	Source Volts $V_S=100$	Source Amperes $I_S=I_I$	Source Watts $P_S=V_S * I_S$	% Efficiency $Eff=P_L / P_S$
0	0	0	100	0	0	100	0	0	0
10	10	100	90	10	900	100	10	1000	10
20	20	400	80	20	1600	100	20	2000	20
30	30	900	70	30	2100	100	30	3000	30
40	40	1600	60	40	2400	100	40	4000	40
50	50	2500	50	50	2500	100	50	5000	50
60	60	3600	40	60	2400	100	60	6000	60
70	70	4900	30	70	2100	100	70	7000	70
80	80	6400	20	80	1600	100	80	8000	80
90	90	8100	10	90	900	100	90	9000	90
99	99	9801	1	99	99	100	99	9900	99

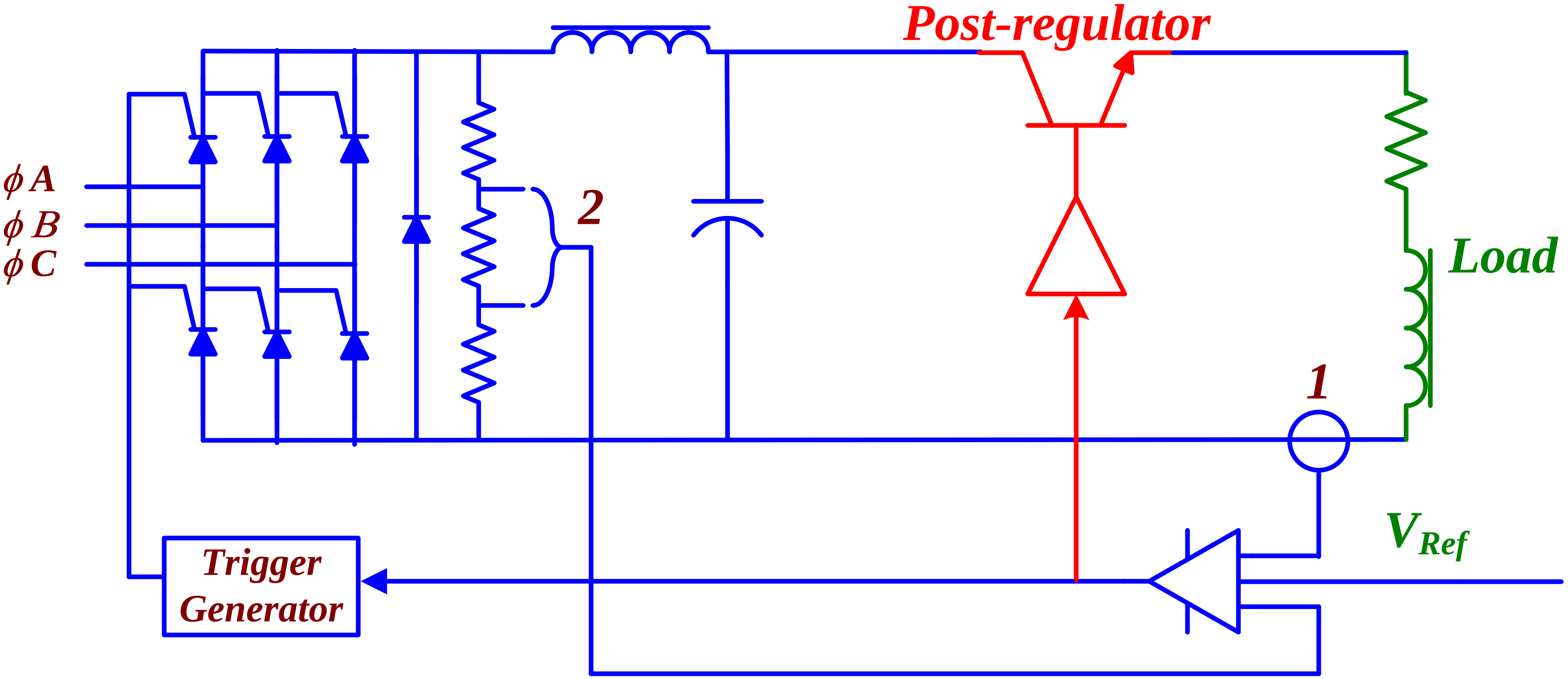
Linear Regulator Disadvantage



SCR Rectifier With Linear Post-Regulator To Improve Efficiency / Response



- SCRs full on for full output
- SCRs phased back for lower outputs to improve efficiency.
- Limited range regulation is done by the post-regulator

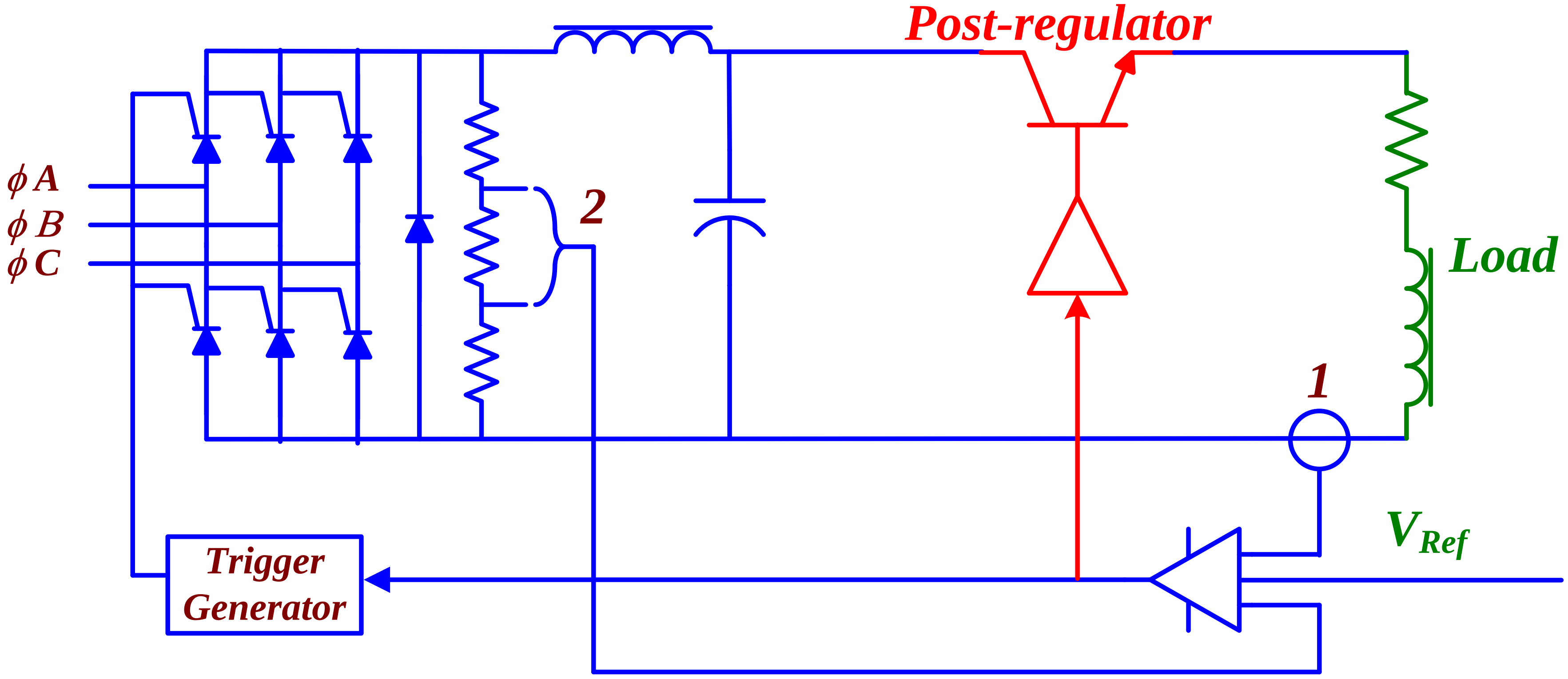


1. *Output I sensed. Deviations due to load or other changes are corrected by SCR rectifier and post-regulator.*

2. *Rectifier V_O is sensed. Slow line changes corrected by BW-limited SCRs. Fast transients corrected by high BW post-regulator*

3. *Bipolar transistor V_{CE} is monitored. If V_{CE} and/or V_{CE}*I_E exceeds a safe value, SCR firing is advanced and rectifier V_O is increased accordingly*

SCR Rectifier With Linear Post-Regulator To Improve Efficiency / Response



Disadvantages

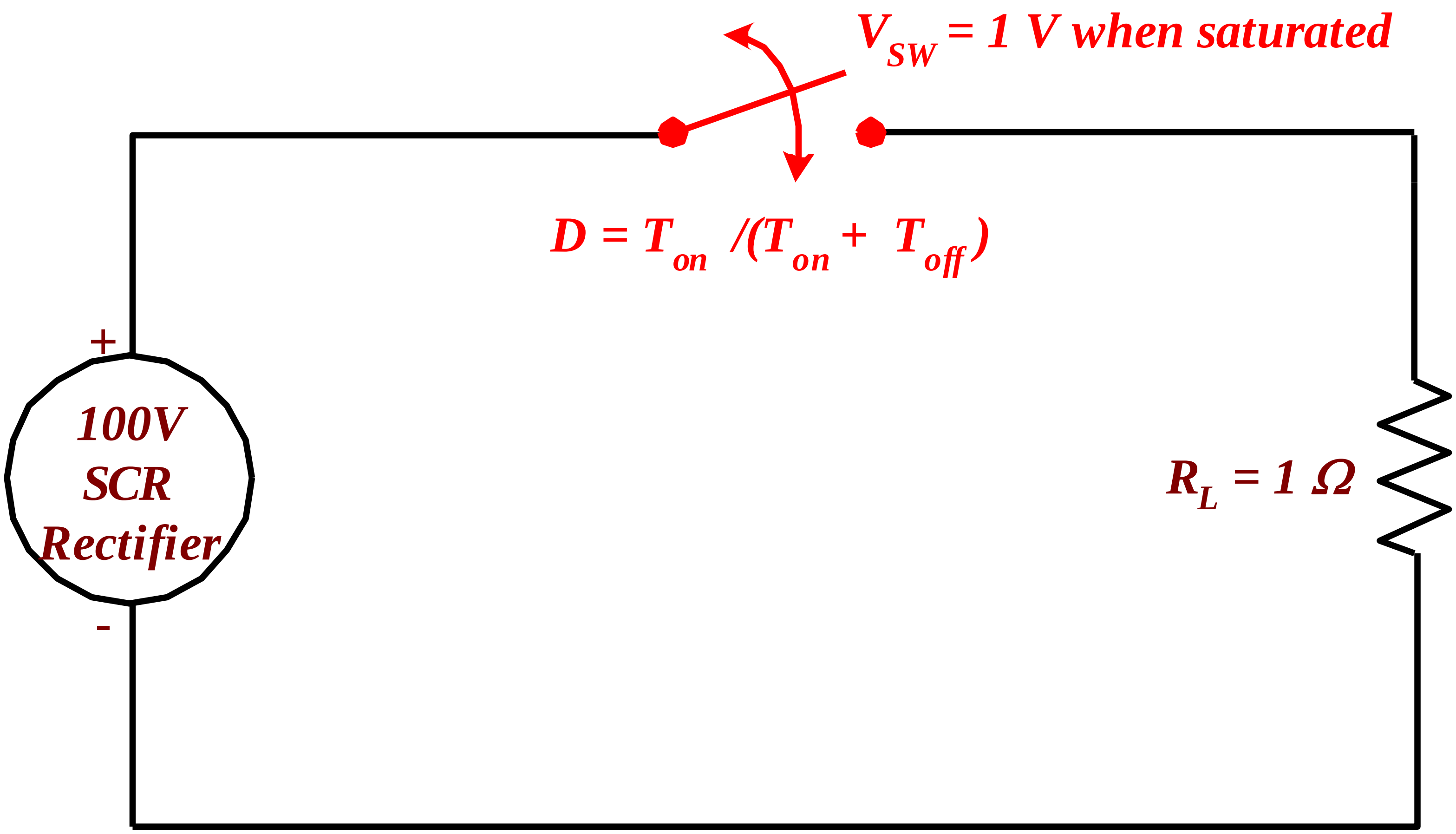
- *Large output changes cannot be accommodated by post-regulator. Requires retardation of SCR rectifier pulses to improve efficiency*
- *Low power factor when SCR gate firing is retarded ($V_{load} << V_{line}$)*
- *Implementation of 2 control loops is complex*

The Present – Switchmode Power Supplies
Circa 1990 - Present

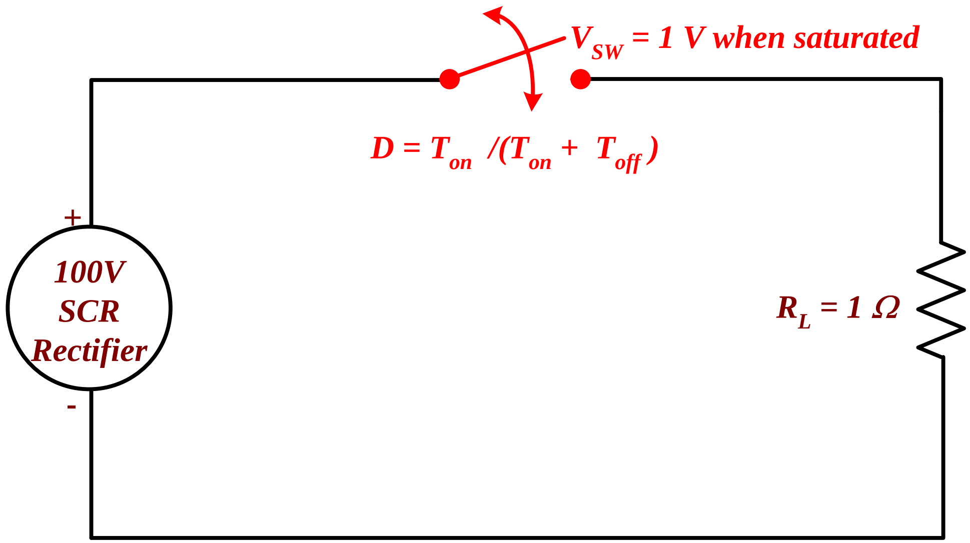
Recalling The Recent Past	
Topology	Disadvantages
• SCRs for rectification and regulation	• Low power factor • High AC line harmonic distortion • Narrow bandwidth • Slow transient response
• SCRs for rectification and gross regulation • Fine regulation by post linear transistors	• Low power factor when line V $\neq$ load V • High AC line harmonic distortion • Complex control loops

The Present Popular Solution	
Topology	*Advantages*
• *SCRs (or diodes) for rectification* • *High speed switches (switch-mode inverters) for regulation*	• *Rectifier SCRs or diodes are full on – hence high power factor (> 0.9) possible* • *High PF means low AC line harmonic distortion (< 5% V, < 25 % I)* • *Fast (10 kHz to 100 kHz) switching means wide bandwidth (> 100 s of Hz), fast transient response (microseconds)* • *Fast switching means more corrections per unit time – better output stability* • *Simple control loops compared to SCR rectifier/post-regulator combination* • *Fast switching, high frequency operation for electrically and physically smaller transformers and filter components*

The Present Popular Solution (Continued)	
Topology	Disadvantages
• SCRs (or diodes) for rectification • High speed switches (switch-mode inverters) for regulation	• High speed, fast-edge switching can generate conducted and radiated electromagnetic interference (EMI)


V_{SW} = 1 V when saturated
$D = T_{on} /(T_{on} + T_{off})$
+
100V
SCR
Rectifier
-
$R_L = 1\ \Omega$

The Switchmode Advantage



$$D = \frac{I_{Lavg}}{I_{peak}} = \frac{I_{Lavg}}{99\,A}$$

$$V_S = 100V$$

$$V_{SWRMS} = 1V * D^{1/2}$$

$$V_{Lavg} = I_{Lavg} * R_L$$

$$I_S = I_{SW} = I_L$$

$$I_{SWRMS} = 99\,A * D^{1/2}$$

$$V_{LRMS} = 99\,V * D^{1/2}$$

$$Eff = \frac{P_L}{P_S} * 100\%$$

$$P_S = P_{SW} + P_L$$

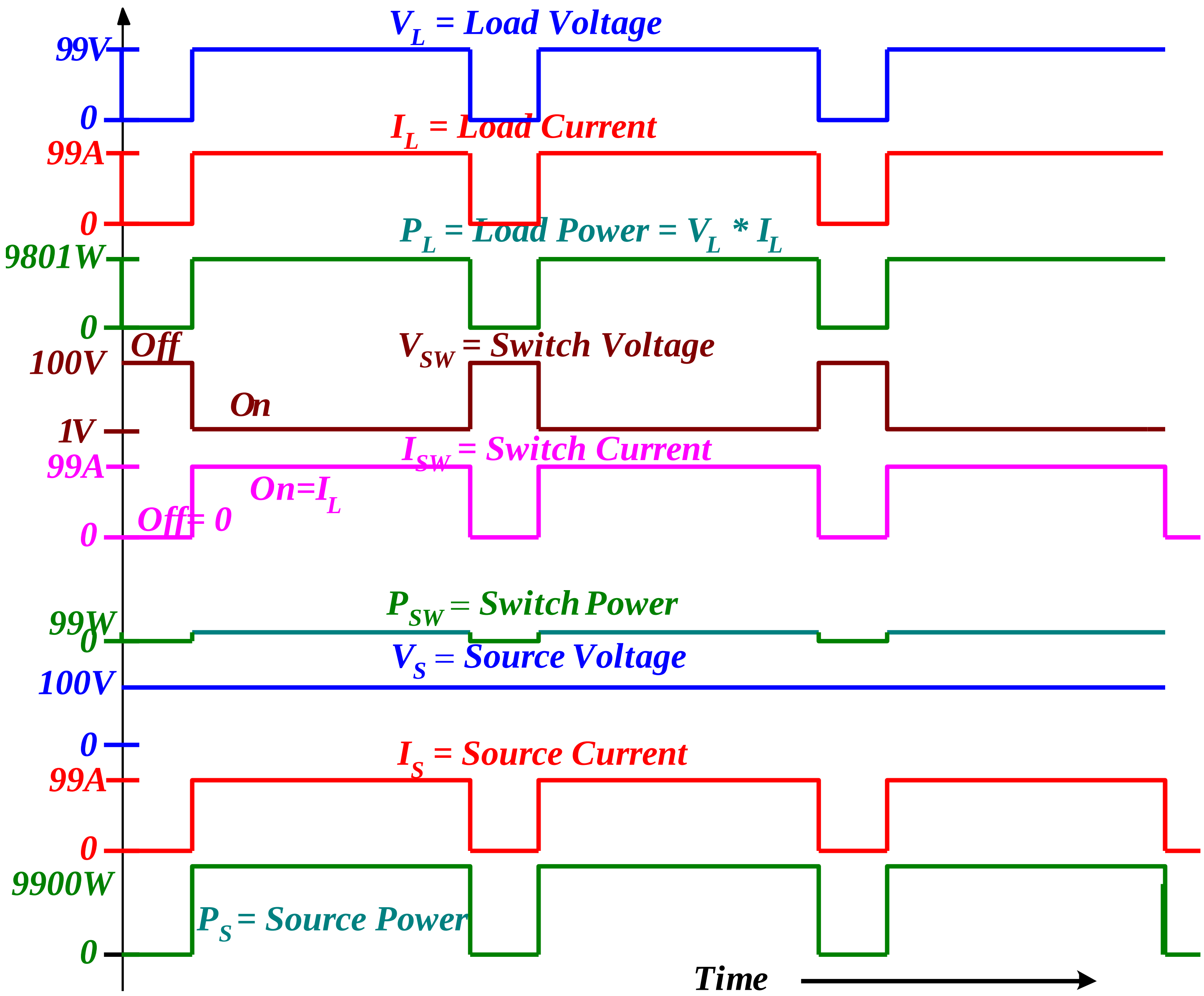
$$P_{SW} = V_{SWRMS} * I_{SWRMS}$$

$$I_{Lavg} = 0 \rightarrow 99\,A$$

$$I_{LRMS} = 99\,A * D^{1/2}$$

$$P_L = V_{LRMS} * I_{LRMS}$$

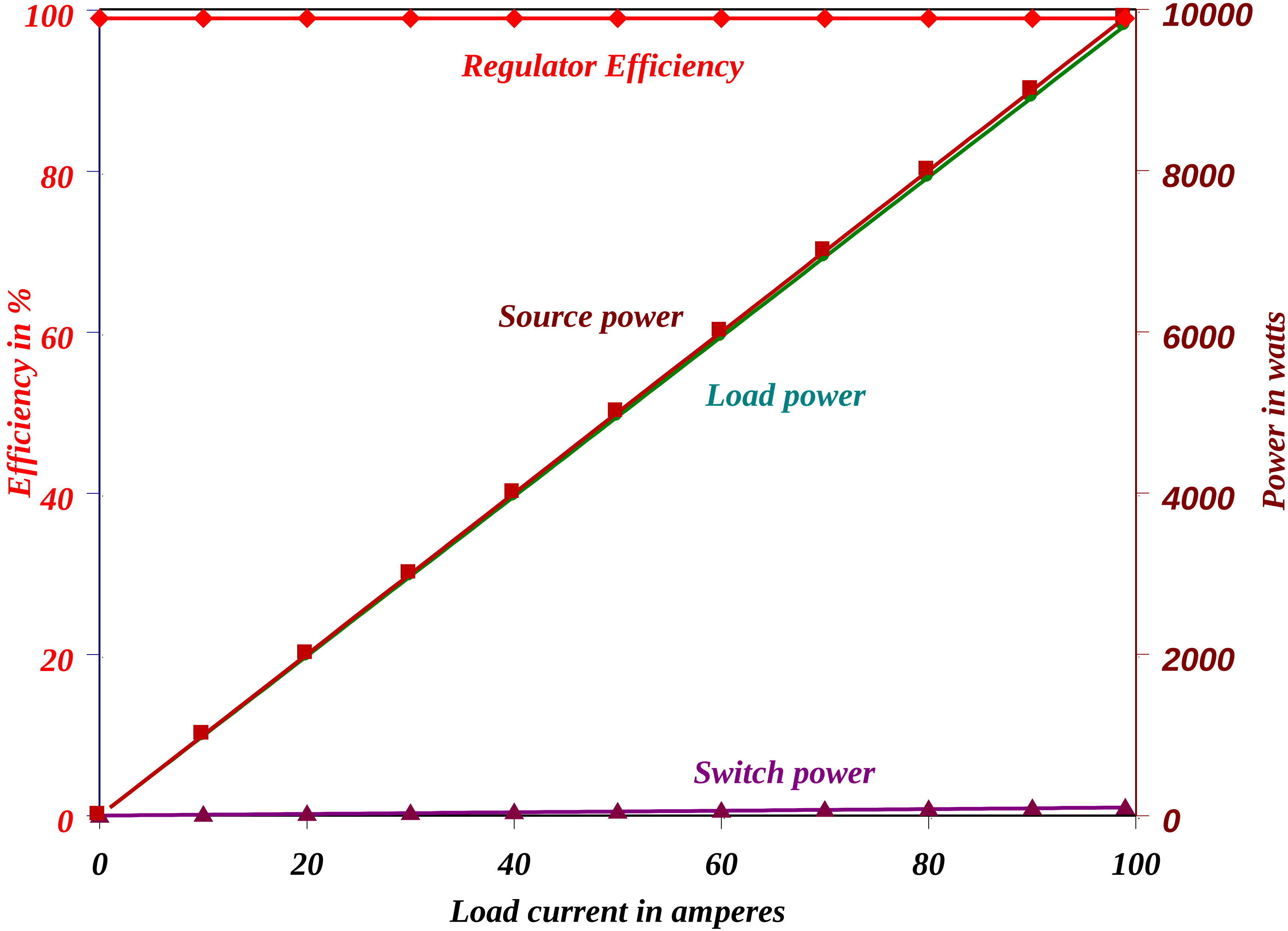
The Switchmode Advantage - Waveshapes



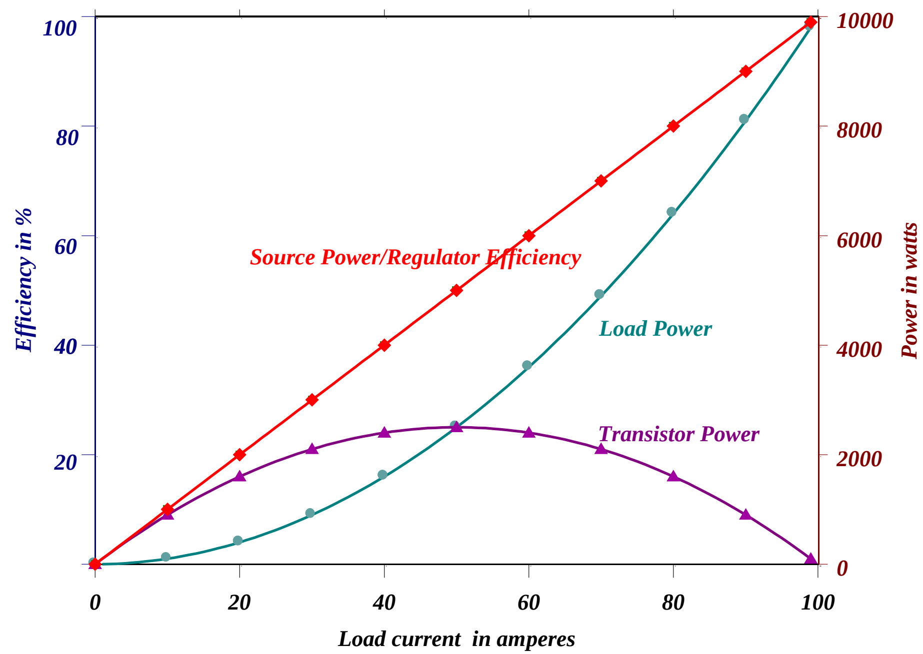
The Switchmode Advantage - Calculations

Avg Load Amps I_{Lavg} = $I_{Desired}$	Duty Factor=I_{Lavg} / Ipeak	Average Load V $V_{Lavg} = I_{Lavg} * R_L$	Load Volts RMS V_{Lrms}=99V*D^0.5	Load Amps RMS I_{Lrms}=99A*D^0.5	Load Power $P_{Lavg} = V_{Lrms} * I_{lrms}$	Switch Volts RMS V_{SWrms} = 1V * D^0.5	Switch Amps RMS I_{SWrms}=99 * D^0.5	Switch Power $P_{SWavg} = V_{SWrms} * I_{SWrms}$	Source Power $P_S = P_{Lrms} + P_{SWrms}$	% Efficiency Eff= P_L / P_S * 100%
0	0	0	0	0	0	0.00	0.0	0	0	NA
10	0.101	10	31	31	990	0.32	31.5	10	1000	99
20	0.202	20	44	44	1980	0.45	44.5	20	2000	99
30	0.303	30	54	54	2970	0.55	54.5	30	3000	99
40	0.404	40	63	63	3960	0.64	62.9	40	4000	99
50	0.505	50	70	70	4950	0.71	70.4	50	5000	99
60	0.606	60	77	77	5940	0.78	77.1	60	6000	99
70	0.707	70	83	83	6930	0.84	83.2	70	7000	99
80	0.808	80	89	89	7920	0.90	89.0	80	8000	99
90	0.909	90	94	94	8910	0.95	94.4	90	9000	99
99	1	99	99	99	9801	1.00	99.0	99	9900	99

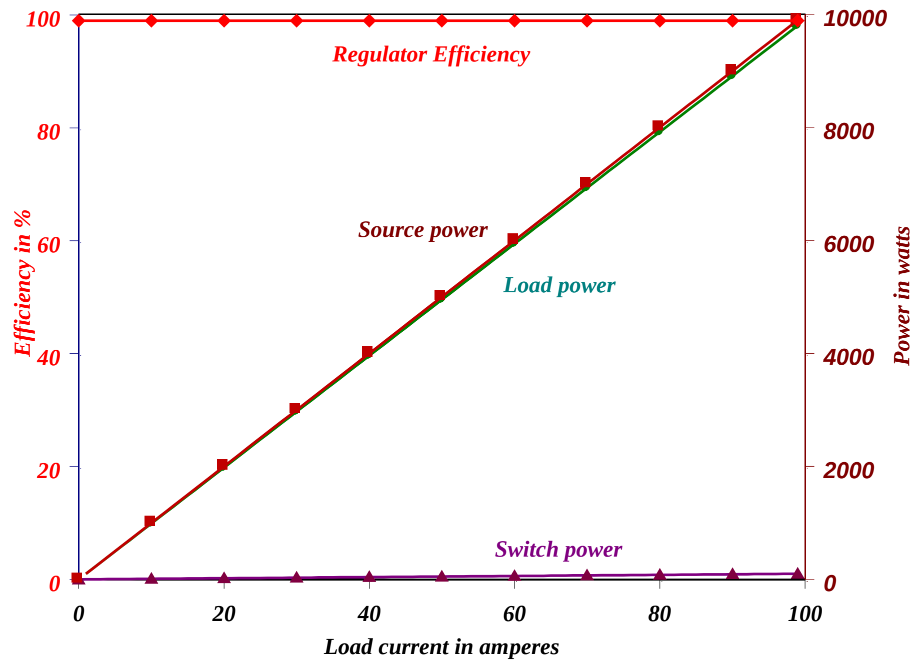
The Switchmode Advantage - Plots



Linear regulator



Switchmode regulator



SCR Regulation Vs Switchmode Regulation

	SCR	Switchmode
Efficiency	Low at low load, high at full load	High, whether low or high load
Operating frequency	60 Hz	10 kHz to 1,000 kHz
Transient Response	Tens of milliseconds	Tens of microseconds
Short-term-stability	100s of ppm	10s of ppm
Input filter	Large	Smaller, HF regulator provides supplemental filtering
Isolation/Line-matching transformer	Large and upstream of the rectifiers	Smaller because of high frequency. Downstream of the regulator
Output filter	None	High frequency ripple = smaller size
Power factor	Low when output is low	Always high
Line distortion	High when output is low	Always low
EMI	High when output is low	High, but higher frequency, easier to filter

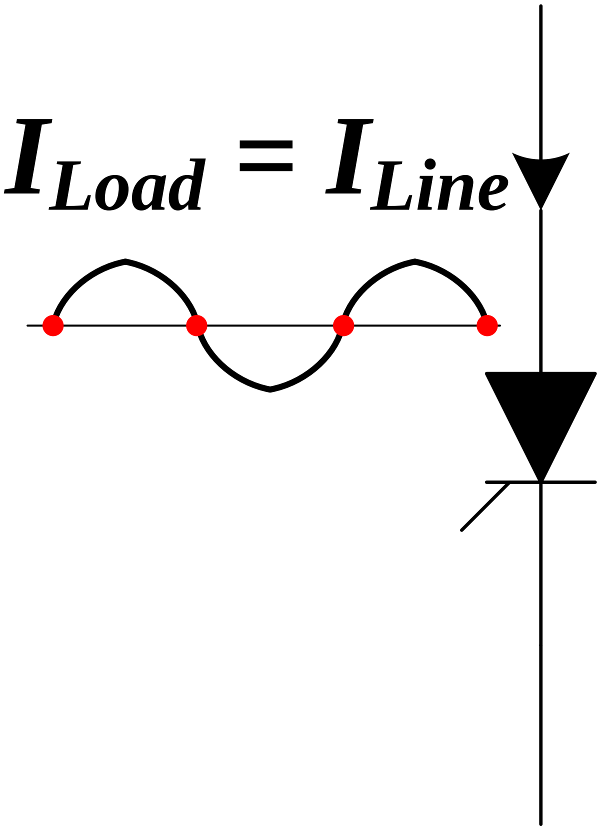
Linear Vs. Switchmode– Advantage Summary

Linear	Switchmode
Output current/voltage is adjusted by varying pass transistor resistance	Output current/voltage is adjusted by varying switch duty factor
Transistor voltage and current are in phase so transistor power loss is high	Switch voltage and current are out of phase so switch power is low
Efficiency is dependent upon the output operating point and is maximum at 100 % load	Efficiency is high and relatively constant

Line Commutated Switches

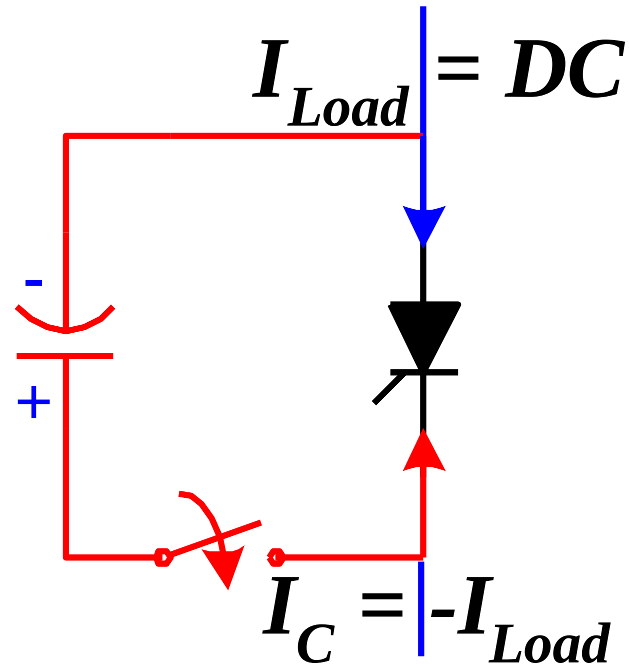
- *Typically thyristor (4 - element) family devices SCRs, Triacs*
- *Employ natural current zero occurs each 1/2 cycle for turnoff*
- *Slow, tied to 60Hz line and no turnoff control*
- *Not suitable as fast switch*

$I_{Load} = I_{Line}$



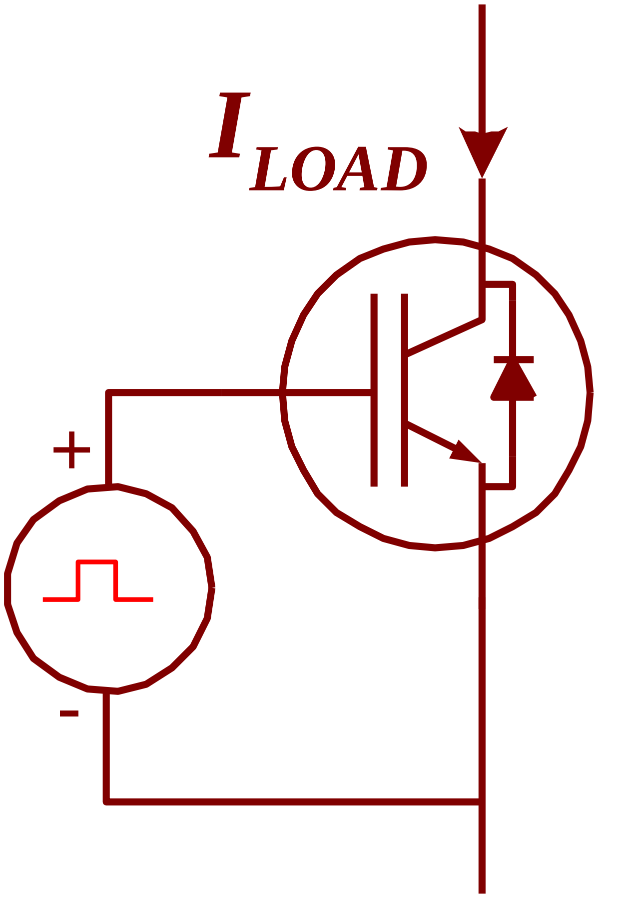
Force Commutated

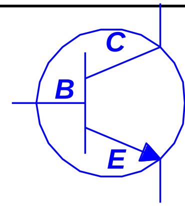
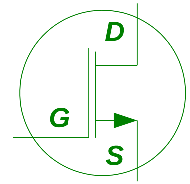
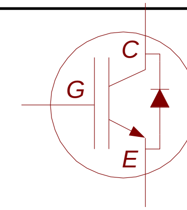
- Typically SCRs, Triacs
- Artificial current zero is manufactured by pre-charged capacitor $I_c = - I_{Load}$
- Complex and power-consuming charging and discharging circuits for capacitor
- Not suitable approach for fast switches



Self Commutated

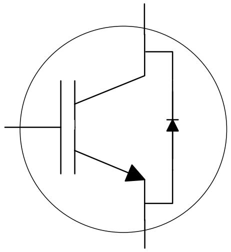
- *Devices have the ability to turn on or turn off by the application of a forward or reverse bias to the control elements (gate – emitter)*
- *Typically Bipolar Junction Transistors (BJTs), Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) or Insulated Gate Bipolar Junction Transistors (IGBTs)*
- *Only self-commutated switches used in modern switchmode power supplies*



Self-Commutated Device	*Bipolar Junction Transistor (BJT)*	*Metal Oxide Field Effect Transistor (MOSFET)*	*Insulated Gate Bipolar Transistor (IGBT)*
Symbol			
Available Ratings	*600 V, 10 → 100 A* *1000V, 10 → 100A*	*150 V, 10 → 600 A* *600 V, 10 → 100 A* *1200V, 10 → 100A*	*600 V, 10 → 800 A* *1200V, 10 → 2400A* *1700V, 50 → 2400A* *3300V, 200 → 1500A* *6500V, 200 → 800A*
Switching Speed	$DC \le fs \le 2\ kHz$	$DC \le fs \le 1{,}000\ kHz$	$DC \le fs \le 20\ kHz$
Vce or Vds f(Vge/Vgs, Ic/Id)	*0.5 V → 1.5 V*	*1.5 V → 6 V*	*1.0 → 3.0V*
*Conduction Loss (Vce*Ic) or (Vds*Id)*	*Lowest*	*Highest*	*Reasonable*
Control Mode	*Current*	*Voltage*	*Voltage*

Insulated Gate Bipolar Transistor (IGBT) Technology

- *Used in vast majority of switchmode power supplies, except MOSFETs for corrector / trim bipolars*
- *Voltage controlled device - faster than BJT*
- *MOSFET faster, but V_{DS} too large*
- *20 kHz for PWM*
- *Robust, failure rate < 50 FITs*
- *Commercially available since 1990*

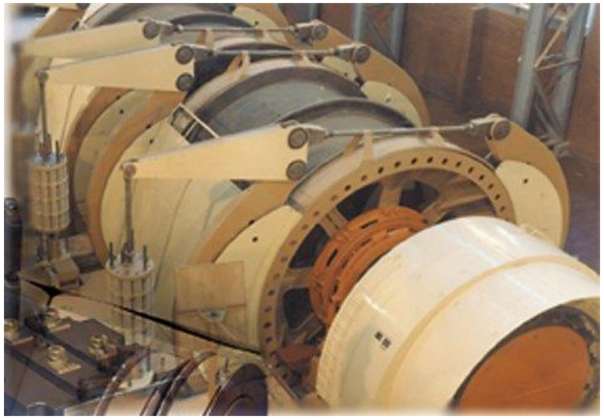


IGBT

Single IGBT

Gate Driver

IGBT Availability	
600V	*10 → 800A*
1200V	*10 → 2400A*
1600 / 1700V	*50 → 2400A*
2500 / 3300V	*200 → 1500A*
4500 / 6500V	*200 → 800A*
Available as 6-pack, half-bridge, single switch	



Manufacturers of IGBTs and IGBT Gate Drivers

ABB	*http://www.abbsem.com/english/igbt.htm*
Concept Technology	*http://www.igbt-driver.com/*
Collmer Semiconductor	*http://www.collmer.com/*
Eupec	*http://www.eupec.com*
International Rectifier	*http://www.irf.com*
Intersil	*http://www.intersil.com/*
IXYS	*http://www.ixys.net*
Mitsubishi	*http://www.mitsubishichips.com/*
Powerex	*http://www.pwrx.com*
Semikron	*http://www.semikron.com*
Toshiba	*http://www.toshiba.com/*
Westcode	*http://www.westcode.com/*

Topologies - Switchmode Power Supplies

- *There are many topologies, but most are combinations of the types that will be discussed here.*
- *Each topology contains a unique set of design trade-offs*

  Voltage stresses on the switches

  Chopped versus smooth input and output currents

  Utilization of the transformer windings
- *Choosing the best topology requires a study of*

  Input and output voltage ranges

  Current ranges

  Cost versus performance, size and weight

Two Broad Categories

Flyback Converters

- *The line-to-load matching/isolation transformer doubles as the output filter choke*
- *Advantage – reduction of one major component*
- *Disadvantage – constrained to low power applications. Not employed in accelerator power supplies*

Forward Converters

- *The line-to-load matching/isolation transformer is separate from the output filter choke*
- *May be used in low and high power systems. Used in the vast majority of accelerator power supplies*
- *Disadvantage – the increased cost and space associated with a separate transformer and choke*

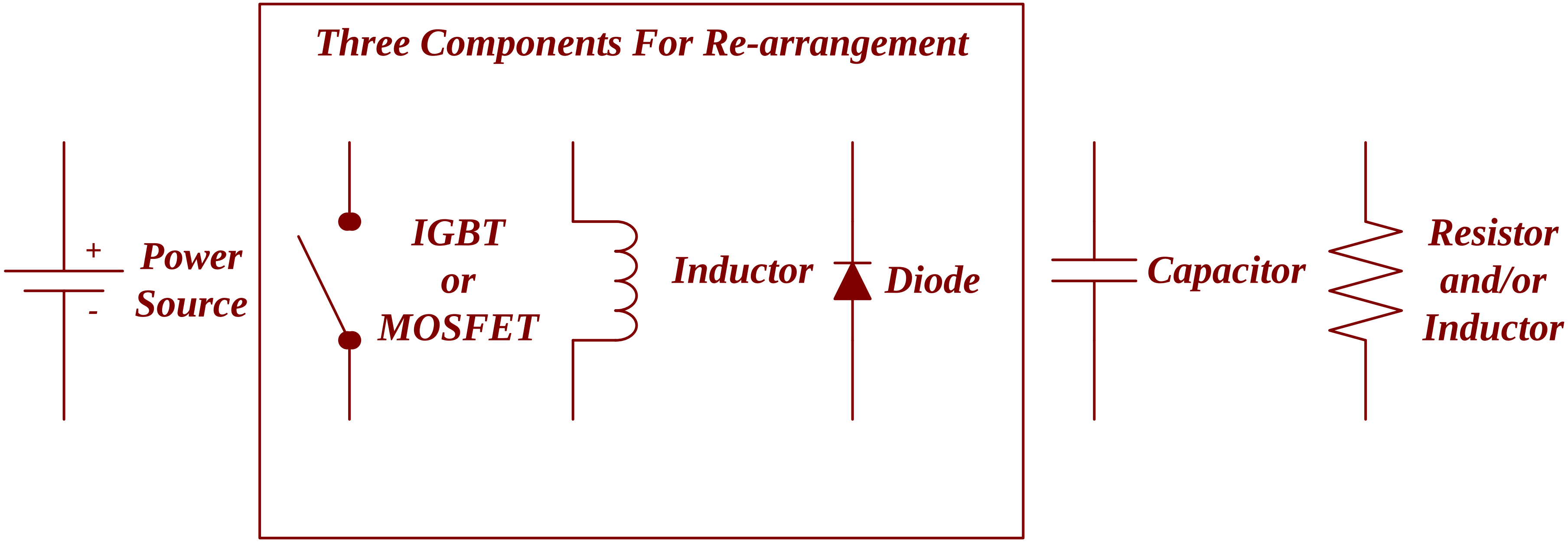
Typical Forward Converters Listed In Order Of Increasing Use

- *Half-bridge Converter*
- *Boost Regulator*
- *Buck Regulator*
- *Full-bridge Converter*

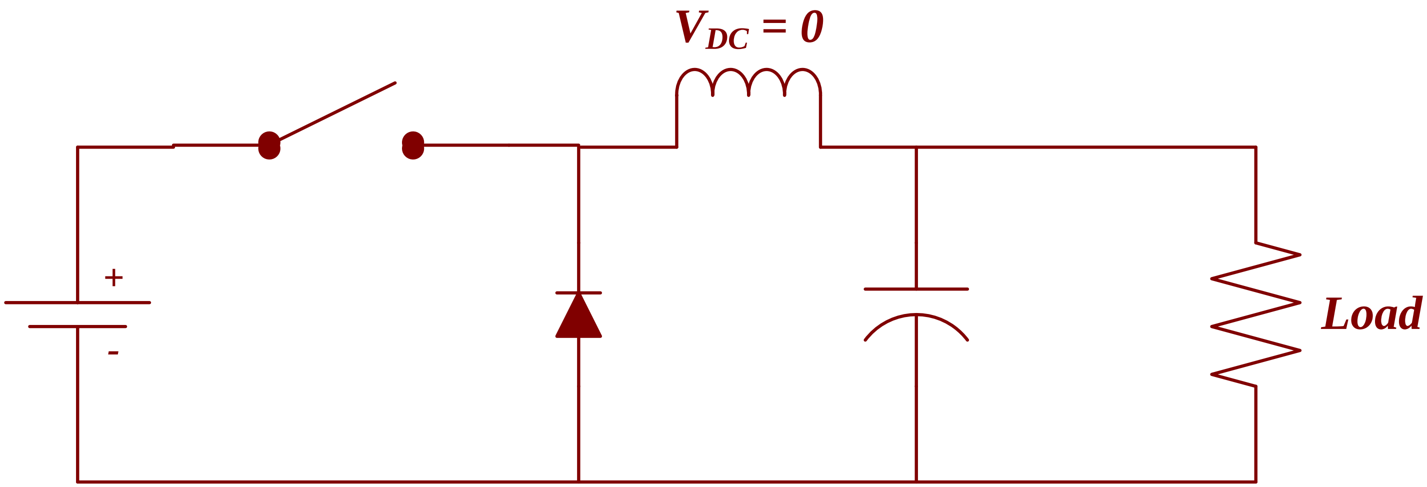
Typical Forward Converters Listed in Order of Increasing Complexity

- *Buck Regulator*
- *Boost Regulator*
- *Half-bridge Converter*
- *Full-bridge Converter*

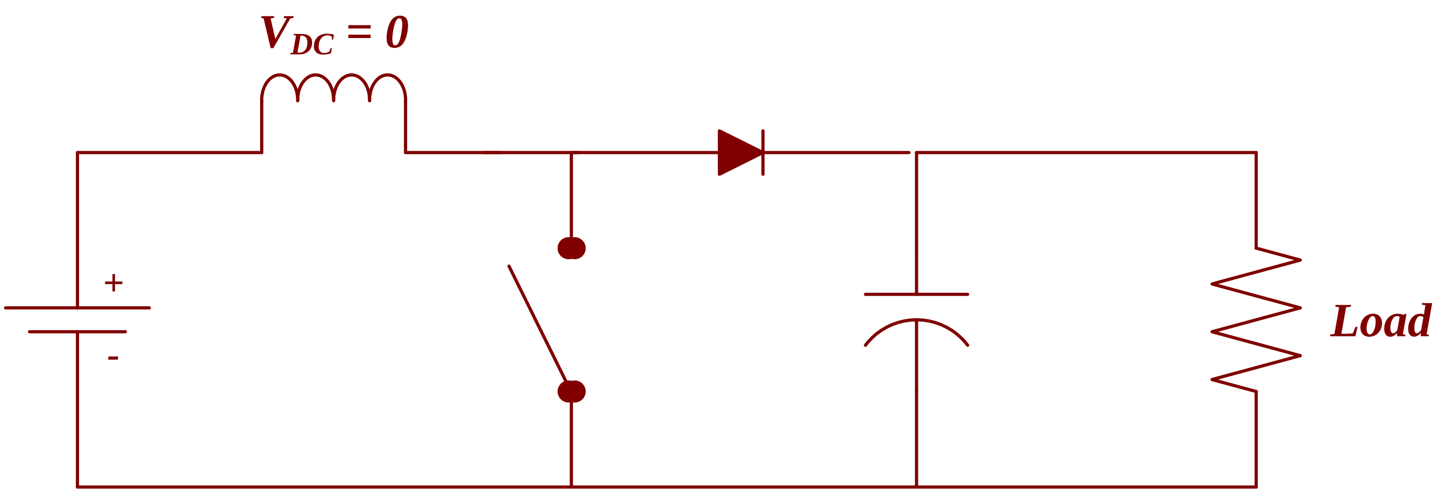
Basic switchmode tool kit



Most fundamental switchmode converter topologies are constructed by rearranging the three components

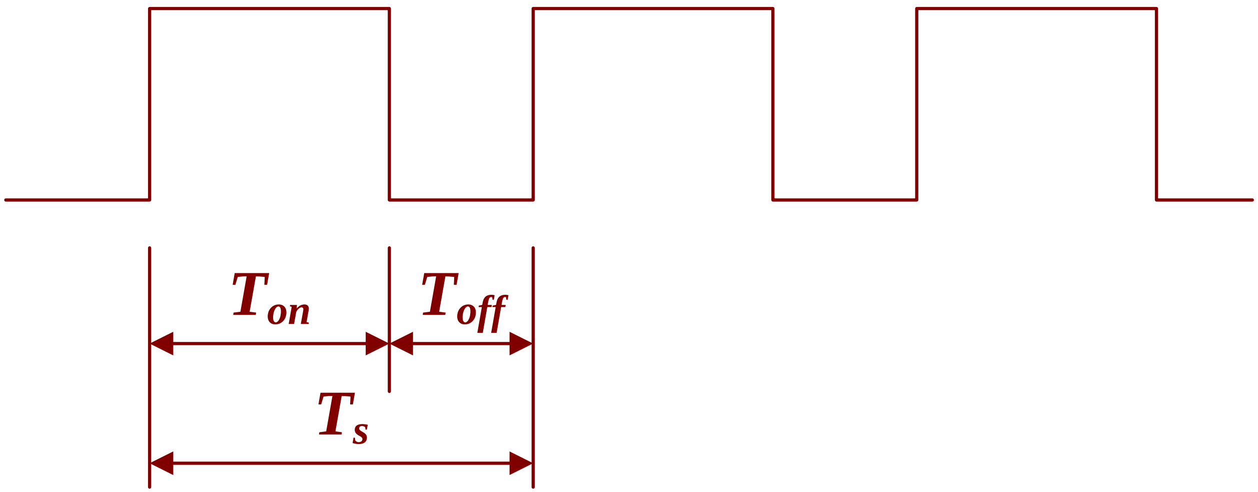


Buck



Boost

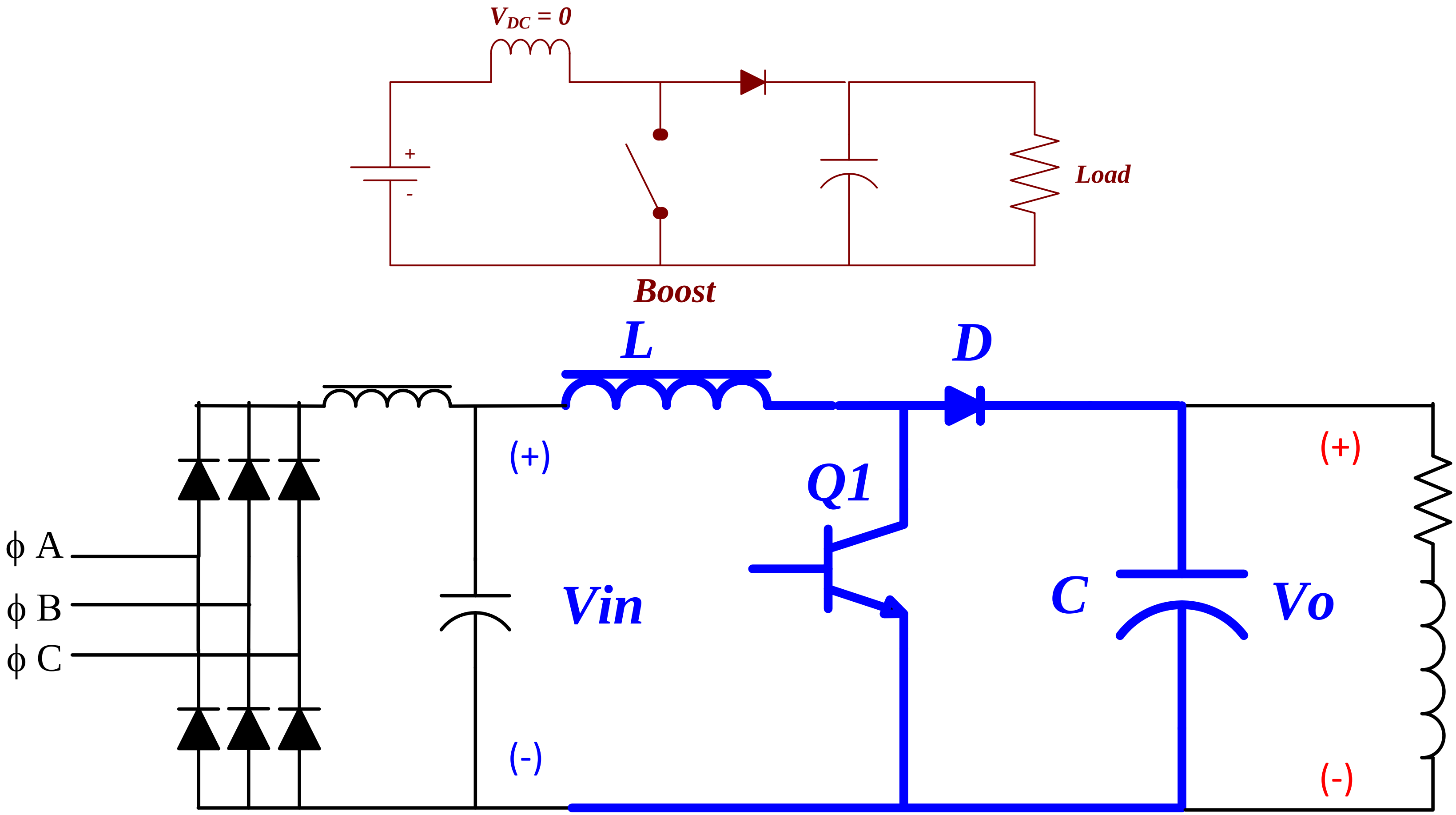
Definition of the Pulse Width Modulated (PWM) Waveform



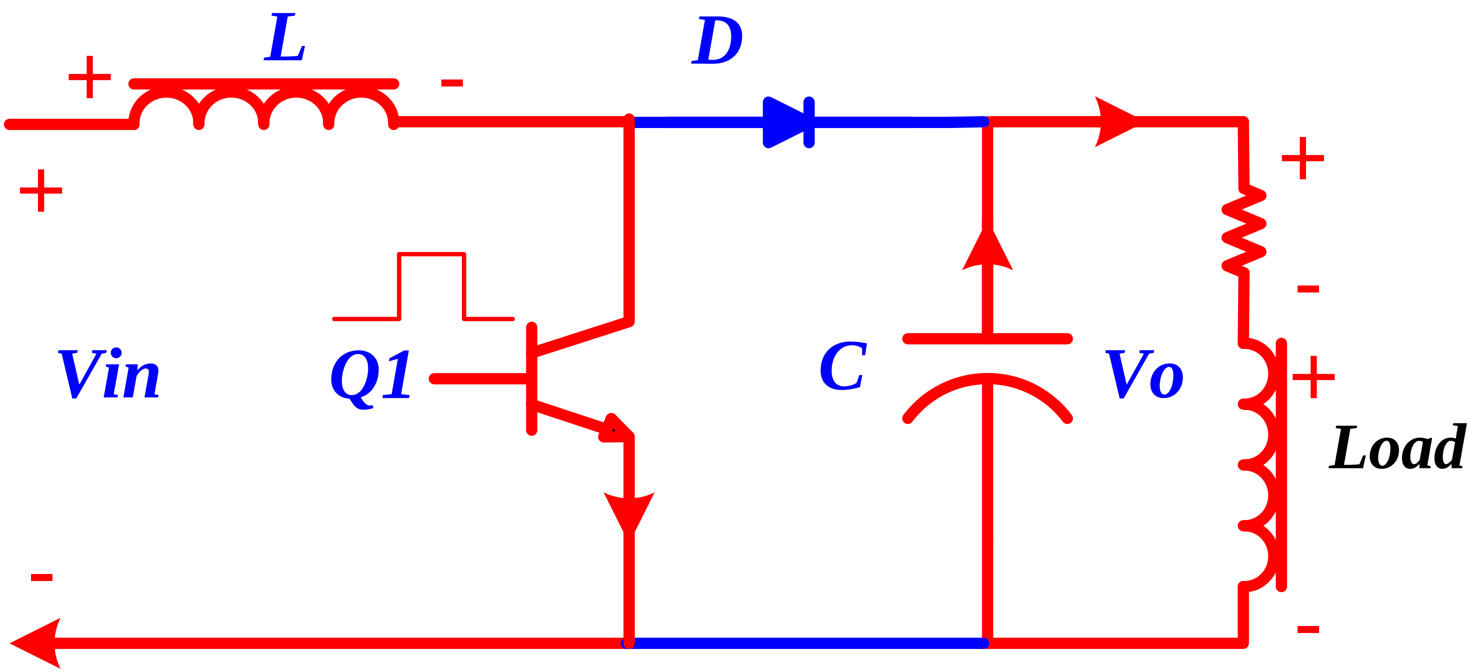
$$Duty\ Cycle = Duty\ \ Ratio = D = \frac{T_{on}}{T_{on} + T_{off}} = \frac{T_{on}}{T_s}$$

$$D' = 1 - D = \frac{T_{off}}{T_{on} + T_{off}} = \frac{T_{off}}{T_s}$$

Topologies - Boost Converter

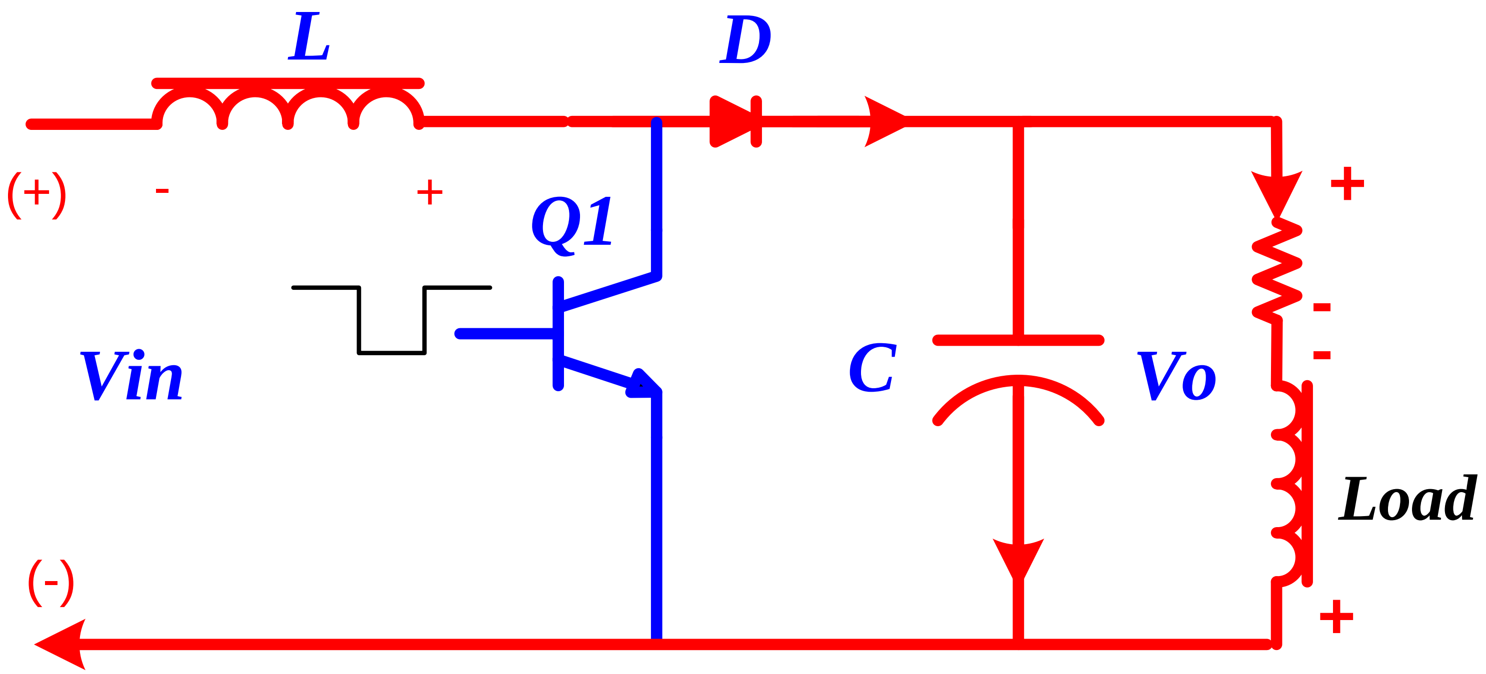


- *Boosts the input voltage to a higher output voltage* $V_o = V_{in}/(1-D)$
- *Input current is smooth (continuous) – output current is discontinuous (chopped)*



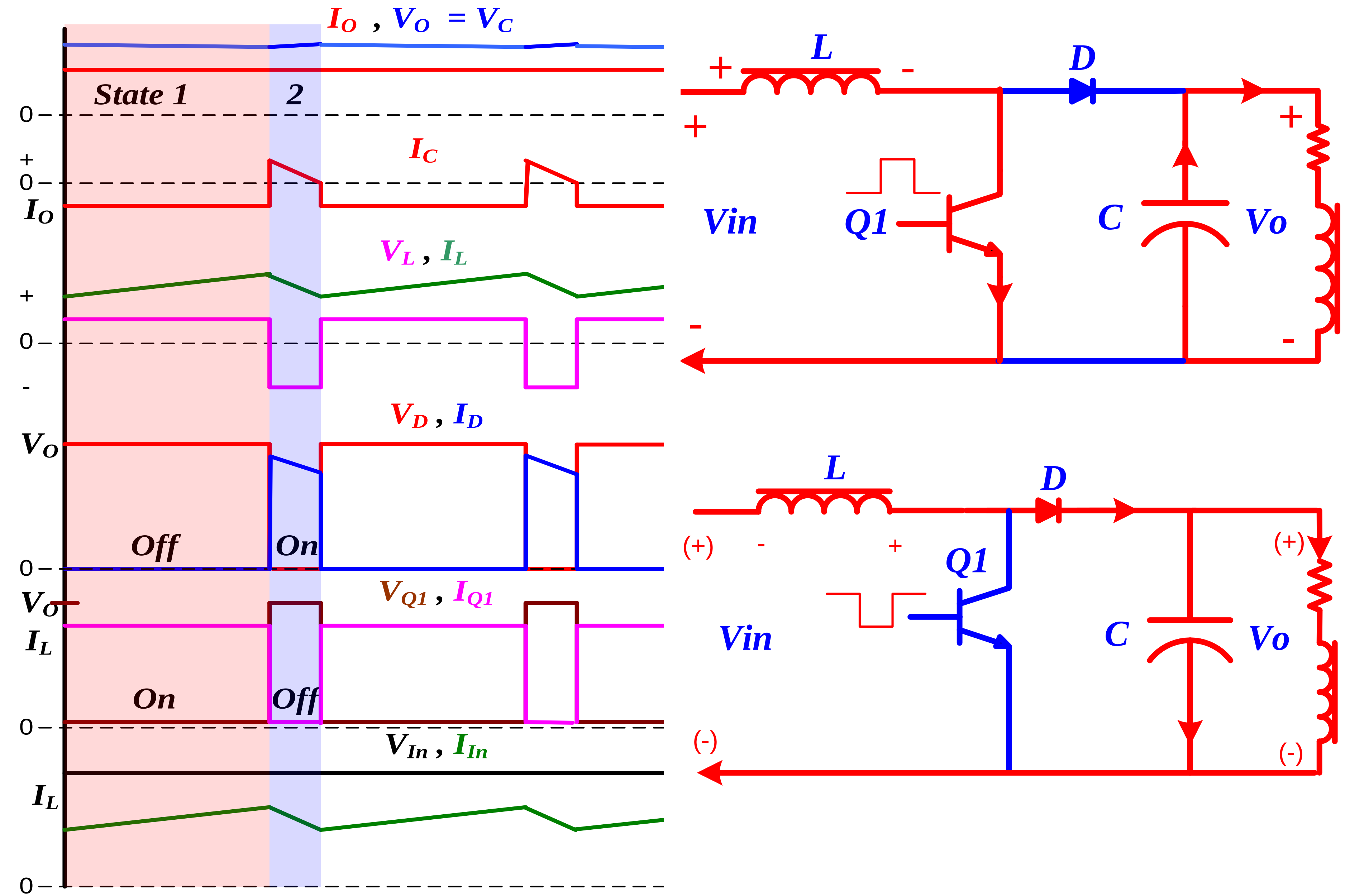
State 1 – Power Transfer

- *Switching device Q1 turned on by square wave drive circuit with controlled on-to-off ratio (duty factor, D)*
- *V_{in} impressed across L*
- *Current in L increases linearly in forward direction*
- *Diode D is reversed biased (open)*
- *Capacitor C discharges into the load*



State 2 - Regulation

- Q1 turned off. L polarity reverses.
- $V_O = V_{In} + V_L$, $V_L = V_O - V_{In}$
- $V_O > V_{In}$, L current decreases linearly
- Diode D is forward biased (closed)
- Capacitor C is recharged



I_O , V_O = V_C
State 1
2
0
I_C
+
0
I_O
V_L , I_L
+
0
-
V_D , I_D
V_O
Off
On
0
V_O
V_{Q1} , I_{Q1}
I_L
On
Off
0
V_{In} , I_{In}
I_L
0
L
D
Vin
Q1
C
Vo
(+)
(-)

Summary

- Output polarity is the same as the input polarity
- In steady-state, L volt-seconds with Q1 on = volt-seconds with Q1 off

$$V_{In} * t_{on} = (V_O - V_{In}) * t_{off}$$

$$V_O = V_{In} *(t_{on} + t_{off}) / t_{off}$$

$$V_O = V_{In} / (1 - D)$$

- Output voltage is always greater than the input voltage because $D \leq 1$
- IGBT duty factor (D) range 0 to 0.95
- Limitation of D yielding greater output voltage is the limitation on the input current through the inductor and diode
- Output voltage is not related to load current so output impedance is very low (approximates a true voltage source).

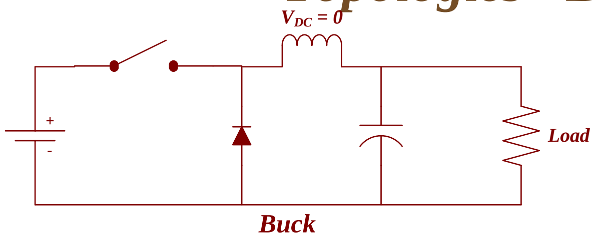
Some Advantages

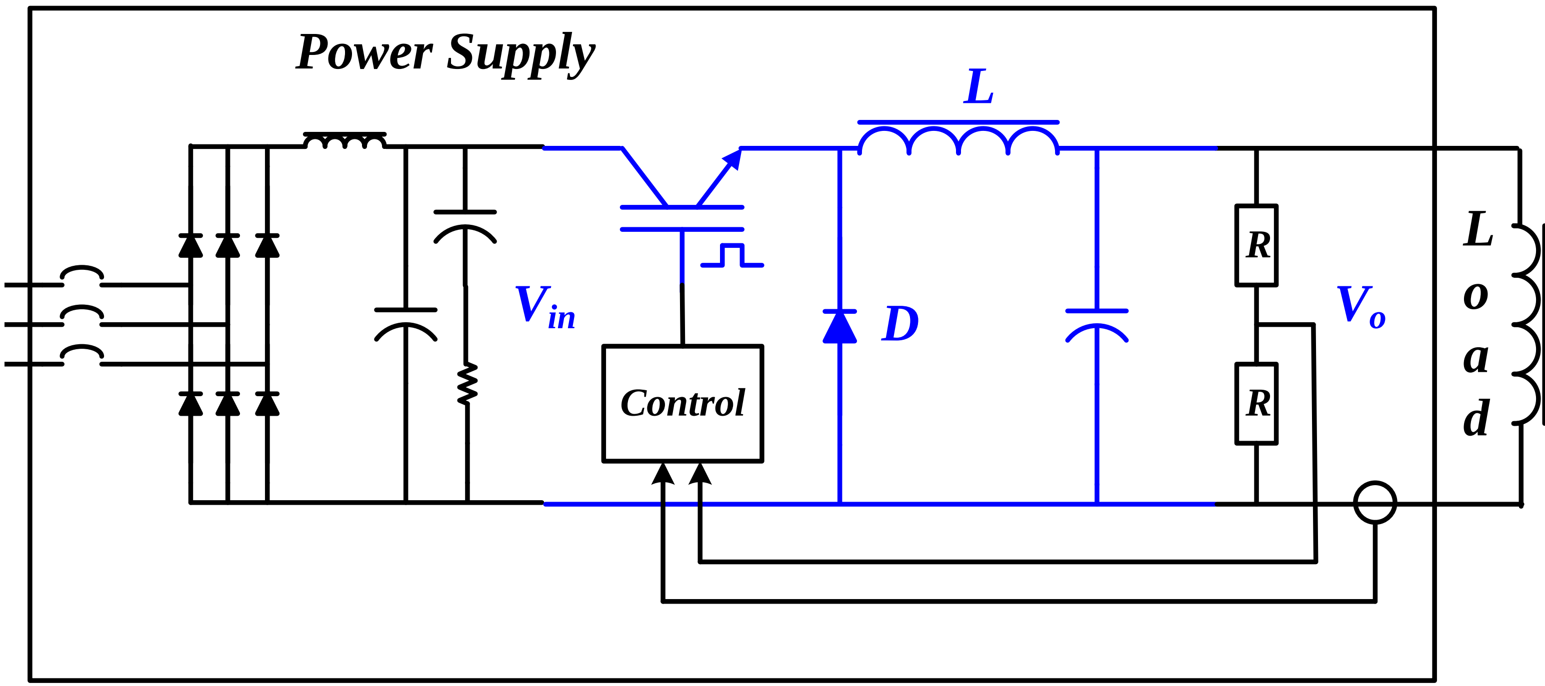
- Few components, 1 switch – simple circuit, high reliability if not overstressed
- Input current is always continuous, so smaller input filter capacitor needed

Some Disadvantages

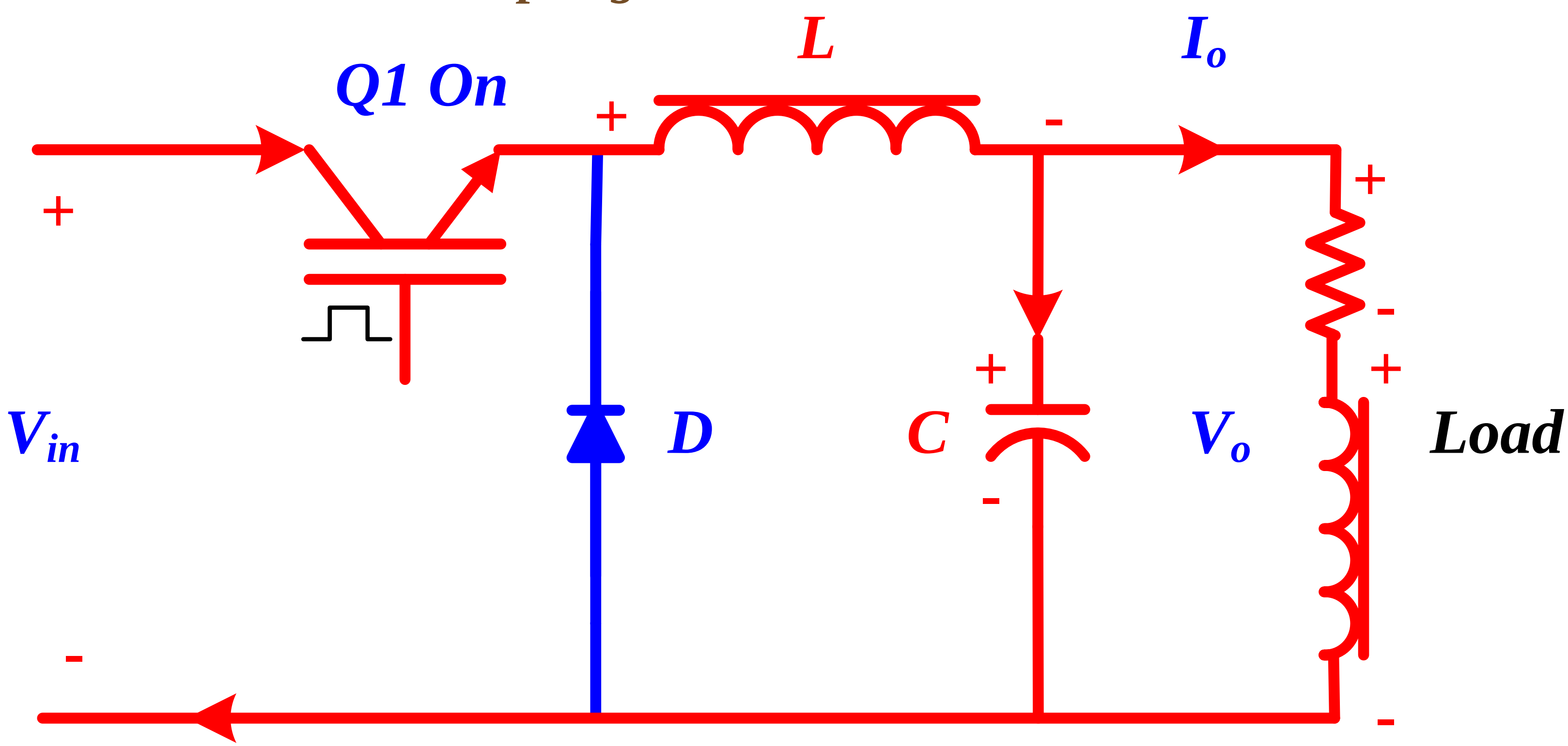
- Capacitor C current is always discontinuous so a much larger output capacitor is needed for same output ripple voltage
- Output is DC and unipolar so no chance of high-frequency transformer or bipolar output
- Low frequency transformer must be used in front of the Boost for isolation and to match the line voltage to the load voltage
- Minimum output voltage equal input voltage

Topologies - Buck Converter (Regulator)



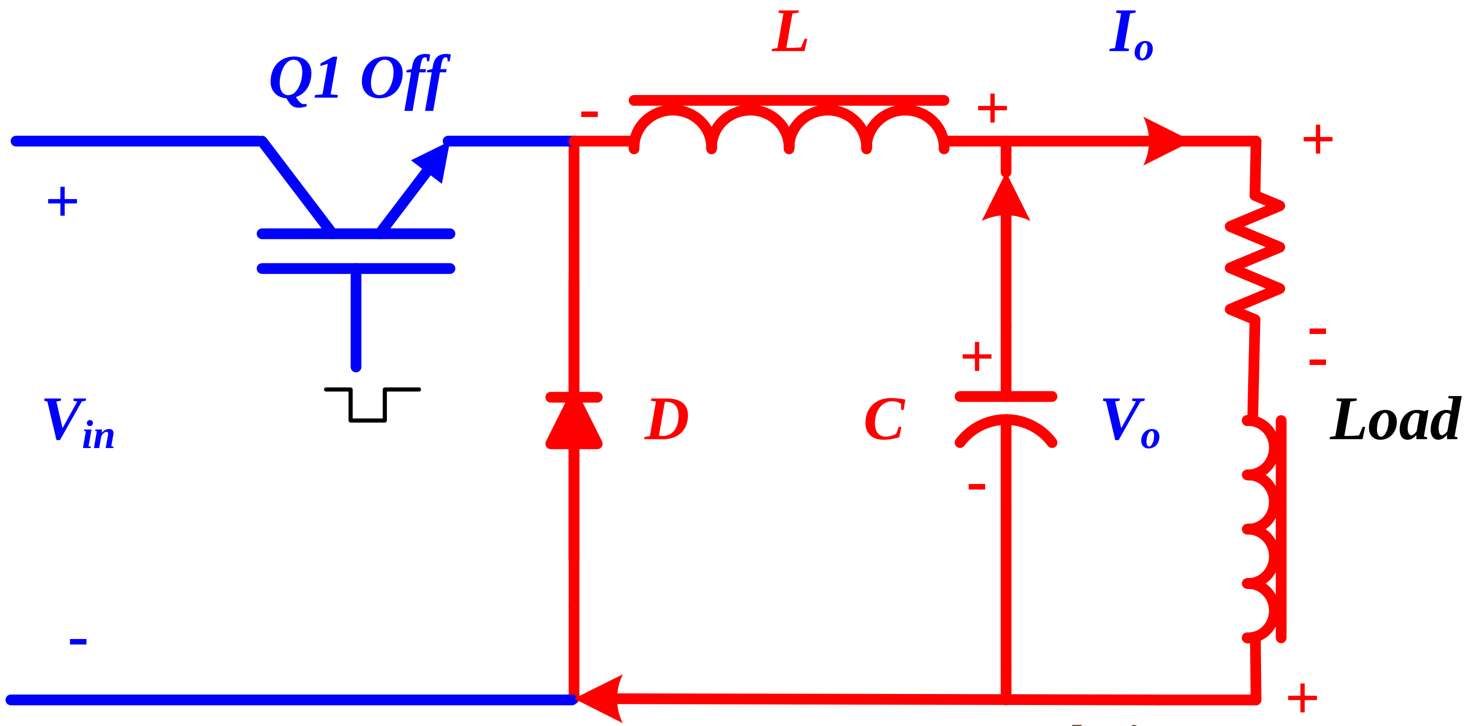


- *Used in the majority of switchmode power supplies*
- *Bucks the input voltage down to a lower voltage*
- *Perhaps the simplest of all*
- *Input current discontinuous (chopped) – output current smooth*



State 1 – Power Transfer

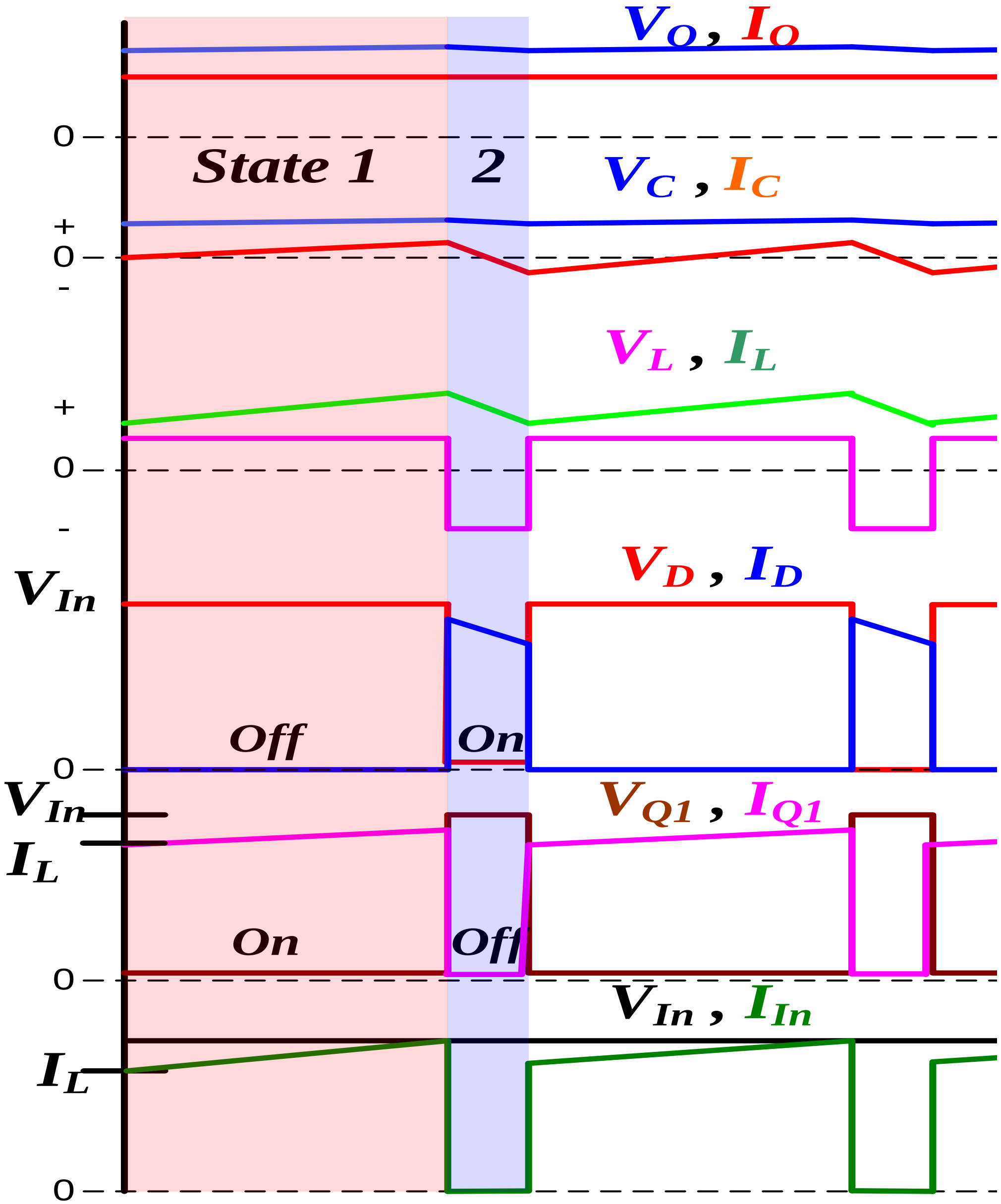
- *Switching device Q1 turned on by square wave drive circuit with controlled on-to-off ratio (duty factor, D)*
- *$V_{in} – V_o$ impressed across L*
- *Current in L increases linearly*
- *Capacitor C charges to Vo*

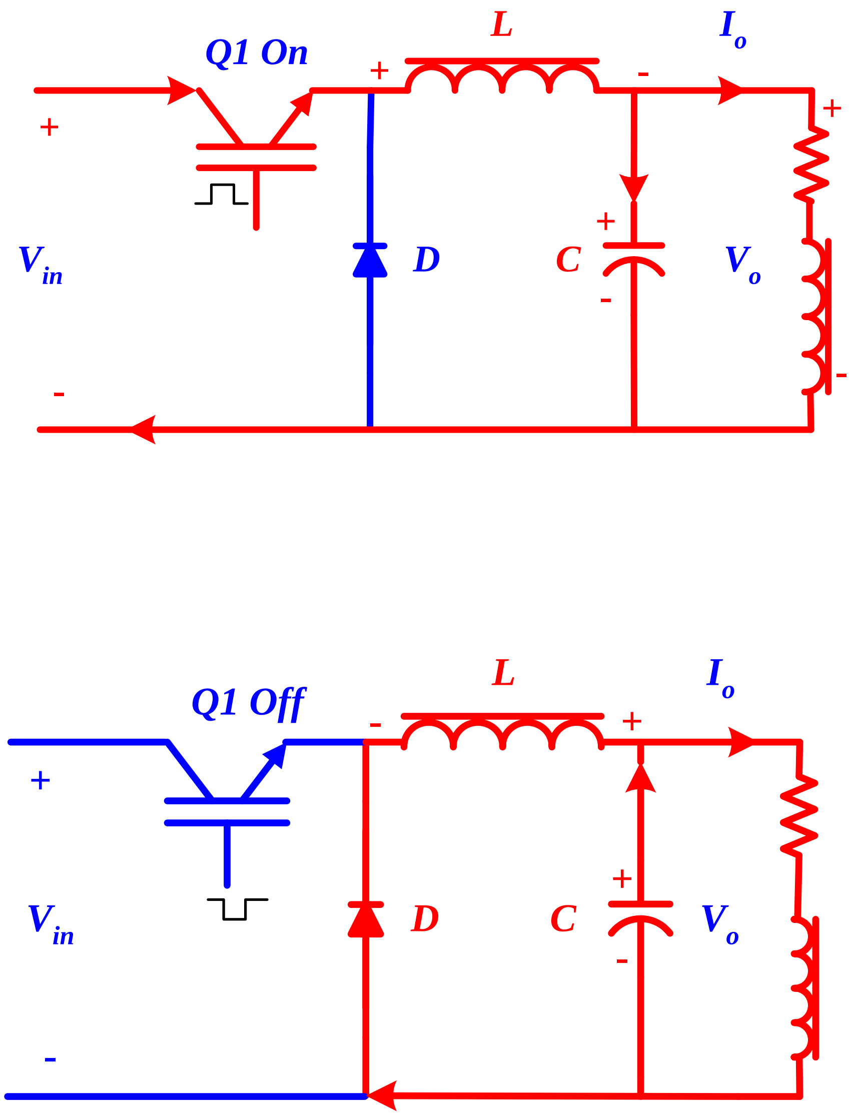


State 2 - Regulation

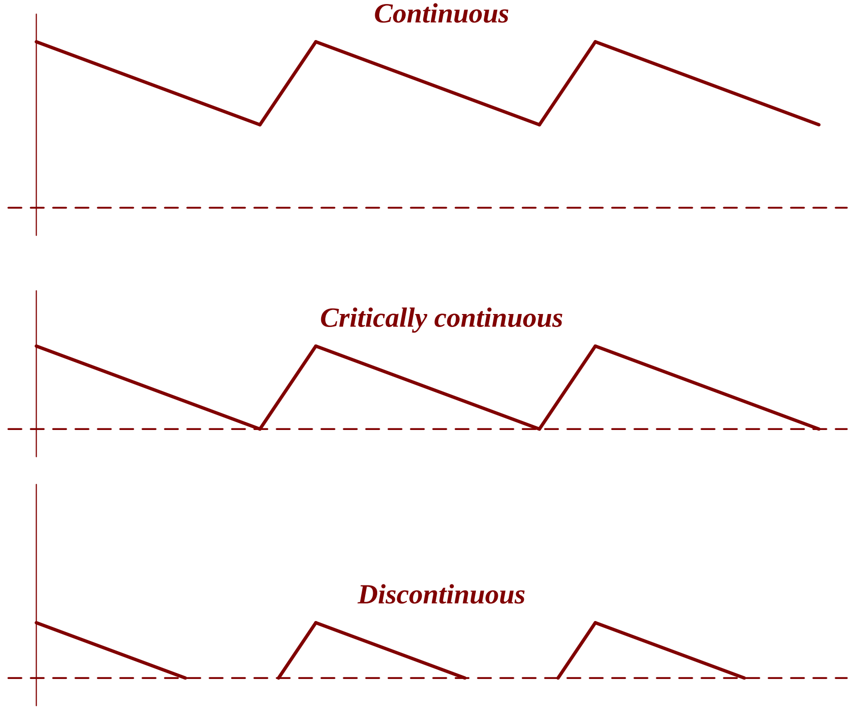
- Switching device Q1 turns off
- Voltage across L reverses: – Vo impressed across L
- Diode D turns on
- Current in L decreases linearly
- C discharges into the Load

Topologies - Buck Converter Waveforms





Buck converter inductor current can be continuous, critically continuous or discontinuous



Discontinuous current is caused by:

- *Too light a load*
- *Too small an inductor*
- *Too small filter capacitor*
- *Discontinuous difficult to control output and output ≠ D* Vin*

Summary

- *Output polarity is the same as the input polarity*
- *In steady-state L volt-seconds with Q1 on = volt-seconds with Q1 off*

$$(V_{In} - V_O) * t_{on} = (V_O * t_{off})$$

$$V_O = V_{In} * t_{on} / (t_{on} + t_{off}) = V_{In} * D$$

- *Output voltage is always less than the input voltage because* $D \leq 1$
- *Switch duty factor (D) range 0 to 0.95*
- *Output voltage is not related to load current so output impedance is very low (approximates a true voltage source)*

An Advantage

- Few components, 1 switch – simple circuit, high reliability if not overstressed

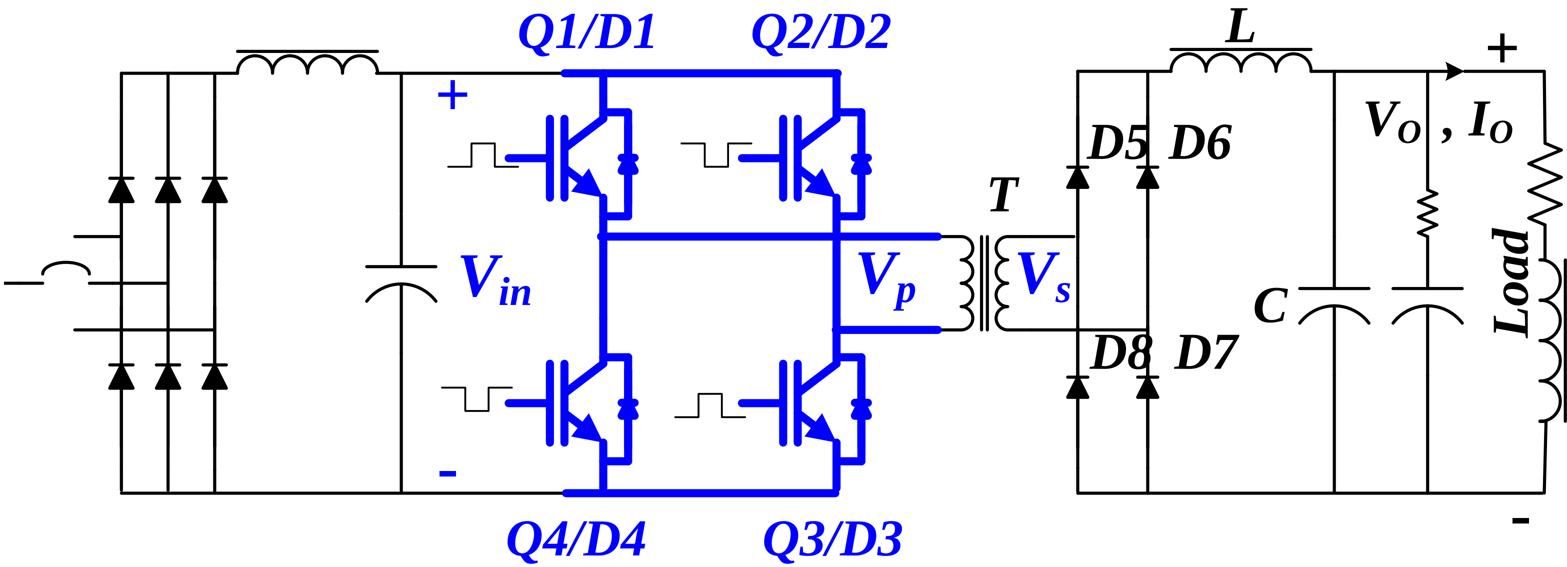
Disadvantages

- Output is DC and unipolar so no chance of high-frequency transformer or bipolar output
- Low frequency transformer must be used in front of the Buck for isolation and to match the line voltage to the load voltage

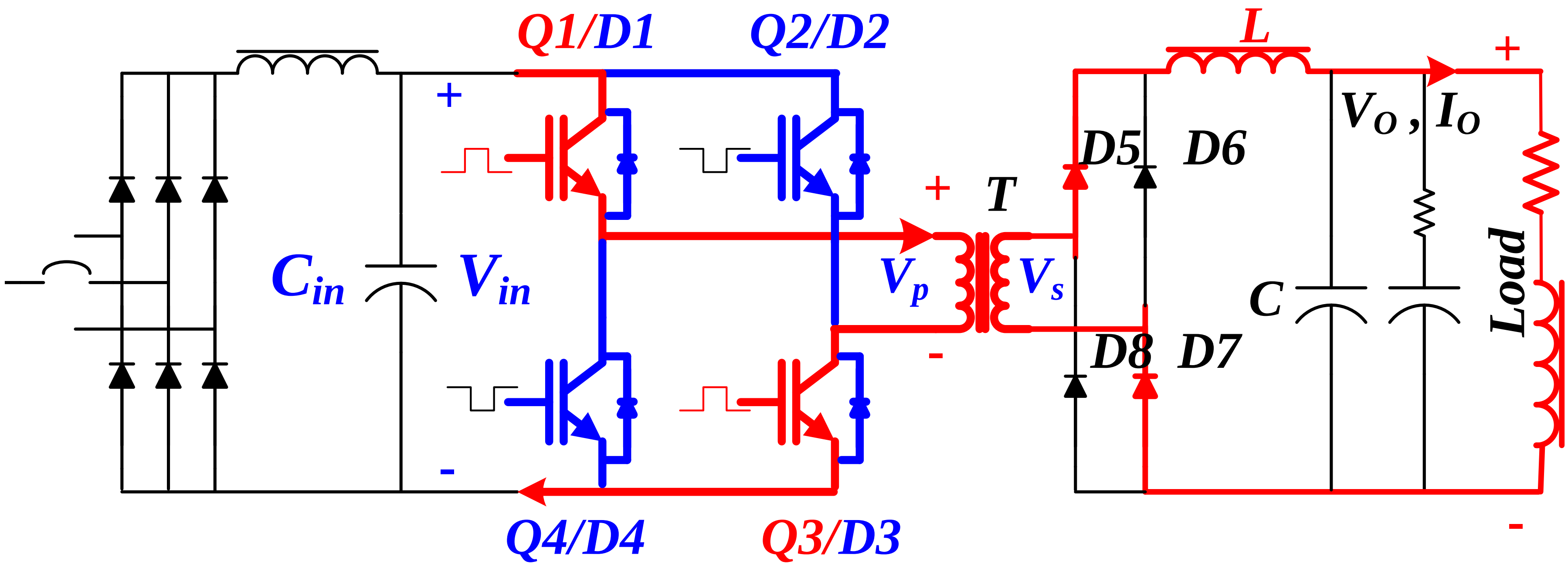
Application

- Used very widely in accelerator power systems, typically for large power supplies (perhaps ≥ 350 kW and used in conjunction with a 12-pulse rectifier with 6-phase transformer)

Topologies - Full-Bridge Converter

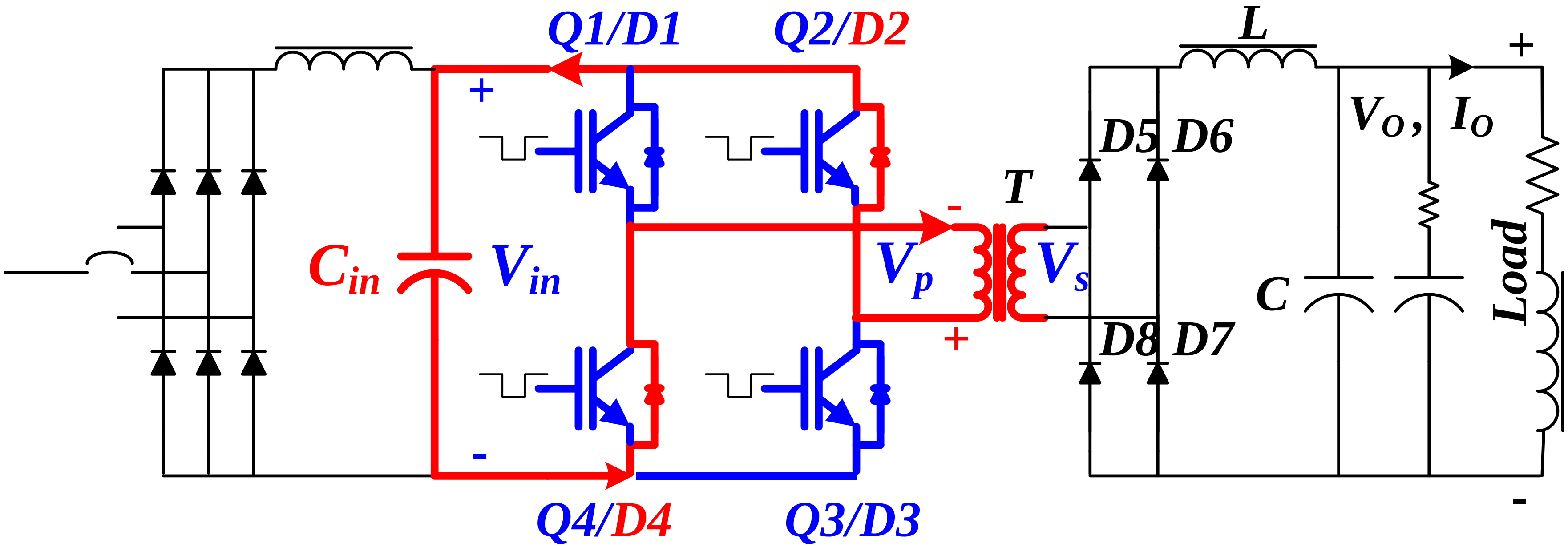


- Full wave rectifier, output ripple is multiples of the input frequency
- Equal in popularity to buck topology for high-power converters
- Used when line and load voltages are not matched
- Voltage stress on switches = input voltage
- Good transformer utilization, power is transmitted on both half-cycles



State 1 - Power

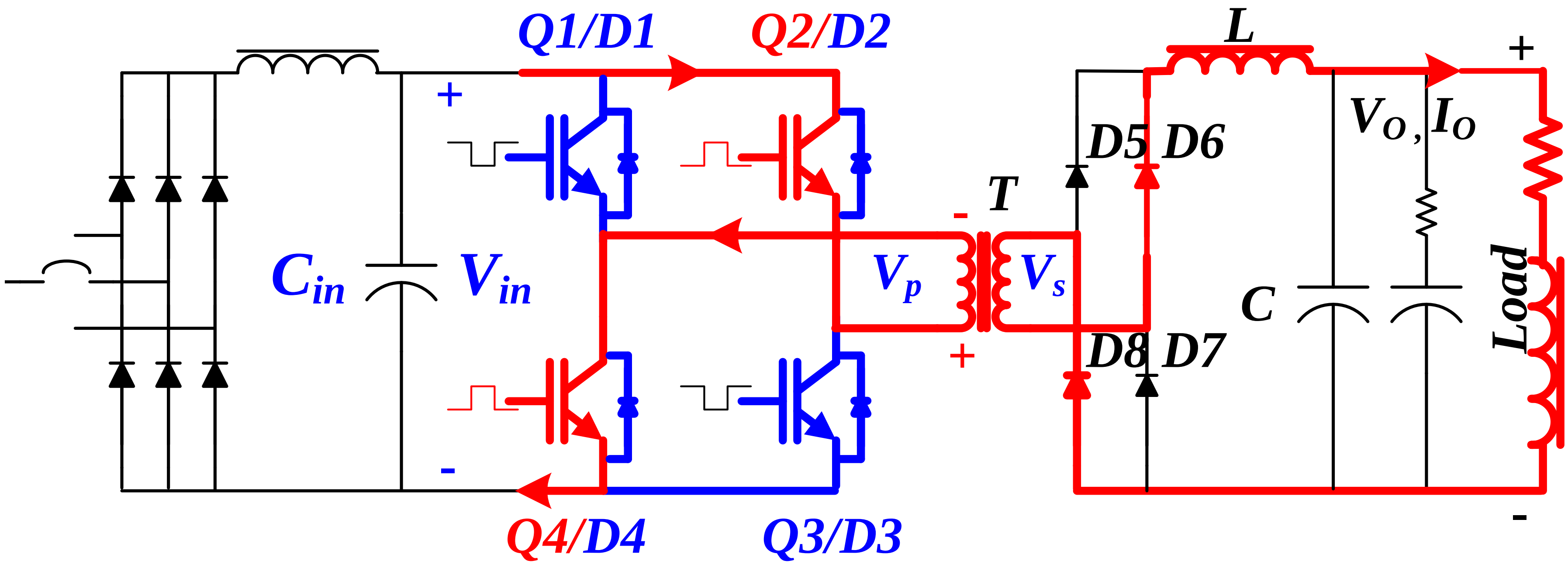
- *Power is derived from the input rectifier and slugs of energy from C_{in}*
- *Q1 and Q3 are closed. Current flows through Q1 and the primary winding of T and Q3*
- *A voltage (V_{in}) is developed across the primary winding of T. A similar voltage is (V_{in} *N) is developed across the secondary winding of T*
- *The secondary voltage causes rectifiers D5 and D7 to conduct current*



State 2 - Power Off

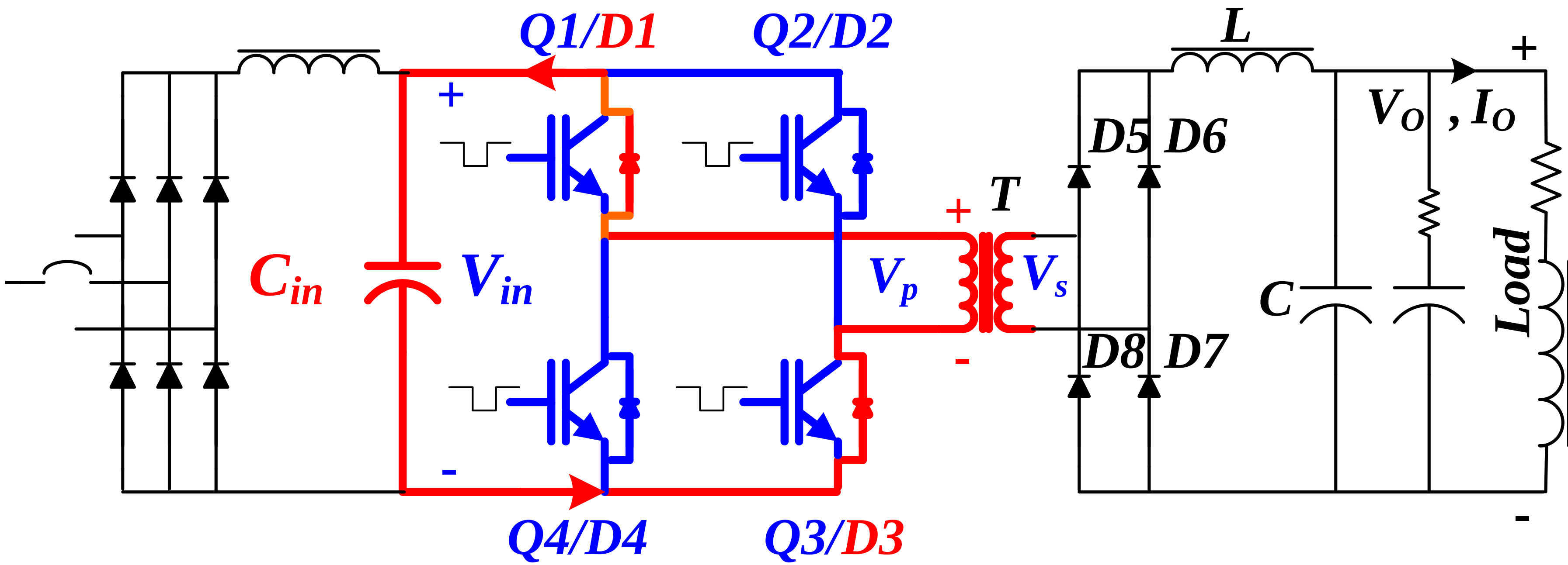
- *Q1 and Q3 are turned off. All switches are off*
- *C_{in} recharges*
- *The transformer primary current flows in the same direction but the voltage reverses polarity. This causes D2 and D4 to conduct. Stored leakage inductance energy is returned to the input filter capacitor. The transformer current decays to zero.*
- *The secondary rectifiers D5, D6, D7 and D8 are all off*

Topologies - Full-Bridge Converter Switching – Q2 and Q4 On, Q1 and Q3 Off



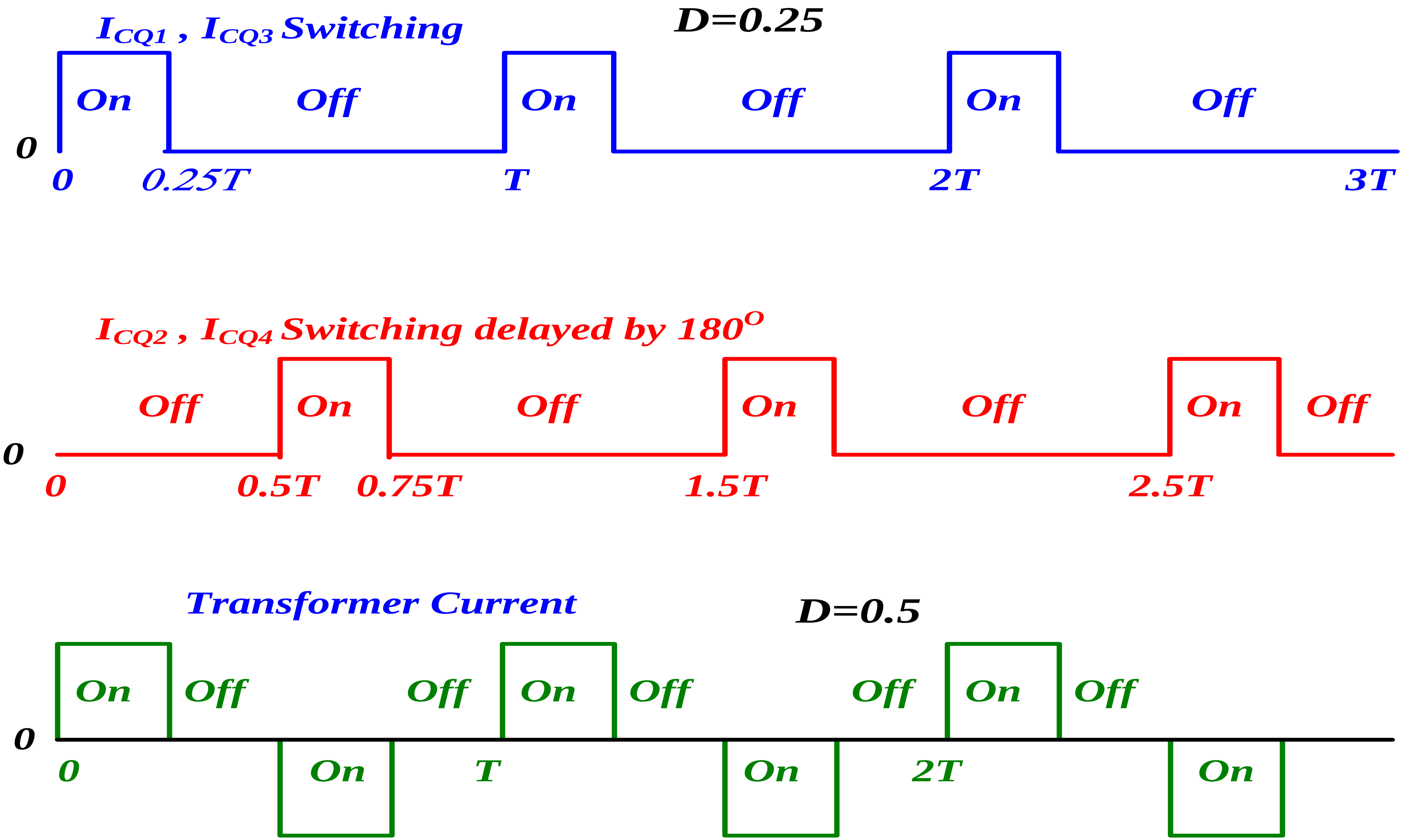
State 3 - Power

- *Power is derived from the input rectifier and slugs of energy from C_{in}*
- *Q2 and Q4 are closed and current flows through Q2, the primary winding of T and Q4*
- *A voltage (V_{in}) is developed across the primary winding of T. A similar voltage (Vin*N) is developed across the secondary winding of T*
- *The secondary voltage causes rectifiers D6 and D8 to conduct current*

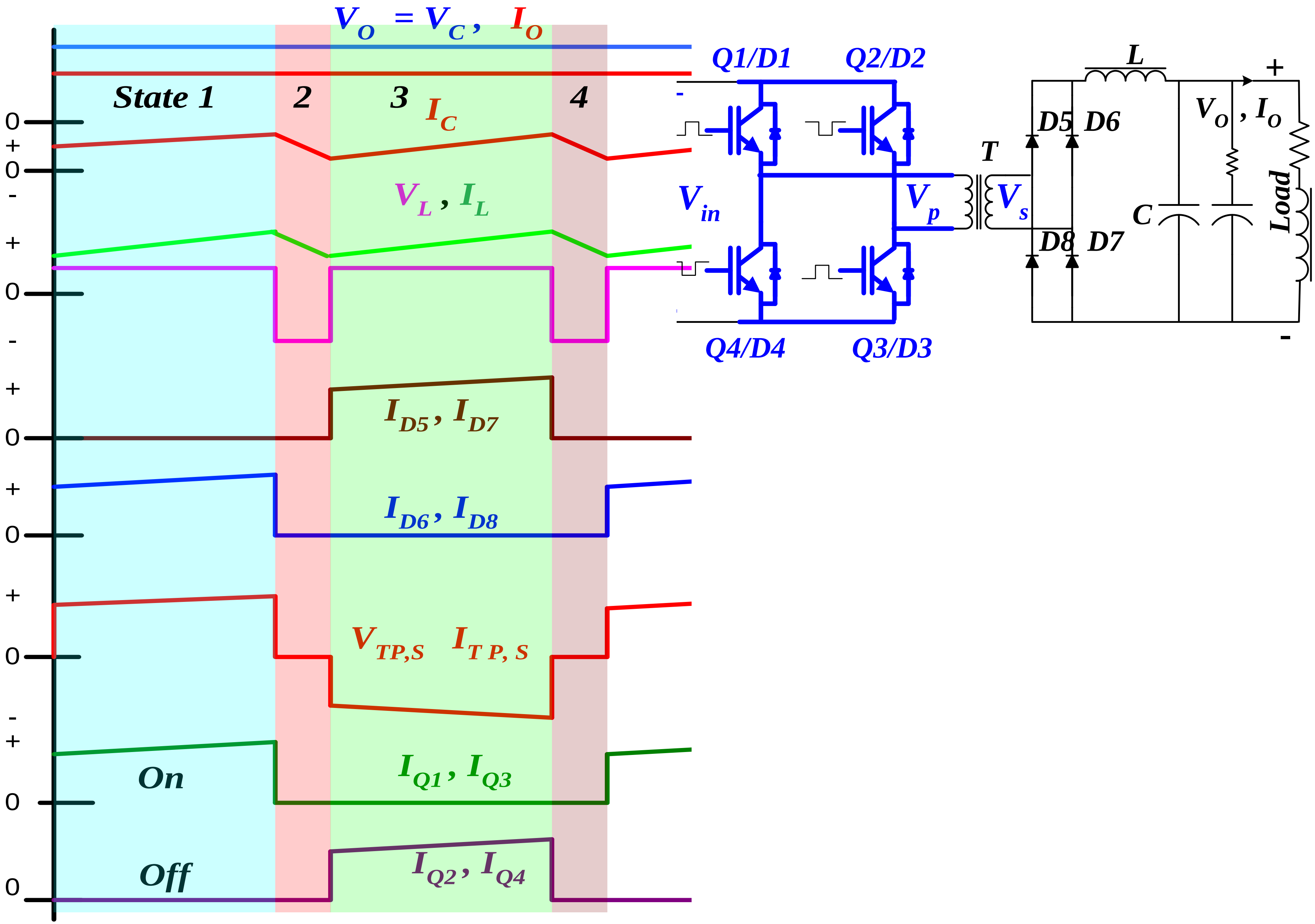


State 4 – Power Off

- *Q2 and Q4 are turned off. All switches are off*
- *C_{in} recharges*
- *The current in the transformer primary flows in the same direction but the voltage reverses polarity. This causes D1 and D3 to conduct. Stored leakage inductance energy is returned to the input filter capacitor. The transformer current goes to zero.*
- *The secondary rectifiers D5, D6, D7 and D8 all turn off*


I_{CQ1} , I_{CQ3} Switching
D=0.25
On
Off
On
Off
On
Off
0
0
0.25T
T
2T
3T
I_{CQ2} , I_{CQ4} Switching delayed by 180^O
Off
On
Off
On
Off
On
Off
0
0
0.5T
0.75T
1.5T
2.5T
Transformer Current
D=0.5
On
Off
Off
On
Off
Off
On
Off
0
0
On
T
On
2T
On

Topologies - Full Bridge Waveforms



Topologies - Full Bridge Waveforms

- *Some inductive energy can be recovered to recharge input filter C_{in}*
- *Same pulses applied to Q1 & Q3 and the same, but 180^{O} delayed, pulses are applied to Q2 & Q4*
- *Switching sequence is Q1 & Q3 are turned on, then turned off after providing the required ON time*
- *After delay (to account for finite switch turn off and turn on), Q2 & Q4 are turned on. After providing the required ON time, Q2 & Q4 are turned off.*
- *Sequence repeats*
- *Q1 and Q4 or Q2 and Q3 are never turned on together*
- *Only the leading edge (or trailing) edge of the gating and current pulse move*
- *Symmetrical +/- pulse obtained. Must be rectified to provide a DC output*
- *The output ripple is twice the switching frequency*

Topologies - Full Bridge Converter

Advantages

- Simple primary winding needed for the main transformer, driven to the full supply voltage in both directions
- Power switches operate under extremely well-defined conditions. The maximum stress voltage will not exceed the supply line voltage under any conditions.
- Positive clamping by 4 energy recovery diodes suppresses voltage transients that normally would have been generated by the leakage inductances.
- The input filter capacitor C_{in} is relatively small
- Modest part count for high reliability.
- Can be used with or without line-to-load matching transformer
- Transformer matches the load to the input line.
- With transformer unipolar output, without transformer, used for bipolar operation
- Capable of high power output (500 kW)

Disadvantage

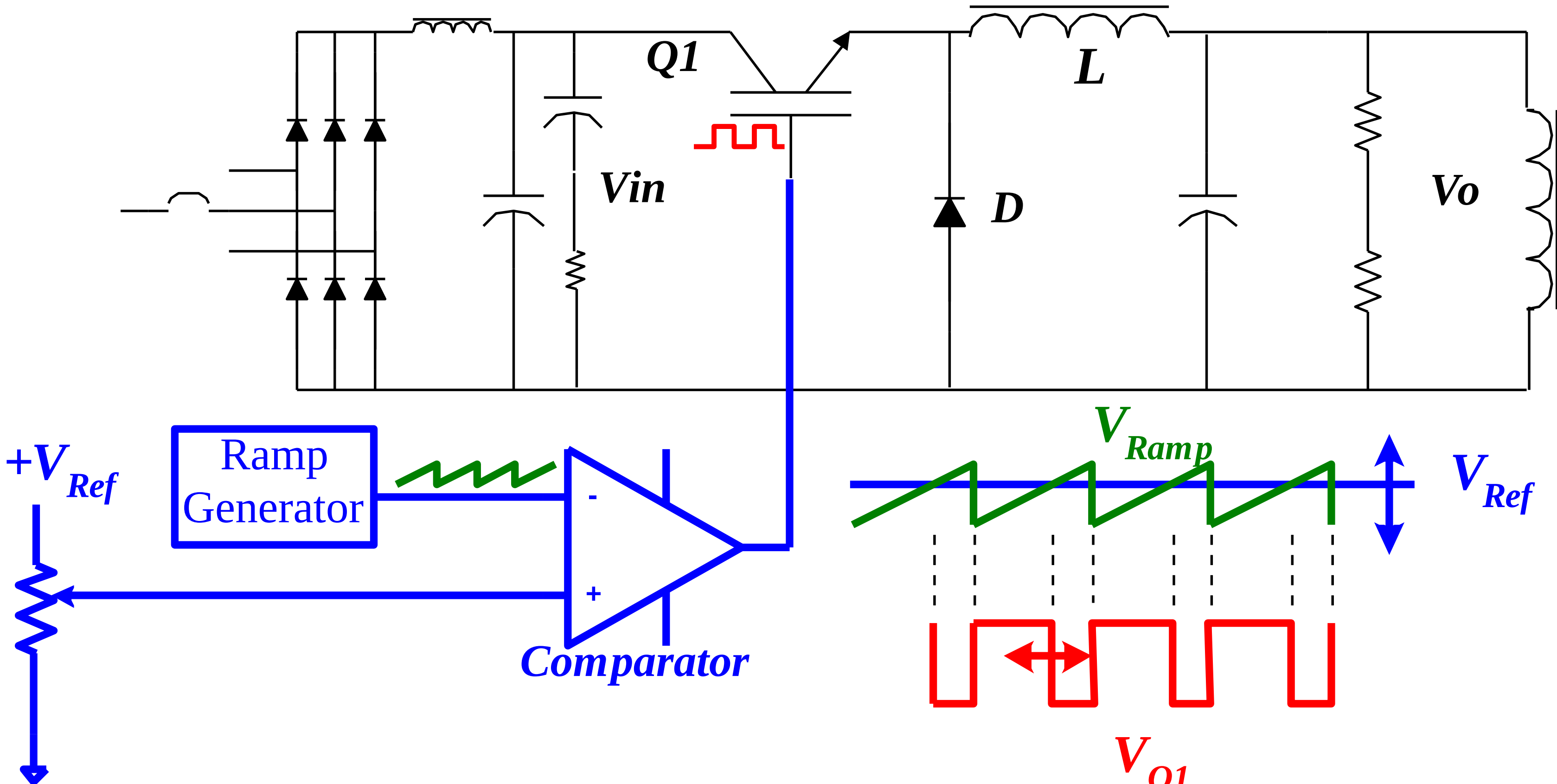
- *Four (4) switches are required, and since 2 switches operate in series, the effective saturated on-state power loss is somewhat greater than in the 2 switch, half-bridge case. In high voltage, off-line switching systems, these losses are acceptably small.*

Topologies - Summary of 3 Forward Converters

Converter Type	Topology	V_o	P_o	Transformer	Output Type
Buck	1 switch	$V_o = V_{in} * D$	Any	Not possible	Unipolar
Boost	1 switch	$V_o = V_{in} / (1-D)$	I_{in} limits Po	Not possible	Unipolar
Full Bridge	4 switches Minor switch losses	$V_o = V_{in} * D * n$	Any	Possible	Unipolar/ bipolar

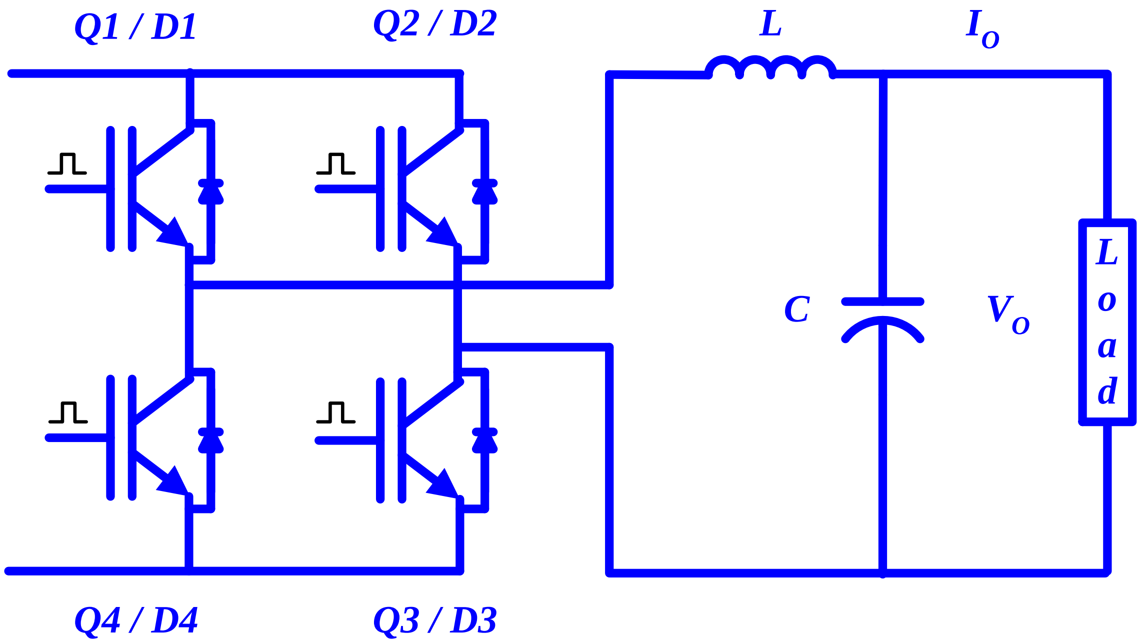
Pulse Width Modulation (PWM) Techniques

Pulse Width Modulation



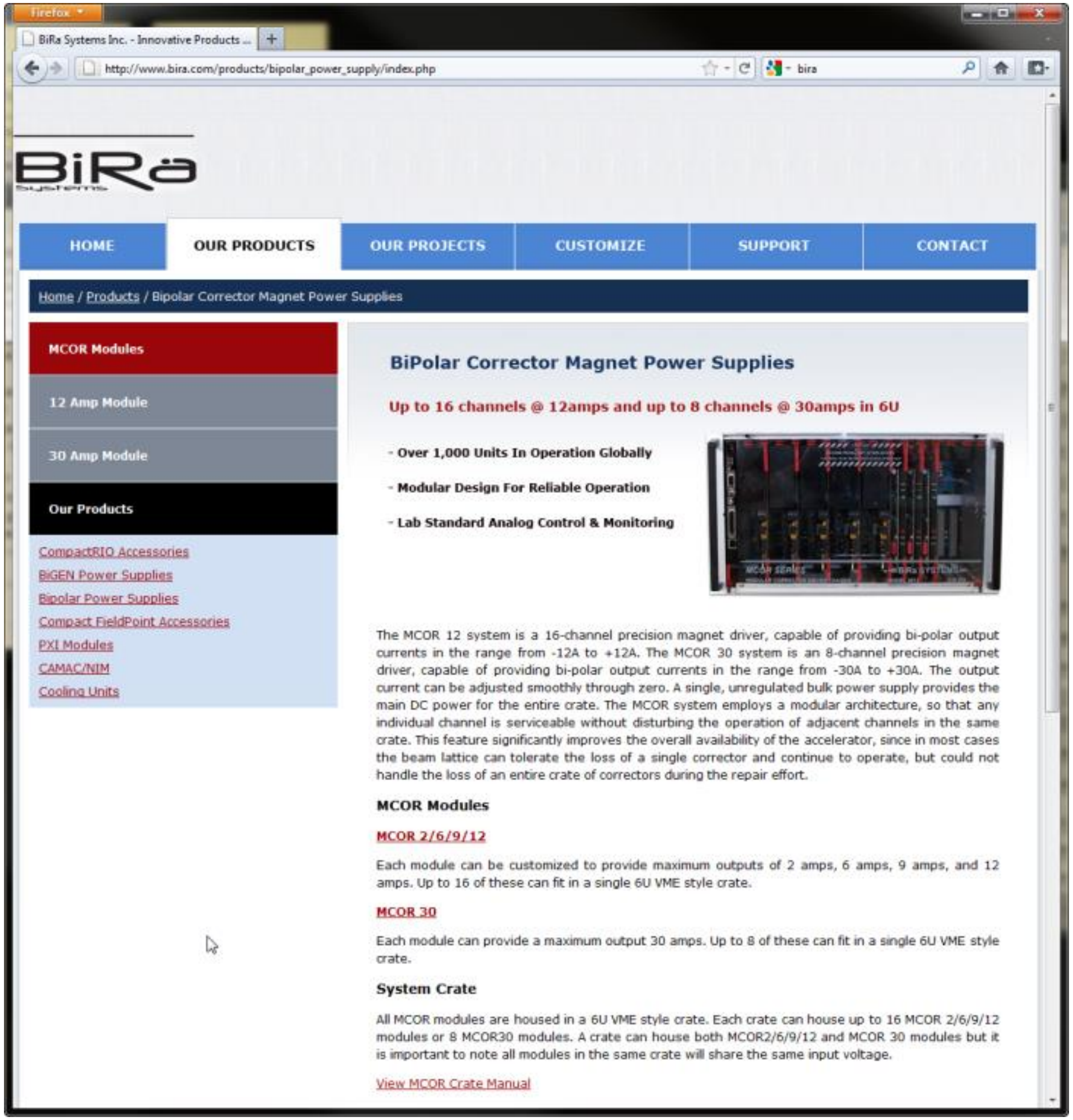
V_{Ref} ↑	$V_{Ref} - V_{Ramp} = V_{Q1}$ pulse width ↑	V_O ↑
V_{Ref} ↓	$V_{Ref} - V_{Ramp} = V_{Q1}$ pulse width ↓	V_O ↓

PWM - Bipolar Bridge



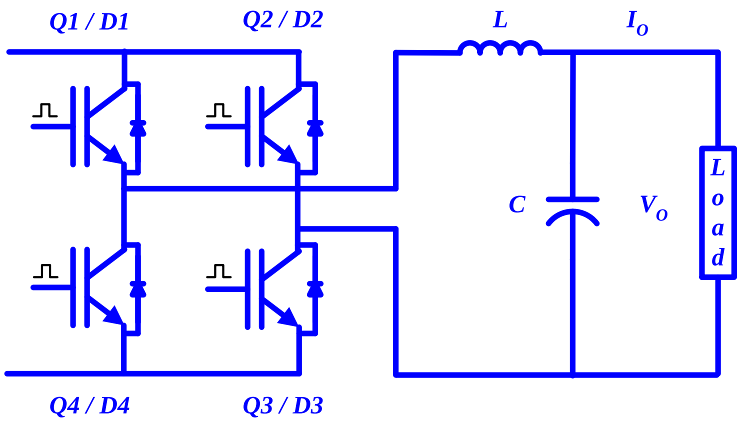
PWM - Bipolar Bridge

http://www.bira.com



PWM - Bipolar Bridge

Generalities



- *Diagonal switching*
- *Two PWMs are usually employed*
- *Switches Q1 and Q3 are the + output leg*
- *Switches Q2 and Q4 are the – output leg*
- *An output rectifier is not required*
- *Since the output desired DC, but contains + and – components, a non-polarized output filter capacitor must be used*
- *2 and 4 quadrant operation is possible*

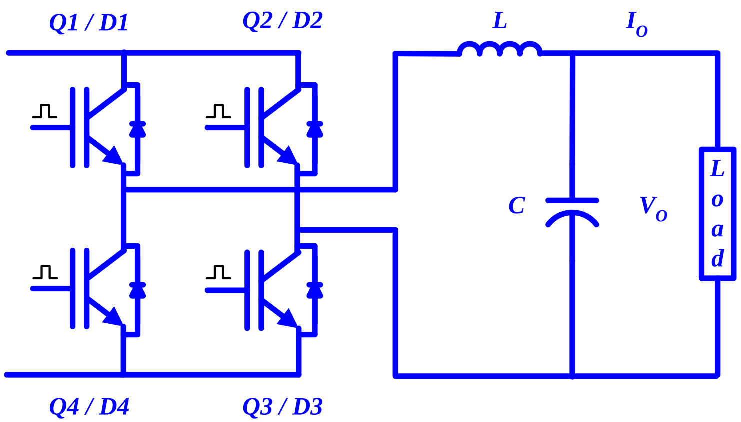
Two types of PWM

- *Sign/magnitude in which the sign of the reference signal determines which pair of switches to turn on and the magnitude determines the pulse duration/duty factor*

- *"50/50" scheme in which there are 2 separate, complimentary PWM signals*

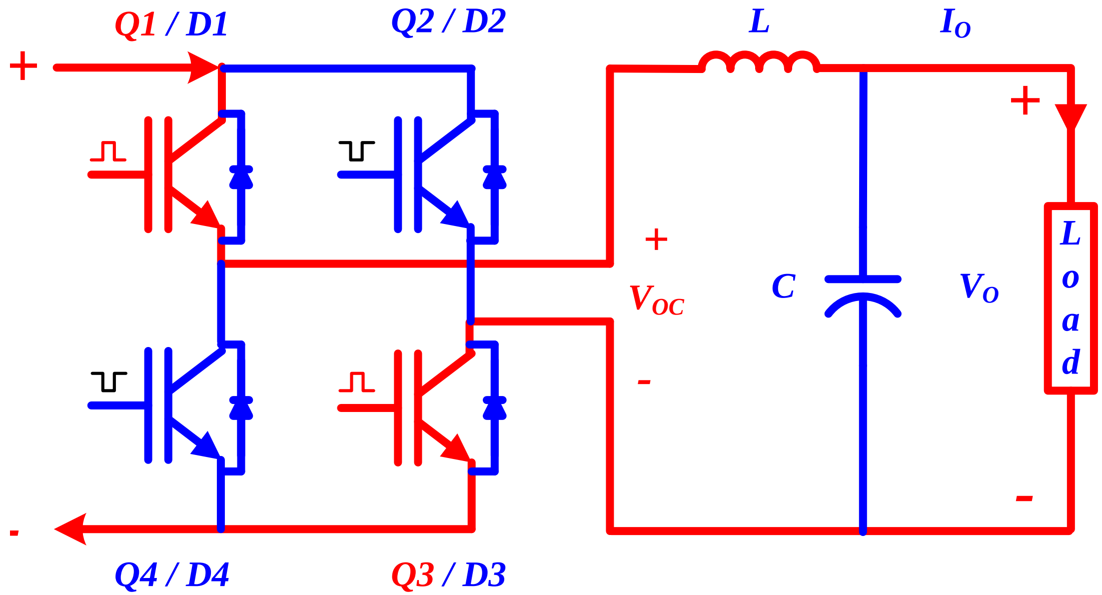
PWM - Bipolar Bridge – Sign / Magnitude PWM

Reference Signal	Q1/Q3 D	Q2/Q4 D
0	Off	Off
+25%	0.25	Off
+50%	0.50	Off
+75%	0.75	Off
+100%	1.00	Off
-25%	Off	0.25
-50%	Off	0.50
-75%	Off	0.75
-100%	Off	1.00

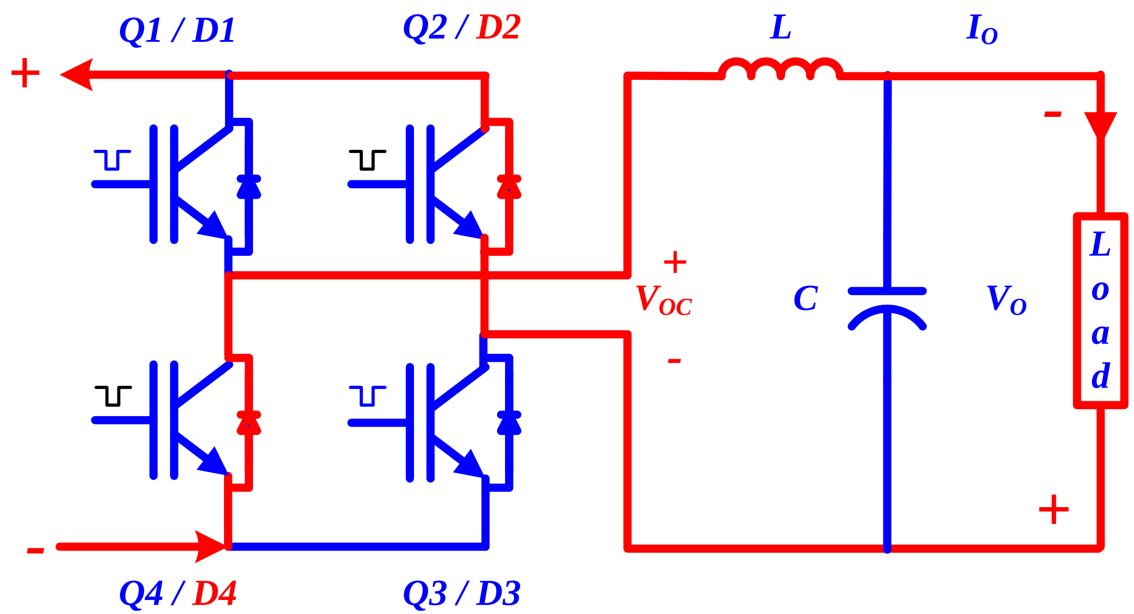


- Switch only one leg at a time
- The 2 switches in the active leg switch on and off together

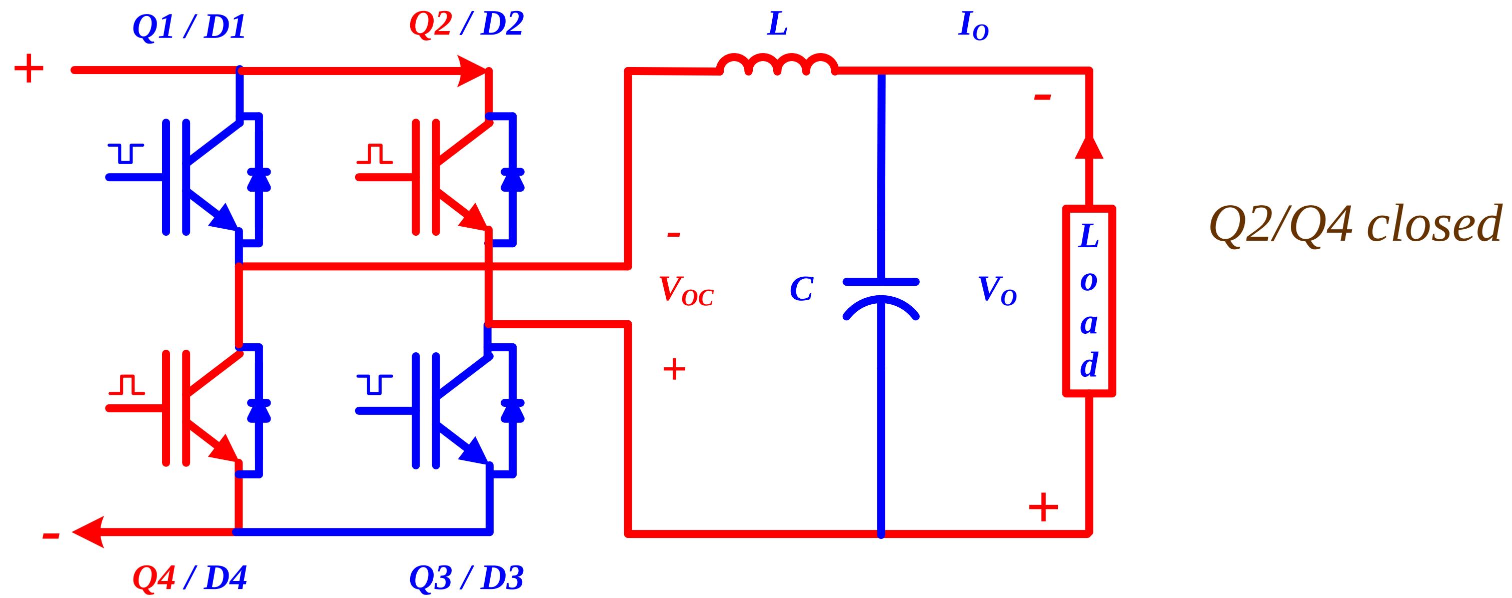
Bipolar Bridge – Sign / Magnitude PWM – (+) Output



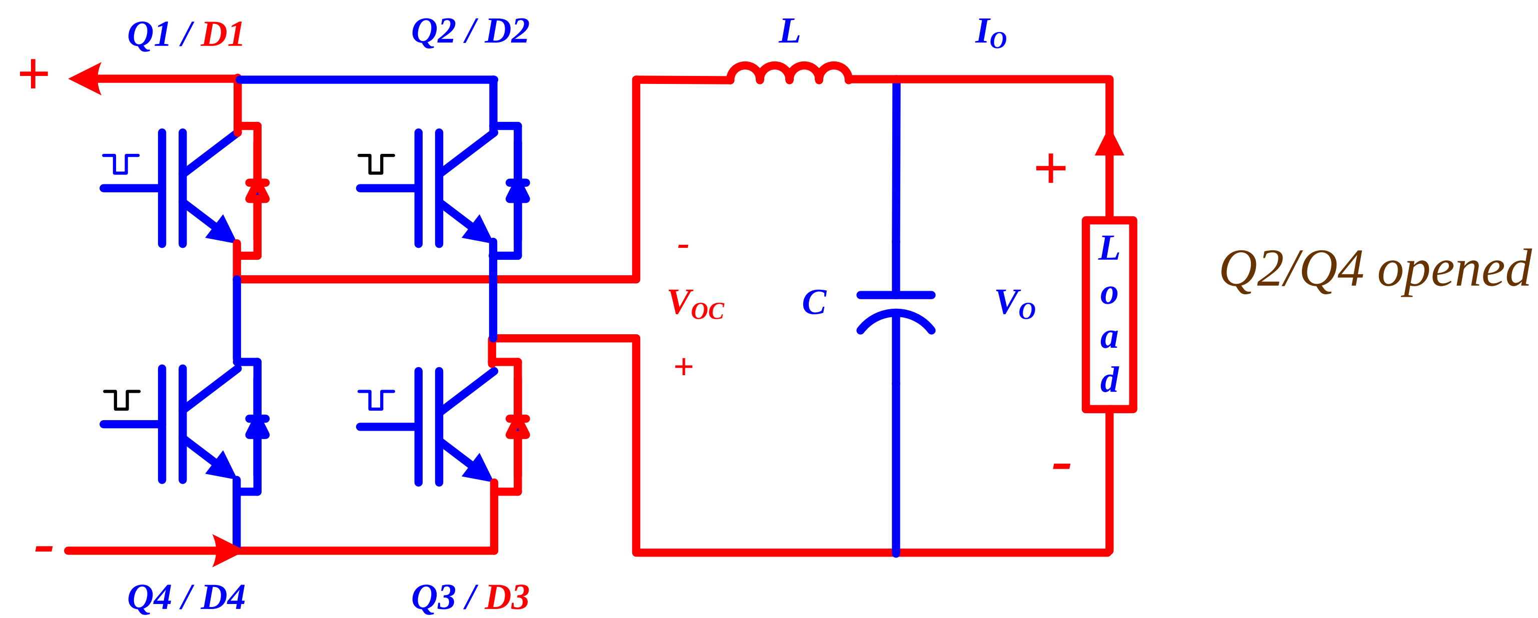
Q1/Q3 closed



Q1/Q3 opened

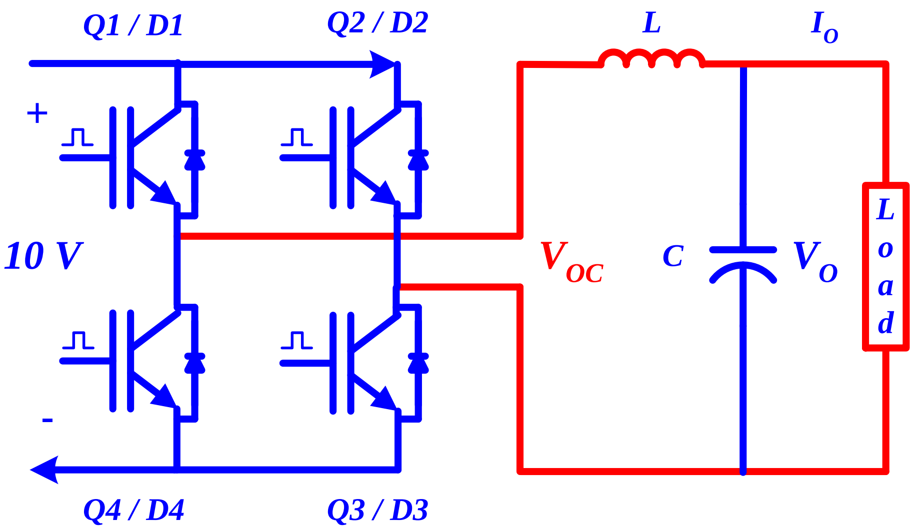


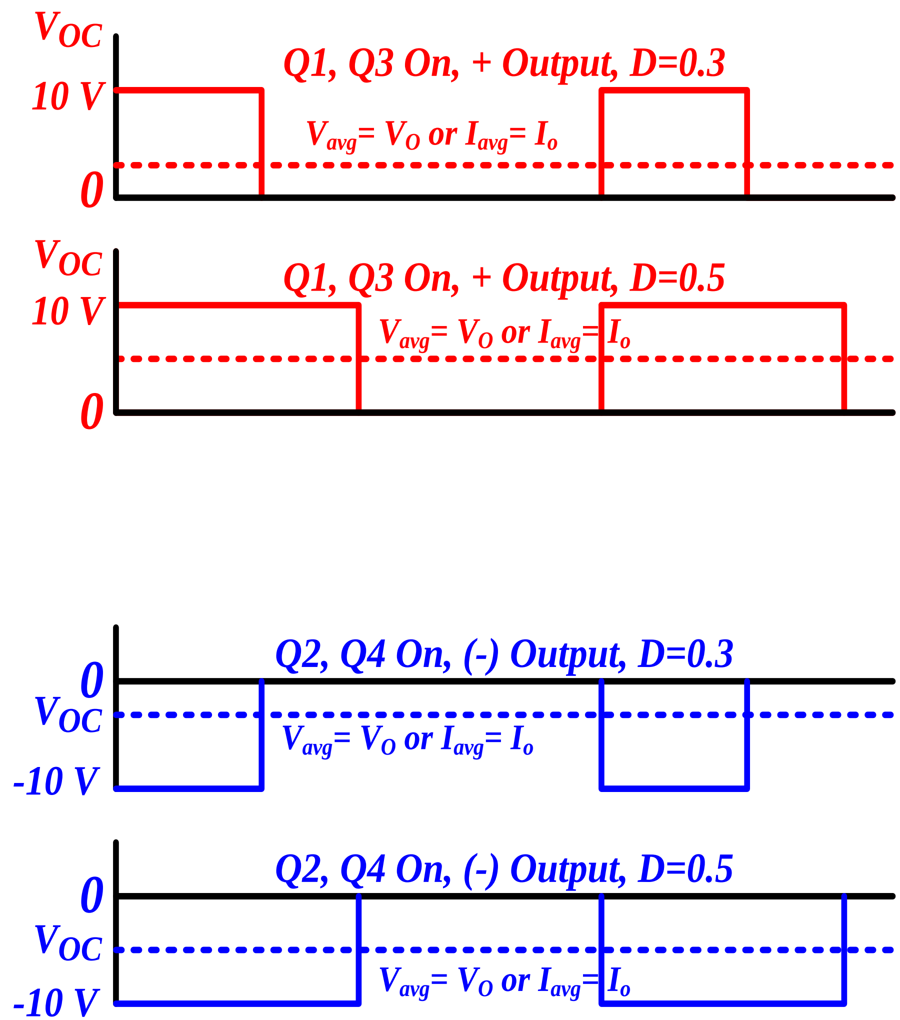
Q1 / D1
Q2 / D2
L
I_O
+
-
-
V_{OC}
+
C
V_O
Load
+
-
Q4 / D4
Q3 / D3
Q2/Q4 closed



Q1 / D1
Q2 / D2
L
I_O
+
+
-
V_{OC}
+
C
V_O
Load
-
-
Q4 / D4
Q3 / D3
Q2/Q4 opened

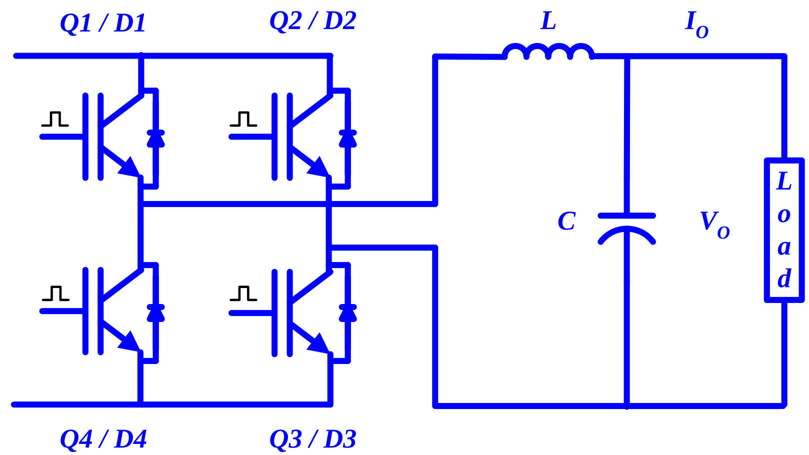
Bipolar Bridge – Sign / Magnitude PWM - Waveforms





"50/50" Bipolar PWM

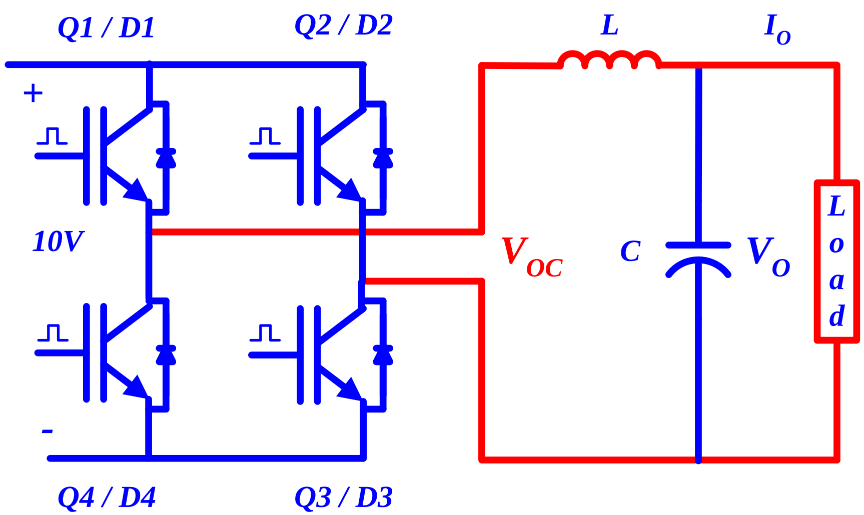
Desired Output Reference Signal	Q1/Q3D	Q2/Q4 D
-100%	0.0%	100.0%
-75%	12.5%	87.5%
-50%	25.0%	75.0%
-25%	37.5%	62.5%
0%	50.0%	50.0%
25%	62.5%	37.5%
50%	75.0%	25.0%
75%	87.5%	12.5%
100%	100.0%	0.0%

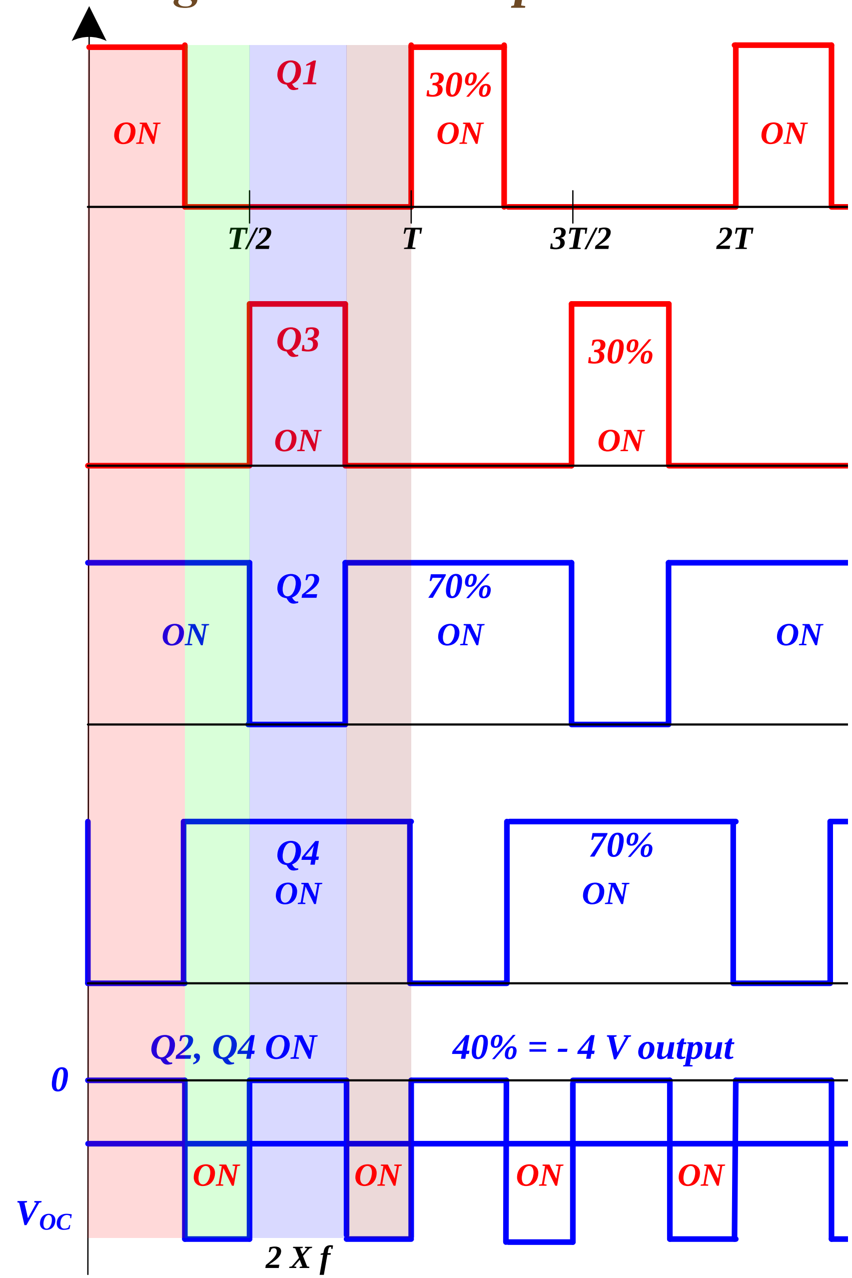


- Both bridge legs are always active
- Q1/Q3 (+) bridge
- Q2/Q4 (-) bridge
- Q1/Q3 180 ^{O} phase shifted
- Q2/Q4 180 ^{O} phase shifted
- Q1 is complement of Q4
- Q2 is complement of Q3

PWM - "50/50" Bipolar Switching For - 4 V Output

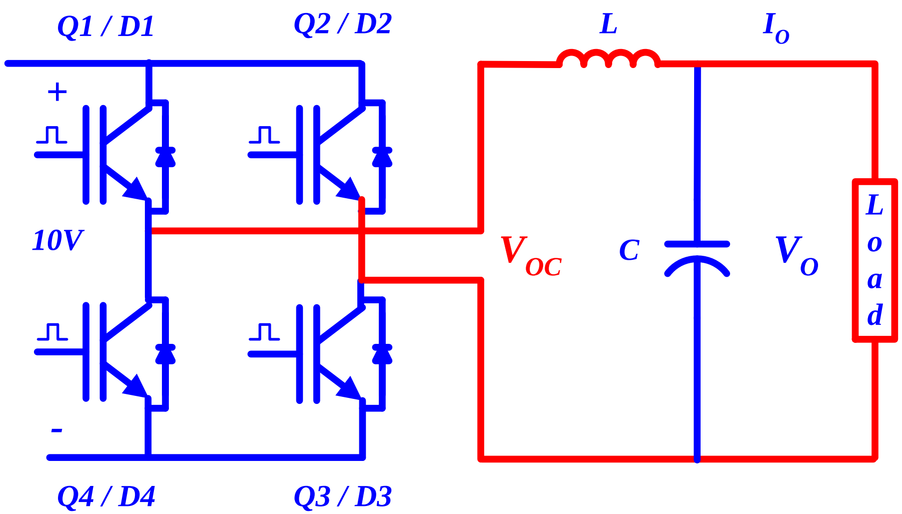
Q1/Q3 on 30%   Q2/Q4 on 70%



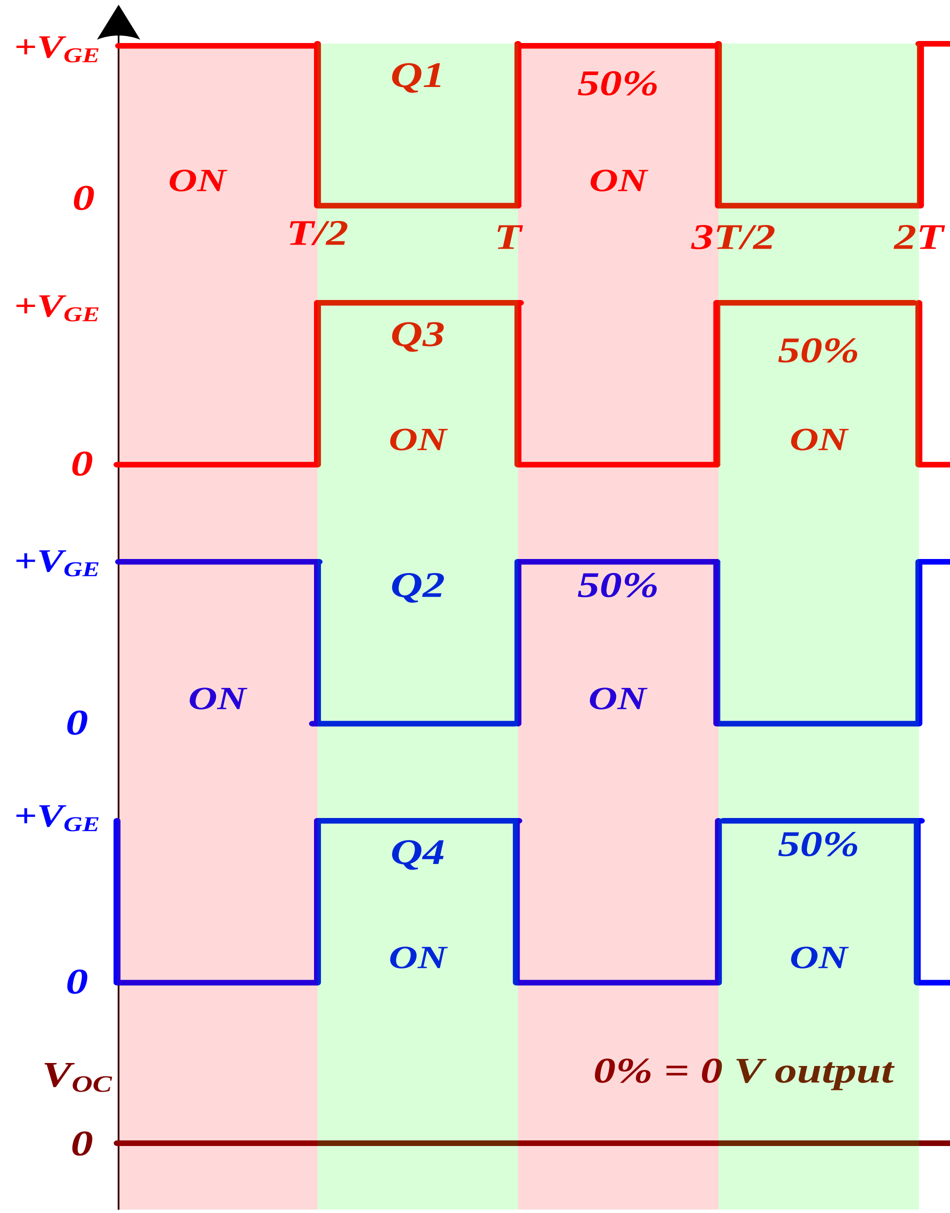


	Q1	Q3	Q2	Q4	V_{OC}
1	On	Off	On	Off	0 V
2	Off	Off	On	On	-10 V
3	Off	On	Off	On	0 V
4	Off	Off	On	On	-10 V

Q1/Q3 on 50%   Q2/Q4 on 50%

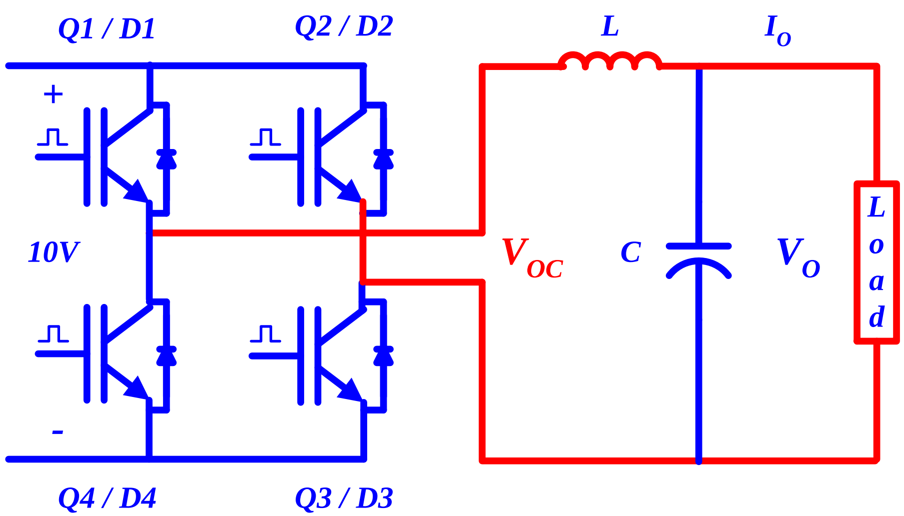


	Q1	Q3	Q2	Q4	VOC
1	On	Off	On	Off	0 V
2	Off	On	Off	On	0 V
3	On	Off	On	Off	0 V
4	Off	On	Off	On	0 V

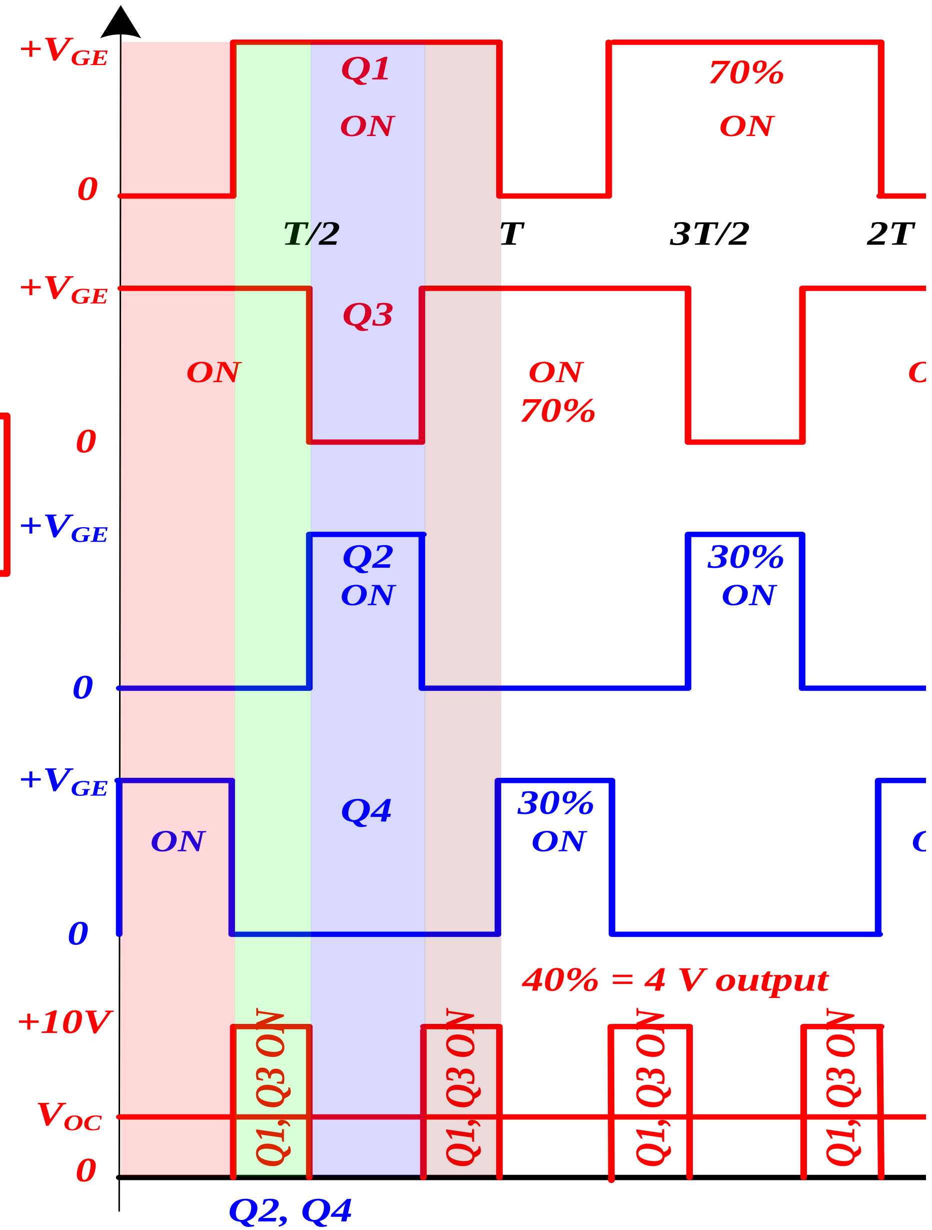


PWM - "50/50" Bipolar Switching For + 4 V Output

Q1/Q3 on 70% Q2/Q4 on 30%



	Q1	Q3	Q2	Q4	V_{OC}
1	Off	On	Off	On	0 V
2	On	On	Off	Off	+10 V
3	On	Off	On	Off	0 V
4	On	On	Off	Off	+10 V

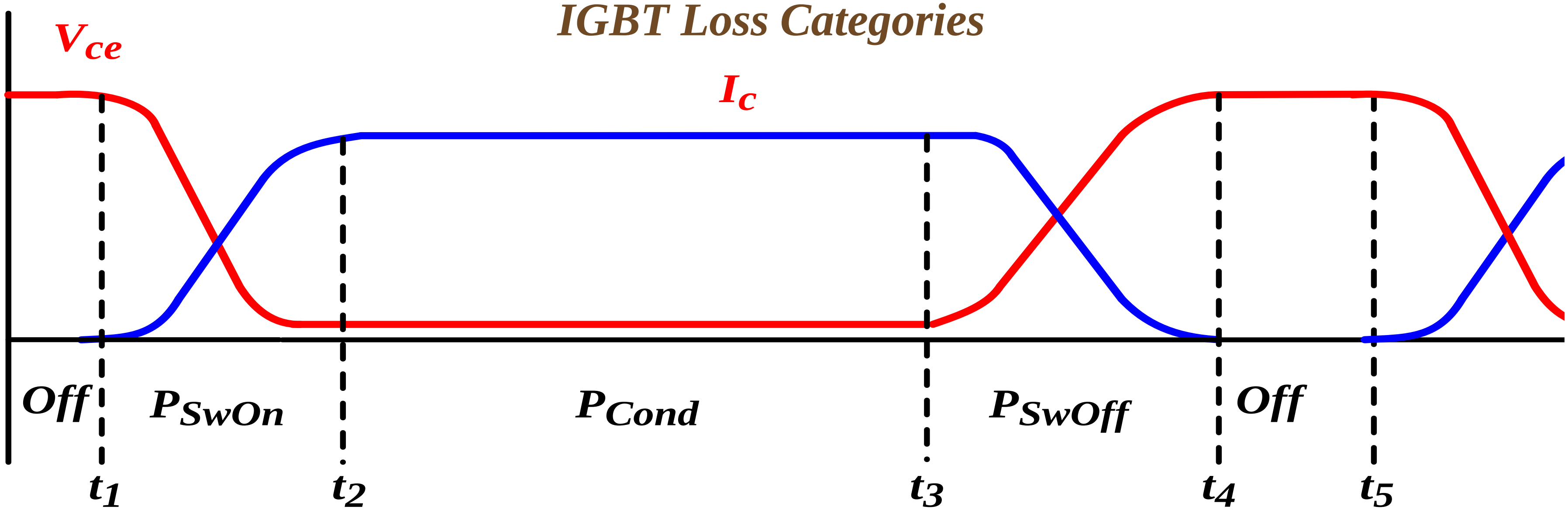


PWM - Bipolar PS PWM Strategies Compared

PWM Type	***Advantages***	***Disadvantages***
Sign/Magnitude		*Output voltage is 1X the switching frequency – difficult to filter* *Zero crossing transitions are discontinuous*
"50/50"	*Output voltage pulse 2X the switching frequency. Easier to filter* *Smoothest transitions through zero.*	

Conducting and Switching Losses

IGBT Loss Categories



Turn-on losses

$$P_{SwOn} = \frac{1}{t_5 - t_1} * \int_{t_1}^{t_2} v_{CE}(t) * i_C(t) * dt$$

Conduction losses

$$P_{Cond} = \frac{1}{t_5 - t_1} * \int_{t_2}^{t_3} V_{CE} * I_C * dt$$

Turnoff losses

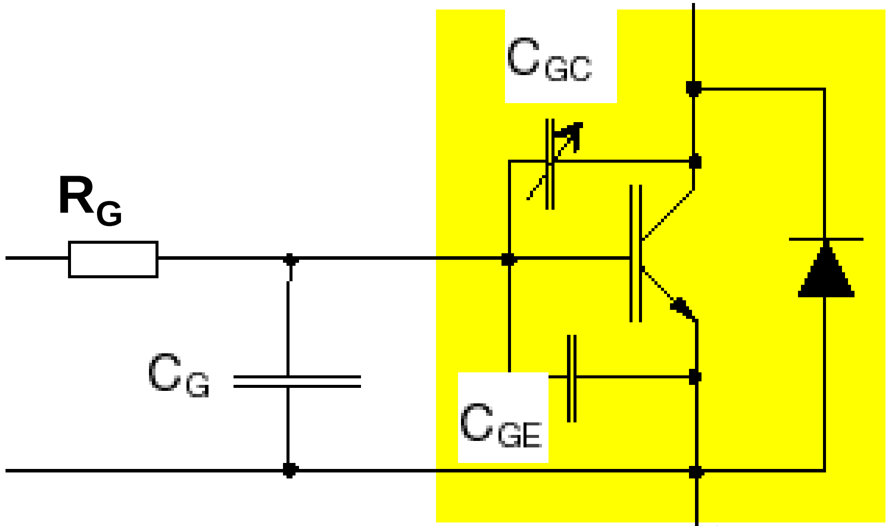
$$P_{SwOff} = \frac{1}{t_5 - t_1} * \int_{t_3}^{t_4} v_{CE}(t) * i_C(t) * dt$$

Reducing Conducting and Switching Losses

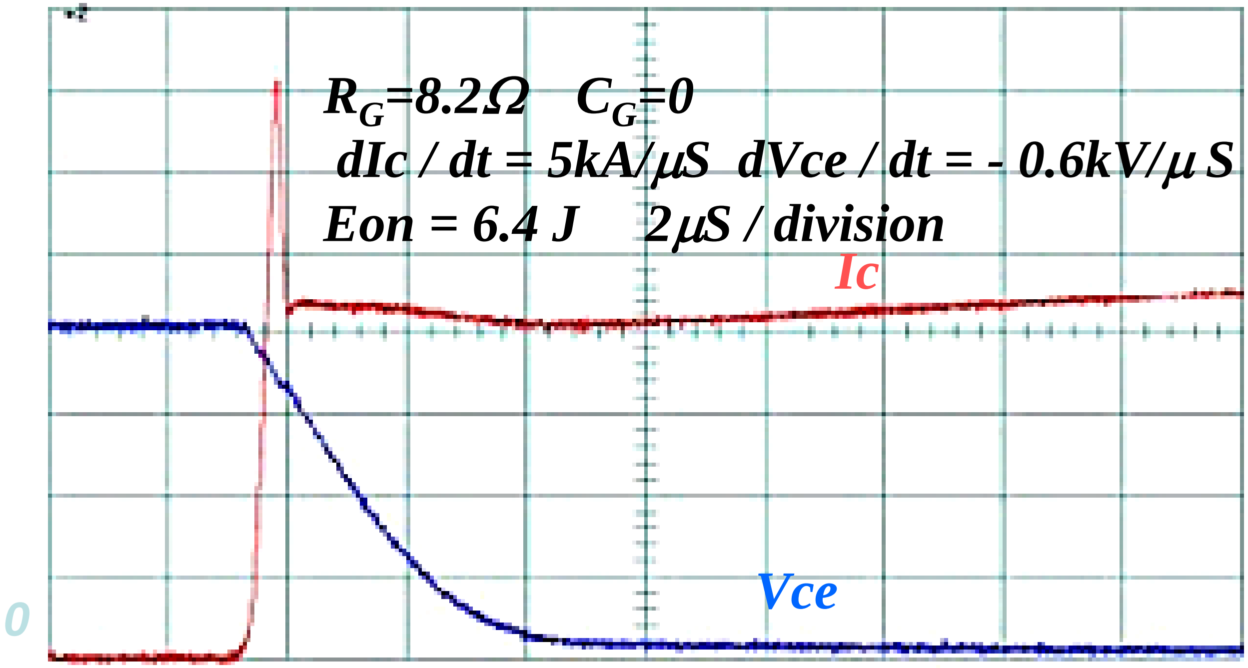
Reduce losses for greater efficiency and:

- *Smaller AC distribution system*
- *Less heat load into cooling water system*
- *Less heat into buildings and building HVAC*
- *Reduce IGBT dissipation*

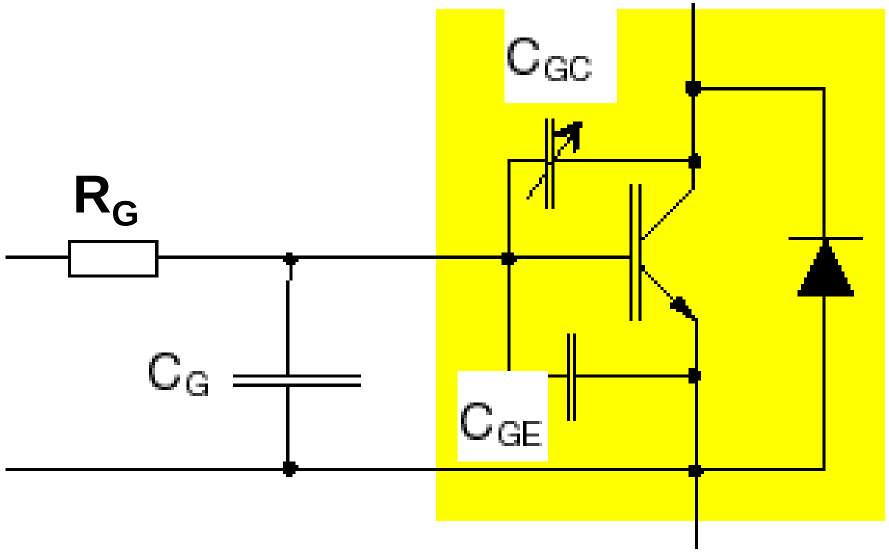
Reducing Turn On Losses By Varying R_G

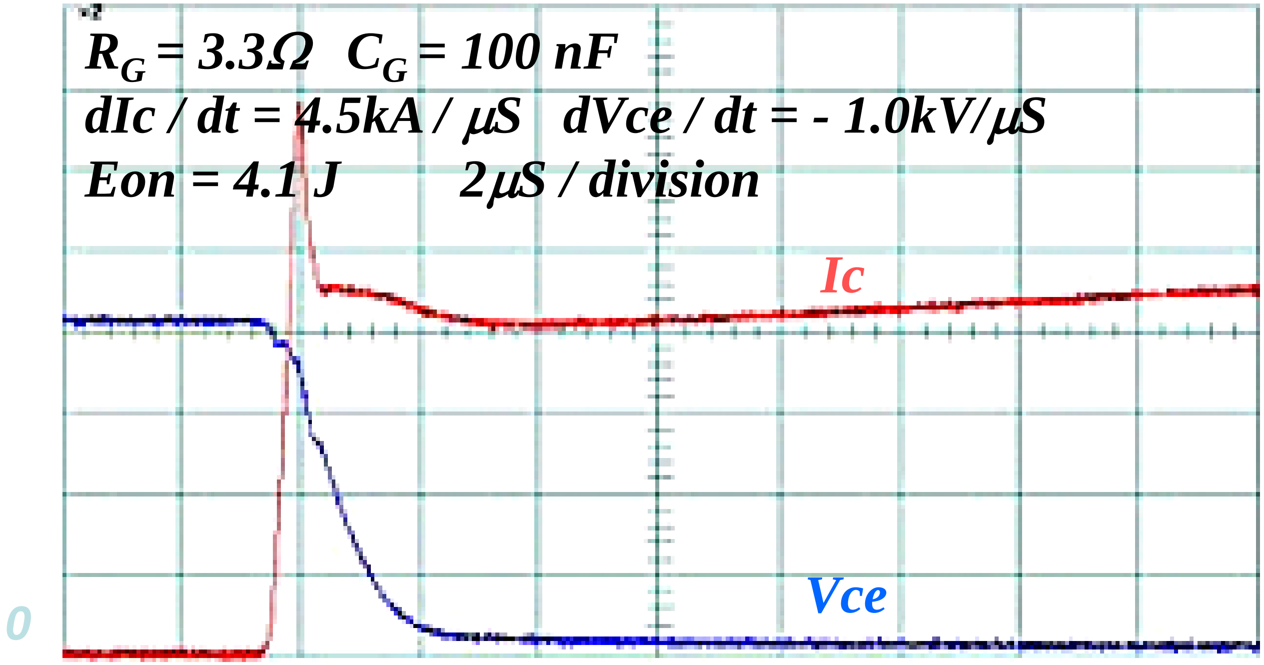


http://www.eupec.com/editorials/effect_cge.htm

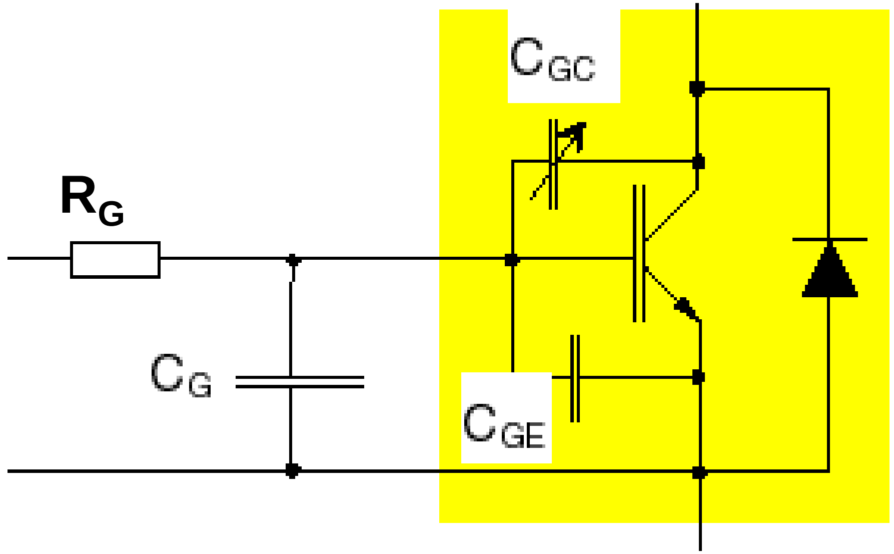


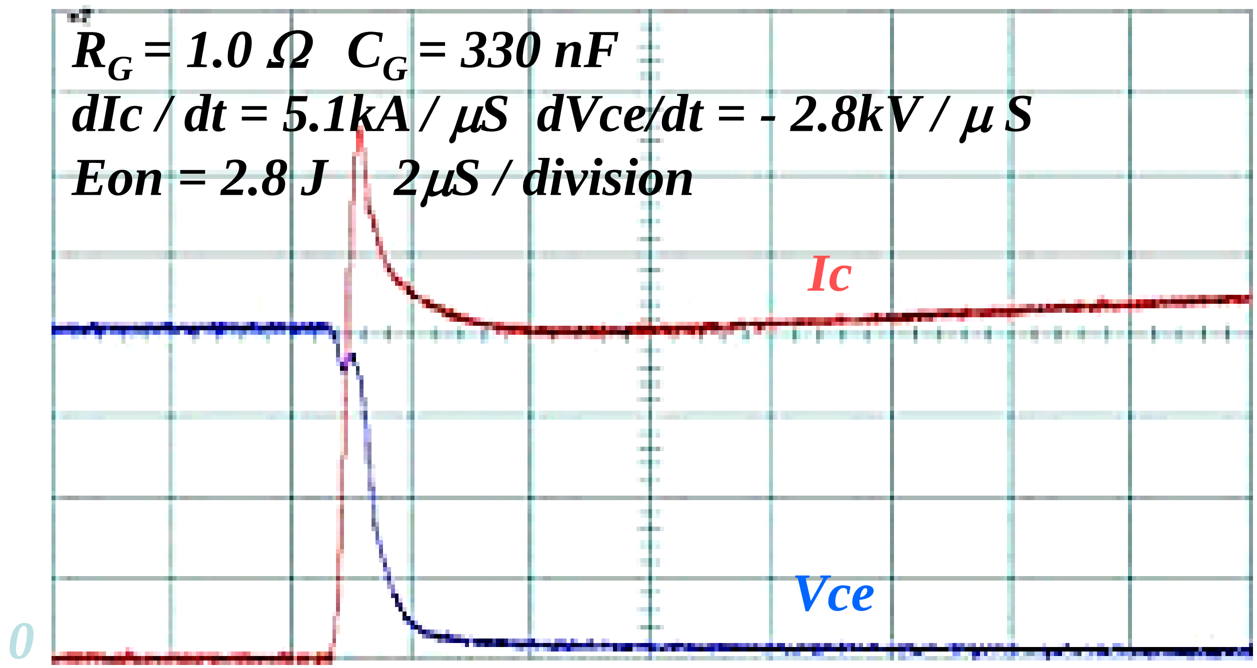
Reducing Turn On Losses By Varying R_G





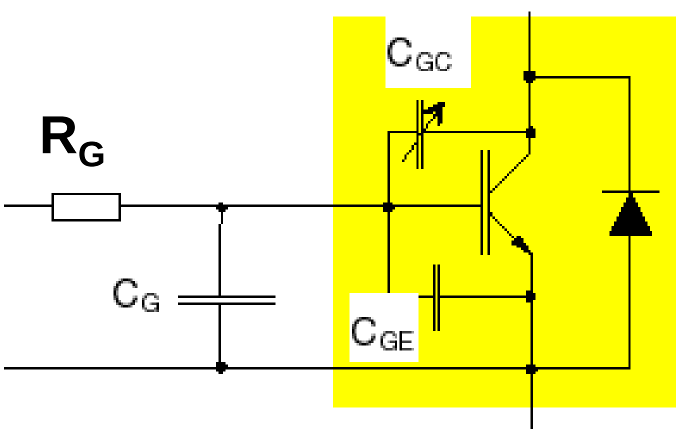
Reducing Turn On Losses By Varying R_G





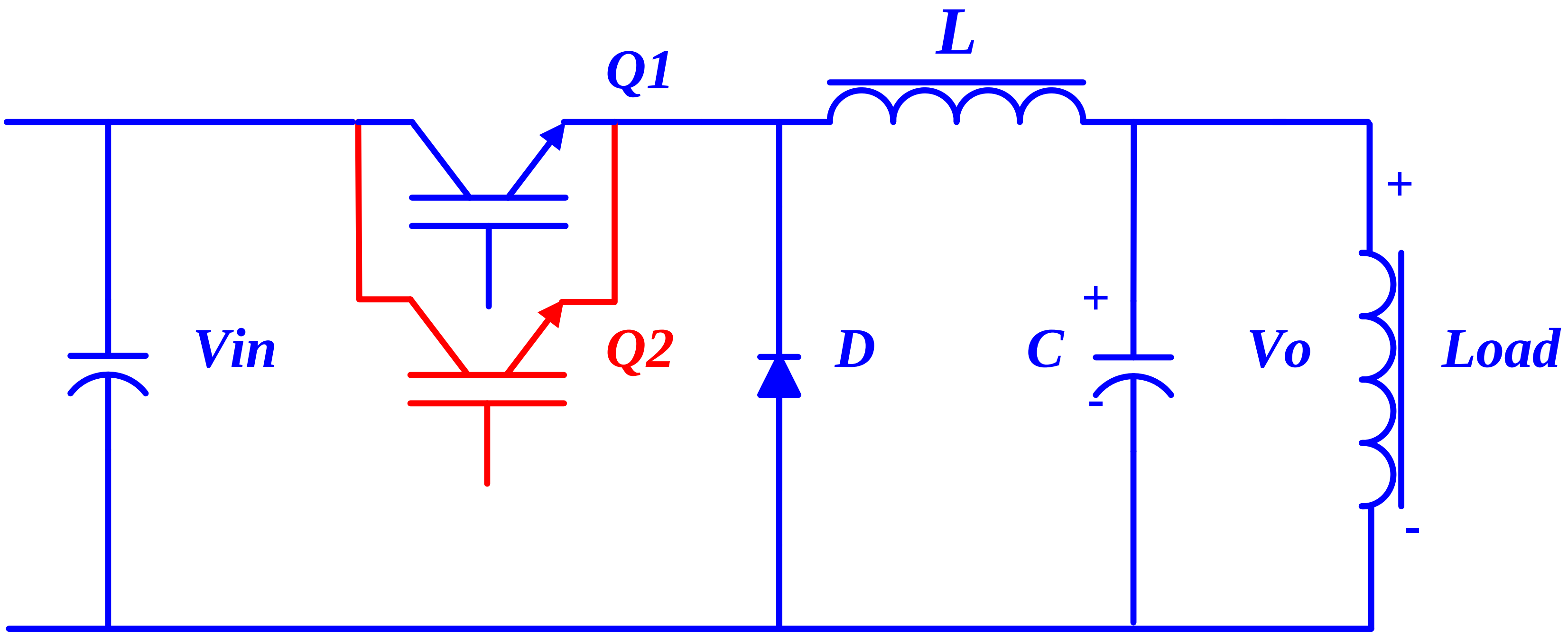
Reducing Turn On Losses By Varying R_G

Case	R_G	dV_{CE} / dt	E_{On}
1	8.2 Ω	- 0.6 kV / μS	6.4 J
2	3.3 Ω	- 1.0 kV / μS	4.1 J
3	1.0 Ω	- 2.8 kV / μS	2.8 J



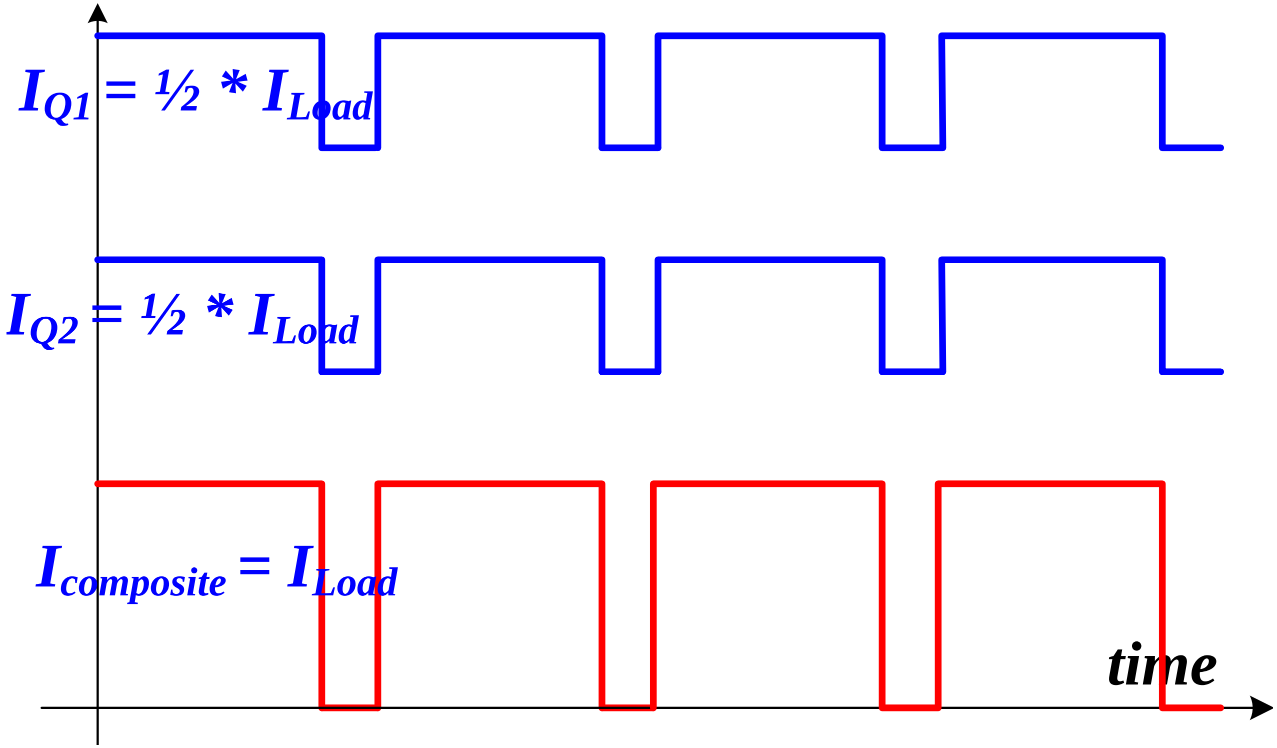
- $P_{Diss} \propto^{-1} - dV_{CE} / dt$
- dV_{CE} / dt is controlled via R_G
- Lower losses but possibly increased EMI because of faster dV_{CE} / dt

Reducing Conduction Losses



- *If the current rating of a single switch is insufficient (conduction loss is too great), add another switch in parallel.*
- *There are then 2 ways to switch Q1 and Q2, switch them ON and OFF together or stagger their On and OFF times*

Conduction Loss Reduction By Simultaneous Switching of Q1 and Q2



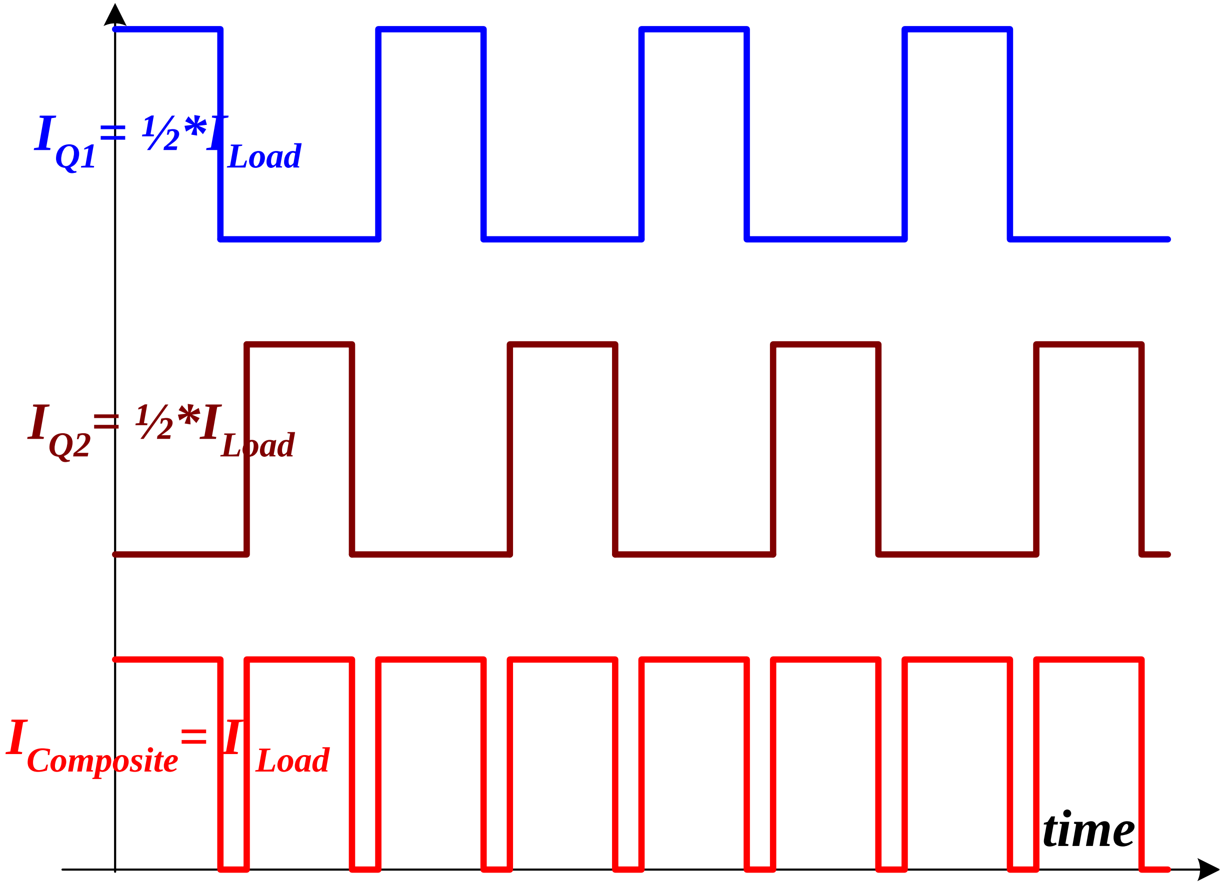
$$V_{RMS\,2Sw-EaSw} = V_{RMS-1Sw} \qquad I_{RMS\,2Sw-EaSw} = \frac{1}{2} * I_{RMS-1Sw}$$

$$P_{Ave1Sw} = V_{RMS1Sw} * I_{RMS1Sw}$$

$$P_{Ave2Sw-EaSw} = V_{RMS1Sw} * \frac{1}{2} I_{RMS1Sw} = \frac{1}{2} * P_{Ave1Sw}$$

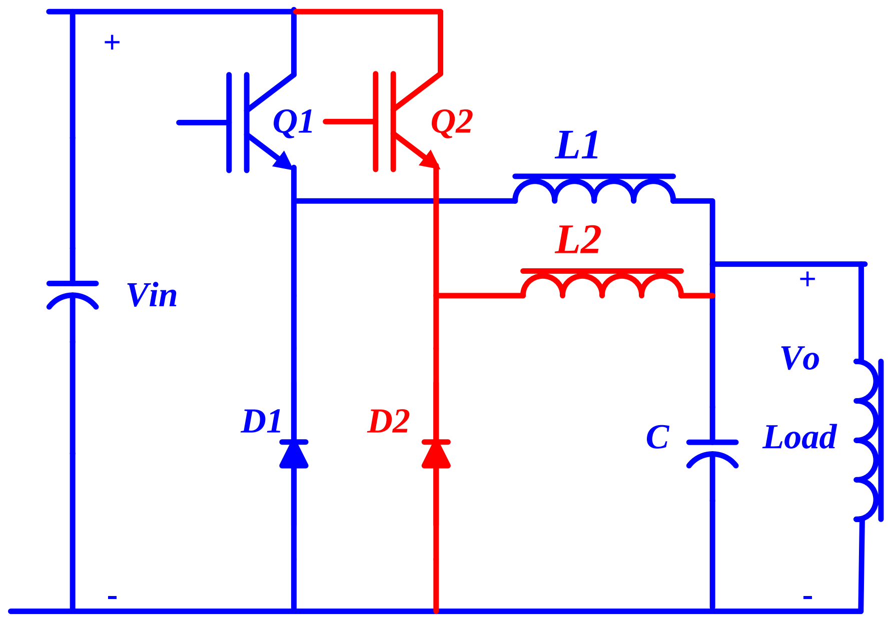
The composite frequency is the same as in Q1 and Q2

Conducted Loss Reduction By Staggered Switching of Q1 and Q2



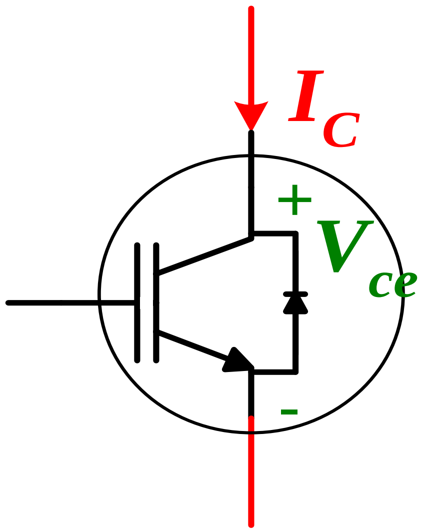
- *Duty factor is each switch is halved*
- *P_{ave} in each switch is 1/2 that of the single switch case*
- *The composite frequency is twice that of Q1 and Q2*

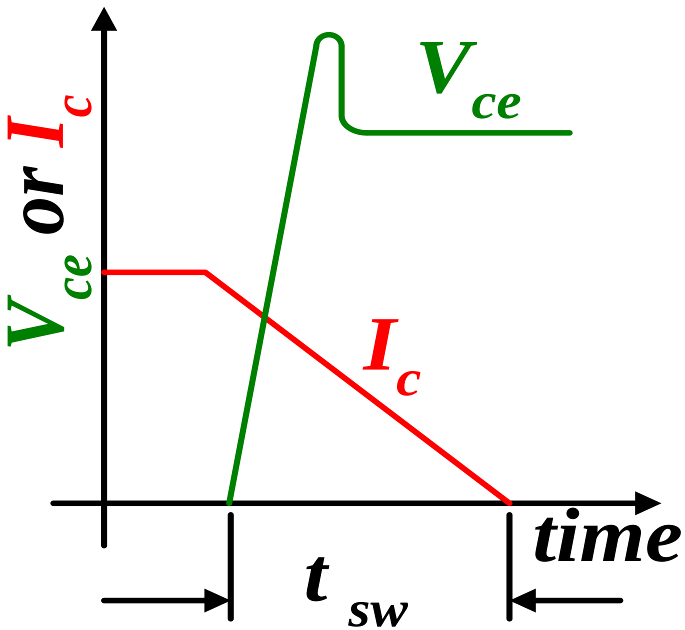
Conducted Loss Reduction By Paralleled Buck Regulators



Features:

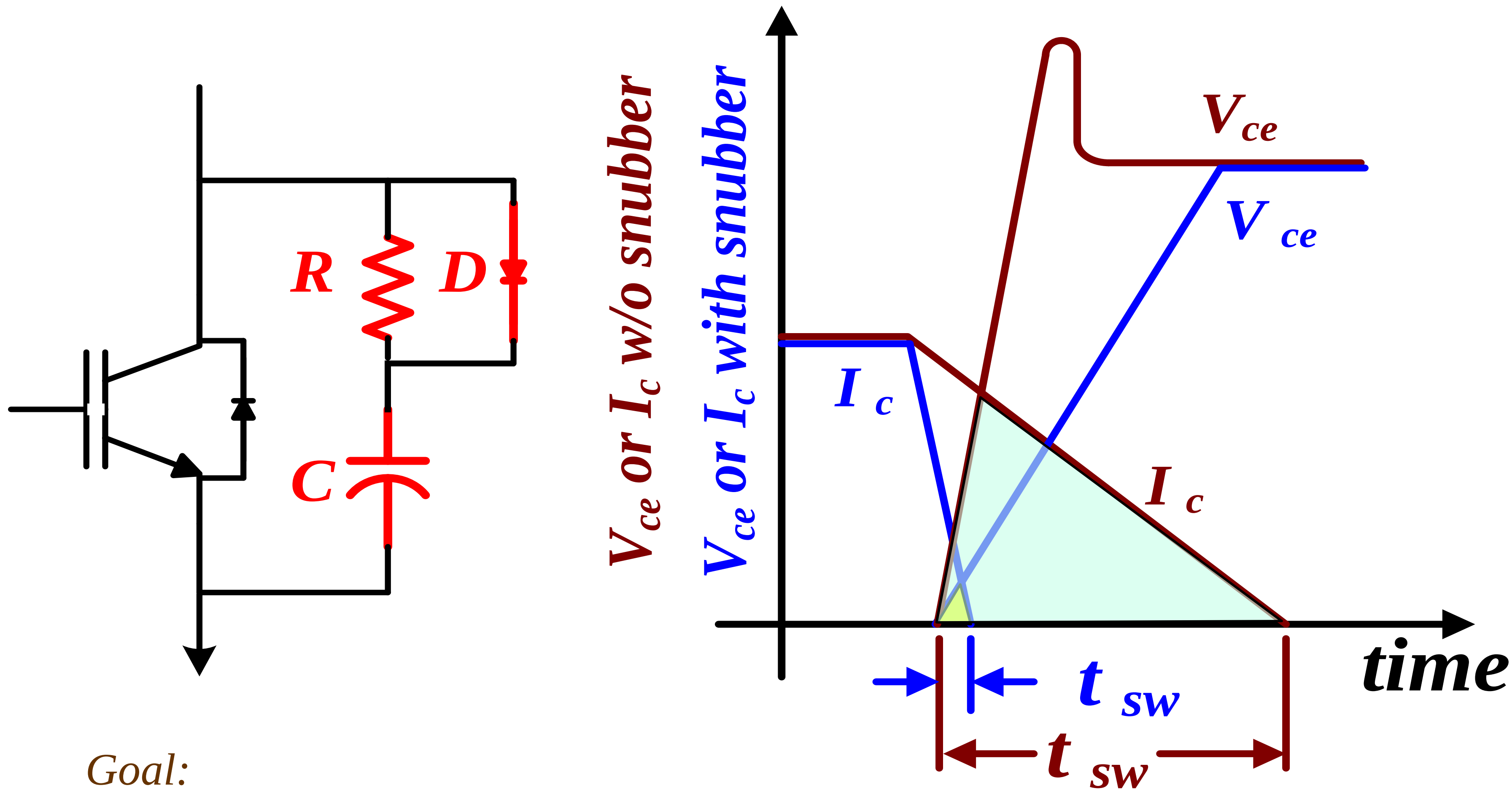
- *A second switch Q1 is added.*
- *Q1 and Q2 are staggered switched*
- *D2 is added, L2 is added*
- *Current in D1, D2 is 1/2 the load current*
- *Current in L1, L2 is 1/2 the load current*
- *L1, L2 energy 1/4 that of single inductor since $E=1/2 * L * I^2$*





$$P_{SwOff} = \frac{1}{T} \int_0^{t_{Sw}} v_{CE}(t)\, i_C(t)\, dt$$

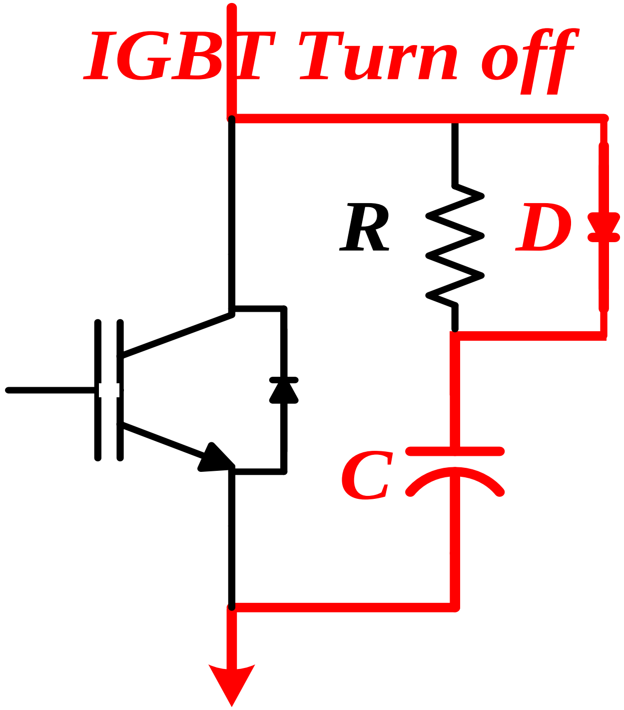
Switch Turnoff Loss Reduction By RCD Snubber



Goal:

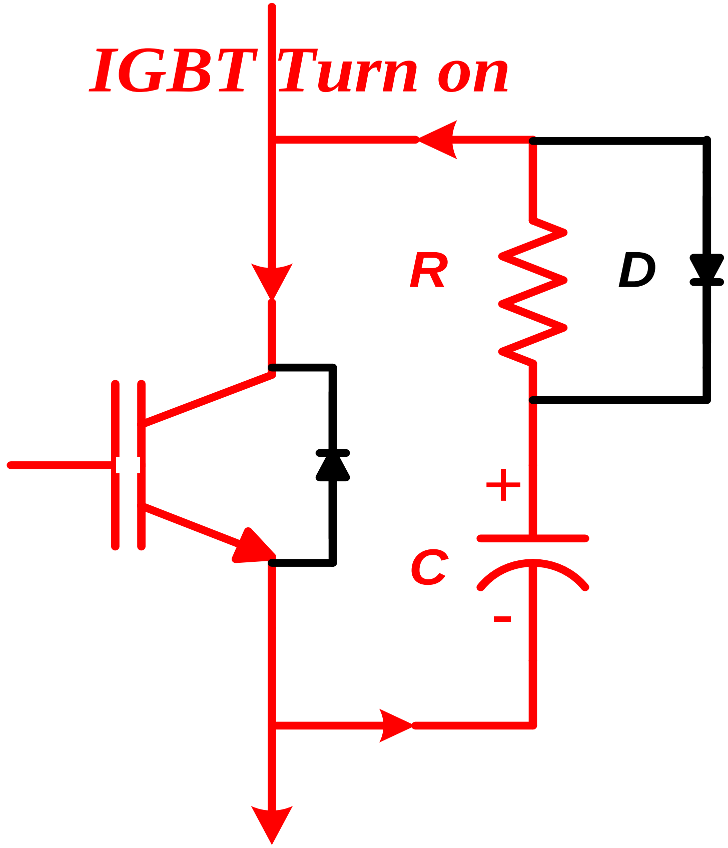
- *To increase the rate of decay of I_C during turnoff*
- *To decrease the rate of V_{CE} build up during turnoff*
- *To realize goal, add a resistor R, capacitor C, diode D snubber network*

Switch Turnoff Loss Reduction By RCD Snubber



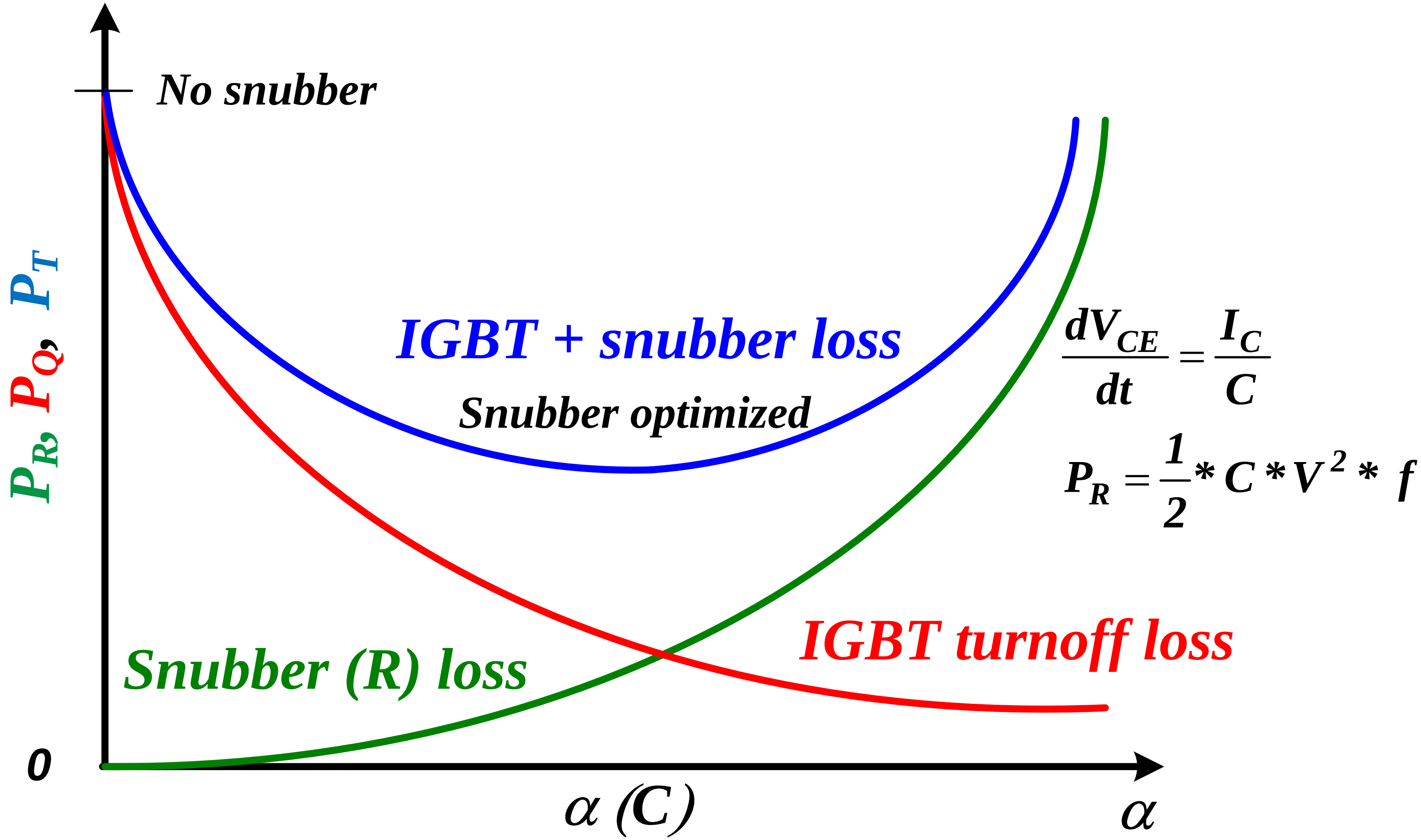
- *When the IGBT turns off, current commutates out of the IGBT into the capacitor, C via the diode D*
- *This aids fast I_C current decay*
- *C becomes linearly charged to the bus voltage*
- *dV_{CE} / dt inversely proportional to C – this slows V_{CE} recovery*

Switch Turnoff Loss Reduction By RCD Snubber



- *When the IGBT turns on, the capacitor C, discharges through R and the IGBT*

Switch Turnoff Loss Reduction By RCD Snubber



- *Small C = fast dV_{CE}/dt, V appears with current still in the IGBT, have IGBT loss*
- *Large C means slow dV_{CE}/dt, current gone before voltage buildup but the resistor losses are high*
- *When the snubber circuit is optimized, the IGBT turnoff loss with snubber + snubber loss < IGBT loss w/o snubber !*

Switch Turnoff Loss Reduction By RCD Snubber

Design criteria

- *R must limit discharge I through IGBT to < IGBT rating*
- $P_R \geq E_C / T = 1/2\, C\, V^2 f$
- *C ripple current rating* $\geq \Sigma$ *(ave charge + ave discharge currents)*
- *C must appreciably discharge each cycle, so R C < minimum expected IGBT on time*
- *D has to be rated to hold off the bus voltage and carry peak capacitor charging current*

Note: *Turn-on losses in the latest IGBTs have been reduced so that snubber circuits are no longer required in most applications*

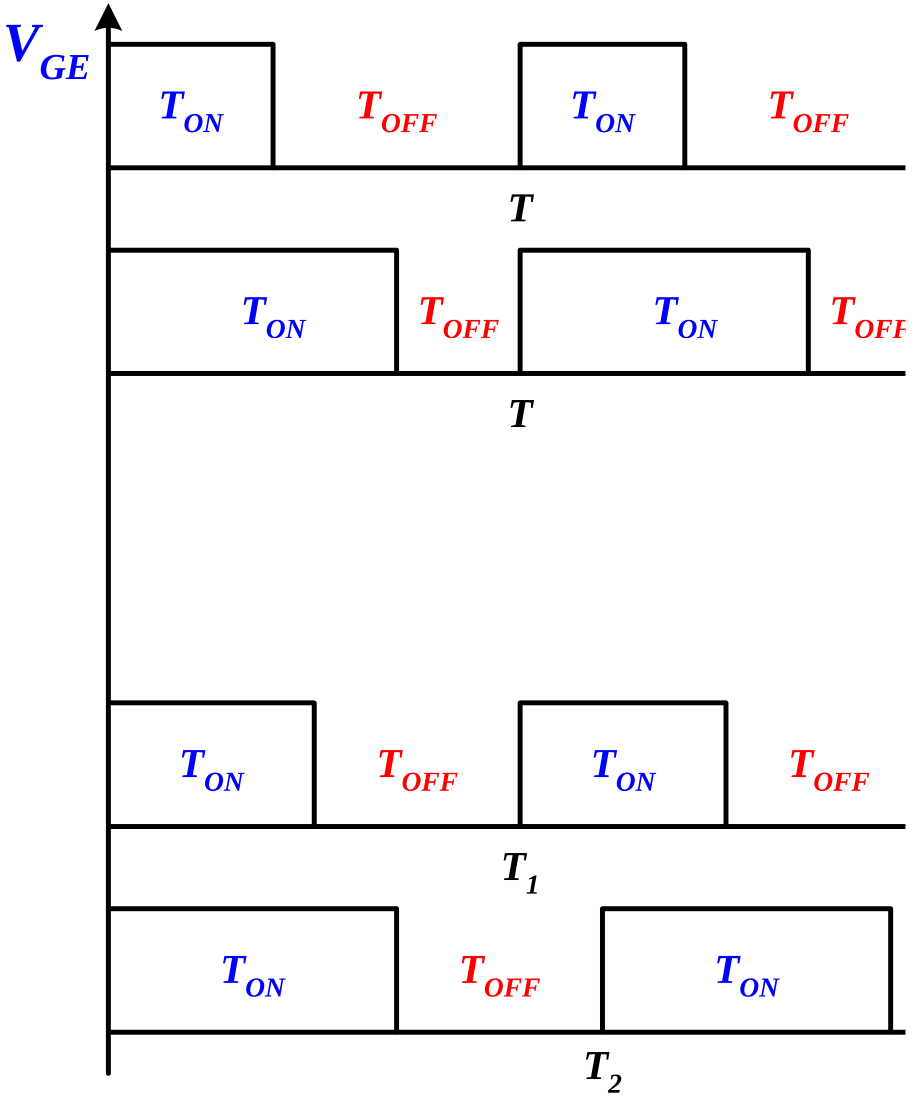
Reducing Switch Losses By Resonant Switching

Resonant Switching Attractions

- *Drastically reduce switch turn-on and turn-off losses*
- *Almost loss-less switching allows higher switching frequencies*
- *Reduce the electromagnetic interference (EMI) associated with pulse width modulation (PWM)*

Two Resonant Switching Methods

- *Zero current switching (ZCS)*
- *Zero voltage switching (ZVS)*
- *ZVS prevalent as disadvantages in ZCS*
- *Lets examine ZVS*



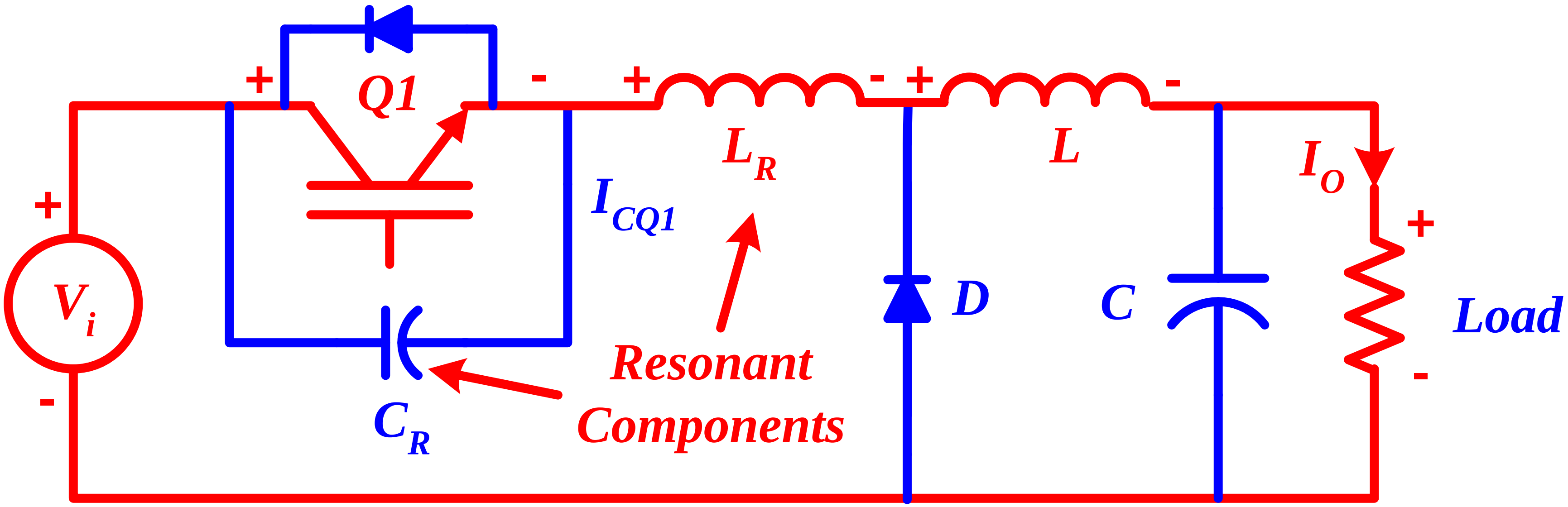
Fixed Frequency Switching

- T_{on} and T_{off} vary

ZVS Resonant Mode Switching

- Frequency varies
- T_{on} varies
- T_{off} fixed to accommodate resonant circuit
- Conversion frequency inversely proportional to load current

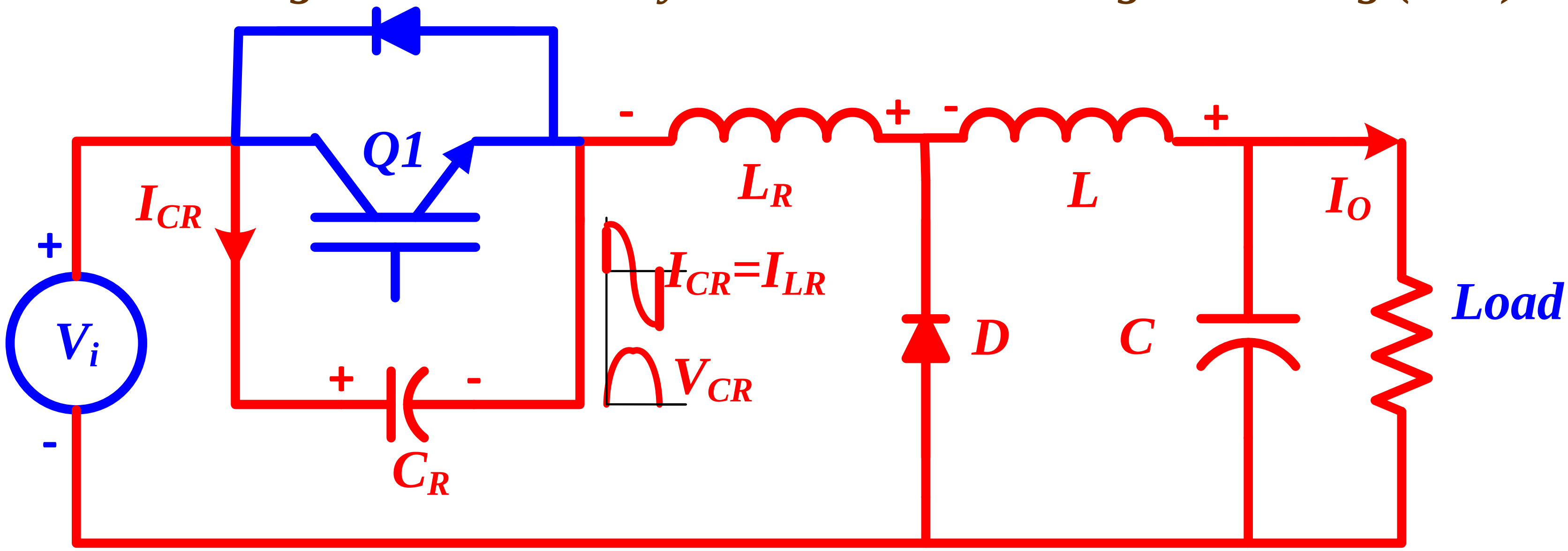
Reducing Switch Losses By Resonant Zero Voltage Switching (ZVS)



Time Interval 1

- *Q1 has been closed and is carrying load current. D and C do not have current flow in this steady-state condition.*
- $V_{CR}=0$ *and* $I_{CR}=0$ *as it has been sinusoidally discharged*
- *Note that* $V_{CR} = V_{CEQ1}$ *and* $I_{CQ1}=I_{LR}$

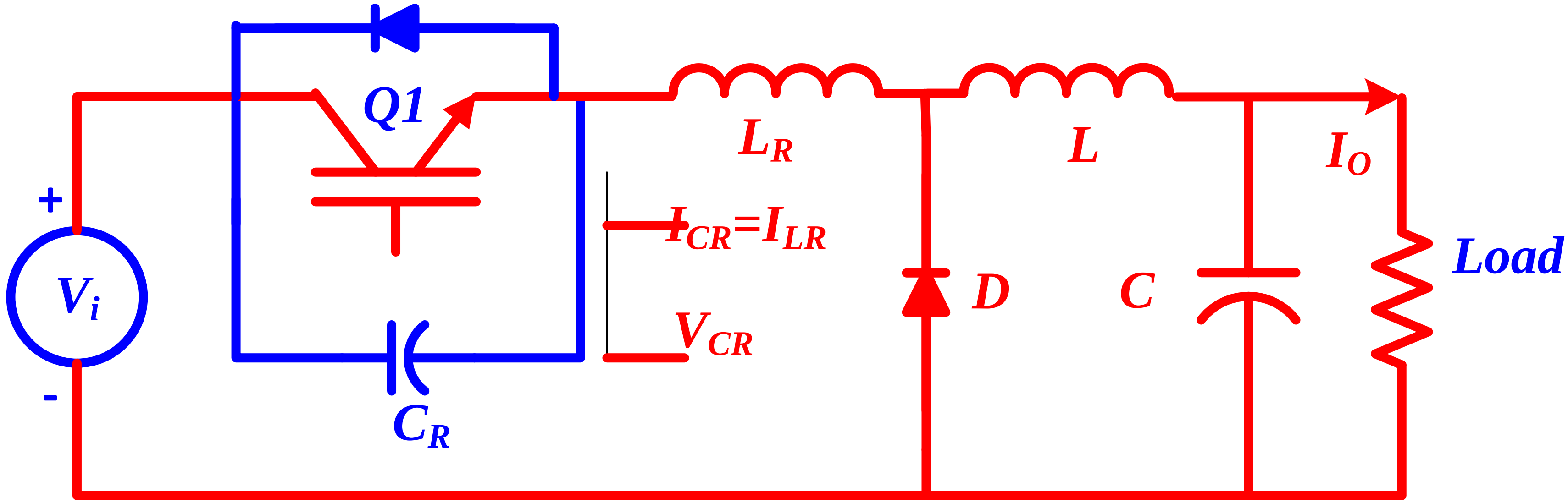
Reducing Switch Losses By Resonant Zero Voltage Switching (ZVS)



Time Interval 2

- *Q1 is opened. Diode D conducts*
- *Current commutates (rushes) into C_R*
- *C_R charges and discharges sinusoidally with frequency determined by C_R and L_R. 1/2 sine wave occurs*
- *V_{CR} is sine wave , I_{CR} is cosine wave = C dV_{CR} / dt*
- *$V_{CEQ1} = V_{CR}$*
- *$I_{CR} = I_{LR}$*

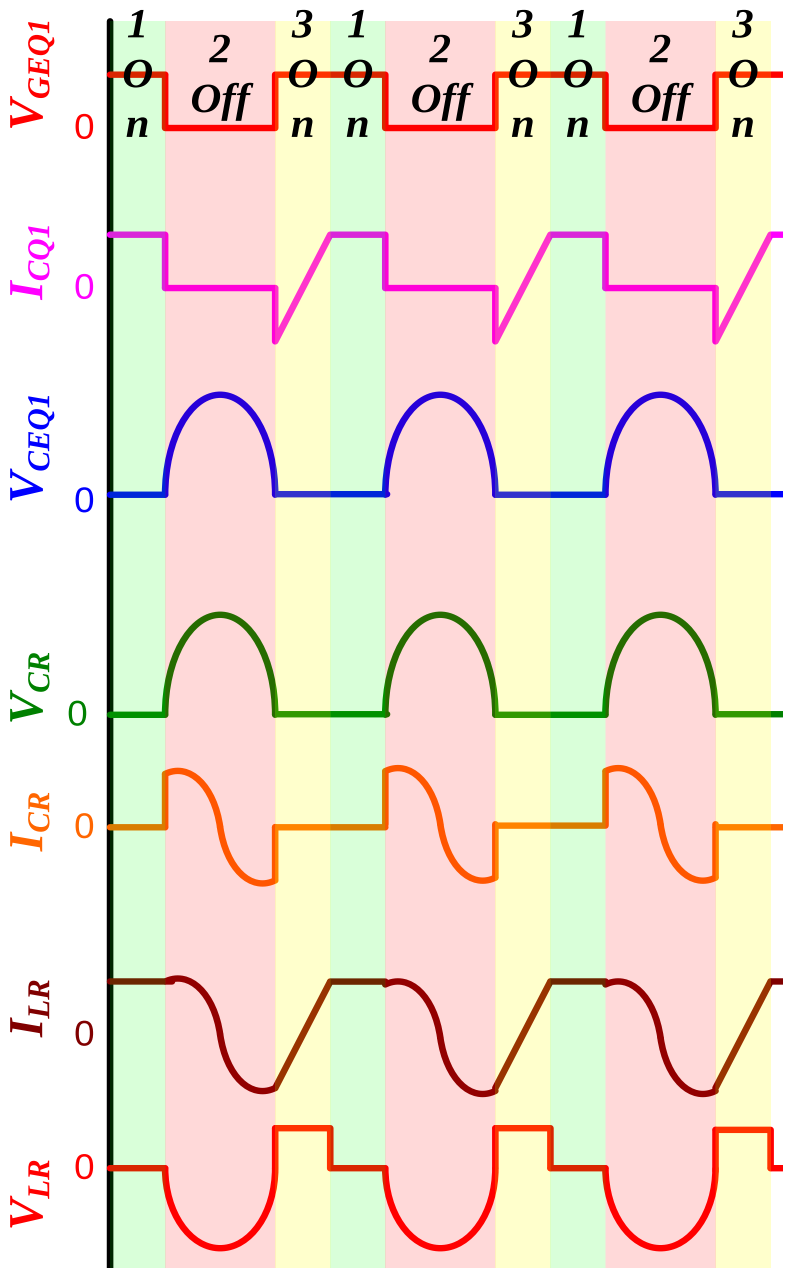
Reducing Switch Losses By Resonant Zero Voltage Switching (ZVS)

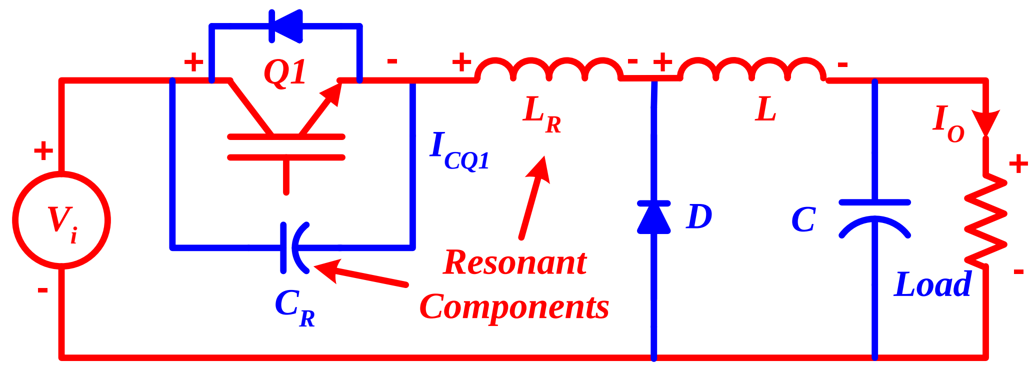


Time Interval 3

- *When V_{CR} discharges to 0 (V_{CEQ1}=0) , Q1 is re-closed.*
- *$I_{CQ1} = I_{LR}$*
- *There is a linear current buildup in Q1 due to L_R and L*

ZVS Waveforms





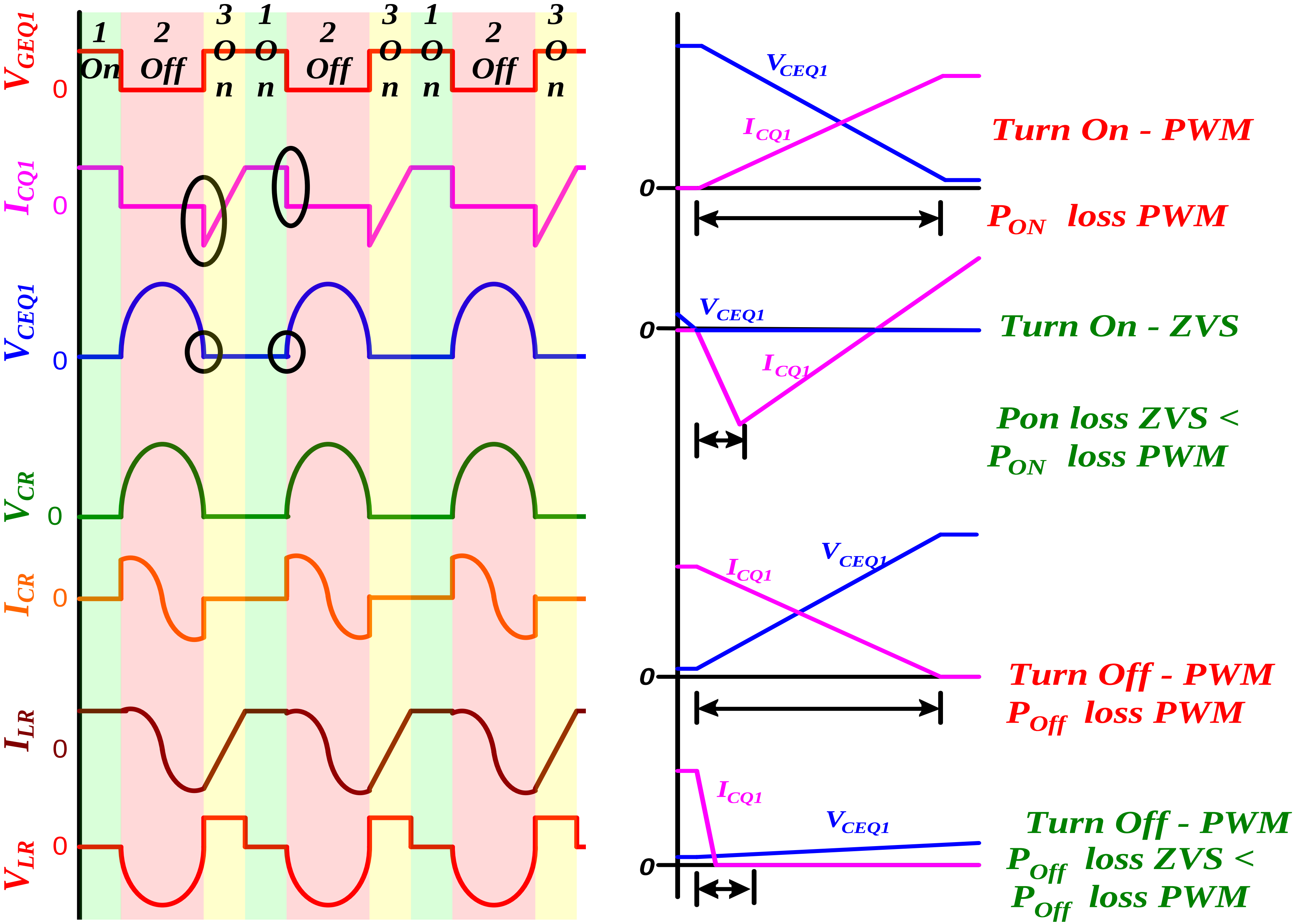
Q1 On

- $V_{CEQ1} = V_{CR} \approx 0$
- $I_{CQ1} = I_{LR}$
- $I_{CR}=0$
- $V_{LR}=L*dI_{LR} / dt=0$

Q1 Off

- $V_{CEQ1} = V_{CR}$
- $I_{CR} = I_{LR}=C*dV_{CR} / dt$

ZVS Waveforms



High Frequency Inductors and Transformers

Low and High Frequency Transformers Compared

	Low frequency	*High frequency*
Standards	*Well defined by ANSI, IEEE, NEMA and UL*	*Not as well defined* *Insulation standard followed*
Operation	*60 Hz* *Sine wave* *3 phase*	*10 kHz to 100 kHz* *Square wave – transformers Triangular wave – inductors* *Single phase*
Core material	*3 to 100 mil laminations of steel or Fe*	*0.5 to 3 mil laminations of Fe or Si-Fe* *Powdered Fe* *Powdered ferrites, Ni-Zn, Mn-Zn*
Winding material	*Single-strand Cu wire* *Layer or bobbin-wound*	*Multi-strand Cu Litz wire* *Cu foil, layer wound*

The power rating of a transformer is dependent upon the kollowing factors

$$V * A = K_1 * K_2 * f * A_C * A_E * J * B_M$$

where

$V * A$ = power rating of the transformer (V*A)

K_1 = waveshape factor (sine or square wave)

K_2 = copper fill factor (0 to 1)

f = excitation frequency (Hz)

A_C = core area (m^2)

A_E = winding area (m^2)

J = conductor current density $\left(\frac{A}{m^2}\right)$

B_M = peak flux density $\left(\frac{Wb}{m^2}\right)$ where a Weber = 1*volt*sec

The transformer area product = $A_C * A_E \propto \frac{V * A}{B_M * f * J}$

Low and High Frequency Transformers Compared

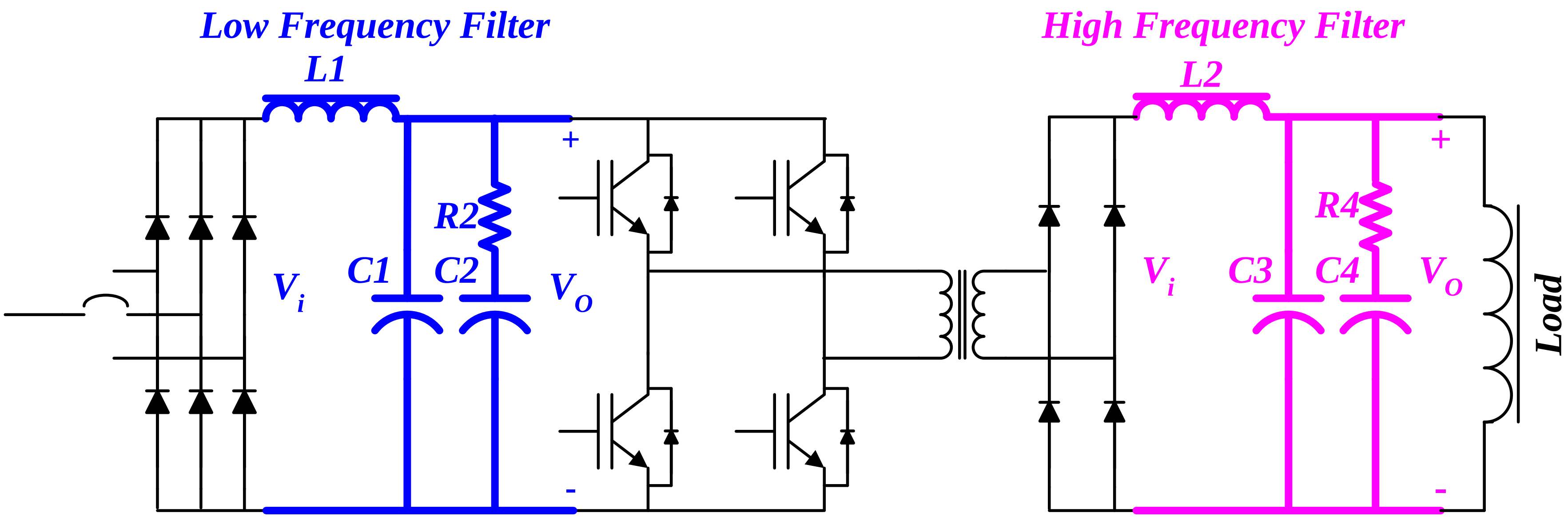
An example of a 10kVA, 480V : 208V Transformer ***At 60Hz the volume and weight would be***					
f	*f* ratio to 60Hz	Volume (in ^{3})	Volume ratio to 60Hz	Weight (lb)	Weight ratio to 60Hz
60 Hz	1	18 X 18 X 18 = 5832 (in ^{3})	1	100	1
20 kHz	333	6H X 5.25W X 3.37D 118 (in ^{3})	1 / 50	5	1 / 20

Some Parameters For HF Inductor Specification

- *Inductance*
- *Ripple current frequency*
- *Peak current*
- *RMS value of AC current*
- *DC current*
- *Saturation DC current*
- *Resonant frequency (an order of magnitude > ripple frequency)*

Ripple Filters

Ripple Filters



Low Frequency	High Frequency
Pass DC – reject f > 60 Hz	Pass DC – reject f > switching frequency
Large L1 to reduce On inrush & high PF	Large L2 to reduce inrush and prevent discontinuous current
R2 C2 for "critical" damping	R4 C4 for "critical" damping

Time Domain $y\,(t) = f\,(t) \otimes x\,(t)$ where $\otimes$ implies the convolution operation

- *Difficult computations, particularly transient calculations, requires solution of differential or difference equations*

Frequency Domain $Y\,(f) = F\,(f) * X(f)$ where * implies multiplication

- *Easier computations, all calculations for steady-state or transient conditions that look algebraic in nature.*

Transfer Function

- *Relates the output response of a circuit/system to the input stimulus*

- *Form is $T\,(f) = Y\,(f) / X\,(f)$ where $X\,(f)$ is the input stimulus and $Y\,(f)$ is the output response* $Y\,(f) = X\,(f) * T\,(f)$

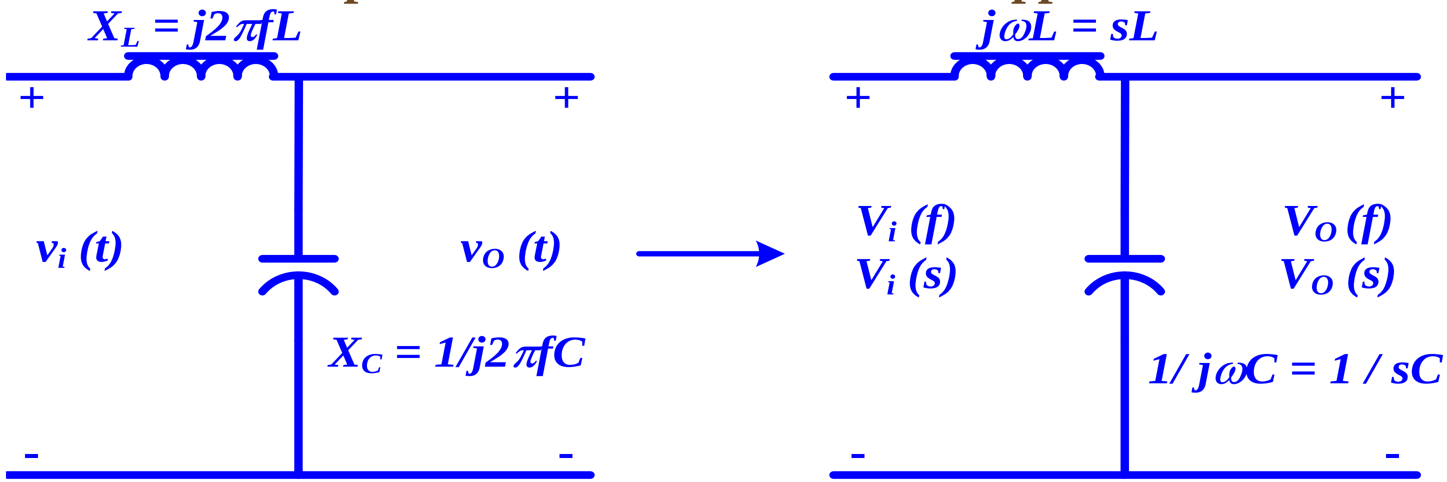
The “s” Operator

- *s is used in the frequency domain and in La Place analysis*
- $s = j\,\omega = j\,2\,\pi\,f \qquad\qquad j = \sqrt{-1}$

Poles and Zeros

- *Zero = 0* *Pole =* ∞
- *Zeros occur at frequencies that cause the transfer function to go to zero. Transfer function = 0 is caused by a zero numerator and or an infinite denominator* $T(s) = 0 / X(s) = 0$ *or* $T(s) = Y(s) / \infty = 0$
- *Poles occur at frequencies that cause the transfer function to become infinite. Transfer function =* ∞ *is caused by an infinite numerator or a zero denominator* $T(s) = \infty / X(s) = \infty$ *or* $T(s) = Y(s) / 0 = \infty$

A Simple Second Order Low Pass Ripple Filter



By voltage divider law $$V_o = V_i * \frac{\frac{1}{sC}}{\frac{1}{sC} + sL} \qquad T = \frac{1}{s^2 LC + 1}$$

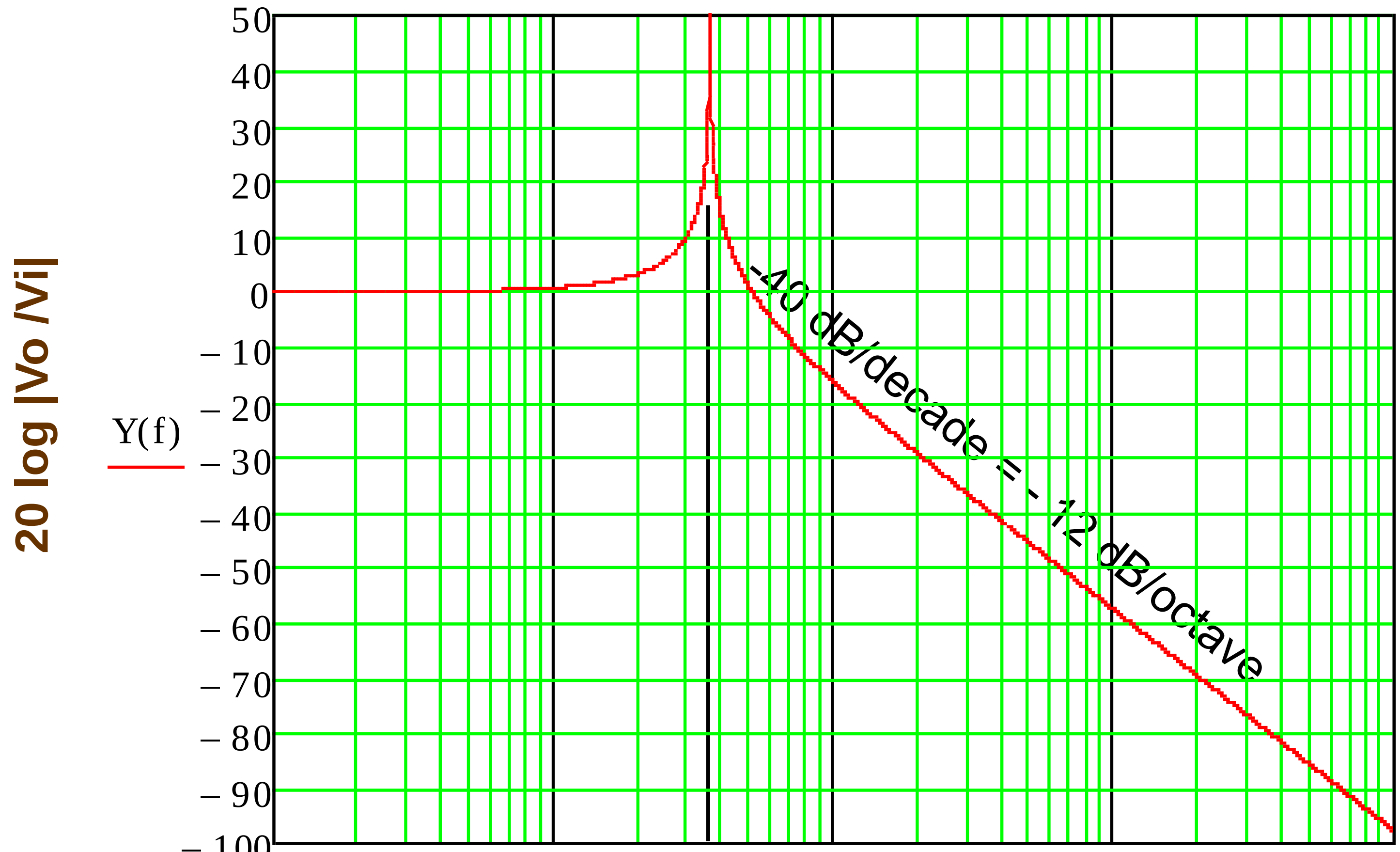
Pole $\quad s^2 LC + 1 = 0 \qquad (j2\pi f_p)^2 LC + 1 = 0$

Resonant frequency (pole) $$f_p = \frac{1}{2\pi\sqrt{LC}}$$

Zero occurs at $\quad (j2\pi f_p)^2 LC + 1 = \infty$

Zero frequency at $\quad f_z = \infty$

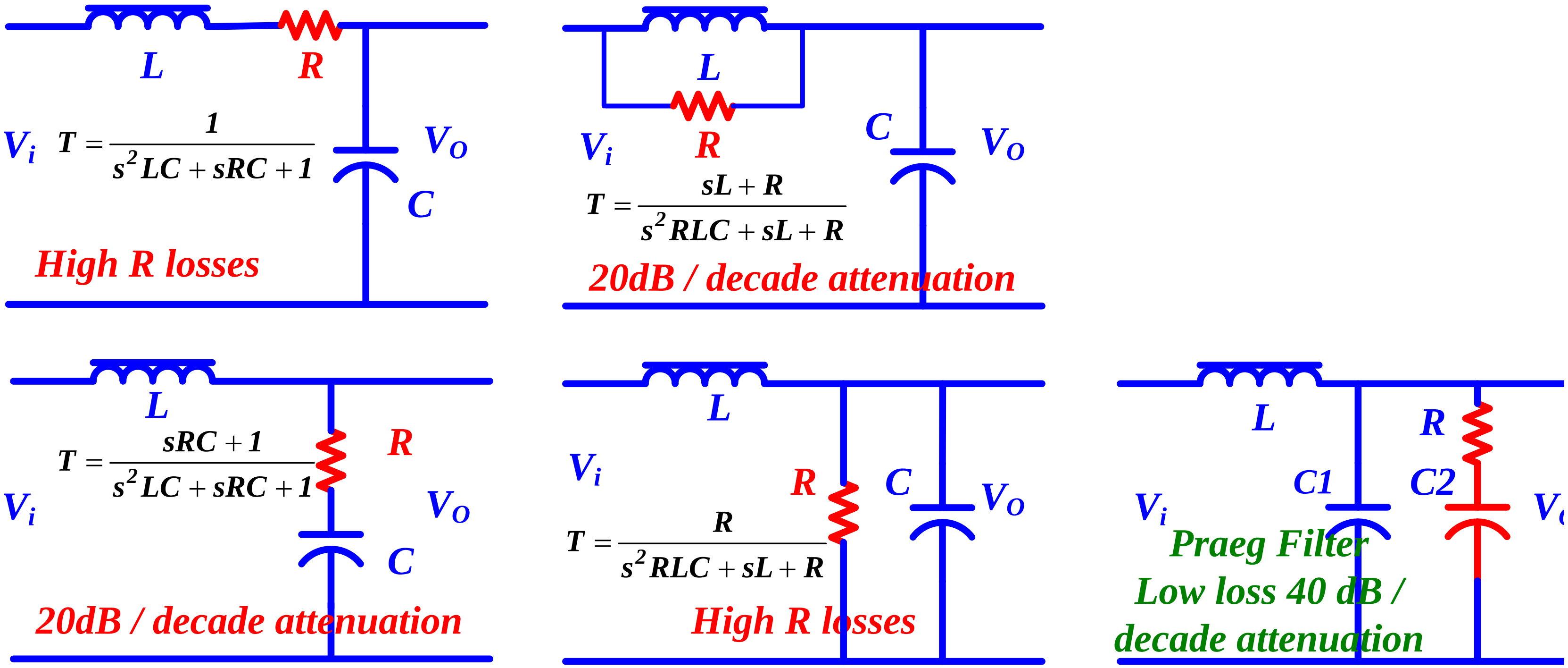
A Simple Low Pass Filter



$$f_p = \frac{1}{2\pi\sqrt{LC}} \longrightarrow f_z = \infty$$

- *Resonant frequency (pole) at f_p will cause problems !*
- *At $f = \infty$, the output goes asymptotically to zero*

The Praeg Low Pass Ripple Filter

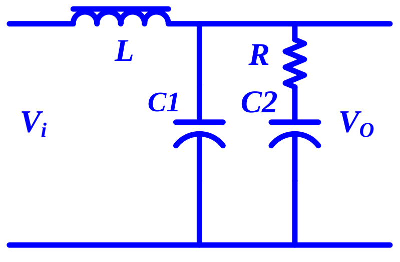


Why important:

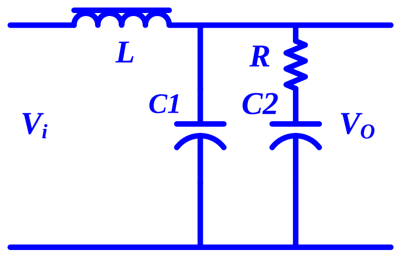
- *Used as low and high frequency filters in virtually every power supply*
- *Provides the filtering of the previous 2nd order filter*
- *Essentially critical damped*
- *No DC current in R, C2*

Component Selection Criteria

- L and C1 must be chosen to yield the desired breakpoint frequency (1/10 of the ripple frequency for 40 dB attenuation)
- C1 and C2 must be rated for the rectifier working and surge voltages
- C1 and C2 must be rated to carry the ripple current at the rectifier output frequency and at the switching frequency
- L must be large enough to offset the leading PF introduced by main filter capacitor, C1
- L must be large enough to limit the inrush current caused by rapid charge of C1 during power supply turn-on to an acceptable level
- L must be rated to carry the DC load current without overheating or saturating
- $C2 \geq 5 * C1$
- $R = (L / C1)^{1/2}$

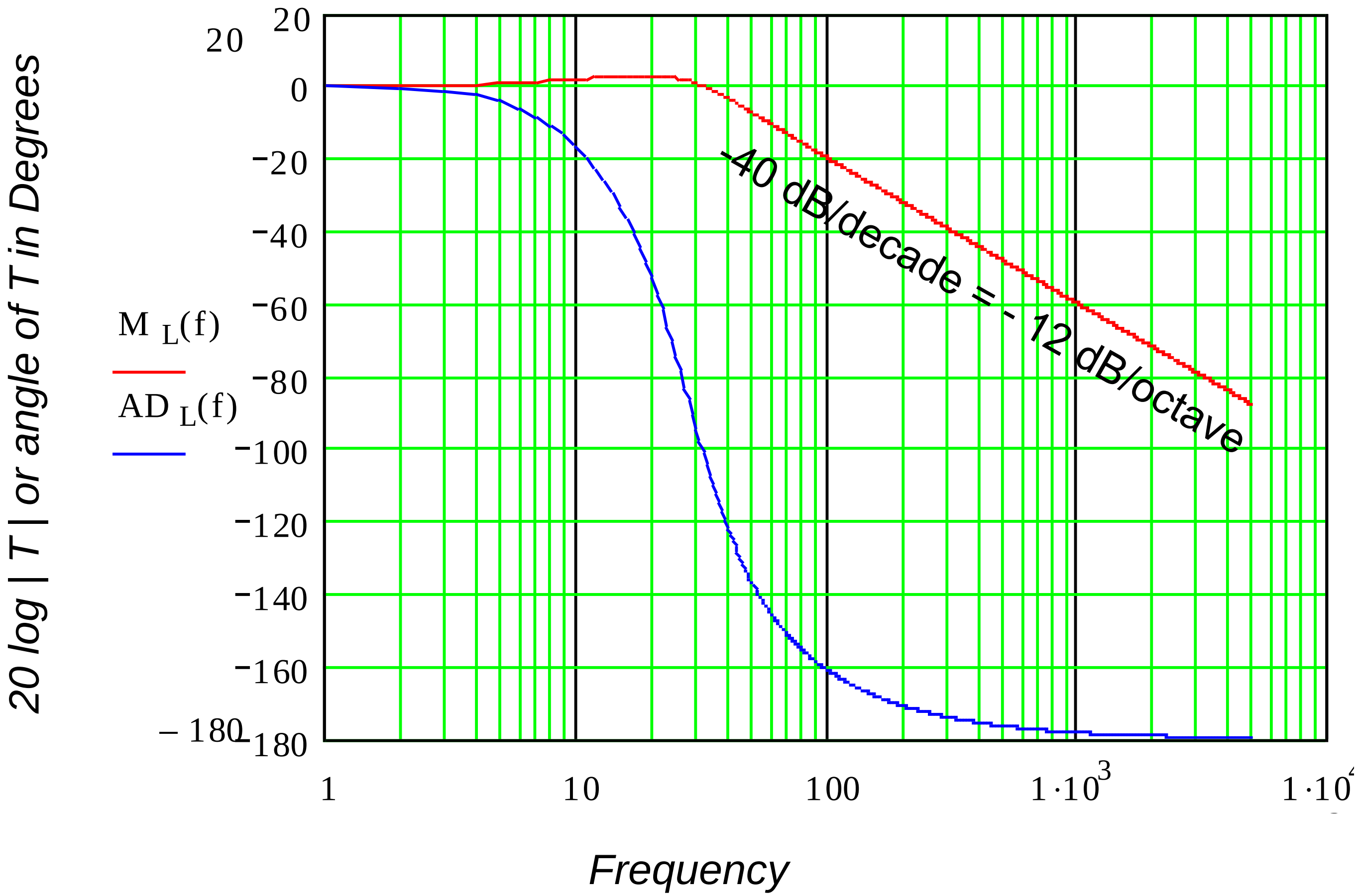


The Praeg Low Pass Ripple Filter



$$T = \frac{s\,R\,C_2 + 1}{s^3 R\,L\,C_1 C_2 + s^2 L(C_1 + C_2) + s\,R\,C_2 + 1}$$

$$C_2 \geq 5 * C_1 \qquad R = \sqrt{\frac{L}{C_1}}$$



360 Hz Praeg Filter

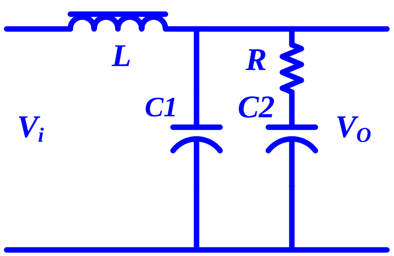
$f := 1\cdot Hz, 2\cdot Hz .. 1000\cdot Hz$ $\quad s(f) := j\cdot 2\cdot\pi\cdot f$ $\quad L := 1.5\cdot 10^{-3}\cdot H$ $\quad f_r := 36\cdot Hz$ $\quad C_1 := \dfrac{1}{4\pi^2\cdot L\cdot f_r^{\,2}}$ $\quad C_1 = 0.0130\,F$

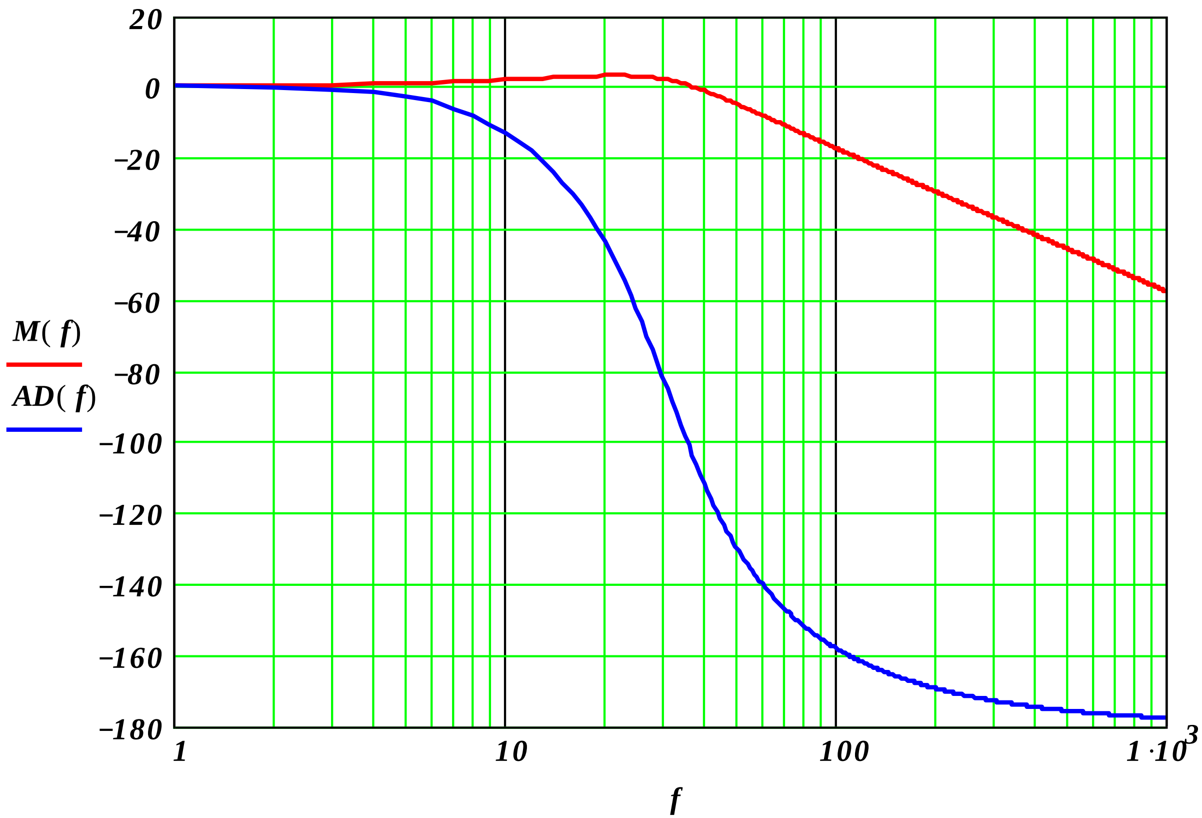
$R := \sqrt{\dfrac{L}{C_1}}$ $\quad R = 0.34\,\Omega$ $\quad C_2 := 5\cdot C_1$ $\quad C_2 = 0.065\,F$

$$T(f) := \frac{s(f)\cdot R\cdot C_2 + 1}{s(f)^3\cdot R\cdot L\cdot C_1\cdot C_2 + s(f)^2\cdot L\cdot\left(C_1 + C_2\right) + s(f)\cdot R\cdot C_2 + 1}$$

$M(f) := 20\cdot\log\left(\left|T(f)\right|\right)$ $\quad AR(f) := \arg(T(f))$

$AD(f) := AR(f)\cdot 57.3$





Higher Frequency Operation Means a Smaller Filter

$$f_{r1} = \frac{1}{2\pi\sqrt{LC}}$$

$$Let\ f_{r2} = nf_{r1} = \frac{n}{2\pi\sqrt{LC}}$$

$$nf_{r1} = \frac{1}{2\pi\sqrt{\frac{L}{n}\frac{C}{n}}}$$

L is smaller by the factor n

C is smaller by the factor n

36 kHz Praeg Filter

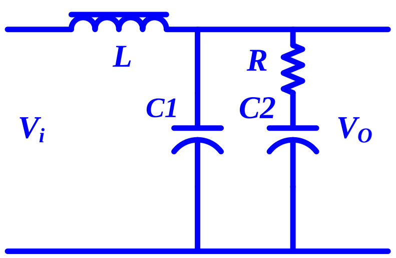
$f := 10 \cdot Hz, 20 \cdot Hz .. 100000 \cdot Hz \quad s(f) := j \cdot 2 \cdot \pi \cdot f \quad L := 1.5 \cdot 10^{-5} \cdot H \quad C_1 := 0.00013 \cdot F \quad f_r := \dfrac{1}{2 \cdot \pi \cdot \sqrt{L \cdot C_1}}$

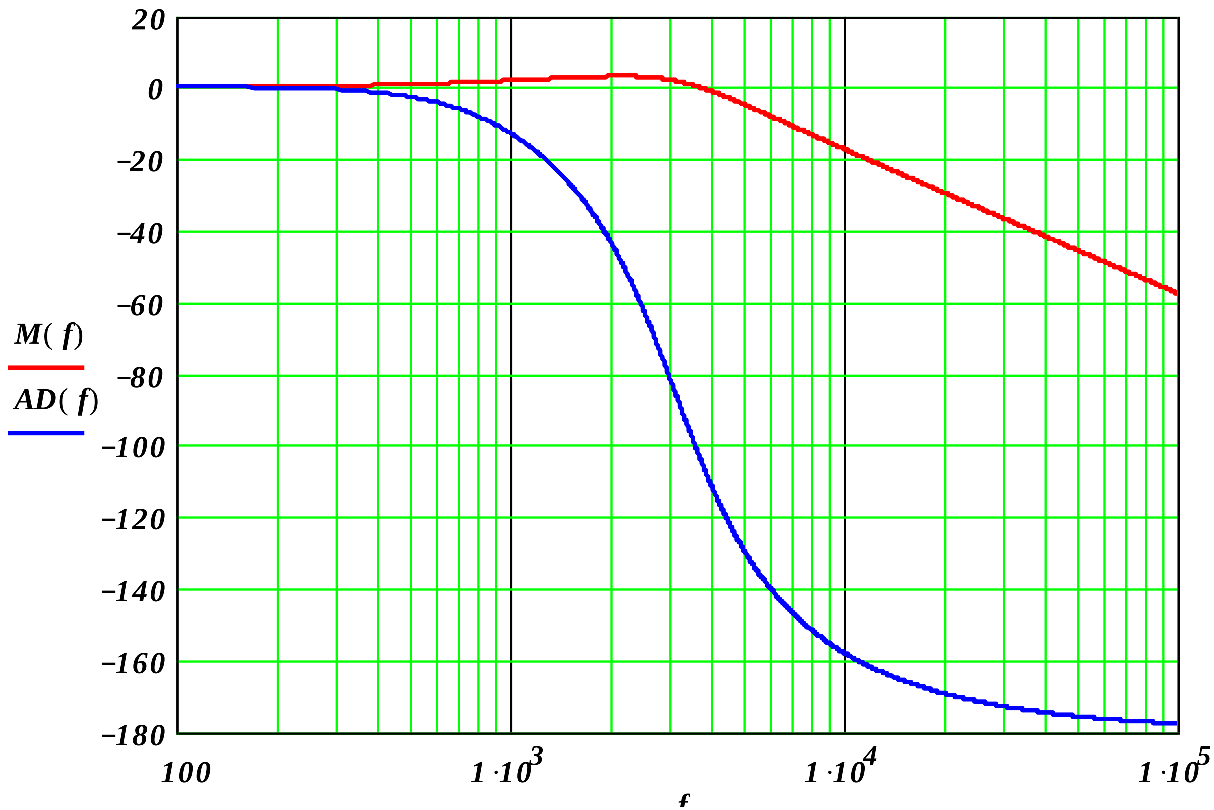
$R := \sqrt{\dfrac{L}{C_1}} \quad R = 0.34\,\Omega \quad C_2 := 5 \cdot C_1 \quad C_2 = 6.5 \times 10^{-4}\,F \quad f_r = 3604\,Hz$

$$T(f) := \frac{s(f) \cdot R \cdot C_2 + 1}{s(f)^3 \cdot R \cdot L \cdot C_1 \cdot C_2 + s(f)^2 \cdot L \cdot (C_1 + C_2) + s(f) \cdot R \cdot C_2 + 1}$$

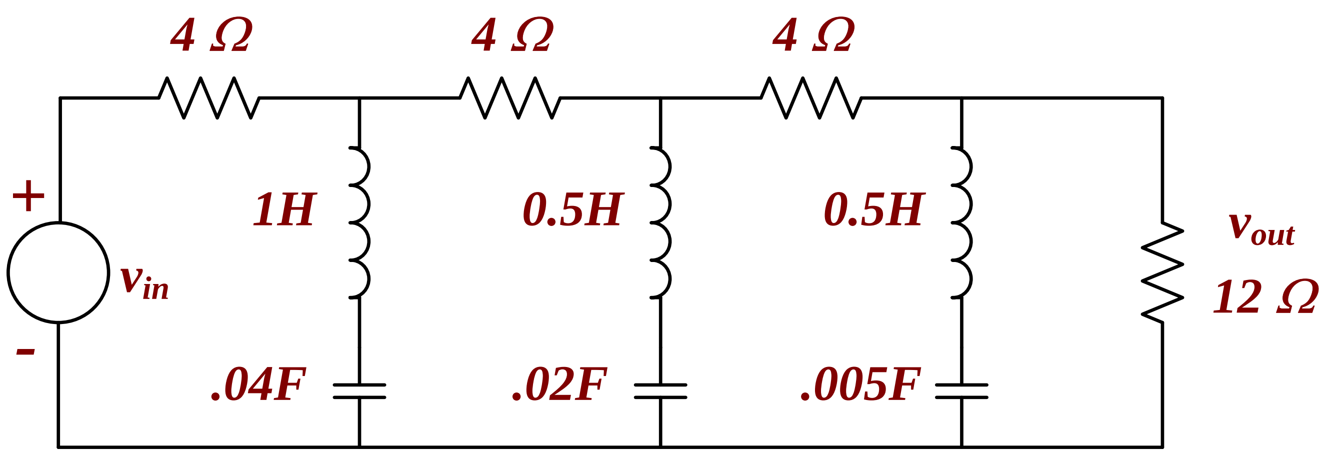
$M(f) := 20 \cdot \log(|T(f)|) \quad AR(f) := \arg(T(f))$

$AD(f) := AR(f) \cdot 57.3$





Given the circuit below:



$$H(j\omega) = \frac{V_{out}(j\omega)}{V_{in}(j\omega)}$$

•*Remember that* $s = j\omega$

Sketch $|H(j\omega)|$ *versus* ω

Other Design Considerations

And Power Supply Costs

$$All\ equipment = \sum (P_{switchgear} + P_{transformer} + P_{AC\,cables} + P_{PS} + P_{DC\,cables})$$

- $Switchgear\ effiency \geq 98\%$ $\quad Switchgear\ losses = P_O * (\frac{1-Eff}{Eff})$

- $Transformer\ efficiency \geq 97\%$ $\quad Transformer\ losses = P_O * (\frac{1-Eff}{Eff})$

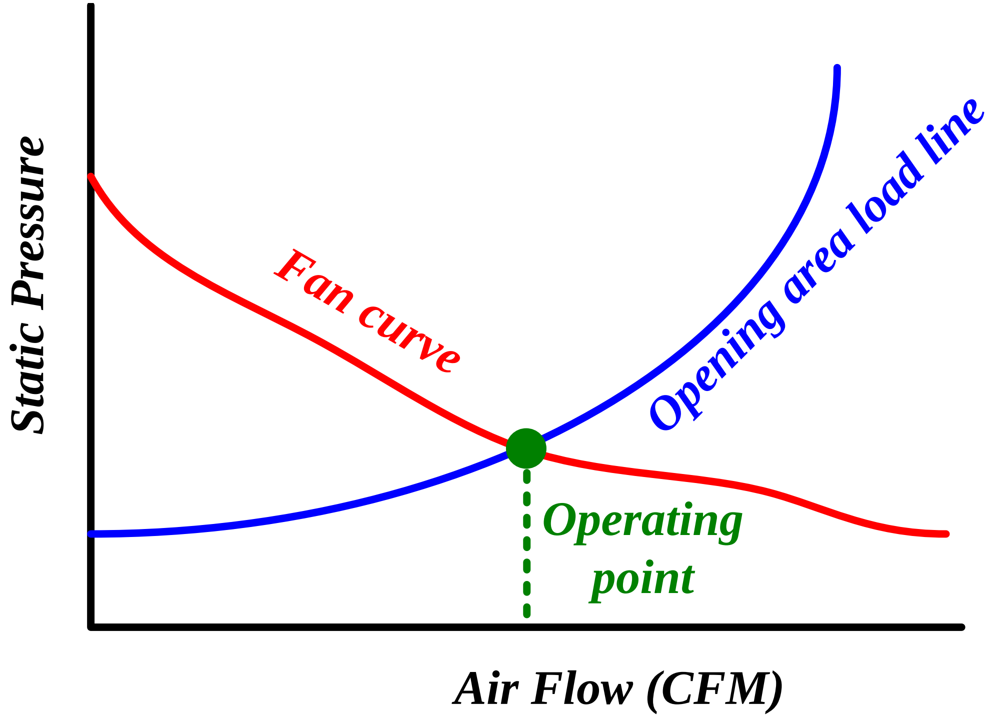
- $P_{AC\,cables} = \sum_j i_{j\,RMS}^2 * \frac{R_j}{ft} * Length_j$

- $Power\ supply\ losses = \sum_j (P_{in\ j} - P_{out\ j})$

- $P_{DC\ output\ cable} = \sum_j i_{j\,DC}^2 * \frac{R_j}{ft} * Length_j$

Other Design Considerations - Rack Cooling

- *Thermal radiation from rack surface*
- *Electronics – maximum 50C inside rack*
- *Max rise in rack = 50C – $T_{ambient\ max}$*
- *Size openings, back pressure drops Bp=(CFM / (k*Opening Area))^2*
- *Fan vs load curve – junction is operating flow point*



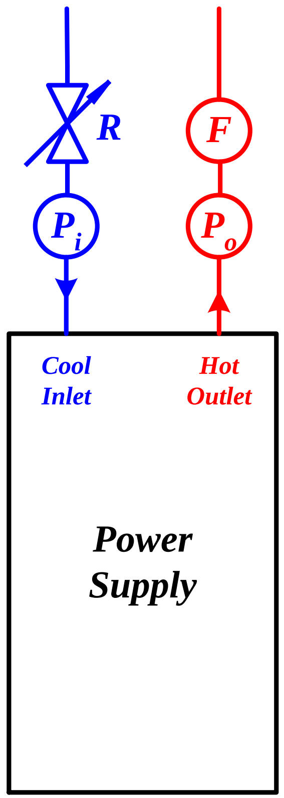
Other Design Considerations - Heat Loading Into Building Water

Power supply heat loss to water $= \sum$ electrical losses of all water-cooled components

Heat lost (dissipated) by PS water cooled components = Heat gained by cooling water system

$Q = M*c*\Delta T$ $\qquad cal = gm * \dfrac{cal}{gm * {}^{O}C} * \left({}^{O}C_{Outlet} - {}^{O}C_{Inlet}\right)$

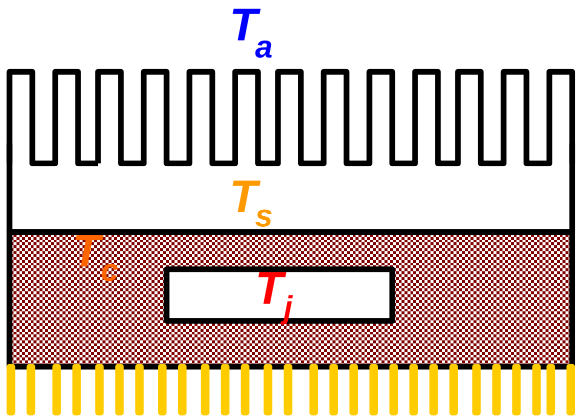
$q = m * c * \Delta T$ $\qquad watt = gpm * \dfrac{264\, watt}{gpm * {}^{O}C} * \left({}^{O}C_{Outlet} - {}^{O}C_{Inlet}\right)$

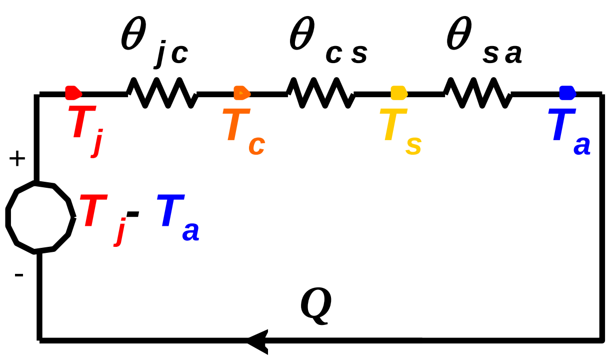


Usually the power loss and the inlet and maximum allowable outlet temperatures are known. The mechanical group will usually ask for an estimate of the water flow requirements. So solving for the flow yields

$$m = \frac{q}{c * \Delta T} = \frac{watt}{\dfrac{264\, watt}{gpm * {}^{O}C} * \left({}^{O}C_{Outlet} - {}^{O}C_{Inlet}\right)}$$

The system pressure drop is $\Delta P = \sum_i P_i$





Q = Power that can be removed by the air or cooling water (W)

T_j = Device junction temperature (^{O}C)

T_c = Device case temperature (^{O}C)

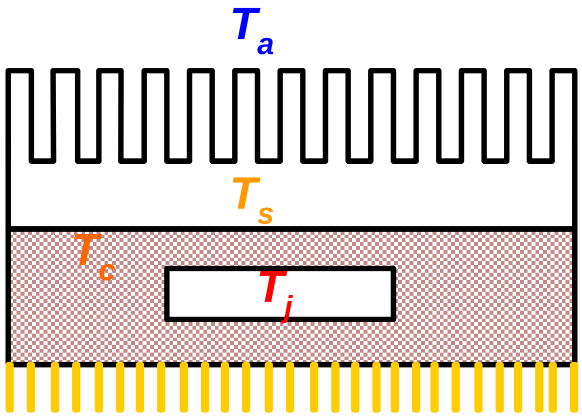
T_s = Heatsink temperature (^{O}C)

T_a = Ambient air or cooling water inlet temperature (^{O}C)

θ_{jc} = junction to case thermal resistance (^{O}C / W)

θ_{cs} = case to heatsink thermal resistance (^{O}C / W)

θ_{sa} = Heatsink to ambient air or cooling water thermal resistance (^{O}C / W)

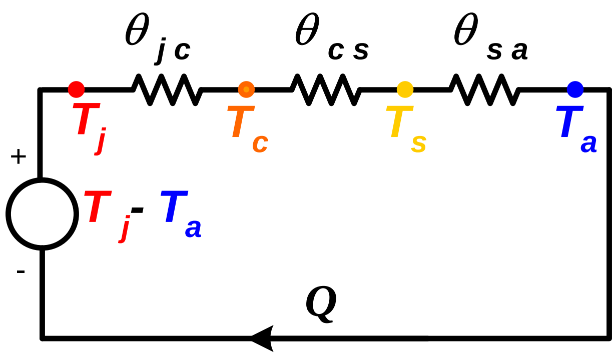


Calculate $Q = \dfrac{T_j - T_a}{\theta_{jc} + \theta_{cs} + \theta_{sa}}$

Q is heat that can be pulled out of the ambient air or cooling water

If calculated Q > q

q is the power disspiated by the device



then all of the device dissipation will be removed by the air or water

Calculate the actual air or water temperature rise from $q = m*c*\Delta T$

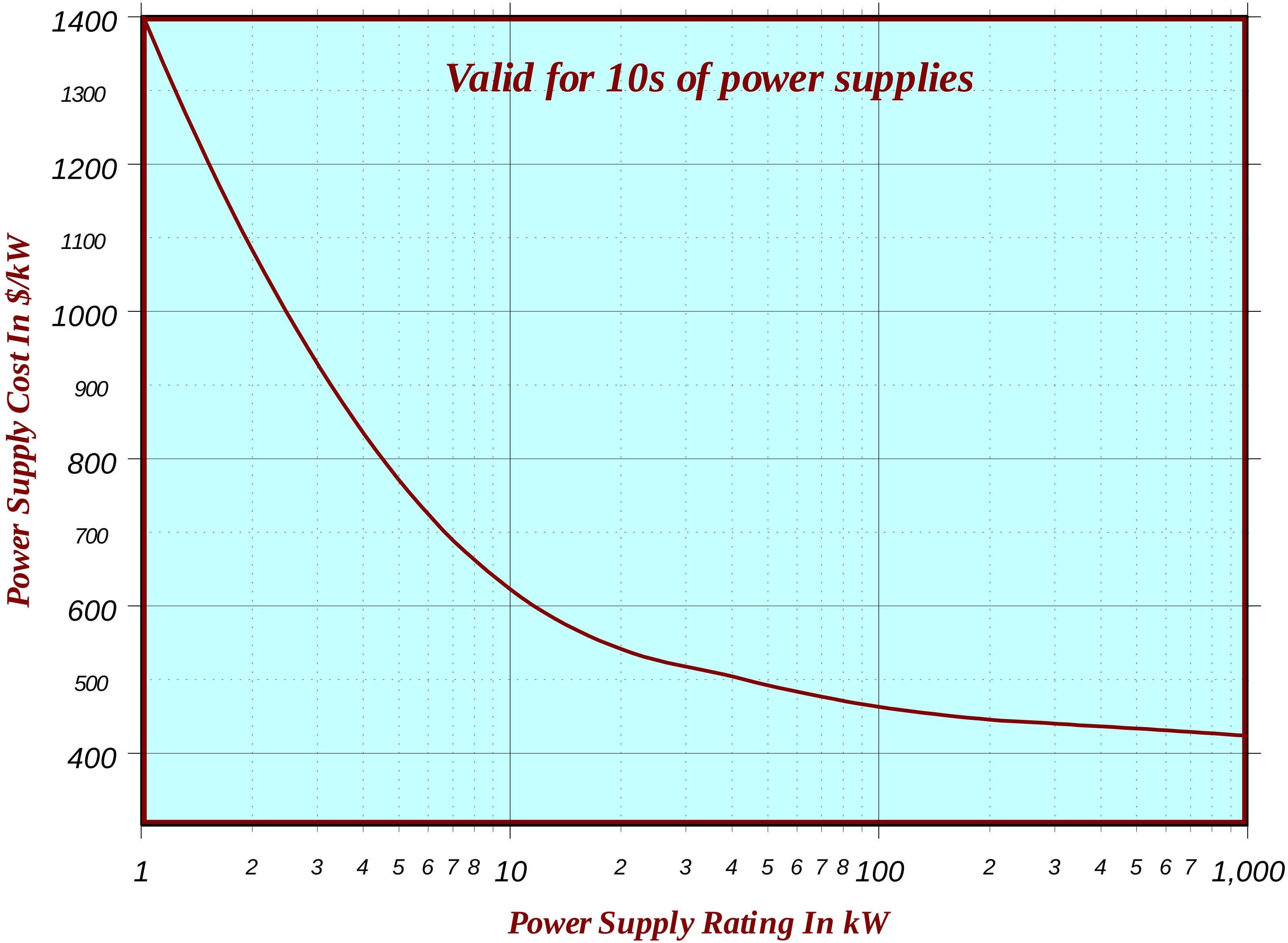
$$\Delta T = \frac{q}{m*c} = \frac{watts}{gpm * \dfrac{264 watt}{gpm * {}^{O}C}}$$

$\Delta T \leq$ the maximum allowable temperature rise

Power Output Vs Mounting / Input Voltage / Cooling Considerations

	Input AC (V)				Cabinet		Cooling	
Power Output	1 ϕ 120	3 ϕ 208	3 ϕ 480	3 ϕ 4160	RM	FS	AC	WC
< 2 kW	X				X		X	
2 kW $\rightarrow$ 5 kW		X			X		X	
> 5 kW $\rightarrow$ 40 kW			X		X		X	
> 40 kW $\rightarrow$ 100 kW			X			X	X	
> 100 kW $\rightarrow$ 1 MW			X			X	X	X
> 1 MW				X		X	X	X

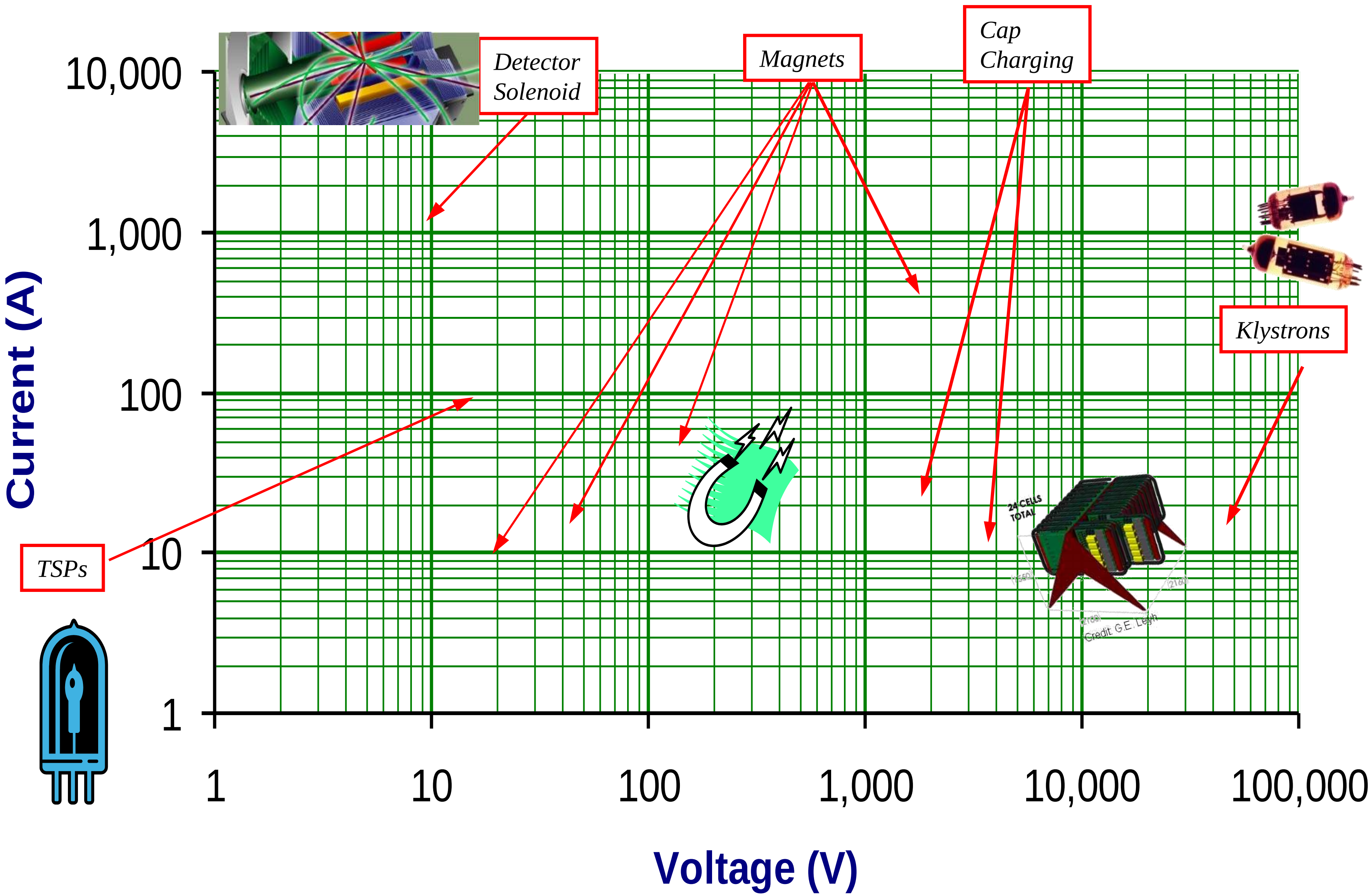
RM = Rack mounted
FS = Freestanding
AC = Air-cooled
WC = Water-cooled


Valid for 10s of power supplies
Power Supply Cost In $/kW
1400
1300
1200
1100
1000
900
800
700
600
500
400
1
2 3 4 5 6 7 8
10
2 3 4 5 6 7 8
100
2 3 4 5 6 7
1,000
Power Supply Rating In kW

Other Design Considerations - Homework Problem # 11

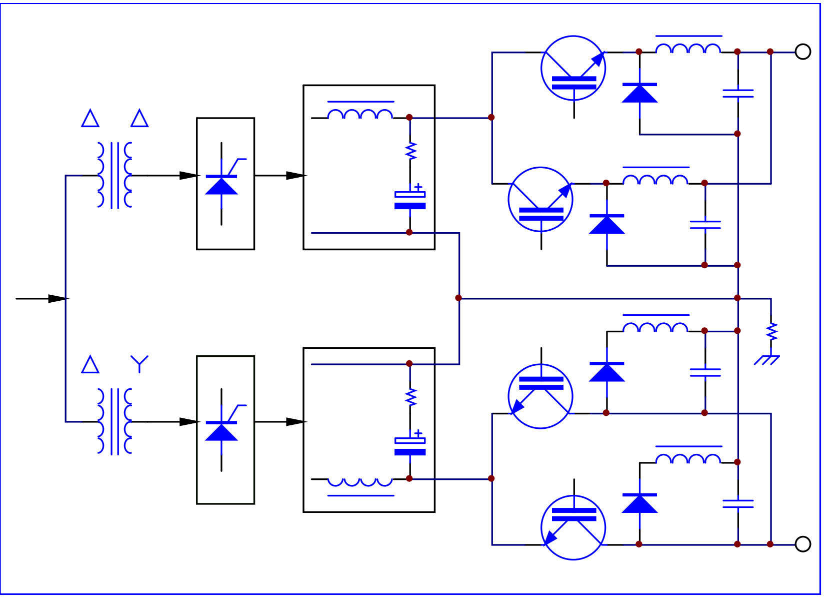
A 100kW power supply is 80% efficient. Approximately 50% of the power supply heat loss is removed by cooling water.

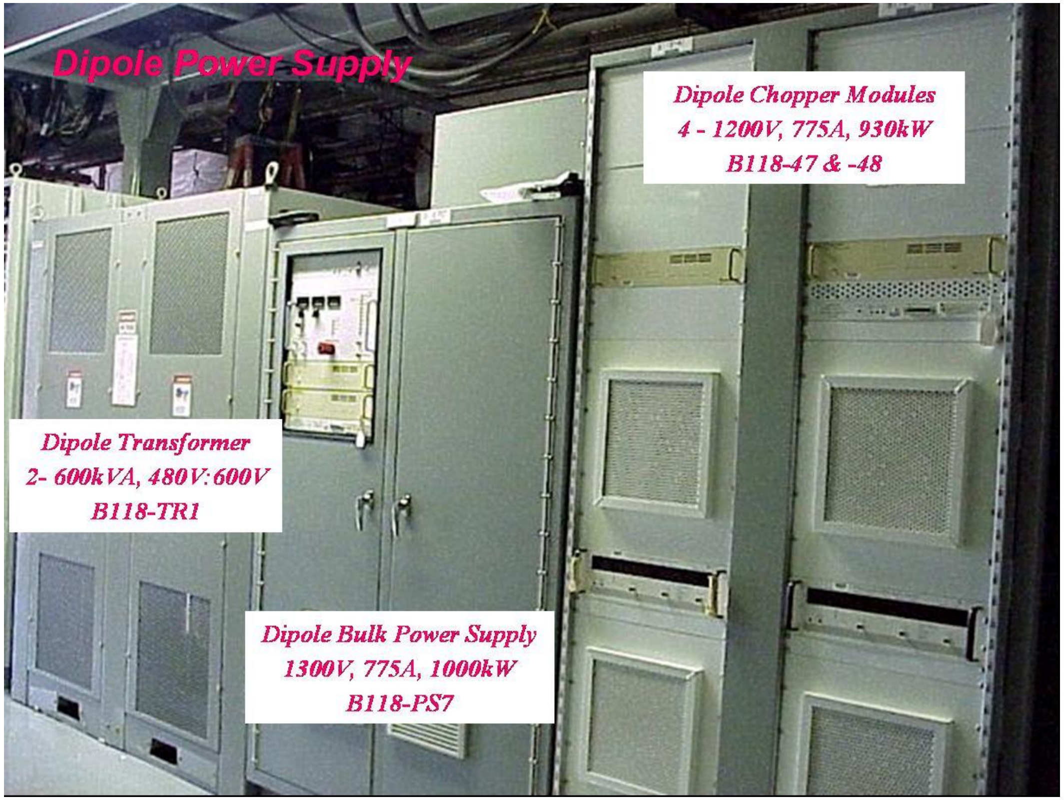
- *How much heat is dissipated to building air and how much heat is removed by the water system.*
- *Calculate the water flow rate needed to limit the water temperature rise to $8^{O}C$ maximum.*


Detector Solenoid
Magnets
Cap Charging
Klystrons
TSPs
10,000
1,000
100
10
1
Current (A)
1
10
100
1,000
10,000
100,000
Voltage (V)
24 CELLS TOTAL
Credit G.E. Leyh

PEP-II and SPEAR3 Dipole Power Supplies

- 1200 VDC, 800 Amperes, 960 KW
- Powers largest magnet string at Spear3, 36 ring bend magnets in series
- Requires 50 PPM (full scale) current regulation, 0.1% voltage regulation
- Requires 600 VAC, 6-Phase AC Input





Storage Ring of the Diamond Project

- The power converter comprises of 8 paralleled modules
- Each module is a non-isolated step down PWM switching regulator operating at a fixed frequency of 2 kHz
- IGBT devices are used as the switching element
- The 8 PWM drives are phase shifted by 360/8° to achieve a 16 kHz output ripple frequency
- 1 quadrant operation

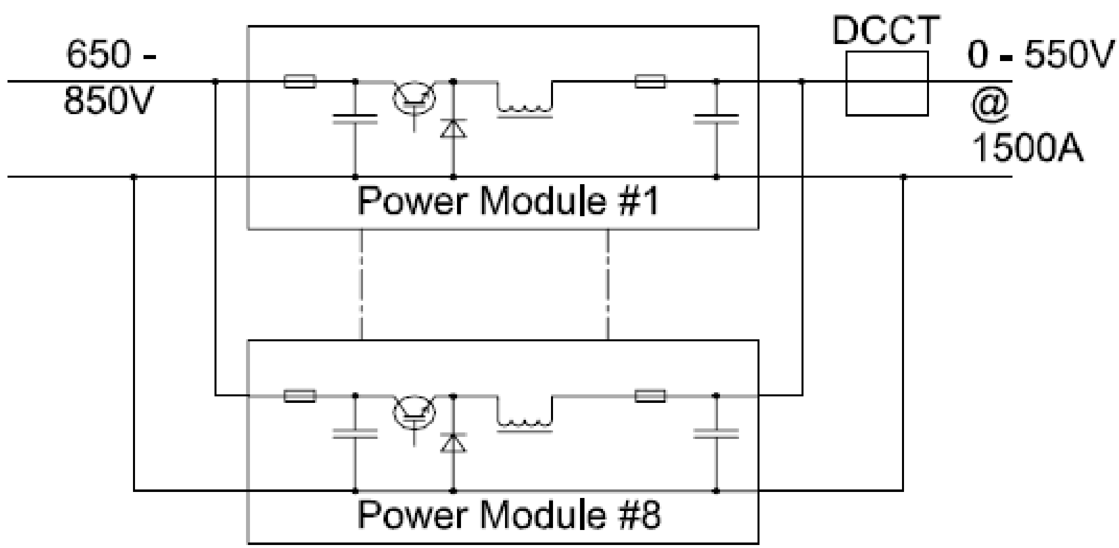


Figure 1: Dipole Converter Topology.

Diamond Booster Magnet Power Converters

- *Booster operates at 5 Hz to accelerate the electrons: 100 MeV to 3 GeV.*
- *Power converters produce an off-set sine wave current with high repeatability at 5 Hz*
- *To avoid disturbance on the ac distribution network, the dipole and quadrupole power converters were designed to present a constant load despite having high circulating energy: 2 MVA in the case of the dipole*
- *Redundancy was introduced wherever this was economically feasible.*
- *Plug-in modules are used to simplify and speed up repairs.*
- *Component standardization and de-rating across all power converters was an additional design goal*

- *Booster dipole PC is rated at peaks of 1000A and 2000V*
- *Three units are sufficient to produce the required output. The fourth is redundant*
- *Each unit is made up of a boost circuit and a 2-quadrant output regulator that produces the required offset sine wave current.*
- *The boost circuit regulates the voltage on the main energy storage capacitor and is controlled to draw constant power from the ac network.*
- *Displaced 4 kHz switching frequency*

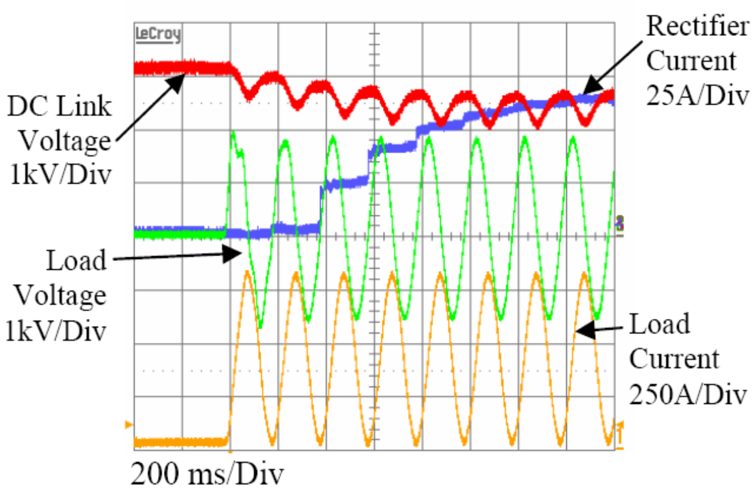


Figure 4: First few cycles after turn on.

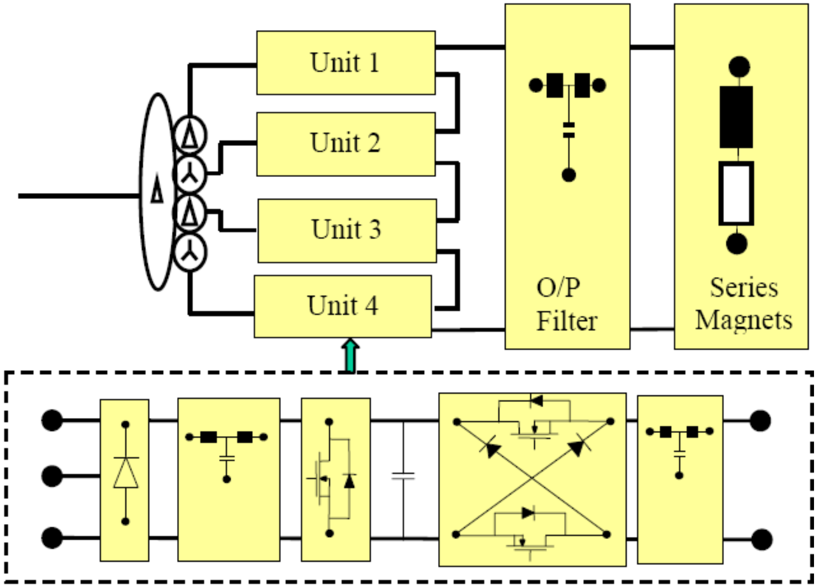
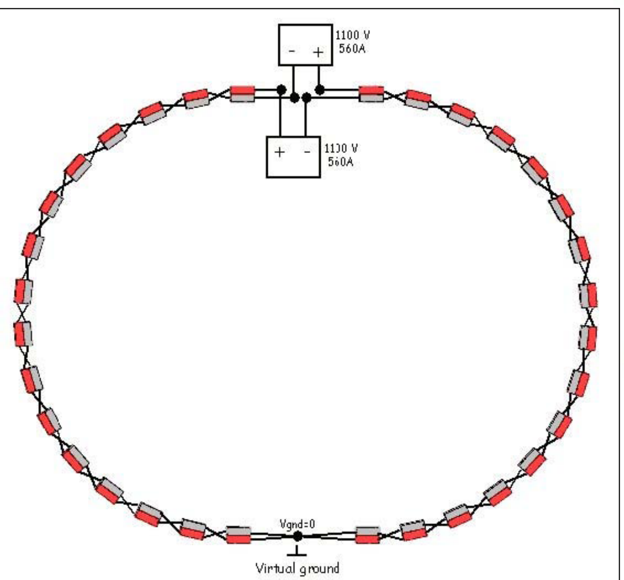


Figure 1: Booster dipole power circuit.

THE 3HZ POWER SUPPLIES OF THE SOLEIL BOOSTER

Table 1: Major booster parameters

Injection energy	110	MeV
Extraction energy	2.75	GeV
Number of dipoles	36	
Dipole magnetic length	2.16	m
Dipole gap	22	mm
Dipole field @2.75GeV	0.74	T
Dipoles inj. current	19.7	A
Dipoles ext.current	541	A
Dipoles load resistance	400	mΩ
Dipoles load inductance	156	mH



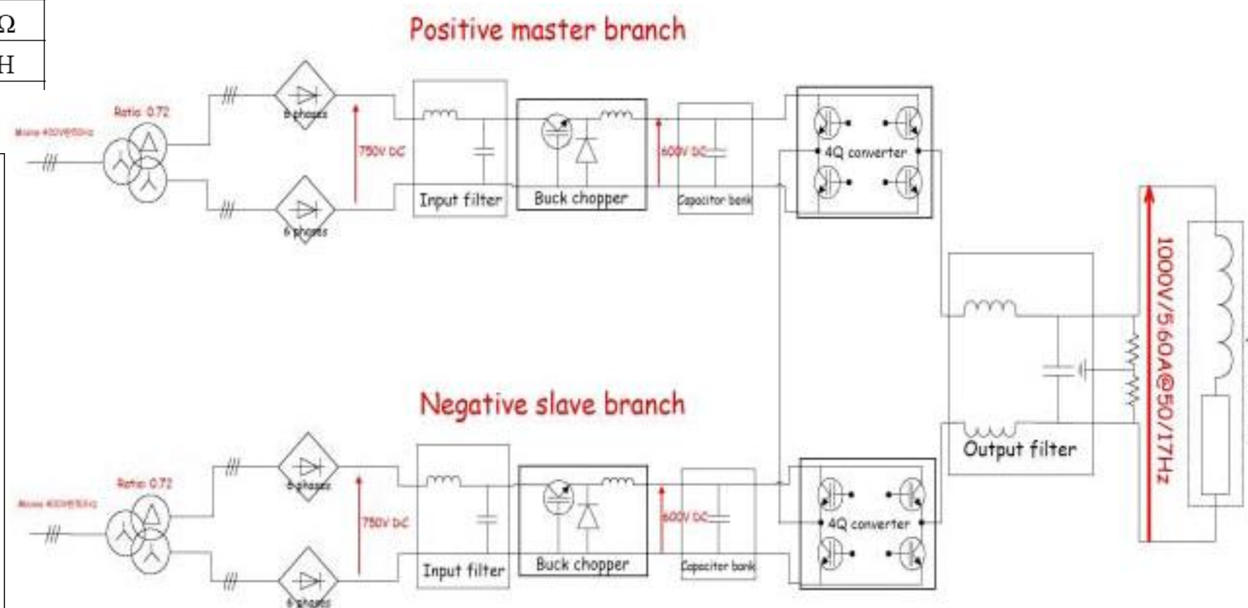
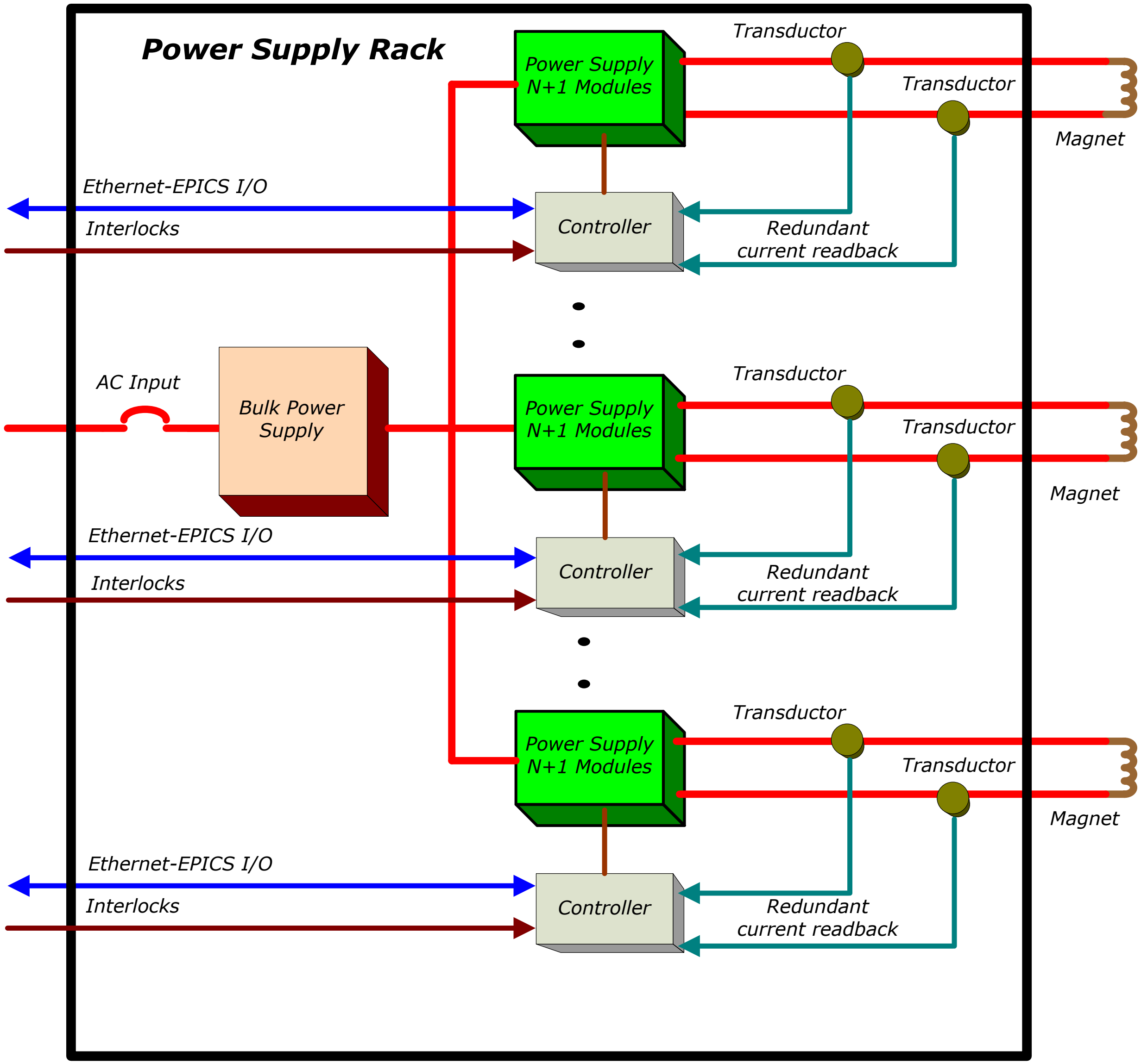


Figure 4: dipoles PS main schematics

Power Supplies for the ATF2



CNAO STORAGE RING DIPOLE MAGNET POWER CONVERTER 3000A / ±1600V

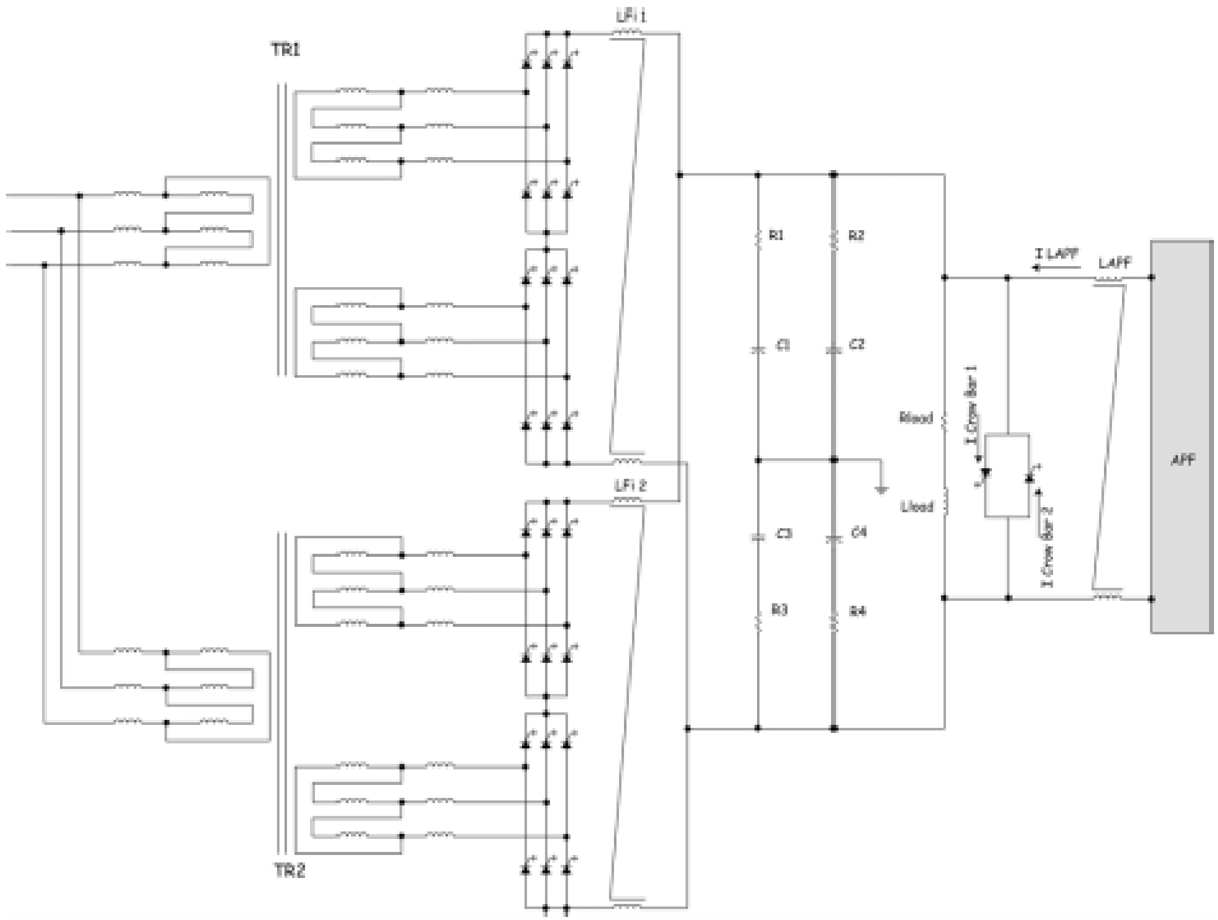


Figure 2: Topology of CNAO synchrotron power supply.

Bipolar Power Supplies at SPEAR3 and LCLS (480W, ±40V, ± 12A)

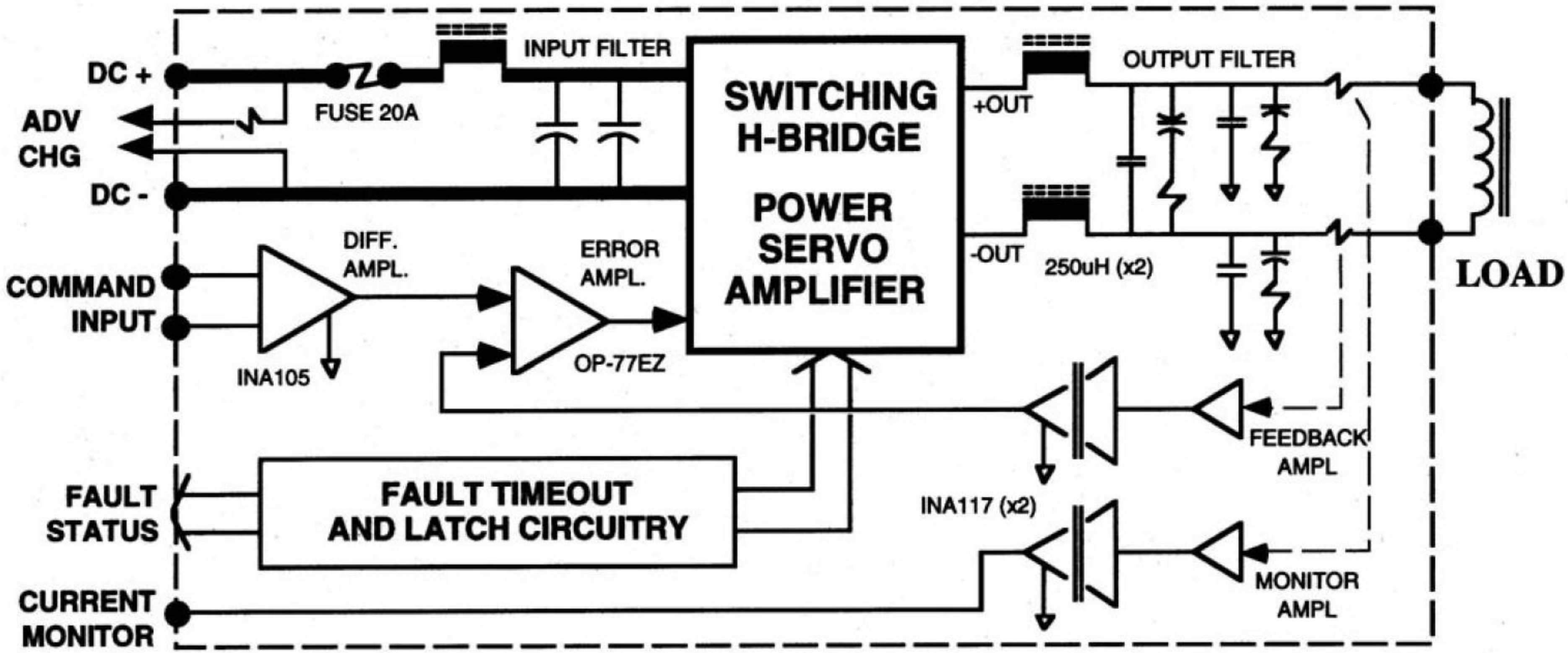


Figure 1.3. MCOR12 Block Diagram.

Bipolar Power Supplies at SPEAR3 and LCLS

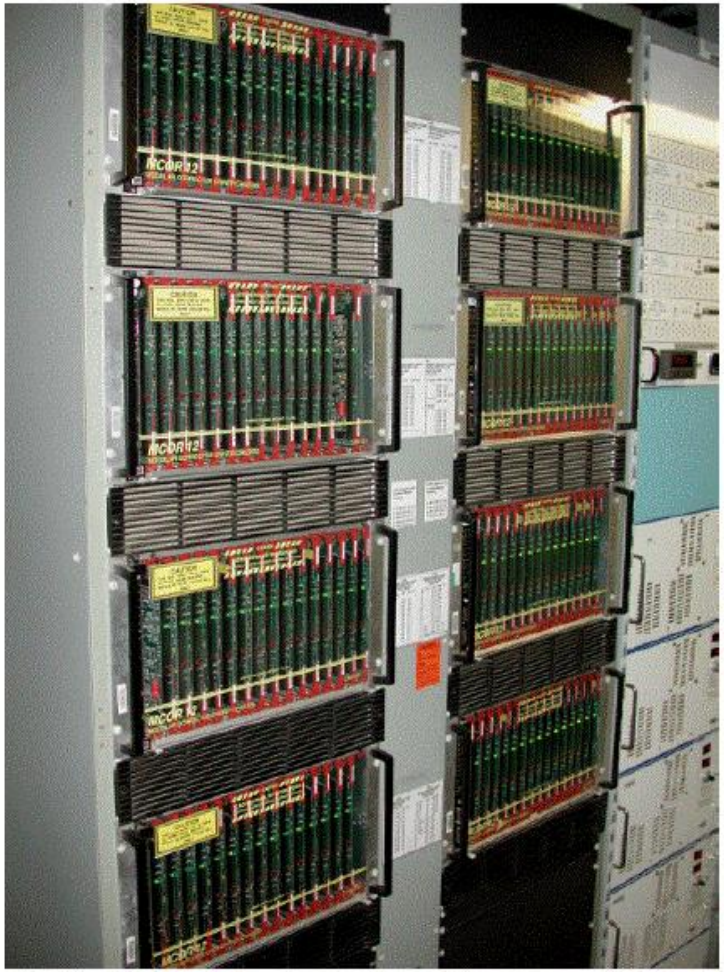
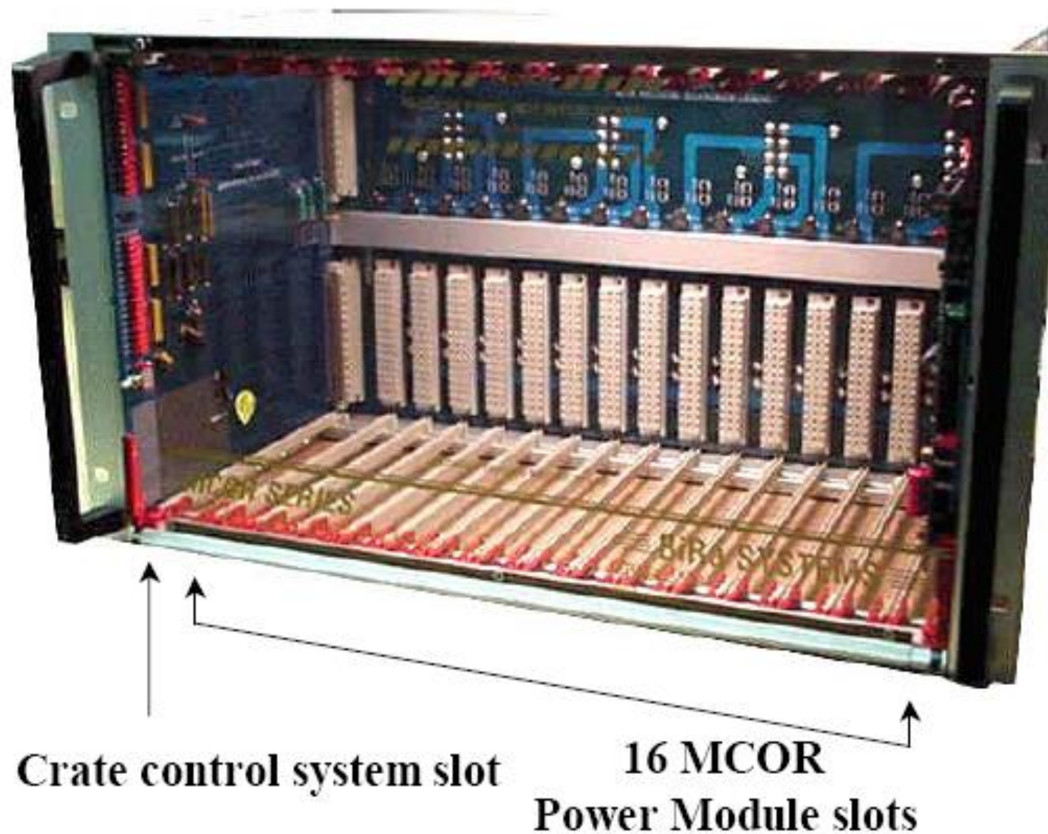


Figure 1.1. A typical MCOR installation



NEW MAGNET POWER SUPPLY FOR PAL LINAC

Table 1: Development specifications of MPS

	Bipolar	Unipolar	
Size (W x H x D)	435x135×450	435×178×450	mm
Input	1ϕ 220V	3ϕ 30V	V
Output	±10/20	50/50	A/V
Output stability	±50ppm	±20ppm	< 1 hour
	±100ppm	±50ppm	> 10 hours
Output resolution	16		bit
Topology	Full-Bridge 4-Q DC/DC converter		
Switch freq.	50		kHz
Output Filter Cut-off freq.	< 5		kHz

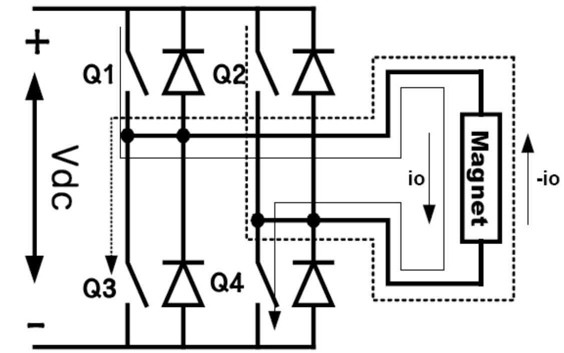


Figure 1: Bipolar MPS operation of full-bridge four-quadrant DC/DC converter.

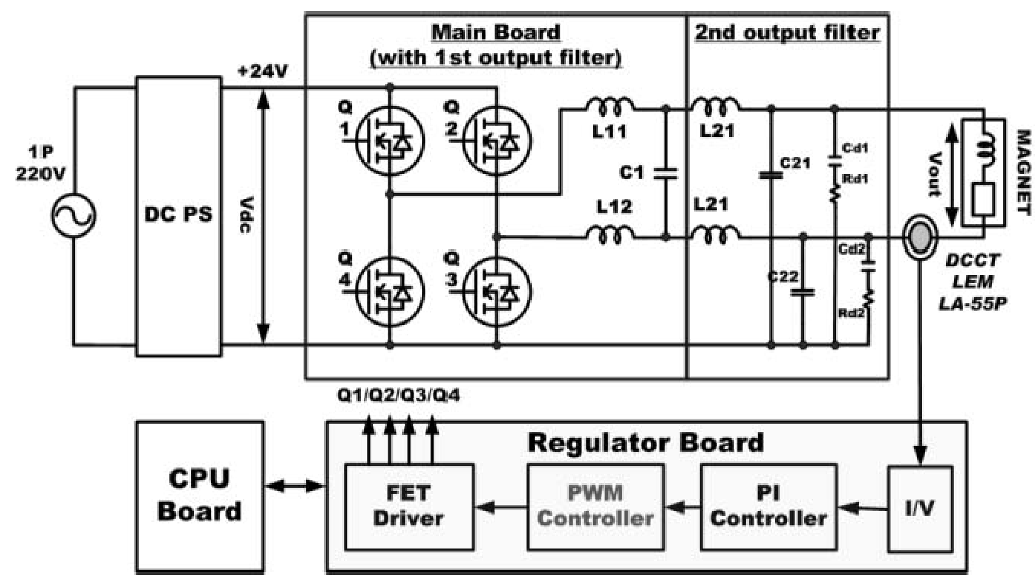
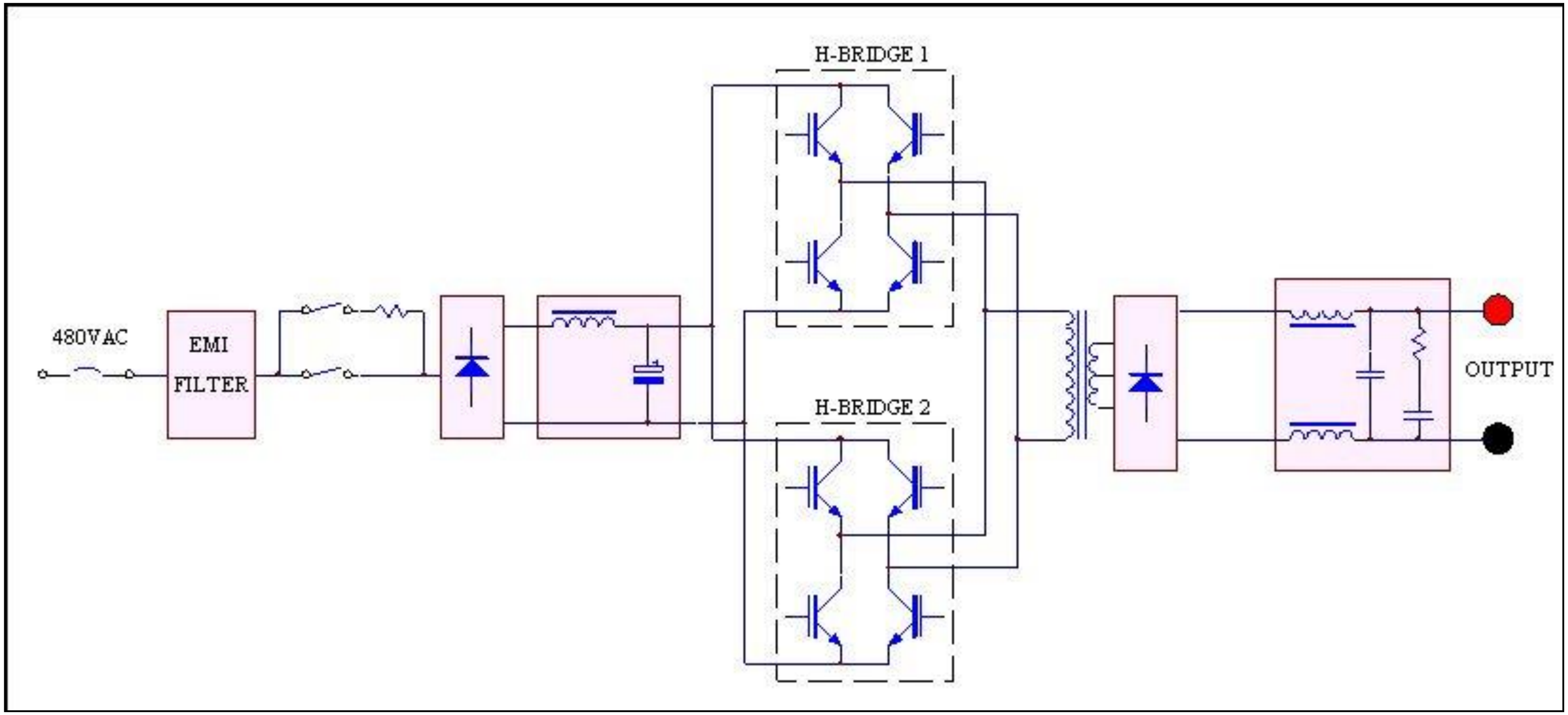


Figure 4: Circuit diagram of bipolar MPS.

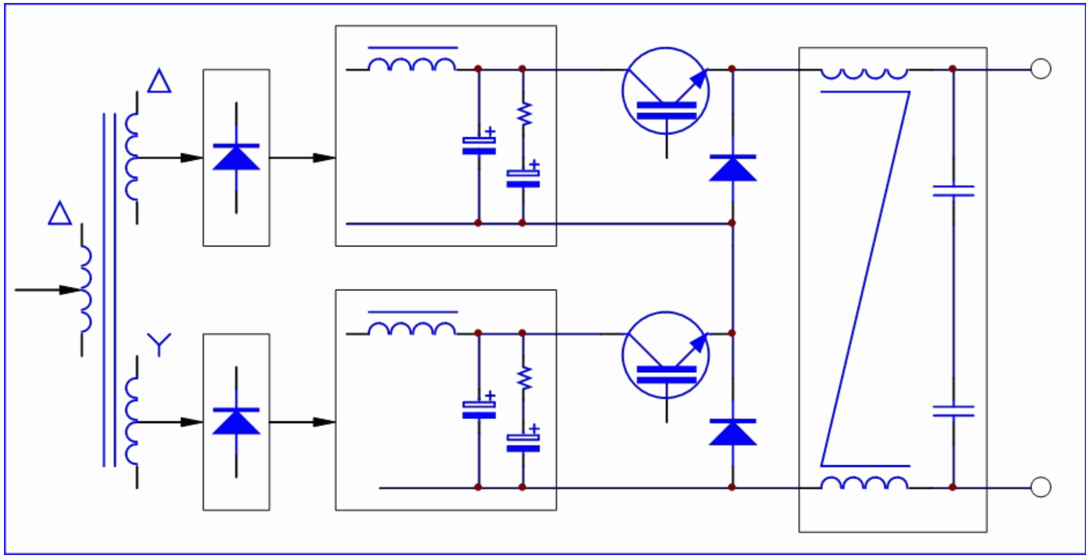
Table 1: LGPS ratings.

LGPS	V	I	P (kW)	Qty
BV1/2	80	900	72	1
QF2L/R	80	1250	100	2
QF5L/R	253	750	190	2
QD4L/R	200	1350	270	2



SPEAR3 Large Power Supplies

- Line-isolated
- 32 kHz Switch-output ripple
- High efficiency
- Fast output response
- Stability better than ±10 ppm
- 100A to 225A
- 70kW to 135kW
- Low cost: US$ 0.26 – 0.39/W



Section 7 – Superconducting Magnet Power Systems

Rationale For Using Superconducting Magnets

- ***Problem***

– *Contemporary high energy physics questions require much higher beam energies*

  – *Higher energies mean larger magnets, larger facilities (size goes like B^{-1}). Conventional magnets consume lots of electrical power, iron cores saturate at about 2T*

– *Synchrotron light sources require high field insertion devices (undulators, wigglers)*

  – *Permanent magnet pole pieces also have limited magnetic fields*

- ***Superconducting Magnets***

– *Are smaller (possess high current density $\Rightarrow$ compact windings, high gradients)*

– *Consume much less power (primarily refrigeration power), consequently lower power bills*

– *Can generate greater magnetic fields (typically to 10T and more). Greater magnetic fields mean smaller bend radius, smaller accelerator and rings, reduced capital expense. Furthermore, no expensive iron core*

Example – Superconducting solenoid

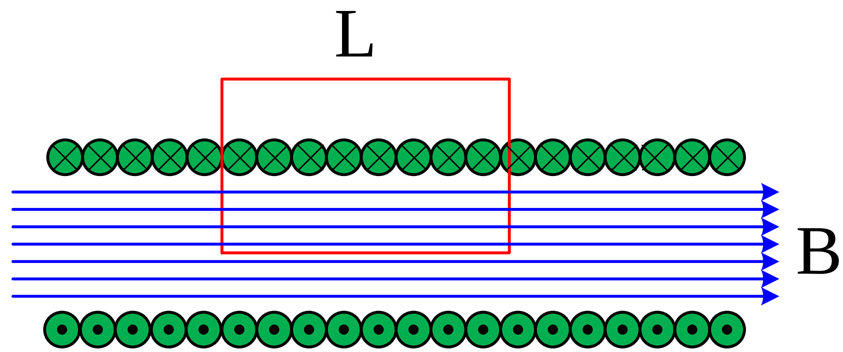
From Ampere's Law

$\oint H \cdot dl = NI_0 \quad B = \mu_o H$

$\mu_o \oint H \cdot dl = \mu_o NI_0$

$BL = \mu_o NI_0$ or

$B = \mu_o NI_0 /L$



B=Tesla, T
$\mu_o = 4\pi * 10^{-7}$ *T*m/A*
N = number of solenoid turns, t
I_0 *= amperes carried per turn, A/t*
L or dl = solenoid length, m

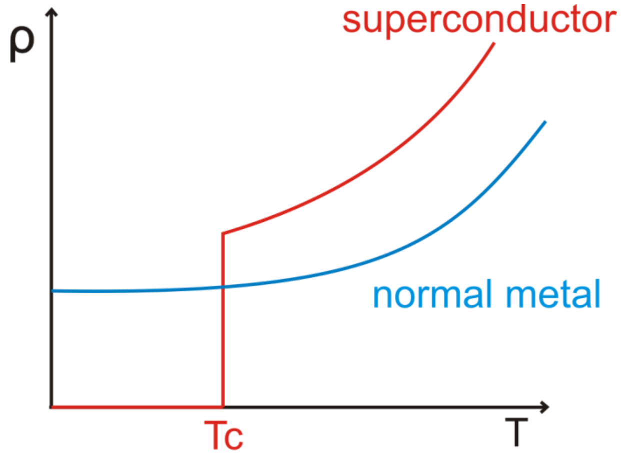
Assume a solenoid 3m long with 2,500 turns and carrying 5,000A

$B = (\mu_o NI_0) /L = (4\pi * 10^{-7} T*m/A*2500t*5{,}000A/t)/3*m = 5.2T$

Normal conductors follow Drude's model

- *Electrons move freely in metal, accelerated by external* $\vec{\boldsymbol{E}}$ *field*
- *After a time* τ *the electron interacts with the lattice of the solid and gives up its energy*
- *Steady state average value of velocity* $\vec{\boldsymbol{v}} = -e\vec{\boldsymbol{E}}\tau/m$
- *Steady state value of current,* $\vec{\boldsymbol{j}} = -ne\vec{v} = (ne^2\tau/m)\vec{\boldsymbol{E}} = \sigma\vec{\boldsymbol{E}}$
- *This defines the conductivity* σ
- *Better conductors have longer times between interactions*
- *"Perfect" conductor has* $\sigma \rightarrow \infty$
- *Resistance of normal metal decreases to finite non-zero value as temperature decreases*

Superconducting Metals

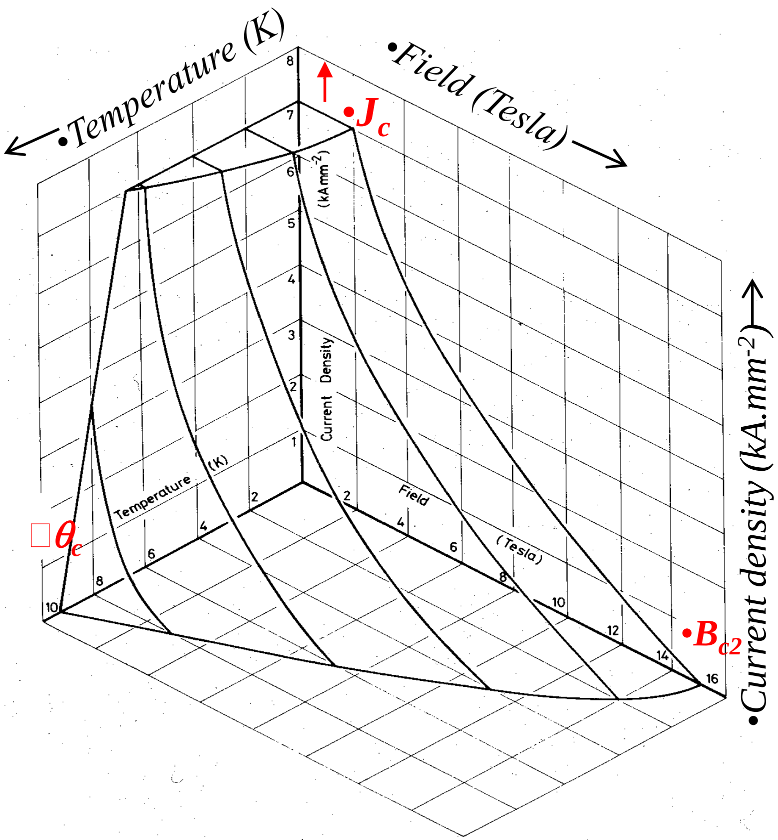


- *Superconducting metal resistance drops to zero at T_C*
- *Superconductors also exhibit Meissner effect*
- *Excludes $\vec{\boldsymbol{H}}$ from the center of the SC*

BCS theory (Bardeen, Cooper, Schrieffer, 1957) explains SC

- *In presence of lattice, conduction electrons can form "Cooper pairs" that lower the energy of the system*
- *Two phase system – normal and SC phases*
- *Band gap forms and Cooper pairs can carry current with no lattice interaction*

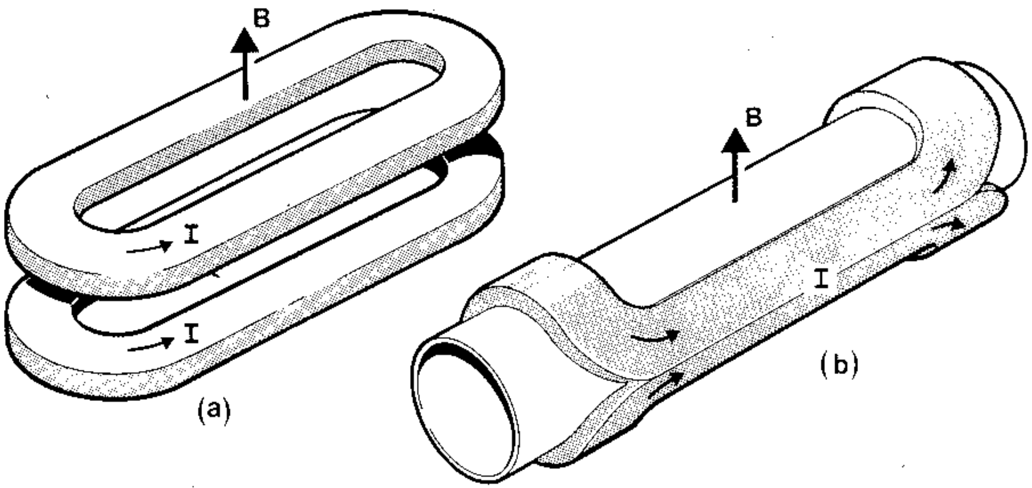
SC current capacity dependent on number of SC pairs



- *Exclusion of $\vec{H}$ (Meissner effect) increases system free energy.*
- *Sufficiently large $\vec{H}$ raises free energy of SC state above that of normal conductor and "quenches" SC state*
- *Many, but not all metals and alloys can exhibit SC behavior*
- *Different materials have different values of T_C, H_C, and J_C.*
- *Niobium or one of its alloys is most common commercially used SC material*

- *Picture shows the 3 dimensional space **critical surface**, which is the boundary between superconducting and normal conducting phases*
  - *Superconducting phase below surface*
  - *Normal conducting above*

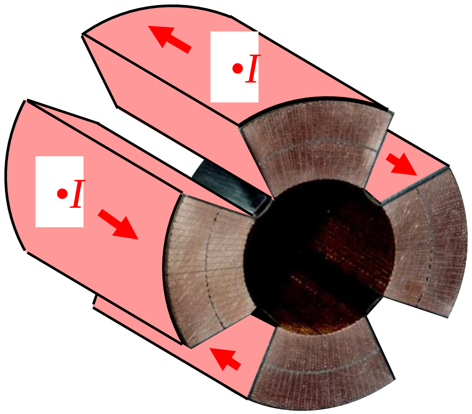
Dipole Magnet

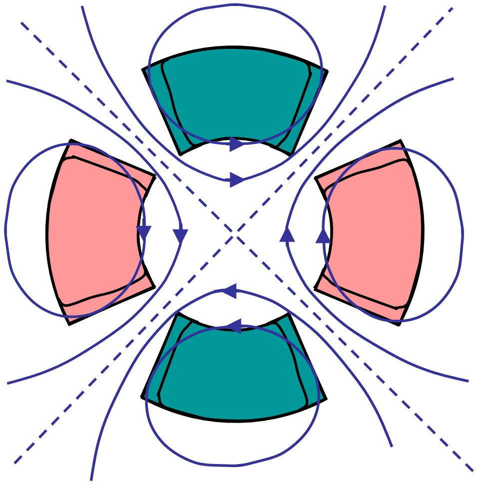


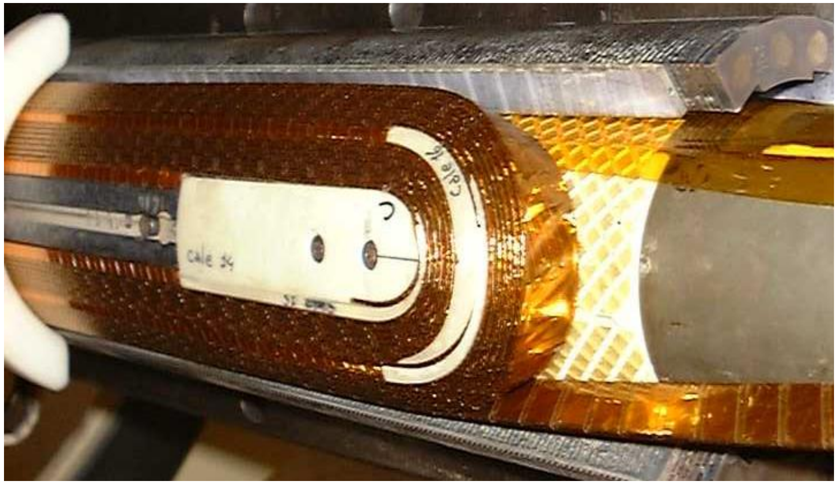
- Conventional magnet typically "iron-dominated"
- Iron pole pieces shape the field
- SC magnets are made from superconducting cable
- Winding location shapes the field according to Ampere's Law
- Windings must have the correct cross section
- Also need to shape the end turns

Quadrupole Magnet

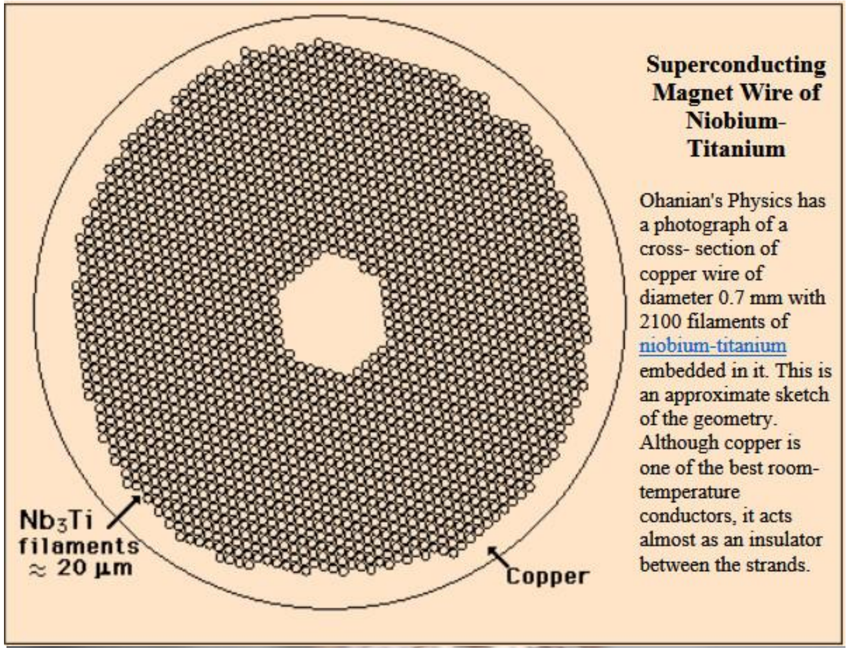
- *Quadrupole windings, gradient fields produce focusing*

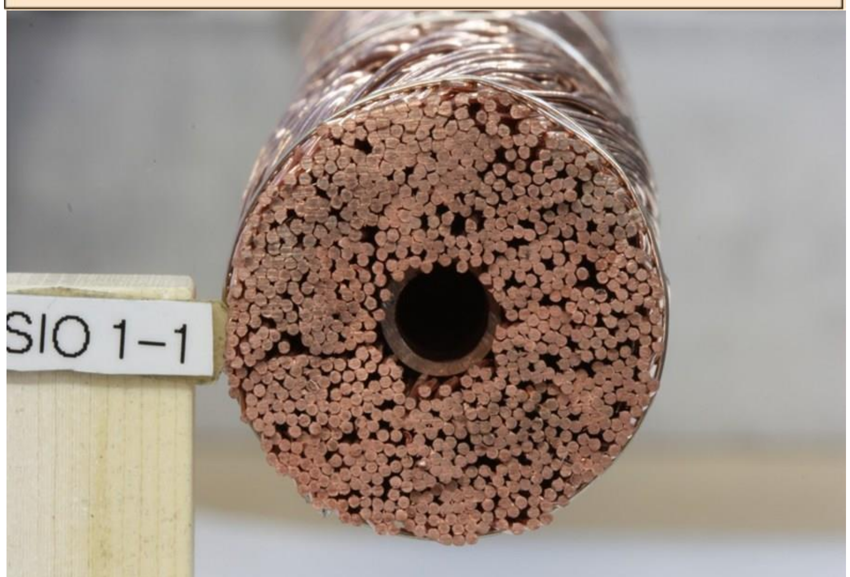






Winding Construction



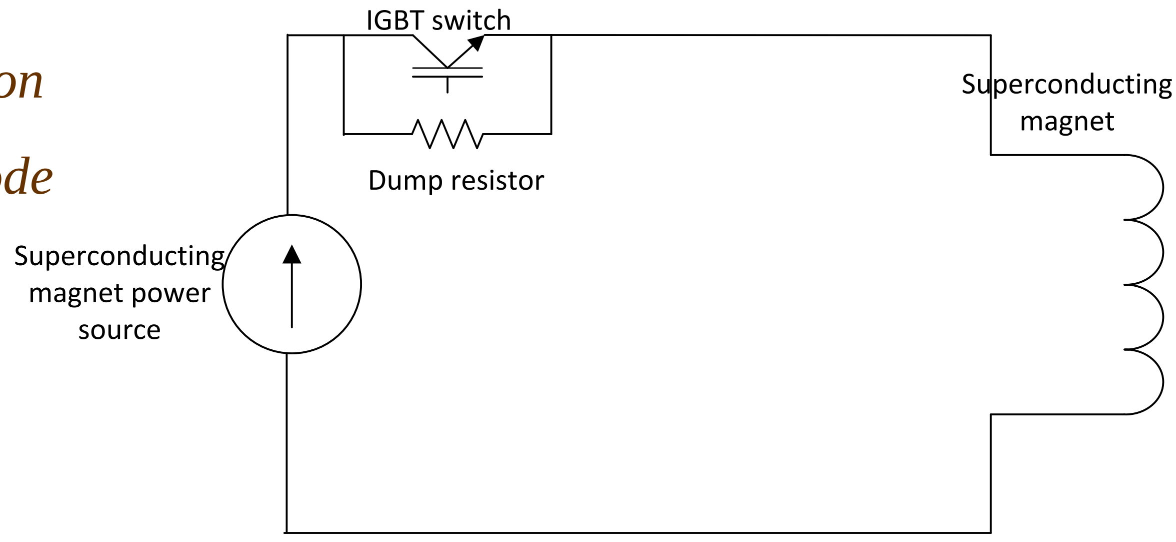


- *The superconductor is made in the form of fine filaments embedded in a matrix of copper. Filament diameter = 10 - 60μm. These form a wire of diameter = 0.3 - 1.0mm. A typical wire is at left.*
- *The composite wires are twisted like a rope as below left.*
- *The choice of the filament material is a trade-off between T_C, B_{Crit}, and ductility*
- *Other filament materials have higher critical temperatures and yield higher fields, but only NbTi (T_C=10°K) is ductile*

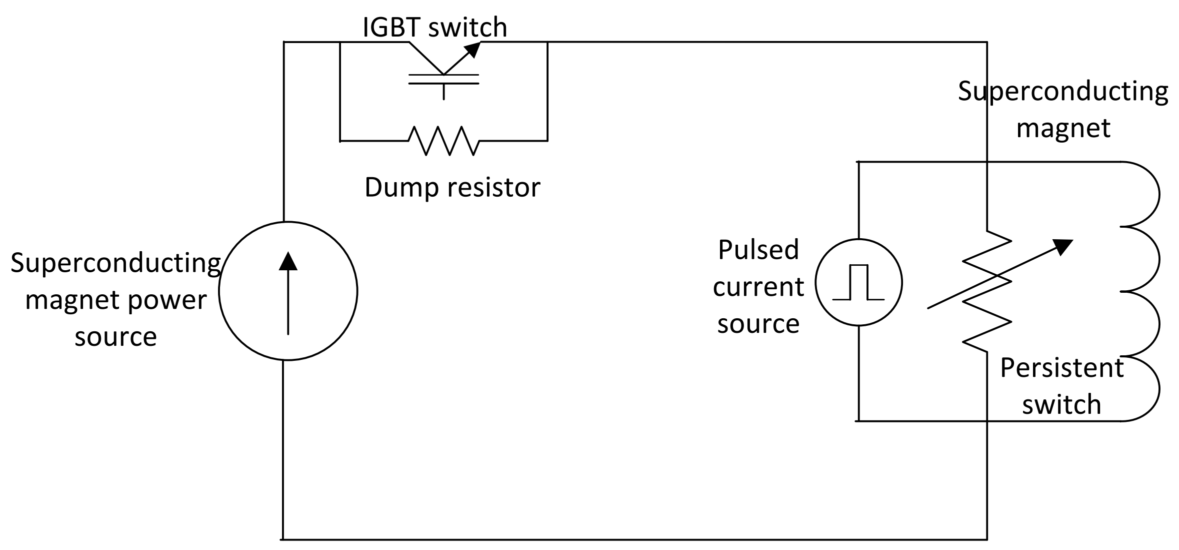
Operating Modes

Two Modes of operation

1. *Power Supply Mode*



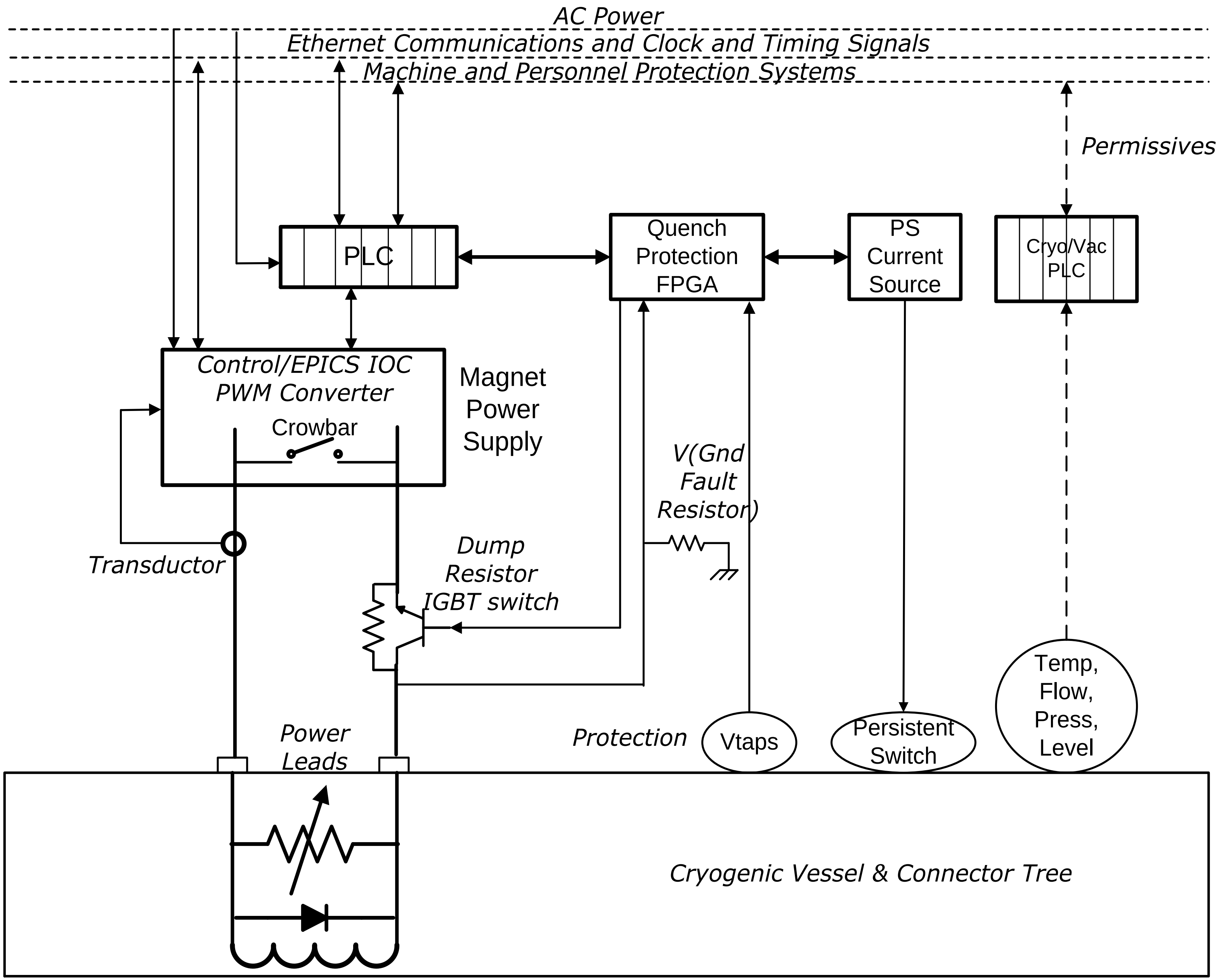
2. *Persistent mode*



Quenches

- *Quench - occurs if the limits of the critical surface are exceeded. The affected magnet coil changes from a superconducting to a normal conducting state.*
- *The resulting drastic increase in electrical resistivity causes Joule heating, further increasing the temperature and spreading the normal conducting zone through the magnet.*
- *High temperatures can destroy the insulation material or even result in a meltdown of superconducting cable*
- *The excessive voltages can cause electric discharges that could destroy the magnet*
- *In addition, high Lorentz forces and temperature gradients can cause large variations in stress and irreversible degradation of the superconducting material, resulting in a permanent reduction of its current-carrying capability.*

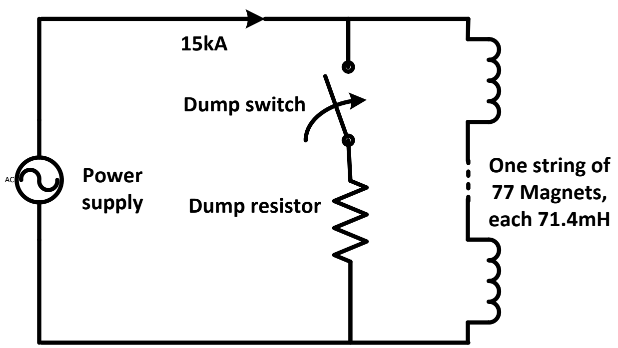
Superconducting Magnet Power System Schematic



Superconducting Magnet Power System Homework Problem #12

A collider has several equal strings of 77 superconducting magnets, each with 71.4mH inductance, carrying 15kA of current. If one, or more quenches, all the energy from the other magnets will dissipate their energies into the quenched magnet, thus destroying it. Design a switched dump resistor to discharge the current at a maximum rate, dI/dt, less than the 300A/s damage threshold, to prevent damage to the superconducting magnet in the event of a quench. Refer to the circuit diagram below.

1. *What is the energy stored in each magnet and in the string when running at its design value?*
2. *What is the total inductance of the string?*
3. *Write the equation that describes the resistor current after closing the switch.*
4. *Find the resistor value to limit the maximum rate of decrease of current in the magnets to 150A/s*
5. *What is the maximum voltage generated across the resistor?*
6. *What is the time constant of this circuit?*
7. *Design a steel dump resistor that has little thermal conductance to the outside world (adiabatic system). Calculate how much steel mass (weight) will limit the temperature increase of the resistor to 500°K. (Steel gets structurally soft at 538°C and melts at 1510°C.)*



Help

$$Q = M\ C_p\ \Delta T$$

$Q =$ *heat (energy) into the system expressed in joules*

M= mass or weight of the resistor

$$C_p = \text{specific heat of material} = 0.466 \frac{J}{gm * {}^oK} \text{ for steel}$$

$\Delta T =$ *Temperature rise of the resistor*

From information in "CERN LHC Magnet Quench Protection System, L. Coull, et. al, 13th International Conference on Magnet Technology, Victoria, Canada, 1993

Section 8 – Pulsed Power Supplies

- *Transmission Lines*
- *Conventional Pulsers*
- *Solid-State Pulsers*
  - *Turn-on Pulser*
  - *Marx Modulator*
  - *Induction Modulator*

Outline

- For the study of pulsed power systems
  - Need to understand basics of transmission lines
  - Once we know the basics, we can follow simple rules to apply them
- If we just state the rules
  - It may sound like black magic and take away the intuition
- Therefore we derive the rules to help in understanding the basics of transmission lines

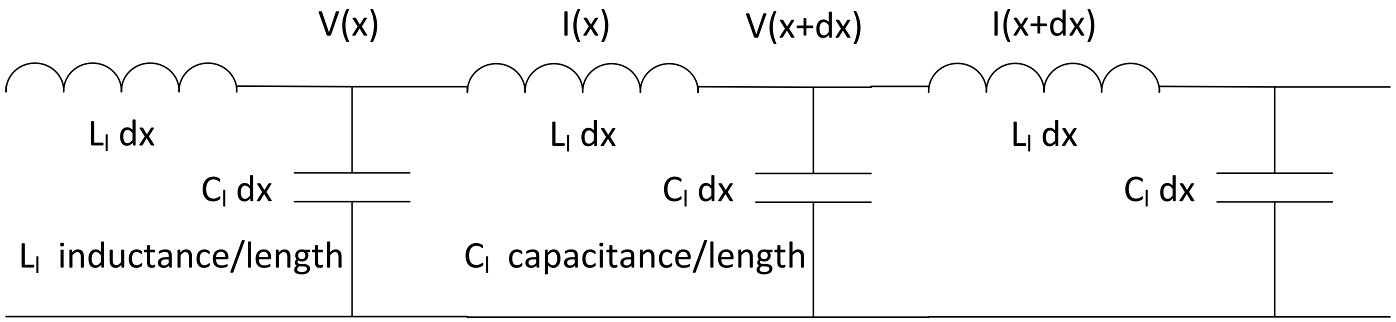
Impedance Matching

- *Power systems differ from low power electronics; it is expensive to produce high power signals*
  - *High voltages*
    - *Semiconductors (and other devices) must be able to withstand voltages across their terminals*
    - *Circuits must be rated to prevent breakdown*
  - *High currents*
    - *Circuit elements must be able to handle current*
  - *High power*
    - *Generated heat must be dissipated*
- *The system requirements give us the minimum power required at the load*
- *By properly designing our circuits, matching impedances, we can minimize the required system power, and therefore the cost and complexity of our systems*

Transmission Line Basics

- *A transmission line is a "controlled impedance" device, usually consisting of two conductors.*
- *Its geometry and material properties determine the electric and magnetic field distributions between the conductors.*
  - *The voltage between the conductors is determined by the integral of the electric field between them.*
  - *The current along the conductors determines the integral of the magnetic field on the conductor surfaces (Ampere's law).*
- *Transmission lines support the propagation of fixed velocity waves in both directions (forward and backward) along the line.*
- *Transmission lines guide transverse electro magnetic (TEM) waves, TE or TM waves are guided by waveguides*

Transmission Line Equations



$$V(x+dx,t) - V(x,t) = -L_l dx \frac{\partial I(x,t)}{\partial t}$$

$$I(x+dx,t) - I(x,t) = -C_l \mathrm{dx} \frac{\partial V(x,t)}{\partial \mathrm{t}}$$

$$\frac{\partial V(x,t)}{\partial x} = -L_l \frac{\partial I(x,t)}{\partial t}; \quad \frac{\partial I(x,t)}{\partial x} = -C_l \frac{\partial V(x,t)}{\partial t}$$

$$\frac{\partial^2 V(x,t)}{\partial x^2} - L_l C_l \frac{\partial^2 V(x,t)}{\partial t^2} = 0$$

$$\frac{\partial^2 I(x,t)}{\partial x^2} - L_l C_l \frac{\partial^2 I(x,t)}{\partial t^2} = 0$$

Transmission Line Equation

From the previous wave equations, one defines a velocity $v = 1/\sqrt{L_l C_l}$ where L_l and C_l are the inductance per unit length and capacitance per unit length, respectively.

For a given length, l, of transmission line, the total inductances and capacitances are $L = L_l l$ and $C = C_l l$, respectively, so that $v = l/\sqrt{LC}$

The propagation time for the wave down the length l line is $\tau = l/v = \sqrt{LC}$

Both of the wave equations solve the "Telegrapher's Equation"

- *General solution of the second order wave equation is a combination of two terms, both with velocity $v = 1/\sqrt{L_l C_l}$*

  $$V(x,t) = V_+(x - vt) + V_-(x + vt)$$

- *V_+ is a forward traveling wave*
- *V_- is a backward traveling wave*
- *V_+ and V_- are determined by initial conditions*

Change variables to $\phi = x - vt; \psi = x + vt.$

Then for any function $f(x - vt)$ *and* $g(x + vt)$

Use the chain rule, recognizing that $\frac{\partial \phi}{\partial x} = \frac{\partial \psi}{\partial x} = 1;\ \frac{\partial \phi}{\partial t} = -\frac{\partial \psi}{\partial t} = -v$

$$\frac{\partial f(x - vt)}{\partial x} = \frac{df(\phi)}{d\phi};\frac{\partial g(x + vt)}{\partial x} = \frac{dg(\psi)}{d\psi}$$

$$\frac{\partial f(x - vt)}{\partial t} = -v\frac{df(\phi)}{d\phi};\frac{\partial g(x + vt)}{\partial t} = v\frac{dg(\psi)}{d\psi}$$

We can rewrite the two terms in the circuit equations

$$\frac{\partial V}{\partial x} = \frac{\partial V_+(x - vt)}{\partial x} + \frac{\partial V_-(x + vt)}{\partial x} = \frac{\mathrm{dV}_+(\phi)}{d\phi} + \frac{dV_-(\psi)}{d\psi}$$

$$\frac{\partial I}{\partial t} = \frac{\partial I_+(x - vt)}{\partial t} + \frac{\partial I_-(x + vt)}{\partial t} = -v\frac{dI_+(\phi)}{d\phi} + v\frac{dI_-(\psi)}{d\psi}$$

Therefore separating the circuit equation $\frac{\partial V}{\partial x} = -L_l \frac{\partial I}{\partial t}$ *into its two components means*

$$\frac{dV_+(\phi)}{d\phi} = L_l v \frac{dI_+(\phi)}{d\phi}; \qquad \frac{dV_-(\phi)}{d\phi} = -L_l v \frac{dI_-(\phi)}{d\phi}$$

Recalling that $v = 1/\sqrt{L_l C_l}$, $Lv = \sqrt{L_l/C_l}$, *integrate to obtain*

$$V_+(x - vt) = \sqrt{L_l/C_l}\, I_+(x - vt) = ZI_+(x - vt)$$

$$V_-(x + vt) = -\sqrt{L_l/C_l} I_-(x + vt) = -ZI_-(x + vt)$$

where we have defined $Z \overset{\text{def}}{=} \sqrt{L_l/C_l}$

(The integration constant is zero for waves.)

This gives the definition of the transmission line impedance Z as the ratio of the voltage wave to the current wave (taking direction of travel into account)

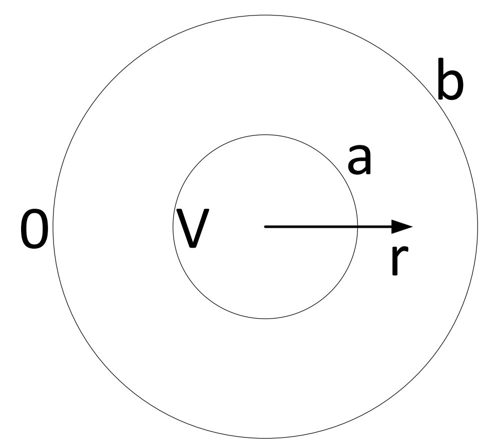
Capacitance/length (voltage between conductors)

$$C = \frac{Q}{Vl} = \frac{\lambda}{V} = \frac{\lambda}{-\int_b^a \vec{\boldsymbol{E}} \cdot d\vec{\boldsymbol{x}}} = \frac{\lambda}{\int_a^b \frac{\lambda}{2\pi r\epsilon} dr} = \frac{2\pi\epsilon}{\log(b/a)}$$

Inductance/length (flux between conductors)

$$L = \frac{1}{Il} \iint \vec{\boldsymbol{B}} \cdot d\vec{\boldsymbol{s}} = \frac{1}{Il} \int_0^l \int_a^b \frac{\mu I}{2\pi r} dr\, dl = \frac{\mu}{2\pi} \log(b/a)$$

- $Z = \sqrt{\frac{L}{C}} = \sqrt{\frac{L_l}{C_l}} = \sqrt{\frac{\mu}{\epsilon}} \frac{1}{2\pi} \log\left(\frac{b}{a}\right)$
- $v = \frac{1}{\sqrt{L_l C_l}} = \frac{1}{\sqrt{\mu\epsilon}} = \frac{l}{\sqrt{LC}}$
- $\tau = \sqrt{LC}$



Wave Equation from Fields

$$\vec{\boldsymbol{\nabla}} \times \vec{\boldsymbol{E}} = -\partial \vec{\boldsymbol{B}}/\partial t; \qquad \vec{\boldsymbol{\nabla}} \times \vec{\boldsymbol{H}} = \partial \vec{\mathbf{D}}/\partial t$$

$$\vec{\boldsymbol{E}} = \frac{\lambda e(z,t)}{2\pi\epsilon r}\hat{\boldsymbol{r}}; \quad \vec{\mathbf{H}} = \frac{Ih(z,t)}{2\pi r}\widehat{\boldsymbol{\theta}}$$

$$\vec{\boldsymbol{\nabla}} \times \vec{\boldsymbol{E}} = \begin{vmatrix} \vec{\boldsymbol{r}} & \vec{\boldsymbol{\theta}} & \hat{\boldsymbol{z}} \\ \partial/\partial r & 1/r\,\partial/\partial\theta & \partial/\partial z \\ E_r & rE_\theta & E_z \end{vmatrix} = \frac{\lambda}{2\pi\epsilon r}\frac{\partial e(z,t)}{\partial z}\widehat{\boldsymbol{\theta}}$$

$$\vec{\boldsymbol{\nabla}} \times \vec{\boldsymbol{H}} = -\frac{I}{2\pi r}\frac{\partial h(z,t)}{\partial z}\hat{\boldsymbol{r}}$$

$$\frac{\partial e(z,t)}{\partial z} = -\frac{\epsilon\mu I}{\lambda}\frac{\partial h(z,t)}{\partial t}; \quad \frac{\partial h(z,t)}{\partial z} = -\frac{\lambda}{I}\frac{\partial e(z,t)}{\partial t}$$

Wave Equation from Fields

Differentiate w.r.t z and use second equation to get

$$\frac{\partial^2 e(z,t)}{\partial z^2} - \mu\epsilon \frac{\partial^2 e(z,t)}{\partial t^2} = 0$$

$$\frac{\partial^2 h(z,t)}{\partial z^2} - \mu\epsilon \frac{\partial^2 h(z,t)}{\partial t^2} = 0$$

This is the telegrapher's equation with

$$v = 1/\sqrt{\mu\epsilon} = 1/\sqrt{\mu_r\mu_0\epsilon_r\epsilon_0} = c/\sqrt{\mu_r\epsilon_r}$$

- *Our wave equation has two solutions,* V_+, V_-
- *We are working with circuit equations, but with the proper identification with EM sources and fields we can use common conservation laws of physics to determine* V_+ *and* V_-
  - $V \sim \vec{\boldsymbol{E}}$
  - $I \sim \vec{\boldsymbol{H}}$

Energy in Transmission Line

The energy of the electromagnetic fields in a volume is

$$\mathcal{E} = \frac{1}{2}\iiint \left(\vec{\boldsymbol{E}} \cdot \vec{\boldsymbol{D}} + \vec{\boldsymbol{B}} \cdot \vec{\boldsymbol{H}}\right) d^3x$$

$$= \frac{1}{2}\iiint \left(\frac{\lambda}{2\pi\epsilon r}\frac{\lambda}{2\pi r} + \frac{\mu I}{2\pi r}\frac{I}{2\pi r}\right) r dr d\theta dz$$

$$= \frac{1}{2}\frac{2\pi}{(2\pi)^2} l(\lambda^2/\epsilon + \mu I^2) \int_a^b \frac{r}{r^2} dr$$

$$= \frac{1}{2}\left[(\lambda l)^2 \frac{1}{2\pi\epsilon l}\log(b/a) + \frac{\mu l}{2\pi}\log(b/a)\, I^2\right]$$

$$\mathcal{E} = 1/2\; Q^2/C + 1/2\; LI^2 = 1/2\; CV^2 + 1/2\; LI^2$$

Energy in Transmission Line

$$\mathcal{E} = \frac{1}{2}CV^2 + \frac{1}{2}LI^2 = \frac{1}{2}\left[CV^2 + L\left(\frac{V}{Z}\right)^2\right]$$

$$= \frac{1}{2}\left(CV^2 + \frac{L}{Z^2}V^2\right) = \frac{1}{2}\left(CV^2 + \frac{L}{L/C}V^2\right) = CV^2 = LI^2$$

In a wave, the EM energy is equally distributed.

- *Half of the energy is in the electric field.*
- *Half is in the magnetic field.*

Power and Momentum Flow

The power flow of fields is determined by the Poynting vector $\vec{\boldsymbol{P}} = \vec{\boldsymbol{E}} \times \vec{\boldsymbol{H}}$. *For the coaxial line*

$$\vec{\boldsymbol{P}} = \frac{\lambda}{2\pi\epsilon r}\hat{\boldsymbol{r}} \times \frac{I}{2\pi r}\widehat{\boldsymbol{\theta}} = \frac{\mathrm{V}}{\mathrm{r}\log(\mathrm{b}/\mathrm{a})}\frac{\mathrm{I}}{2\pi r}\hat{\mathbf{z}}$$

Power flow along the line is

$$P = \int_S \vec{\boldsymbol{P}} \cdot d\vec{\boldsymbol{s}} = \frac{VI}{2\pi\log(b/a)}\int_0^{2\pi} d\theta \int_a^b \frac{dr}{r} = VI$$

The momentum of an EM field is $\vec{\boldsymbol{p}} = \vec{\boldsymbol{P}}/c^2$ *so the momentum flow is* VI/c^2 *(with direction* $\pm$*)*

Energy Stored in Charged Line

Two models of a charged transmission line

1. *Transmission line statically charged to voltage V*

   $\mathcal{E} = \frac{1}{2}(C_l d)V^2$ *(C_l capacitance/length)*

2. *Two co-moving waves on the transmission line*

$$(V = V_+ + V_-);\;\; V_+ = V_- = V/2$$

$$\mathcal{E} = \frac{1}{2}[(C_l d)V_+^2 + (L_l d)I_+^2] + \frac{1}{2}[(C_l d)V_-^2 + (L_l d)I_-^2]$$

$$= [(C_l d)V_+^2 + (C_l d)V_-^2] = 2(C_l d)V_+^2$$

$$= 2(C_l d)\left(\frac{V}{2}\right)^2 = \frac{1}{2}(C_l d)V^2$$

Calculated energy the same in both cases

Momentum in Charged Line

1. *Momentum of EM field on line of length d statically charged to voltage V*
   - $(I = 0) \Rightarrow (P = 0) \Rightarrow (\vec{\boldsymbol{p}} = 0)$
2. *Momentum of two co-moving waves*
   - *Power $V_+ I_+$ propagating in positive direction*
   - *Power $V_- I_-$ propagating in negative direction*
   - *Total momentum*

$$\vec{\boldsymbol{p}}_{\boldsymbol{T}} = \vec{\boldsymbol{p}}_+ + \vec{\boldsymbol{p}}_- = V_+ I_+ - V_- I_-$$

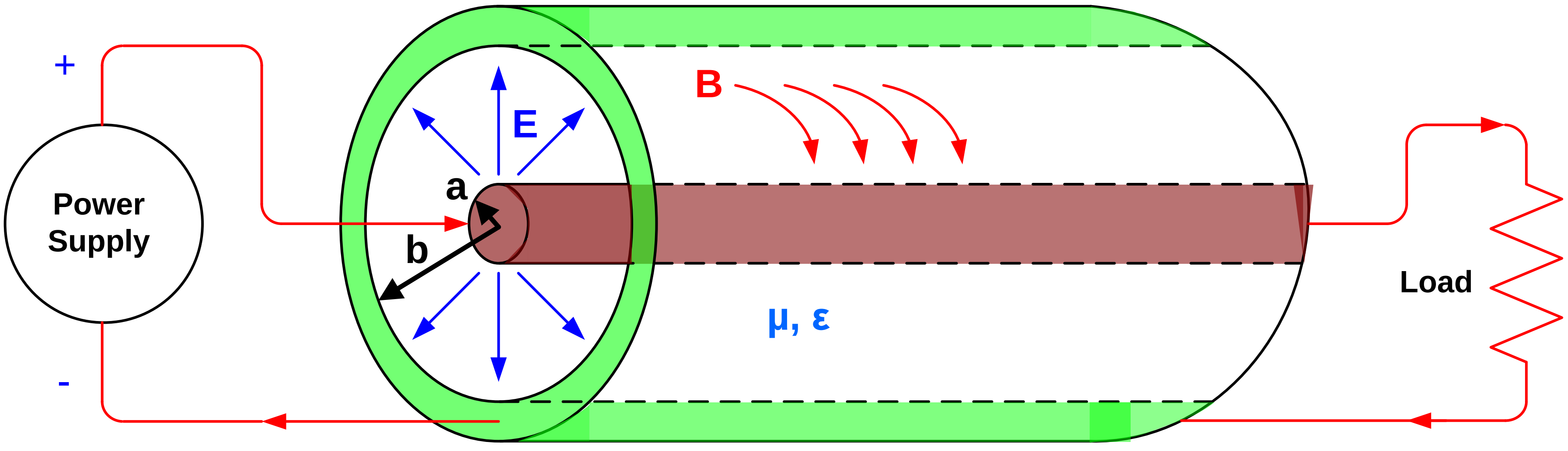
$$= 1/Z[(V/2)^2 - (V/2)^2] = 0$$

- *Calculated momentum the same in both cases*

Transmission Line Types

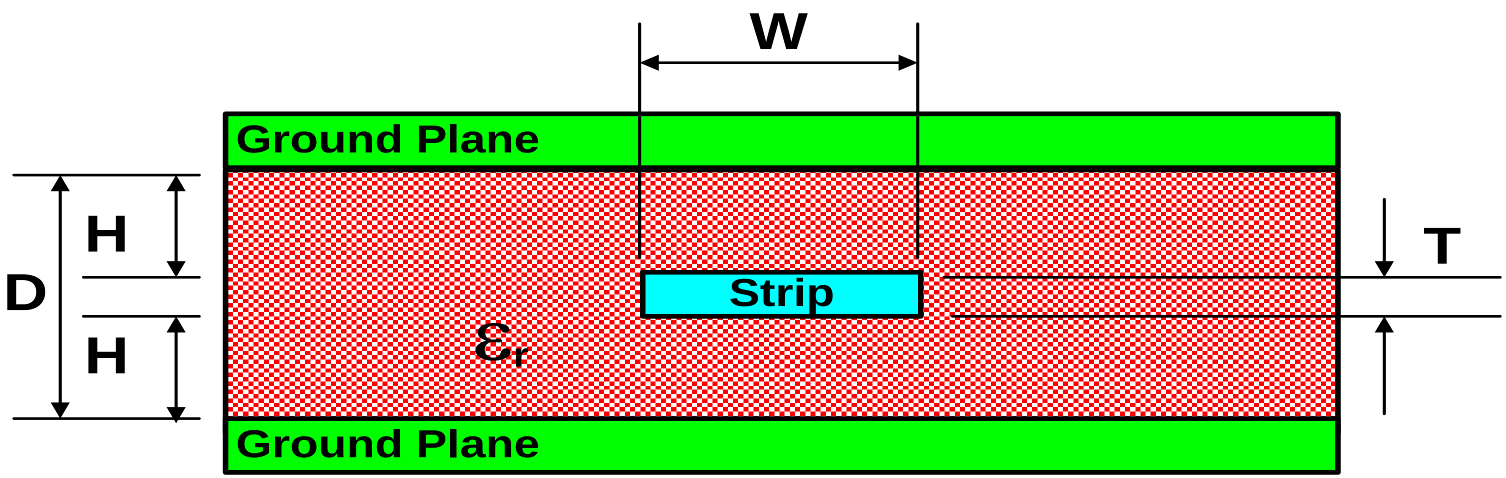
- *Coaxial transmission lines*
  - *Voltage between two coaxial conductors*
  - *Currents of equal magnitude and opposite sign are carried on the conductors*
  - *Conductors separated by air or dielectric*
  - *Transverse electromagnetic (TEM) transmission line media*
  - *Ideally non-dispersive (propagates all frequency components equally), with no cutoff frequency*
  - *No external electric or magnetic fields*

- *Coaxial transmission lines and cables*



$$Z_0 = \frac{\ln b/a}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}$$

- *Planar transmission line - Stripline consists of a single strip buried in a dielectric separated from two or more ground planes*

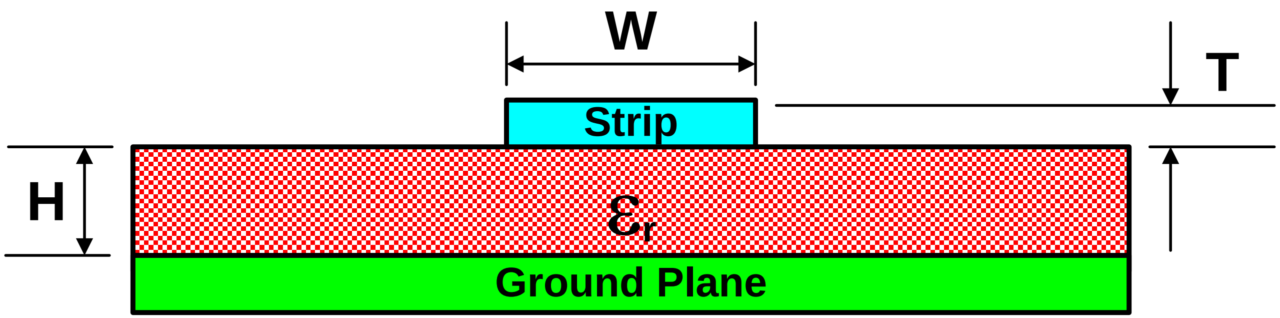


Characteristic Impedance

$$Z_O = \frac{60}{\sqrt{\varepsilon_r}} \ln\left[\frac{4H}{0.67\pi W\left(0.8 + \frac{T}{D}\right)}\right] \text{ ohms}$$

Transmission Line Types

- *Planar transmission line - Microstrip line consists of a single strip on dielectric separated from a ground plane*



when $\left(\frac{W}{H}\right) < 1$

Effective Dielectric Constant
$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\left(1 + 12\left(\frac{H}{W}\right)\right)^{-1/2} + 0.04\left(1 - \left(\frac{W}{H}\right)\right)^2\right]$$

Characteristic Impedance
$$Z_o = \frac{60}{\sqrt{\varepsilon_e}} \ln\left(8\frac{H}{W} + 0.25\frac{W}{H}\right) \quad \text{ohms}$$

when $\left(\frac{W}{H}\right) \geq 1$

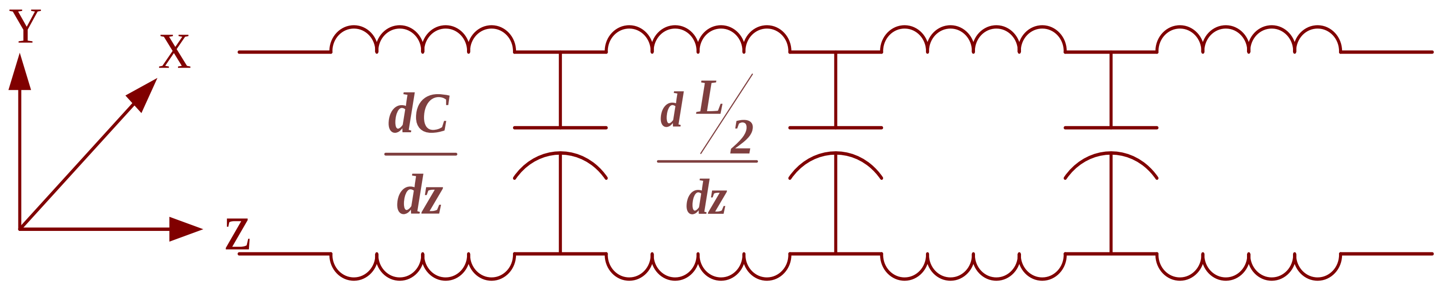
Effective Dielectric Constant
$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\left(1 + 12\left(\frac{H}{W}\right)\right)^{-1/2}\right]$$

Characteristic Impedance
$$Z_o = \frac{120\pi}{\sqrt{\varepsilon_e}\left[\frac{W}{H} + 1.393 + \frac{2}{3}\ln\left(\frac{W}{H} + 1.444\right)\right]} \quad \text{ohms}$$

Transmission Line Types

- *Lumped element transmission lines*
  - *Combination of series inductors, shunt capacitors*
  - *Single inductor-capacitor combination is a resonant circuit*
  - *Series of an infinite combination of series L, shunt C turns into an ideal transmission line*
  - *Electric fields of lines stored in capacitors*
  - *Magnetic fields of lines stored in series inductors*

Lumped Element Transmission Lines

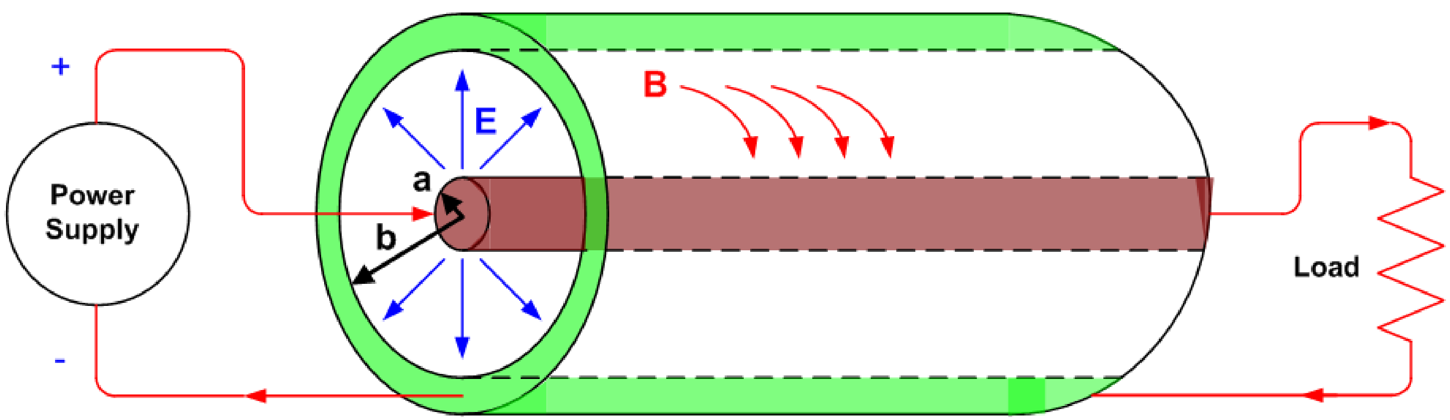


$E = \hat{y}E_y \quad H = \hat{x}H_x \qquad Z_0 = \sqrt{\frac{L}{C}}$ Characteristic impedance - 377 ohms for air (free space)

for air (and most dielectrics) $\mu_r = 1$, for air $\varepsilon_r = 1$ (most other dielectrics $\varepsilon_r > 1$, n = number of sections

$Z_0 = \frac{\ln b/a}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}$ For coaxial line, $50\Omega \le Z_0 \le 80\Omega$

$v = \frac{1}{\sqrt{\mu_0\mu_r\varepsilon_0\varepsilon_r}}$ = wave velocity wavelength $\lambda = \frac{v}{f}$ time delay $= t_d = n * \sqrt{LC}$



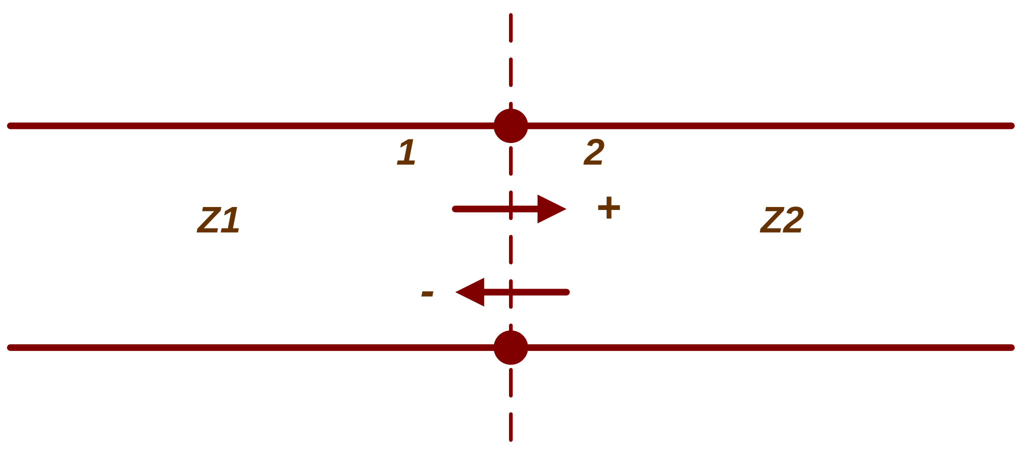
Transmission Line Boundary Conditions

- *Join two transmission lines together*
  - *If the impedances of both lines are the same, the electric and magnetic fields (voltage and current) can propagate without interruption.*
  - *If not, the boundary conditions on the fields force a reflection of part of the signal*

Transmission Line Equations at an Interface

The general situation at an interface between two transmission lines of impedance Z_1 and Z_2 is

- *A source generates an incident voltage and current,*(V_1^+, I_1^+) *moving forward on Line 1, with* $V_1^+ = Z_1 I_1^+$
- (V_1^+, I_1^+) *at the interface causes a transmitted voltage and current,* (V_2^+, I_2^+)*, moving forward on Line 2, with* $V_2^+ = Z_2 I_2^+$
- (V_1^+, I_1^+) *at the interface might also cause a reflected voltage and current,* (V_1^-, I_1^-)*, moving backward on Line 1, with* $V_1^- = Z_1 I_1^-$



The voltages on each side of the interface must be equal

$$V_1^+ + V_1^- = V_2^+$$

The current must be conserved at the interface

$$I_1^+ = I_1^- + I_2^+$$

Express this in terms of the voltages and impedances

$$\frac{V_1^+}{Z_1} = \frac{V_1^-}{Z_1} + \frac{V_2^+}{Z_2} = \frac{V_1^-}{Z_1} + \frac{V_1^+ + V_1^-}{Z_2}$$

Solve for the Reflection Coefficient, $\Gamma = V_1^- / V_1^+$

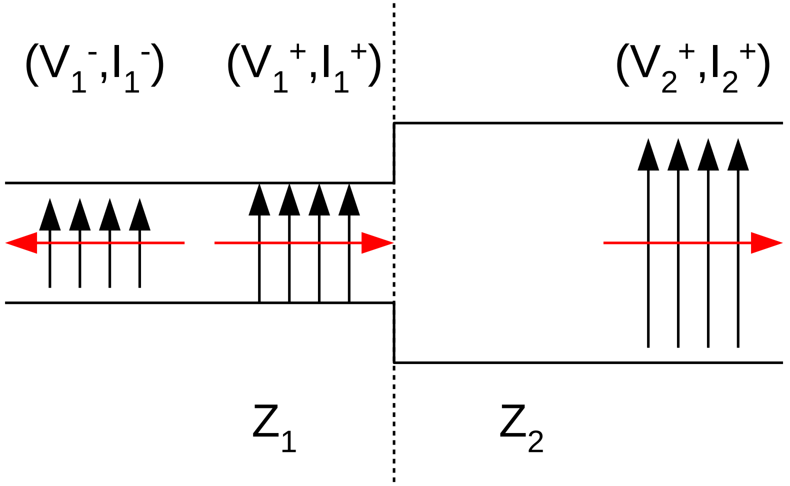
$$\Gamma = \frac{V_1^-}{V_1^+} = \frac{1/Z_1 - 1/Z_2}{1/Z_1 + 1/Z_2} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

The Transmission Coefficient, T *is defined as*

$$T = \frac{V_2^+}{V_1^+} = \frac{V_1^+ + V_1^-}{V_1^+} = 1 + \Gamma$$

$$= \frac{Z_2^+ + Z_1^+ + Z_2^+ - Z_1^+}{Z_2^+ + Z_1^+}$$

$$= \frac{2Z_2^+}{Z_2^+ + Z_1^+}$$



The flow of energy, power, is conserved at the interface (assume all voltages and impedances are real)

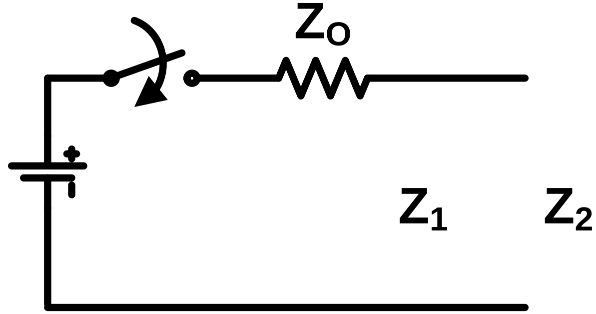
$$P_{IN} = V_1^+ I_1^+ = \frac{(V_1^+)^2}{Z_1}$$

$$P_{REV} = \frac{(\Gamma V_1^+)^2}{Z_1} = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}\frac{(V_1^+)^2}{Z_1}$$

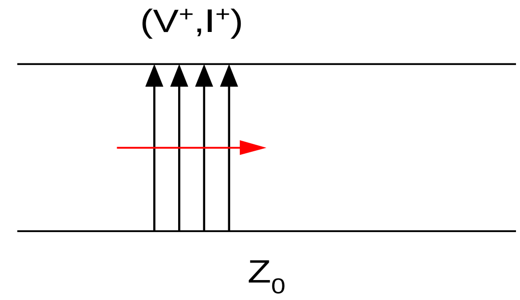
$$P_T = \frac{(TV_1^+)^2}{Z_2} = \frac{1}{Z_2}\frac{4Z_2^2}{(Z_2 + Z_1)^2}\frac{Z_1}{Z_1}(V_1^+)^2$$

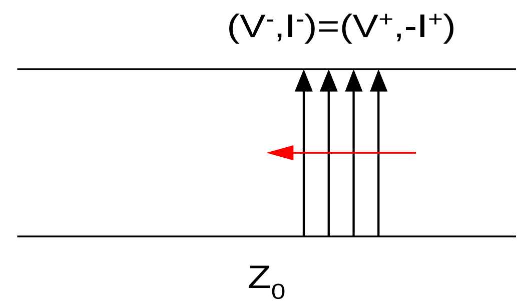
Transmission Line Simple Examples

Open Line

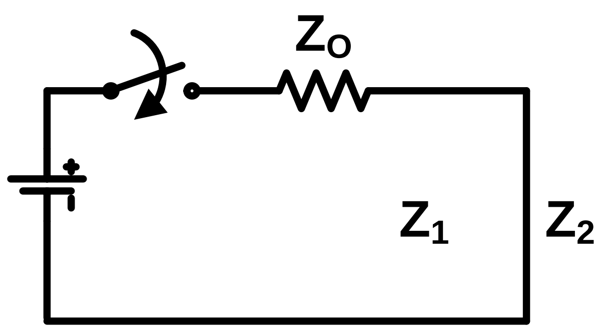


- $Z_1 = Z_0; \;\; Z_2 = \infty$
- $\Gamma = 1$
- $I_2 = 0$
- *Voltage totally reflected without inversion*

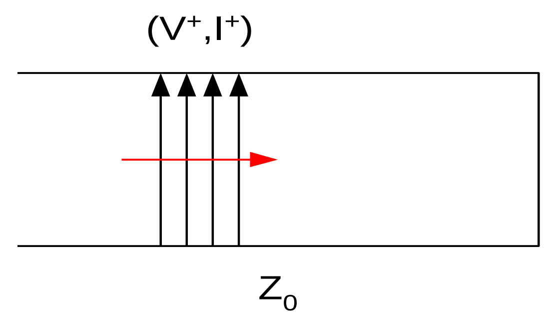


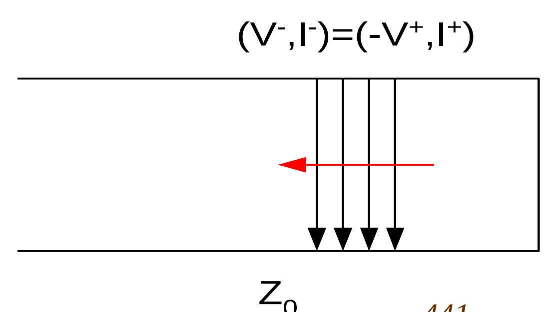


Shorted Line



- $Z_1 = Z_0; \quad Z_2 = 0$
- $\Gamma = -1$
- $V_2 = 0$
- *Voltage totally reflected with inversion*





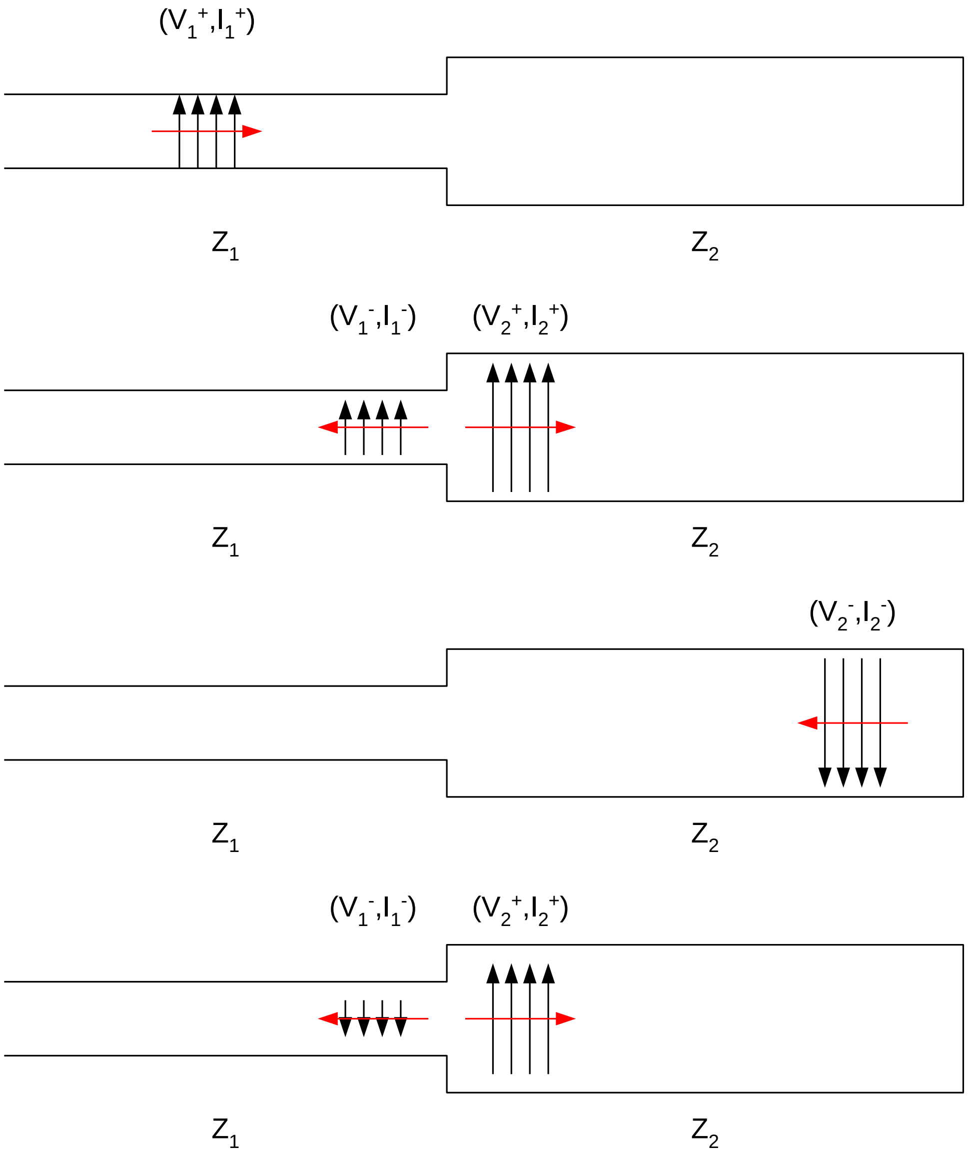
Transmission Line More Complicated Example

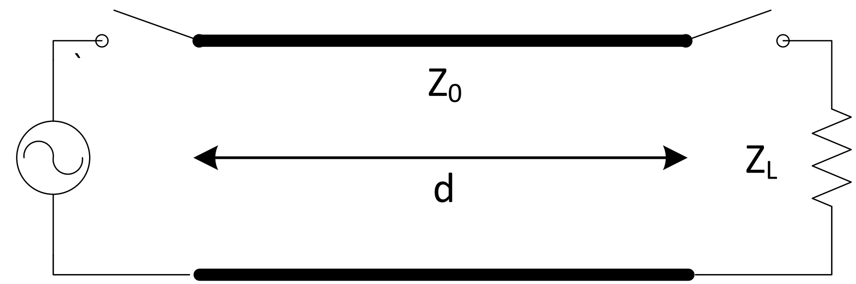
- *Pulse sent down line on controlled impedance*

- *First interface is with higher impedance device ($Z_2 > Z_1$)*
  - *Transmitted pulse*
  - *Reflected pulse*

- *Transmitted pulse reflects off short*

- *Reflected transmitted pulse reaches first interface*
  - *Transmitted pulse down original line*
  - *Reflected pulse on second line*





Now apply this to a PFN

- *Charge the PFN to V*
- *Open charging switch*
- *Close discharge switch*
  - *Energy, momentum conserved*
  - V_+, V_- *waves with* $V_+ = V_- = V/2$
  - *Duration of pulse is time for a full round trip*

$$\tau = \frac{2d}{v} = 2d\sqrt{LC}$$

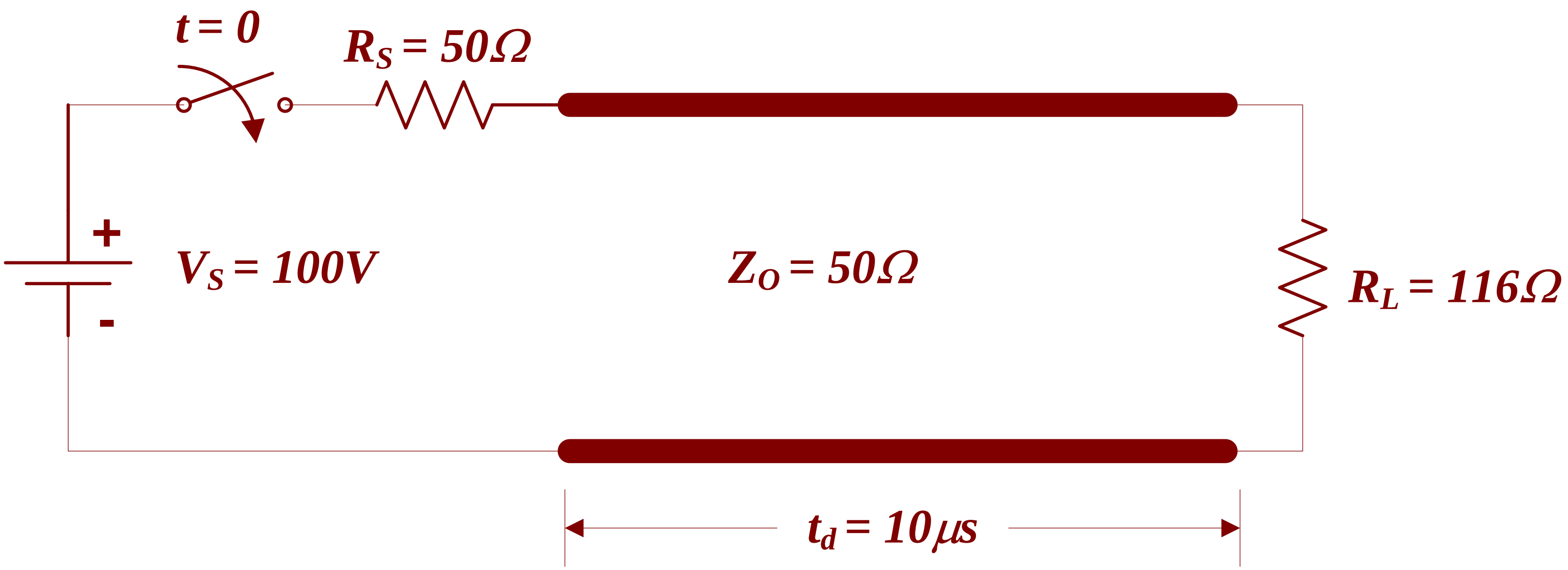
Transmission Line Homework Problem #13

A. A transmission line can be formed using lumped Ls and Cs. Calculate the delay of a line composed of 8 sections of inductances L=4mH per section and capacitance C=40pF per section.

B. The frequency of a signal applied to a two-wire transmission cable is 3GHz. What is the signal wavelength if the cable dielectric is air? Hint – relative permittivity of air is 1

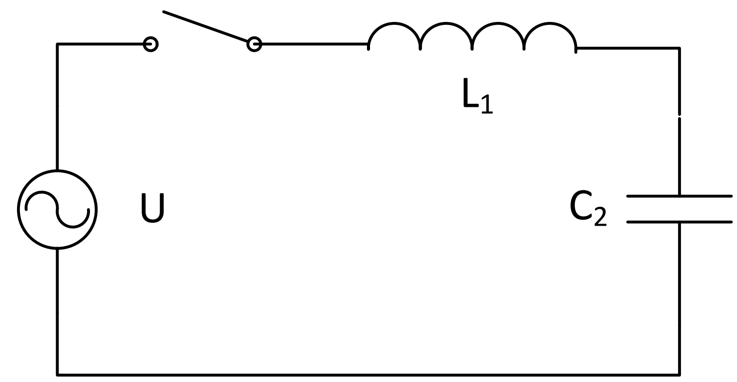
C. What is the signal wavelength if the cable dielectric has a relative permittivity of 3.6?

For the transmission line shown below, calculate the Reflection Coefficient Γ, the reflected voltage and the voltage and current along the line versus time.



Resonant Charging

$$KVL:\ \ U = L_1 \frac{di_1}{dt} + v_2$$



$$KCL:\ \ i_1 = C_2 \frac{dv_2}{dt}$$

$$\begin{pmatrix} \dot{i_1} \\ \dot{v_2} \end{pmatrix} = \begin{pmatrix} 0 & -1/L_1 \\ 1/C_2 & 0 \end{pmatrix} \begin{pmatrix} i_1 \\ v_2 \end{pmatrix} + \begin{pmatrix} 1/L_1 \\ 0 \end{pmatrix} u$$

$$s\begin{pmatrix} I_1 \\ V_2 \end{pmatrix} - \begin{pmatrix} i_1(0) \\ v_2(0) \end{pmatrix} = A\begin{pmatrix} I_1 \\ V_2 \end{pmatrix} + BU$$

$$where\ \mathrm{A} = \begin{pmatrix} 0 & -1/L_1 \\ 1/C_2 & 0 \end{pmatrix}\ and\ \mathrm{B} = \begin{pmatrix} 1/L_1 \\ 0 \end{pmatrix}$$

In matrix notation

$$(sI - A)X = x(0) + BU$$

$$\mathrm{X} = (sI - A)^{-1}x(0) + (sI - A)^{-1}BU$$

$$(sI - A)^{-1} = \begin{pmatrix} s & 1/L_1 \\ -1/C_2 & s \end{pmatrix}^{-1} = \frac{1}{s^2 + 1/L_1C_2}\begin{pmatrix} s & -1/L_1 \\ 1/C_2 & s \end{pmatrix}$$

$$\begin{pmatrix} I_1 \\ V_2 \end{pmatrix} = \frac{1}{s^2 + \omega_0^2}\begin{pmatrix} s & -1/L_1 \\ 1/C_2 & s \end{pmatrix}\left[\begin{pmatrix} i_{10} \\ v_{20} \end{pmatrix} + \begin{pmatrix} U_0/L_1 s \\ 0 \end{pmatrix}\right]$$

where $U(s) = U_0/s$ *and* $\omega^2 = 1/L_1C_2$.

Assume initial values of $(i_{10}, v_{20}) = (0,0)$, *then*

$$\begin{pmatrix} I_1 \\ V_2 \end{pmatrix} = \frac{1}{s^2 + \omega_0^2} \begin{pmatrix} 1/L_1 \\ \omega_0^2/s \end{pmatrix} U_0$$

$$I_1 = \frac{1}{\omega_0 L_1} \frac{U_0 \omega_0}{s^2 + \omega_0^2} \Rightarrow i_1(t) = U_0 \sqrt{\frac{C_2}{L_1}} \sin(\omega_0 t)$$

$$V_2 = \frac{1}{s} \frac{U_0 \omega_0^2}{s^2 + \omega_0^2} = \left(\frac{1}{s} - \frac{s}{s^2 + \omega_0^2} \right) U_0$$

$$\Rightarrow v_2(t) = (1 - \cos \omega_0 t) U_0$$

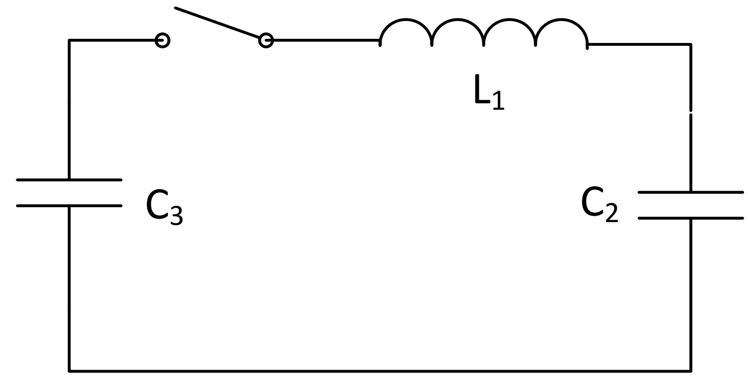
At time $t = \pi/\omega_0, \cos(\omega_0 \pi/\omega_0) = -1$

Voltage doubles, $v_2(\pi/\omega_0) = 2U_0$

- *Use diode to prevent circuit ringing down*

Resonant Charging Intuition

- *Second order undamped system implies oscillation*
  - *Resonant frequency* $\omega_0 = 1/\sqrt{LC}$
  - *Voltage and current across each reactive element* $\pi/2$ *out of phase* $\Rightarrow$ $\sin\omega_0 t\,,\cos\omega_o t$
  - *Step change of current across inductor requires infinite voltage* $\Rightarrow$ $i(t) = I_0\sin\omega_0 t\,; v_C(t) = V_0\cos\omega_0 t$
  - *Energy oscillates between inductor and capacitor* $\Rightarrow$ $1/2\ LI_0^2 = 1/2\ CV_0^2 \Rightarrow V_0 = \sqrt{L/C}\,I_0$
- *Output oscillates about "steady state" value* (U_0)
  - *Starts at* $v_C(0) = 0$
  - *Maximum value* $v_C(\pi/\omega_0) = 2U_0$



Two capacitors now in series

$C_S = C_2 C_3/(C_2 + C_3)$

$\omega_0 = 1/\sqrt{L_1 C_S}$

$Z = \sqrt{L_1/C_S}$

Initial conditions

$v_3(0) = U_0, i_1(0) = v_2(0) = 0$

There are several ways to calculate the final voltage on C_2.

1) Integrate the current through L_1 for the time $(0, \pi/\omega_0)$

$$Q_2 = \int_0^{\pi/\omega_0} i_1(t)dt = U_0 \sqrt{\frac{C_S}{L_1}} \int_0^{\pi/\omega_0} \sin\omega_0 t\, dt = U_0 \sqrt{\frac{C_S}{L_1}} \sqrt{L_1 C_S}\, 2$$

$$= 2C_S U_0 \Rightarrow v_2\left(\frac{\pi}{\omega_0}\right) = 2\frac{C_S}{C_2} U_0 = 2\frac{C_3}{C_3 + C_2} U_0$$

2) Find the charge transfer necessary to change the voltage across the series capacitors from U_0 to $-U_0$.

$$q_{30} = C_3 U_0$$

$$q_{3f}/C_3 - q_{2f}/C_2 = \left(q_{30} - q_{2f}\right)/C_3 - q_{2f}/C_2 = -q_{30}/C_3 = -U_0$$

$$\left(\frac{1}{C_2} + \frac{1}{C_3}\right) q_{2f} = \frac{C_3 + C_2}{C_3 C_2} q_{2f} = \frac{2}{C_3} q_{30} \Rightarrow q_{2f} = \frac{2C_2}{C_3 + C_2} q_{30}$$

$$\Rightarrow v_{2f} = [2C_3/(C_3 + C_2)] \cdot U_0; \;\; v_{3f} = [(C_3 - C_2)/(C_3 + C_2)] \cdot U_0$$

3) Use conservation of energy and charge to find circuit equations

$$\mathcal{E}_T = \mathcal{E}_0 = q_{30}^2/(2C_3); q_T = q_2 + q_3 = q_{30} = q_{2f} + q_{3f}$$

$$q_{3f}^2/(2C_3) + q_{2f}^2/(2C_2) = q_{30}^2/(2C_3)$$

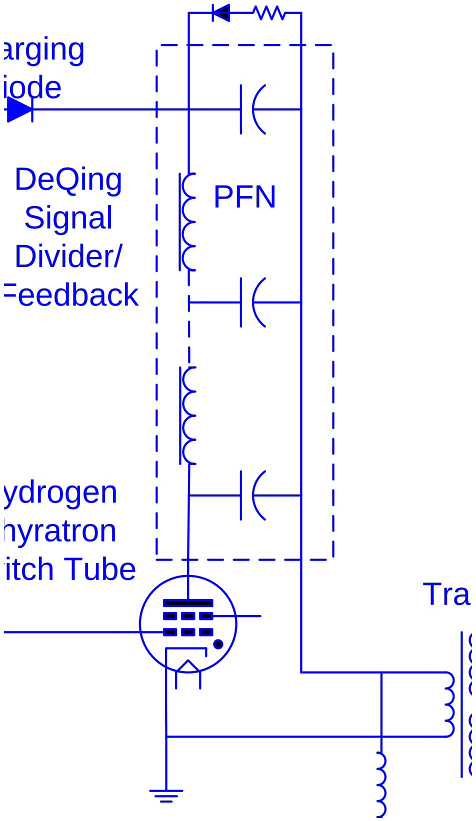
$$\left(q_{30}^2 - q_{3f}^2\right)/(2C_3) = \left(q_{30} + q_{3f}\right) \cdot \left(q_{30} - q_{3f}\right)/(2C_3)$$

$$= \left(q_{30} + q_{3f}\right) \cdot q_{2f}/(2C_3) = q_{2f}^2/(2C_2)$$

$$q_{2f} = \left(q_{30} + q_{3f}\right)(C_2/C_3) = (2\mathrm{q}_{30} - \mathrm{q}_{2\mathrm{f}})(\mathrm{C}_2/\mathrm{C}_3)$$

$$\mathrm{q}_{2\mathrm{f}} = [2C_2/(C_3 + C_2)] \cdot q_{30} \Rightarrow v_{2f} = [2C_3/(C_3 + C_2)] \cdot U_0;$$

Conventional Pulsers - The Pulse Forming Network (PFN)



Flatness is directly proportional to the number of LC meshes

Rise-time is determined by the LC of the mesh closest to the load

Pulse width T is twice the one way transit time t of the wave in the PFN

The one-way transit time is

$$t = n * \sqrt{L * C}$$

and the pulse width T is

$$T = 2 * n * \sqrt{L * C}$$

The load impedance and pulse width are usually specified. From these two parameters the PFN LC can be specified. The nominal L and C in each mesh is the total L and C divided by the number of meshes.

$$Z = \sqrt{\frac{L}{C}}$$

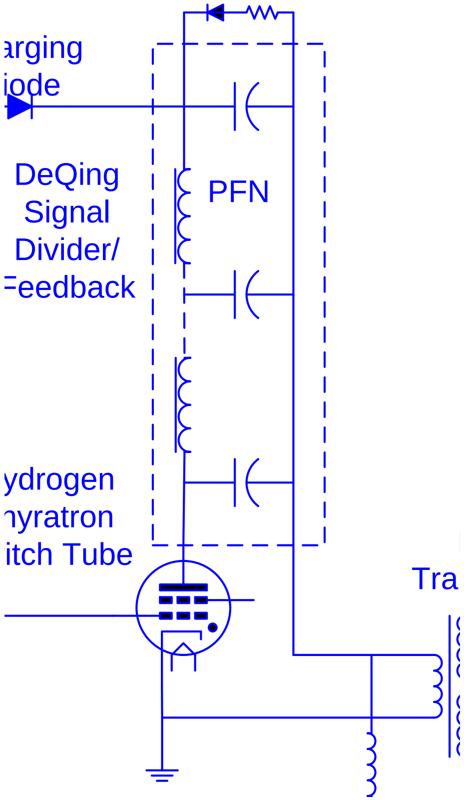
$$T = 2 * Z * C$$

$$C = \frac{T}{2 * Z}$$

$$L = \frac{T * Z}{2}$$

Since the PFN impedance is matched to the load impedance, all the PFN stored energy is dissipated in the load

Conventional Pulsers - The Pulse Forming Network (PFN)



The PFN is typically tuned to the impedance of the load in order to reduce voltage and current reflections. The effective output voltage at the load obeys the voltage divider law and is effectively

$$V_{load} = V_{pfn} * \frac{Z_{load}}{Z_{load} + Z_{pfn}}$$

$$V_{pfn} = V_{load} * \frac{Z_{load} + Z_{pfn}}{Z_{load}}$$

Because typically the PFN has the same impedance as the load,

$$V_{pfn} = 2 * V_{load}$$

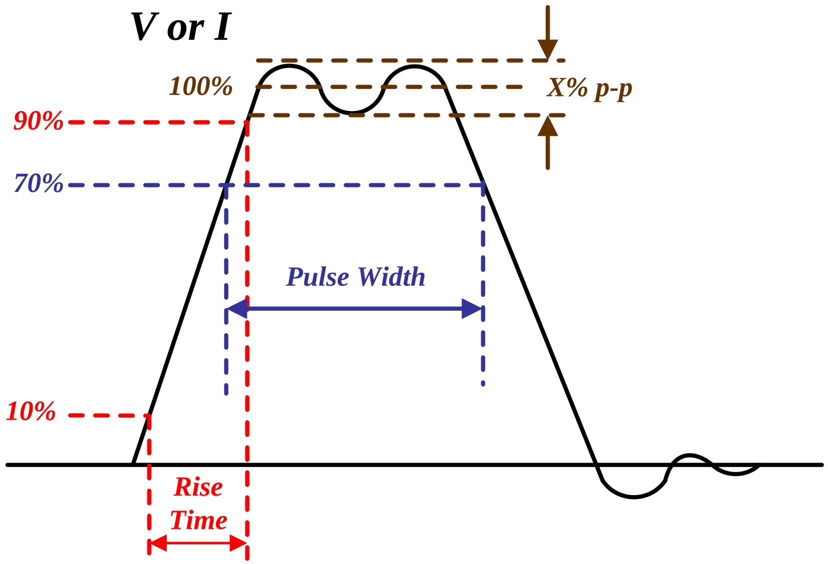
Therefore the PFN must be charged to twice the desired load voltage.

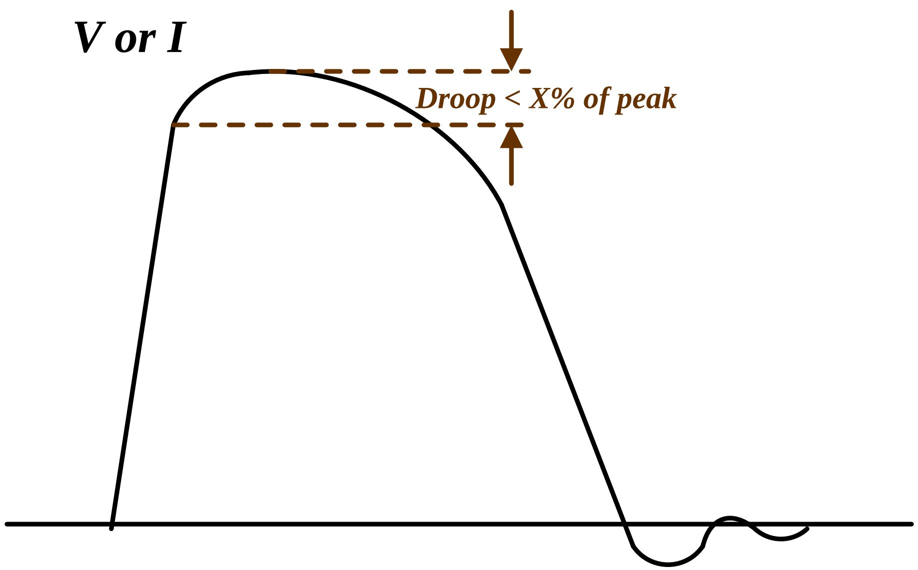
Conventional Pulsers - Transmission Line PFN

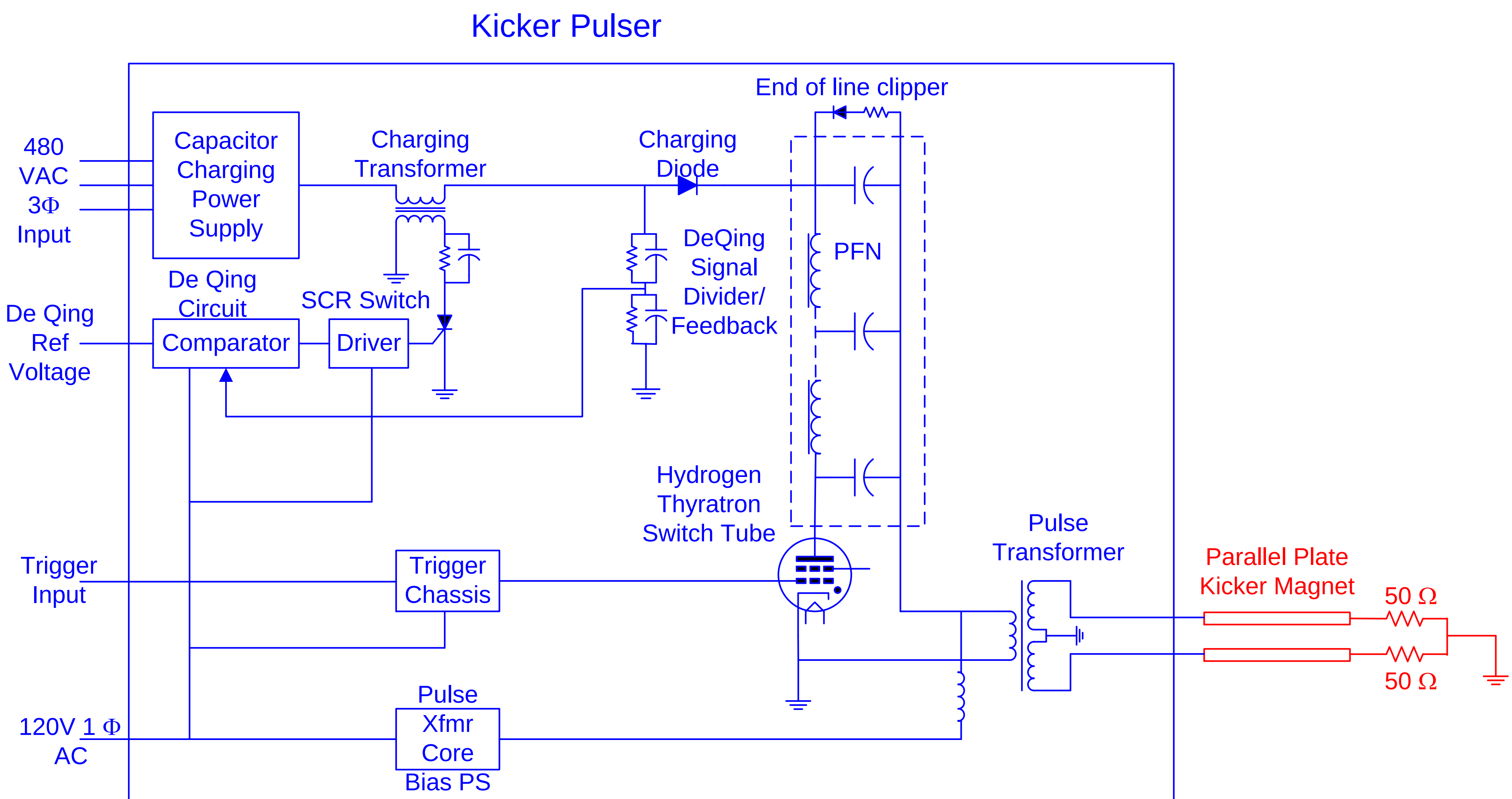
- *Open transmission lines are often used for Pulse Forming Networks (PFNs)*
  - *They are typically charged up from a high impedance source*
  - *Their open end is connected to a normally open switch that closes to connect the PFN to the load*
- *This situation can be viewed as a traveling wave reflecting back and forth off of two open ends*
  - *Total voltage on the line is the sum of the incident and reflected waves ($V_{PFN} = 2V_{LOAD}$)*
  - *Pulse has length 2 l / v, since the tail of the pulse must reflect off of the other open end before it reaches the load*

Note: l = the length of the open transmission line and v = wave velocity

Conventional Pulsers - The Pulse Forming Network (PFN)





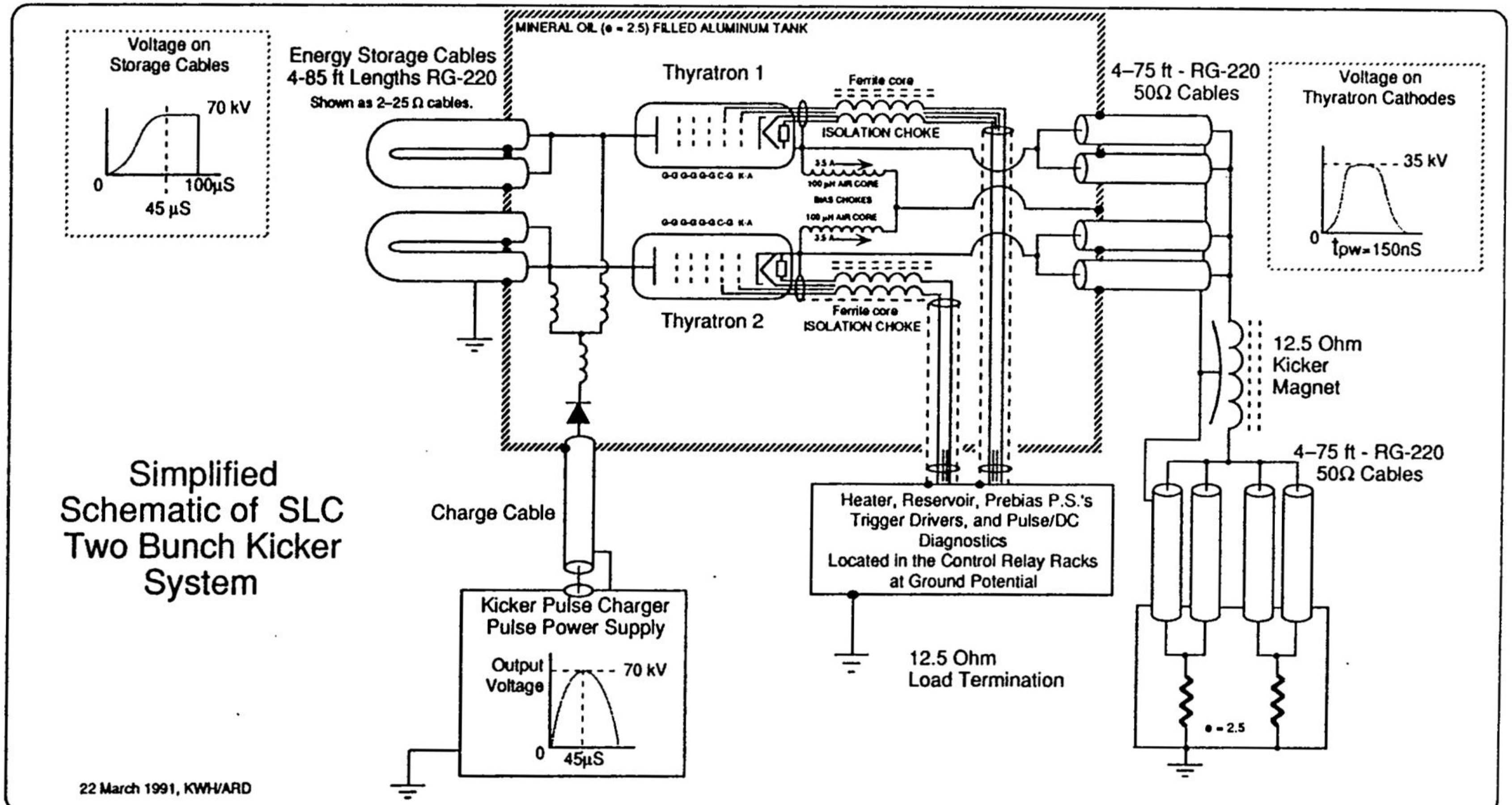

Kicker Pulser
End of line clipper
480
VAC
3Φ
Input
Capacitor
Charging
Power
Supply
Charging
Transformer
Charging
Diode
DeQing
Signal
Divider/
Feedback
PFN
De Qing
Circuit
SCR Switch
De Qing
Ref
Voltage
Comparator
Driver
Hydrogen
Thyratron
Switch Tube
Pulse
Transformer
Parallel Plate
Kicker Magnet
50 Ω
50 Ω
Trigger
Input
Trigger
Chassis
120V 1 Φ
AC
Pulse
Xfmr
Core
Bias PS

Conventional Pulsers - Kicker or Fast Modulator

- *Improve the rise time of modulator pulse using Cable PFN*
- *In line Switch with PFN*
- *Blumline with Shunt Switch*

Conventional Pulsers - Kicker Modulator

- *Conventional Inline Kicker Modulator*
- *Thyratron for switches*
- *Improve the rise time of modulator pulse using Cable PFN*



Conventional Pulsers - Why We Use a Pulsed Modulator to Drive a Klystron

$$Klystron\ perveance = P = \frac{I_{klystron}}{(V_{beam\ voltage})^{3/2}}$$

The perveance of 5045 klystron is 2 micropervs

The peak RF power from a 5045 is 65MW, the beam volatge is 350kV

$$I_{klystron} = P * (V_{beam\,voltage})^{3/2} = 2 * 10^{-6} * (350kV)^{3/2} = 414A$$

The power needed to achieve 65MW of RF $= V_{beam\ voltage} * I_{klystron}$

$$= 350kV \ * \ 414A = 144.0MW\,!$$

Pulsed power is the right approach

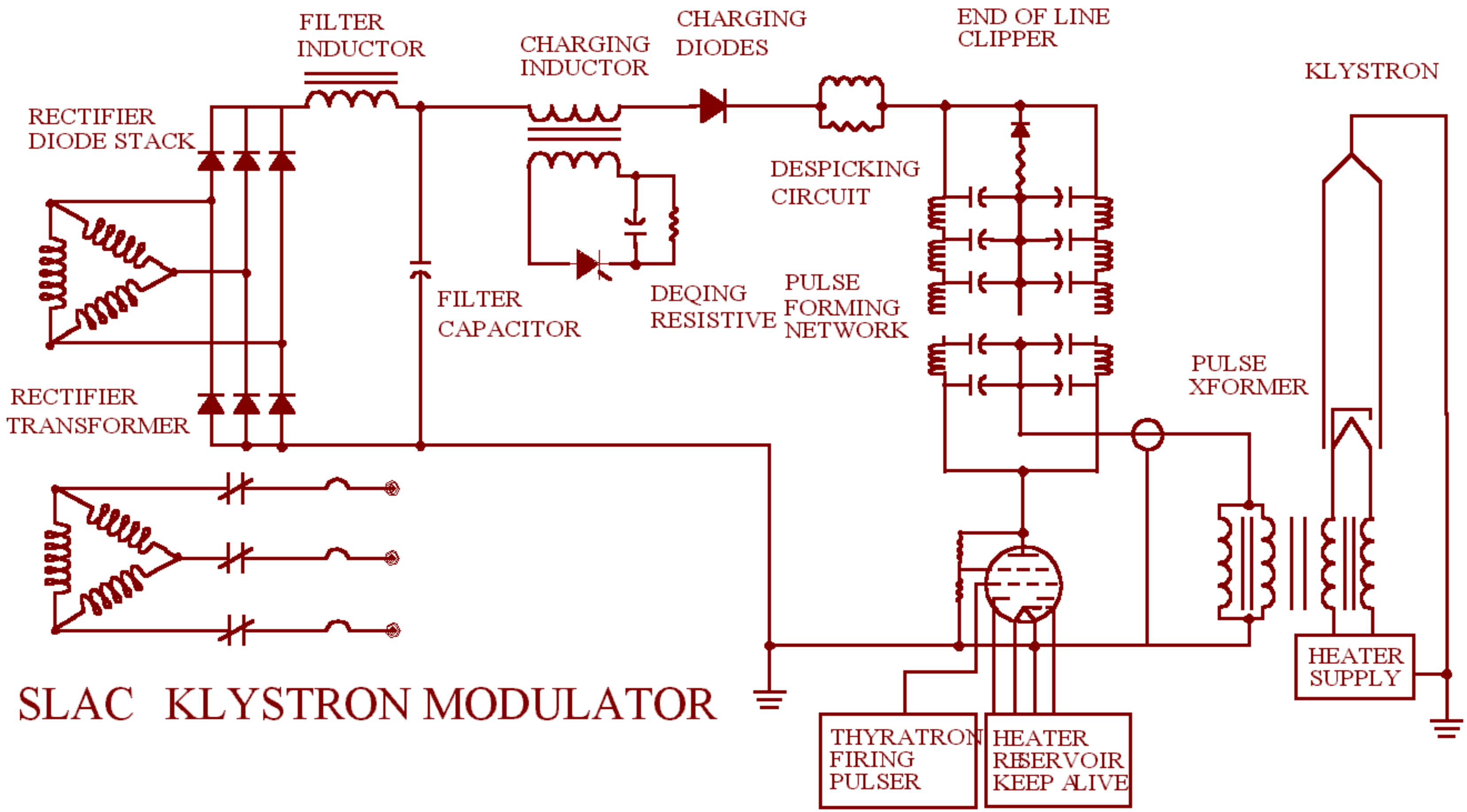
Smaller power source

Less cooling required (klystron efficiency is 45%)

*Average power = peak power *duty cycle(on-time*PRR)*

*Average power = 144.9MW *5μS*60Hz=42.4kW much lower power*

Conventional Pulsers - Present Klystron Modulator Power Supply

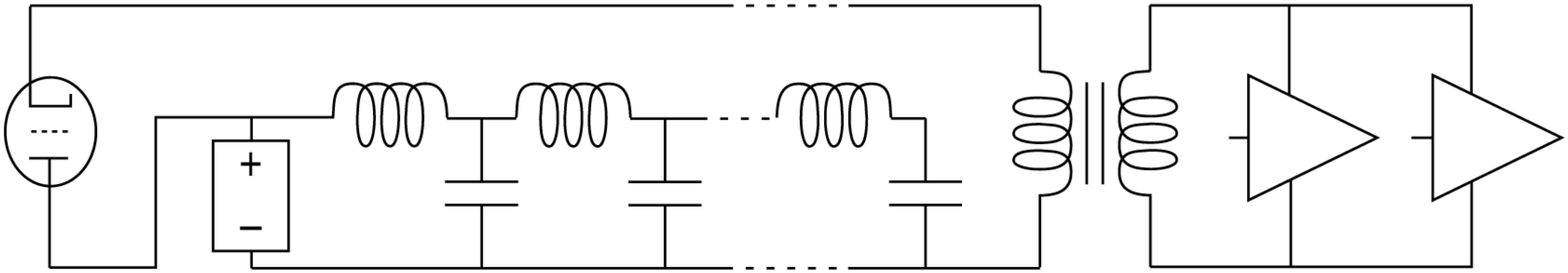


- *Primary VVT, with diode rectifier*
- *High voltage secondary with diodes and filter capacitor*
- *Protected against secondary faults*

Conventional Pulsers - Klystron Modulator with PFN

Thyratron

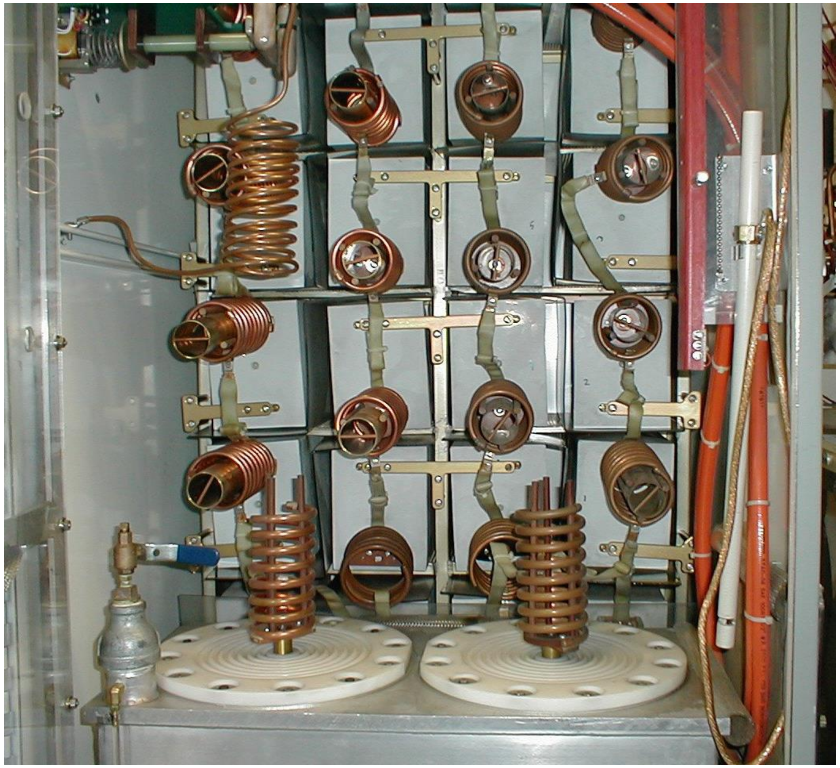
1:14 Transformer



Charging Supply

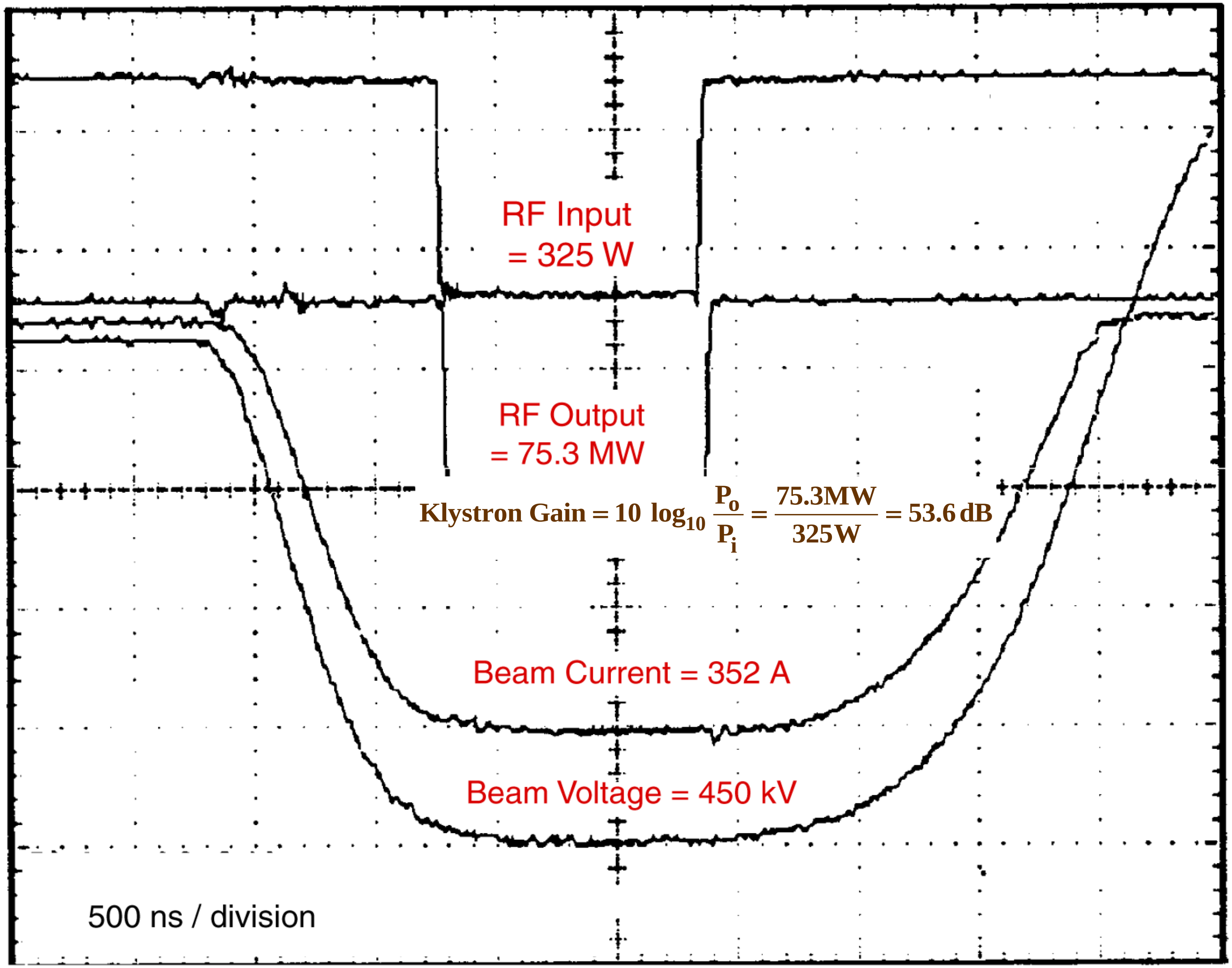
Pulse Forming Network

75 MW Klystrons



Conventional Pulsers - Klystron Modulator PS – Cabinet Details

Conventional Pulsers - Conventional Klystron Modulator



$$\text{Klystron Gain} = 10\ \log_{10} \frac{P_o}{P_i} = \frac{75.3\text{MW}}{325\text{W}} = 53.6\,\text{dB}$$

Equations of Motion:

$$\frac{d\vec{p}}{dt} = \vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$
$$\frac{dE}{dt} = q\vec{v} \cdot \vec{F}$$

where $\vec{p} = \gamma m\vec{v}$ *is the relativistic momentum,* $\gamma = 1/\sqrt{1-\beta^2}$,

and $\vec{\beta} = \vec{v}/c$.

For a system with only magnetic fields, $\vec{E} = 0$, *the energy E is constant*

$$\frac{dE}{dt} = q\vec{v} \cdot \left(\vec{v} \times \vec{B}\right) = 0$$

so we need to solve the differential equation

$$\frac{d\vec{v}}{dt} = \frac{q}{\gamma m}\vec{v} \times \vec{B}$$

since γ *is constant.*

We will choose our coordinate system so that the beam travels in the $\hat{z}$ *direction and we want to deflect the beam in the* $\hat{x}$ *direction. Therefore* $\vec{B} = B\hat{y}$.

Kicker Current Equations

Our coupled differential equations are

$$\frac{dv_x}{dt} = -\frac{qB}{\gamma m} v_z$$
$$\frac{dv_z}{dt} = \frac{qB}{\gamma m} v_x B$$

Differentiating the second equation and substituting in the first equation we get

$$\frac{d^2 v_z}{dt^2} = -\left(\frac{qB}{\gamma m}\right)^2 v_z = -\omega_B^2 v_z, \qquad \omega_B = \frac{qB}{\gamma m}$$

This is the familiar harmonic oscillator equation with solutions

$$v_z(t) = v_{z0} \cos \omega_B t + \frac{v_{z1}}{\omega_B} \sin \omega_B t$$

We set our initial conditions such that $v_{z0} = \omega_B \rho, v_{z1} = 0$. *Then*

$$v_z(t) = \omega_B \rho \cos \omega_B t$$
$$v_x(t) = -\omega_B \rho \sin \omega_B t$$

ρ is the radius of curvature of the particle trajectory through the magnet.

Kicker Current Equations

Integrating again, we get the equations for the particle coordinates

$$z(t) = \rho \sin \omega_B t + z_0$$
$$x(t) = \rho \cos \omega_B t + x_0$$

ρ *is the radius of curvature of the particle trajectory through the magnet.*

Now we relate the desired curvature of the beam to its properties and the strength of the magnetic induction.

$$|p| = \gamma m v = \gamma m \omega_B \rho = qB\rho$$
$$\rho = \frac{p}{qB} = \frac{cp}{cqB} = \frac{c\gamma m\beta c}{cqB} = \frac{\beta\gamma mc^2}{cqB} = \frac{\beta E}{cqB}$$

All of these equations have been written in MKS units. Accelerators use a mix of units. The unit of magnetic induction, B *is Tesla, but the unit of energy is* GeV*. The unit of* E/q *is the volt, which is also the ratio of an electron-Volt to the electron charge. Therefore this equation is unchanged if we measure* q *in units of electric charge and* E *in units of eV.*

$$1\ eV = 1.602 \times 10^{-19}\ J$$
$$1\ e^- = 1.602 \times 10^{-19}\ C$$

Inserting the units for a particle with a fundamental charge, the equation for the curvature in a dipole magnetic field is

$$\rho = \frac{\beta E(eV)}{c(m/s)B(T)} = \frac{\beta E(eV)}{2.998 \times 10^{8} B(T)} = \frac{10^{9}\beta E(GeV)}{2.998 \times 10^{8} B(T)}$$

$$\rho = \frac{\beta E(GeV)}{0.2998 B(T)}$$

For ultra-relativistic beams, $\beta \approx 1$

$$E = 3\ GeV\ (electrons)$$

$$\gamma = \frac{3000}{0.511} = 5870.8$$

$$\beta = 0.9999999855$$

Kicker is usually designed to deflect the beam a certain angle θ. *If the* B *field is constant over a length* L,

$$\rho \sin\theta = L$$

$$BL = \frac{\beta E}{0.2998} \sin\theta$$

Example:

A 1 meter long kicker is required to deflect a 3 GeV electron beam by 2 mrad. Assuming a uniform field in the kicker, calculate the magnetic induction required for this deflection.

$$BL = \frac{\beta E}{0.2998}\sin\theta$$

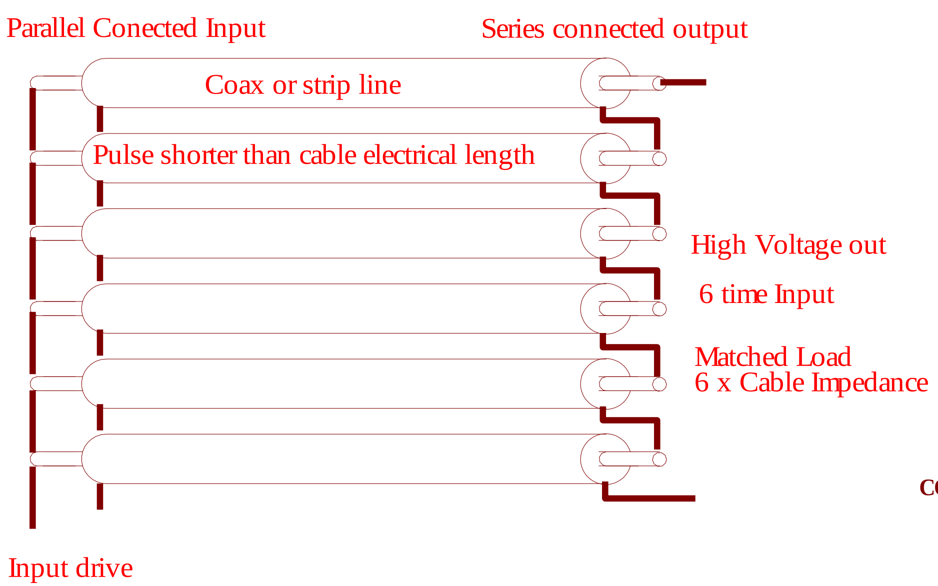
$$B = \frac{3}{0.2998}2\times 10^{-3} = 0.020\ T$$

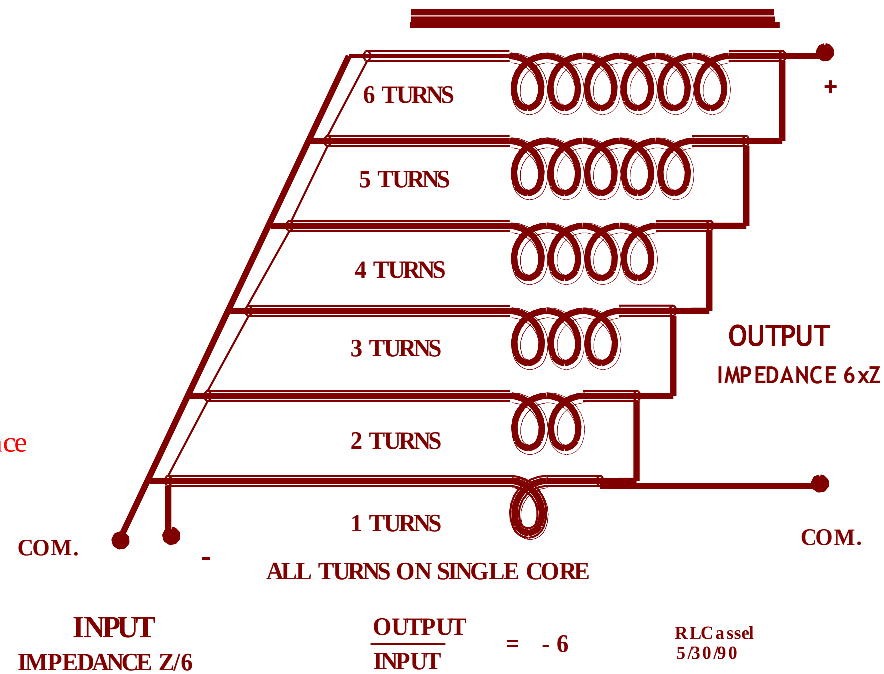
Assuming that the magnet has two conductors and the circumference of the loop of the magnetic field from each conductor passing through the beam trajectory is 0.150 meters, calculate the current that flows through each conductor.

$$\oint \vec{H}\cdot\vec{dl} = 2I = 0.150H = \frac{0.150B}{\mu_0}$$

$$I = \frac{0.150B}{2\cdot 4\pi\times 10^{-7}} = \frac{0.150\cdot 0.020}{2\cdot 4\pi\times 10^{-7}} = 1194\ A$$

- *Cable Pulse Transformer parallels multiple cable inputs and series connects the outputs. The pulse length must be < 2X the electrical length of the cable and must drive a matched load.*
- *Fast rise time with simple transformer*
- *Disadvantage stray capacitance and floating cable return limits transformer usage*



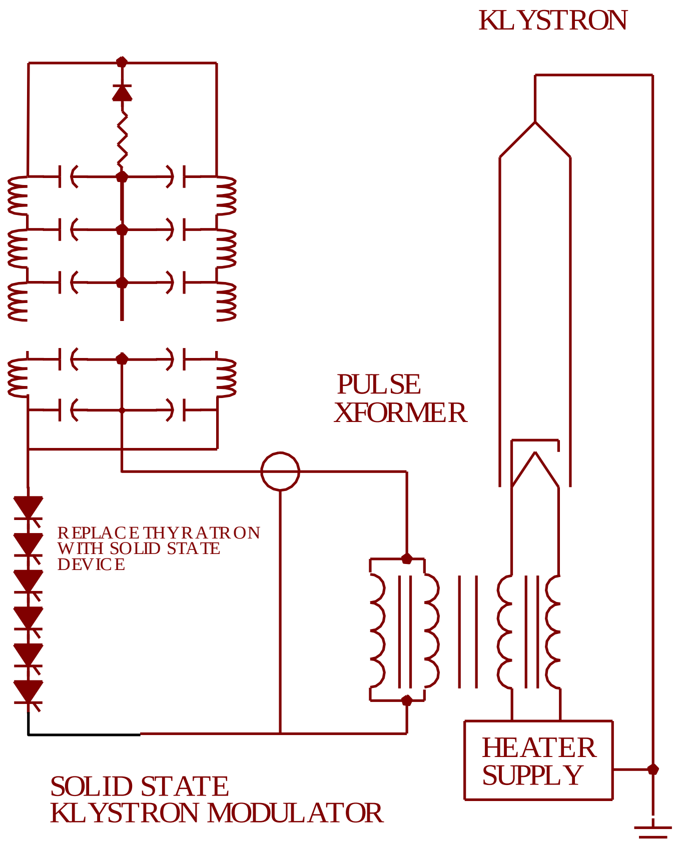


Comparison of Thyratron and Solid-State Pulser Parameters

Parameter	Thyratron	Solid-state
Control turn-on	Yes	Yes
Control turn-off	No	Yes
Pulse Shaping	PFN	IGBT
Output Voltage	1/2 PFN voltage	Same as device voltage

Solid-State Pulsers

- *Replace Thyratron with solid-state switch SCR, IGBT, MOSFET, etc*
- *Having a high enough di/dt capability is the problem*
- *For many applications IGBTs without PFNs are being used at the present time*



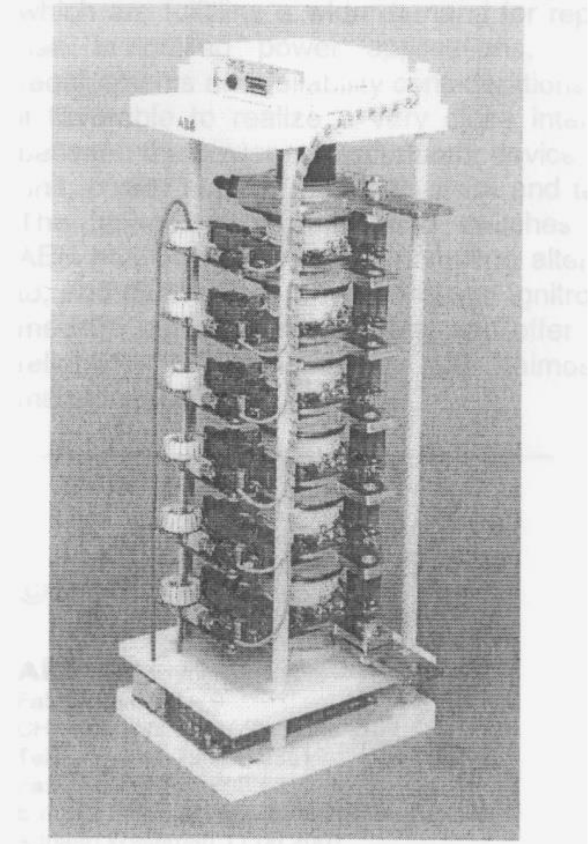
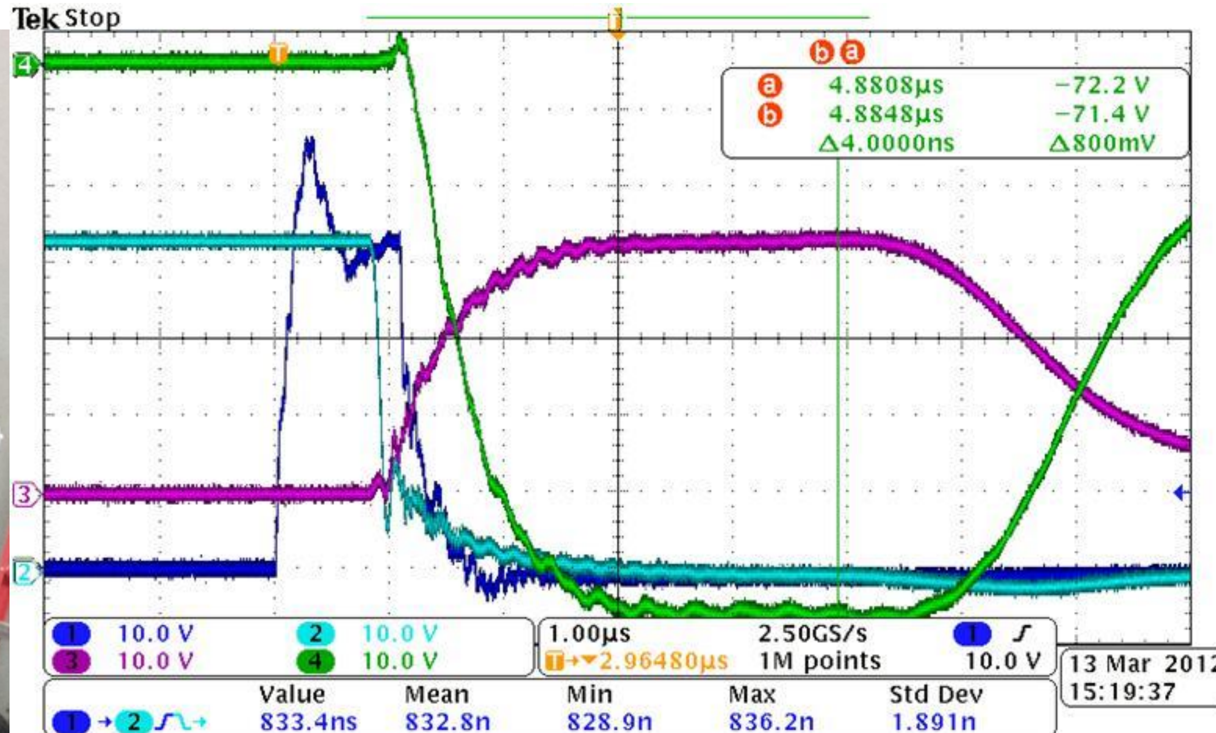
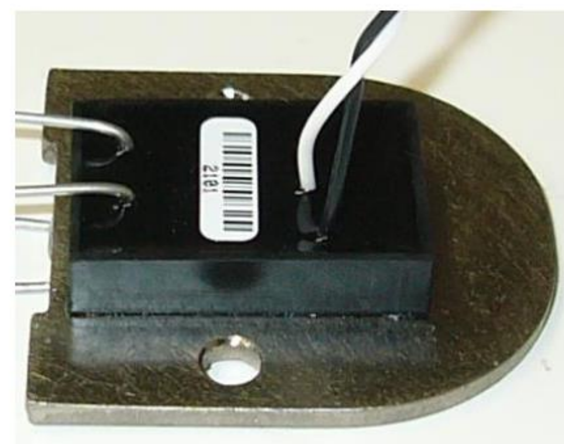


Fig. 11) Switch Assembly SPR-08F45-6-WC



Model S38 Thyristor Module



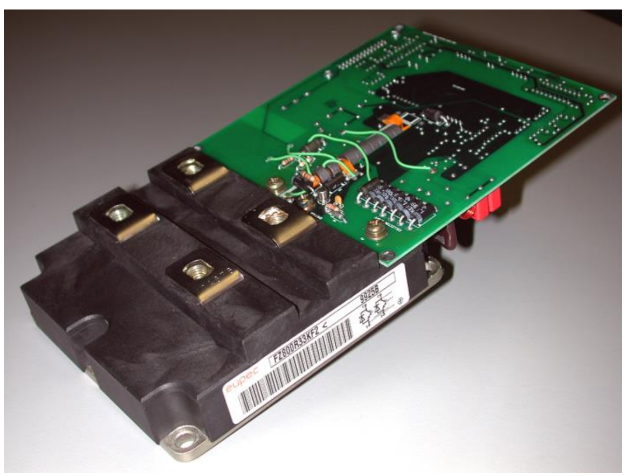
Features:

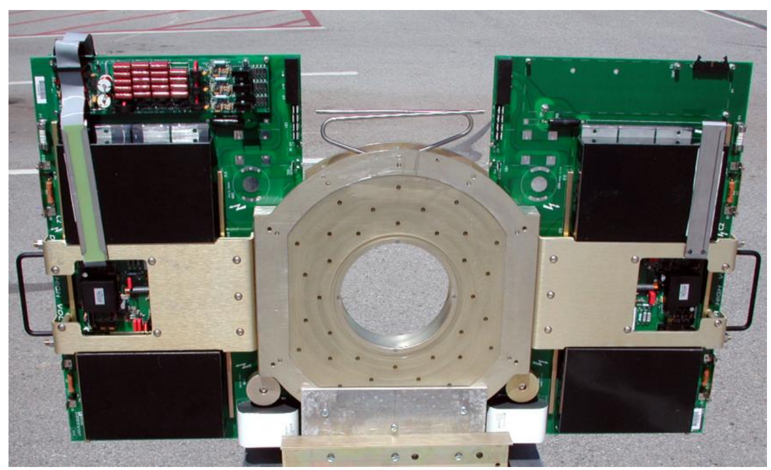
- 4700V Peak Off-State Voltage
- 14kA Peak Non-Repetitive Current
- 30kA/µS Maximum di/dt
- 100nS turn-on delay time
- Low Inductance

Solid-State Induction Modulators

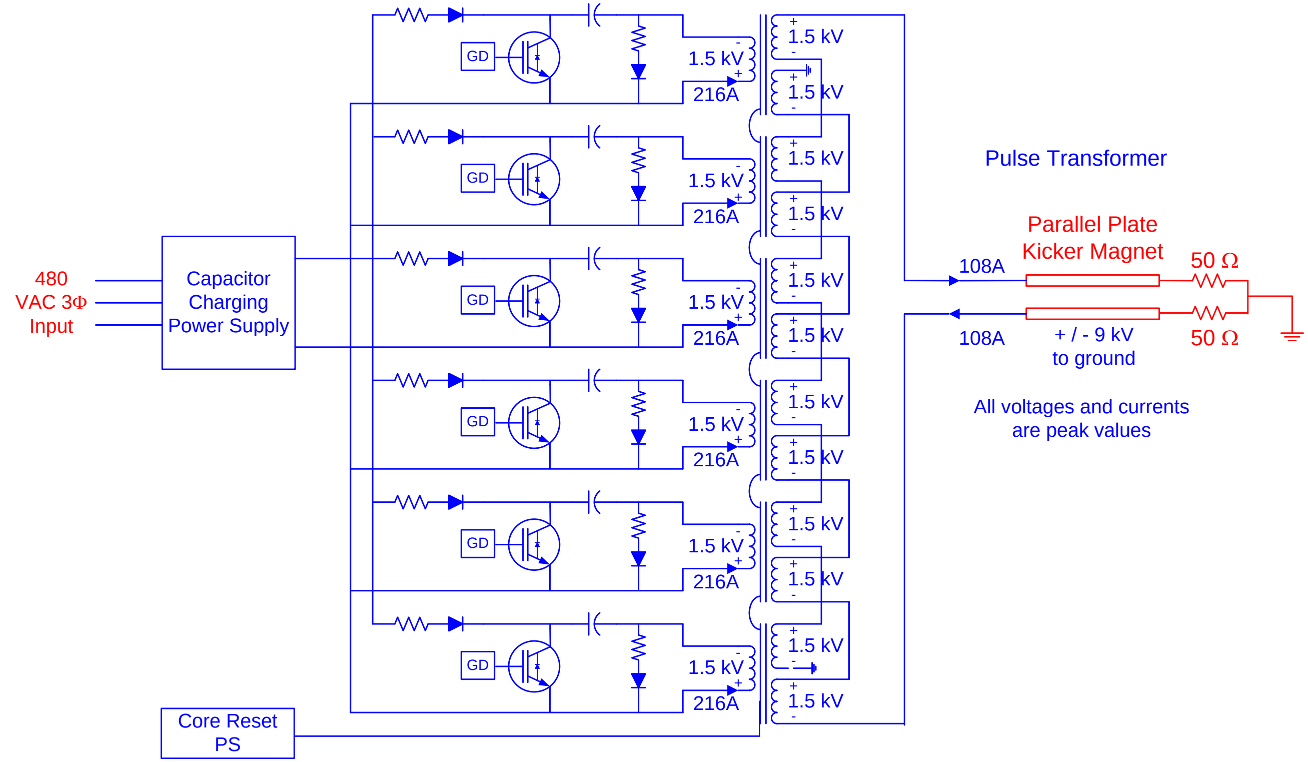
- *Fractional turn pulse transformer*
  - *–Similar to a induction accelerator*
  - *–Multiple primaries driven in parallel*
  - *–The secondary connected in series*

- *Solid-state driver consists of*
  - *– A solid state switch that turns on and off*
  - *– DC capacitor per primary winding*

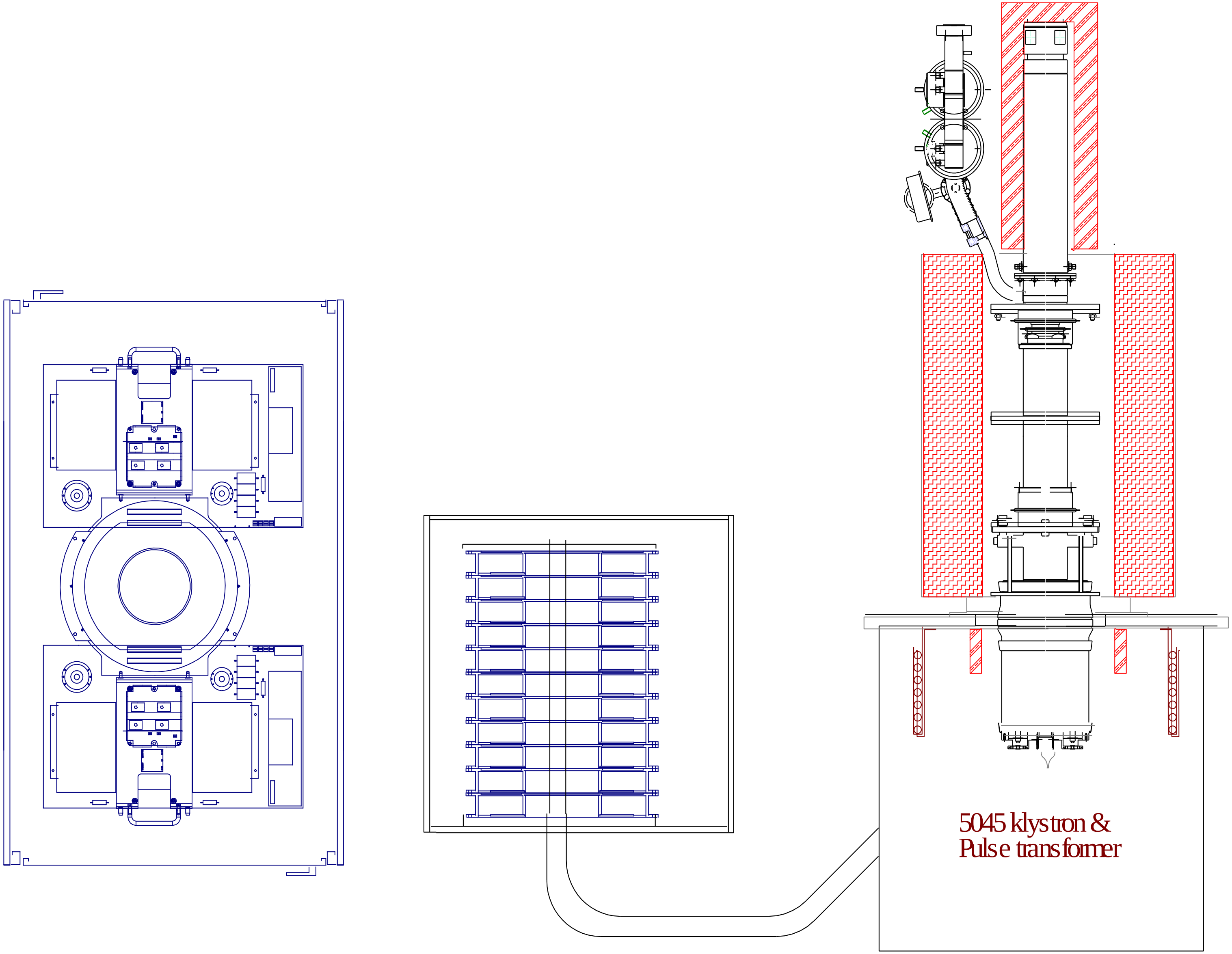




A Solid-State Turn-On Pulser



- *All pulse capacitors are pre-charged simultaneously*
- *IGBTs are all switched on together*
- *Capacitors are then simultaneously discharged producing sinusoidal V and I pulses in the pulse transformer and magnet. The secondary winding voltages are additive*
- *At the end of the pulse the IGBT is turned off. The magnet current decay causes a voltage reversal at the free-wheeling diode*
- *The freewheeling diodes conduct and the magnet current decays exponentially to zero*

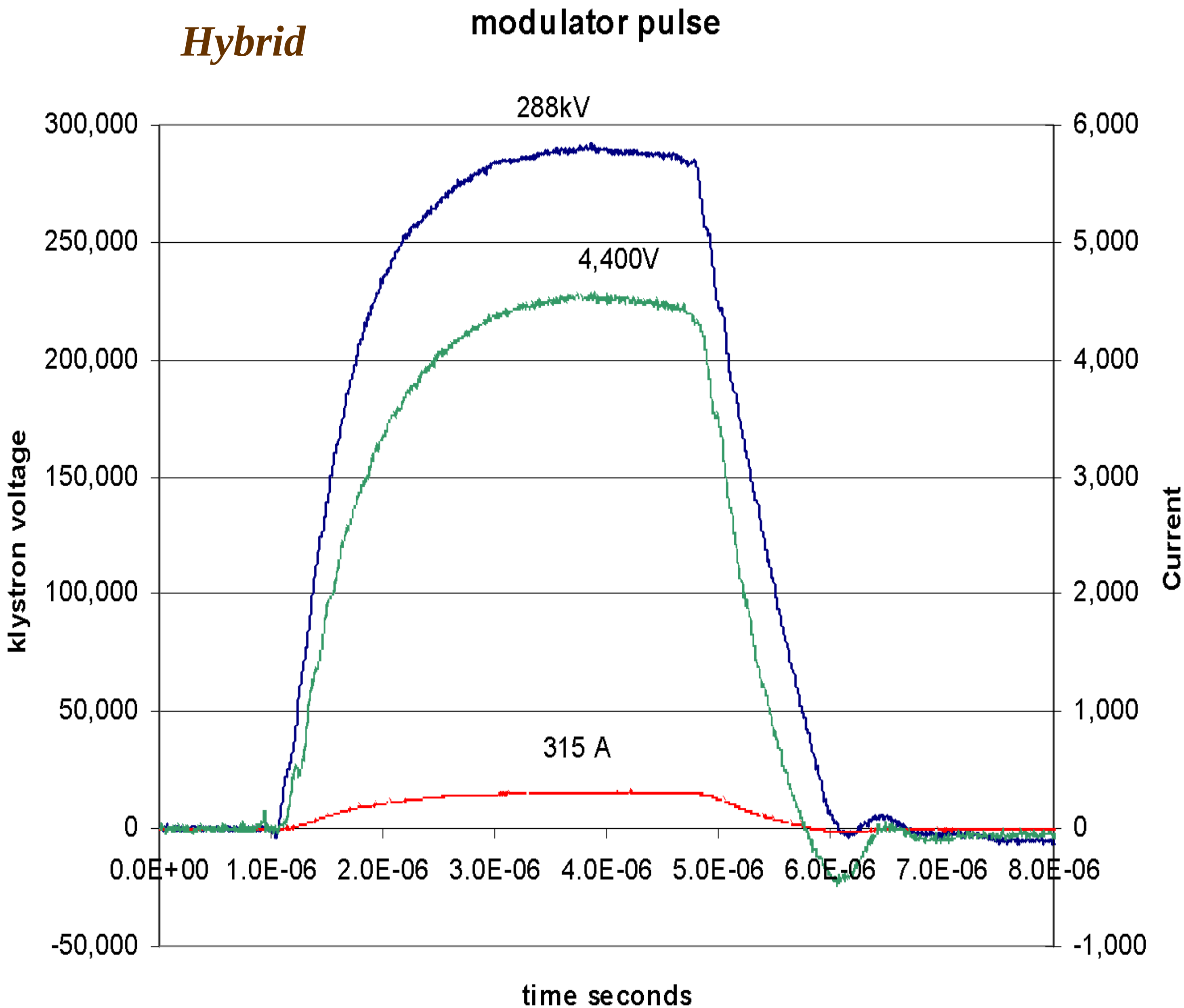

5045 klystron &
Pulse transformer

Hybrid

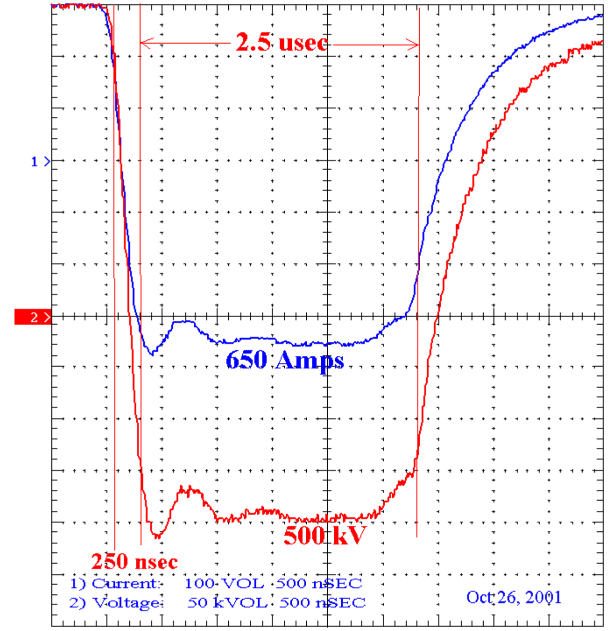
- Solid-state 10 - stack installed alongside Gallery line-type PFN unit
- 22 kV => 330 kV via 15:1 xfmr
- Prototype currently at 255 kV @ 2.2 μsec @ 120 PPS

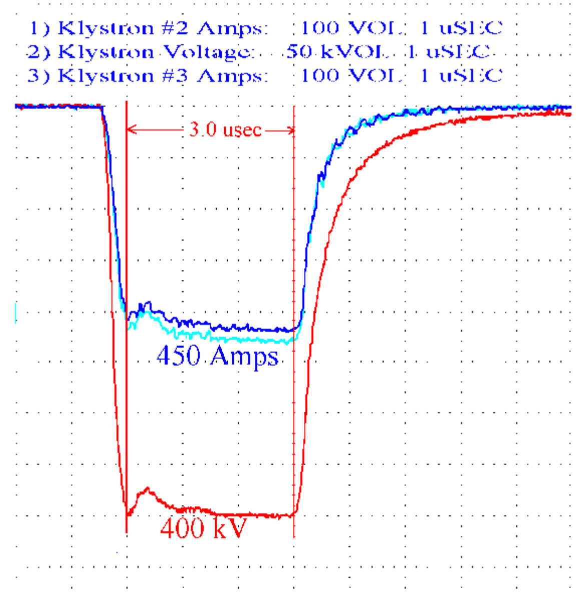
Solid-State Induction Klystron Modulator

Hybrid



Solid-State Induction Klystron Modulator





SOLID STATE DRIVERS

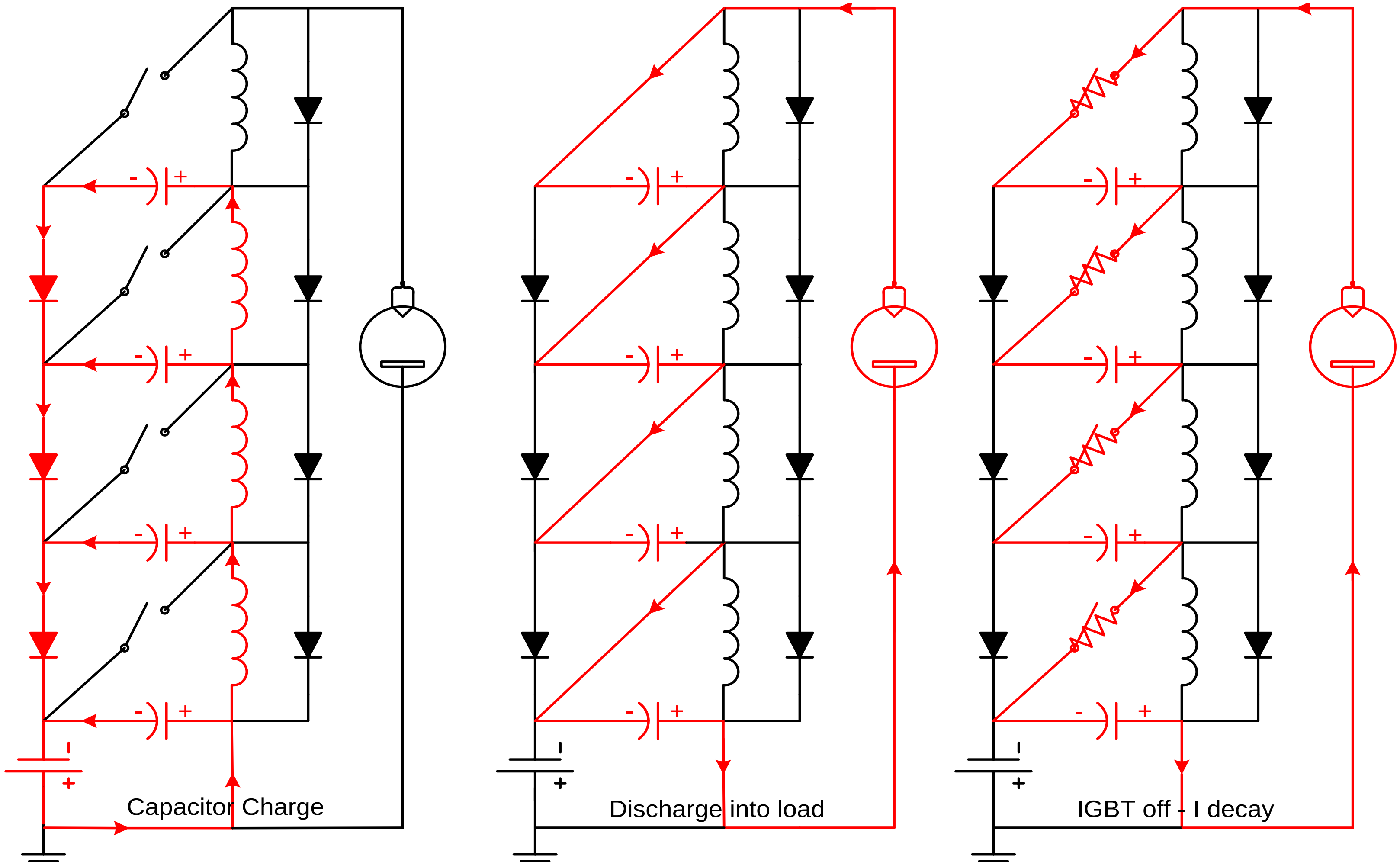
- *152 IGBT Drivers (two per each primary)*
- *1800 Volts per IGBT*
- *2700 Amps per Driver*

CORES AND SECONDARY

- *76 Primaries @ 5400 A*
- *3-Turns Secondary*
- *400kV @ 1800A, 725MW for 3.2μs, 350kW Ave.*

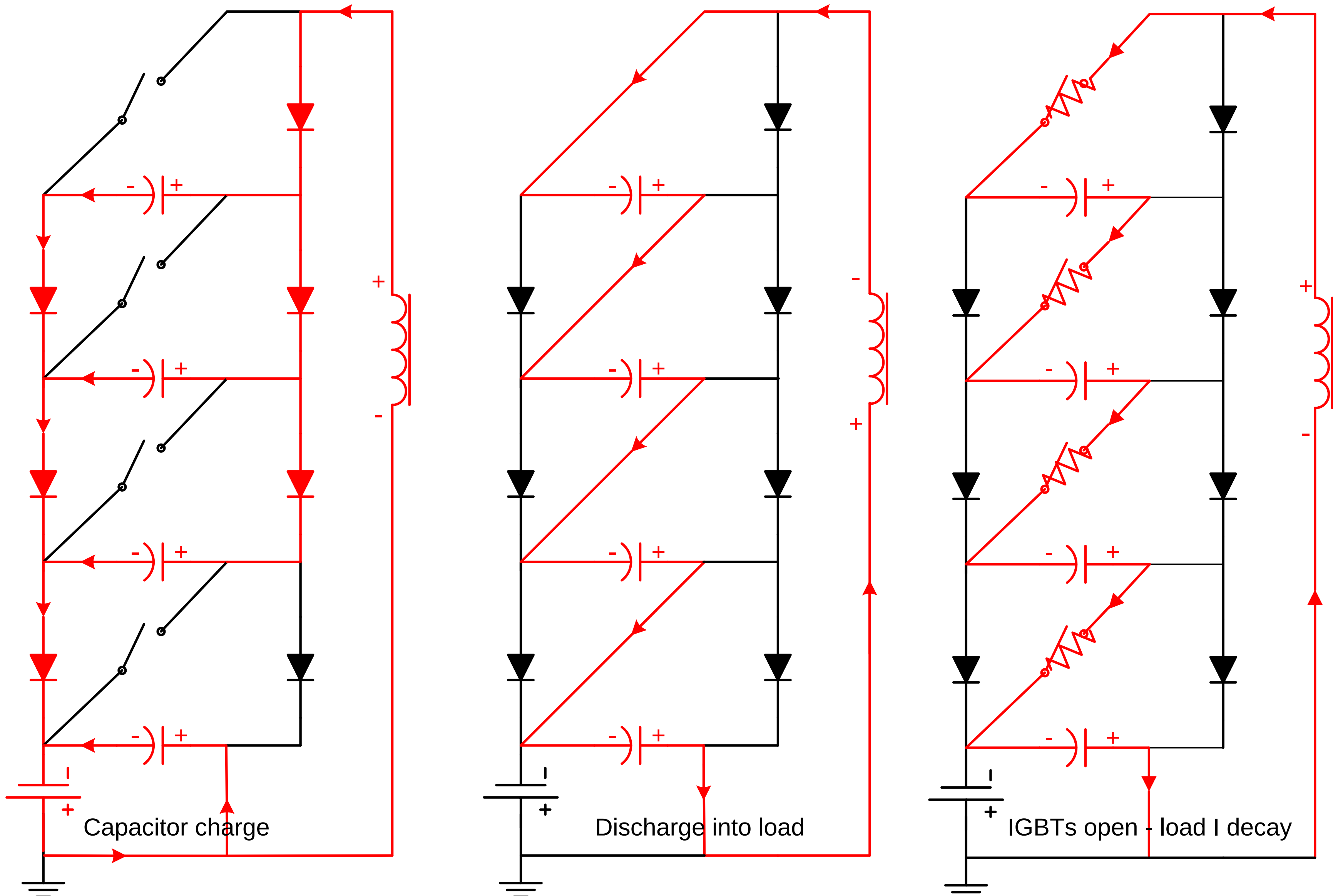
Solid-State Marx Generator for Modulators or Kickers

- *Marx Generator charges capacitors in parallel for quickness, discharges them in series for high output voltage. For long pulses, advantage is to avoid the need for large iron core transformers based on volt-second product*

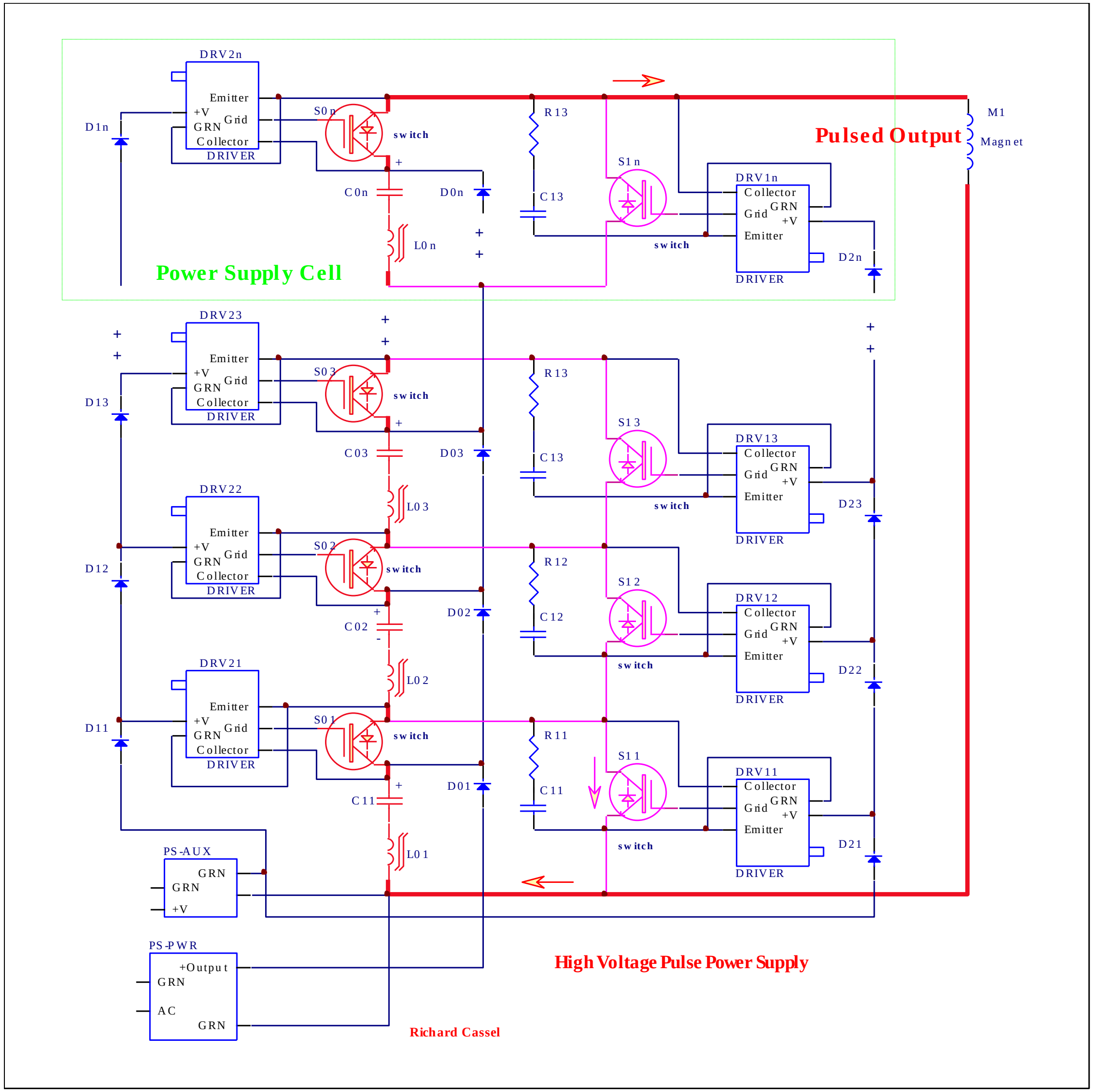


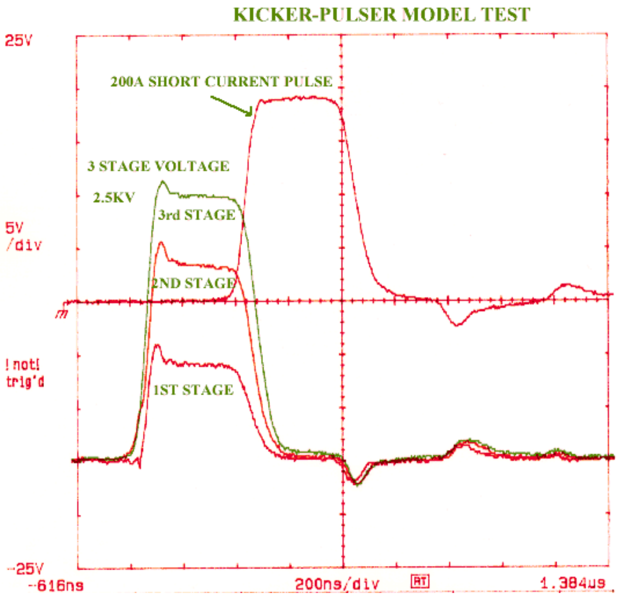
Solid-State Marx Generator for Modulators or Kickers

- *If the load is a magnet, the charging inductors are not required*



- *Another implementation, using solid-state switches in place of the charging inductors for smaller size and less diversion of capacitor current from load*

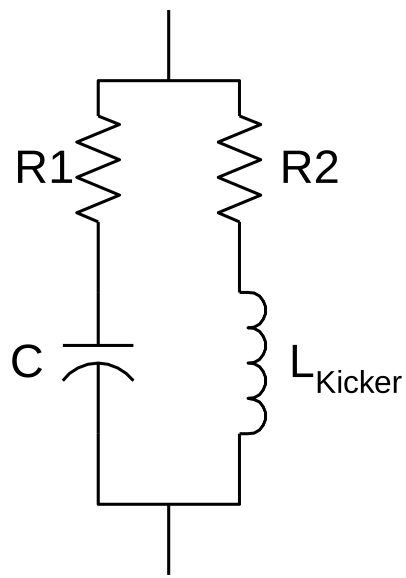




Solid-State Pulsers - Homework Problem # 15

A controlled impedance transmission line often drives a kicker. The kicker is usually well modeled as an inductor. A matching circuit can be built around the kicker and its inductance so that this circuit, including the kicker magnet, has constant, frequency independent, impedance which is matched to the transmission line.

Assuming that the transmission line impedance is Z_0 and the kicker inductance is L_{Kicker} derive the values of R1, R2, and C necessary to make a frequency independent (constant) impedance Z_0.



A. What is the significance of the value $\sqrt{\dfrac{\mu_o}{\varepsilon_o}}$?

B. What is the significance of the values $\dfrac{1}{\sqrt{\mu_o \varepsilon_o}}$ and $\sqrt{L*C}$?

C. Calculate the speed of light in mediums with dielectric constants of:
$\varepsilon_r = 1$ $\varepsilon_r = 2$ $\varepsilon_r = 4$ $\varepsilon_r = 8$ $\varepsilon_r = 16$

Section 9

- *Magnetics*
  - *The Electric - Magnetic Equivalence*
  - *Field Due to a Current*
  - *Magnetic Units Including Turns*
  - *Cores and Materials*
  - *Transformer Design Issues*
  - *Inductors*

The Electric - Magnetic Equivalence

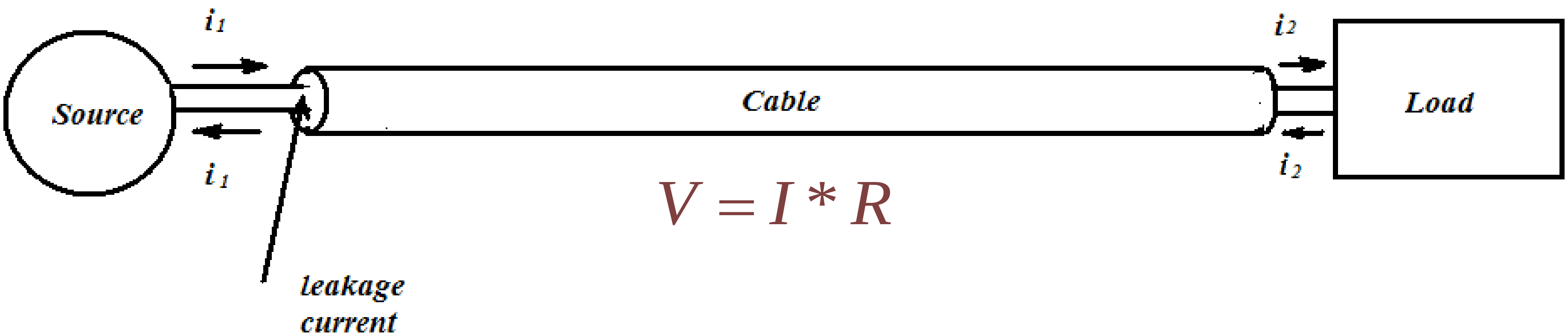
- *Various magnetic types, such as transformers and filter inductors, play a key role in many of the components used in power supplies*
- *Magnets are also extensively used in accelerators to guide, direct, steer and focus beams*
- *Magnetic circuits are analogous to electric circuits and are important for the analysis of magnetic devices. The equations for both electric and magnetic circuits show strong similarities*

Electrical	***Closest Magnetic***
EMF (Volts)	*MMF (A*turn, F)*
Current (Amperes)	*Flux (Wb / turn, Φ)*
Resistance (ohms, Ω)	*Reluctance (A*turns / Wb, R)*
*Resistivity (ohm*m, ρ)*	
Conductance (mhos, σ)	*Permeance (Wb / A*turn, P)*
Conductivity (Siemens/m)	*Permeability (Henries / m, μ)*

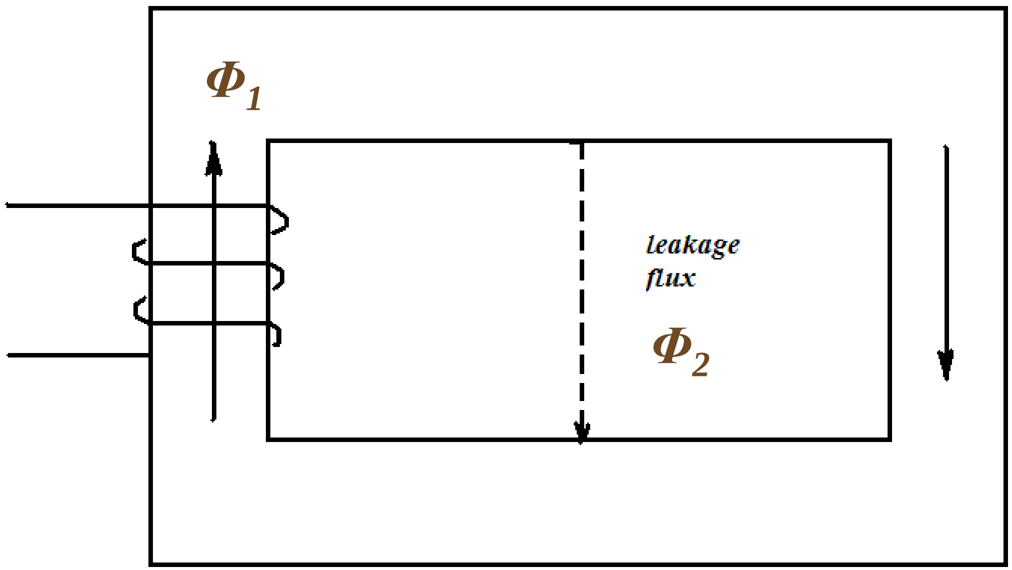
Magnetic Units Including Turns

Symbol	Description	SI units	cgs units
N	Winding turns	turn (t)	t
H	Field intensity	(A·t)/m	Oersted (Oe)
B	Flux density	tesla (T)	gauss (G)
μ	Permeability	T·m/A or H/m	G/Oe
F	Magnetomotive force	A·t	gilbert (Gb)
Φ	Flux	weber/t (Wb/t)	maxwell
R	Reluctance	A·t/Wb	
P	Permeance	henry/t or (Wb/A*t)	H/t
I	Current	ampere (A)	A
L	Inductance	henry (H)	H

Electric-Magnetic Circuit Comparisons

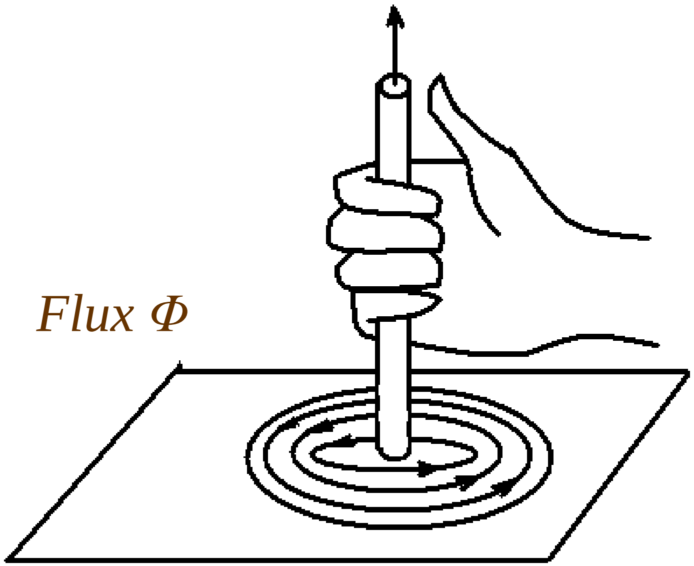


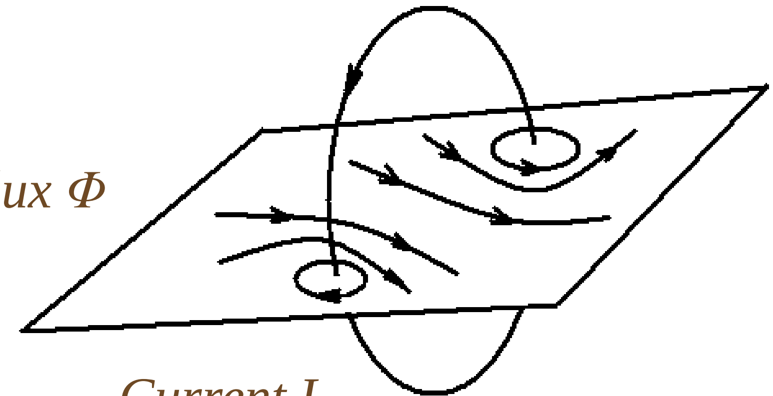
$$V = I * R$$

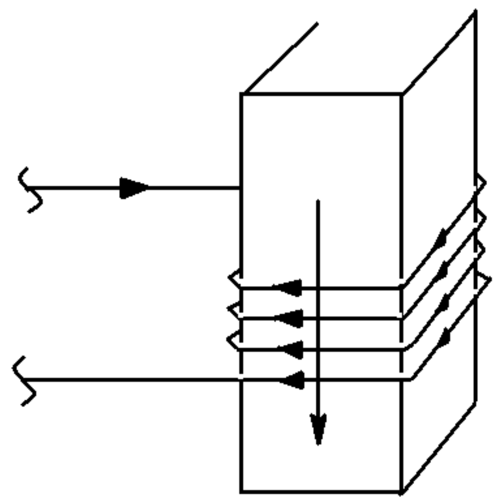


$$F = \Phi * R$$

Field Due to a Current







Right Hand Rule:

- *Thumb = Current*
- *Fingers Point in Direction of Magnetic Field*

H Field Around A Wire

$$I = \oint H \bullet dl$$

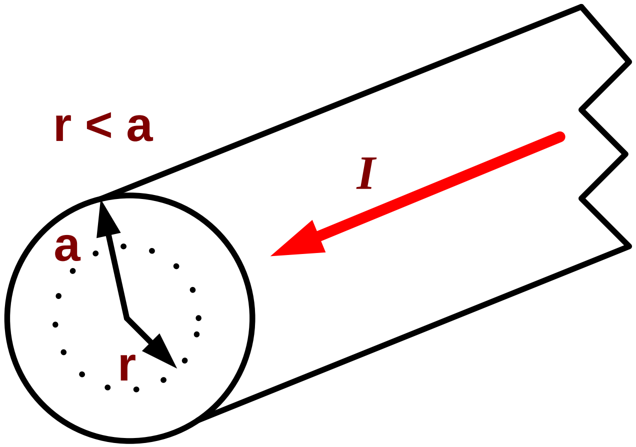
For uniform current density

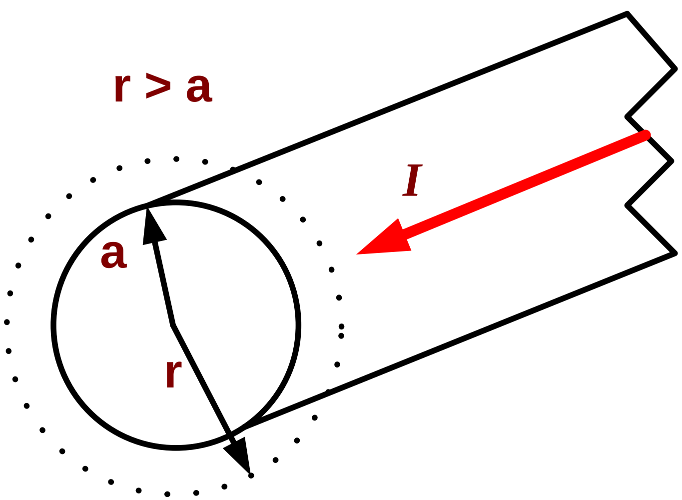
$$H = \frac{I'}{l} \qquad l = 2\pi r$$

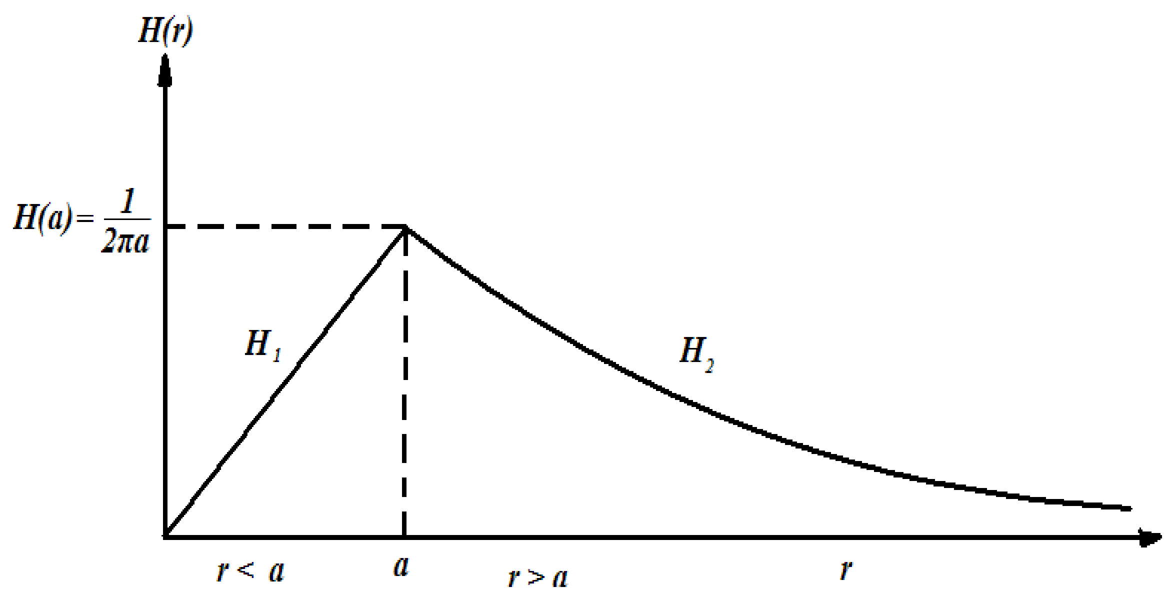
$I' =$ The fraction of the total current flow in the wire

$$\text{For} \quad r \le a \Rightarrow I' = \frac{r^2}{a^2} I \qquad H_1 = \left(\frac{I}{2\pi}\right)\frac{r}{a^2}$$

$$\text{For} \quad r > a \Rightarrow I' = I \qquad H_2 = \frac{I}{2\pi r}$$







Permeability Definitions

- μ_0 = permeability of vacuum = $4*\pi*10^{-7}$ H/m
- μ_r = relative permeability
- μ_m = material permeability = B/H at any given point
- $\mu_m = \mu_0 * \mu_r$
- *Permeability is an important core parameter*
- *Ferromagnetic materials used in transformer and inductor cores because of their high permeability*

Core Materials
Air
Alloys
Amorphous
Iron Powder
Manganese-Zinc Ferrite
Molybdenum Permalloy Powder
Nickel-Zinc Ferrite
Sendust
Silicon Steel

Energy Relationships

Energy stored in the electric field

l_e = electric field length

A_e = area enclosing the electric field

v = volume enclosing the electric field

ε = permittivity of material

E = electric field intensity

$$U_e = \frac{1}{2}\int_{vol} \varepsilon E^2 dv, \quad E = \frac{V}{l_e}$$

$$U_e = \left(\frac{\varepsilon A_e}{l_e}\right)\frac{V^2}{2}$$

$$C = \frac{\varepsilon A_e}{l_e}$$

$$U_e = \frac{CV^2}{2}$$

Energy stored in the magnetic field

l_m = magnetic field length

A_m = area enclosing the magnetic field

v = volume enclosing the magnetic field

μ = permeability of the material

H = magnetic field intensity

$$U_m = \frac{1}{2}\int_{vol} \mu H^2 dv, \quad H = \frac{I}{l_m}$$

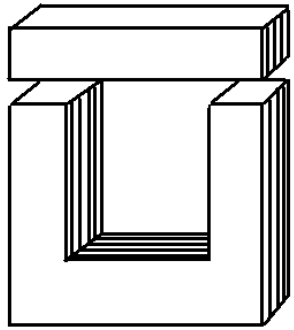
$$U_m = \left(\frac{\mu A_m}{l_m}\right)\frac{I^2}{2}$$

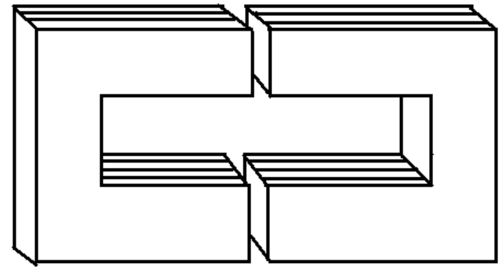
$$L = \frac{\mu A_m}{l_m}$$

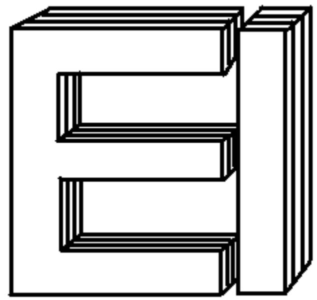
$$U_m = \frac{LI^2}{2}$$

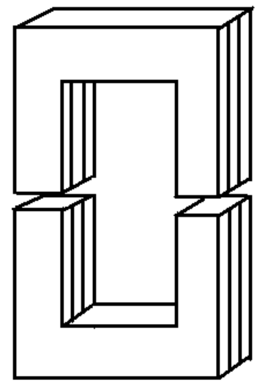
Core Shapes

- *U-U, U-I cores*
- *E-E, E-I, ETD cores*
- *POT cores*
- *RM cores*
- *PQ and PM cores*
- *EP, EFD and ER cores*
- *Toroid*

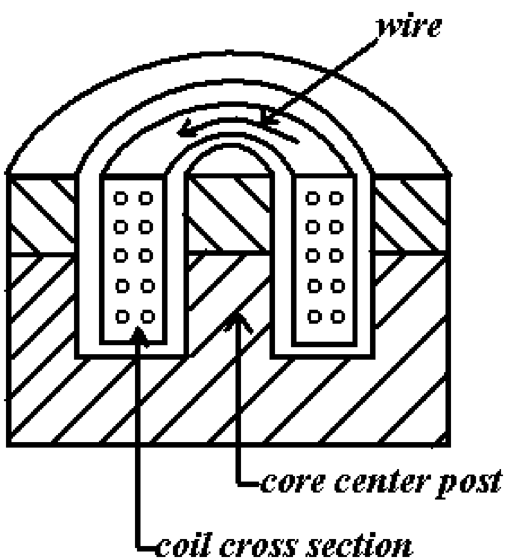

U-I

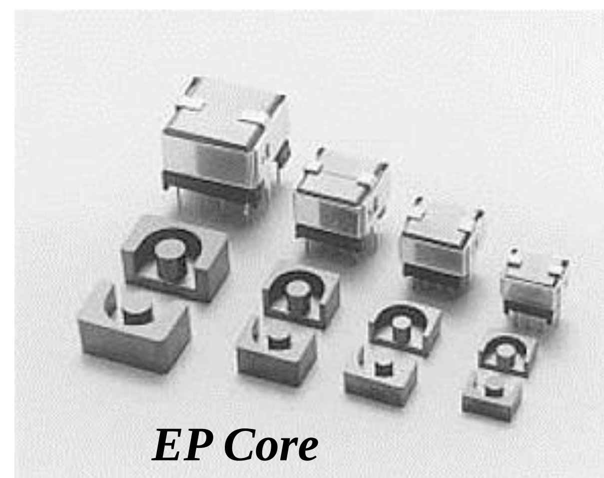

cut C core

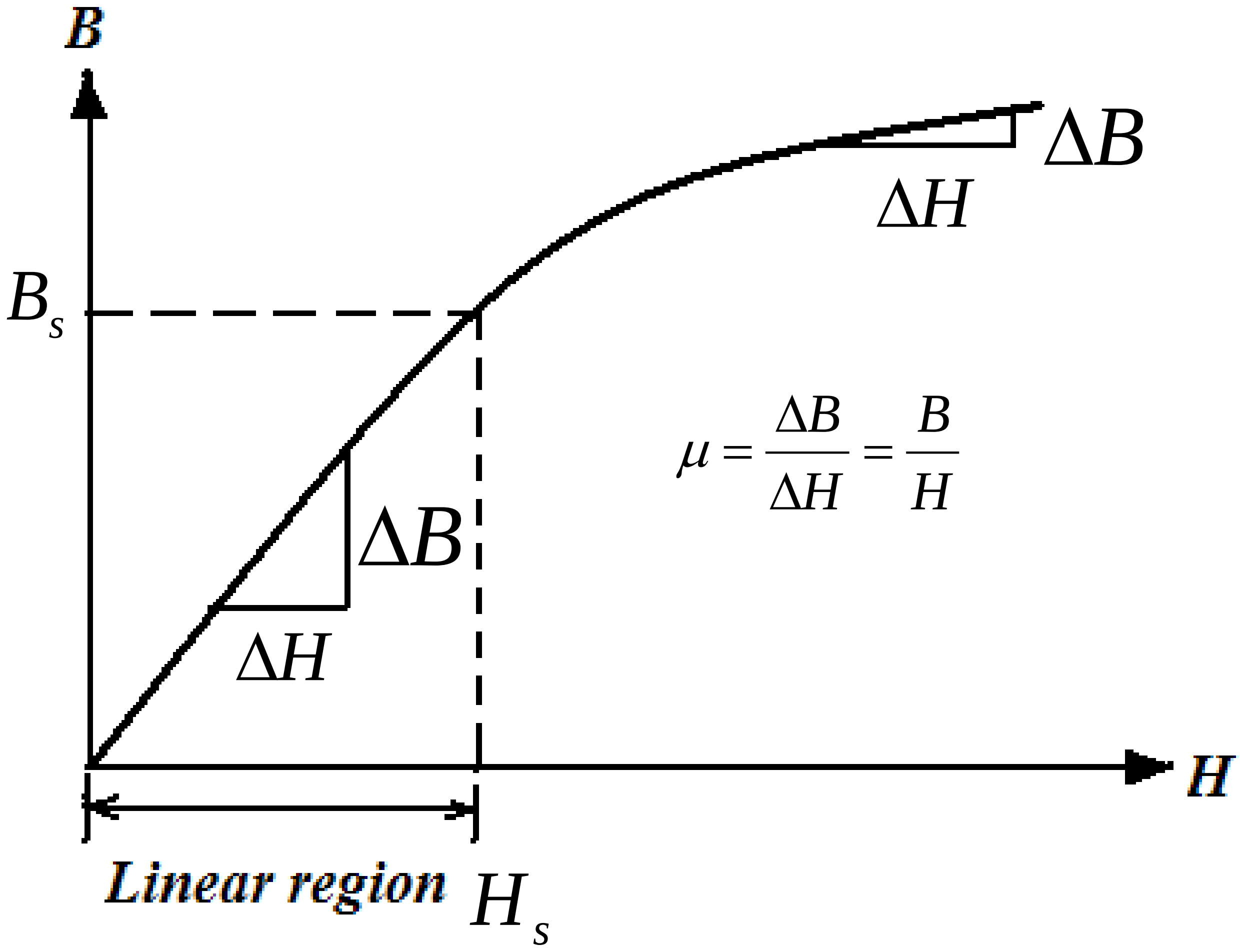

E Core

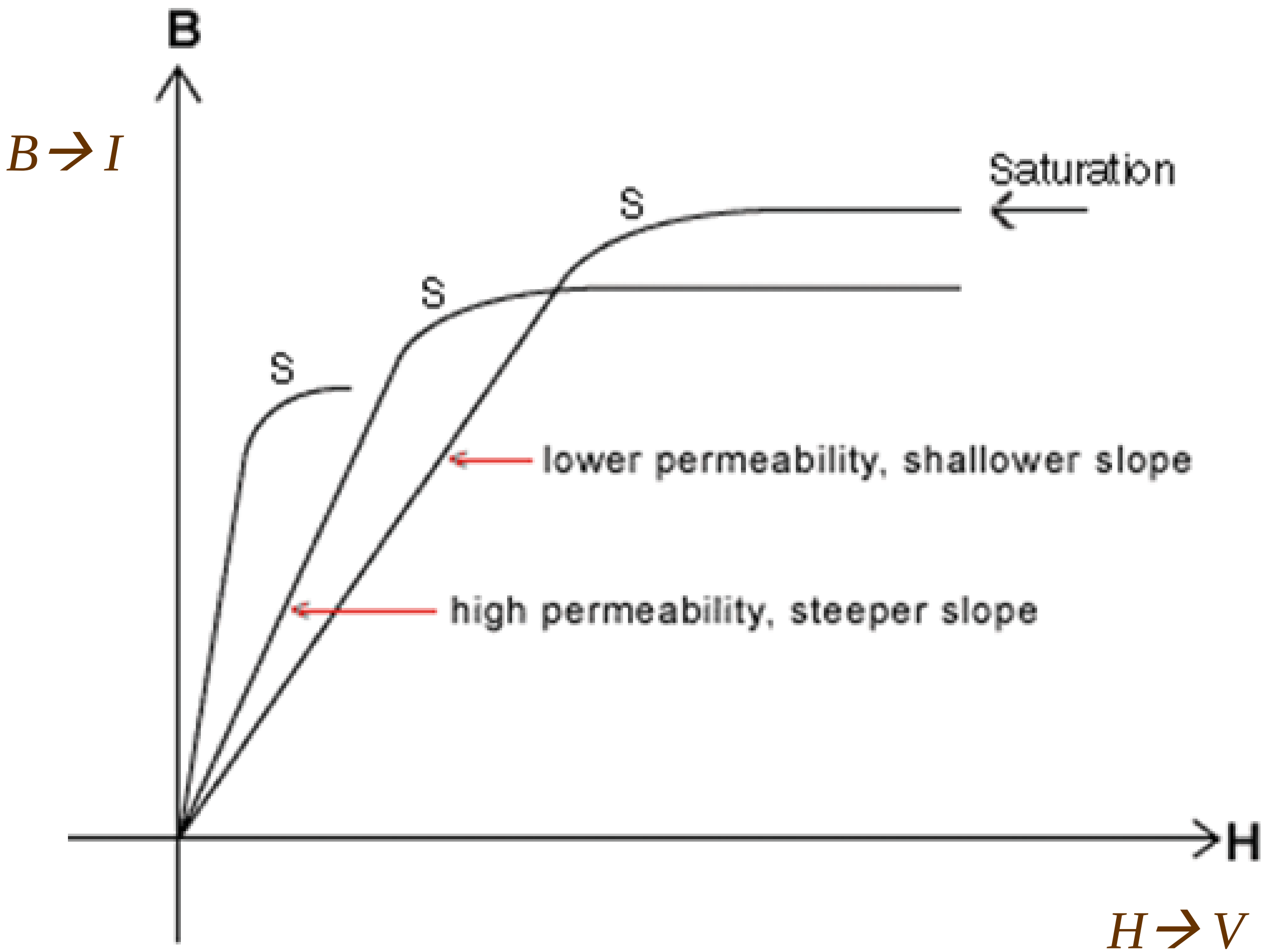

U-U

Pot cores

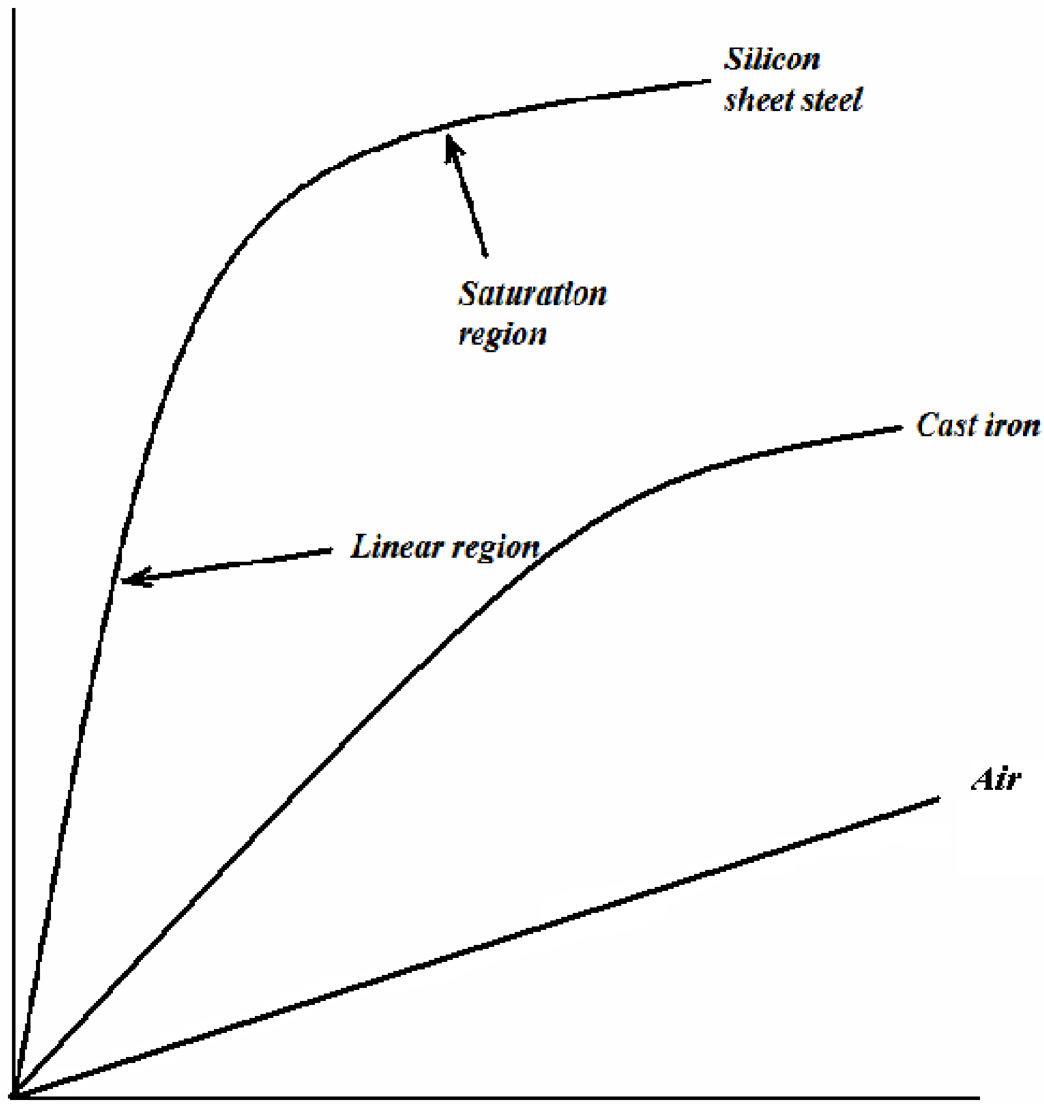





B
ΔB
ΔH
B_s
$\mu = \frac{\Delta B}{\Delta H} = \frac{B}{H}$
ΔB
ΔH
H
Linear region
H_s


B
$B \rightarrow I$
Saturation
S
S
S
lower permeability, shallower slope
high permeability, steeper slope
H
$H \rightarrow V$

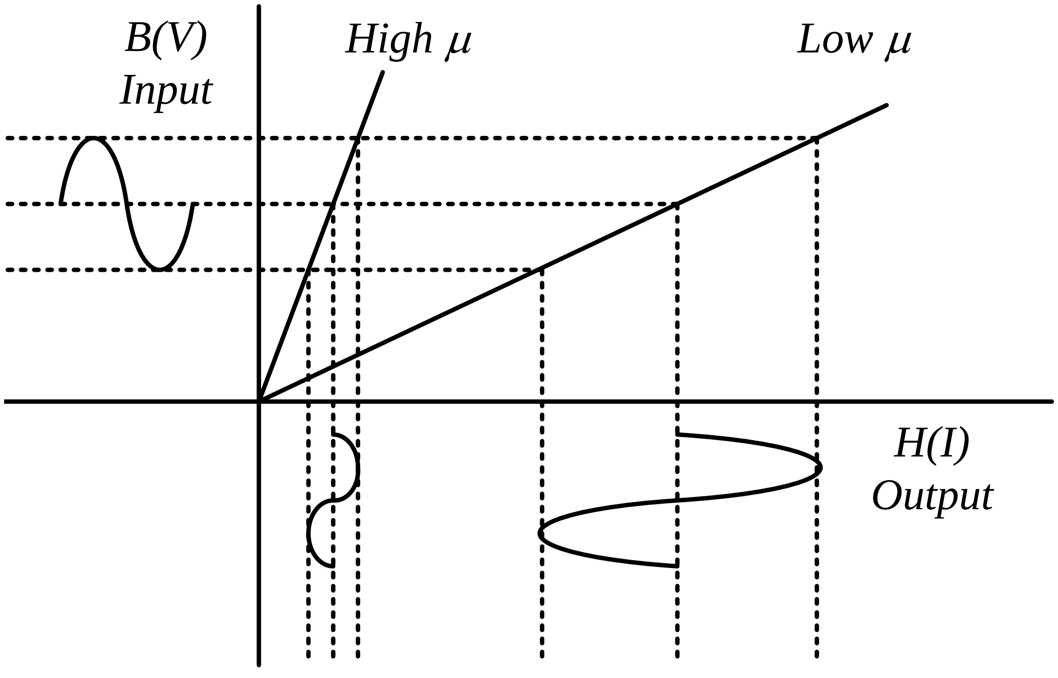
Material Comparison



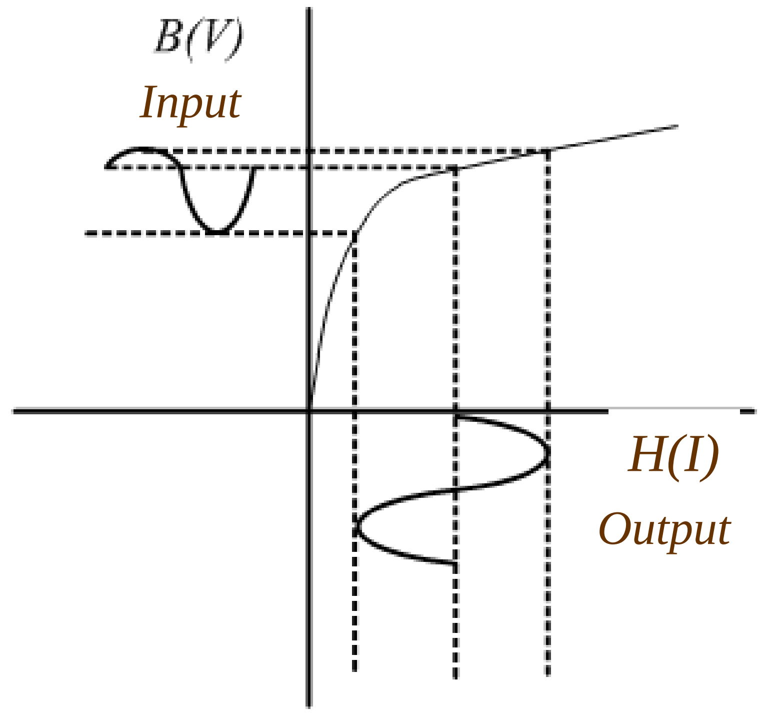
Core Material Guidelines

Material	**Frequency Range**	**B_{sat}**	**Cost**
Ferrites	Good to microwaves	0.2 T	Low
MPP (Moly Permalloy Powder)	200kHz	0.2 to 0.55 T	High
Powdered Fe	1MHz	0.4 to 1 T	Low
Laminated Si-Fe	2kHz	1T	Low
Laminated Electrical Steel	2kHz	0.5 to 1.8 T	Low
Ni-Fe Alloys	100kHz	0.5 to 1.8 T	High

Effect of permeability magnitude on transformer operation



Effect of permeability nonlinearity on transformer operation



Relationship Between v(t) and B(t)

$$v(t) = -\frac{d\Phi(t)}{dt} = V_{max}\cos 2\pi f t$$

$$v_t(t) = \frac{v(t)}{N_p} = \frac{V_{max}\cos 2\pi f t}{N_p}$$

$$v_t(t) = \text{ volts per primary winding turn}$$

$$\Phi(t) = -\int v_t(t)dt = \int_s B(t)\bullet dA_c$$

$$A_c = \text{core crossectional area}$$

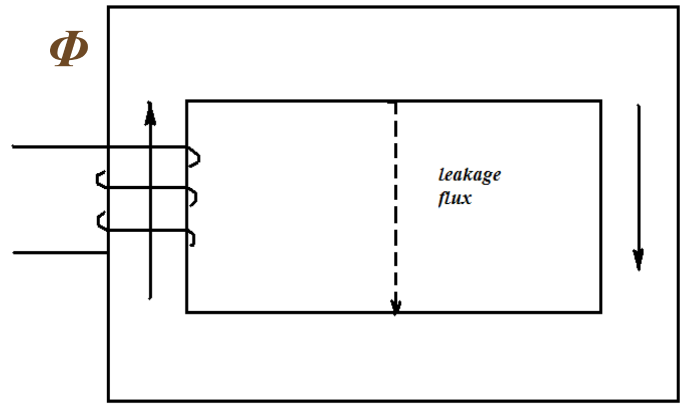
$$\int_s B(t)\bullet d\,A_c = -\int v_t(t)dt = -\int \frac{V_{max}\cos 2\pi f t}{N_p}\,dt$$

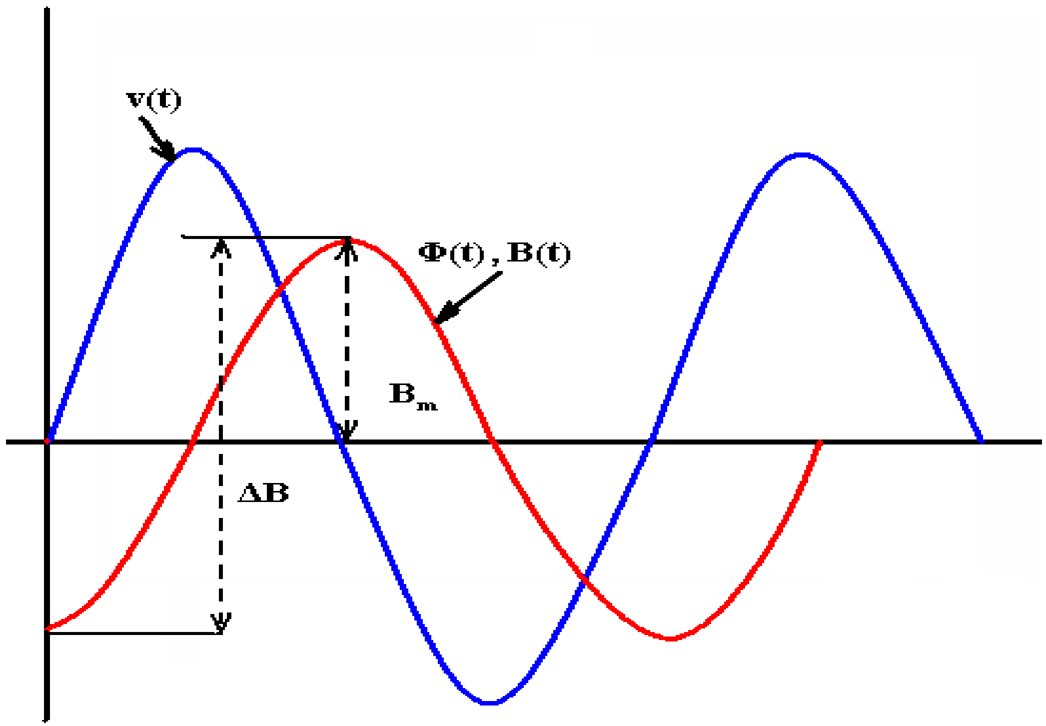
$$B(t)\,A_c = \frac{V_{max}\sin 2\pi f t}{2\pi f N_p}$$

$$B(t) = \frac{V_{max}\sin 2\pi f t}{2\pi f N_p A_c}$$

B_{max} occurs when $\sin 2\pi f t = 1$ and $V_{max} = \sqrt{2}\,V_{rms}$

$$B_{max} = \frac{\sqrt{2}\,V_{rms}}{2\pi f N_p A_c} = \frac{V_{rms}}{4.44\, f N_p A_c}$$





Transformer Design – Ensure Sufficient Core Crossection

$$B_{max} = \frac{V_{rms}}{4.44 * f * A_c * N_p * 10^{-8}}$$

where

B_{max} = maximum allowable flux density in gauss

V_{rms} = voltage applied to the primary in volts

$4.44 = \frac{\sqrt{2}}{2\pi}$ converts peak AC to rms and ω to $f(Hz)$

f = frequency of the applied voltage in hertz

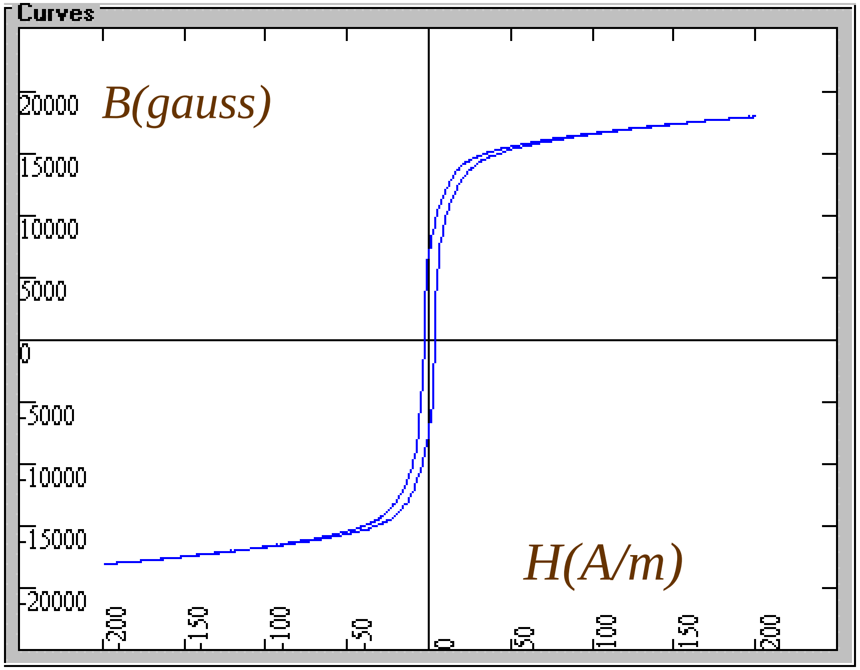
A_c = Core crossectional area in cm^2

N_p = Number of primary winding turns

10^{-8} = conversion from engineering to SI units

Example for a 480V, 600kVA, laminated electrical steel core

$$B_{max} = \frac{480V * 1.05(\text{voltage safety factor})}{4.44 * 60Hz * 300cm^2 * 60\,turns * 10^{-8}} = 10{,}510\ gauss$$

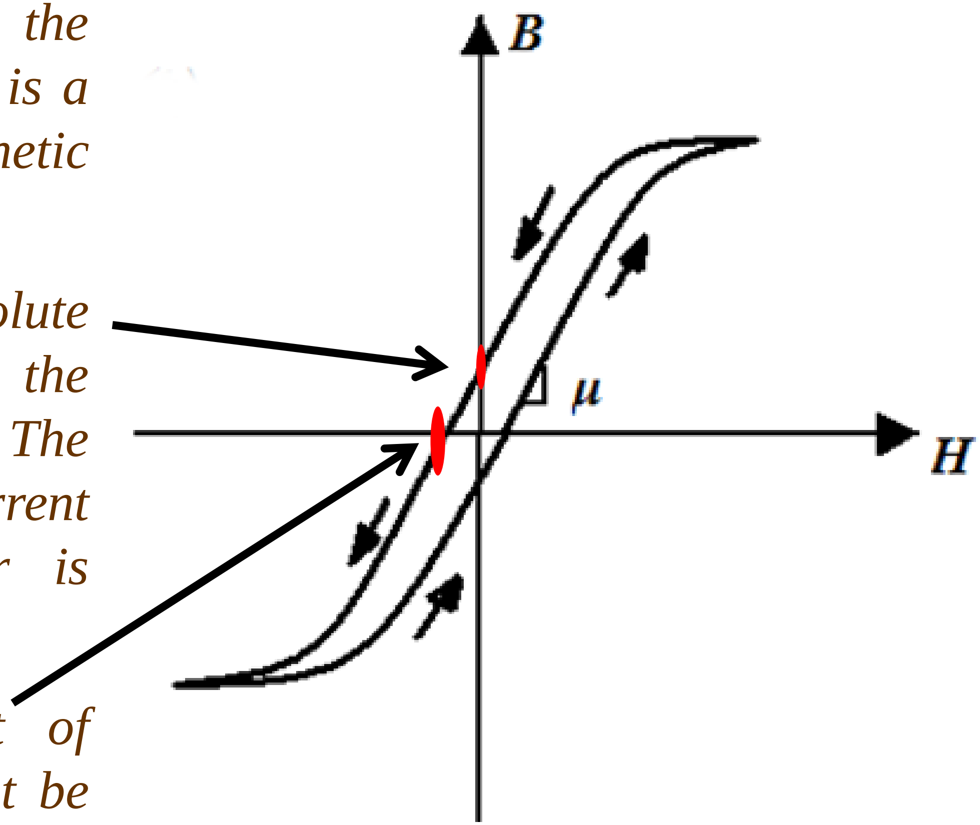


For square wave or rectangular wave excitation

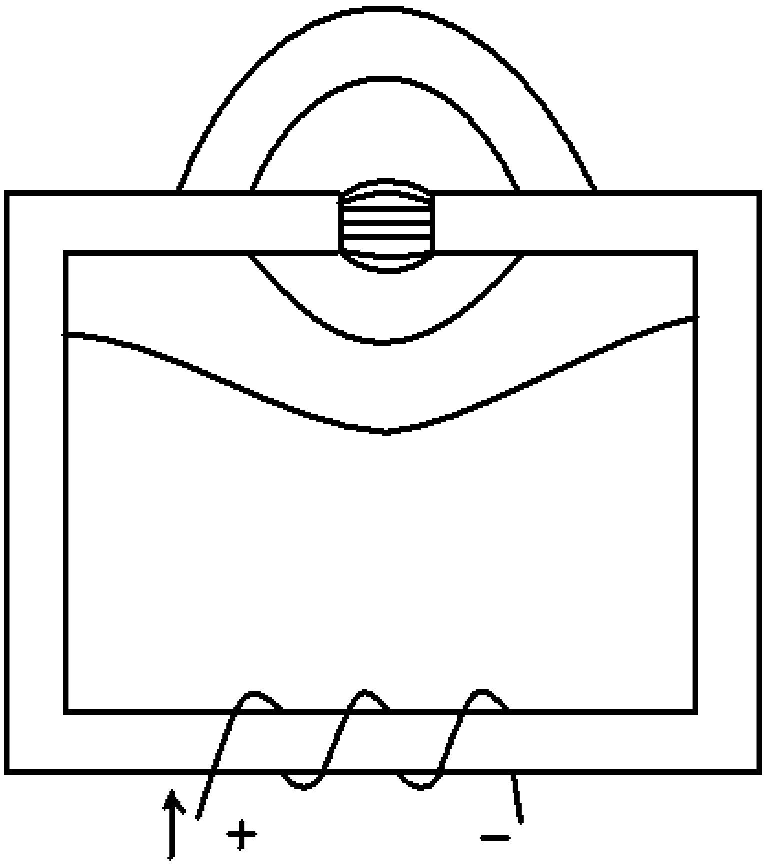
$$B_{max} = \frac{V_{peak}}{2\pi * f * A_c * N_p * 10^{-8}}$$

V_{peak} = peak applied voltage

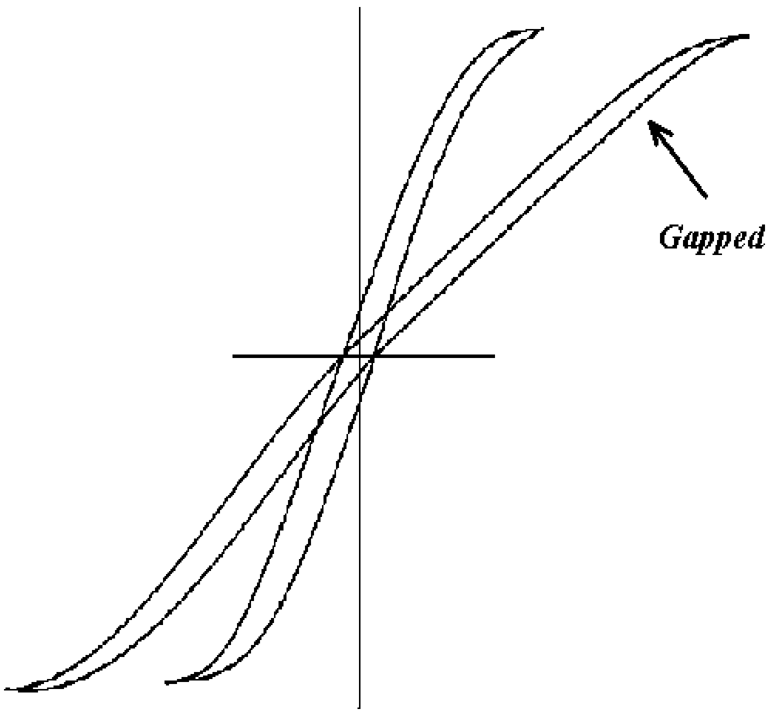
- *Four quadrant B-H curves are known as hysteresis curves. Note that the curve is open in the middle. This is a consequence of the magnetic microstructure.*
- ***Remanence** is defined as the absolute value of the magnetic field when the applied voltage is removed. The remnant field can cause inrush current problems when the transformer is re-energized*
- ***Coercive Force** - The amount of reverse magnetic field which must be applied to a magnetic material to make the magnetic flux return to zero.*



Effect of Air Gap



Inductor With An Air Gap



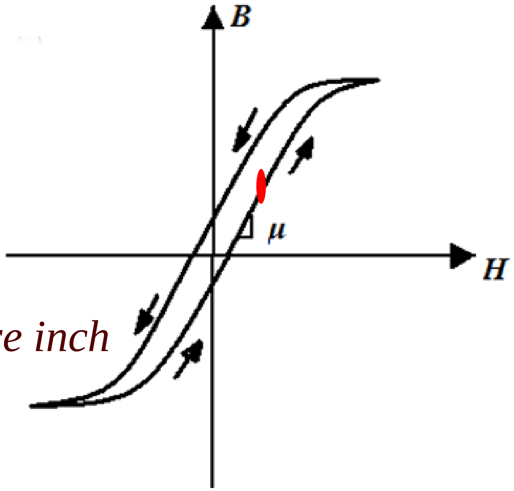
B-H Loop

Why We Use Air Gaps

- They are unavoidable in many cores
- In an inductor they permit increased energy storage for a given B by reducing the effective permeability
- Air gaps also stabilize the inductance value for both bias and manufacturing variations
- In general gaps are undesired in transformers but very useful in inductors
- An air gap may be discrete or distributed

For the 480V, 600kVA transformer

$$i_{max} = \frac{10^3 * h * A_c * ((B_r + 2 * B_{max}) - 130)}{3.2 * N_p * A_s}$$



i_{max} = maximum instantaneous current in amperes

h = the length of the coil in inches=40

A_c = the crossectional area of the core in sq inches=46.5

B_{max} = Maximum flux density=10,500G=1.05T=68 kilolines per square inch

B_r = residual flux density in kilolines (Maxwells) per square inch

= 60% of 1.05T, expressed as 41 kilolines per square inch

N_p = number of primary turns=60

A_s = effective square inches of the air-core magnetic field=69.4

Example $I_{fl} = \frac{600kVA}{\sqrt{3} * 480V} = 722A$, the inrush current is

$$i_{inrush} = \frac{10^3 * 40 * 46.5 * ((41 + 2 * 71) - 130)}{3.2 * 60 * 69.4} = 6.56kA$$

This is about 9X the transformer full load (operating) current

Reduce the inrush current by increasing the number of primary turns and/or increasing the effective area of the air-core magnetic field

Transformer Losses

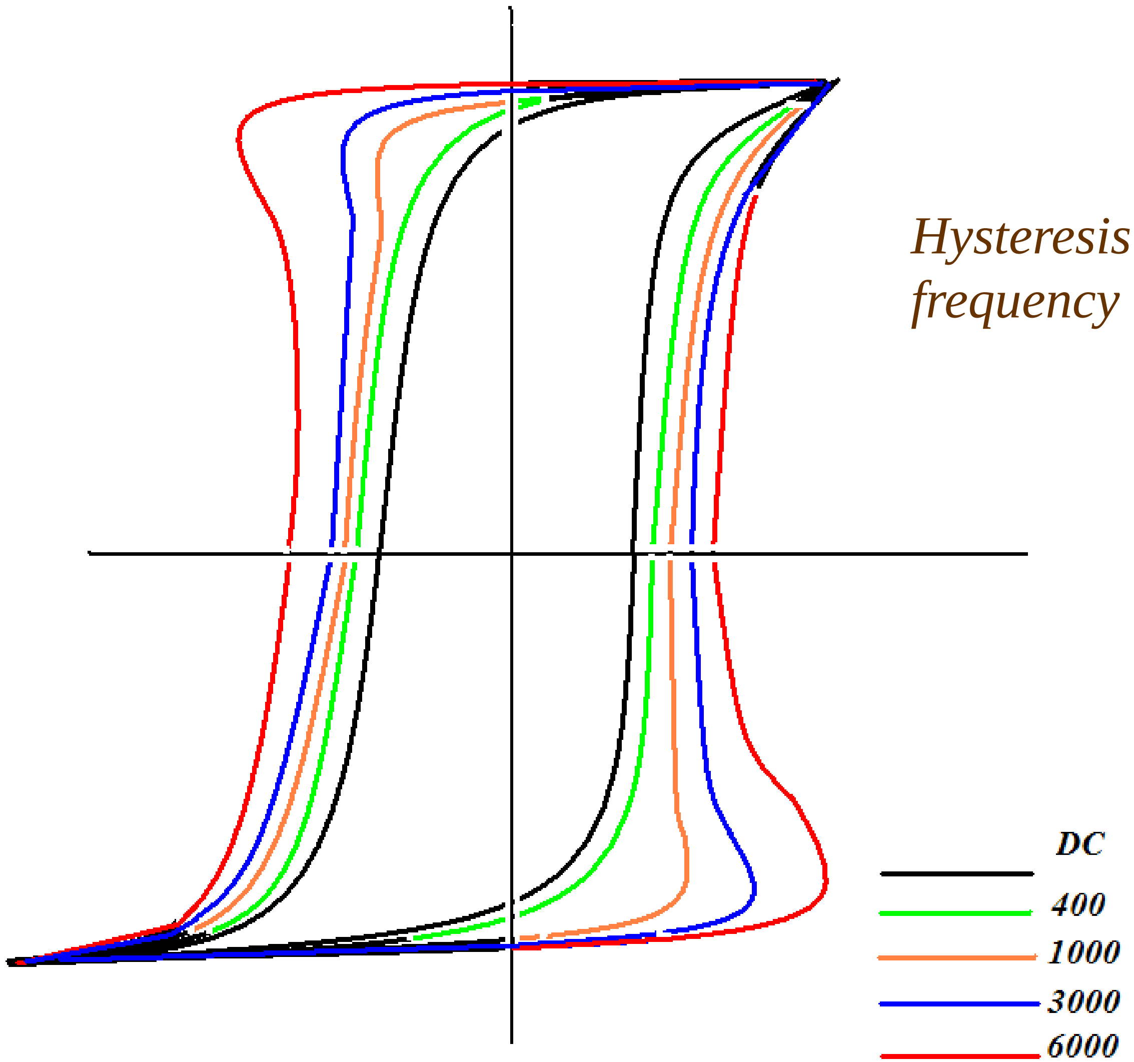
There are always energy losses in transformers. These energy losses generate heat in the form of core losses and winding losses. The losses are from the following sources:

1. *Hysteresis loss from sweeping of flux from positive to negative and the area enclosed by the loop is the loss. Hysteresis loss is due to the energy used to align and re-align the magnetic domains. The smaller the loop area, the smaller the energy loss per cycle*

2. *Eddy current loss from the circulating currents within the cores due to flux – generated voltages.*

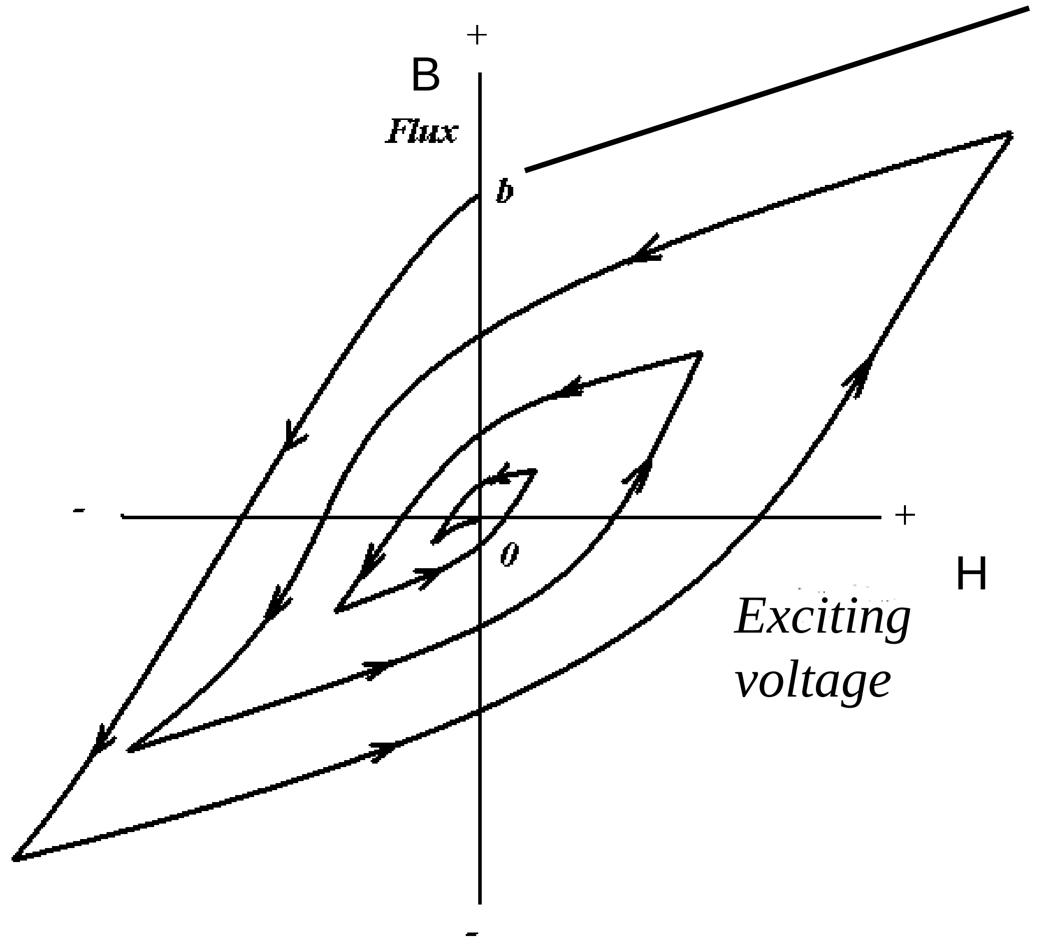
3. *Copper or winding loss. This is also dependent on the wire size, switching frequency, etc. Skin effect and proximity effect will contribute to this loss.*

Effect of Frequency on B-H Characteristics



Hysteresis increases as frequency increases

Demagnetization Or Degaussing



Removing residual magnetism from a ferromagnetic circuit by using decreasing excitation

Skin Effect

- *As the frequency of a given ac current in a conductor is increased, the power dissipation increases*
- *We ascribe this to an increase in ac resistance of the conductor but in actuality it is due to a rearrangement of the current distribution within the conductor*
- *The increase in loss is due to a tendency for the current to concentrate on the perimeter of the conductor rather than being uniform over the conductor area as it would be at dc*
- *This effect becomes more severe as frequency is increased*
- *This is called "skin effect"*

$$\delta = \frac{1}{\sqrt{\pi \mathbf{f} \mu \sigma}} \quad \textbf{\textit{meters}}$$

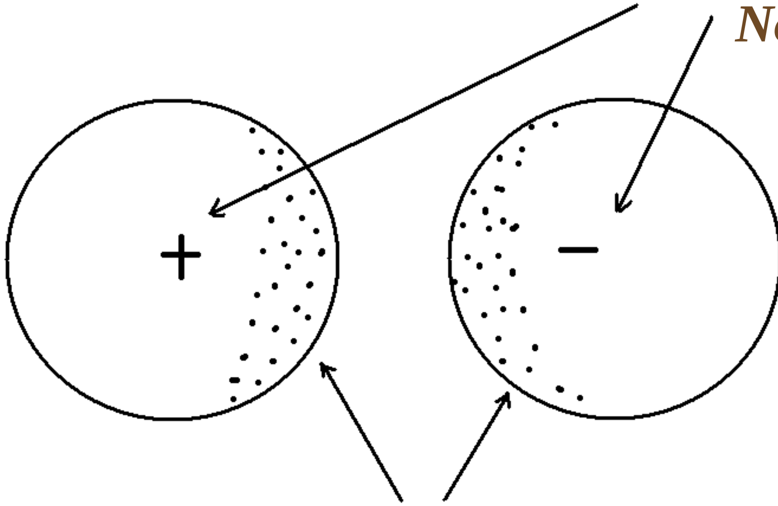
63% of the current is carried in this depth.

Proximity Effect

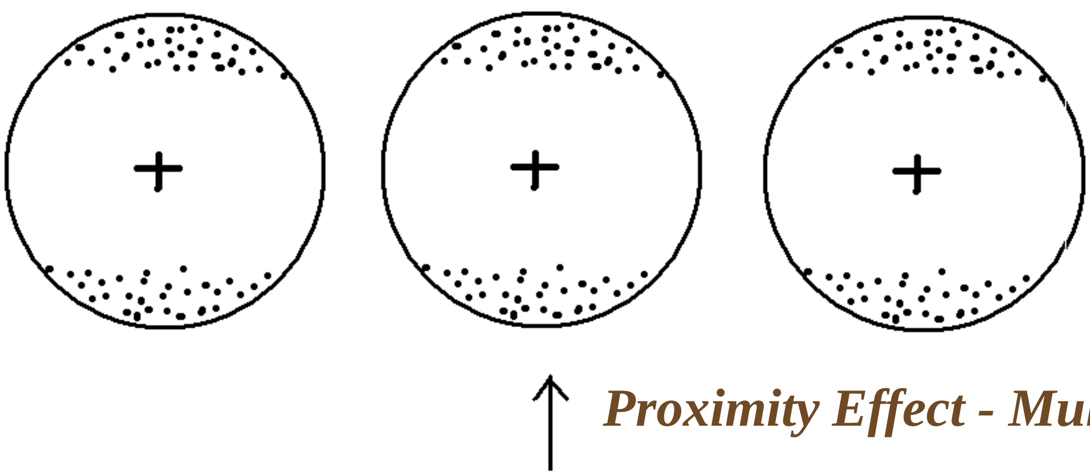
- *A current carrying conductor will generate a magnetic field*
- *This field can induce eddy currents in nearby conductors, increasing losses in addition to any skin effect. The eddy currents obey Lenz's Law. They flow in a direction that reduces the flux in the conductor*
- *This is referred to as "proximity effect"*
- *In a transformer or inductor, the inner windings operate in a field created by the outer windings*
- *This can also limit the conductor size*
- *As a general rule the wire diameter or the layer thickness is usually less than twice the skin depth at the operating frequency. For multi-layer windings wire diameters of less than 0.5 skin depth may be required.*

Proximity Effect

Note Opposing Currents



Current Concentrates At One Side



Proximity Effect - Multiple Parallel Wires

Inductors

Purposes

- *Used as filters for smoothing power supply ripple*
- *Used as fault current limiting reactors in AC power currents*
- *Used to limit di/dt in certain pulsed circuits*

Requirements

- *Must carry high DC current*
- *Must select core size that is able to store the required magnetic energy (volt-seconds)*
- *An air gap is sometimes employed to extend DC current capability without saturating. Iron and Ferrites are manufactured with distributed air gaps.*

Basic Equation for An Inductor

$$L = \frac{\mu_0 \mu_r N^2 A_c}{\mu_r l_g + l_c}$$

where

N = *the number of winding turns (dimensionless)*

A_c = *the core cross sectional area in* m^2

l_c = *the length of the magnetic path in the core in m*

l_g = *the effective length of the air gap in m*

μ_r = *core material permeability under the operating conditions (dimensionless)*

$$\mu_0 = \frac{4\pi * 10^{-7}\,H}{m}$$

Section 10 - Controls

Kirchoff's current law - sum of all current into a node is 0

Kirchoff's voltage law - sum of all voltages around a loop is 0

Voltage-current relations across passive elements

$$V = R * I \qquad V = L * \frac{di}{dt} \qquad I = C\frac{dv}{dt}$$

$$v(t) = Ri(t) + L\frac{di(t)}{dt}$$ *Real magnet with R and L components*

Represent the current i(t) as a complex exponential

$i(t) = I\,e^{j\omega t}$ *then the equation for v becomes*

$$Ve^{j\omega t} = R\,I\,e^{j\omega t} + L\,j\omega I\,e^{j\omega t} = (R + j\omega L)\,I\,e^{j\omega t}$$

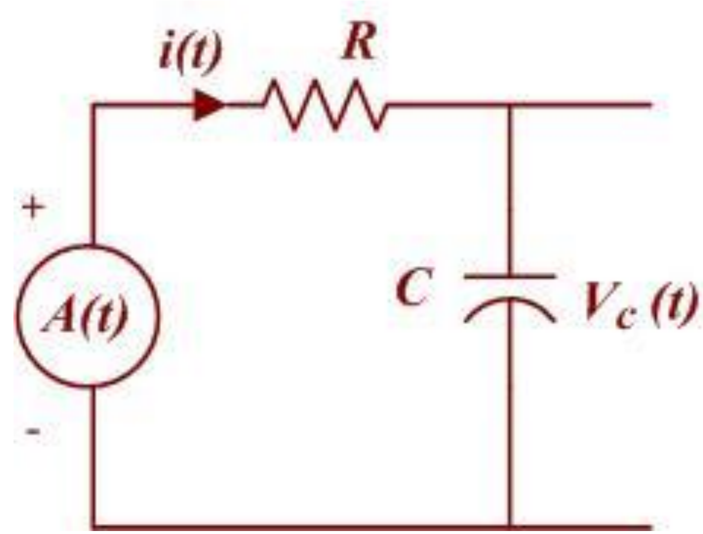
$I\,e^{j\omega t}$ *is the eigenfunction*

$(R + j\omega L)$ *is the eigenvalue, which, is the impedance,* $Z(\omega)$

$$KVL \quad -A(t)+R\,i(t)+v_c(t)=0 \qquad But\ i(t)=C\frac{dv_c(t)}{dt}$$

System equation

$$RC\frac{dv_c(t)}{dt}+v_c(t)=A(t) \qquad Let\ RC=\tau$$



Solution

$$v_c(t)=v_c(0)e^{-\frac{t}{\tau}}+\tau^{-1}e^{-\frac{t}{\tau}}\int_0^t A(u)e^{\frac{u}{\tau}}\,du$$

For the case when A is constant

$$v_c(t)=\left[v_c(0)e^{-\frac{t}{\tau}}+A(1-e^{-\frac{t}{\tau}})\right]$$

This is now in the form of an initial value multiplied by an eigenfunction and an input multiplied by the same eigenfunction

Repeat the same problem using Laplace transforms

$$C\frac{dv_c(t)}{dt} = \frac{\left[-v_c(t)+A(t)\right]}{R}$$

Transform both sides

$$C\left[sV_c(s)-v_c(0)\right] = -\frac{1}{R}V_c(s)+\frac{1}{R}A(s)$$

$$\left(sC+\frac{1}{R}\right)V_c(s) = Cv_c(0)+\frac{1}{R}A(s)$$

$$V_c(s) = \frac{1}{s+\tau^{-1}}v_c(0)+\frac{\tau^{-1}}{s+\tau^{-1}}A(s) \qquad let\ \tau^{-1}=\alpha$$

For the case when A is constant

$$= \frac{1}{s+\alpha}v_c(0)+A\frac{1}{s}\frac{\alpha}{s+\alpha}$$

Take the inverse transform

$$v_c(t) = v_c(0)e^{-\alpha t}+A(1-e^{-\alpha t})$$

$$v_c(t) = v_c(0)e^{\frac{-t}{\tau}}+A(1-e^{\frac{-t}{\tau}})$$ *Same result as on the previous page*

Take the inverse transform to obtain

$$v_c(t) = v_c(0)e^{-\frac{t}{\tau}} + A\left(1 - e^{-\frac{t}{\tau}}\right), \text{ as before}$$

From the transform equation

$$V_c(s) = \frac{1}{s+\tau^{-1}} v_c(0) + \frac{\tau^{-1}}{s+\tau^{-1}} A(s)$$

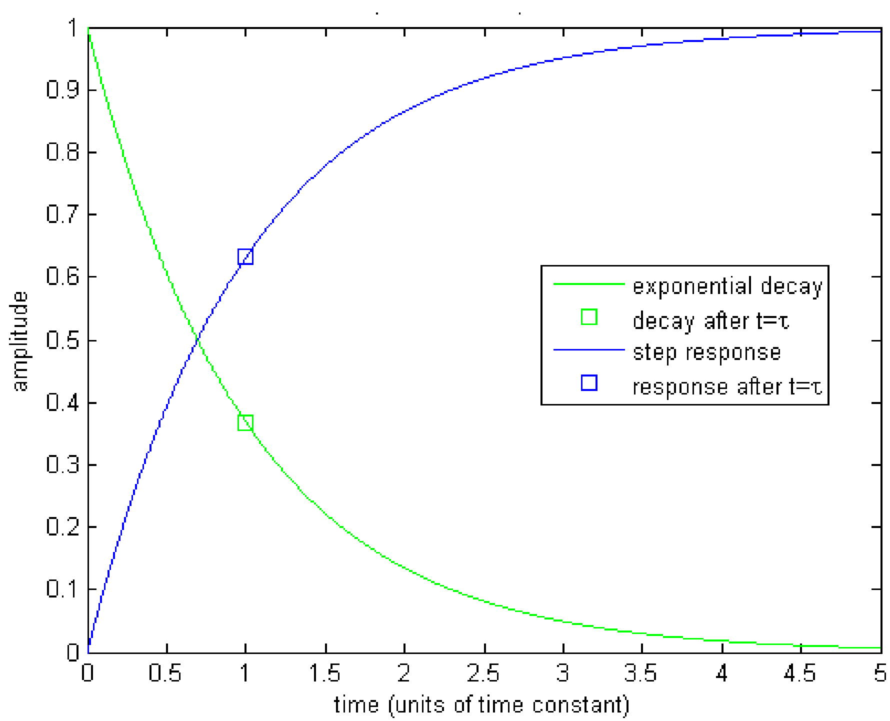
we can immediately read off the system transfer function

as the ratio of $\dfrac{V_c(s)}{A(s)} = \dfrac{\tau^{-1}}{s+\tau^{-1}}$ *when the initial conditions are zero.*

We also see that both the transfer function and the response to the initial conditions have the same poles and therefore similar frequency characteristics

- *Dynamics are determined by the numerator and denominator of transfer function*
- *The values of s for which the numerator or denominator vanishes are called "zeroes" and "poles", respectively*
- *One pole circuits all have the same shape response and depend only on the time constant, τ = RC or L/R*
- *A one pole circuit rises to 63% or decays to 37% of its final value at t= τ*

$$H(s) = \frac{\tau^{-1}}{s + \tau^{-1}}$$



- Since we will analyze our systems primarily in the frequency domain, it is important to understand the properties of a one pole system as a function of frequency.
- We can calculate the transfer function using algebra on the system impedances

$$H(j\omega) = \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}}$$

$$= \frac{\tau^{-1}}{j\omega + \tau^{-1}}$$

$$= \frac{1}{1 + j\omega\tau}$$

$$\text{Magnitude} \qquad \left|H(j\omega)\right| = \frac{1}{\sqrt{1+(\omega\tau)^2}}$$

$$\left|H(j\omega)\right|_{dB} = 20\log_{10}\left|H(j\omega)\right|$$

$$= -10\log_{10}\left[1+(\omega\tau)^2\right]$$

$$\cong 0 \quad \text{for } \omega\tau << 1$$

$$\text{3 dB (half-power) point} = -10\log_{10} 2 \quad \text{for } \omega\tau = 1$$

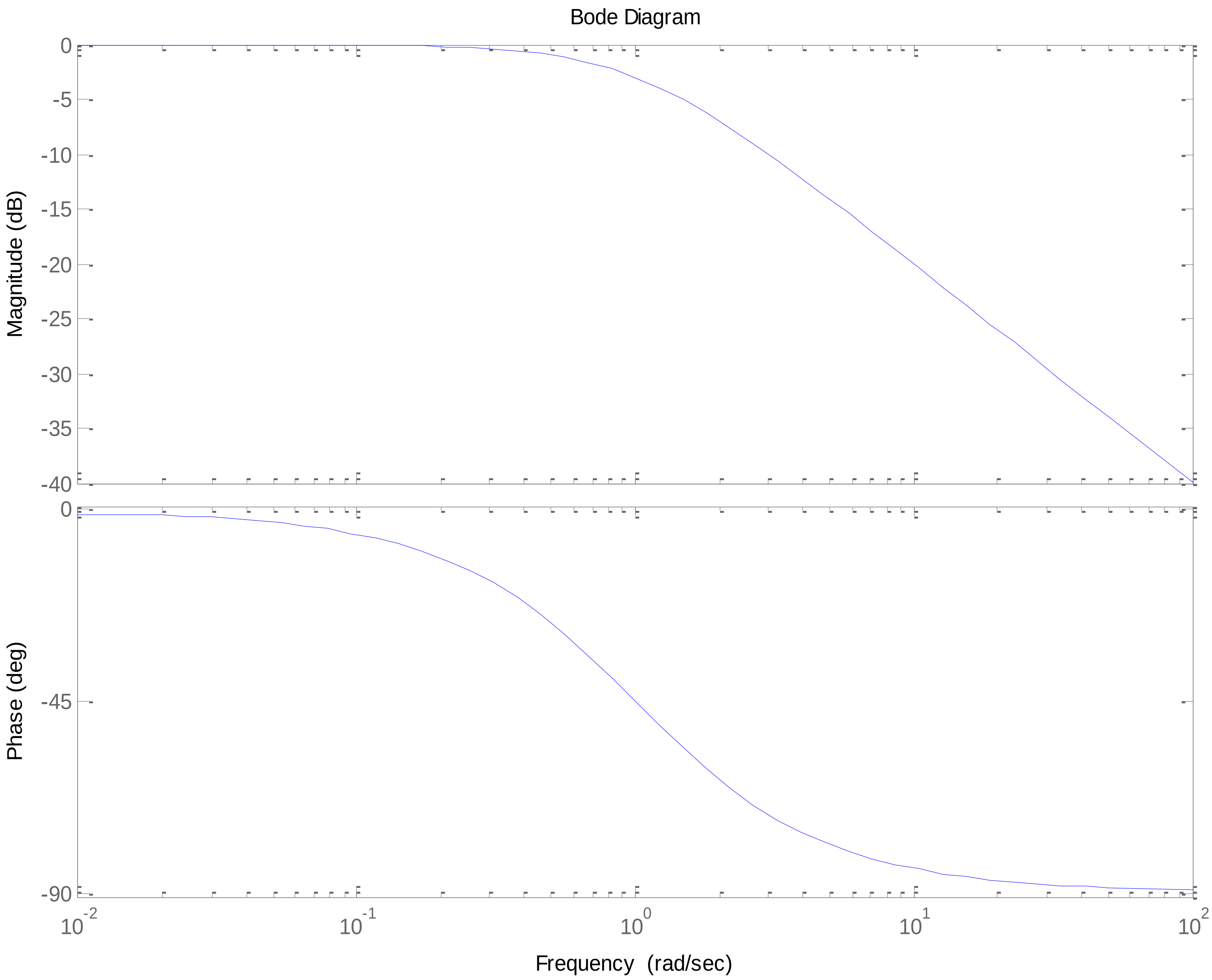
$$\text{20 dB per decade attenuation} \cong -20\log_{10}\omega - 20\log_{10}\tau \quad \text{for } \omega\tau >> 1$$

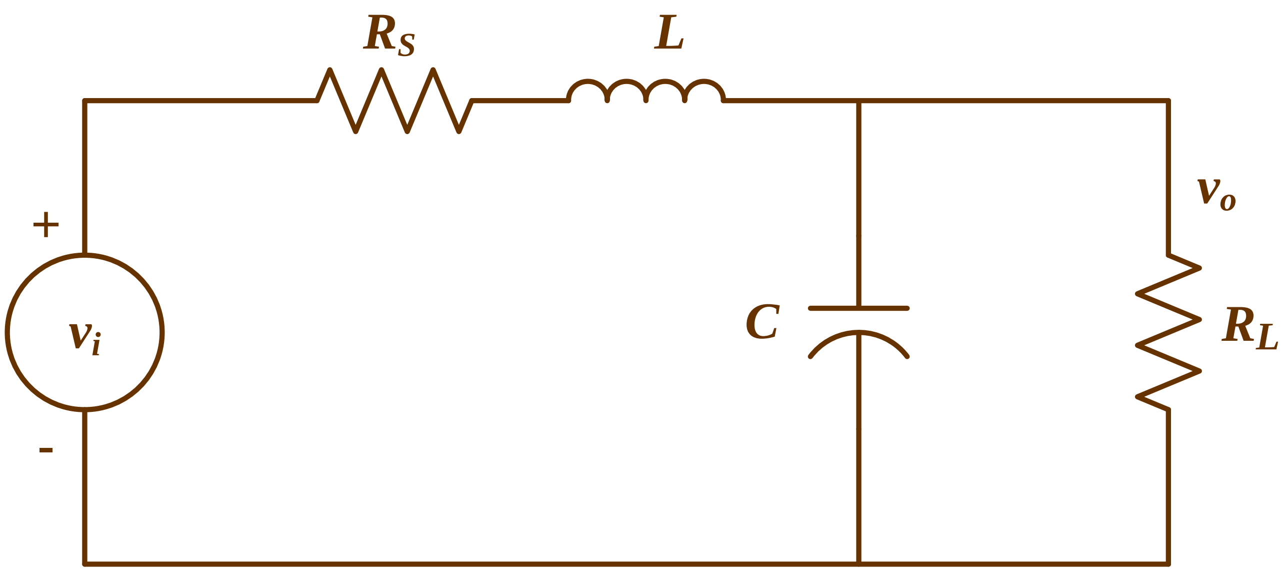
$$\text{Phase} \qquad \angle H(j\omega) = -\arctan(\omega\tau)$$

$$\cong 0 \qquad \omega\tau << 1$$

$$= -45^0 \qquad \omega\tau = 1$$

$$\cong -90^0 \qquad \omega\tau >> 1$$


Bode Diagram
Magnitude (dB)
0
-5
-10
-15
-20
-25
-30
-35
-40
Phase (deg)
0
-45
-90
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Frequency (rad/sec)



$$Z_S = R_S + j\omega L = R_S + sL$$

$$Z_L = \frac{\frac{R_L}{j\omega C}}{R_L + \frac{1}{j\omega C}}$$

$$= \frac{\frac{R_L}{sC}}{R_L + \frac{1}{sC}}$$

Find transfer function of voltage divider

$$H(j\omega) = \frac{\dfrac{R_L / j\omega C}{R_L + 1/j\omega C}}{R_S + j\omega L + \dfrac{R_L / j\omega C}{R_L + 1/j\omega C}} = \frac{R_L}{-R_L LC\omega^2 + j\left(R_L R_S C + L\right)\omega + \left(R_S + R_L\right)}$$

$$= \frac{1}{LC}\frac{1}{-\omega^2 + j\left(R_S/L + 1/R_L C\right)\omega + \left(1 + R_S/R_L\right)\left(1/LC\right)} \qquad let\ \omega_0^2 = 1/LC$$

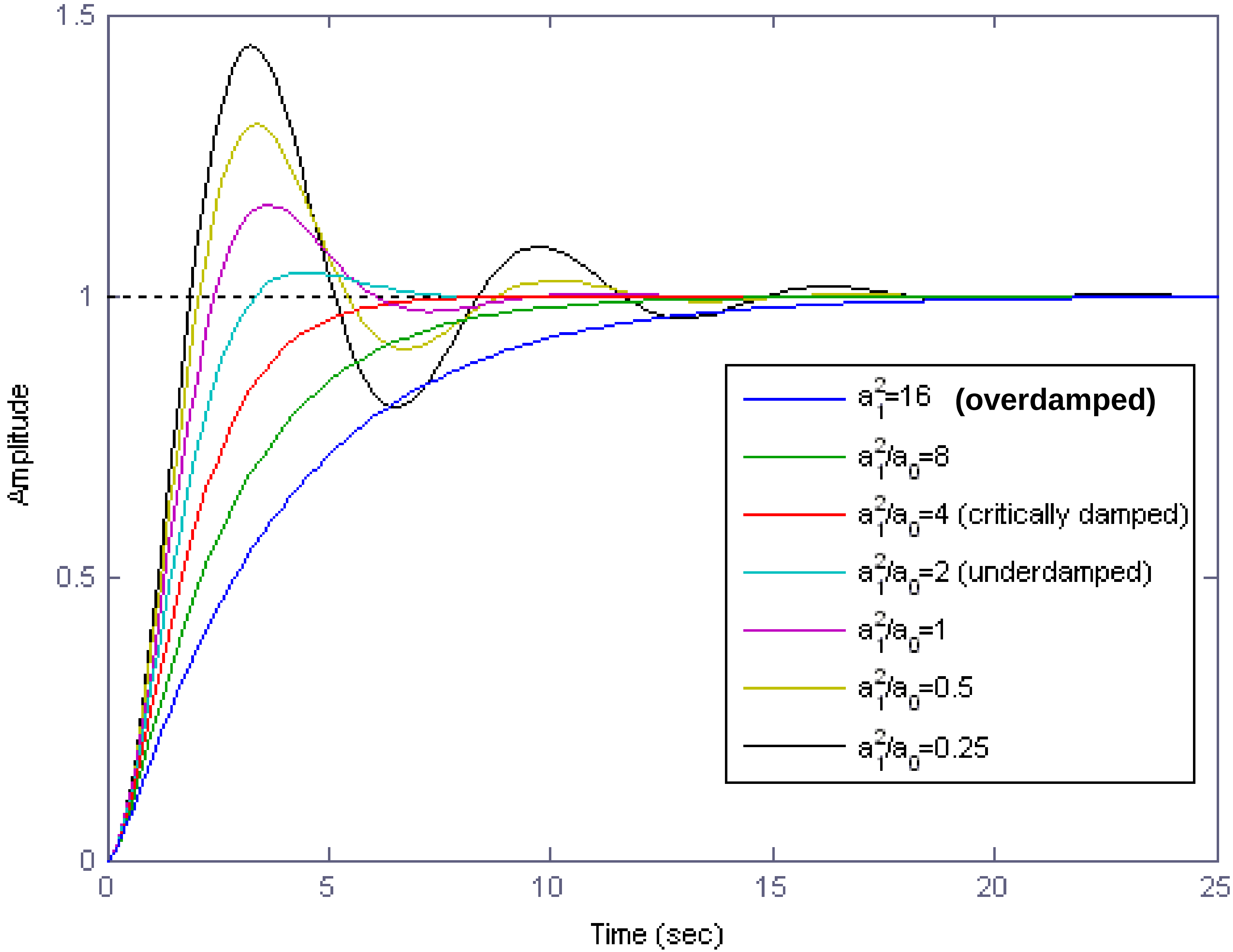
$$= \frac{\omega_0^2}{-\omega^2 + j\left(R_S/L + 1/R_L C\right)\omega + \left(1 + R_S/R_L\right)\omega_0^2}$$

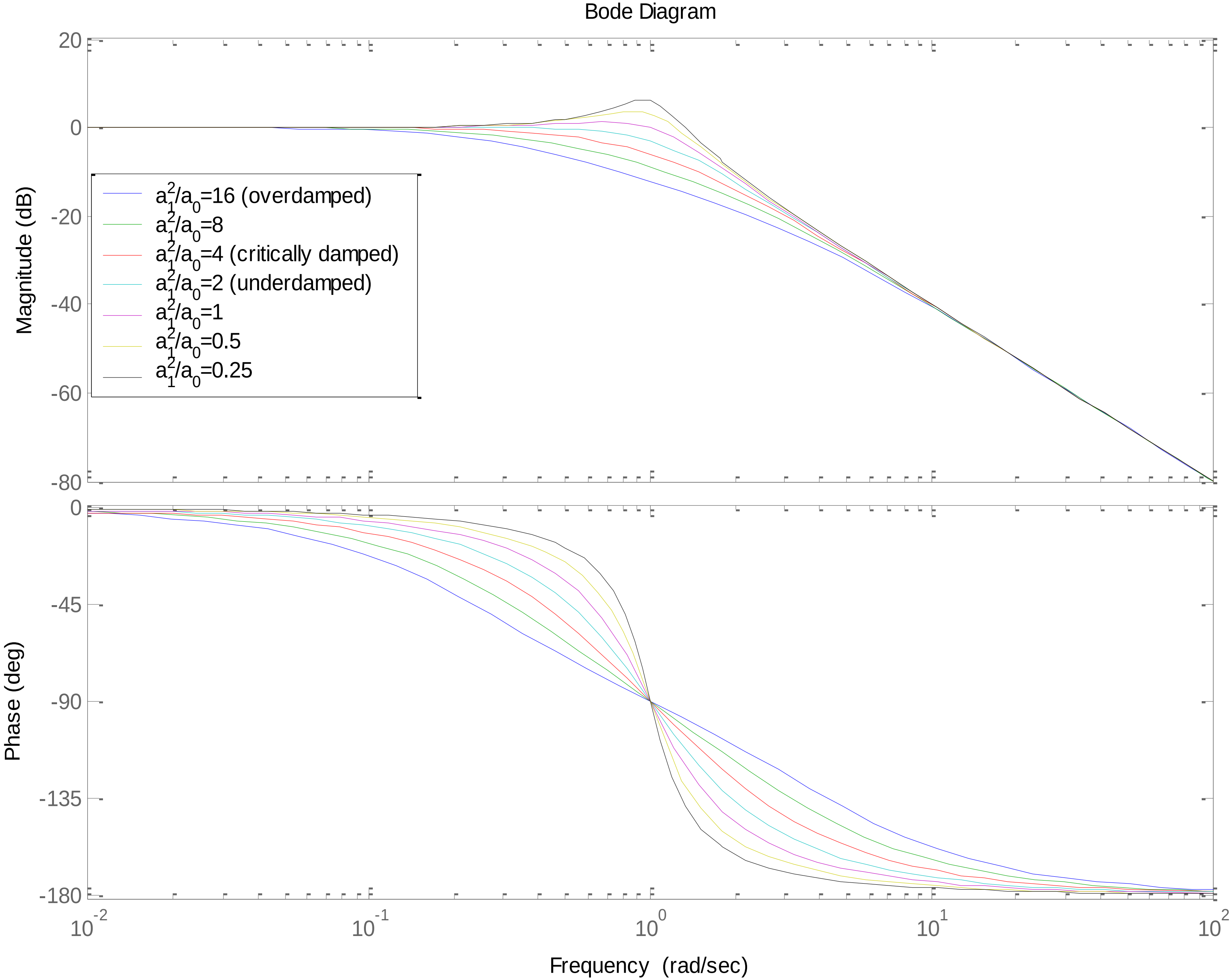
This has the form

$$H(s) = \frac{a_0}{s^2 + a_1 s + a_0} \qquad = \frac{a_0}{\left(s - s_1\right)\left(s - s_2\right)}$$

$$s_1 = -\frac{a_1}{2} + \sqrt{\left(\frac{a_1}{2}\right)^2 - a_0} \qquad s_2 = -\frac{a_1}{2} - \sqrt{\left(\frac{a_1}{2}\right)^2 - a_0}$$

- *Two pole circuits have two degrees of freedom. One degree sets the system time scale. One degree sets the stability parameter*
- *For a given time scale, the more stable the system, the slower its response. Two pole systems can be separated into three categories*
- *Over-damped system radical is positive, roots are real* $a_1^2 / a_0 > 4$
  - *Both poles are real*
  - *No oscillation in step response*
- *Critically damped system radical is zero, roots are real* $a_1^2 / a_0 = 4$
  - *Both poles are real and identical*
  - *Fastest step response with no oscillation*
- *Under-damped system radical is negative, roots are complex* $a_1^2 / a_0 < 4$
  - *Poles are complex conjugates of each other*
  - *Step response is faster than the other two, but has overshoot*


1.5
1
0.5
0
Amplitude
0
5
10
15
20
25
Time (sec)
a12=16 (overdamped)
a12/a0=8
a12/a0=4 (critically damped)
a12/a0=2 (underdamped)
a12/a0=1
a12/a0=0.5
a12/a0=0.25


Bode Diagram
Magnitude (dB)
20
0
-20
-40
-60
-80
a_1^2/a_0=16 (overdamped)
a_1^2/a_0=8
a_1^2/a_0=4 (critically damped)
a_1^2/a_0=2 (underdamped)
a_1^2/a_0=1
a_1^2/a_0=0.5
a_1^2/a_0=0.25
Phase (deg)
0
-45
-90
-135
-180
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Frequency (rad/sec)

Summarizing

- *Low and high frequency behavior is almost independent of a_1*
- *At low frequencies the magnitude is constant and the phase approaches 0^0*
- *At high frequencies the magnitude decreases 40 dB/decade (20 dB/pole) and the Phase approaches -180^0 (-90^0/pole)*
- *At ω_0 a_1 determines attenuation and phase slope*
- *Increased rise time and overshoot are the result of additional response near ω_0*
- *A resonant circuit is a lossless ($R_S = 0$ and $R_L = \infty$ in diagram) second order circuit often encountered in pulsed-power systems. Real systems have loss (and damping), but can be well approximated by resonant circuits*
- *The resonant frequency is* $f = \dfrac{1}{2\pi\sqrt{LC}}$

- *Bode plots are a standard way to present properties of feedback systems*
- *Each pole*
  - *Corresponds to a 6 dB/octave (20 dB/decade) roll-off in amplitude above the pole*
    - *Represent magnitude on log-log plot with a straight line that has a 6 dB/octave kink at the pole*
  - *Corresponds to a 90 degree phase shift at high frequencies*
    - *0 angle shift at* $f_c/10$
    - *-45 degree shift at* f_c
    - *-90 degree shift at* $10^* f_c$

- *Complex conjugate poles are slightly more complex*

  Far from the poles they have the same behavior as two real poles

  - *12 dB/octave*
  - *180 degree phase shift*

  Near the pole frequency, their behavior depends on the damping factor of the complex pole pair

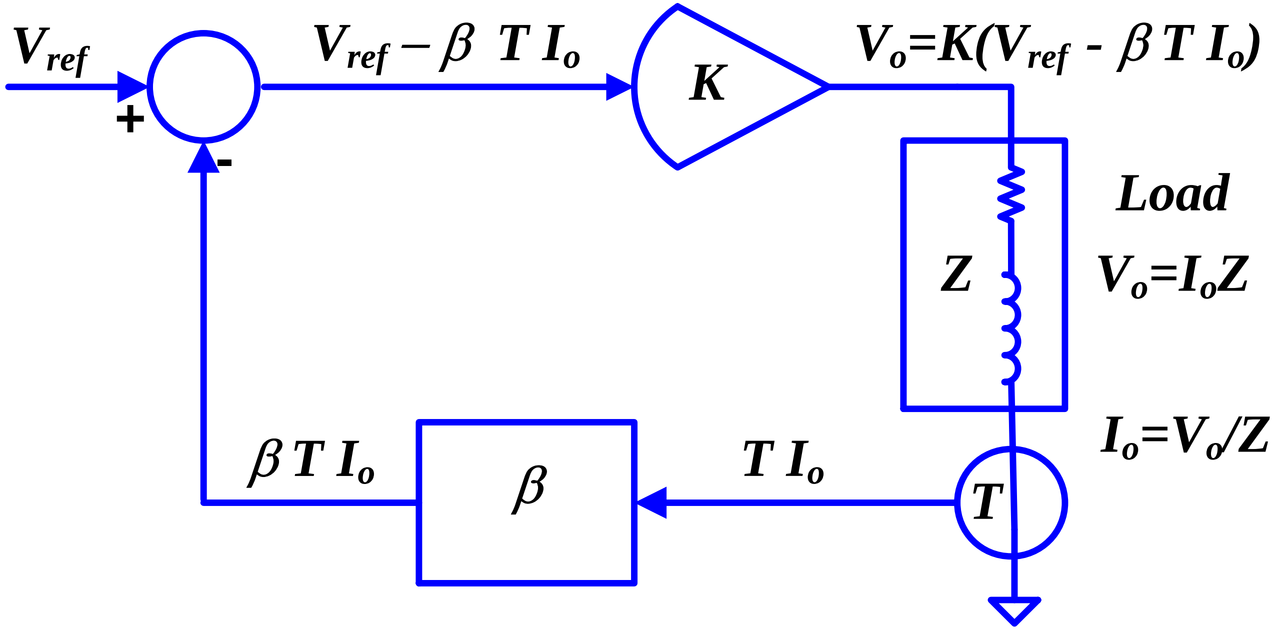
- *Similar rules exist for zeros*

  6 dB/octave increase in gain above zero

  +45 degree phase shift at the zero

- *Purpose of a power supply is to provide stable power*
- *Use feedback circuits to*
  - *Regulate a system, that is, keep the output fixed at a desired constant value*
  - *Control a system, that is, force the output to follow a variable control input*

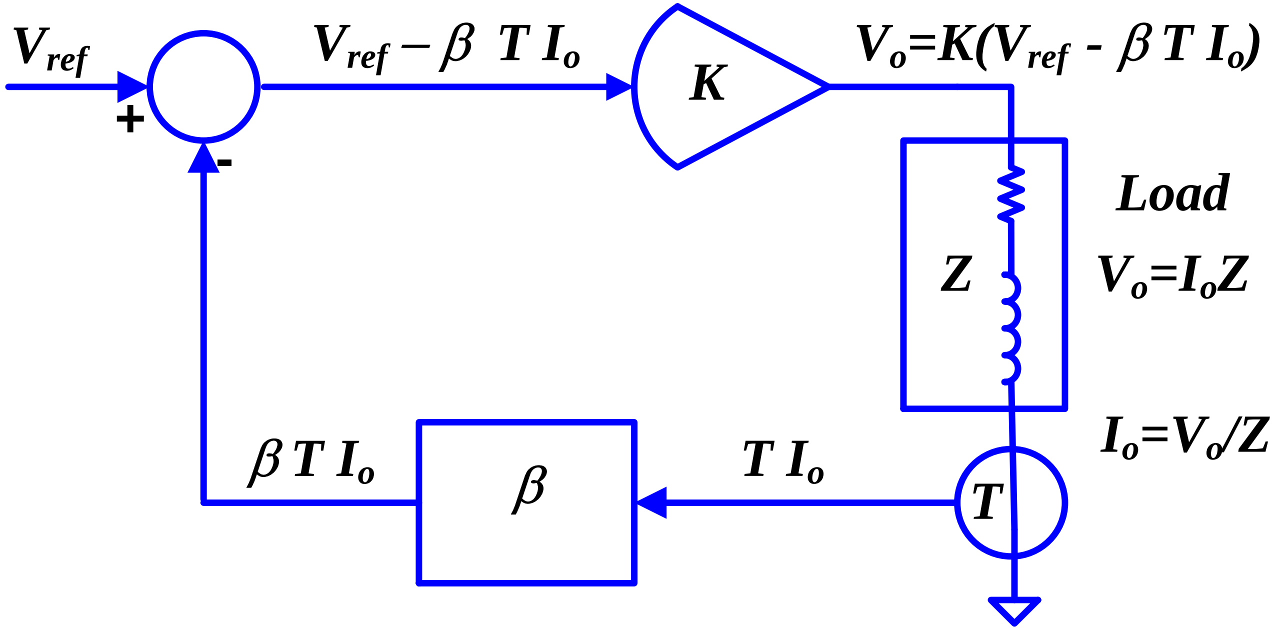
Stability - Introduction



$$V_o = K\,(V_{ref} - \beta\ T\ I_o\,)$$

$$I_o Z = K\,(V_{ref} - \beta\ T\ I_o\,)\ \textit{rearranging gives}\ \frac{I_o}{V_{ref}} = A_{CL} = \frac{K / Z}{1 + \beta\ T\ K / Z}$$

- A_{CL} is called the closed loop gain
- For $\beta\ T\ K / Z >> 1$ $\qquad A_{CL} = \dfrac{1}{\beta\ T}$
- Power amplifier and load characteristics (K, Z) relatively unimportant, gain and stability dependent upon feedback loop β T



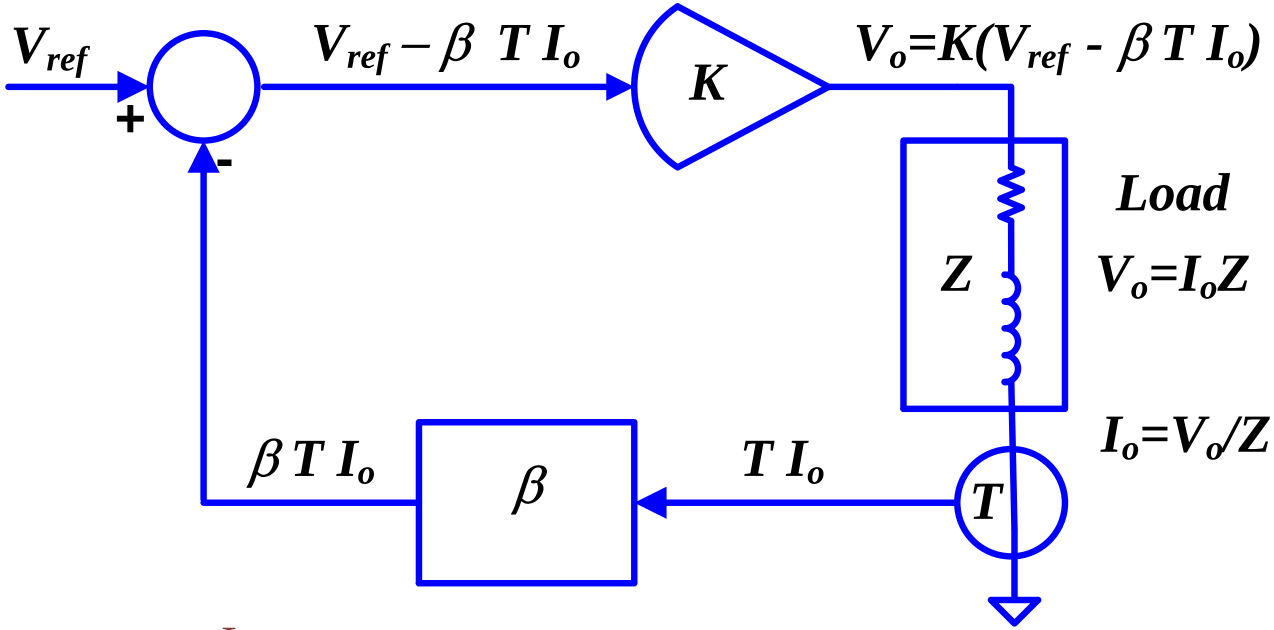
The feedback loop ensures the output always follows the input

$I_o = K/Z\ (Vref - \beta\ T\ I_o)$		
$Vref$	$Vref - \beta\ T\ I_o$	I_o
$Vref \downarrow$	$Vref - \beta\ T\ I_o \downarrow$	$I_o \downarrow$
$Vref \uparrow$	$Vref - \beta\ T\ I_o \uparrow$	$I_o \uparrow$
$I_o \downarrow$	$Vref - \beta\ TI_o \uparrow$	$I_o \uparrow$
$I_o \uparrow$	$Vref - \beta\ T\ I_o \downarrow$	$I_o \downarrow$

Three Types of Stability

- Stability against oscillation
- Stability against short and long-term output voltage or current drift
- Stability (Regulation) against rapid, short changes in line voltage or load characteristics

Stability Against Oscillation

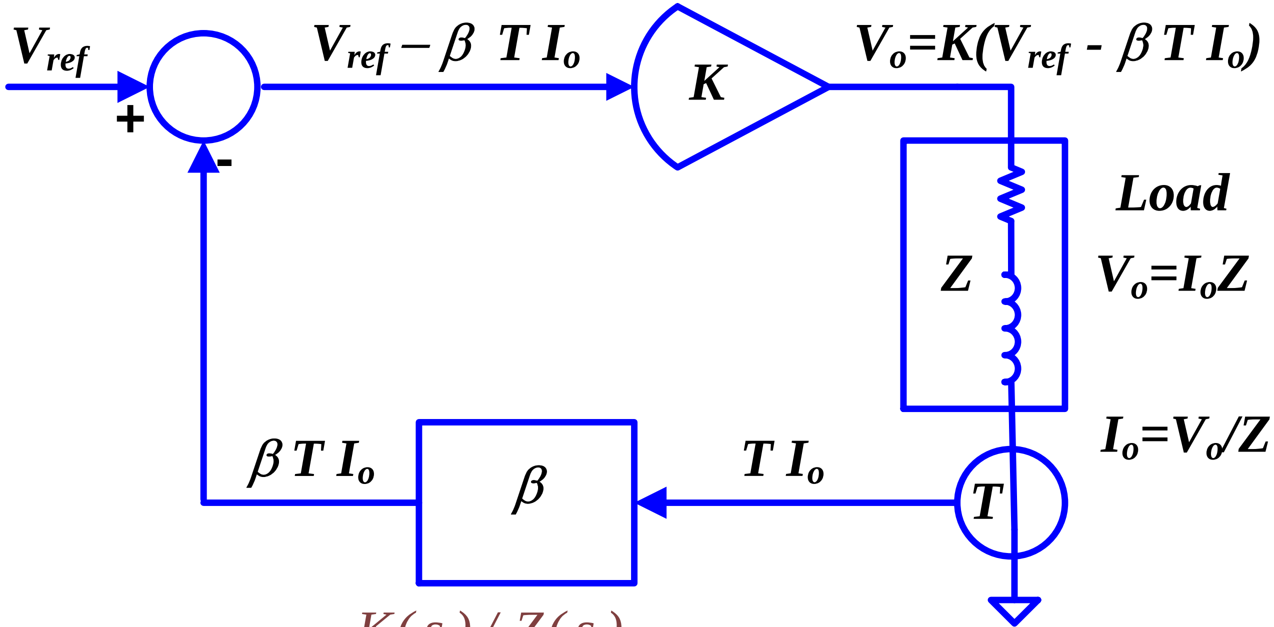


$$\frac{I_o}{V_{ref}} = A = \frac{K / Z}{1 + \beta\ T\ Z / K}$$

$$\frac{I_o(s)}{V_{ref}(s)} = A(s) = \frac{K(s) / Z(s)}{1 + \beta(s) T(s) Z(s) / K(s)}$$

All the elements of the transfer function, gain, or in this case, the transconductance, are all functions of frequency $s = j\,\omega = j\,2\,\pi\,f$

Stability Against Oscillation



$$\frac{I_o(s)}{V_{ref}(s)} = A(s) = \frac{K(s)/Z(s)}{1+\beta(s)T(s)K(s)/Z(s)}$$

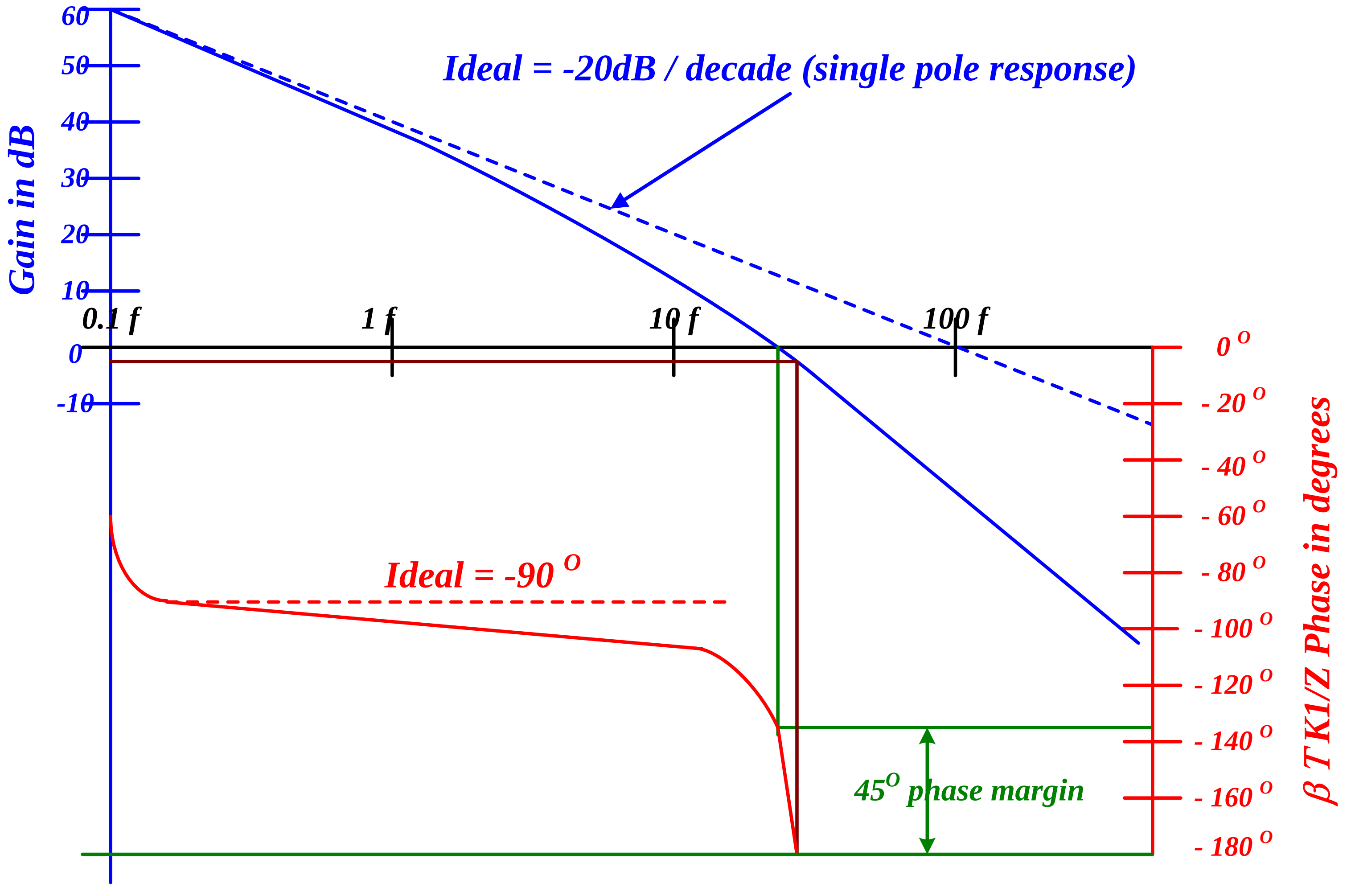
Very simply : 1+β(s) T(s)K(s)/Z(s) must not = 0 or approach 0 (avoid singularity)

β(s) T(s) K(s)/ Z(s) must not = -1 in order to avoid oscillations

$$|\beta|e^{j\alpha}\,|T|e^{j\beta}\,|K|e^{j\chi}\,/\,|Z|e^{j\varphi} = |\beta||T||K||1/Z|e^{j(\alpha+\beta+\chi-\varphi)}$$

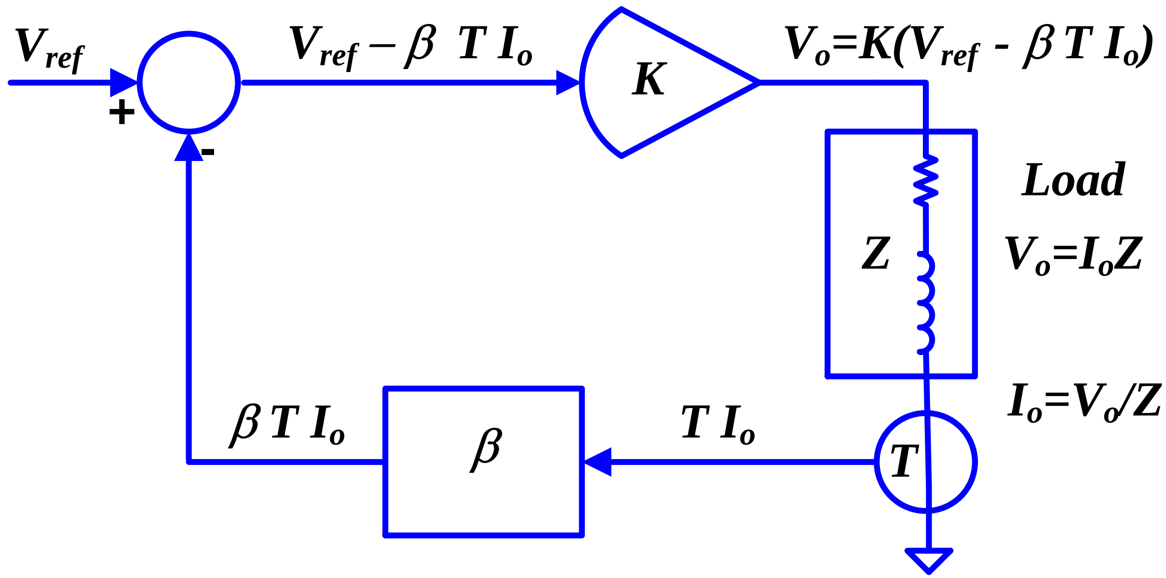
$$|\beta||T||Z||1/K| \neq 1 \quad \text{when} \quad \alpha+\beta+\chi-\varphi = \pm 180^{o}$$

Stability Against Oscillation



- For stability, the phase shift must be < 180 ^{O} when the |gain| =1
- For stability, the |gain| must be < 1 when the phase shift is 180 ^{O}

Factors Affecting Power Supply Drift Stability



Short-Term (24 hour) Stability - *essentially stability against cyclic or diurnal temperature changes.*

$$\frac{I_o}{V_{ref}} = A_{CL} = \frac{K/Z}{1+\beta\ T\,K/Z}$$

Since $\beta\ T\,K/Z >> 1,\quad \dfrac{I_o}{V_{ref}} = A_{CL} = \dfrac{1}{\beta\ T}$ $\quad$ *K is unimportant,*

stability primarily dependent on transductor T, feedback factor β*, and upon* V_{ref} *stability*

In most instances Vref and the error amplifier are temperature stabilized

Factors Affecting Short-Term (24 hour) Power Supply Drift Stability

- *The diurnal temperature cycle can be as much as 40 ^{o}F (22 ^{o}C). This globally affects the internal parts as well as the external setpoint*

- *All parts (resistors, capacitors, semiconductors, op-amps, etc) are temperature dependent.*

- *The load is also temperature dependent and is subject to the same diurnal changes*

- *The input line voltage will change during the course of the day as more premises load is consumed or shed*

Ensuring Short-Term Drift Stability

General

- *Use low-temperature coefficient parts or balance (+) coefficient parts with (-) coefficient parts*

- *Enclose the power supply in a controlled environment where temperature change is held to a minimum*

- *10 to 50 ppm attainable w/o temperature control (5 to 10 ppm) with temperature control*

For the read-back signal, use:

- *Precision, low-temperature coefficient current transductors (0.3 ppm / ^{O}C) with metal film burden resistor (0.9 ppm / ^{O}C) $\simeq$ 1.2 ppm / ^{O}C*
- *Precision, low-temperature coefficient resistors for current shunt or voltage read-back (10 ppm / ^{O}C)*

Stability - Zero Flux Current Transductors

LEM (was Danfysik)
Model 866
0 - ±600 A
±400 mA out
0.3 ppm / ^{O} C
DC – 100 kHz
10 kA / mS
Separate burden resistor

LEM (was Danfysok) Model 860 Series
0 - ±1000 A, ±2000 A, ±3000 A
±10 V out
0.3 ppm / ^{O} C
DC – 100 kHz
10 kA / mS

Stability - Isotek Model A-H, Manganin < 10 ppm/ ^{O}C Shunt Resistor

http://www.isotekcorp.com

Long-Term Stability

- *All parts are subject to aging.*
- *Resistors increase or decrease in value*
- *Capacitor dielectrics breakdown*
- *Capacitor electrolytes dry out or evaporate and leak*
- *Semiconductor bias points change*
- *Op-amp scale, linearity, monotonicity, gain and offsets change with time*

Factors That Affect Long-Term Stability

Stability Enhancement

- *Accelerate initial aging components prior to intended use by baking at elevated temperatures*

- *Accelerate aging by exposure to electron beam*

Factors that Affect Transient Stability (Regulation)

- *Two types of Regulation – Load and Line*
- *Classic definition of Load Regulation (0% is best)*

$$\%V_R = \frac{V_{NL} - V_{FL}}{V_{FL}} * 100\% \qquad \%I_R = \frac{I_{NL} - I_{FL}}{I_{FL}} * 100\%$$

- *Classic definition employing V_{NL} is usually not applicable. A limited version uses "decreased load or increased load" instead of a no-load condition*

$$\%V_R = \frac{V_{DL} - V_{FL}}{V_{FL}} * 100\% \qquad \%I_R = \frac{I_{DL} - I_{FL}}{I_{FL}} * 100\%$$

- *In addition, the recovery time for the power supply output voltage or current to return the original condition is also specified*

"The power supply shall have a voltage regulation of 0.5% for load changes of ± 5% from nominal with voltage recovery in ≤ 2 milliseconds"

Factors that Affect Stability (Regulation) Against Transient Effects

- *Line Regulation – Definition (HL= output voltage under high line, NL= output voltage under nominal line, LL = output voltage under low line)*

$$\%V_R = \frac{V_{HL} - V_{NL}}{V_{NL}} * 100\% \qquad \%I_R = \frac{I_{HL} - I_{NL}}{I_{NL}} * 100\%$$

$$\%V_R = \frac{V_{NL} - V_{LL}}{V_{NL}} * 100\% \qquad \%I_R = \frac{I_{NL} - I_{LL}}{I_{NL}} * 100\%$$

- *In addition, the recovery time for the power supply output voltage or current to return the original condition is also specified*

"The power supply shall have a voltage/current regulation of 0.5% for line changes of ± 5% from nominal with voltage/current recovery in ≤ 2 mS"

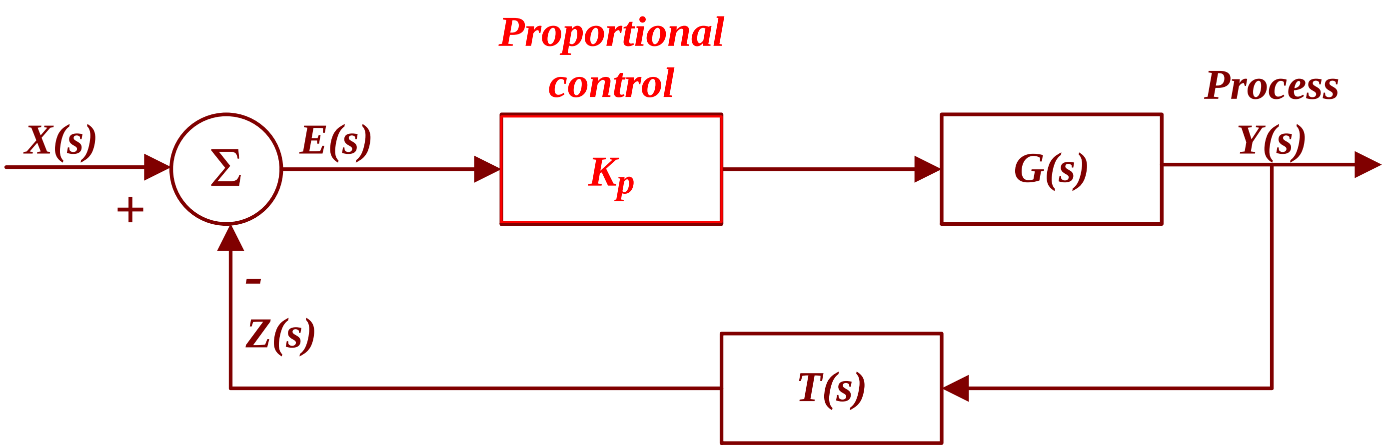
Factors that Affect Stability (Regulation) Against Transient Effects

The ability of a power supply to respond to a transient condition depends upon the speed, depth and duration of the transient. The transient can be mitigated by the use of:

- *Large filter capacitors and inductors in the input and output filters to maintain the input and output load voltage and current against line voltage changes and load changes..*
- *Employ fast regulating circuits. Regulating speed should be at least as fast as the fastest expected transient.*

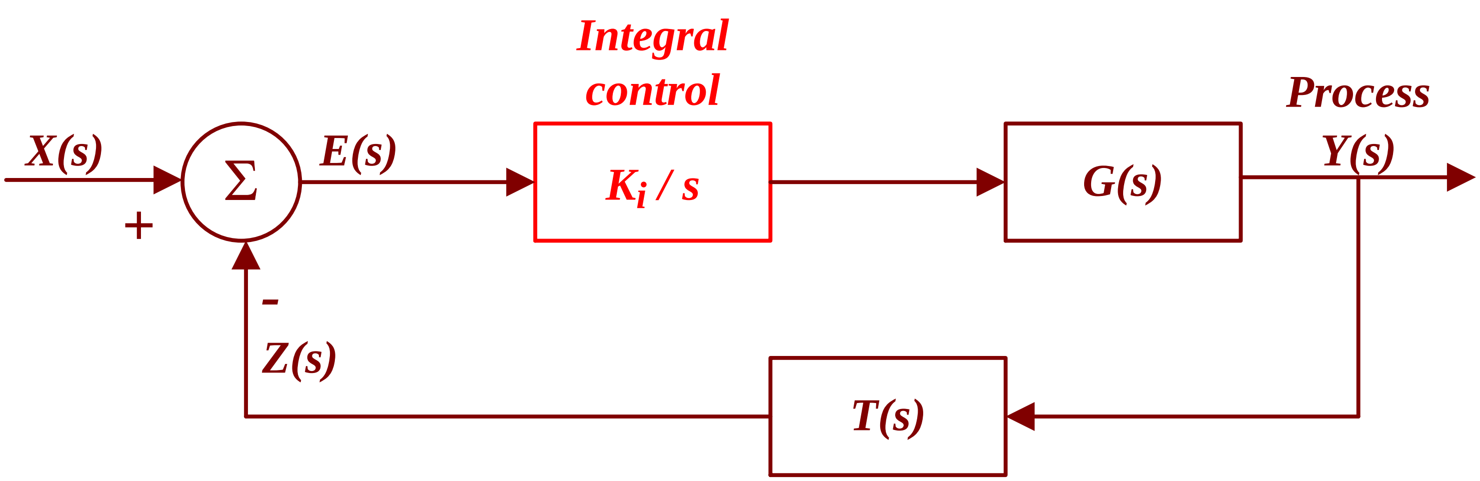
PID Loops - Proportional Control

- Earliest controllers proportional only
- Proportional control consists of just a gain
- It has good response to instantaneous changes in the process or other cause of error
- Control effort is the product of the error and a finite gain Kp
- Eventually effort is too small to reduce error to zero
- There is always an error - it can never be eliminated

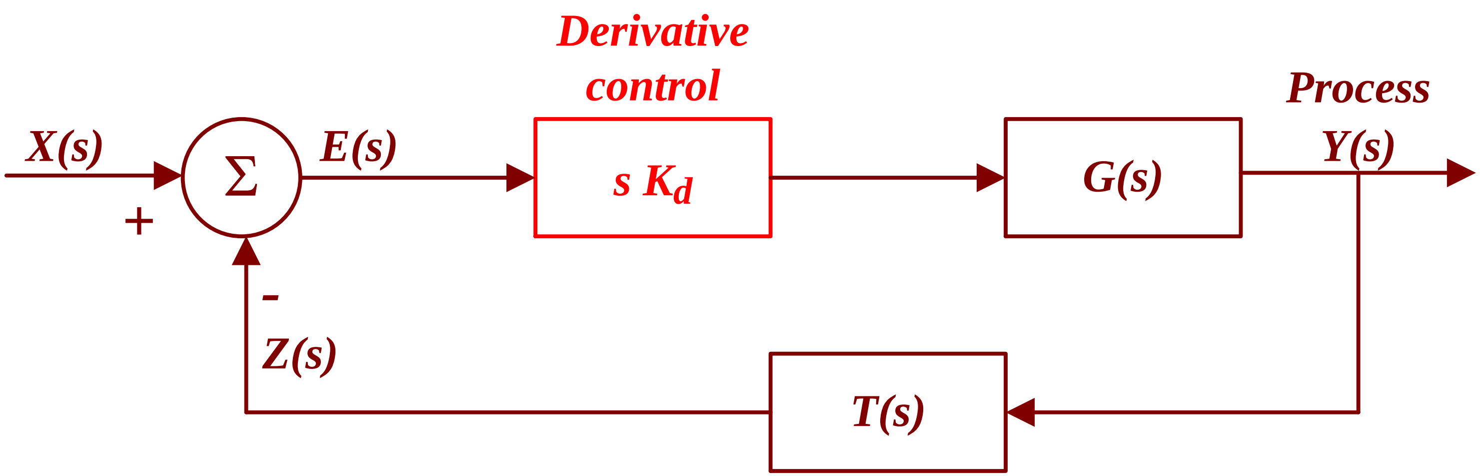


PID Loops - Integral Control

- *Integral control consists of a pure integrator*
- *The control effort is now* $\int e(t)dt$
- *Eliminates* DC *errors*
- *Limits high frequency response*
- *Introduces a phase delay that can cause sluggishness or oscillation*

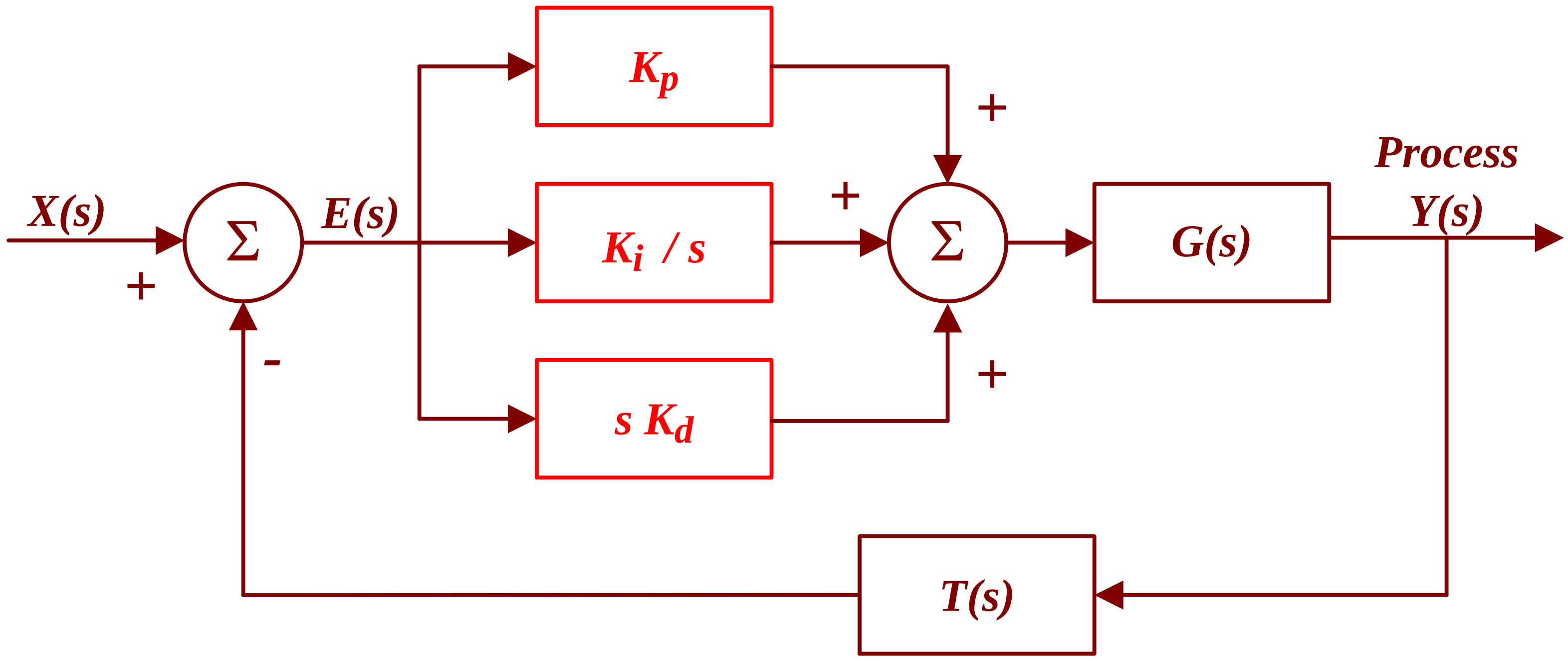


- *Responds to the change of the error signal*
- *Control effort increases with frequency of error signal* $s\,K_d$
- *Useful either to cancel a pole or to predict periodic behavior*
- *Can emphasize high frequency noise*



PID Loops - Summary

- *PID stands for Proportional, Integral, and Derivative control*
- *Standard, general purpose classical control element*
- K_p *general cancelling of error signals*
- K_i *eliminates DC error*
- K_d *provides nimble circuit for fast changes in the error signal or process*

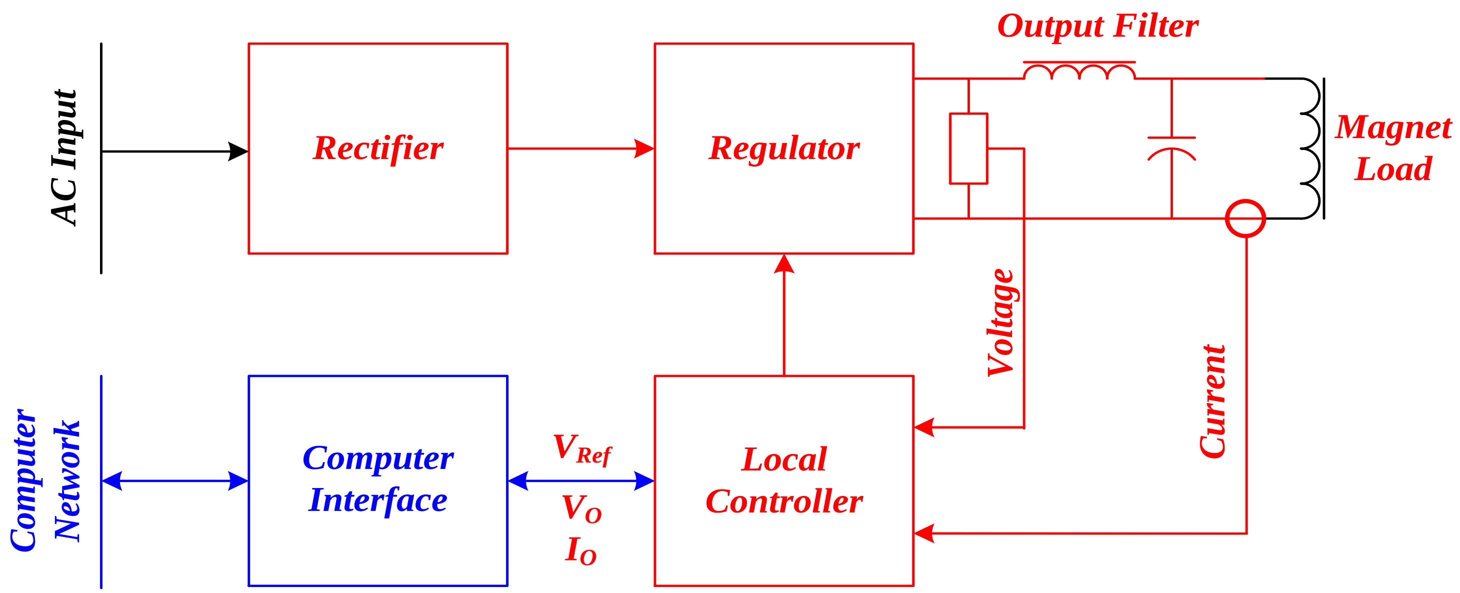


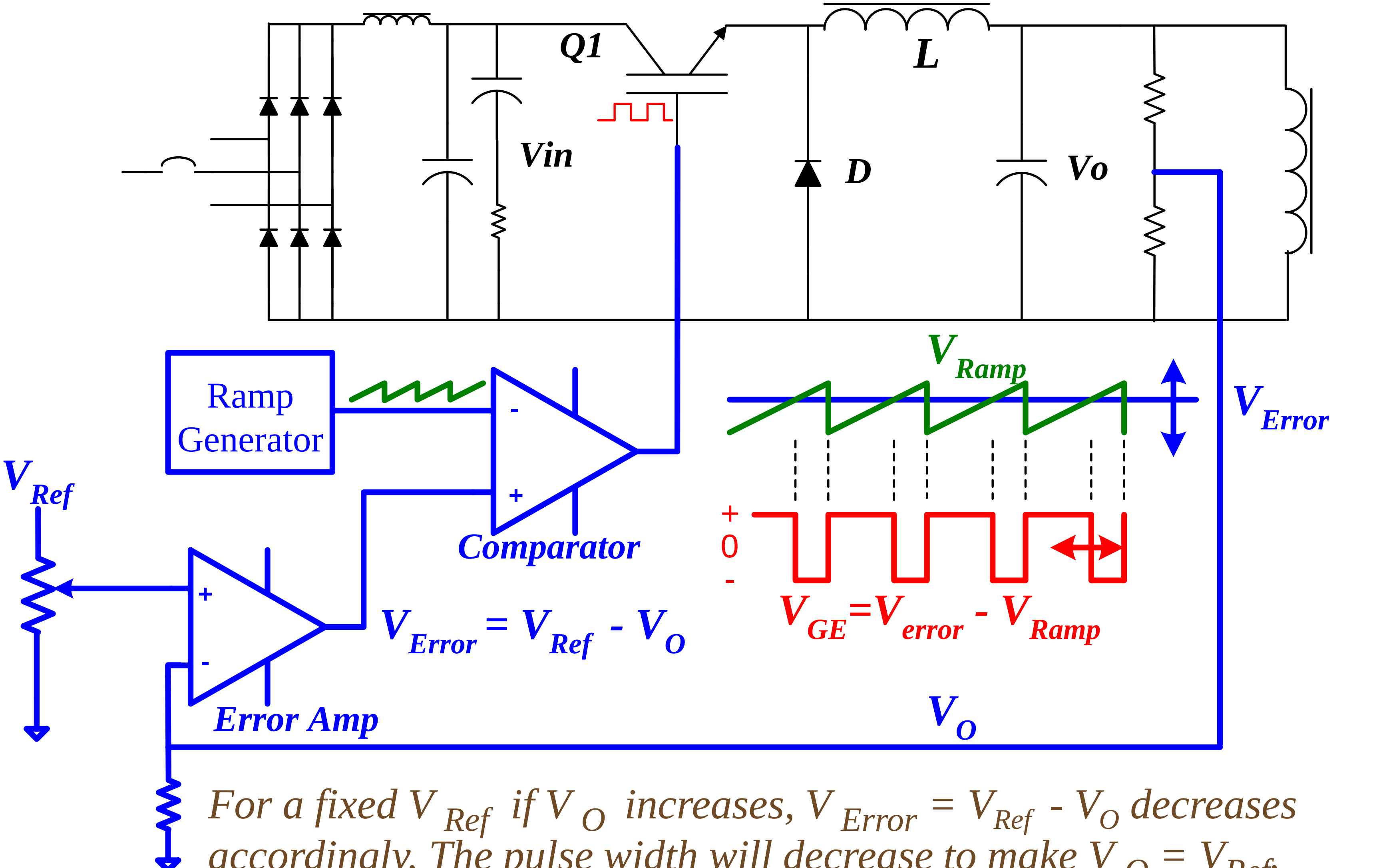
Feedback and Stability Summary

- *The transfer function is the relation between the input, x, and the output, y*
- *By increasing feedback gain, y more closely approaches the desired output*
- *The efficiency of feedback for a dynamic (time-varying) system involves not only the gains, but also the speed of the system response. Some common terms that characterize the dynamics are*
  - *Bandwidth is the frequency range over which the feedback achieves (close) to its nominal gain (3 dB point)*
  - *DC Response is a measure of how closely the system tracks a constant input. Improve the DC Response by increasing the loop gain*
  - *Step Response is the action of the system in response to an input step*
  - *Settling Time is how long it takes to settle to within a certain fraction of its final value*
  - *Overshoot is any ringing occurs as the system achieves its final value*
  - *Ramp response is a measure of how well the system follows an input ramp command*

Purposes

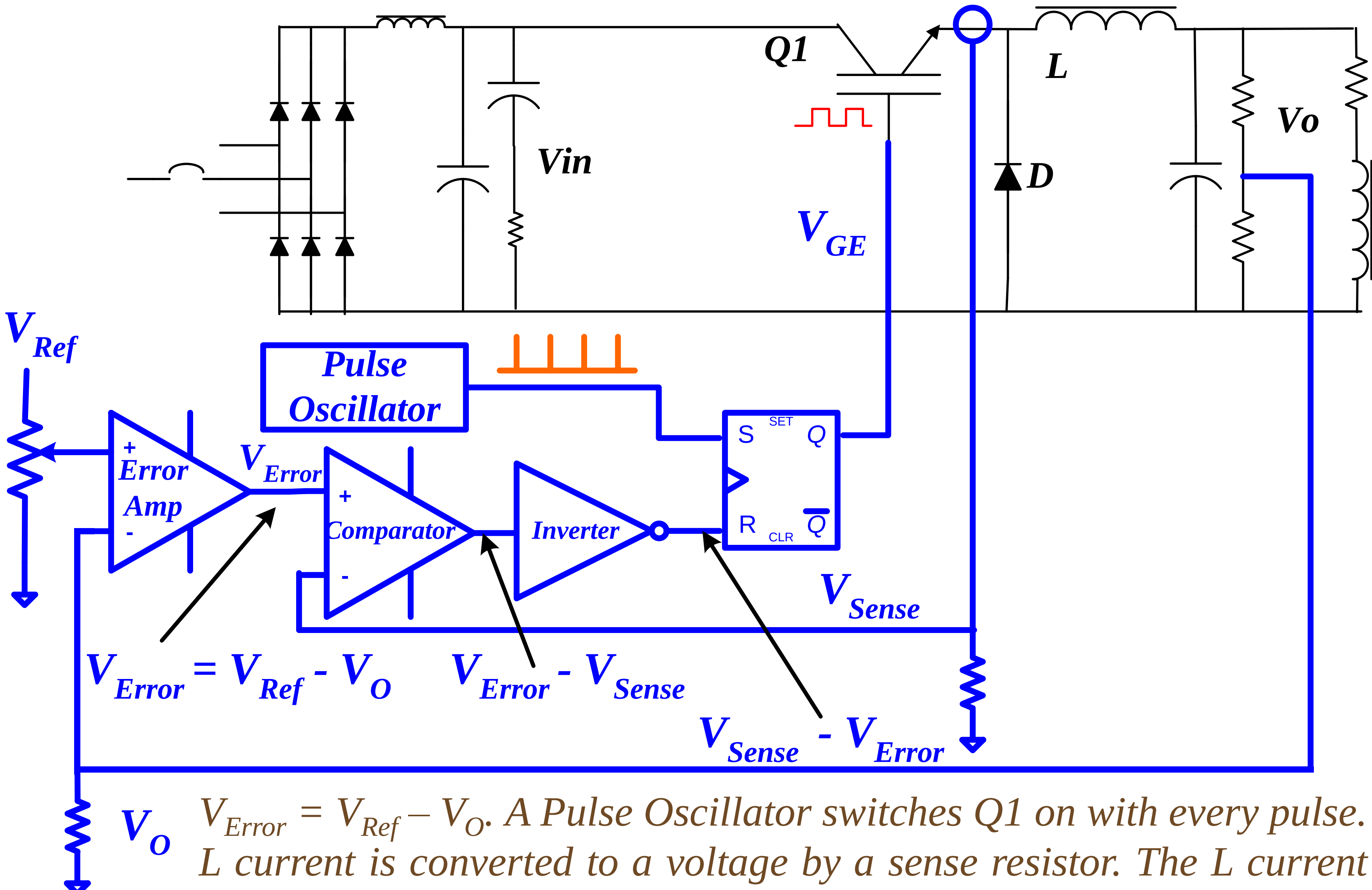
- Sets the output voltage or current to a desired value
- Regulates the output voltage or current to the desired value in the presence of line, load and temperature changes
- Monitors load and power supply actual versus desired performance



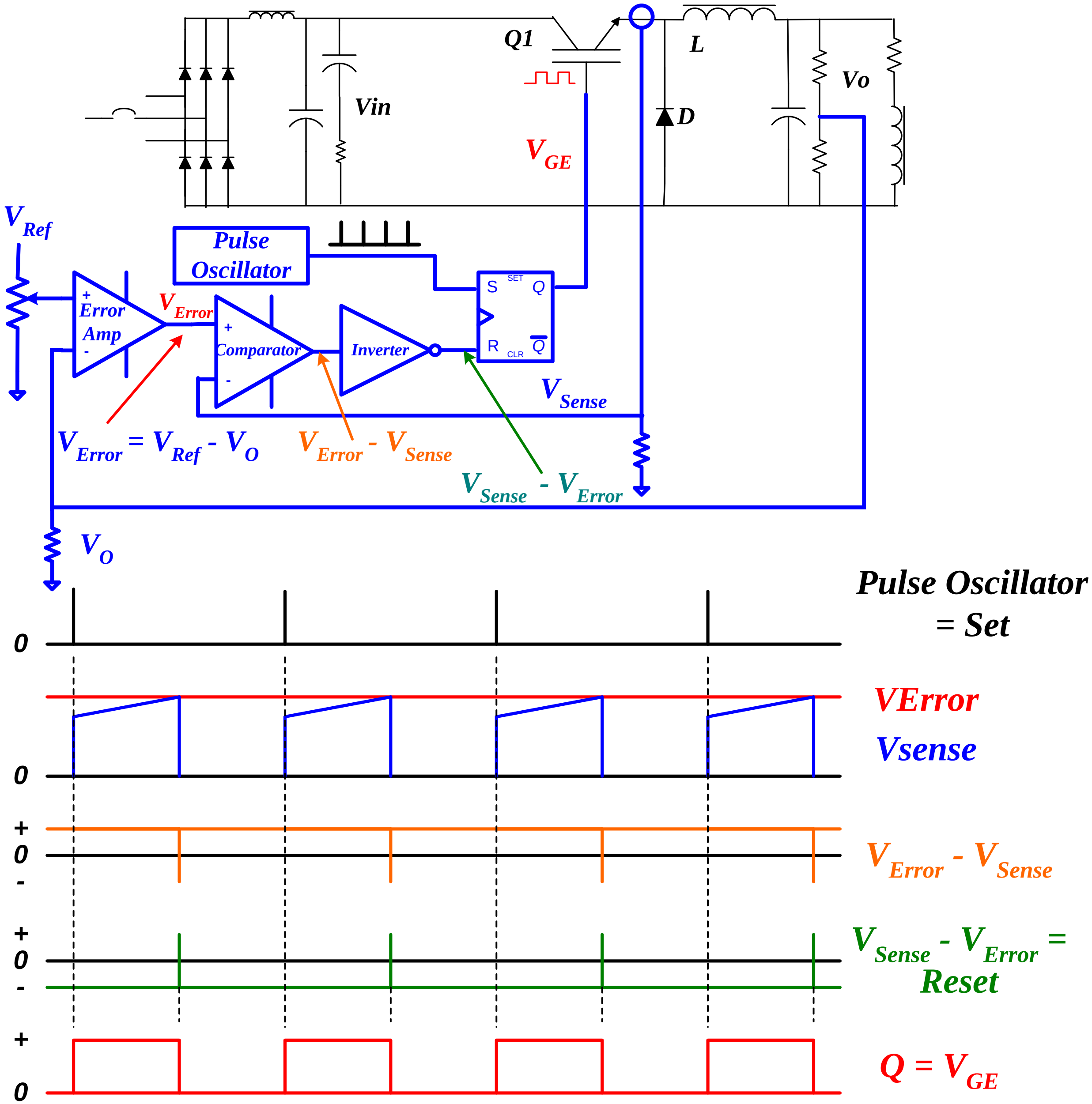


For a fixed V_{Ref} if V_O increases, $V_{Error} = V_{Ref} - V_O$ decreases accordingly. The pulse width will decrease to make $V_O = V_{Ref}$.

If V_O decreases, V_{Error} increases accordingly. The pulse width will increase to keep $V_O = V_{Ref}$.

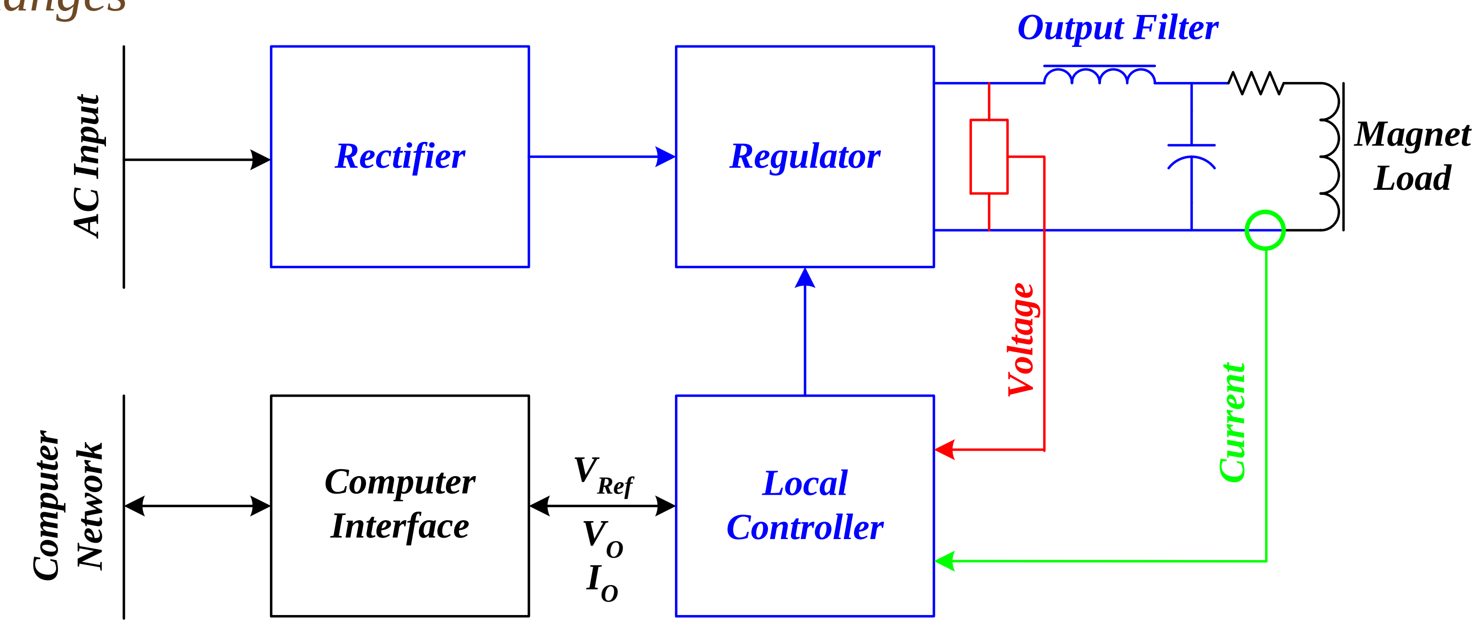


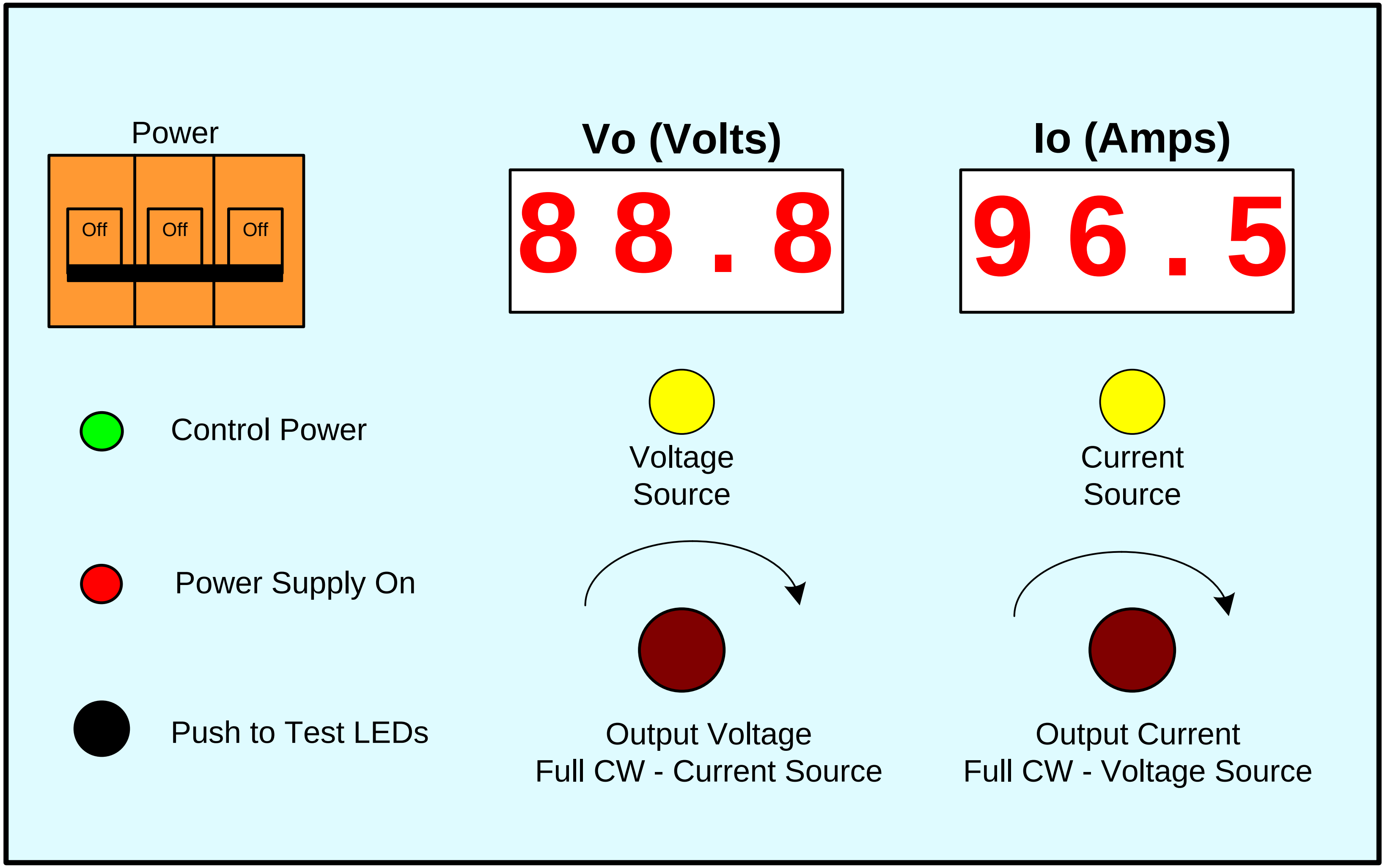
$V_{Error} = V_{Ref} – V_O$. A Pulse Oscillator switches Q1 on with every pulse. L current is converted to a voltage by a sense resistor. The L current builds up to the threshold set by the error voltage which then turns off Q1 in order to keep the output voltage or current constant.


Q1
L
Vin
Vo
D
V_{GE}
V_{Ref}
Pulse Oscillator
S SET Q
R CLR Q̄
Error Amp
V_{Error}
Comparator
Inverter
V_{Sense}
$V_{Error} = V_{Ref} - V_O$
$V_{Error} - V_{Sense}$
$V_{Sense} - V_{Error}$
V_O
0
+
-
Pulse Oscillator = Set
VError
Vsense
$V_{Error} - V_{Sense}$
$V_{Sense} - V_{Error}$ = Reset
$Q = V_{GE}$

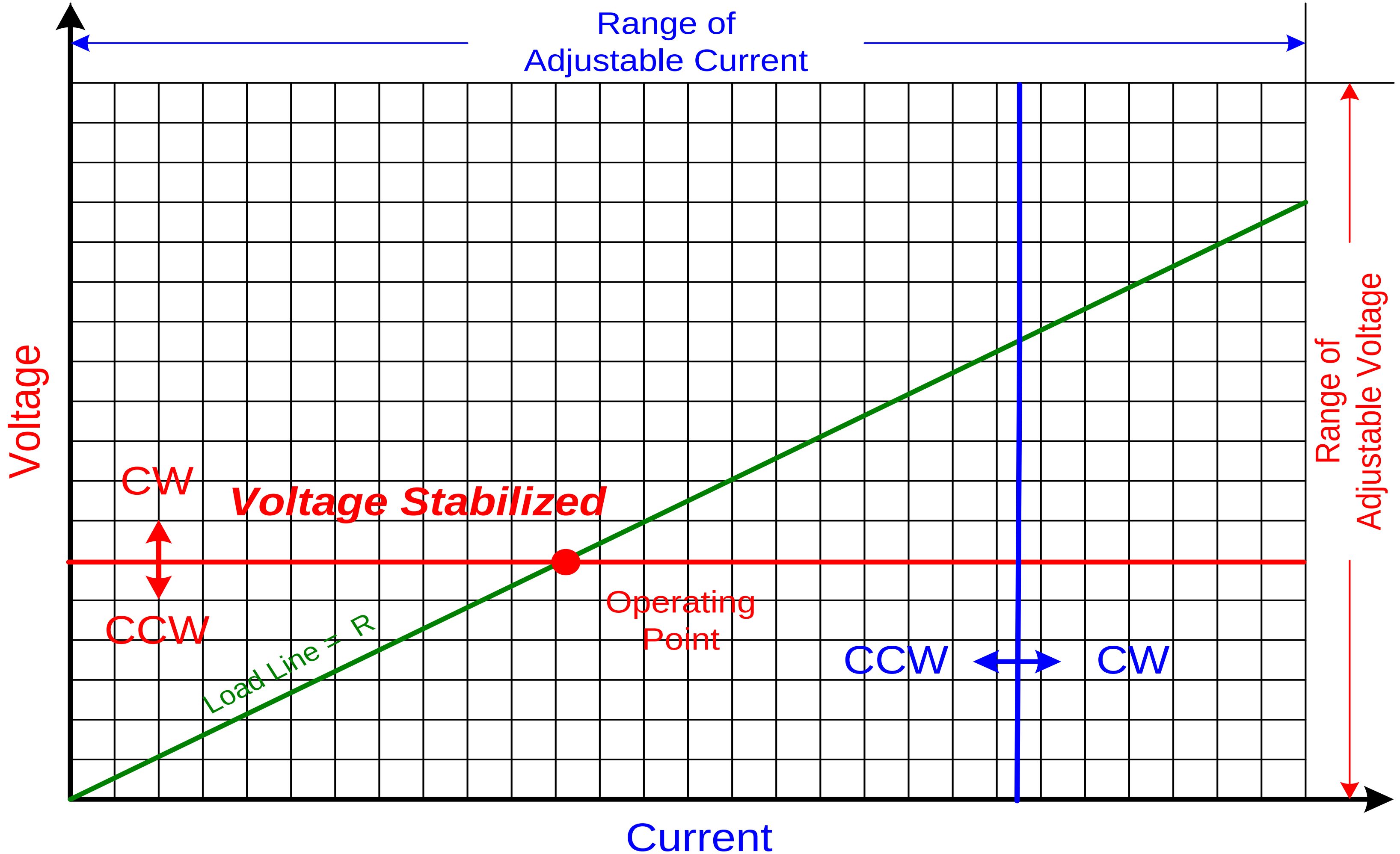
Summary

- *Typically 2 control loops – voltage and current*
- *The outer loop defines the source type – voltage or current stabilized*
- *The outer loop has lower BW and corrects for drift due to slow temperature changes and aging effects*
- *The inner loop has higher BW and compensates for fast transients, AC line changes*

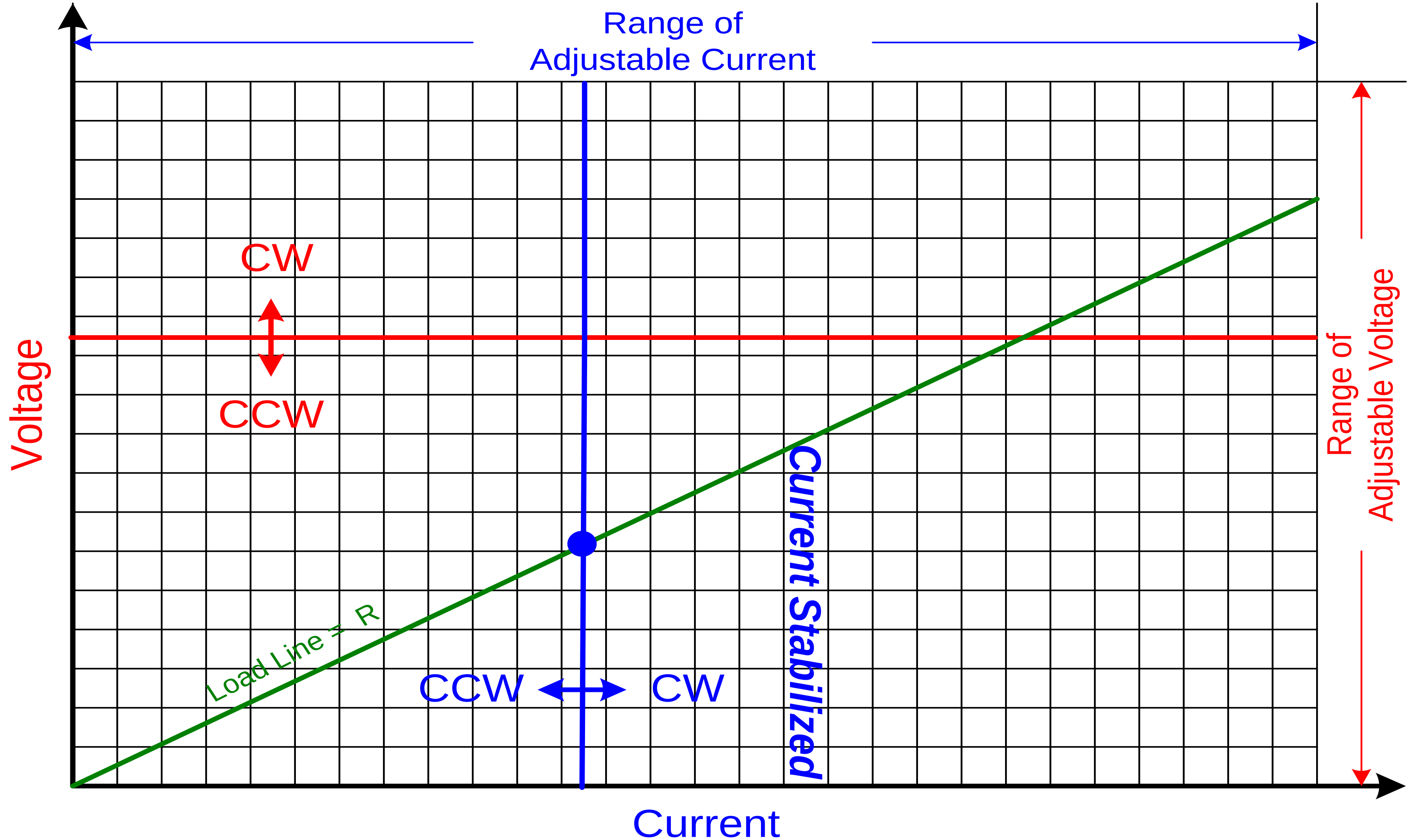




Power Supply Front Panel

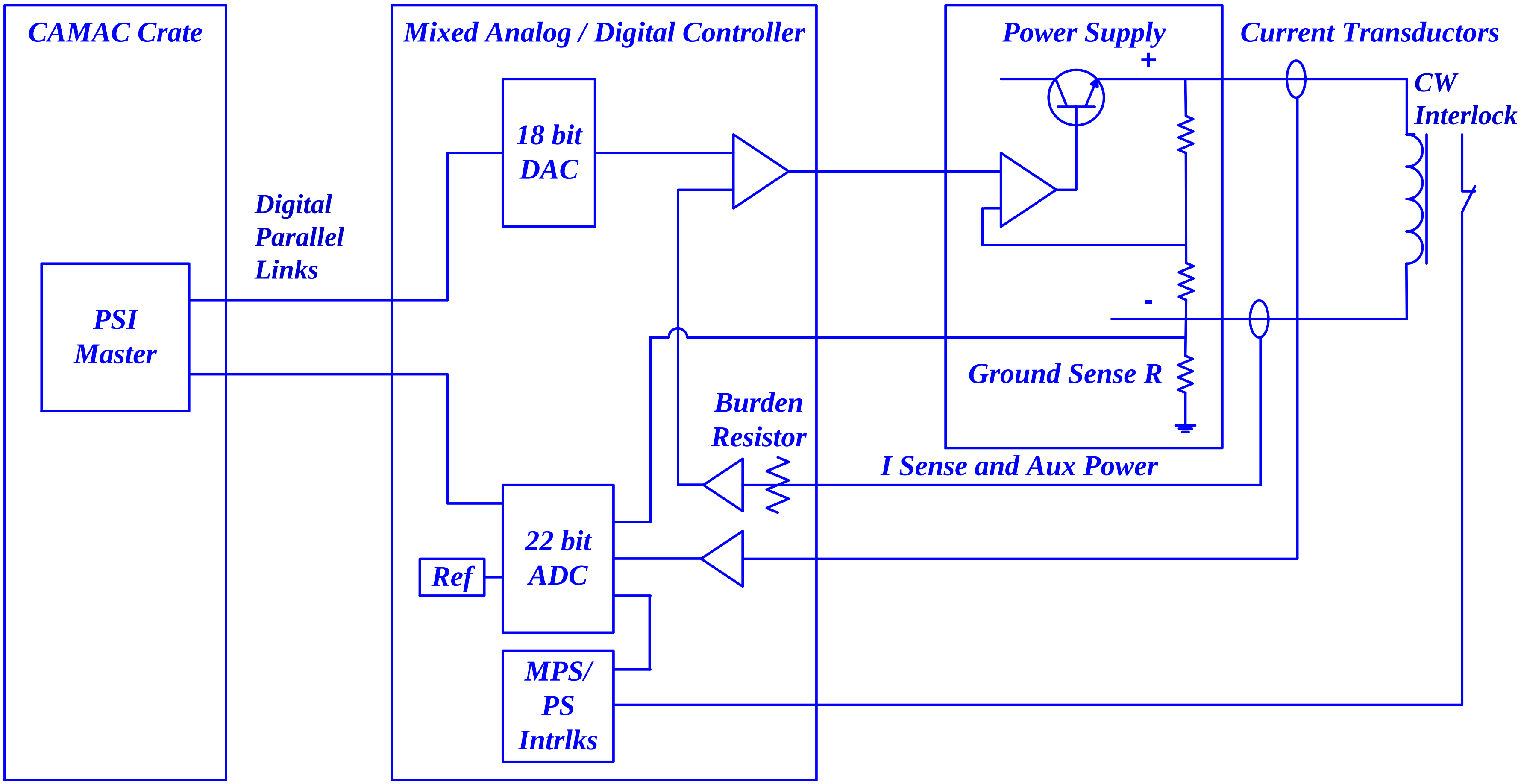


Constant Voltage Mode. *The power supply will operate in this mode whenever the current demanded by the load is less than that defined by the front panel current control. The output voltage is set by the front panel voltage control. The output current is set by the load resistance and the Vset.*

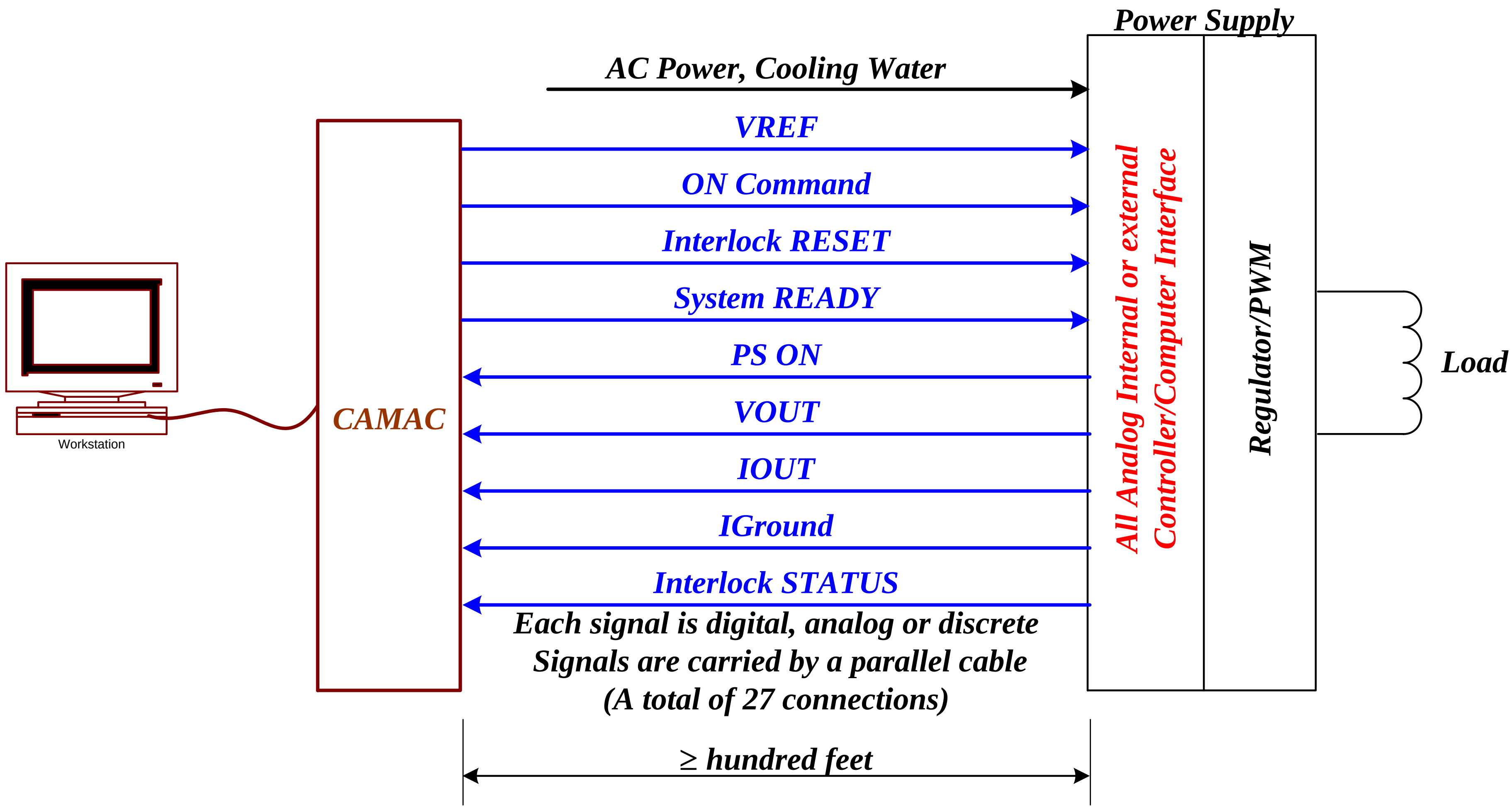


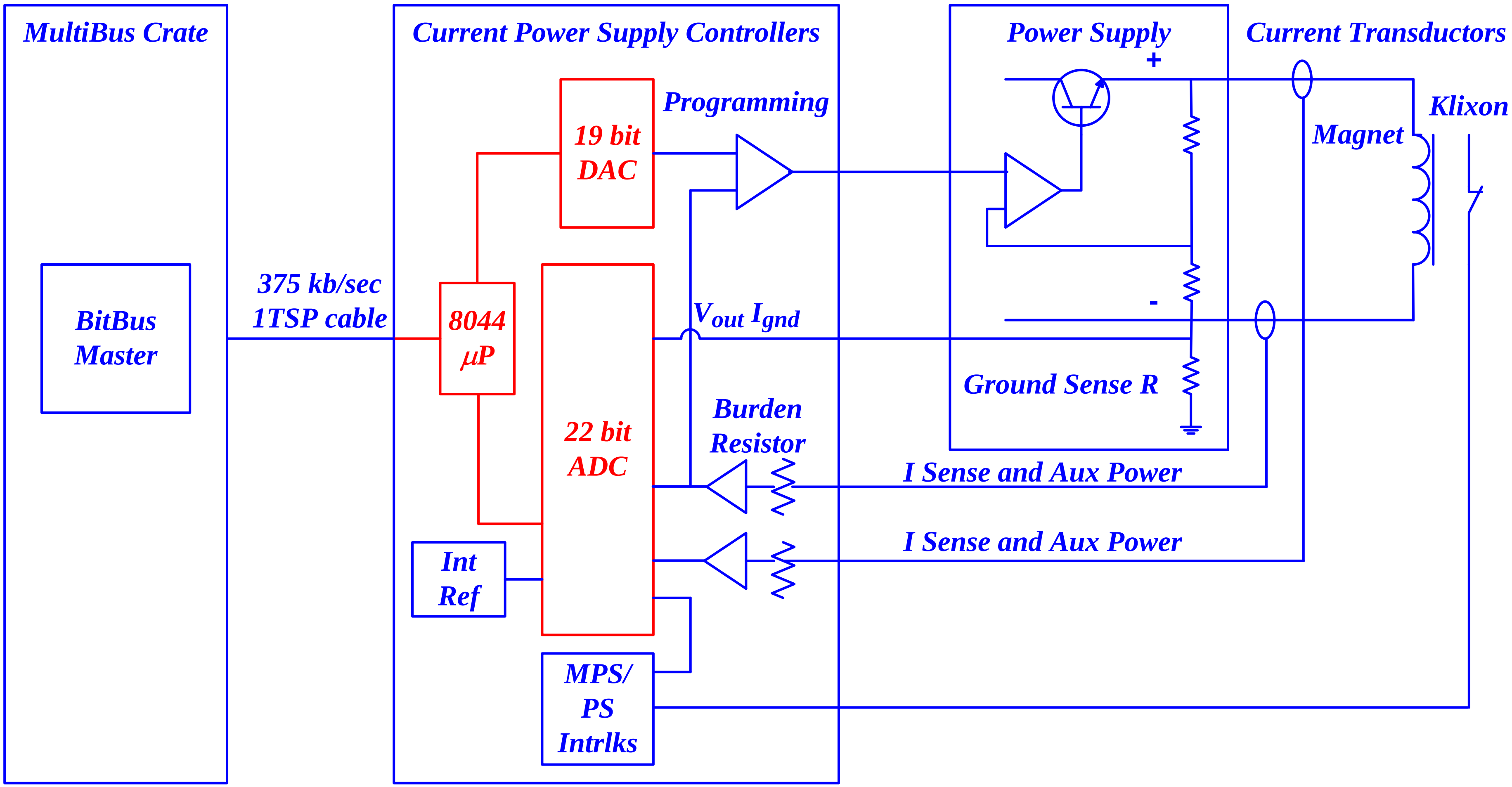
Constant Current Mode. *The power supply will operate in this mode whenever the voltage demanded by the load is less than that defined by the front panel voltage control. The output current is set by the front panel current control. The output voltage is set by the load resistance and the I set.*

All-Analog Power Supply Controllers – Circa 1970s to 1980s

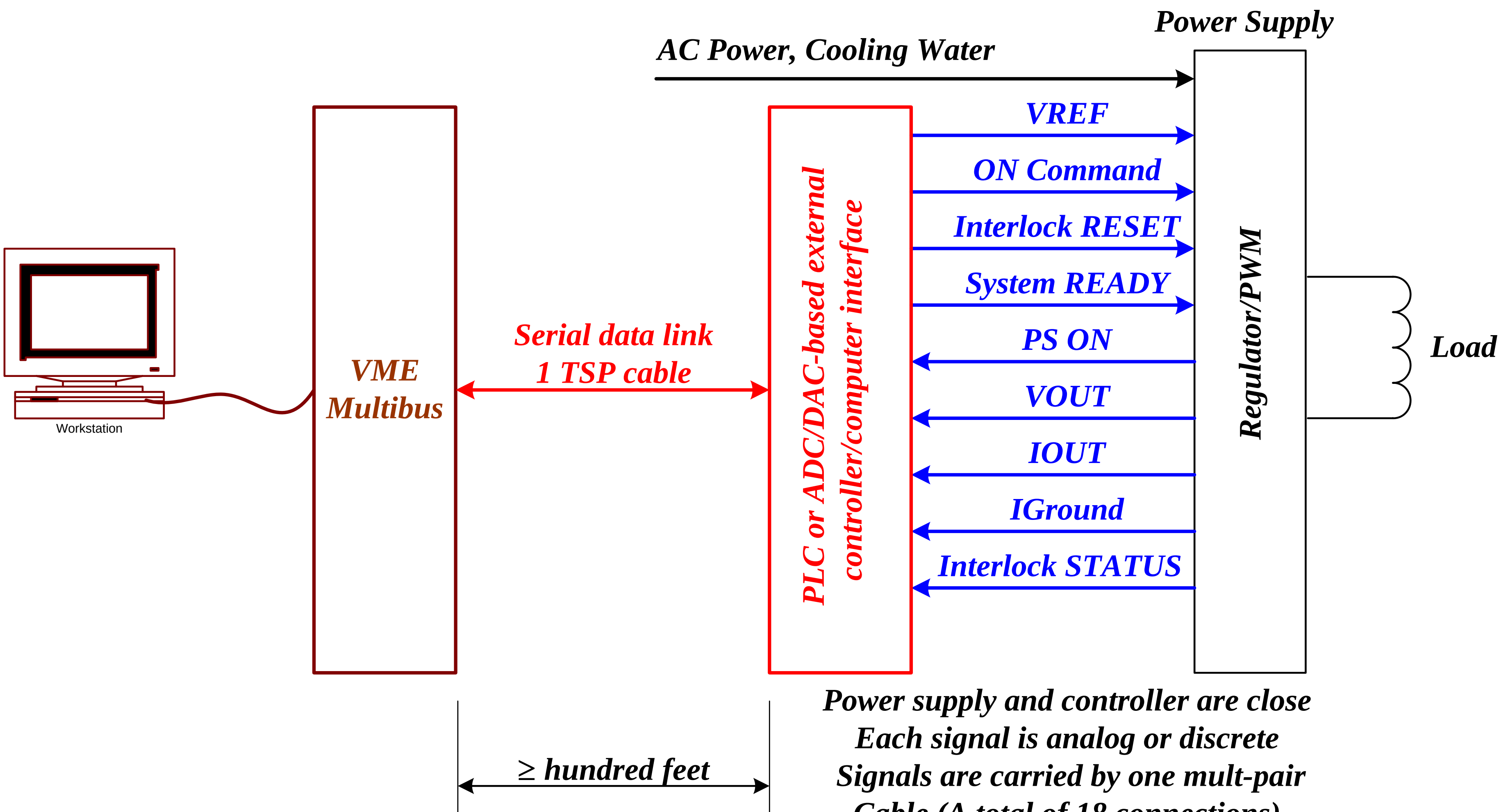


All-Analog Power Supply Controllers – Circa 1970s to 1980s



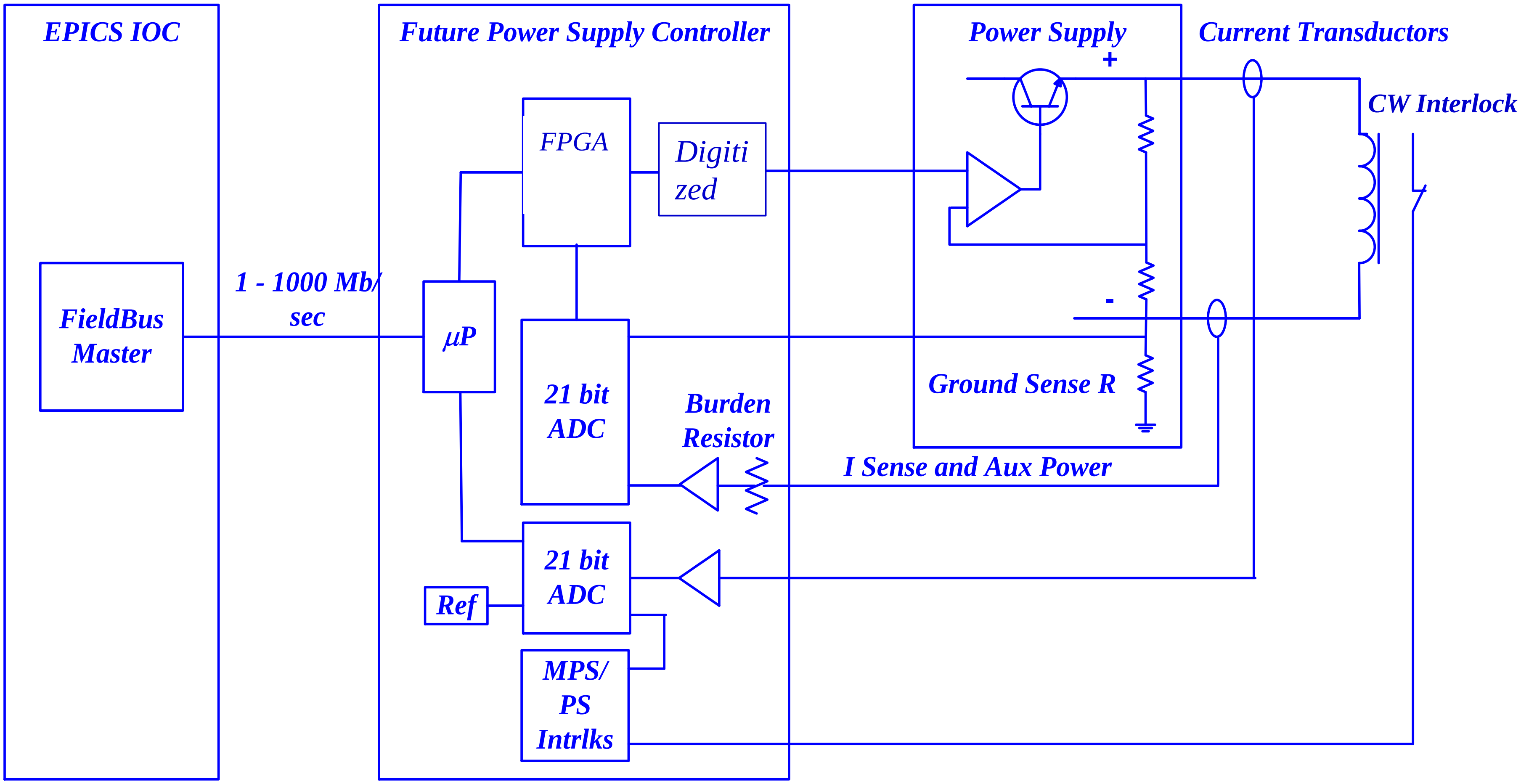

MultiBus Crate
BitBus Master
375 kb/sec
1TSP cable
Current Power Supply Controllers
8044 μP
19 bit DAC
22 bit ADC
Int Ref
MPS/ PS Intrlks
Programming
Vout Ignd
Burden Resistor
Power Supply
+
-
Ground Sense R
I Sense and Aux Power
I Sense and Aux Power
Current Transductors
Magnet
Klixon

Hybrid Analog/Digital Power Supply Controllers – Circa 1980s to Present

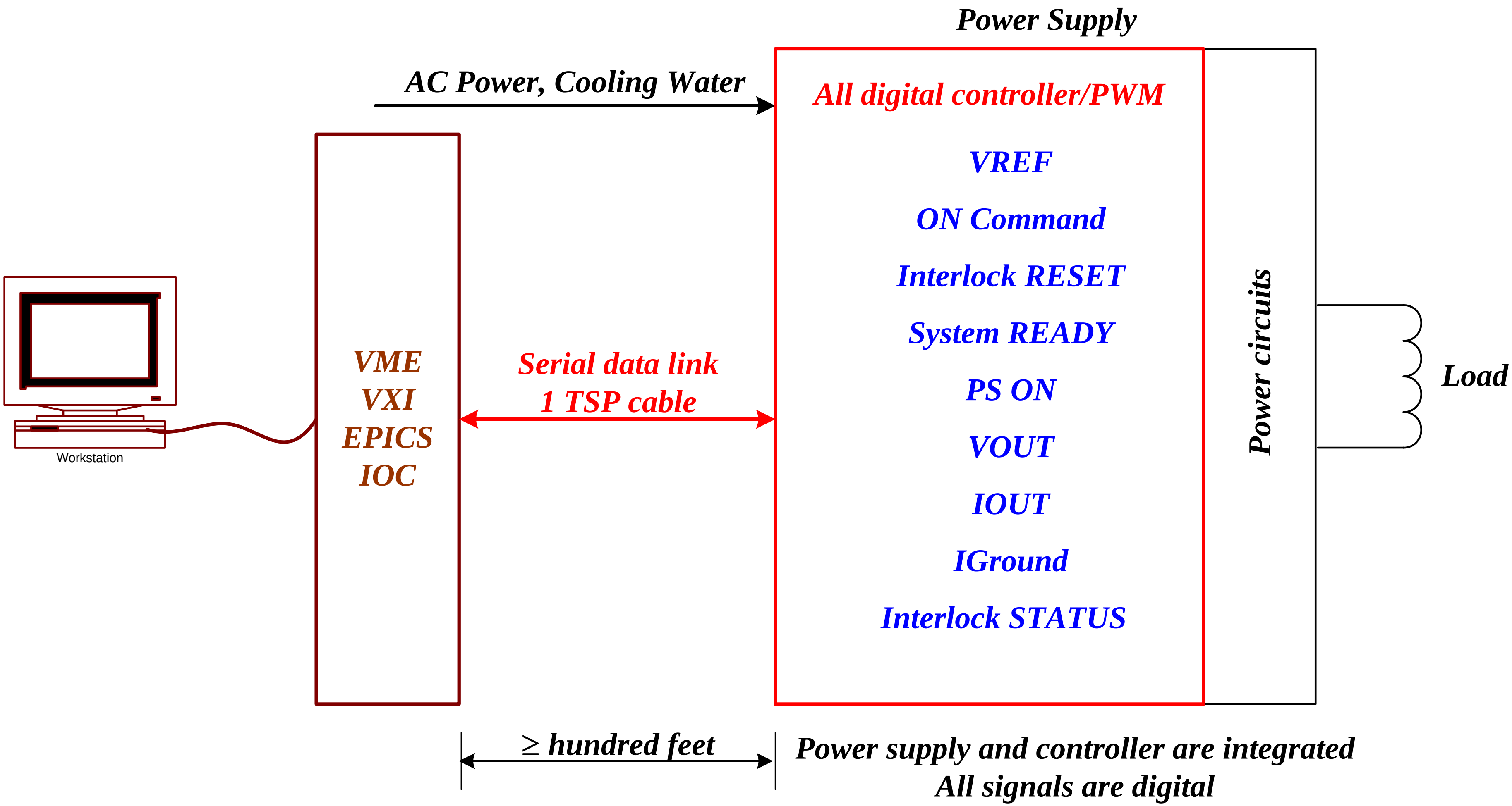


Power supply and controller are close
Each signal is analog or discrete
Signals are carried by one mult-pair Cable (A total of 18 connections)

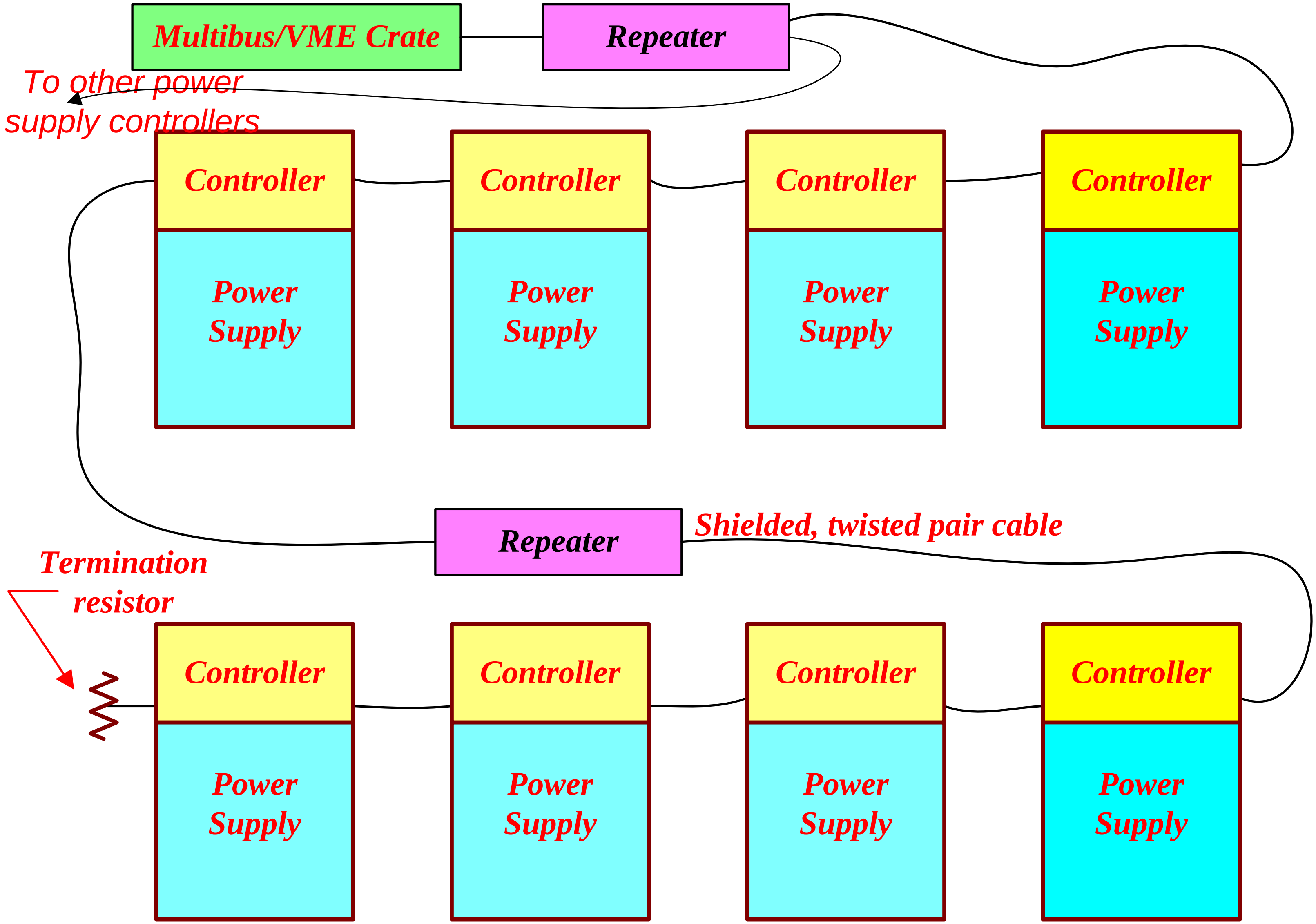
All Digital Power Supply Controllers – Circa the Future



All Digital Power Supply Controllers – Circa the Future



Daisy - Chaining of Power Supply Controllers



Controls Type	Characteristics
All analog controls	• *Long, expensive multi-conductor cable* • *Cables subject to noise pickup, ground loops, losses in signal strength* • *Installation rigid, difficult to modify*
Hybrid analog/digital controls	• *PLCs, ADCs / DACs subject to noise pickup, ground loops, must keep out of power supply* • *Serial data cable can be daisy-chained* • *Installation rigid, difficult to modify*
All digital controls	• *Integrated high level digital signals exhibit greater immunity to noise pickup, ground loops* • *Serial data cable can be daisy-chained* • *Installation flexible, control system can be modified in software or firmware* • *Will require novel implementation of interlocks, voltage and current transductors*

Some Communication Busses

Bus Type	Single / Differential	Protocol	Data Rate	Length	Connector	Comments
RS232	$-12 \rightarrow +12V$ SE	Serial	115kb/s	5m	25 /15/9pin sub D	Inexpensive wiring
BitBus IEEE 1118	0-5V Differential	Serial	375kb/s	300m	9 pin sub D	Inexpensive wiring
IEEE488 GPIB		Parallel	8Mb/s	20m	24 pin	Measurement Equipment
Ethernet	Optical/SE Differential	Serial	1Gb/s		RJ8, RJ45 Optical	Move lots of data packets
USB 2.0		Serial	12Mb/s	5m	4 pin USB	Hot-swappable
Firewire IEEE1394	3.3V Differential	Serial	800Mb/s	46m	4 pin / 6 pin Optical	Hot-swappable
SCSI	3.3V Diff/ Optical	Parallel	1.28Gb/s	12m	68 pin 80 pin	
eSATA		Serial	3Gb/s			Hot-swappable

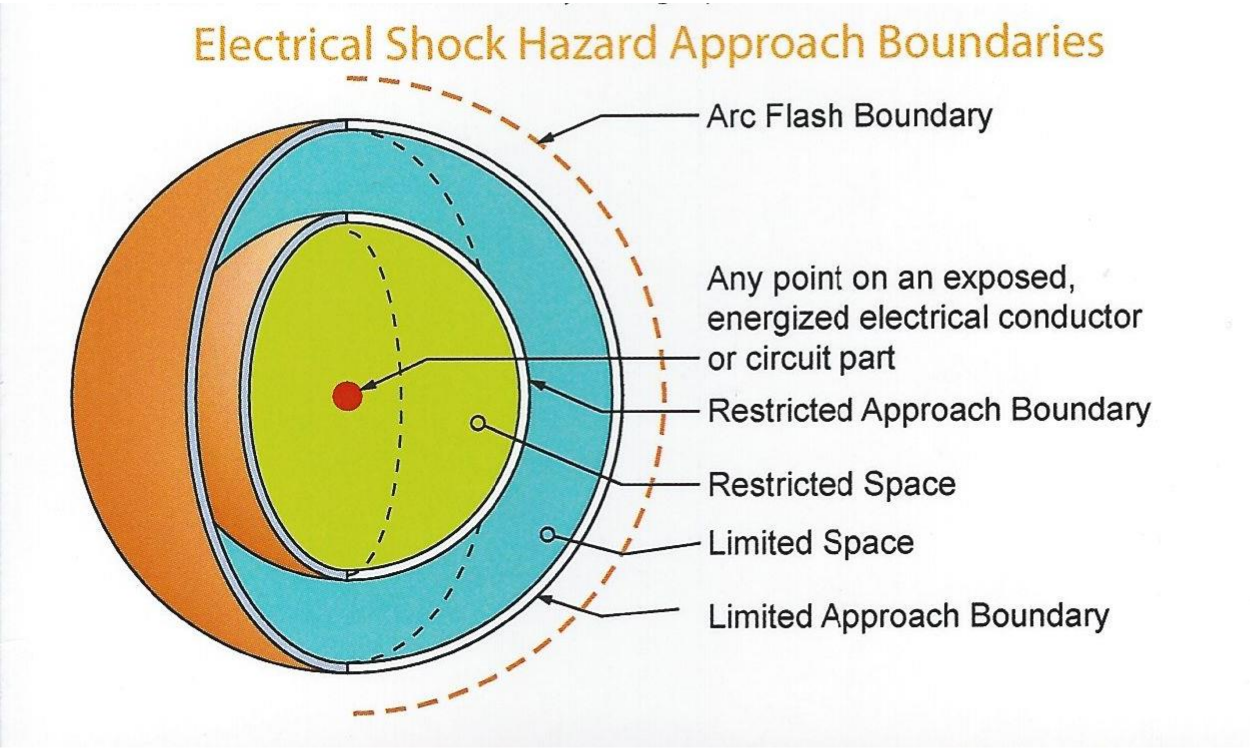
Section 11 – Personnel and Equipment Safety

- *NFPA 70E - Safety in the Workplace*
  - *The Voltage Hazard*
  - *Arc Flash*
- *NFPA 70 – National Electrical Code*
- *Interlocks*
  - *Personnel Protection Systems (PPS)*
  - *Load Protection Systems-Machine Protection Systems (MPS)*
  - *Power Supply Protection*
  - *Programmable Logic Controllers (PLCs)*
- *Lockout/Tagout (LOTO)*

NFPA 70E

NFPA 70E - 2004 - Standard for Electrical Safety in the Workplace

- *Addresses employer and employee safety in the workplace*
- *Focus is on procedures, personnel protective equipment*
- *Attempts to mitigate effects of three major electrical hazard types – shock, arc flash and arc blast*



- Limited approach boundary is the distance from an exposed live part within which a shock hazard exists

- Restricted approach boundary is the distance from an exposed live part within which there is an increased risk of shock, due to electrical arc over for personnel working in proximity to the live part

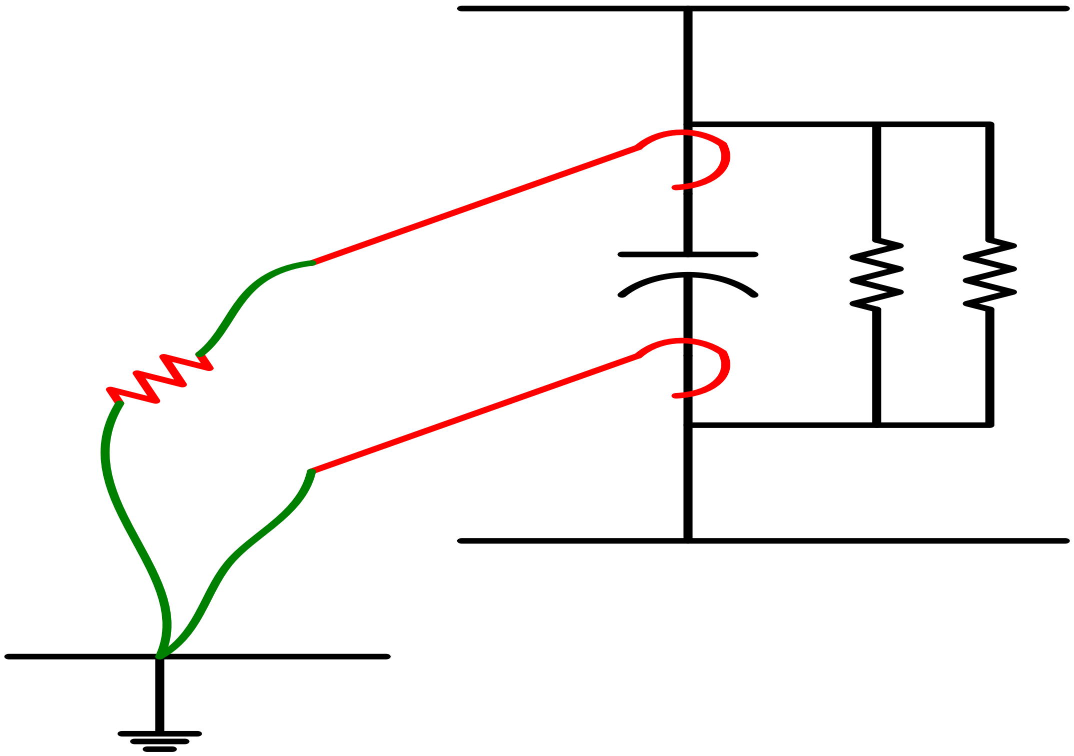
NFPA 70E - Approach boundaries - deal with the voltage hazard

Nominal Voltage, Phase to Phase	Limited Approach Boundary		Restricted Approach Boundary
	Exposed Moveable Conductor	Exposed Fixed Circuit Part	
Less than 50	Not Specified	Not Specified	Not Specified
50 to 150	10 ft 0 in.	3 ft 6 in.	Avoid Contact
151 to 750	10 ft 0 in.	3 ft 6 in.	1 ft 0 in.
751 to 15 kV	10 ft 0 in.	5 ft 0 in.	2 ft 2 in.
15.1 kV to 36 kV	10 ft 0 in.	6 ft 0 in.	2 ft 7 in.
36.1 kV to 46 kV	10 ft 0 in.	8 ft 0 in.	2 ft 9 in.
46.1 kV to 72.5 kV	10 ft 0 in.	8 ft 0 in.	3 ft 3 in.
72.6 kV to 121 kV	10 ft 8 in.	8 ft 0 in.	3 ft 4 in.
138 kV to 145 kV	11 ft 0 in.	10 ft 0 in.	3 ft 10 in.
161 kV to 169 kV	11 ft 8 in.	11 ft 8 in.	4 ft 3 in.
230 kV to 242 kV	13 ft 0 in.	13 ft 0 in.	5 ft 8 in.
345 kV to 362 kV	15 ft 4 in.	15 ft 4 in.	9 ft 2 in.
500 kV to 550 kV	19 ft 0 in.	19 ft 0 in.	11 ft 10 in.
765 kV to 800 kV	23 ft 9 in.	23 ft 9 in.	15 ft 11 in.

Mitigating Voltage Hazard - Rubber Electrical Insulating Gloves

- *They are marked with the class appropriate for the voltage, and should be subject to periodic electrical tests*
- *Leather protective gloves should be worn outside the rubber gloves to provide protection from cuts, abrasions, or punctures*
- *Before each use, check for signs of damage or color change. Replace if contamination or any physical damage is evident*
- *Gloves should be stored in a closed, dry container*

The possibility of residual voltage on capacitors is high. Use one or more ground stick to remove the voltage (stored energy)



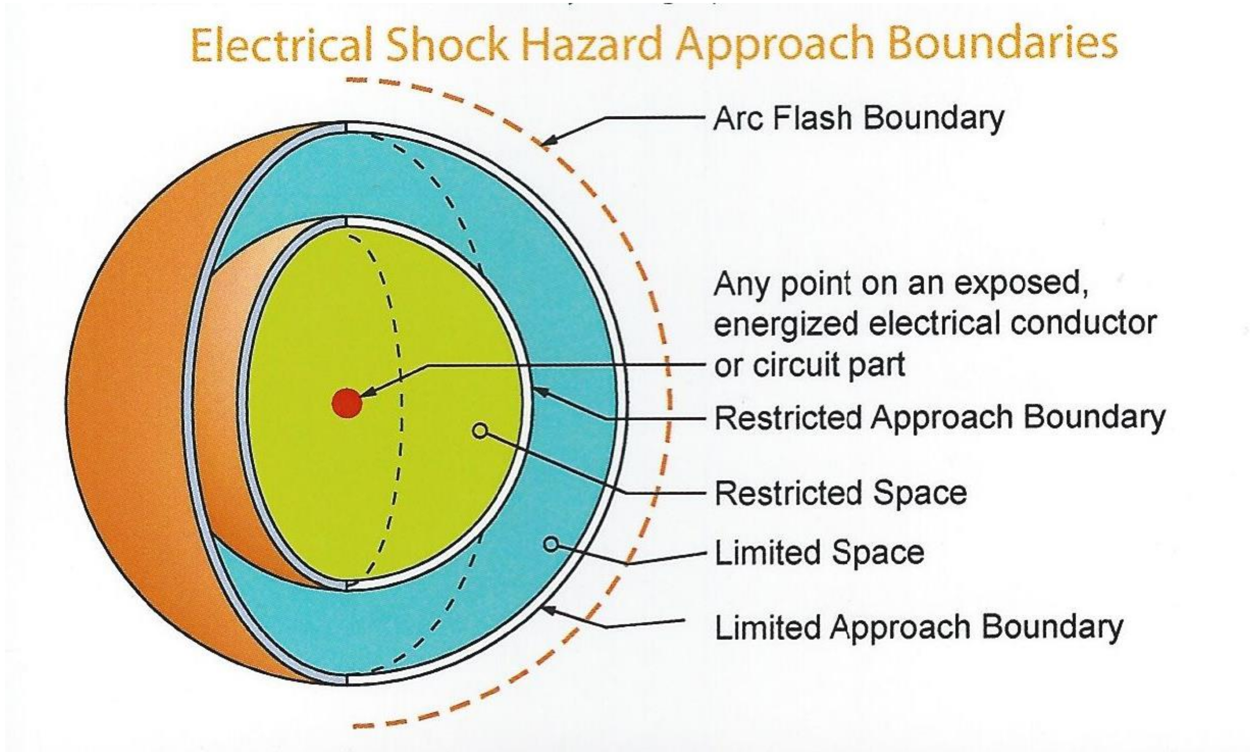
- *Short circuit through air*
- *Caused when circuit insulation or isolation is compromised*
- *A burn and explosion hazard, not an electrocution hazard*
- *Temperature can greatly exceed 5000 F*
- *Instantaneous, almost too fast for the eye to comprehend*
- *Arc flashes occur 5 – 10 times a day in electric equipment in US alone.*

NFPA 70E - Possible Causes of Arc Flash

- *Tool inserted or dropped into a breaker or service area*
- *Equipment cover removal causes a short*
- *Loose connections on bus work*
- *Improper bus work fabrication*
- *Insulation breakdown due to environmental factors or equipment aging*
- *Failure to ensure equipment is de-energized before work*
- *Primarily applications above 208 VAC*

Injuries Associated with Arc Flash

- *Third Degree Burns, Blindness, Hearing Loss, Nerve Damage, Cardiac Arrest, Concussion, Death*



- *Arc flash hazard - a dangerous condition associated with the release of electrical energy caused by an electrical arc. Typically due to the molten plasma formed by the melting of conductors during an electrical short circuit*
- *Arc flash protection boundary - The distance form exposed live parts within which a person could receive a second degree (curable) burn (1.2 cal/cm ^{2} = 5 J/cm ^{2})*

- *An arc generates power that radiates out from a fault*

$$P_{arc} = V_{arc} * I_{arc}$$

- *The total energy is the product of the arc power and duration of the arc*

$$E_{arc} = P_{arc} * t$$

- *The energy density decreases with distance from the arc*
- *An arc-flash hazard occurs when the energy density on the torso or face exceeds 1.2 cal/cm^2, the energy density at which a second degree burn occurs. Note: This is comparable to holding the flame from a cigarette lighter on your skin for 1 second*
- *Flash protection boundaries and energies are calculated using NFPA 70E [example Table 130.7(C)(9)(a)] and IEEE1584*
- *The calculations entail knowing the voltage class of the equipment, some details about its manufacture, the available short circuit and the opening times of the protective circuit breaker(s)*

- *The hazard/risk category is determined by selecting the row for which $E_{min} \leq E < E_{max}$ at the working distance.*

E_{min} (cal/cm^2)	E_{max} (cal/cm^2)	Hazard/Risk Category
1.2	4	1
4	8	2
8	25	3
25	40	4

- *The appropriate Personal Protective Equipment (PPE) required is then determined from Table 130.7(C)(10) and Table 130.7(C)(11) of NFPA 70E*

NFPA 70E – Mitigation of Arc Flash

- Decrease available energy by using smaller upstream transformer (lower short circuit current)
- Decrease clearing time
  - Size breaker trip units more aggressively
  - Choose breakers for instantaneous trip times (smaller frame sizes generally trip faster than larger frame sizes)
  - Choose breakers with adjustable trip units including adjustments for instantaneous trips
- Protective devices upstream of transformers need to allow "inrush" current when transformer is energized. Using only upstream sensors, it is difficult to be as aggressive as desirable for arc-flash protection downstream of transformer. Add overcurrent devices on transformer secondary

NFPA 70E – Mitigation of Arc Flash

- *Insert fast acting breakers or fuses in separate enclosures between the transformer and the equipment that needs to be operated. In general, separate the enclosures contain arc-flash generated in that enclosure*
- *Increase distance between worker and source of arc-flash*
  - *Use remote controls to operate high arc-flash hazard devices*
  - *Use extension handles on breakers to increase working distance of operation*
  - *Install meters to use for verification that system is de-energized if work is required on system*
  - *Install IR view-ports on panels that need to be monitored for over-temperature*
- *Install protective devices that sense arcs and not just overcurrent*

NFPA 70E - More Information

More information

- *http://ieeexplore.ieee.org/servlet/opac?punumber=8088*
- *NFPA 70E 2015 Edition*
- *http://www.mt-online.com/articles/0204arcflash.cfm*
- *http://www.eaton.com/ecm/idcplg?IdcService=GET_FILE&dID=12075*
- *http://www.eaton.com/ecm/idcplg?IdcService=GET_FILE&dID=118182*
- *http://ecatalog.squared.com/pubs/Circuit%20Protection/0100DB0402.pdf*

NFPA 70 - National Electrical Code

National Electrical Code NFPA 70

- *Deals with hardware design, inspection and installation*
- *Most Articles do not pertain directly to power systems, but some examples that do are:*

1. *Sizing of raceways and conduits to carry power and control cables.*
2. *Sizing of power cables for ampacity.*
3. *Discharge of stored energy in capacitors*

Example of cable ampacity sizing

A power supply provides 375A to a magnet via cables. The ambient temperature is 45C (104F), maximum and the cables are installed in cable tray. The cable tray fill conforms to the requirements of NEC Article 392.

Use NEC Table 310-15(B)(17) for single conductor cables in free air at 30C. The derating for the 45C ambient is 0.87. The derating for the single copper conductor with 90C insulation and 600V rating in a cable tray is 0.65 if placed touching other cables in the cable tray. The required amapcity is

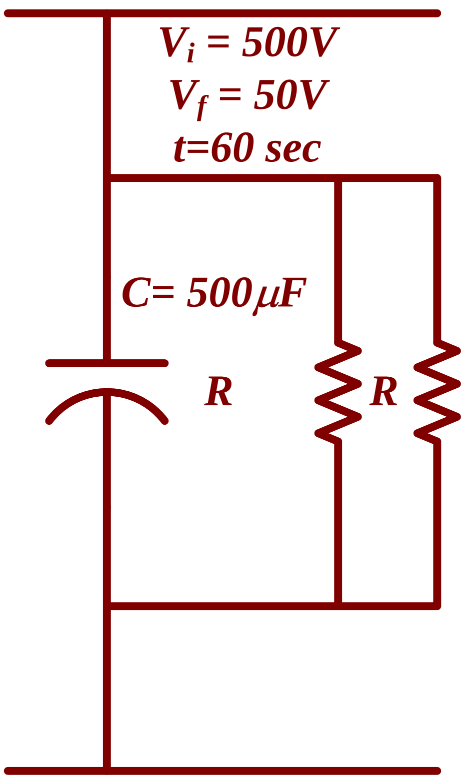
$$\text{Ampacity} = \frac{I_{PS}}{\text{deratings}} = \frac{375\,A}{0.87 * 0.65} = 663\,A$$

From Table 310-15(B)(17) the basic amapcity of 500kcmil cable is 700A > 663A.

Use two 1/C500kcmil cables to connect the PS to the magnet

NFPA 70 - National Electrical Code

- *Example of capacitor bleeder resistor sizing per NEC Article 460. Code requires permanent fixed energy discharge devices on capacitors operating at > 50V working voltage*
- *< 600 V , discharge to 50 V or less in 1 minute*
- *> 600 V , discharge to 50 V or less in 5 minutes*
- *Redundant bleeder resistors recommended*



$$V_f = V_i e^{\frac{-t}{RC}}$$

$$R = \frac{-t}{C \ln(V_f / V_i)} = \frac{-60 * sec}{500\,\mu F \ln(50V / 500V)}$$

$$R = 50\,kohm$$

$$P_R = \frac{V_i^2}{R} = \frac{(500V)^2}{50k\Omega} = 5W$$

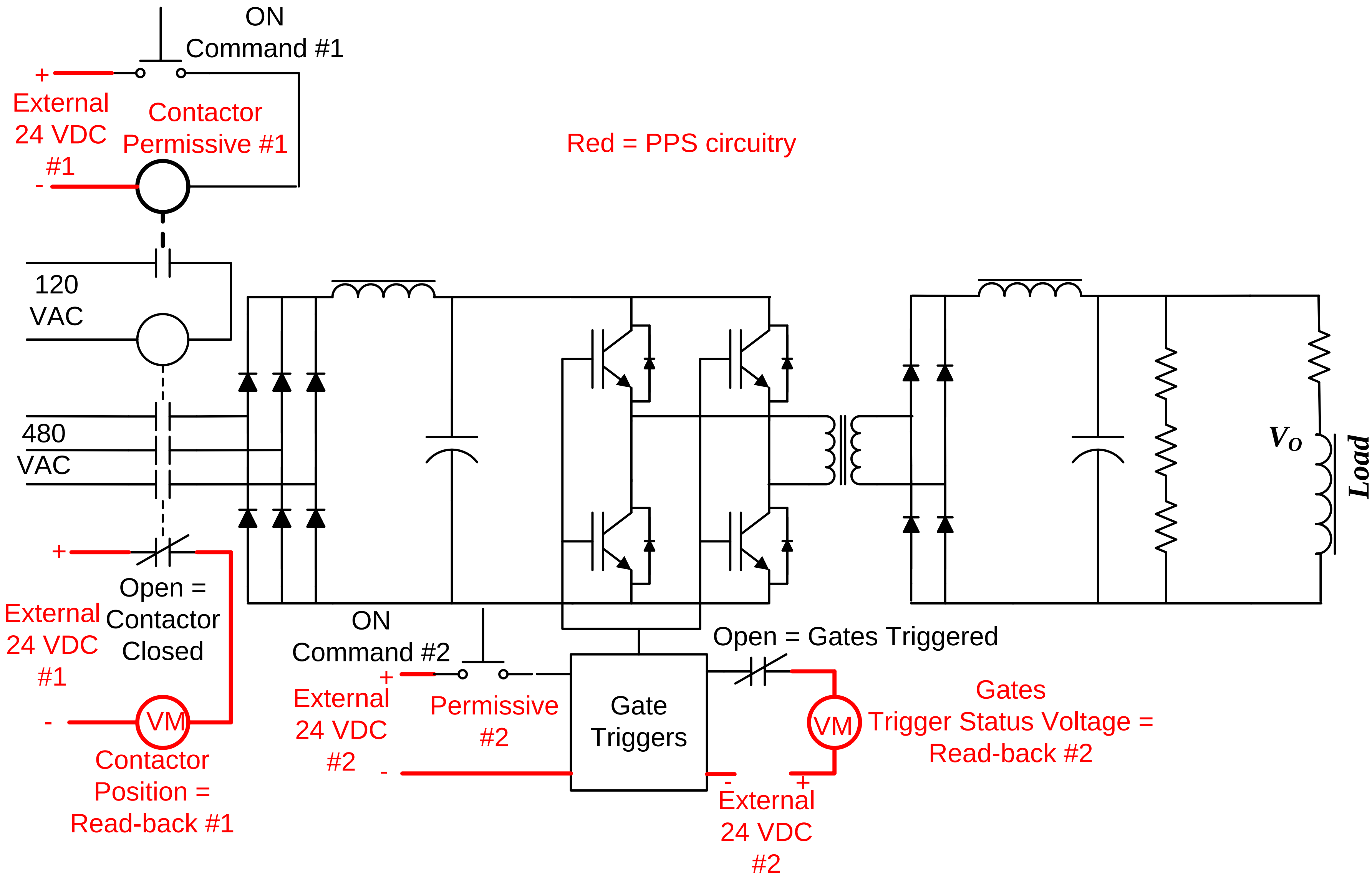
Use two 5W, 100kΩ resistors in parallel

3 Types

- *Personnel Protection System (PPS)*
- *Load Protection - Machine or Magnet Protection System (MPS)*
- *Power Supply Protection – Power Supply Internal Interlocks*

Personnel Protection System (PPS) at SLAC

- *Protection from hazards external to power supply (example accelerator housing door opened)*
- *Hazards are defined as voltages > 50 V, currents > 5m A, energy storage > 10 J.*
- *Must be hardwired (recently SLAC introduced PLC-based PPS)*
- *Two (2) PPS permissives are needed for power supply turn-on*
- *Two (2) separate and different read-backs are required*
- *Permissives and read-backs are usually 24 VDC systems*
- *Permissives and read-backs must be fail-safe*
- *If PPS is not practical, then energized equipment must be enclosed or live terminals covered*



Many variations of this example

Machine (or magnet) protection systems protect loads from damage.

Magnet Cooling Water Temperature / Flow Sensors

- *Usually employ a simple normally closed (NC) contact that opens when a pre-determined temperature has been reached.*

- *Water flow monitoring switches open when flow drops below a pre-established safe value*

- *Temperature / Flow switches are wired to the source power supply. If the water temperature is too high or if the flow drops the contacts open and turn the power supply off*

Vacuum Interlock System

- *Sensors are similar to that described in the magnet cooling water system*

Orbit Interlock System

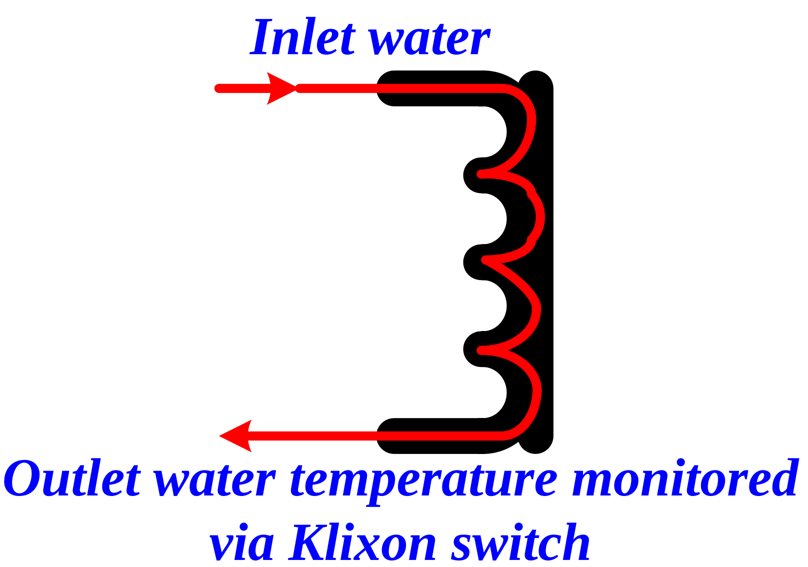
- *Sensors consist of Beam Position Monitors and switches. Function is essentially the same in the magnet cooling water system*

Water Temperature Sensors

- *Thermal switches - Klixons (a trade name) are NC contact bimetal switches mounted on the load cooling water outlet line. Their contacts open when temperature exceeds a pre-established safe value*

- *Multiple-winding, multiple water path magnets employ simple series connected Klixons.*

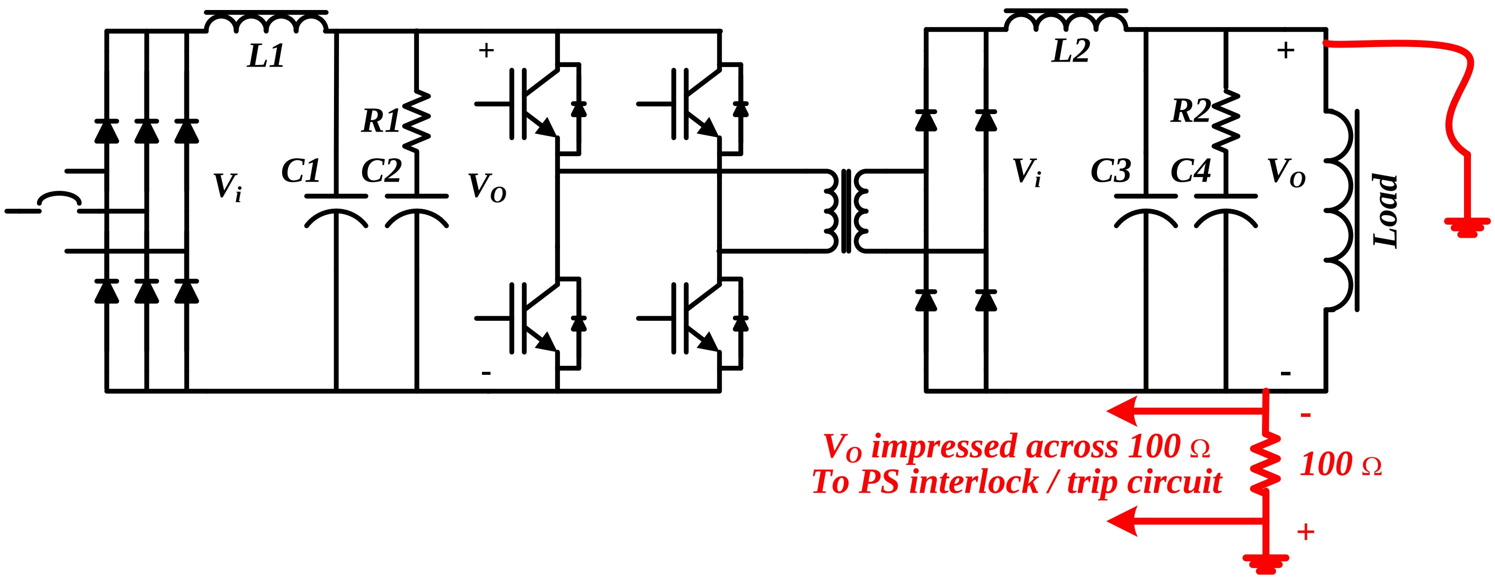
- *Klixons are wired to the source power supply. If the load overheats, the contacts open and turn off the power supply*



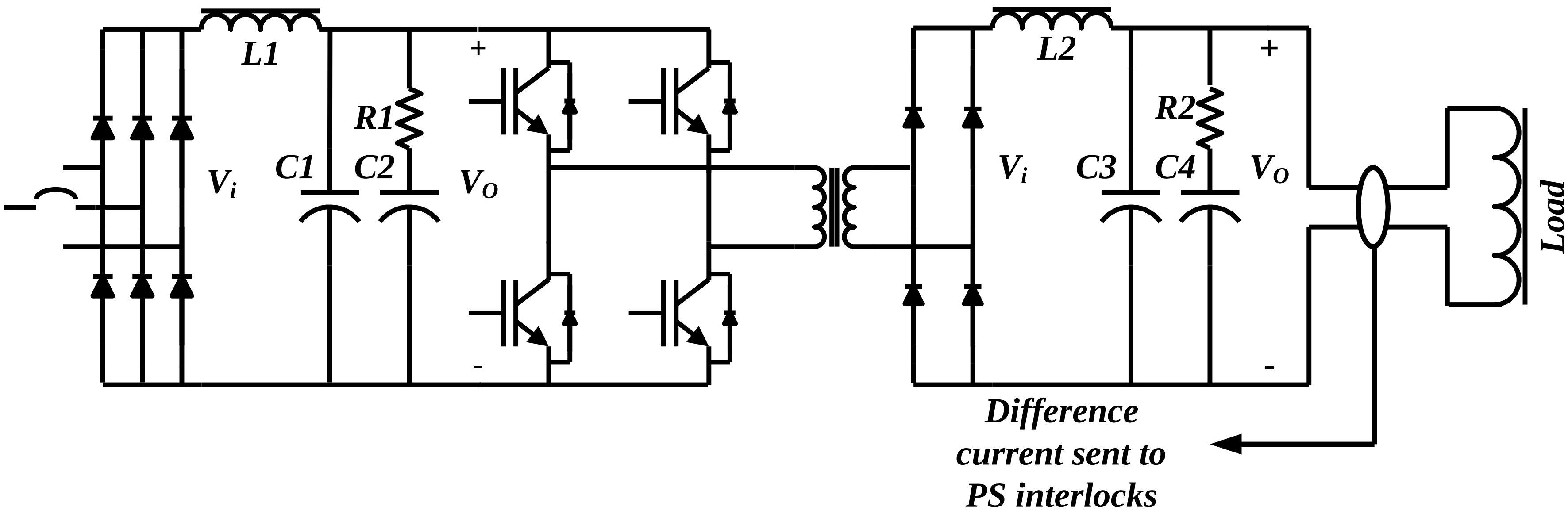
Klixon switches

Ground Fault Detection / Protection Systems

- *Loads are usually located in crowded, dense areas with a multitude of other equipment. This makes them vulnerable to ground faults*
- *Power supplies are usually isolated from ground so that a single ground fault does not cause load-catastrophic ground fault current. Fix first fault before the second fault occurs*



Ground Fault Detection / Protection Systems



Some Internal Interlocks

Internal interlocks protect the power supply itself

- *Low input supply voltage*
- *Phase loss detection*
- *Output DC over-current*
- *Low frequency filter inductor temperature*
- *Heat-sink temperature or heat-sink cooling water flow*
- *IGBT temperature*
- *IGBT over-current*
- *Ground Fault current*
- *Output over-voltage*
- *Cabinet or chassis over-temperature*

Example of a PLC and its Use

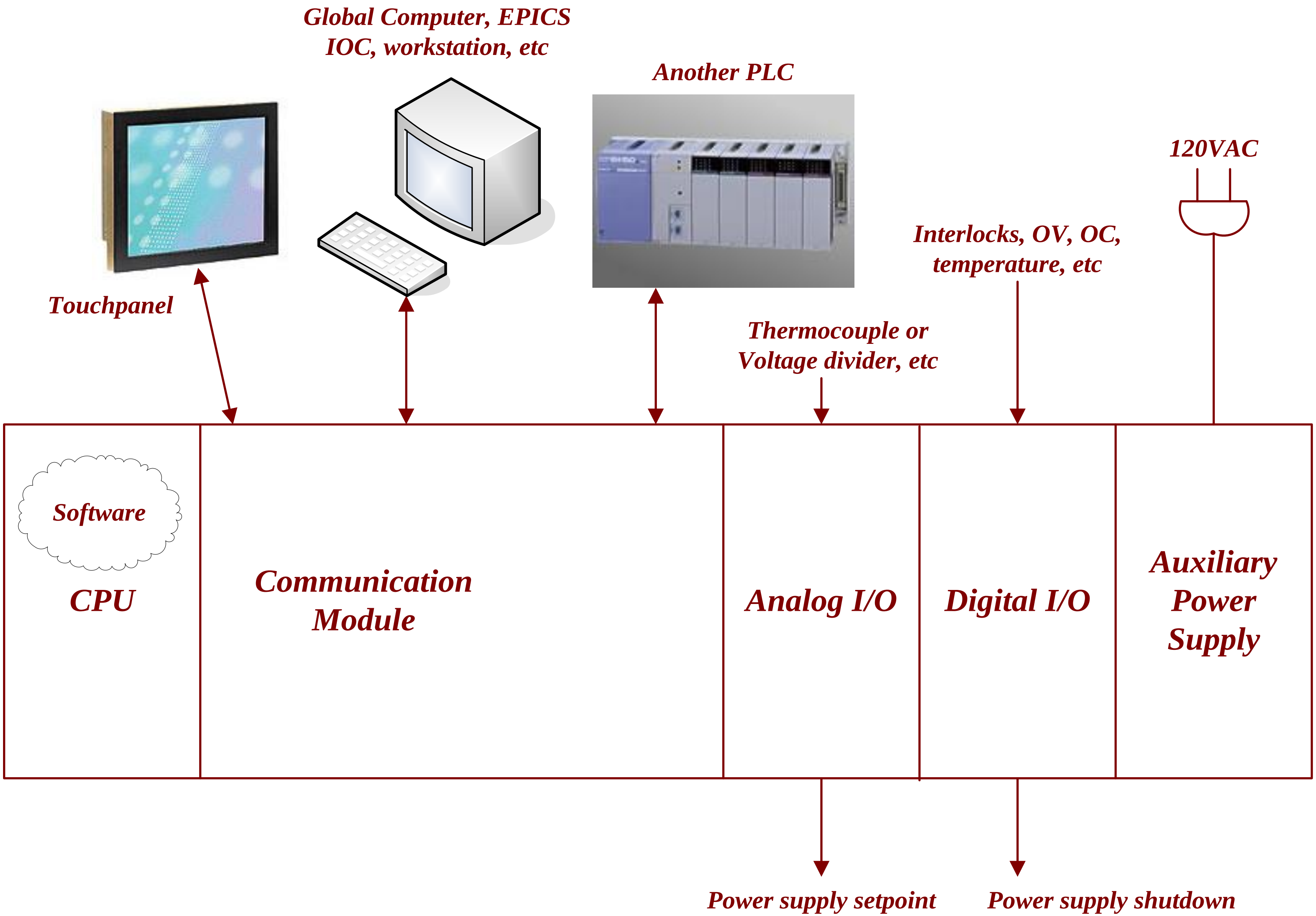
Manufacturers are many

- *Allen-Bradley*
- *Rockwell International (AB)*
- *Siemens*
- *General Electric*
- *IDEC*

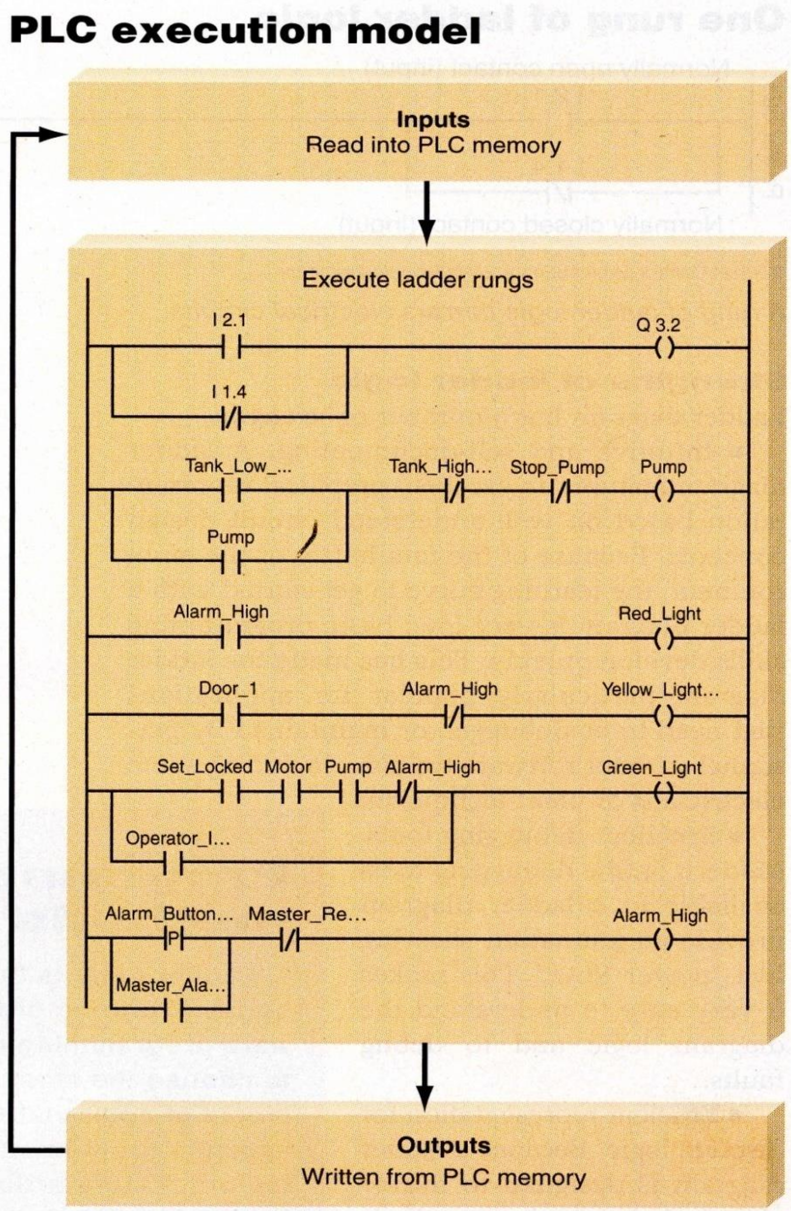
Programming logic

- *Ladder logic*
- *C language*
- *LabView*
- *Functional block diagrams*
- *Structured text*

PLC Uses and Networks



Ladder Logic



Source: Control Engineering *and* National Instruments

Ladder diagrams evolved in the 1960s when the automobile industry needed a more flexible and self-documenting alternative to relay and timing cabinets. A microprocessor was added and software designed to mimic the relay panels.

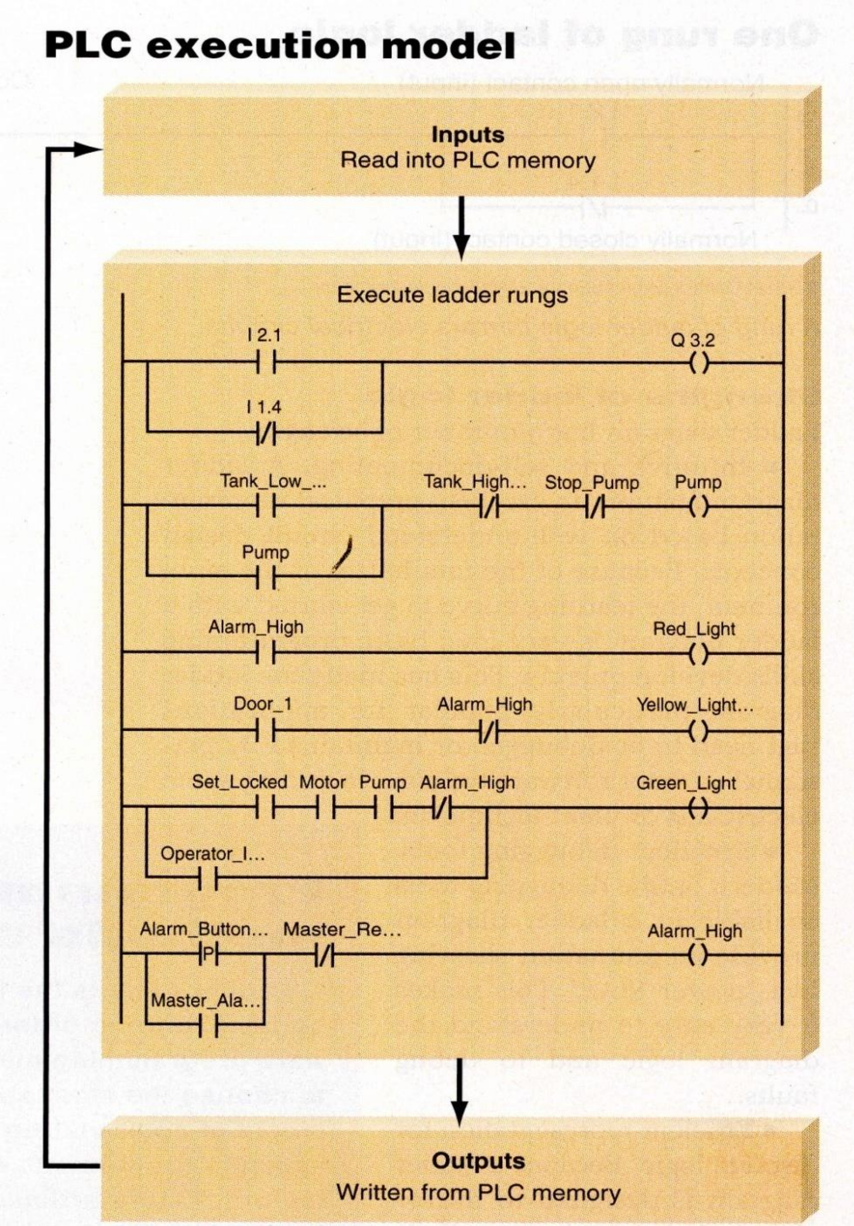
Left rail is the "power bus". The right rail is the "ground bus". Power flows through NO or NC contacts to power coils.

Each contact and coil is linked to a Boolean memory location.

Series contacts look like "AND" and parallel contacts look like "OR"

Execution is left to right and top to bottom

Ladder Logic



Source: Control Engineering *and National Instruments*

Most widely used to program PLCs

Strengths

- *Intuitive – can be learned very quickly by with little or no software training*
- *Excellent debugging tools, include animation showing live "power flow". This makes the logic easy to understand and debug*
- *Efficient representation for discrete logic*

Weaknesses

- *Hierarchical data and logic flow.*
- *Poor data structure. Rungs are executed in a left-to-right, top-to-bottom order. Timing is limited by the PLC processor speed*
- *Limited execution control*
- *Arithmetic operations are limited*

PLCs implement specific functions such as:

I/O control	*Timing*	*Report generation*	*Arithmetic*
Logic	*Communication*	*Data file manipulation*	*Counting*

PLC Versus Programmable Automation Controllers (PAC)

Consider a PAC upgrade if your application requires:

- *advanced control algorithms*
- *extensive database manipulation*
- *HMI functionality in one platform*
- *Integrated custom control routines*
- *complex process simulation*
- *very fast CPU processing*
- *memory requirements that exceed PLC specifications*

Lock & Tag for Personnel Safety During Maintenance

- *Procedures and requirements for servicing and maintaining machines and equipment*
- *Provision for locking off source power, the discharge of stored energy prior and the total de-energization of equipment before working on exposed electrical circuits or other hazardous equipment in which unexpected energization, startup or release of energy could cause injury to personnel*

Required by

- *Occupational Safety and Health Administration (OSHA) under 29CFR1910.147*

Applicability

- *For working on exposed electrical circuits that would expose personnel to any electrical hazard operating at > 50 V, >50A, >10J. All types of equipment containing electrical, mechanical, hydraulic, pneumatic, chemical and/or thermal active or stored energy*

Items Locked Out (Off) – Tagged Out (Off)

The power source or power device

Application by

Authorized employee trained in LOTO and qualified to lock-off the equipment

Interlocks As LOTO

Interlocks are not used as a substitute for lock and tag

For Locking and Tagging

- *Padlocks, usually red-colored for personal use. Yellow-colored for administrative lock-out*
- *Tags*
- *Specialty locks (Kirk-Key Locks) for complex systems*
- *Master lock boxes*

Section 12 - Reliability, Availability and Maintainability

Reliability

According to IEEE Standard 90, reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time

Availability

The degree to which a system, subsystem, or equipment is operable and in a committable state during a mission (accelerator operation).

The ratio of the time a unit is functional during a given interval to the length of the interval.

Importance

Reliability is important because accelerators are expected to perform like industrial factories; i.e., to be on-line at all times. In particular, accelerator power supplies are expected to be available when needed, day after day, year after year. Reliability must be considered when subsystems are complex (contain large part count) or when a system is composed of a large number of subsystems or the accelerator simply will not function.

Failures lead to annoyance, inconvenience and a lasting user dissatisfaction that can play havoc with the accelerator's reputation. Frequent failure occurrences can have a devastating effect on project performance and funding.

PDF, CDF and MTBF

In this section we attempt to estimate the lifetime of complex systems. Each component of these systems will fail at a random time . Knowing the failure rates of the components, we use probability theory to estimate the system lifetime (probability of success)

We begin by introducing the non-negative probability density funtion (PDF), f(t). We then define a cumulative distribution function (CDF), F(t)which has specific properties

- *There is no probability that the component has failed before being built, so* $F(-\infty)=0$
- *It is certain that at some point in time the component will fail, so with F(t)normalized ,* $F(\infty)=1$
- *F(t) is an increasing function of t.*
- *Lastly* $0 \leq F(t) \leq 1$

The CDFcan be expressed in terms of the PDF, $F(t)=\int_{-\infty}^{t} f(t)\,dt$ *or more typically* $F(t)=\int_{0}^{t} f(t)\,dt$

f(t) is normalized such that $F(t)=\int_{-\infty}^{\infty} f(t)dt=1$

The probability that the component (hence system) has failed between t_1 *and* t_2 *is* $\int_{t_1}^{t_2} f(t)\,dt = F(t_2)-F(t_1)$

The average value of time that components of this type will fail is given by $\langle t\rangle = t\int_{0}^{t} f(t)\,dt = MTBF = MTTF$

where MTBF and MTTF are the mean time between failure or mean time to fail, respectively

Exponential Density (Distribution) Function

One probability density (distribution) function is the exponential distribution. It accurately predicts the lifetime of a component with an exponential decay, e.g., the lifetime of radioactive particles. Although there are other distributions that might be more appropriate, the exponential works reasonably well for a large class of components and is easy to use.

$f(t) = \lambda e^{-\lambda t}$ *where* λ = *failure rate of the component (number of failures / time)*

$$\int_0^\infty \lambda e^{-\lambda t}\, dt = 1$$

$$F(t) = \int_0^t \lambda e^{-\lambda t} dt = 1 - e^{-\lambda t}$$

where $1 - e^{-\lambda t}$ = *probability of failure*

lastly $\langle t \rangle = 1/\lambda$ = *MTBF = time (usually hours)*

Reliability

We now define the reliability $R_i(t)$ of the i^{th} component as the probability that the component is still functioning after a time t. We also define a complementary function $Q_i(t)$ that gives the probility that the component has failed

$Q_i(t) = 1 - e^{-\lambda t}$ *and since probability of failure=1 - reliability we see that*

$R_i(t) = e^{-\lambda t} =$ *reliability (probability of success)*

A series system is such that all subsystems or elements must work in order for the entire system to work. For such a system the total system reliability is the product of the individual component reliabilities

$$R_T = R_1 * R_2 * \ldots . * R_n = \prod_1^n R_i = \text{ probability of system success}$$

The probability of system failure is

$$Q_T = 1 - R_T = 1 - \prod_1^n R_i = 1 - \prod_1^n (1 - Q_i)$$

For a two component system $R_T = R_1 * R_2$

and $Q_T = 1 - (1 - Q_1)(1 - Q_2) = Q_1 + Q_2 - Q_1 * Q_2$

The probability of system failure is less than the sums of the probabilities for each component because of the subtraction of the failure probability products

A parallel system is such that only one subsystem or element must work in order for the entire system to work. For such a system it is easier to calculate the total system reliability by first calculating the probability of the total system failure, since all elements must fail in order for the entire system to fail. Therefore

$$R_T = 1 - Q_T = 1 - \prod_1^n Q_i = 1 - \prod_1^n (1 - R_i)$$

A general system will not be simply series or parallel. It might have some redundancy, meaning that some, but not all, of the subsystems need to work for the entire system to be functional. We break the system into individual components and examine every possible combination of the states, working or failed. These combinations are all mutually exclusive, so we just sum the probabilies of each functioning combination to get the probability of system success.

Consider a parallel system of 3 identical units requiring 2 to work for a functioning system

There are $2^n = 8$ *mutually exclusive states to examine*

$Q_1 * Q_2 * Q_3,\ \ Q_1 * Q_2 * R_3,\ Q_1 * R_2 * Q_3,\ \ Q_1 * R_2 * R_3,$

$R_1 * Q_2 * Q_3,\ \ R_1 * Q_2 * R_3,\ R_1 * R_2 * Q_3,\ \ R_1 * R_2 * R_3$

Of these states the fourth, sixth, seventh and eighth describe a functing system. Therefore the total system reliability is

$R_T = Q_1 * R_2 * R_3 + R_1 * Q_2 * R_3 + R_1 * R_2 * Q_3 + R_1 * R_2 * R_3$

Recognizing that $Q_i + R_i = 1$

$R_T = Q_1 * R_2 * R_3 + R_1 * Q_2 * R_3 + R_1 * R_2 * Q_3 + R_1 * R_2 * (1 - Q_3)$

$R_T = Q_1 * R_2 * R_3 + R_1 * Q_2 * R_3 + R_1 * R_2$

The counting on the previous page gets complicated very quickly. Fortunately the calculations can be expressed in a combinational formula which gives the system reliability for m of n components connected in parallel

$$R_T = \sum_{k=m}^{n} \frac{n!}{(n-k)!k!} (R_k)^k (Q_k)^{n-k}$$

For a system described by an exponential distribution

$$R_T = \sum_{k=m}^{n} \frac{n!}{(n-k)!k!} (e^{-\lambda_k t})^k (1-e^{-\lambda_k t})^{n-k}$$

Glossary - Math Expressions

Failure rate is constant	λ	(hr^{-1})
Mission time	t	(hr)
Probability Density Function (PDF)	$f(t) = \lambda e^{-\lambda t}$	$(dimensionless)$
Cumulative Density Function (CDF)	$F(t) = 1 - e^{-\lambda t}$	$(dimensionless)$
Reliability (Success probability)	$R(t) = e^{-\lambda t}$	$(dimensionless)$
Expected time to failure (MTBF)	$E(T) = \int_{-\infty}^{\infty} t\, f(t)\, dt = \frac{1}{\lambda}$	(hr)

Glossary - Math Expressions

Failure rate of N series critical components	$\lambda_{composite}$	$= \sum_{i=1}^{N} \lambda_i$	(hr^{-1})
Reliability of N series components	$R_T(t)$	$= \prod_{i=1}^{N} e^{-\lambda_i t} = \prod_{i=1}^{N} R_i(t)$	$(dimensionless)$
Failure N series components	$Q_T(t)$	$= 1 - R_T(t) = 1 - \prod_{i=1}^{N} (1 - Q_i(t))$	$(dimensionless)$
Reliability of N parallel components	$R_T(t)$	$= 1 - \prod_{i=1}^{N} (1 - R_i(t))$	$(dimensionless)$

The reliability of parallel connected m out of n components

$$R_{system}(t) = \sum_{k=m}^{n} \left(\frac{n!}{(n-k)!\,k!} \right) \left(e^{-\lambda_k t} \right)^k \left(1 - e^{-\lambda_k t} \right)^{n-k} \qquad (dimensionless)$$

λ_k = constant = failure rate of individual component

k = index counter, m = minimum number of components needed for operation

n = total number of components in the system

Special cases occurs when $m = n$ or when $m=n=1$

$R(t) = e^{-n\lambda t}$ $\qquad$ $R(t) = e^{-\lambda t}$

Glossary - Math Expressions

MTBF of series critical components	$MTBF = 1/\lambda_{composite}$	(hr)
MTBF of N series identical components	$MTBF_{composite} = MTBF_i / N$	(hr)
Mean time to repair or recover is	$MTTR$	(hr)
Availability is	$A = \dfrac{MTBF}{MTBF + MTTR}$	$(dimensionless)$
Availabilty of series components	$A_{composite} = \prod_{i=1}^{N} A_i$	$(dimensionless)$
Availbilty of identical components	$A_{composite} = A^N$	$(dimensionless)$

Glossary of Terms and Definitions

Availability	*Ratio of operating time to operating + downtime A=MTBF/(MTBF+MTTR). This is a dimensionless number*
MTBF	*Mean time between failures in hours*
$MTBF_O$	*The increased MTBF in hours that considers equipment operation at lower than rated power levels*
$MTBF_R$	*MTBF with operation at ratings - in hours*
MTTR	*The mean time to repair and recover beam in hours*
R(t)	*Reliability or probability of success over the mission time (Typically 9 months = 6600hours)*
λ, λ_O, λ_R	*Failure rates in hr* $^{-1}$*. These are the reciprocals of the MTBFs*
1/1	*One full rated power supply. Rated power = delivered power*
1/2	*One out of two redundant power module configuration*
2/3	*Two out of three redundant power module configuration*
3/4	*Three out of four redundant power module configuration*
4/5	*Four out of five redundant power module configuration*

Homework Problem # 17

A. At least 1 of 4 parallel identical power supplies in an accelerator must continue to operate for the system to be successful. Let R_i =0.9. Find the probability of success.

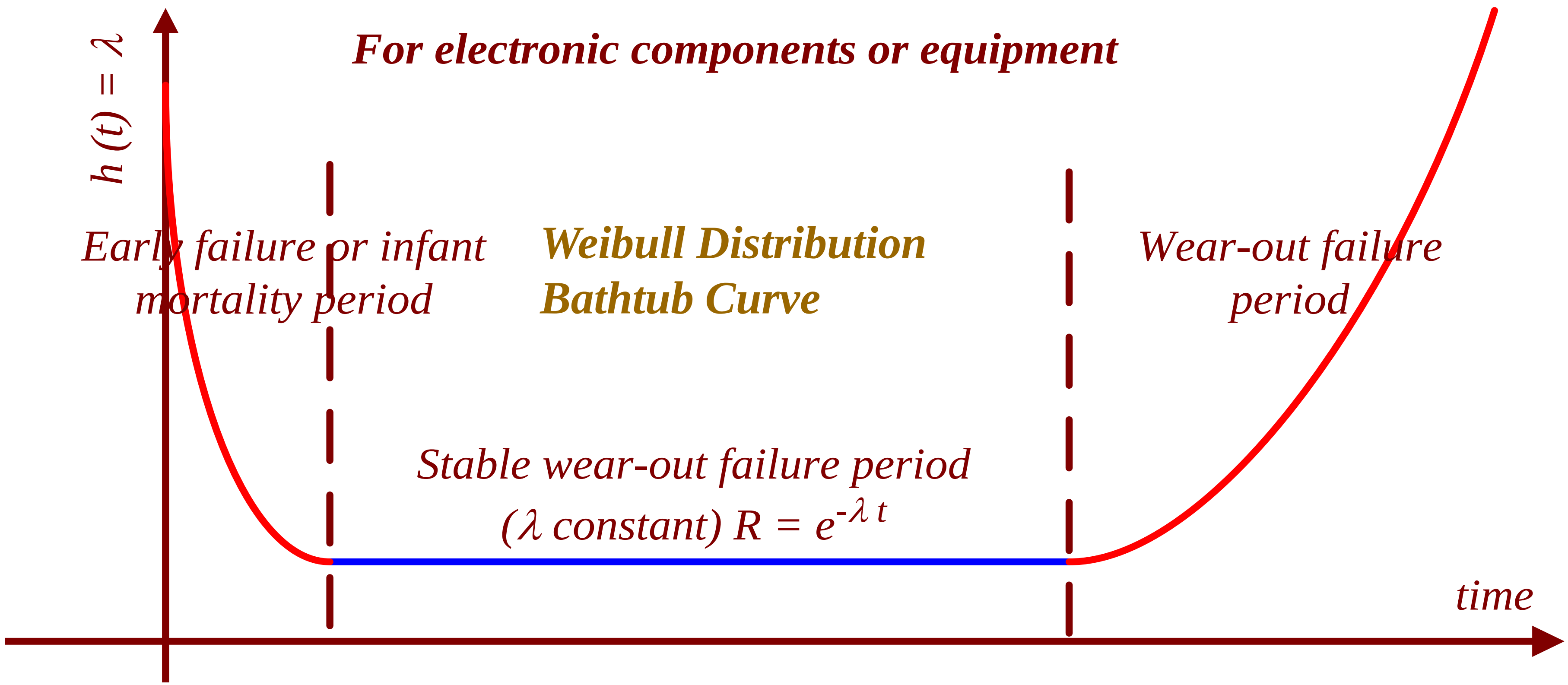
B. Repeat for at least 2 out of 4 success

C. Repeat for at least 3 out of 4 success

D. Repeat for 4 out of 4 success

Solution:

Glossary - Failure Rate Curve



- ***Infant mortality*** *manufacturing defects, dirt, impurities. Infant mortality reduced for customer by burn-in and stress-screening*
- ***Stable wear-out*** *statistics, manufacturing anomalies, out-of tolerance conditions*
- ***Wear-out failure*** *dry electrolytic capacitors, aged and cracked cable insulation*

Reliability Calculation Standards

MIL-HDBK-217F (USA)	• *Internationally used* • *Parts count* • *Parts stress* • *Broad in scope* • *Pessimistic*
Telcordia (Bellcore) (USA)	• *National use* • *Parts count* • *Parts stress* • *Narrow scope (telecommunications)* • *Optimistic*
CNET 93 (France)	• *Limited to France* • *Parts count* • *Parts stress* • *Broad in scope*
HRD5 (UK)	• *Limited to UK* • *Parts count* • *Parts stress* • *Broad in scope*

Parts Count

- Appropriate failure rate is assigned to each part in the subsystem (power supply) that is mission critical
- Failure rates are functions of environment (Ground fixed Π_{GF} /Ground benign Π_{GB}/Ground mobile, Π_{GM}) and ambient temperature (Π_T)
- The parts count method is simple and used early in system design when detailed information is unknown
- Failure rates are summed and the following information is obtained

$$MTBF = \frac{1}{\sum \lambda} \qquad R(t) = e^{-\sum \lambda t}$$

Parts Stress – *Same as the Parts Count method, except it takes into account more detailed information about the components and their operating stresses. The detailed information is implemented via additional* Π *reliability factors, such as:*

Π_{GB} = *ground benign* $0 < \Pi_{GB} < \infty$

Π_{T} = *ambient temperature* $0 < \Pi_{T} < \infty$

Π_{MQ} = *manufacturing quality* $0 < \Pi_{MQ} < \infty$

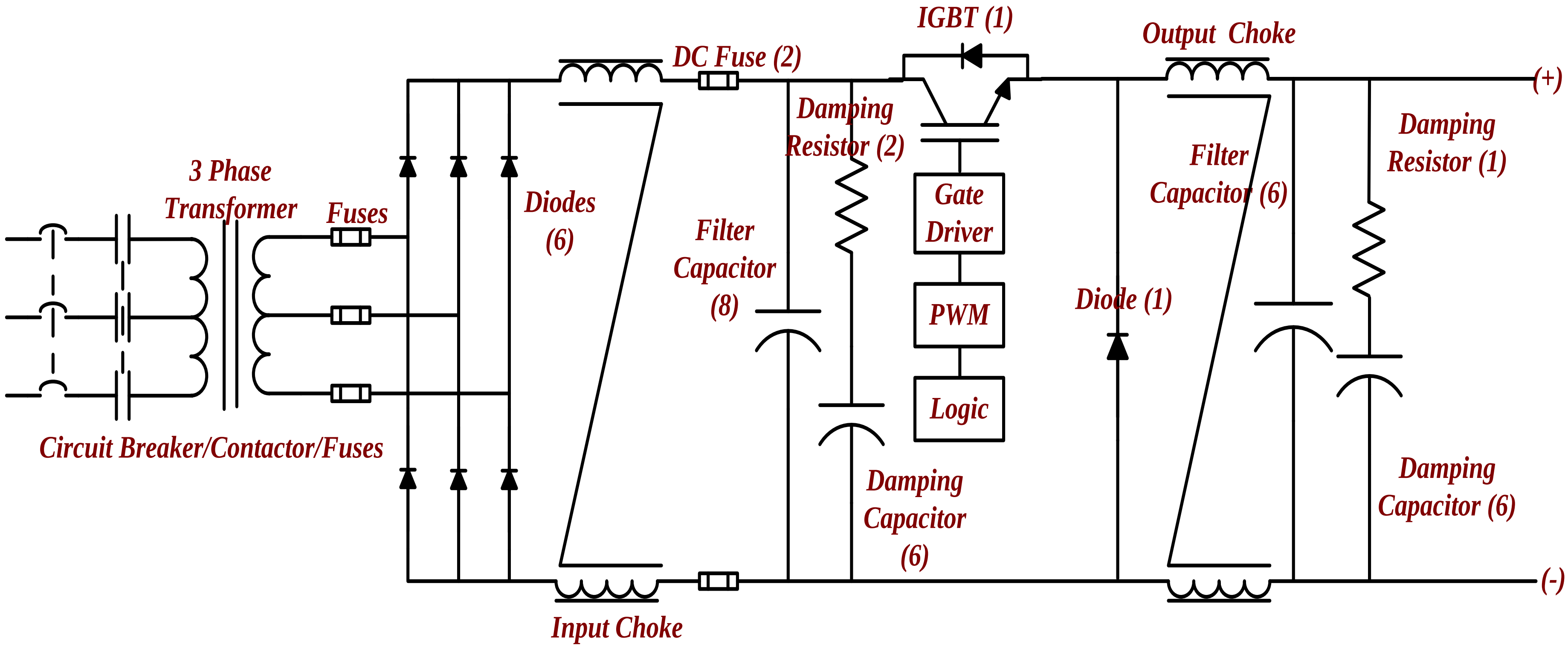
Π_{VS} = *voltage stress factor* $0 < \Pi_{VS} < \infty$

Π_{IS} = *current stress factor* $0 < \Pi_{IS} < \infty$

Π_{PS} = *power stress factor* $0 < \Pi_{PS} < \infty$

$$\lambda_{resultant} = \lambda_{initial} * \Pi_{GB} * \Pi_{T} * \Pi_{MQ} * \Pi_{VS} * \Pi_{IS} * \Pi_{PS}$$

Example of Reliability Calculation – Power Supply



Example of Reliability Calculation – Power Supply

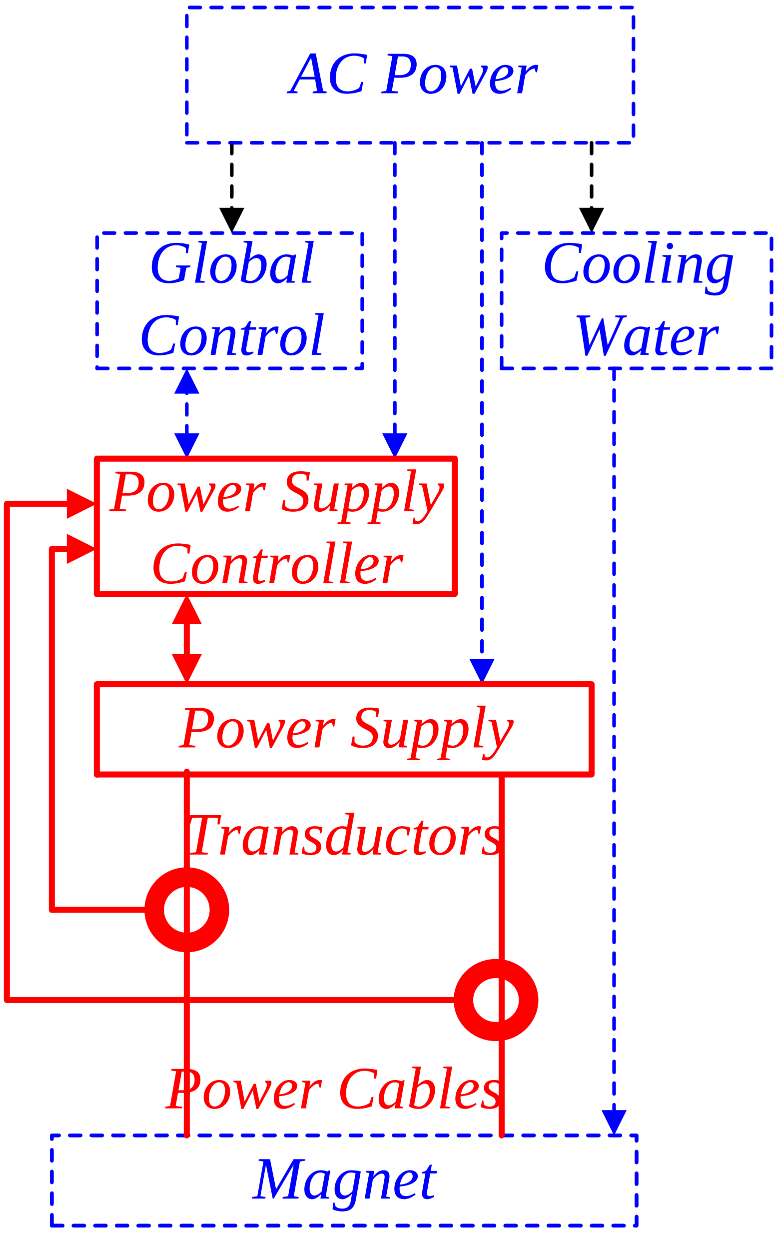
Component Description	Qty	λ	π_{GB}	π_{T}	π_{MQ}	π_{VS}	π_{IS}	π_{PS}	Mission Loss	Total Rate λ_T 10^{-6}
Circuit Breaker/Contactor/Fuse	5	0.42	1.00	1.10	1.00	1.01	1.05	1.10	Yes	2.695
3 Phase Transformer	1	0.05	1.00	1.10	1.00	1.50	1.50	1.50	Yes	0.186
Input/Output Filter Choke	2	0.02	1.00	1.10	1.10	1.42	1.60	1.75	Yes	0.144
Secondary/DC Link Fuse	2	0.08	1.00	1.10	1.89	1.02	0.95	0.90	Yes	0.291
Main Filter Capacitor	8	0.23	1.00	1.12	1.50	1.25	1.25	1.05	Yes	5.057
Damping Capacitors/Resistor	15	0.02	1.00	1.10	1.00	1.00	1.00	1.00	No	0.000
IGBT/Diode	8	0.03	1.00	1.10	1.50	1.00	1.00	1.00	Yes	0.330
Heatsink Assembly	1	0.01	1.00	1.10	1.00	1.00	1.00	1.00	Yes	0.011
Gate Driver/PWM	2	0.50	1.00	1.10	1.00	1.10	1.10	1.15	Yes	1.524
Logic Board	1	3.50	1.00	1.10	1.00	1.00	1.00	1.00	Yes	3.850
Output Filter Capacitor	6	0.25	1.00	1.10	1.00	1.25	1.25	1.00	Yes	2.578
MTBF and Total Failure Rate								60,000		16.667

Homework Problem # 18

Calculate the MTBF of a "typically commercial" 5 kW, switchmode power supply with EMI filter and appropriate electromechanical safety features amounting to 10% of the total number of components. The power supply operates at 50C ambient temperature. The power supply consists of the following components with the listed failure rates.:

- *2 each ICs, plastic linear, λ = 3.64 failures per million hours each*
- *1 each opto-isolator, λ = 1.32 failures per million hours each*
- *2 each hermetic sealed power switch transistors, λ = 0.033 failures per million hours each*
- *2 each plastic power transistors, λ = 0.026 failures per million hours each*
- *4 each plastic signal transistors, λ = 0.0052 failures per million hours each*
- *2 each hermetic sealed power diodes, λ = 0.064 failures per million hours each*
- *8 each plastic power diodes, λ = 0.019 failures per million hours each*
- *6 each hermetic sealed switch diodes, λ = 0.0024 failures per million hours each*
- *32 each composition resistors, λ = 0.0032 failures per million hours each*
- *3 each potentiometers, commercial, λ = 0.3 failures per million hours each*
- *8 each pulse type magnets, 130C rated, λ = 0.044 failures per million hours each*
- *12 each ceramic capacitors, commercial, λ = 0.042 failures per million hours each*
- *3 each film capacitors, commercial, λ = 0.2 failures per million hours each*
- *9 each Al electrolytics, commercial, λ = 0.48 failures per million hours each*

Example of Reliability Calculation – Power System



Example of Reliability Calculation – Power System

Single System Availabilty		
Component	MTBF	Availability
PS Controller	110,000	0.9999818
Power Supply	60,000	0.9999667
Transductor 1	381,500	0.9999948
Transductor 2	381,500	0.9999948
Cables	14,000,000	0.9999999
System	32,184	0.9999379

t=6574 hrs/year MTTR=2 hrs components/system

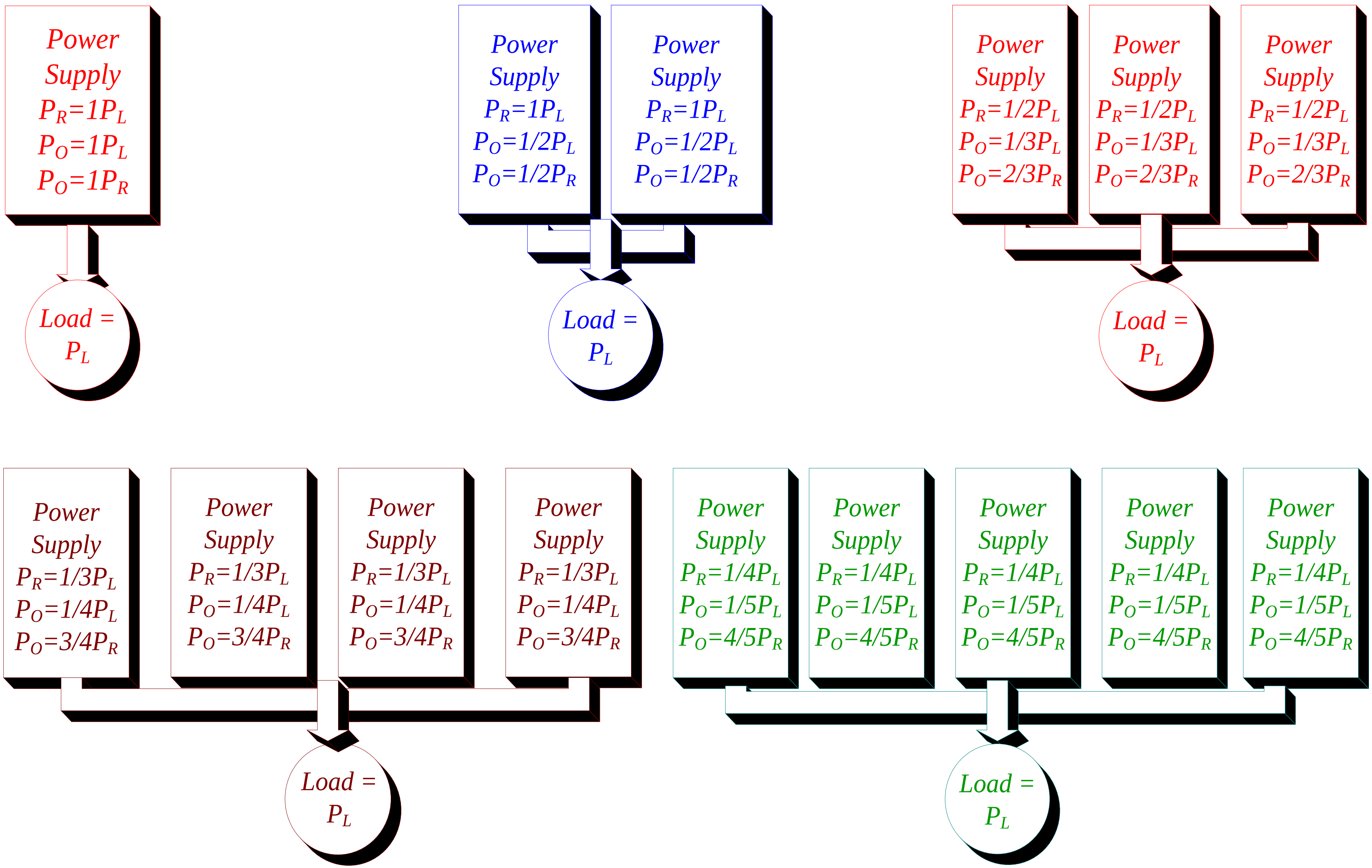
Relex by Relex Software

See Reference Appendix for web link to this manufacturers products

RelCalc by T-Cubed

See Reference Appendix for web link to this manufacturers products

Reliability/Availability Improvement By Redundancy



Reliability/Availability Improvement By Redundancy

- *Two types - Standby and Active*

  1. Standby - the redundant parts are off and only operate when the first part fails. This requires more vigilance on the part of the control system and is not covered here.

  2. Active - the redundant part(s) are on, albeit operating at a reduced power level until asked to assume increased or full load. This is easier to implement than Standby redundancy and is the more common method. We will examine this further

Availability Improvement By Oversizing and Redundancy

The general, exponential form of the Binomial Distribution for m out of n parts is

$$R(t) = \sum_{k=m}^{n} \left(\frac{n!}{(n-k)!\,k!} \right) \left(e^{-\lambda t} \right)^{k} \left(1 - e^{-\lambda t} \right)^{n-k}$$

λ = constant = failure rate

k = index counter

m = minimum number of power modules needed for operation

n = total number of power modules in the system

Special cases occurs when $m = n$ or when $m = n = 1$

$R(t) = e^{-n \lambda t}$ $\qquad$ $R(t) = e^{-\lambda t}$

Binomial Expansion 2 out of 3 example

$$R_{2/3}(t)=\sum_{k=m=2}^{n=3}\left(\frac{n!}{(n-k)!k!}\right)(e^{-\lambda t})^{k}(1-e^{-\lambda t})^{n-k}$$

$$k=2$$

$$\frac{3!}{1!2!}e^{-2\lambda t}(1-e^{-\lambda t})=3\ \ e^{-2\lambda t}\ \ \ (1-e^{-\lambda t})$$

3 cases, probability of success, probability of failure

S	S	F
S	F	S
F	S	S

3 Cases

$$k=3$$

$$\frac{3!}{0!3!}e^{-3\lambda t}(1-e^{-\lambda t})^{0}=1\ \ e^{-3\lambda t}$$

1 case, probability of success, no failure

S	S	S

1 Case

$$R_{2/3}(t)=3e^{-2\lambda t}-2e^{-3\lambda t}$$

Derivation

When $\lambda(t)$ is a function of time

General form $R(t) = e^{-\lambda(t)t}$

$$\frac{dR(t)}{dt} = -\frac{d\lambda(t)}{dt}e^{-\lambda(t)t} - \lambda(t)e^{-\lambda(t)t}$$

$$\frac{d\lambda(t)}{dt} \text{ is } << \lambda(t)$$

$$\frac{dR(t)}{dt} = -\lambda(t)e^{-\lambda(t)t} \quad \text{but } e^{-\lambda(t)t} = R(t)$$

$$\lambda(t) = \frac{-\frac{dR(t)}{dt}}{R(t)}$$

If λ is a constant then the above reduces to $\lambda(t)=\lambda$

$$MTBF(t) = \frac{R(t)}{-\frac{dR(t)}{dt}}$$

For the m out of n case, where $m \neq n$

n quantity of $\frac{m}{n}$ *rated power supplies. Each power supply operates at* $\frac{m}{n}$ *rated* P_R

$$P_O = \frac{m}{n} P_R$$

$$MTBF_O = \frac{P_R}{P_O} MTBF_R = \frac{n}{m} MTBF_R \qquad \lambda_O = \frac{m}{n} \lambda_R$$

linear relationship is conservative

$$R_{Om/n}(t) = \sum_{k=m}^{n} \left(\frac{n!}{(n-k)!\,k!} \right) \left(e^{-\lambda_O t} \right)^k \left(1 - e^{-\lambda_O t} \right)^{n-k} = n e^{-m\lambda_O t} - m e^{-n\lambda_O t}$$

$$MTBF_{Om/n}(t) = \frac{n e^{-m\lambda_O t} - m e^{-n\lambda_O t}}{mn\lambda_O e^{-m\lambda_O t} - mn\lambda_O e^{-n\lambda_O t}}$$

$$A_{Om/n}(t) = \frac{MTBF_{Om/n}(t)}{MTBF_{Om/n}(t) + MTTR}$$

For the case of 1 power supply with a power rating equal to the required operational power

$$P_R = P_O$$

$$MTBF_R = MTBF_O$$

$$\lambda_R = \lambda_O$$

$$R_O = e^{-\lambda_O t} = e^{-\lambda_R t}$$

$$A_O = \frac{MTBF_O}{MTBF_O + MTTR} = \frac{MTBF_R}{MTBF_R + MTTR}$$

For the m=1 out of n=2 case

2- full rated rated power supplies. Each power supply operates at $\frac{1}{2}$ *rated* P_R

$$MTBF_O = \frac{P_R}{P_O} MTBF_R = 2\,MTBF_R \qquad \lambda_O = \frac{1}{2}\lambda_R$$

$$R_{O1/2}(t) = 2e^{-\lambda_O t} - e^{-2\lambda_O t}$$

$$MTBF_{O1/2}(t) = \frac{2e^{-\lambda_O t} - e^{-2\lambda_O t}}{2\lambda_O e^{-\lambda_O t} - 2\lambda_O e^{-2\lambda_O t}}$$

$$A_{O1/2}(t) = \frac{MTBF_{O1/2}(t)}{MTBF_{O1/2}(t) + MTTR}$$

For the m=2 out of n=3 case

3-1/2 rated power supplies. Each power supply operates at 2/3 rated P_R

$$MTBF_O = \frac{P_R}{P_O} MTBF_R = \frac{3}{2} MTBF_R \qquad \lambda_O = \frac{2}{3}\lambda_R$$

$$R_{O2/3}(t) = 3e^{-2\lambda_O t} - 2e^{-3\lambda_O t}$$

$$MTBF_{O2/3}(t) = \frac{3e^{-2\lambda_O t} - 2e^{-3\lambda_O t}}{6\lambda_O e^{-2\lambda_O t} - 6\lambda_O e^{-3\lambda_O t}}$$

$$A_{O2/3}(t) = \frac{MTBF_{O2/3}(t)}{MTBF_{O2/3}(t) + MTTR}$$

For the m=3 out of n=4 case

4-3/4 rated power supplies. Each power supply operates at 3/4 rated P_R

$$MTBF_O = \frac{P_R}{P_O} MTBF_R = \frac{4}{3} MTBF_R \qquad \lambda_O = \frac{3}{4}\lambda_R$$

$$R_{O3/4}(t) = 4e^{-3\lambda_O t} - 3e^{-4\lambda_O t}$$

$$MTBF_{O3/4}(t) = \frac{4e^{-3\lambda_O t} - 3e^{-4\lambda_O t}}{12\lambda_O e^{-3\lambda_O t} - 12\lambda_O e^{-4\lambda_O t}}$$

$$A_{O3/4}(t) = \frac{MTBF_{O3/4}(t)}{MTBF_{O3/4}(t) + MTTR}$$

For the m=4 out of n=5 case

5-4/5 rated power supplies. Each power supply operates at 4/5 rated P_R

$$MTBF_O = \frac{P_R}{P_O} MTBF_R = \frac{5}{4} MTBF_R \qquad \lambda_O = \frac{4}{5}\lambda_R$$

$$R_{O4/5}(t) = 5e^{-4\lambda_O t} - 4e^{-5\lambda_O t}$$

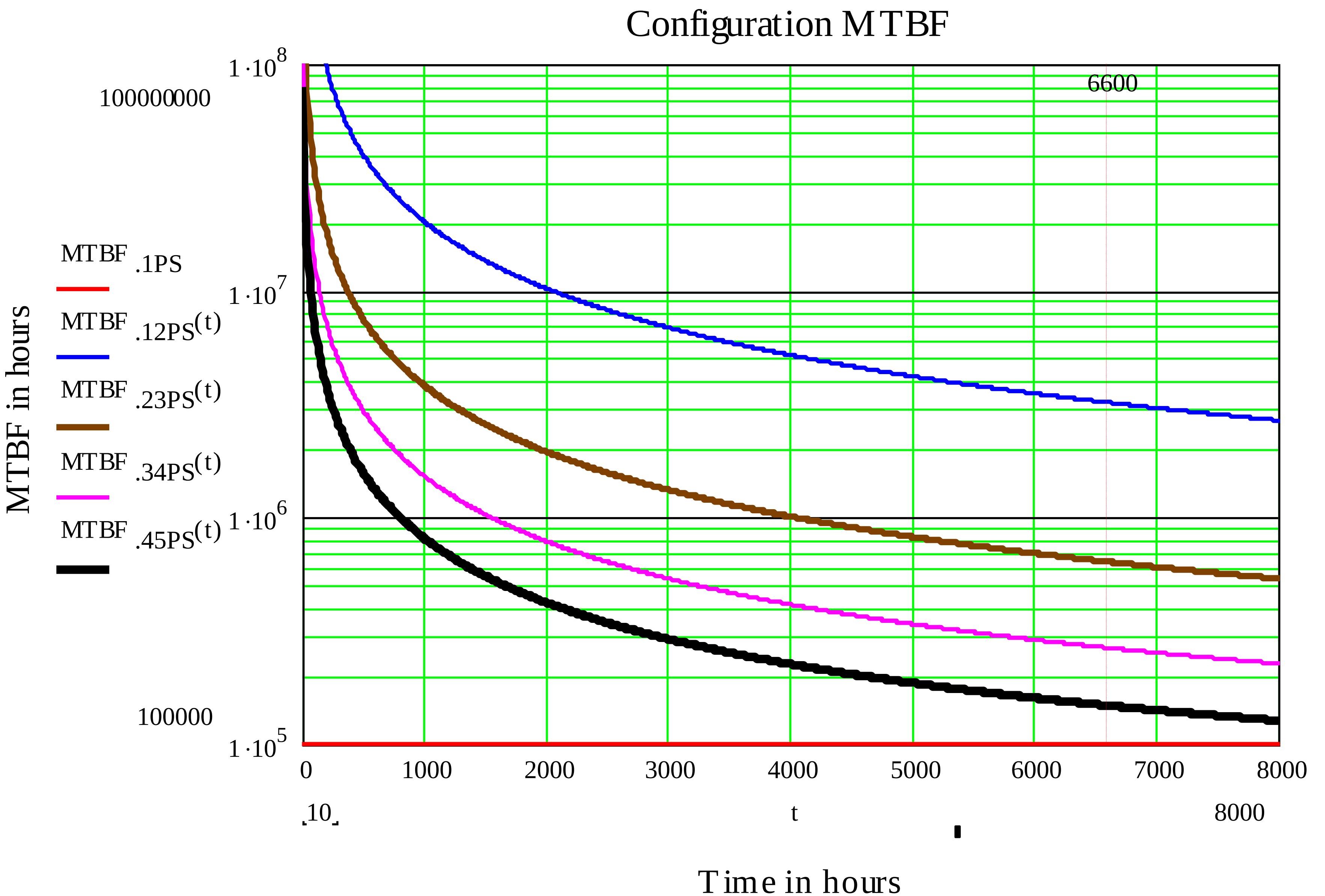
$$MTBF_{O4/5}(t) = \frac{5e^{-4\lambda_O t} - 4e^{-5\lambda_O t}}{20\lambda_O e^{-4\lambda_O t} - 20\lambda_O e^{-5\lambda_O t}}$$

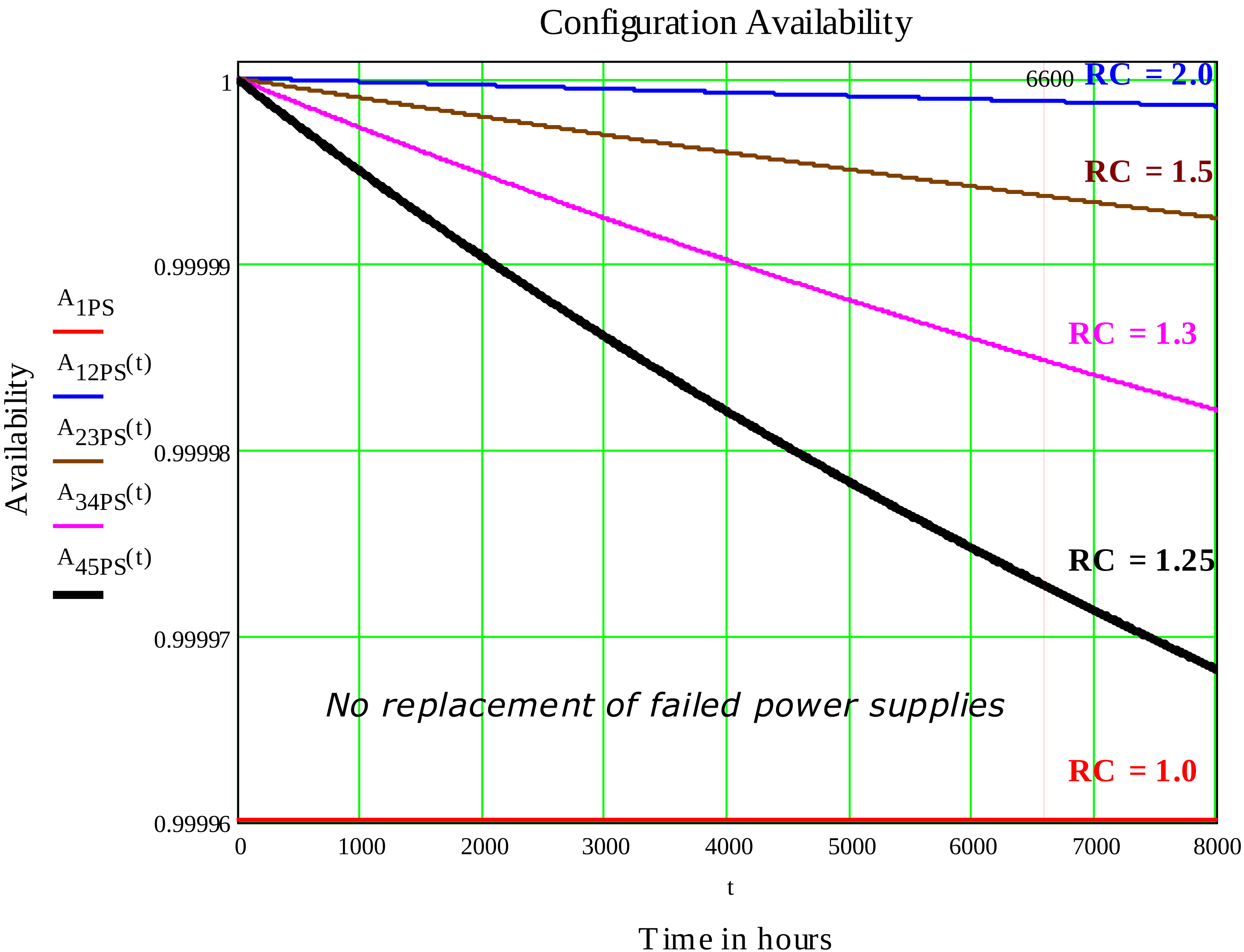
$$A_{O4/5}(t) = \frac{MTBF_{O4/5}(t)}{MTBF_{O4/5}(t) + MTTR}$$

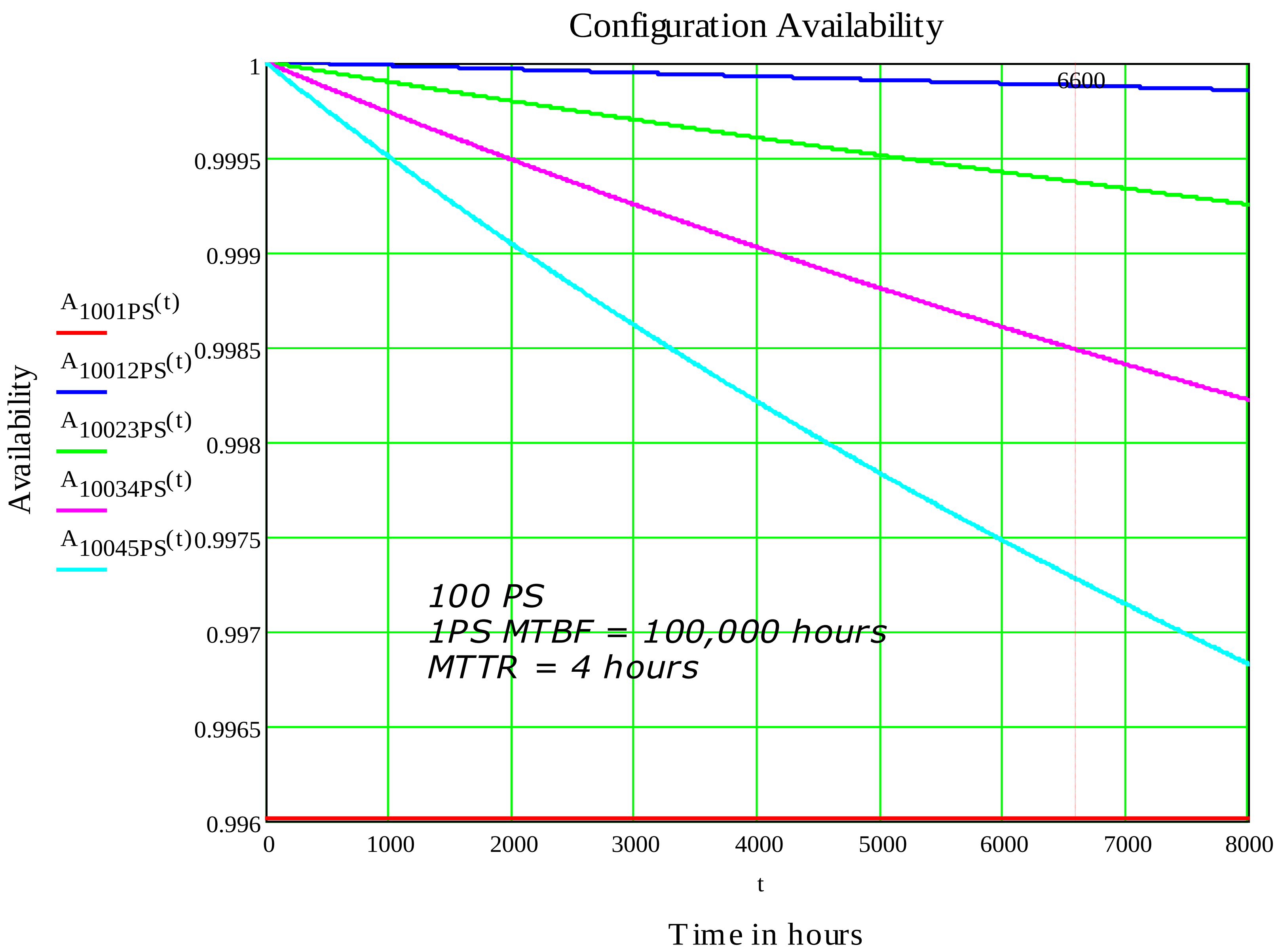
Active Redundancy Power Supply Reliability Summary

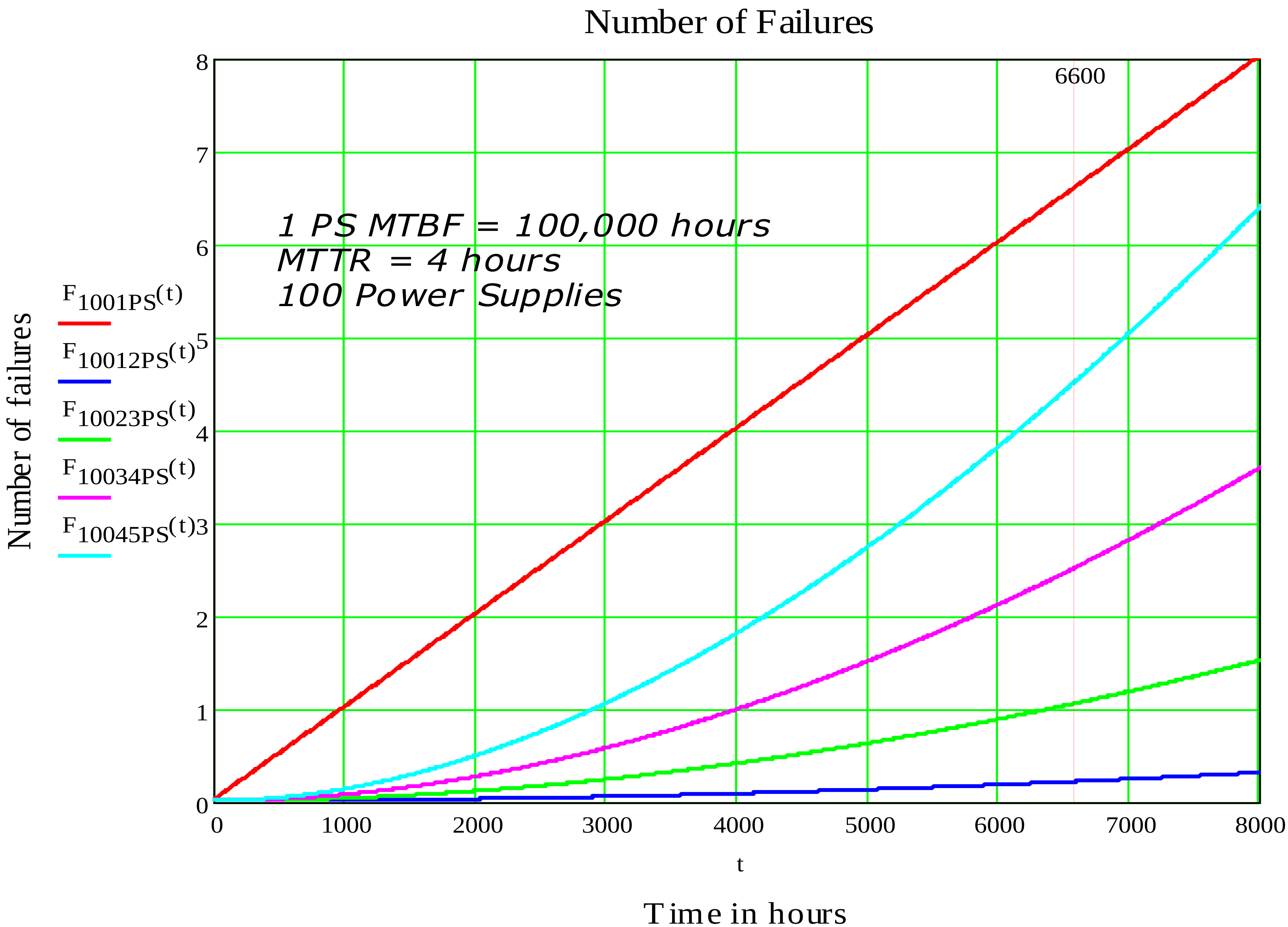
PS		Redundant Power Supplies		
1FR	$\lambda_O = \lambda_R$	$R_O = e^{-\lambda_O t}$	$MTBF_O = MTBF_R$	$A_O = \dfrac{MTBF_O}{MTBF_O + MTTR}$
1/2	$\lambda_O = \frac{1}{2}\lambda_R$	$R_{O1/2} = 2e^{-\lambda_O t} - e^{-2\lambda_O t}$	$MTBF_{O1/2}(t) = \dfrac{2e^{-\lambda_O t} - e^{-2\lambda_O t}}{2\lambda_O e^{-\lambda_O t} - 2\lambda_O e^{-2\lambda_O t}}$	$A_{O1/2}(t) = \dfrac{MTBF_{O1/2}(t)}{MTBF_{O1/2}(t) + MTTR}$
2/3	$\lambda_O = \frac{2}{3}\lambda_R$	$R_{O2/3} = 3e^{-2\lambda_O t} - 2e^{-3\lambda_O t}$	$MTBF_{O2/3}(t) = \dfrac{3e^{-2\lambda_O t} - 2e^{-3\lambda_O t}}{6\lambda_O e^{-2\lambda_O t} - 6\lambda_O e^{-3\lambda_O t}}$	$A_{O2/3}(t) = \dfrac{MTBF_{O2/3}(t)}{MTBF_{O2/3}(t) + MTTR}$
3/4	$\lambda_O = \frac{3}{4}\lambda_R$	$R_{O3/4} = 4e^{-3\lambda_O t} - 3e^{-4\lambda_O t}$	$MTBF_{O3/4}(t) = \dfrac{4e^{-3\lambda_O t} - 3e^{-4\lambda_O t}}{12\lambda_O e^{-3\lambda_O t} - 12\lambda_O e^{-4\lambda_O t}}$	$A_{O3/4}(t) = \dfrac{MTBF_{O3/4}(t)}{MTBF_{O3/4}(t) + MTTR}$
4/5	$\lambda_O = \frac{4}{5}\lambda_R$	$R_{O4/5} = 5e^{-4\lambda_O t} - 4e^{-5\lambda_O t}$	$MTBF_{O4/5}(t) = \dfrac{5e^{-4\lambda_O t} - 4e^{-5\lambda_O t}}{20\lambda_O e^{-4\lambda_O t} - 20\lambda_O e^{-5\lambda_O t}}$	$A_{O4/5}(t) = \dfrac{MTBF_{O4/5}(t)}{MTBF_{O4/5}(t) + MTTR}$

Active Redundancy MTBF Plot




Configuration Availability
1
0.99999
0.99998
0.99997
0.99996
0
1000
2000
3000
4000
5000
6000
7000
8000
t
Time in hours
Availability
A_{1PS}
$A_{12PS}(t)$
$A_{23PS}(t)$
$A_{34PS}(t)$
$A_{45PS}(t)$
6600
RC = 2.0
RC = 1.5
RC = 1.3
RC = 1.25
RC = 1.0
No replacement of failed power supplies


Configuration Availability
Availability
1
0.9995
0.999
0.9985
0.998
0.9975
0.997
0.9965
0.996
0
1000
2000
3000
4000
5000
6000
7000
8000
6600
t
Time in hours
$A_{1001PS}(t)$
$A_{10012PS}(t)$
$A_{10023PS}(t)$
$A_{10034PS}(t)$
$A_{10045PS}(t)$
100 PS
1PS MTBF = 100,000 hours
MTTR = 4 hours


Number of Failures
8
7
6
5
4
3
2
1
0
0
1000
2000
3000
4000
5000
6000
7000
8000
6600
t
Time in hours
Number of failures
1 PS MTBF = 100,000 hours
MTTR = 4 hours
100 Power Supplies
F1001PS(t)
F10012PS(t)
F10023PS(t)
F10034PS(t)
F10045PS(t)

Homework Problem # 19

Two inverter stages in an uninterruptible power supply are to be connected in parallel. each is capable of full-load capability. The calculated failure rate of each stage is l = 200 failures per million hours.

A. *What is the probability that each inverter will remain failure free for a mission time of 1000 hours and*

B. *What is the probability that the system will operate failure free for 1000 hours?*

Solution:

Homework Problem # 20

For a critical mission, 3 power supplies, each capable of supplying the total required output, are to be paralleled. The power supplies are also decoupled such that a failure of any power supply will not affect the output. The calculated failure rate of each power supply is 4 per million hours.

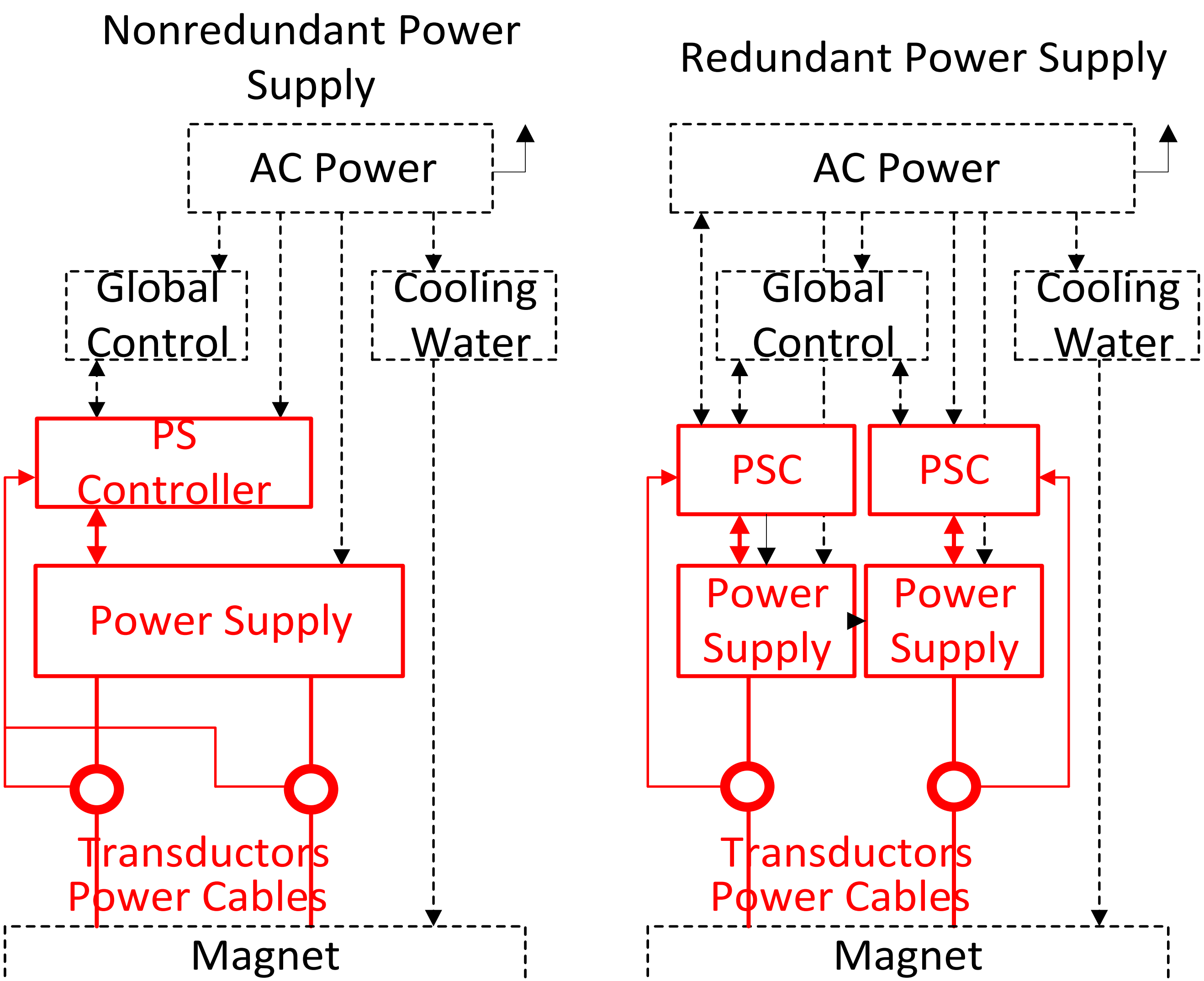
A. What is the probability that each power supply will operate failure free for 5 years?

B. What is the probability that the system will operate failure free for 5 years? That is, only 1 out of the 3 power supplies is needed in order for the system to operate. Solution below.

SLAC Next-Generation
High Availability Power Supply

Dave MacNair
SLAC National Accelerator Laboratory
Power Conversion Department (PCD)

Why High Availability is Essential

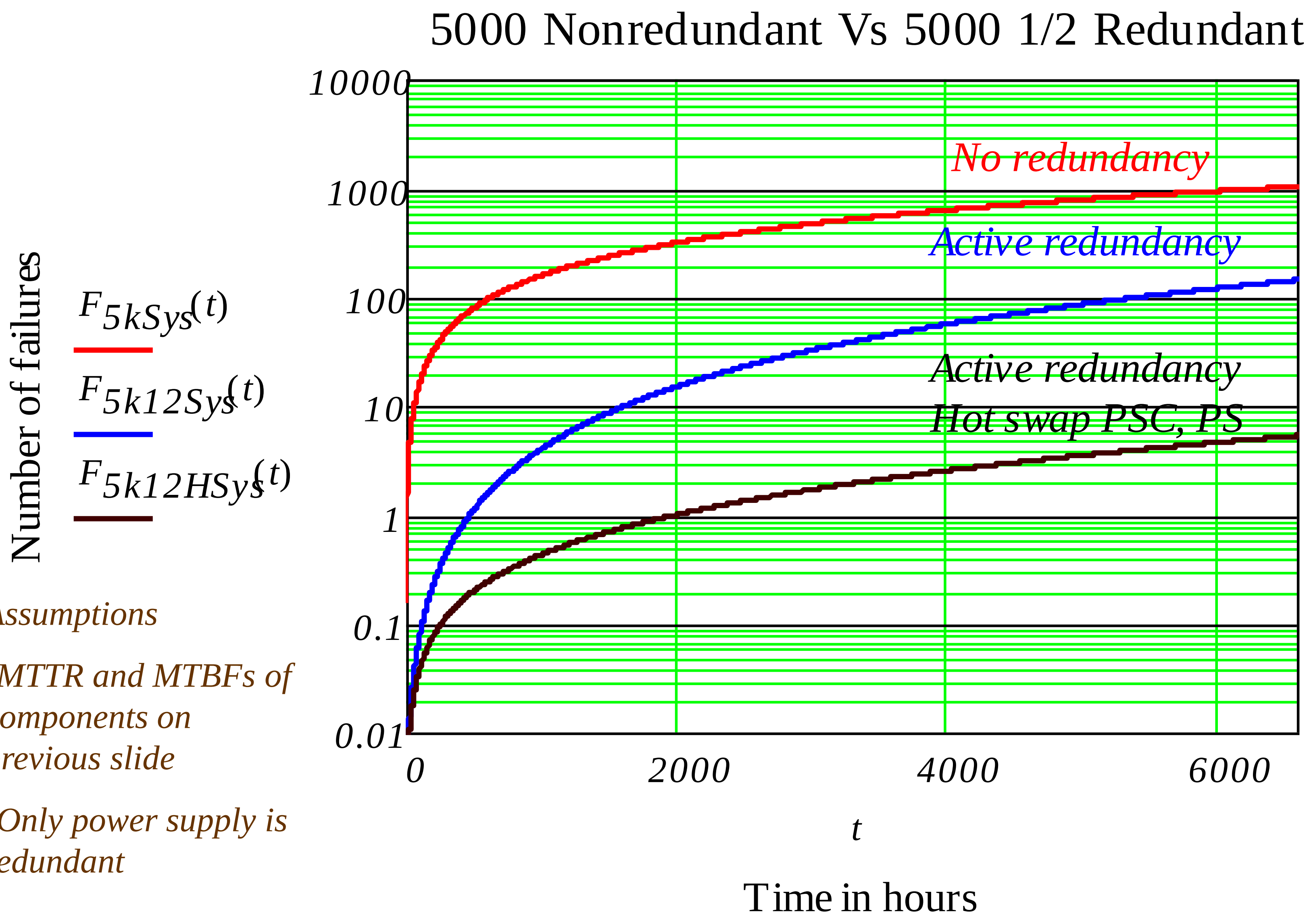


Item	*MTBF kHrs*
PSC	*110*
PS	*60*
Transductor	*381.5*
Cables/ Connectors	*14000*

MTTR = 2 Hours

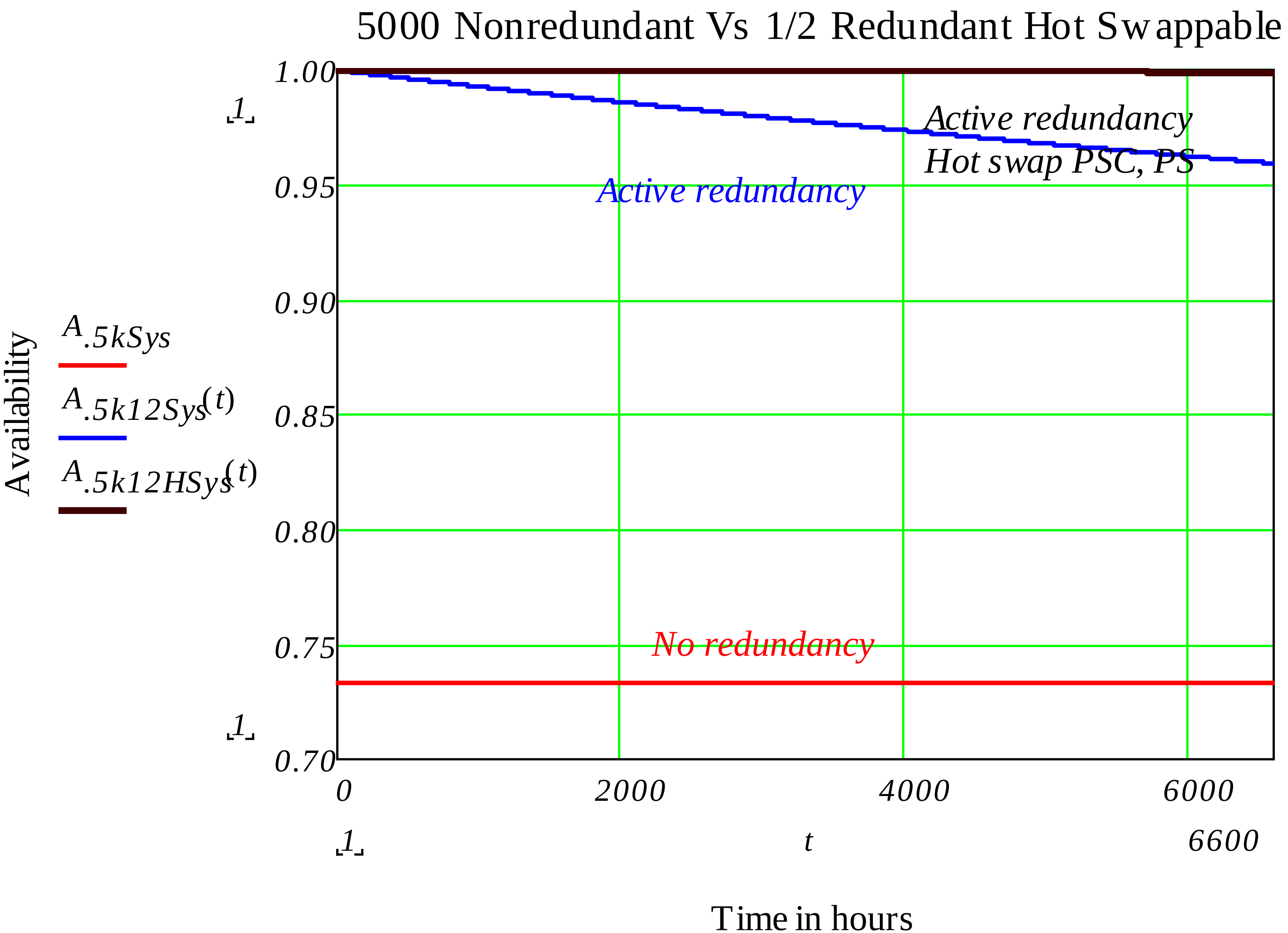
PAC 2001 Chicago, Illinois

Bellomo, Donaldson, MacNair



Assumptions

- *MTTR and MTBFs of components on previous slide*
- *Only power supply is redundant*



It is clear that redundancy and hot swap are needed

SLAC Projects with Non-redundant or Redundant Power Supplies

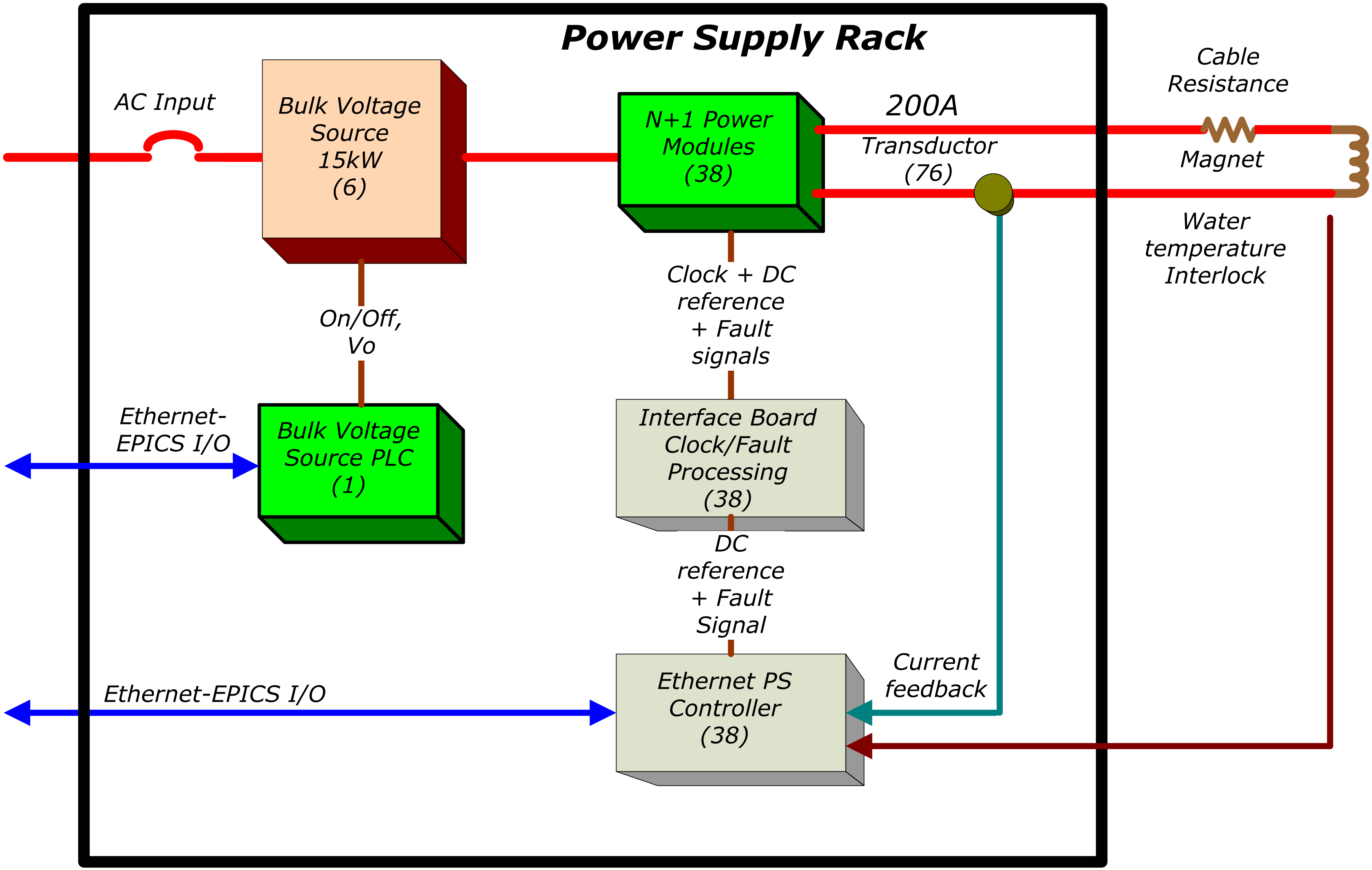
Non-redundant - PEP II, SPEAR 3, LCLS (1994 – 2006)

- *Power supply quantity is hundreds, not thousands*
- *Power supply availability budget is modest 98%*
- *Non-redundant supplies satisfied availability budget*
- *Redundant power systems not readily available from industry*
- *Redundant systems would not fit within cost and schedule constraints*

Redundant - KEK ATF 2 (2006 – 2008)

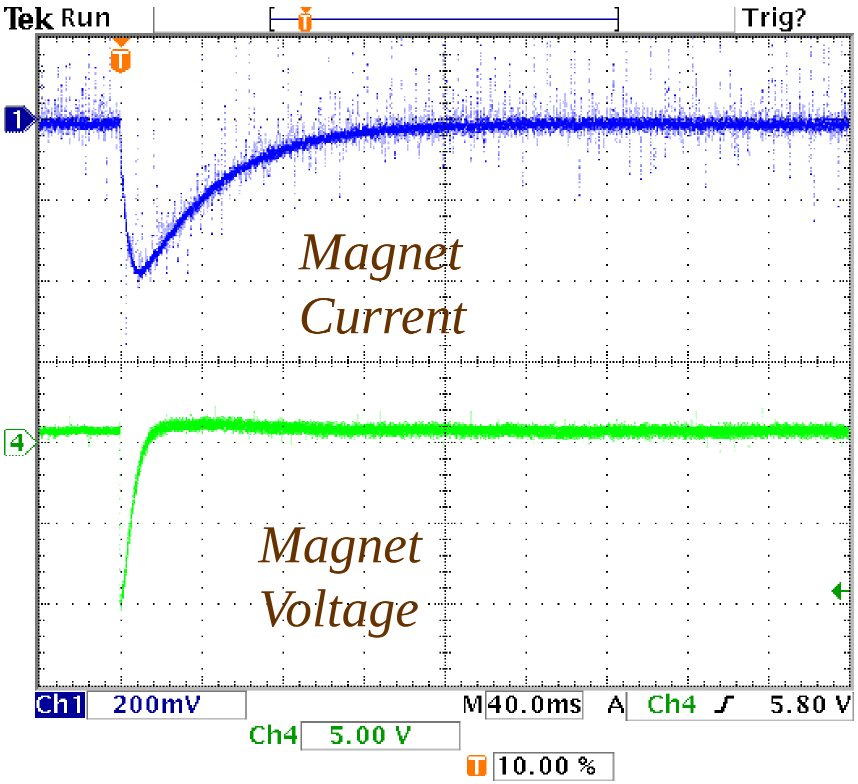
- *Mock-up of ILC Final Focus accelerator*
- *Magnet power supplies ILC-like*

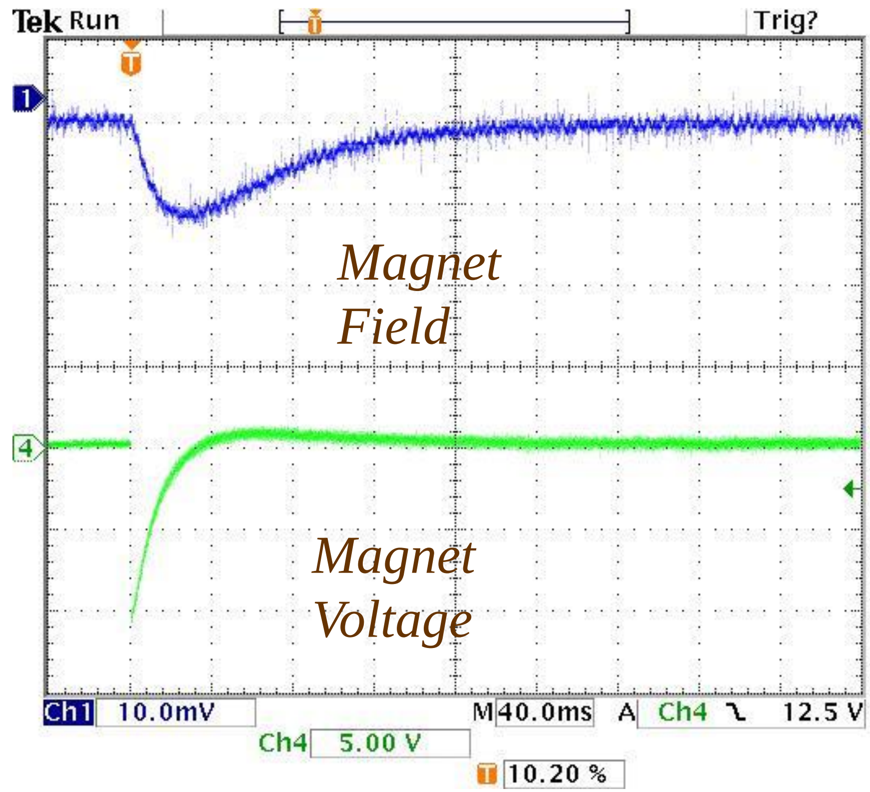
ATF2 Block Diagram



ATF2 – at KEK

ATF2 Current and Field Recovery Plots





- *During power module loss measured 6A magnet current drop at 150A*
- *100 Gauss drop at 3.1 kilogauss. 200mS recovery with no overshoot, no re-standardize needed*

Next Generation High Availability Power Supply (HAPS)

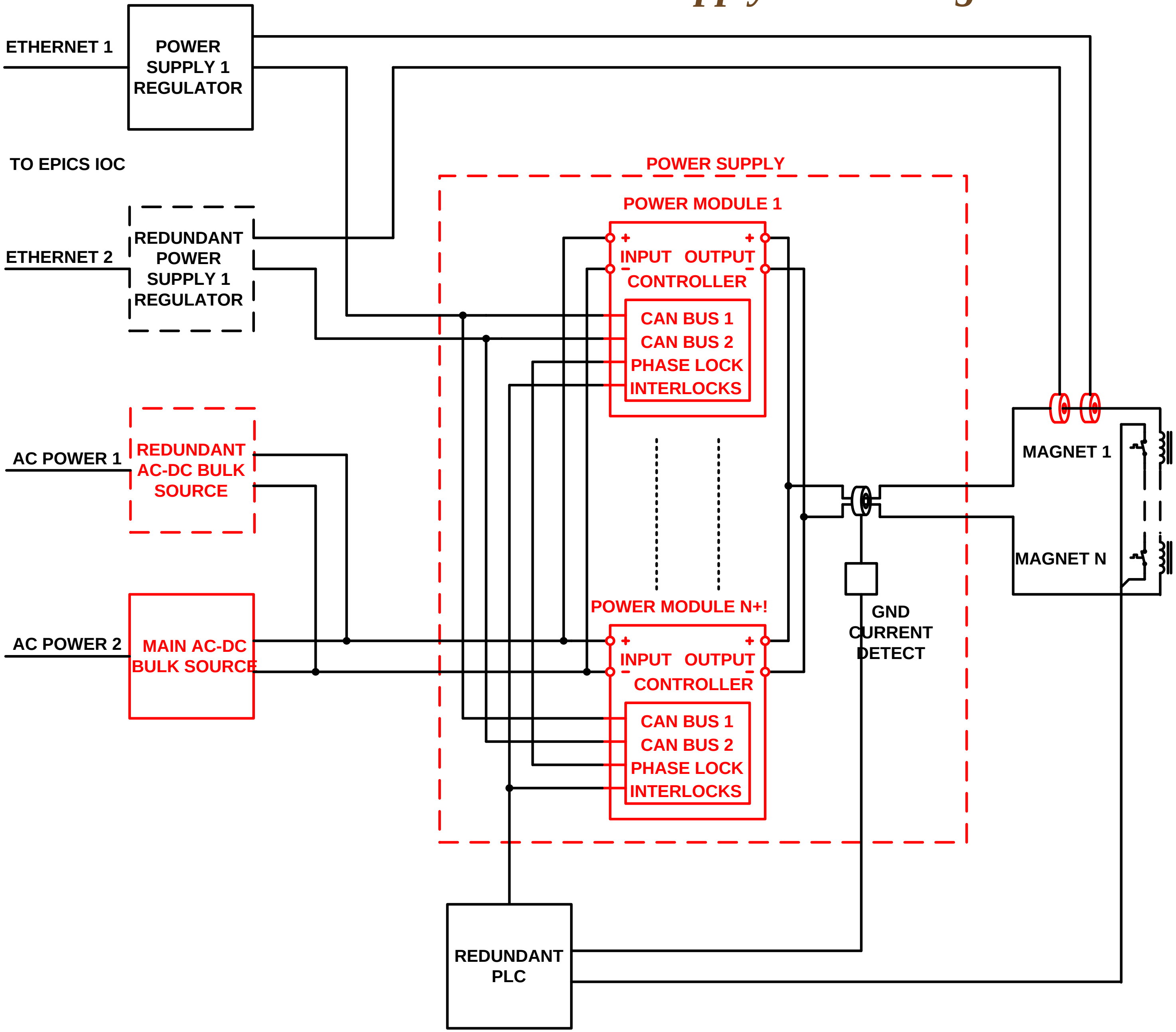
Goals

- *All components N+1 modular and redundant*
- *Power module hot-swappable*
- *Unipolar or bipolar output from a single unipolar bulk voltage source*
- *Imbedded controller with digital current regulation*
- *Capable of driving superconducting magnets*
- *High bandwidth for use in BBA or closed orbit correction systems*
- *High stability and precision output current*
- *High accuracy read-backs*
- *Scalable to higher output levels*

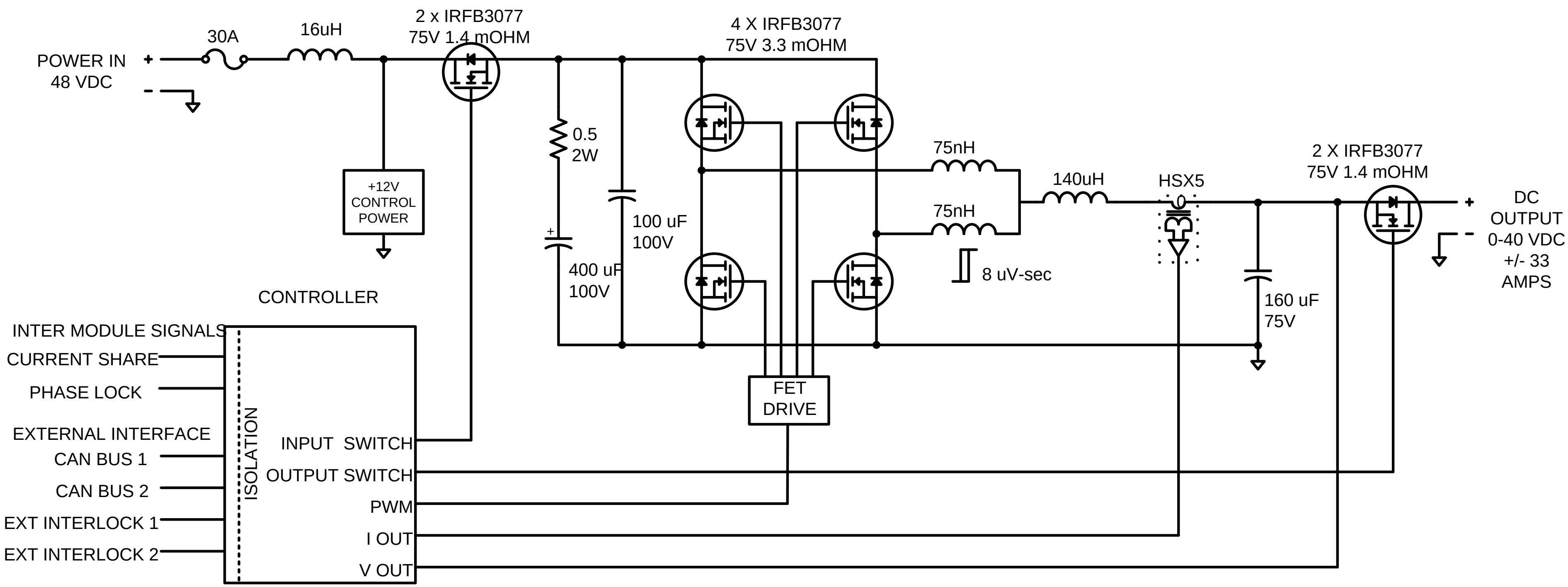
Applications

- *ILC and other future accelerators*

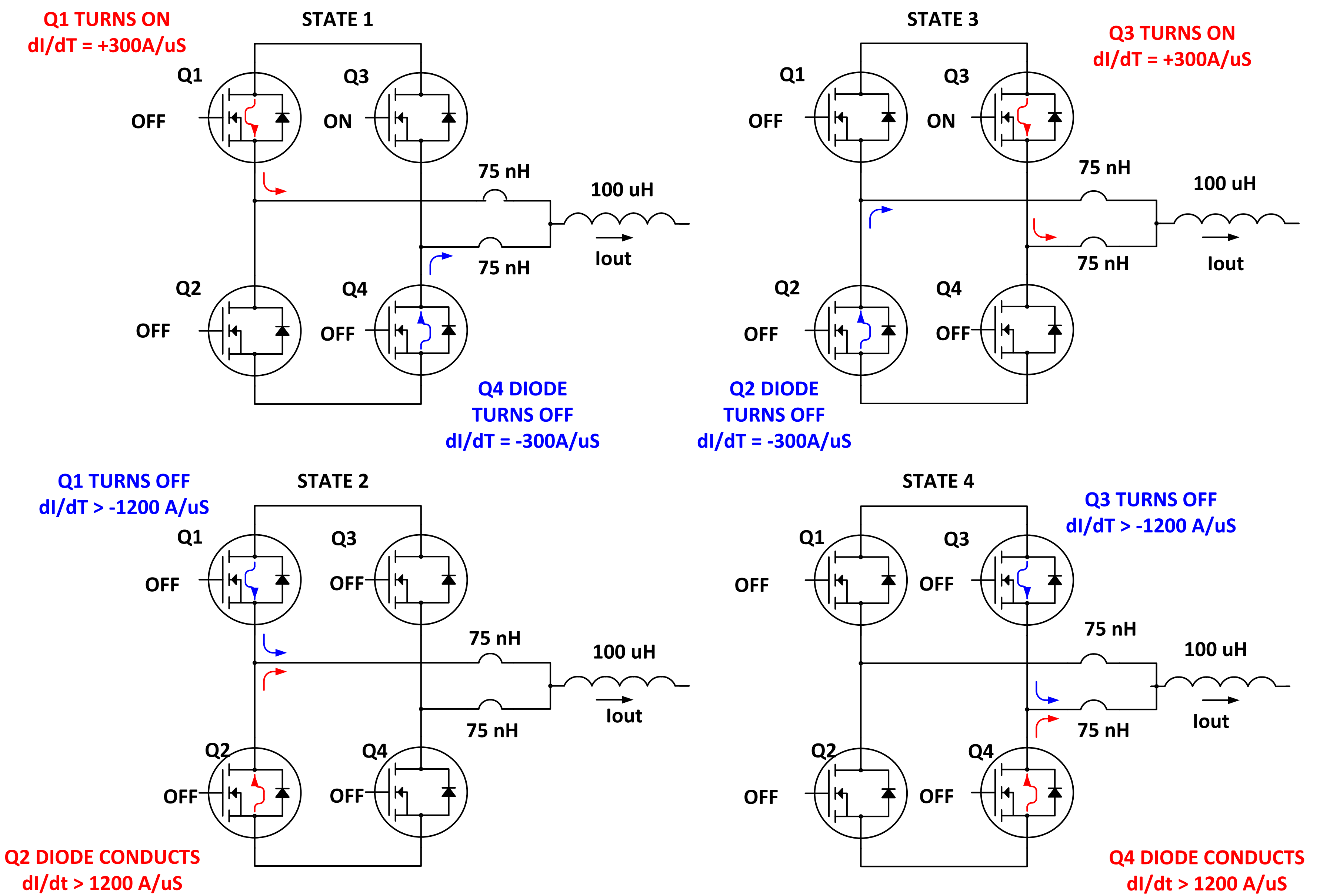
Next Generation Power Supply Block Diagram



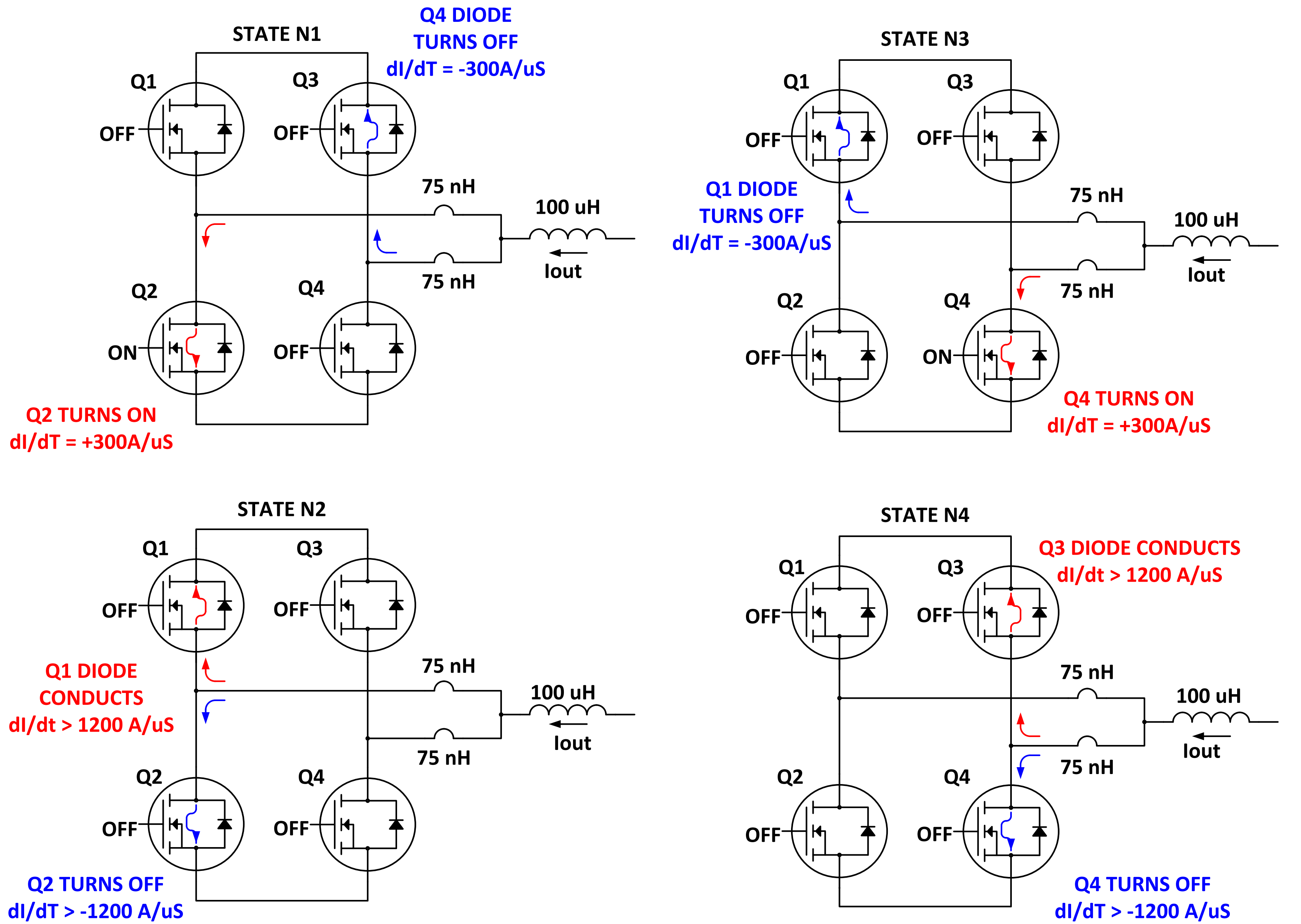
Next Generation Power Module Schematic



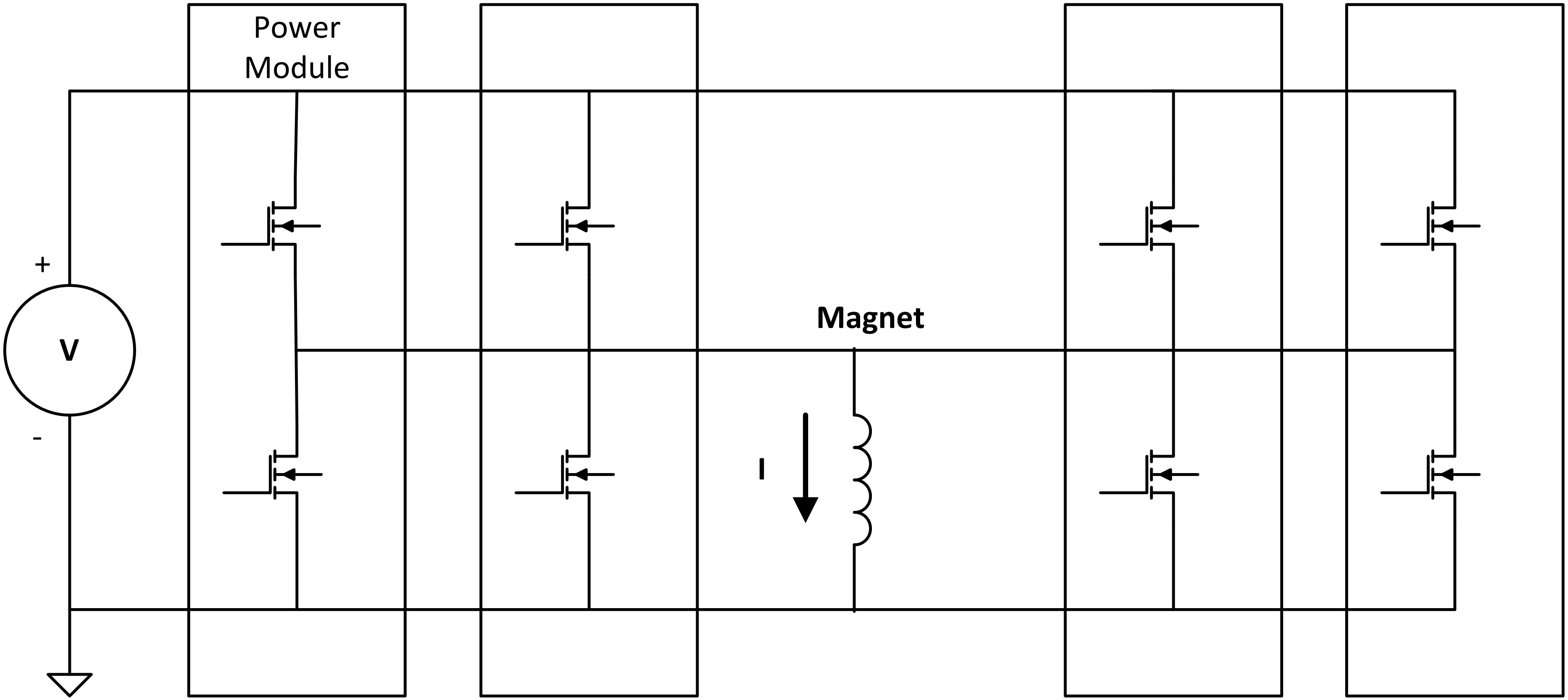
Next Generation Positive Output Current (Q1 – Q2 – Q3 – Q4)



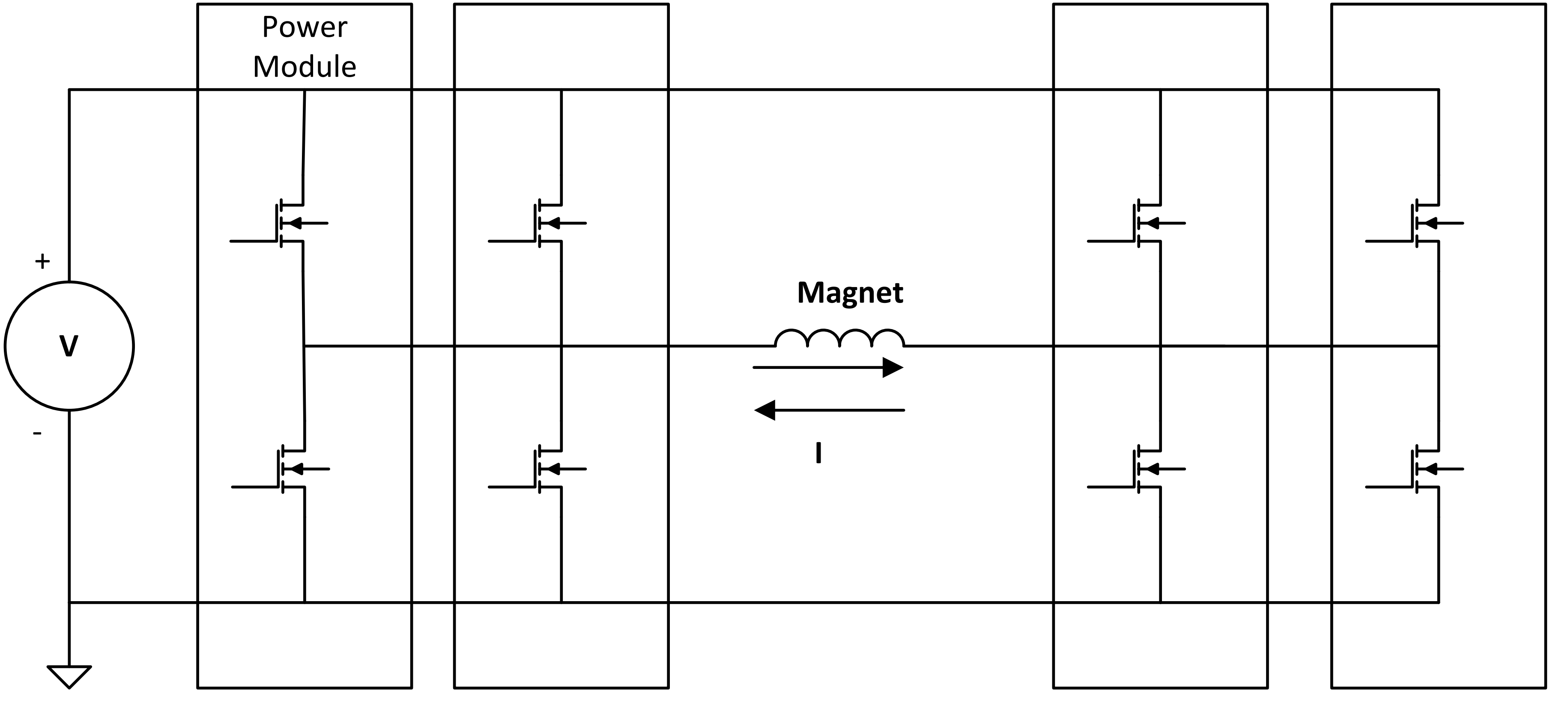
Next Generation Negative Output Current (Q2 – Q1 – Q4 – Q3)



Power Modules Connected for Unipolar Output



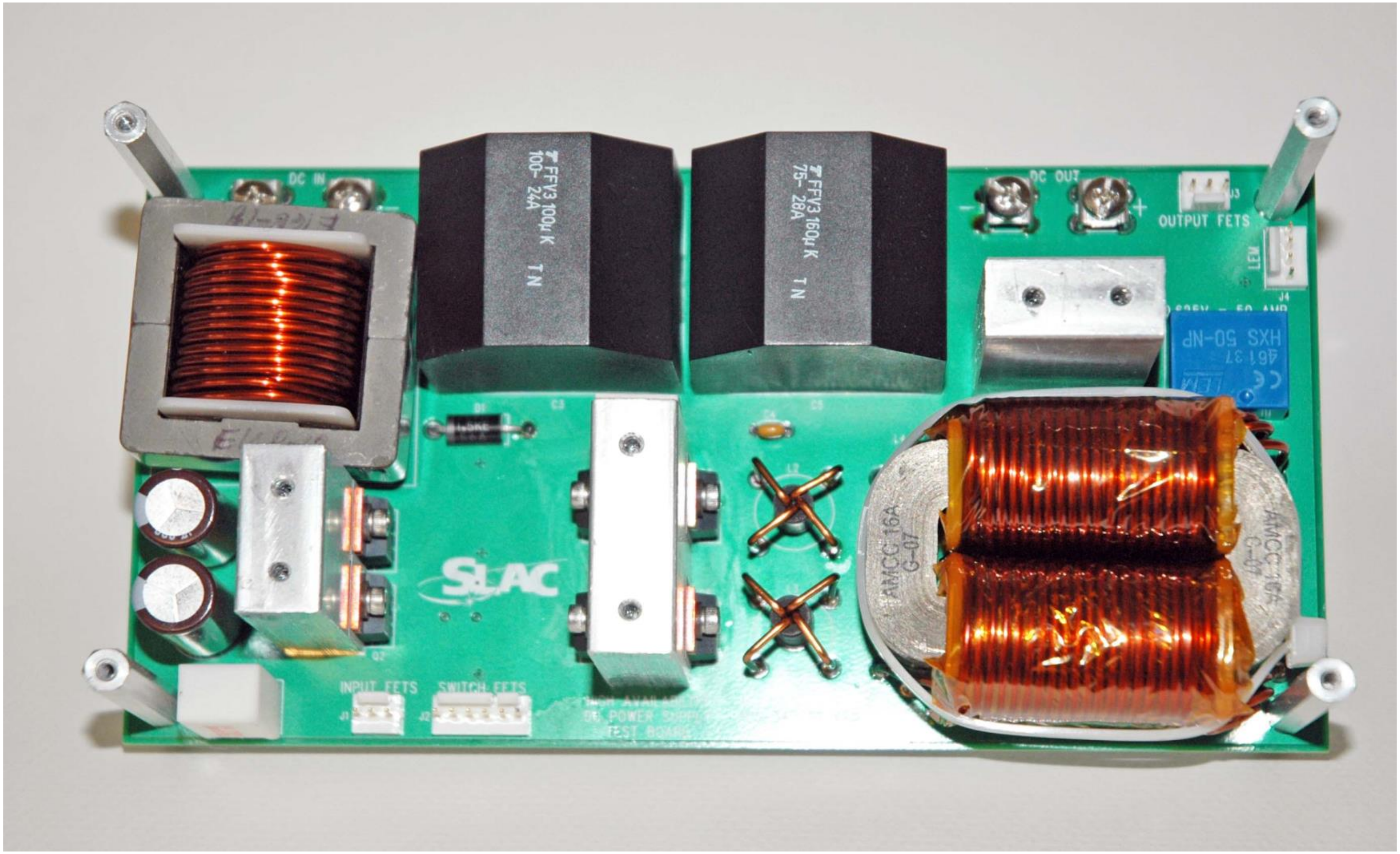
Power Modules Connected for Bipolar Output



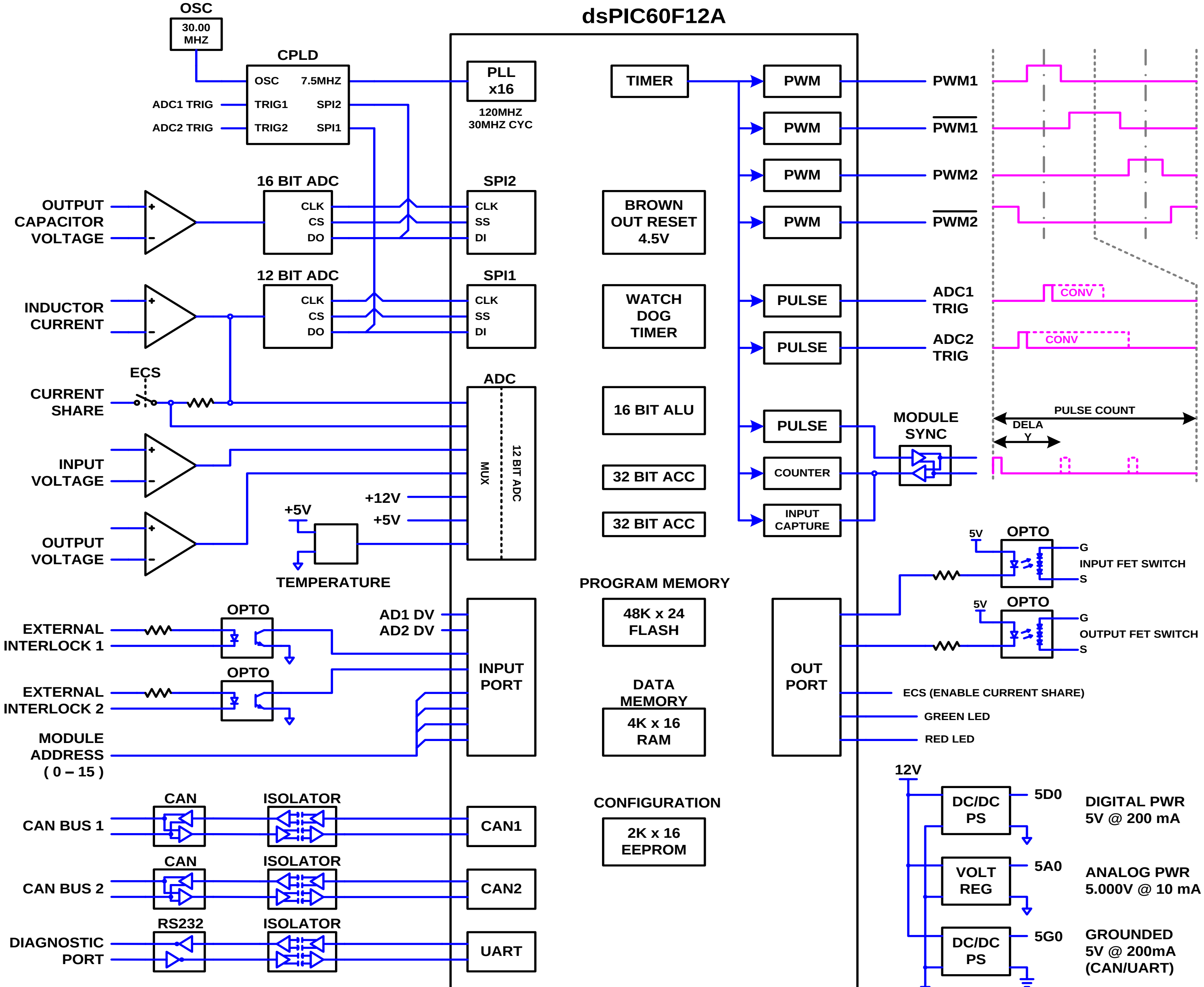
Next Generation Power Modules are "Bricks"

- *Input: 48V*
- *Output V: 0 to 40V*
- *Output I: 0 to 33A*
- *Output P: 0 to 1,320W*
- *2" X 4" X 8"*

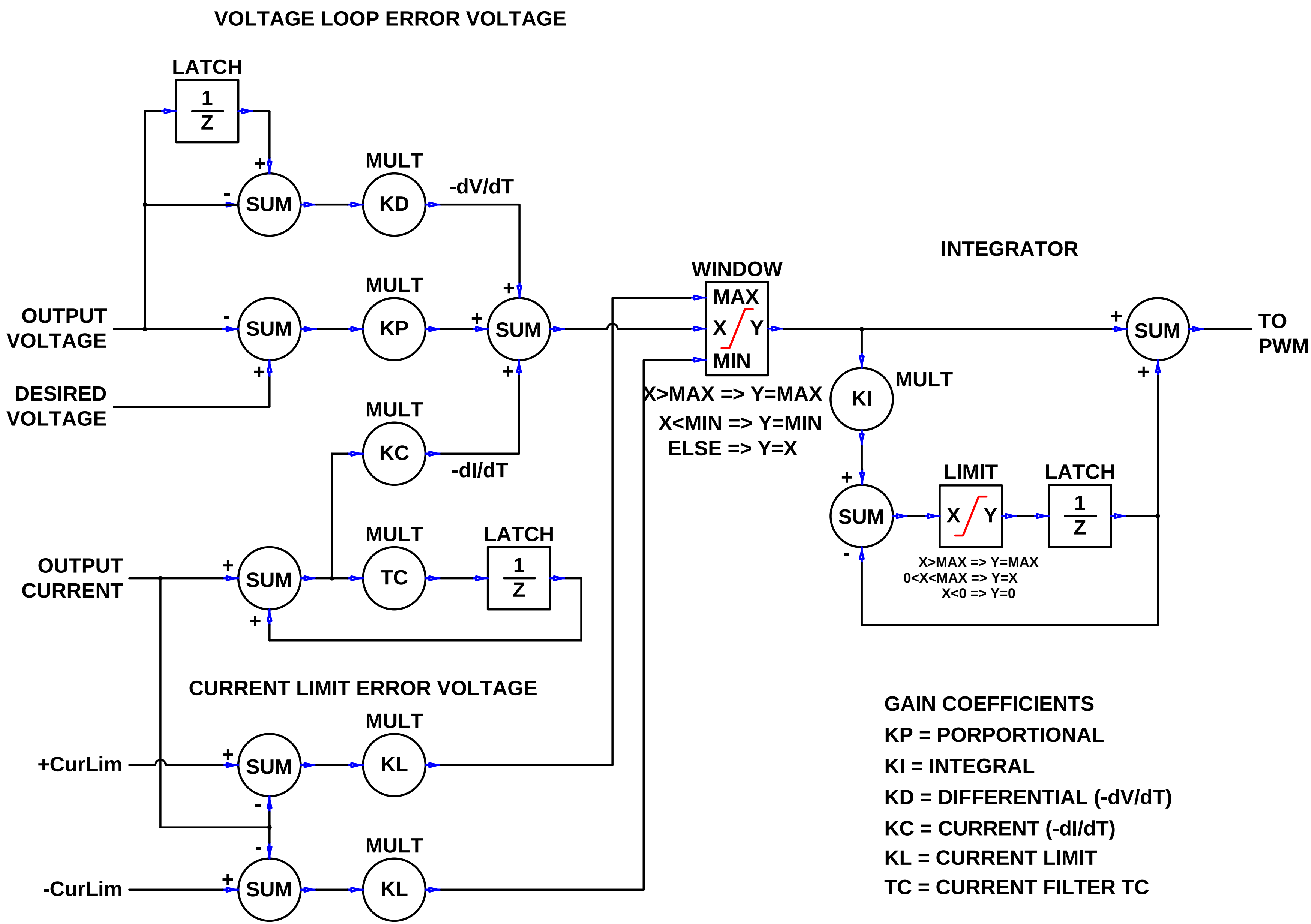
Next Generation Power Module Layout



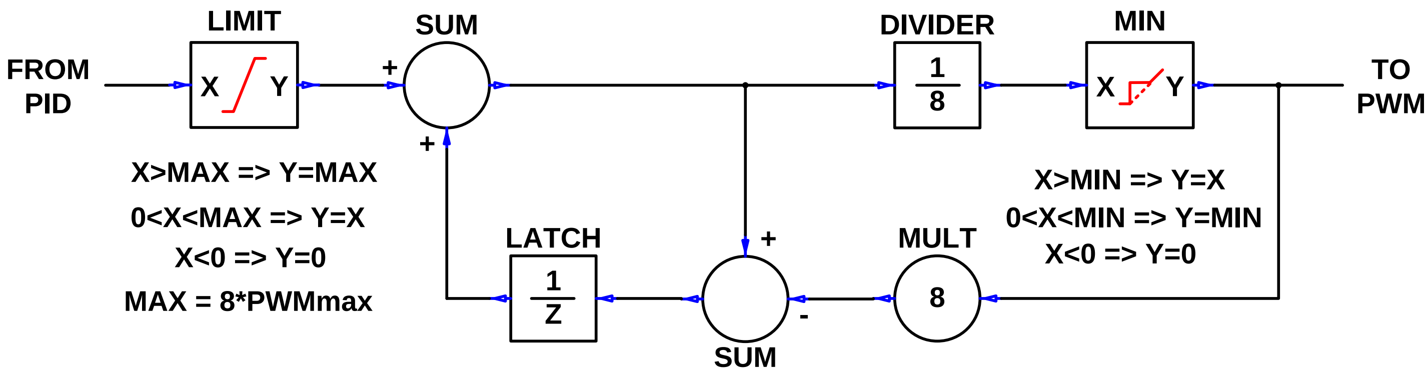
Next Generation Controller

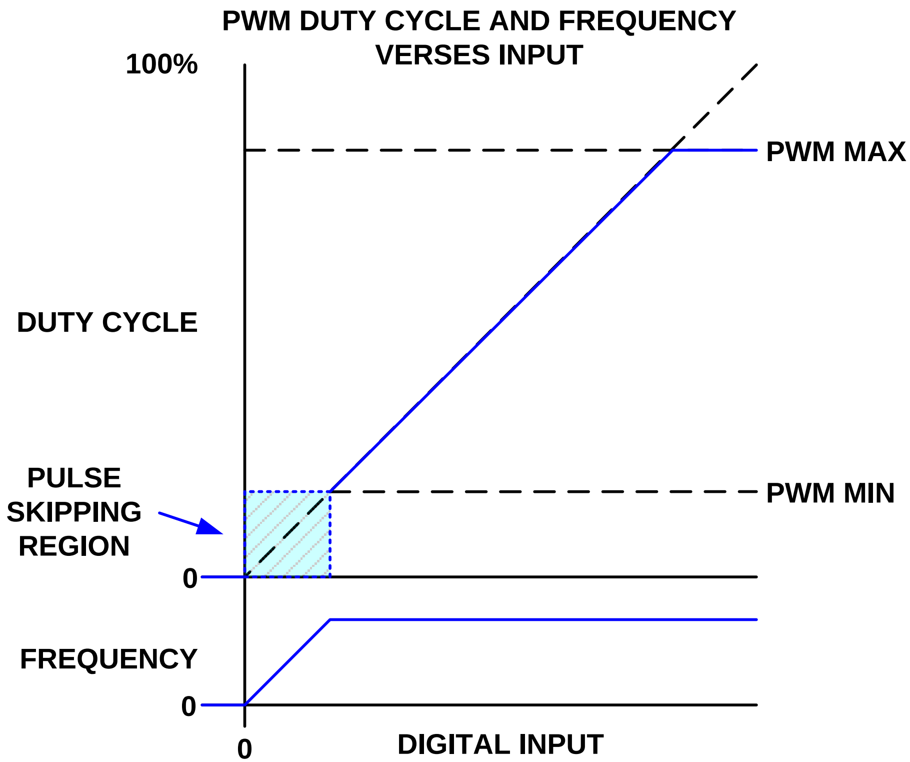


Next Generation PID Loops

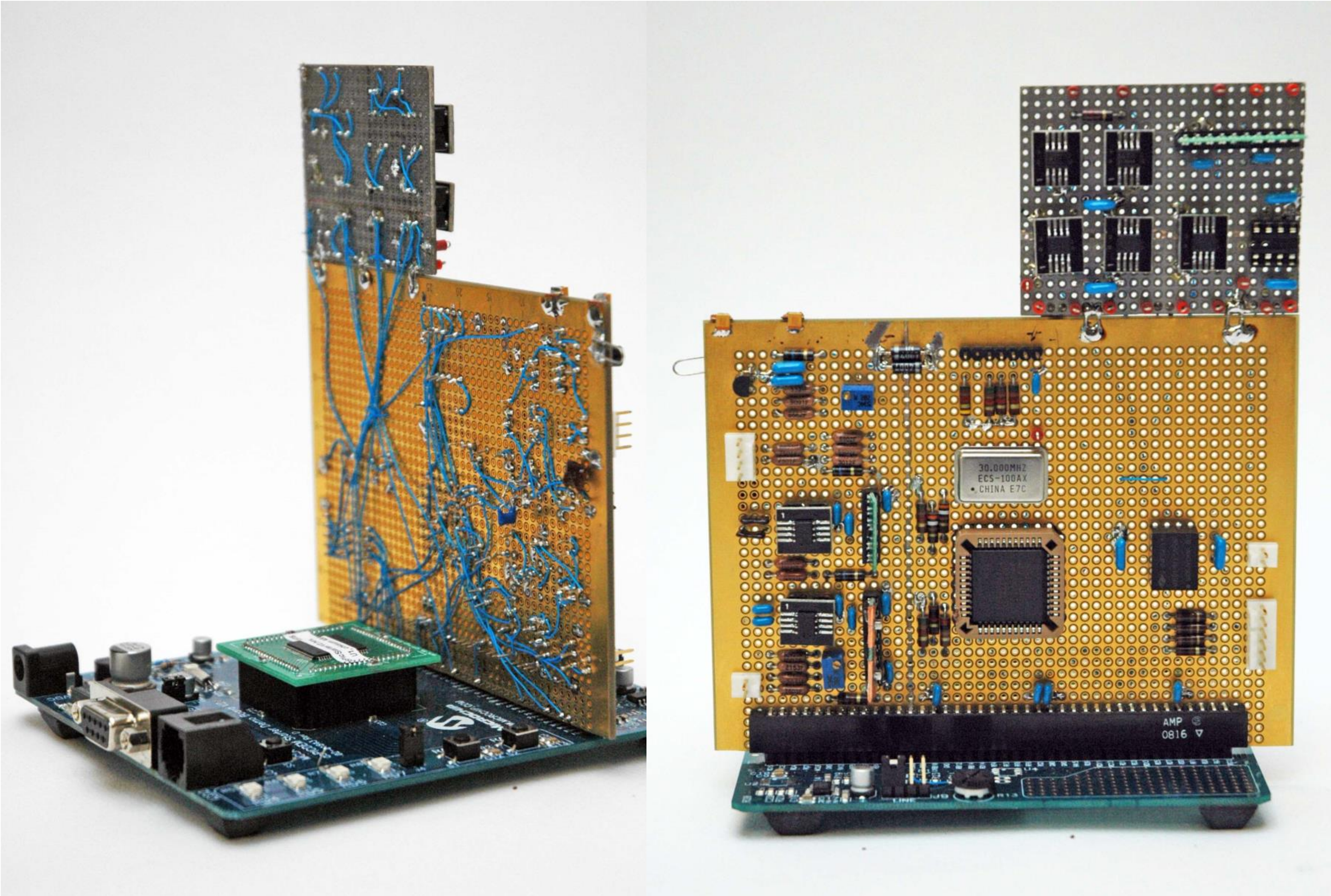


Next Generation PWM Control

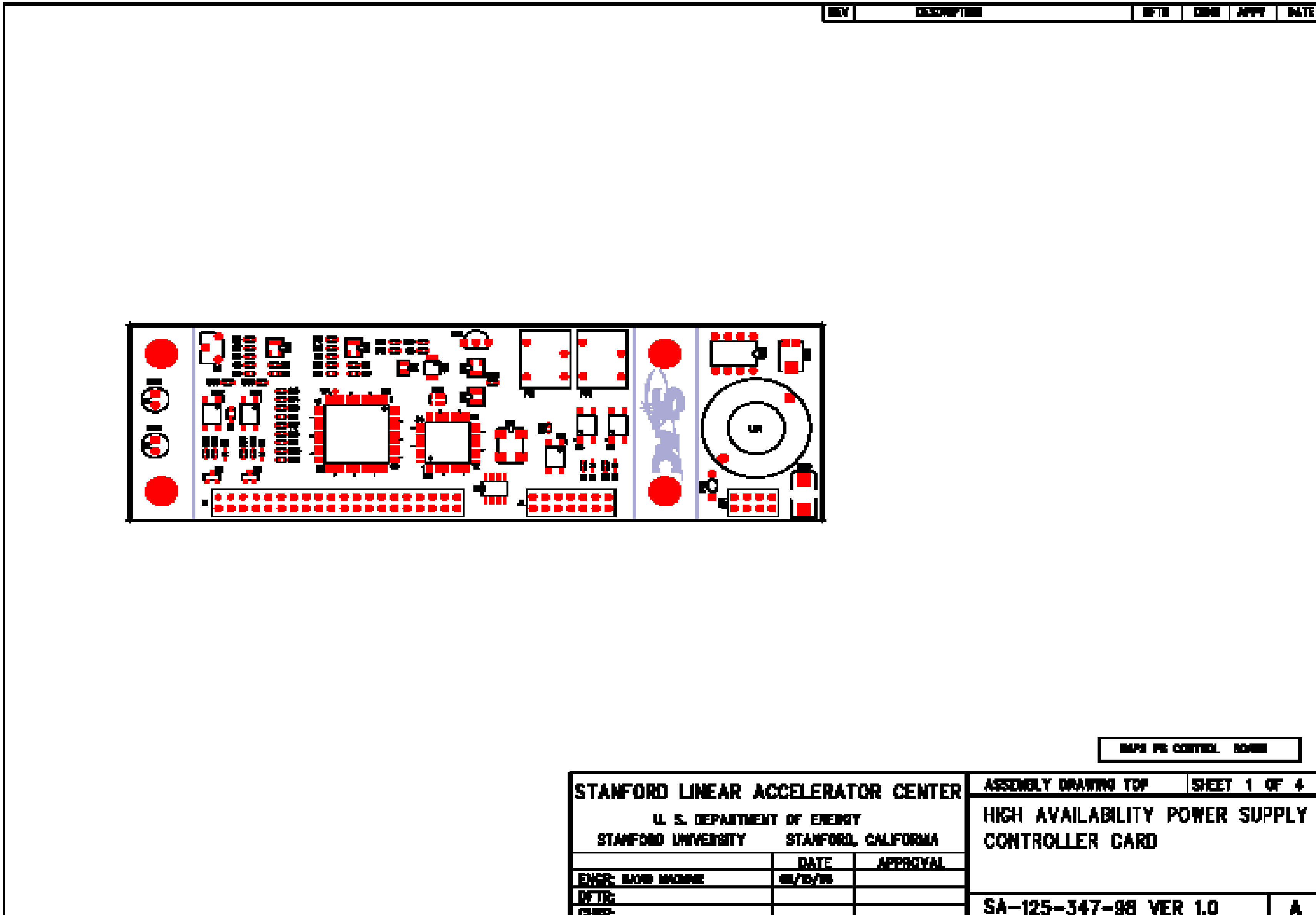




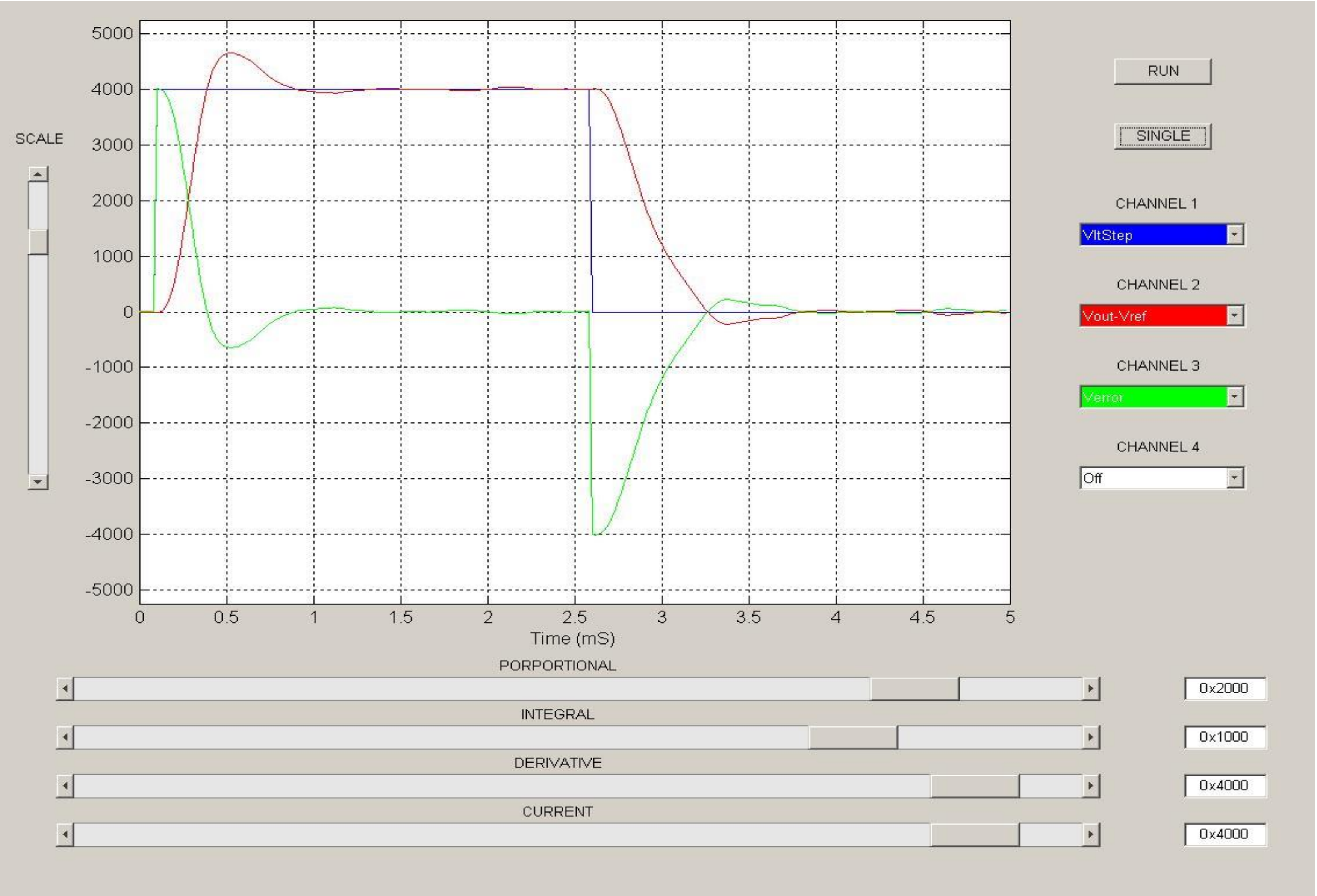
Next Generation Prototype Controller with Development Board



Next Generation – Controller Card



Next Generation – MATLAB Tuning Program



To date

- *Five power modules with embedded controllers have been built*
- *The modules have been tested individually and run as pairs*
- *Demonstrated*
    - *4 modules, 40V, 100A, 4,000W unipolar output then reconfigure*
    - *4 modules, 40V, 33A, 1,320W bipolar output*

Future

- *Design the outer current control loop components*
- *Demonstrate operation of a completely redundant power supply*

Confidence Levels

- *MTBF previously discussed relates to the laws of large quantities and 50% confidence limits*
- *Confidence intervals are bounded with upper and lower limits. The broader the limits, the higher the confidence*
- *Electronic equipment, a one-sided, lower limit is appropriate*

t = *time in hours*

f = *number of failures*

$$MTBF_{Predicted} = t / f$$

K_L *from chi-square distribution*

$$MTBF_{LL} = MTBF_{Predicted} * K_L$$

K_L Multipliers For MTBF Confidence Levels

Failures	Lower Limit K_L				
f	60%	70%	80%	90%	95%
1	0.620	0.530	0.434	0.333	0.270
2	0.667	0.600	0.515	0.422	0.360
3	0.698	0.630	0.565	0.476	0.420
4	0.724	0.662	0.598	0.515	0.455
5	0.746	0.680	0.625	0.546	0.480
500	0.965	0.954	0.942	0.930	0.915

Excerpted and abridged from W. Grant Ireson, Reliability Handbook, McGraw-Hill, NY 1966

Confidence Limit Example

If a power supply is to operate for 3 years before the first failure, what is the MTBF prediction for an 80% confidence level? Repeat for a 90% confidence level.

Solution:

$$3\ years = 26280\ hours = MTBF$$

From the confidence limit table $K_L = 0.434$ for 80% and $f = 1$

Therefore, $MTBF_{80\%} = MTBF * 0.434 \geq 11{,}406\ hours$

For $MTBF_{90\%} = MTBF * 0.333 \geq 8{,}751\ hours$

Fault Modes And Effects Criticality Analysis (FMECA)

FMECA is

- *A systematic way to prioritize the addressing of "weak links".*
- *An inductive, bottoms-up method of analyzing a system design or manufacturing process in order to properly evaluate the potential for failures*

It Involves

- *Identifying all potential failure modes, determining the end effect of each potential failure mode, and determining the criticality of that failure effect.*

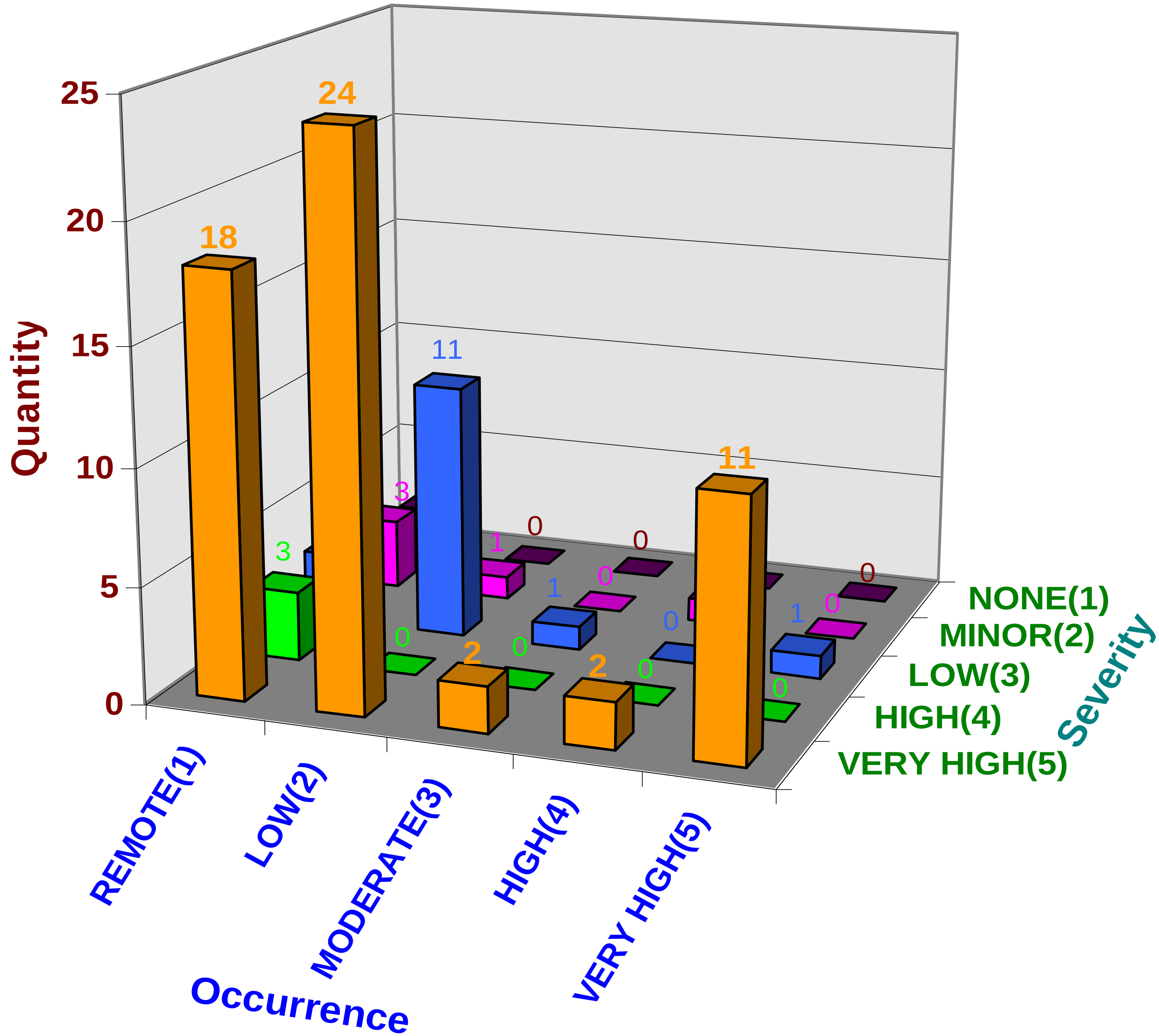
3 Major Iterations

- *Used in the Design, Fabrication and Operation Stages*

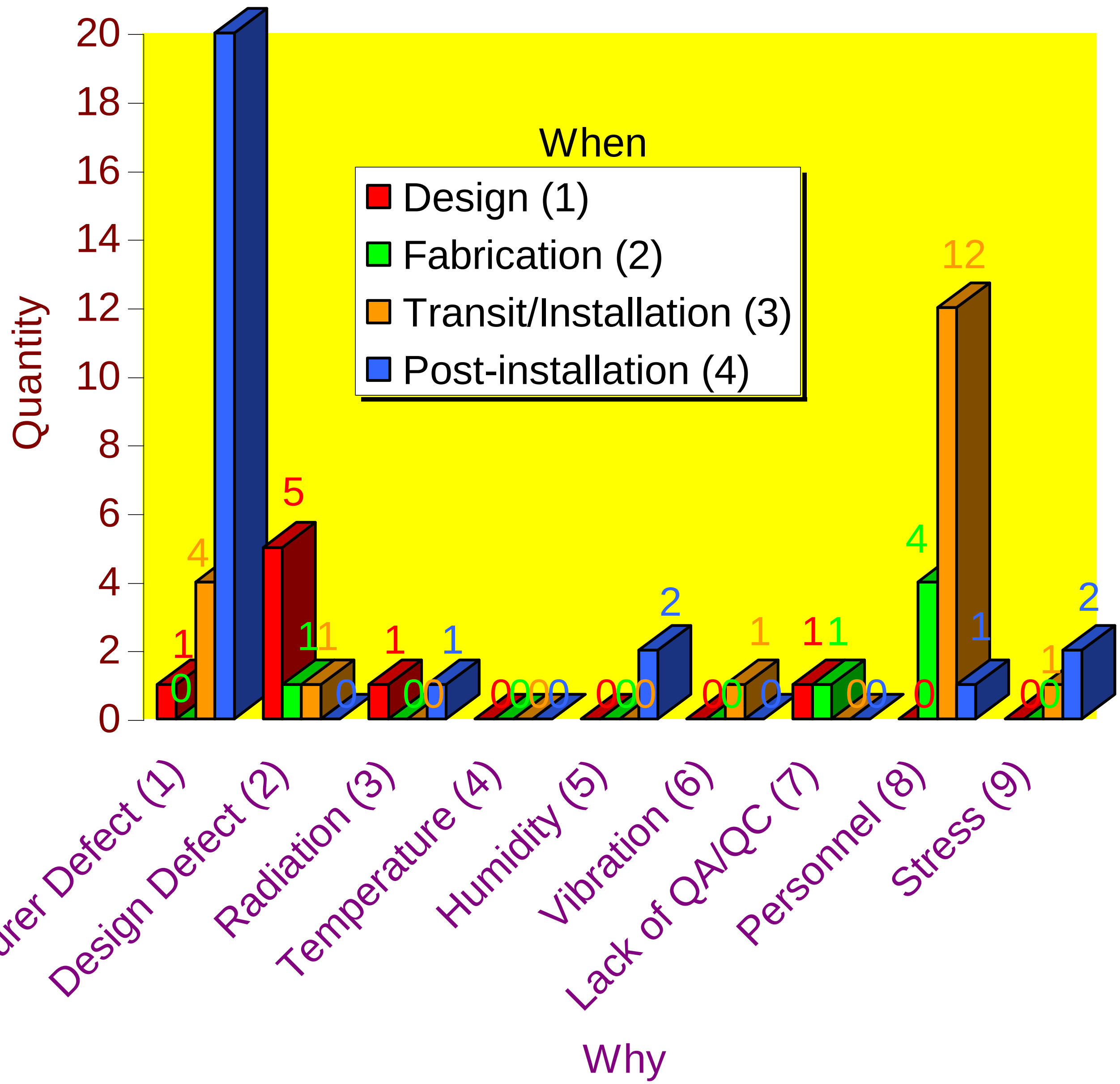
Fault Modes And Effects Criticality Analysis (FMECA)

Part Name/ #	Part Function	Potential Failure Mode	Potential Effects of Failure	SEV	Potential Causes of Failure	OCC	Design Evaluation Technique	DET	RPN	WHEN	WHY
Coils	Provide magnetic field	coil to coil or coil to magnet steel short	magnet goes off line	5	coils moved during installation of magnet or adjacent beamline component, or alignment of magnet	5	protype test	1	25	3	2
Coils	Provide magnetic field	klixon trip due to overheating	magnet goes off line	5	inadequate water pressure differential across magnet	5	prototype test, calculation	1	25	1	2
Coils	Provide magnetic field	klixon trip due to overheating	magnet goes off line	5	too many loads on water circuit	5	prototype test, calculation	1	25	1	2
Coils	Provide magnetic field	klixon trip due to overheating	magnet goes off line	5	conducter sclerosis	3	n/a	1	15	4	9
Coils	Provide magnetic field	klixon trip due to overheating	magnet goes off line	5	foreign object in water line or coil which blocks water flow	2	n/a	1	10	4	8
Coils	Provide magnetic field	klixon trip due to overheating	magnet goes off line	5	damaged (crimped) coil which restricts water flow	2	n/a	1	10	3	8
Coils	Provide magnetic field	water leak	magnet goes off line due to ground fault	5	water hose brakes because of radiation damage	5	n/a	1	25	4	3
Coils	Provide magnetic field	water leak	magnet goes off line due to ground fault	5	corrosion in aluminum/copper conductor	2	n/a	1	10	4	9
Coils	Provide magnetic field	water leak	magnet goes off line due to ground fault	5	erosion of coil from excess water velocity	4	n/a	1	20	4	2
Coils	Provide magnetic field	water leak	magnet goes off line due to ground fault	5	break in braze joint between copper block and coil	3	prototype test	1	15	3	8
Fittings	Make water connection	water leak	magnet goes off line due to ground fault	5	cracked fittings from incorrect installation procedure	4	n/a	1	20	3	8
Jumpers	Connection between coils	short at jumper	magnet goes off line due to ground fault	5	sloppy installation	5	n/a	1	25	3	8
Jumpers	Connection between coils	short at jumper	magnet goes off line due to ground fault	5	poor design	5	design review, prototype	1	25	1	2
Jumpers	Connection between coils	loose jumpers	excessively high temperatures leading to melting of materials	5	poor design or incorrect procedures used at installation	5	n/a	1	25	3	8

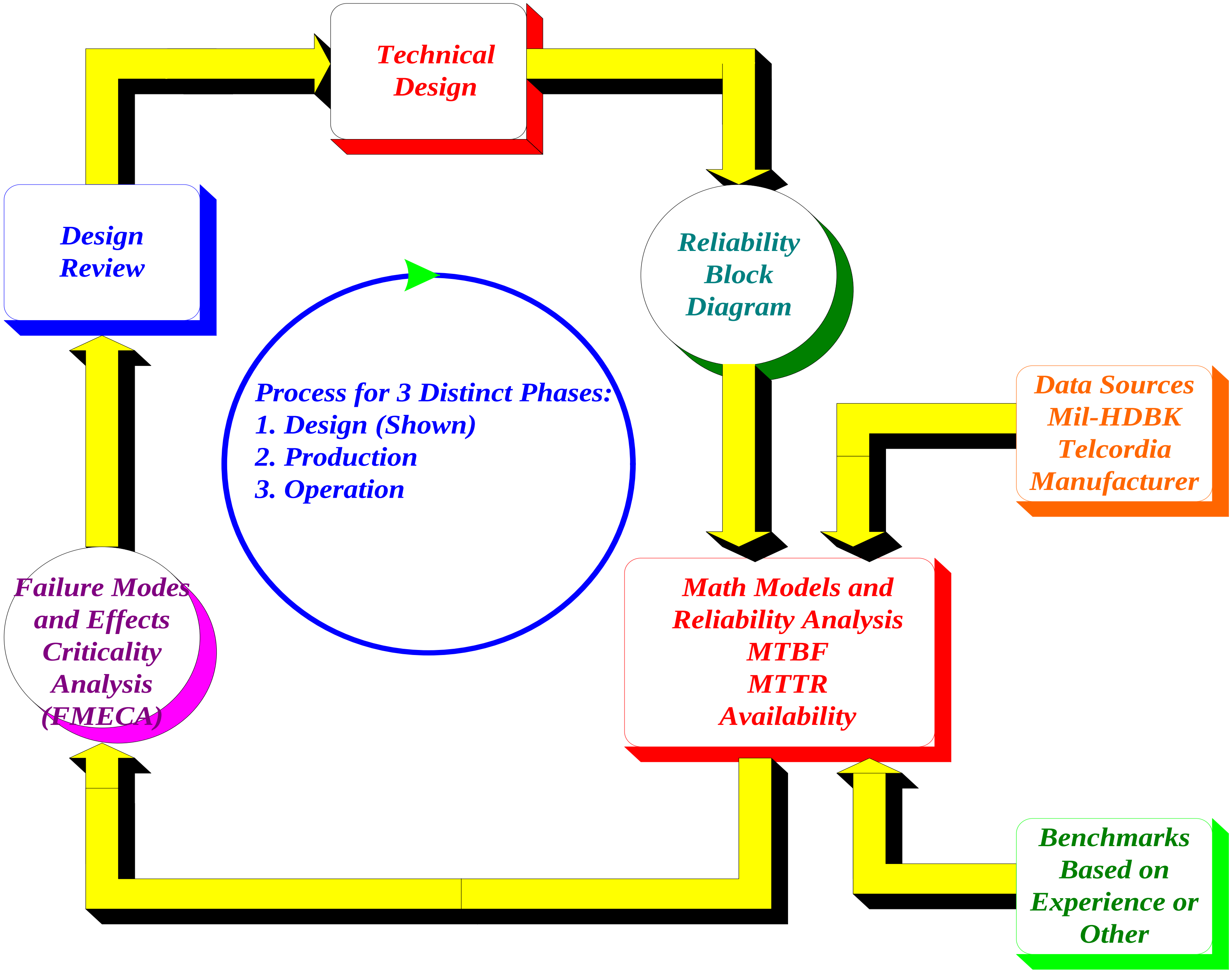
Fault Modes And Effects Criticality Analysis (FMECA)



FMECA When and Why Plot



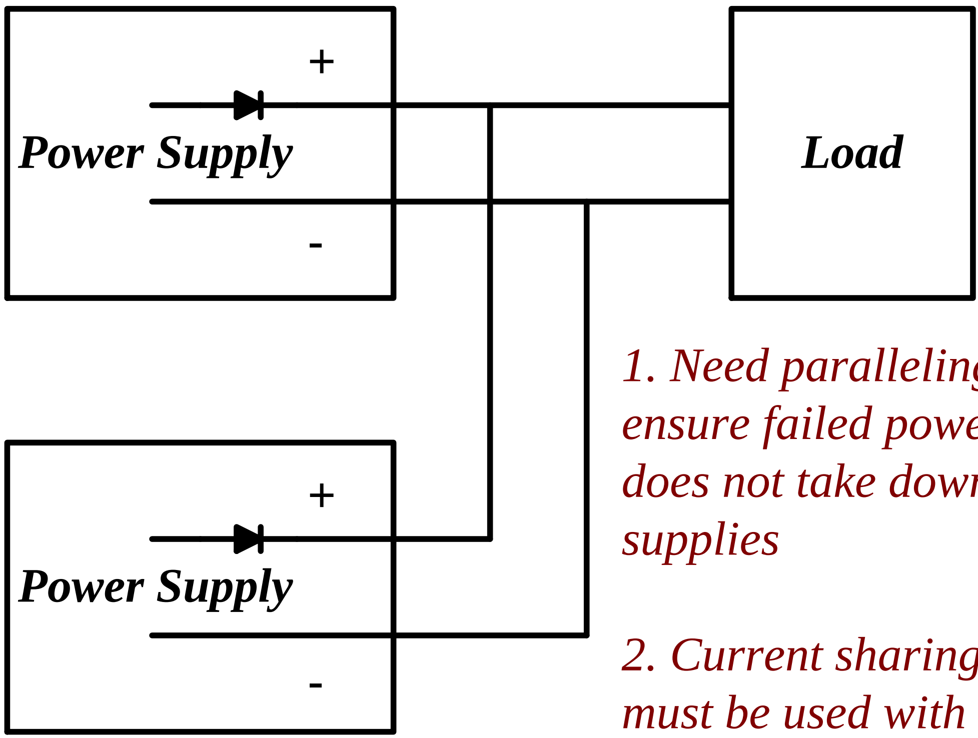
Reliability Process Diagram



Cold swap *– input bus and power supply must be off when it is exchanged*

Warm swap *– input bus is on but power supply is off when exchanged*

Hot swap *– input bus is on and power supply is on when exchanged. Typically used with redundant, full rated power supplies*



1. Need paralleling diodes to ensure failed power supply does not take down both power supplies

2. Current sharing circuitry must be used with the power supplies

Section 13 - Power Supply Specifications

Power Supply Specifications

List of Specifications to be given to the Power Supply Designer	
Requirement	**Example**
1. Site conditions	Elevation, ambient temperature range, humidity, seismic requirements
2. Intended use and system	Storage ring accelerator dipole magnet power supply
3. Function	DC or pulsed, voltage or current source
4. Load parameters and description	Inductance, capacitance and resistance
5. Output ratings	Maximum voltage, current, operating or pulse time, pulse width and repetition rate
6. Input voltage and phases	208V, 1 ϕ 208V, 3 ϕ 480V, 3 ϕ
7. Efficiency	Up to 94% achievable at full load output

List of Specifications to be given to the Power Supply Designer	
Requirement	**Example**
8. Input power factor	Up to 0.95 achievable for 6 pulse Up to 0.97 achievable for 12 pulse
9. Input line THD	< 5% voltage <24% current
10. Conducted EMI 10kHz to 30MHz	MIL-STD-461E FCC Class A Industrial FCC Class B Residential
11. Line regulation	0.05 % of rated output voltage change for a 5% line voltage change. Recovery in 500μ S
12. Short-term (1 to 24 hour) stability	Allowable voltage or current deviation - 10s of ppm achievable
13. Output voltage ripple (PARD)	DC to 1 MHz, peak-to-peak, 0.05 % of rated voltage output

List of Specifications to be given to the Power Supply Designer	
Requirement	**Example**
14. Output pulse amplitude stability	
15. Output pulse – to pulse deviation in time (jitter)	*1 nanosecond for solid-state converters. 10s of nanoseconds for thyratron triggers*
16. Load regulation	*0.05 % of rated output voltage change for 10 % line change. Recovery in 500μ S*
17. Type of control system	*Analog, mixed analog-digital, all digital Communication bus*
18. Interlocks	*•Low input voltage - loss of input phase •Output over voltage – over current •Excessive ground current •Insufficient cooling air flow – cabinet over temperature •Insufficient cooling water flow – cooling water over temperature*

List of Specifications to be given to the Power Supply Designer	
Requirement	**Example**
19. Interlocks (continued)	*•MPS fault* *•PPS violated* *•Cabinet doors open*
20. Cooling methods	*Water cooling for biggest power dissipating devices (IGBTs, rectifiers, chokes)* *<50 kW – all air cooled* *> 50kW – some measure of water cooling*
21. Front panel controls	*•Local / remote operation* *•Output voltage or current* *•Ground current limit* *•Output current limit*

Power Supply Specifications

List of Specifications to be given to the Power Supply Designer	
Requirement	**Example**
22. Front panel displays	•Output voltage •Output current •Ground current •Voltage or current mode • Current limited operation
23. Component deratings	Voltage, current and power
24. Mean time between failure (MTBF)	MTBF = 1/ (sum of all parts failure rates)
25. Mean time to repair (MTTR)	Establish from MTBF and operational Availability requirement
26. Availability	
27. Maintainability	

Power Supply Specifications

List of Specifications to be given to the Power Supply Designer	
Requirement	**Example**
28. Physical size	*Based on output power – typically 1 to 4 W / cu in*
29. Rack or free-standing	*< 17kW rack-mounted > 17kW free-standing*
30. Compliance with UL or other nationally-recognized inspection/test laboratories	*Underwriters Laboratories - UL National Recognized Test Laboratory - NRTL*
31. Seismic	*Must satisfy site earthquake design criteria Damage criteria and response spectra curves - separate or combined accelerations*
32. Quality Assurance	*Must satisfy project quality assurance/quality control criteria*

Section 14 - References

References And Useful Textbooks

References	Used in
Elements Of Power System Analysis, Stevenson, McGraw-Hill	Textbook
IEEE 90 - IEEE Standard Computer Dictionary: A Compilation of IEEE Standard Computer Glossaries. Institute of Electrical and Electronics Engineers. New York, NY: 1990	Textbook
"Power Electronic Converter Harmonics", Derek Paice, IEEE Press, 1996	Textbook
Rectifier Circuits Theory And Design, Johannes Schaefer, John Wiley & Sons, Inc NY	Textbook
Switchmode Power Supply Handbook, Keith Billings, McGraw-Hill, February 1999, ISBN 0070067198	Textbook
EMI and Emissions: Rules, Regulations and Options, Daryl Gerke and Bill Kimmel, Electronic Design News, February 2001	Section 3
EMI Control Methodology and Procedures, Donald White and Michel Mardiguian, Interference Control Technologies, 4th Edition	Section 3
http://www.iijnet.or.jp/murata/index.html for feedtrhu filters	Section 3

References And Useful Textbooks

References	Used in
"Case Studies on Mitigating Harmonics in ASD Systems to Meet IEEE519-1992 Standards", Mahesh Swamy, Steven Rossiter, Michael Spencer, Michael Richardson - IEEE Industry Application Society Proceedings October 1994	Section 3
IEEE 519 – 1992 "Standard Practices and Requirements for Harmonic Control in Electrical Power Systems"	Section 3
Circuit Techniques for Improving the Switching Loci of Transistor Switches in Switching Regulators,E.T. Calkin and B.H. Hamilton, IEEE Transactions On Industry Applications, July 1976	Section 4
How to Select a Heatsink http://www.aavidthermalloy.com/technical/papers/pdfs/select.pdf	Section 4
IGBT Theory : http://www.elec.gla.ac.uk/groups/dev_mod/papers/igbt/igbt.html	Section 4
Magnetics Designer for Transformers, chokes and inductors, Intusoft Corporation http://www.i-t.com/engsw/intusoft/magdesgn.htm	Section 4

References And Useful Textbooks

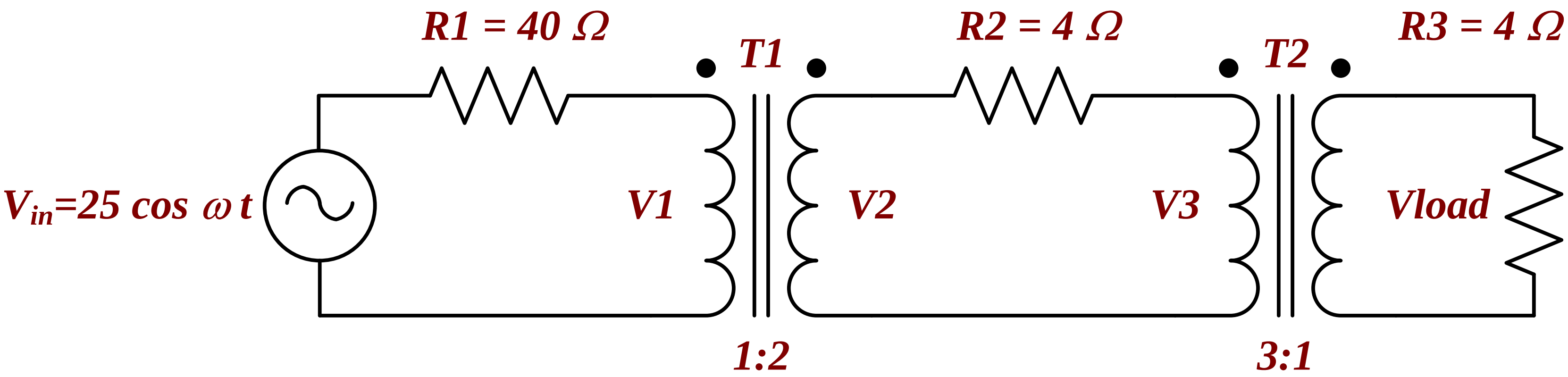
References	Used in
Power Electronics Modeling Software, Integrated Engineering Software, http://www. integratedsoft.com	Section 4
PSPICE simulator for switching regulators, Linear Technologies, http://www.linear.com/insider	Section 4
PSPICE circuit simulator, Micro-Cap, Spectrum Software, http://www.spectrum-soft.com	Section 4
Zero Voltage Switching Resonant Power Supplies http://www-s.ti.com/sc/psheets/slua159/slua159.pdf	Section 4
SCSI information http://www.scsita.org/aboutscsi/index01.html	Section 5
MIL-STD-1629 "Procedures for Performing a Failure Mode, Effects, and Criticality Analysis".	Section 7
RelCalc by T-Cubed	Section 7
Relex by Relex Software	Section 7

References And Useful Textbooks

References	Used in
Table of Laplace Transforms http://www.vibrationdata.com/Laplace.htm	Section 6
Table of Fourier Transforms http://mathworld.wolfram.com/FourierTransform.html	Section 6

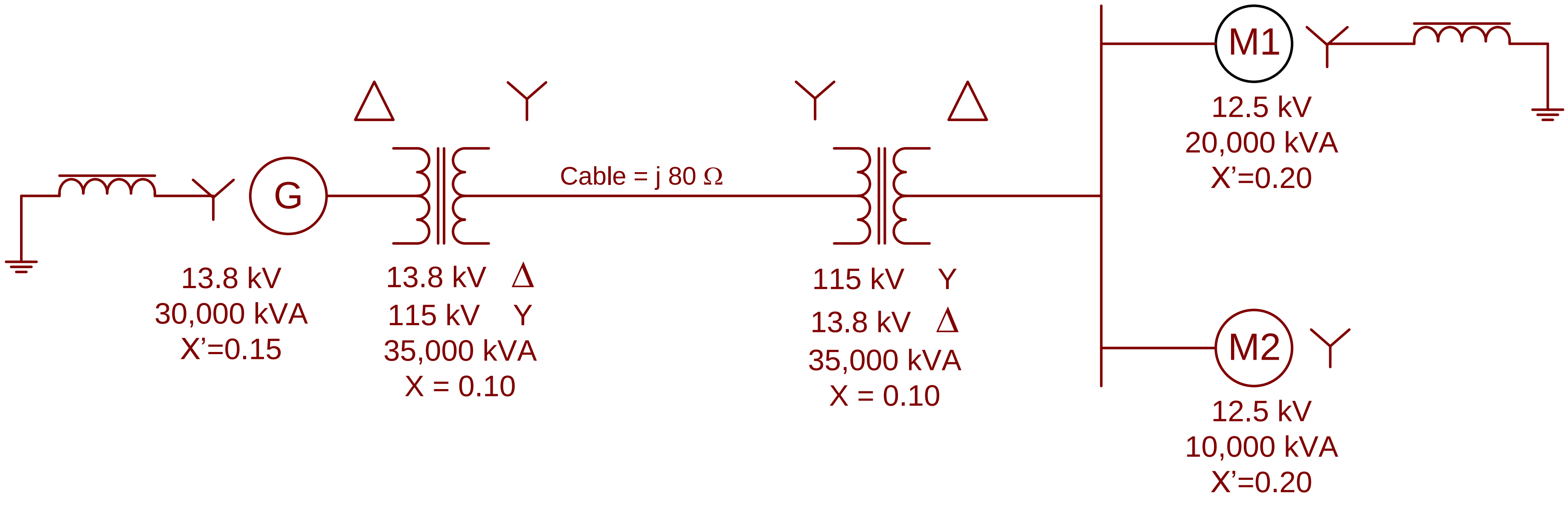
Section 15 - Homework Problems

Calculate the output voltage in the circuit shown below.



Referring to the one-line diagram below, determine the line currents in the:

A. Generator   ***B. Transmission Line***   ***C. M1***   ***D. M2***



Homework Problem # 3

A 1000kVA, 12.47kV to 480V, 60Hz three phase transformer has an impedance of 5%. Calculate:

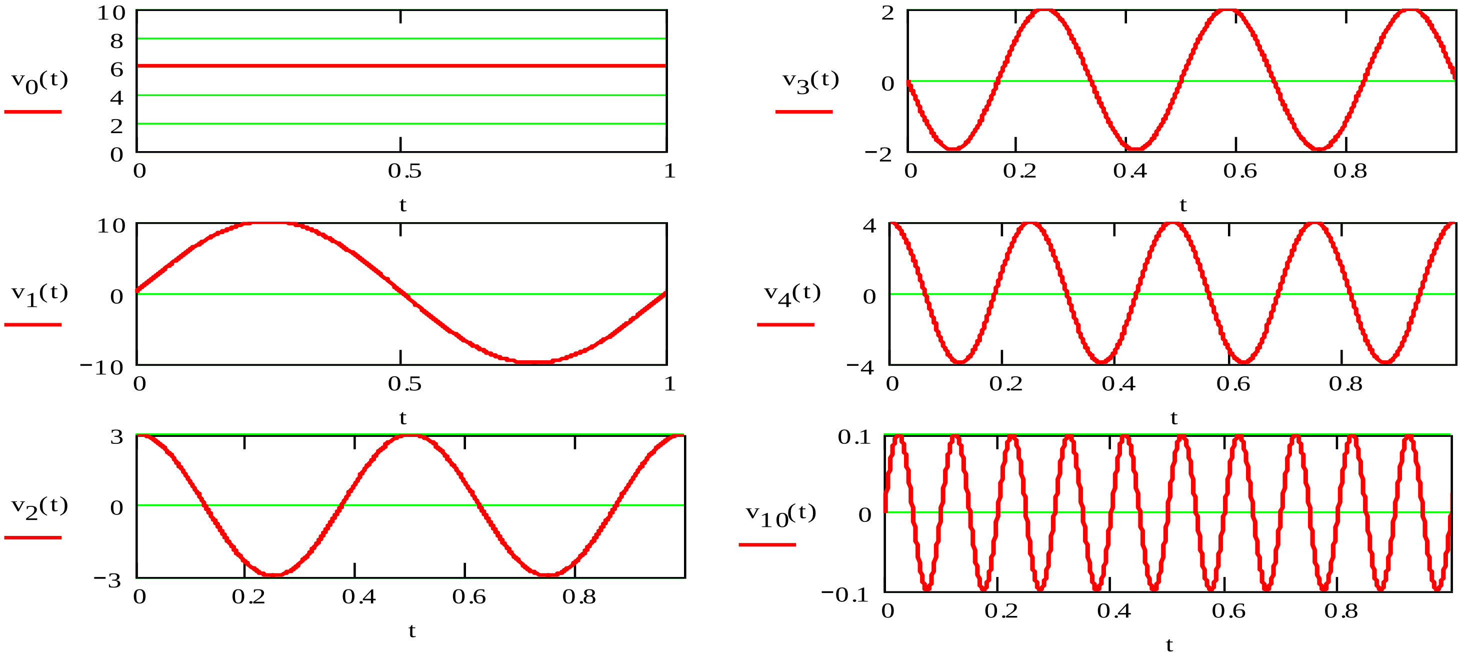
a. The actual impedance and leakage inductance referred to the primary winding

b. The actual impedance and leakage inductance referred to the secondary winding

c. The magnetizing inductance referred to the primary winding

Homework Problem # 4

A waveform v(t) was analyzed and found to consist of 6 components as shown here.



*a. Write the mathematical expression for each component in terms of ω=(2*π)/T*

b. Show the harmonic content graphically by plotting the frequency spectrum

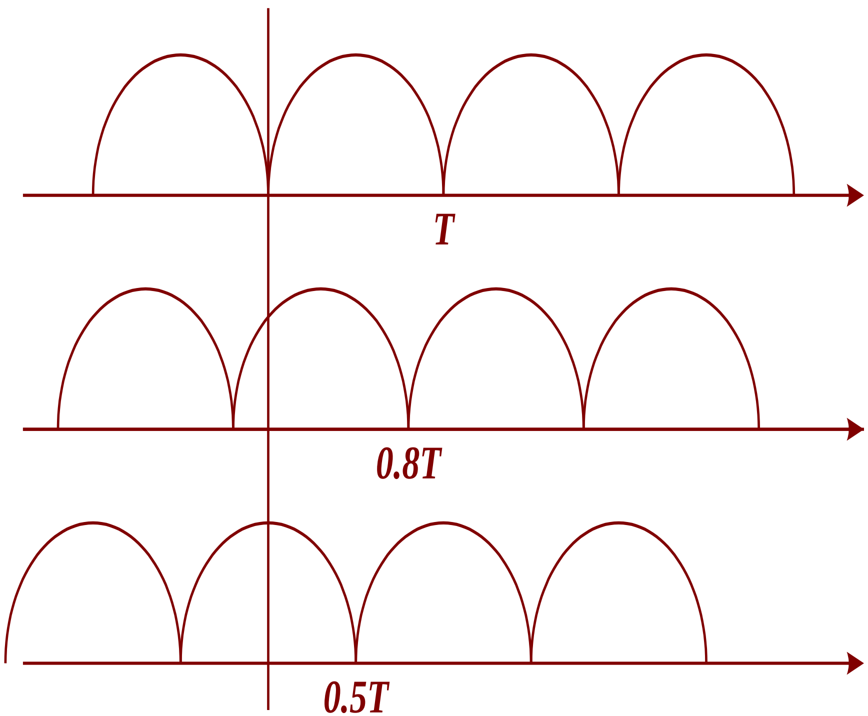
c. Give the numerical result of

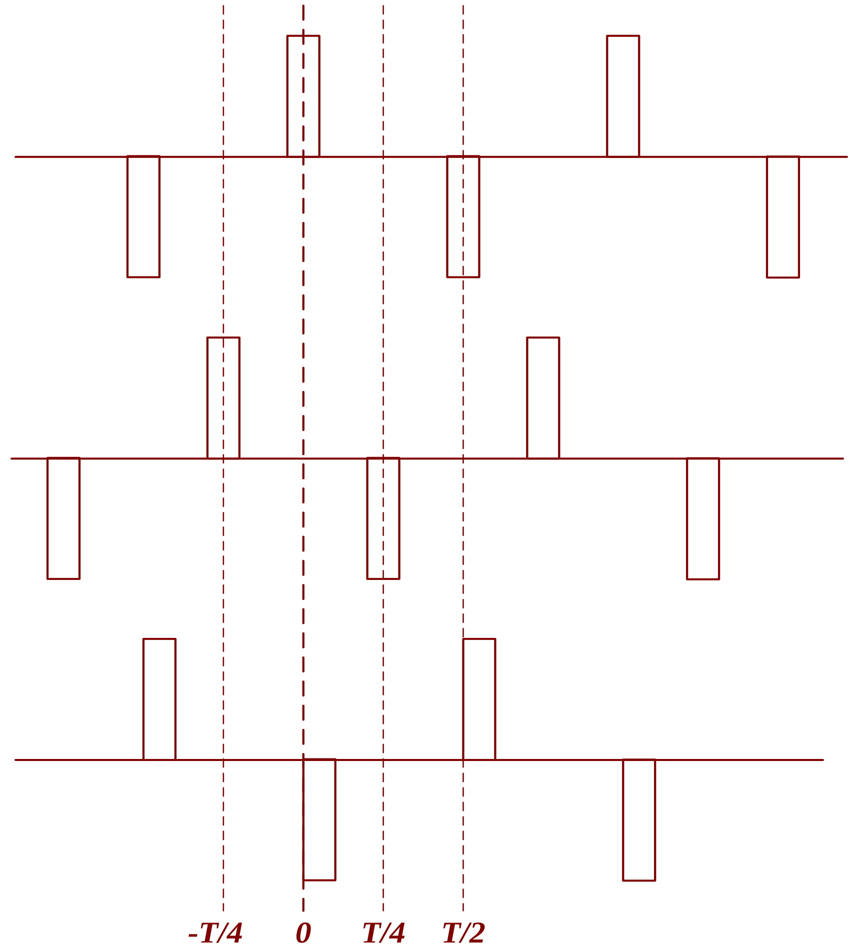
$$b_3 = \frac{2}{T}\int_0^T v(t)\sin 3\omega t\,dt \qquad \text{Help:} \int \sin^2(3\omega t)\,dt = \frac{t}{2} - \frac{\sin 6\omega t}{12\omega}$$

$$b_4 = \frac{2}{T}\int_0^T v(t)\sin 4\omega t\,dt \qquad \text{Help:} \int \cos(4\omega t)\sin(4\omega t)\,dt = \frac{\sin(4\omega t)^2}{8\omega}$$

Homework Problem # 5

Each waveform below can be written as a Fourier series. The result depends upon the choice of origin. For each of the 6 cases, state the type of symmetry present, non-zero coefficients and the expected harmonics.

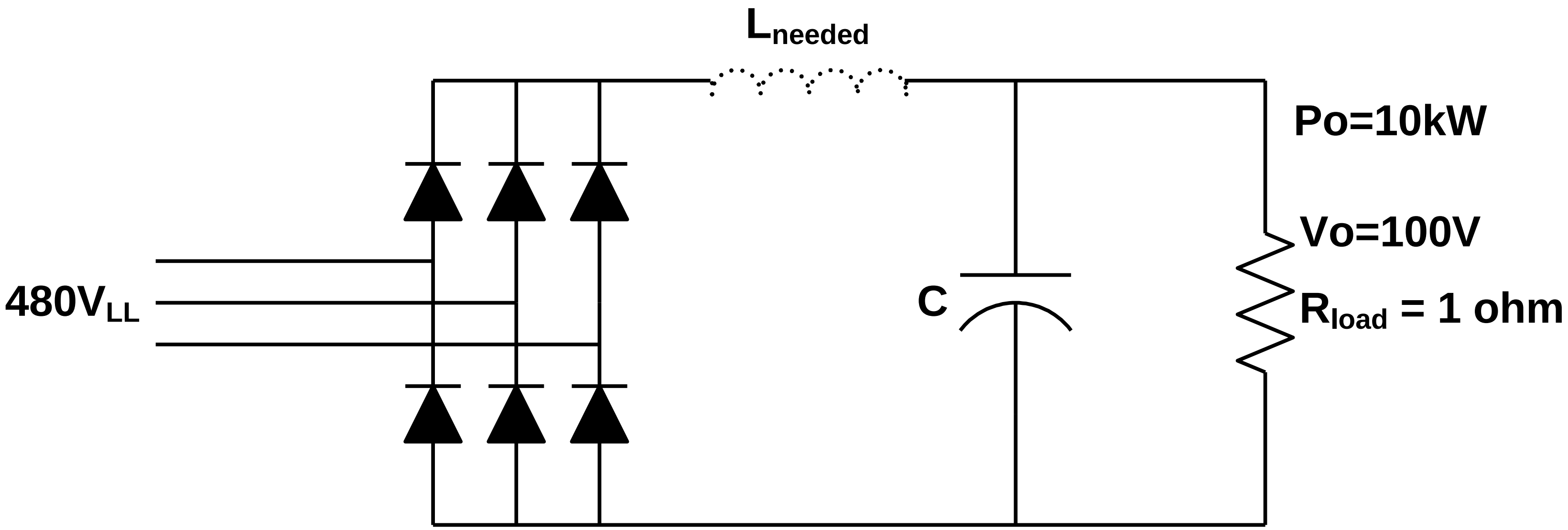


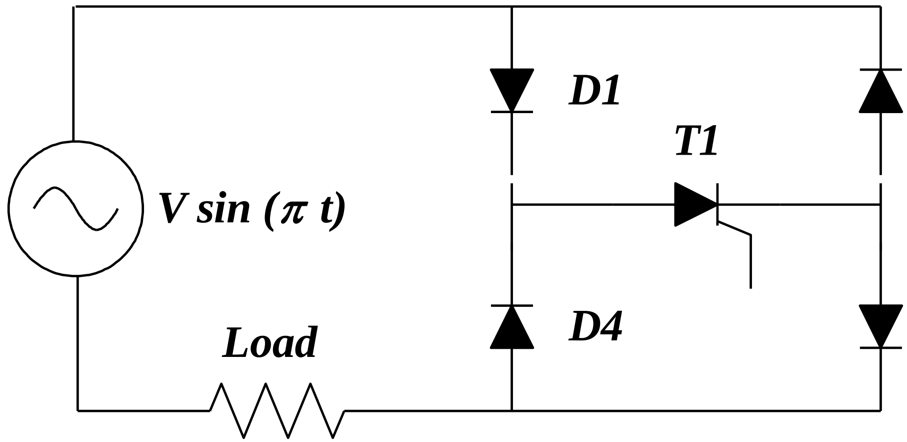


Homework Problem # 6

A uniform magnetic field B is normal to the plane of a circular ring 10 cm in diameter made of #10 AWG copper wire having a diameter of 0.10 inches. At what rate must B change with time if an induced current of 10 A is to appear in the ring? The resistivity of copper is about 1.67 $\mu\,\Omega - cm$.

A 10kW power supply with 3-phase 480V input has an efficiency of 90% and operates with a leading power factor of 0.8. The power supply output is 100V. Determine the size of an added inductor to improve the power factor to 1.00. Below is the circuit diagram.





Assume ideal components in the phase-controlled circuit above. For a purely resistive load:

A. Explain how the circuit operates

B. Draw the load voltage waveform and determine the boundary conditions of the delay angle α

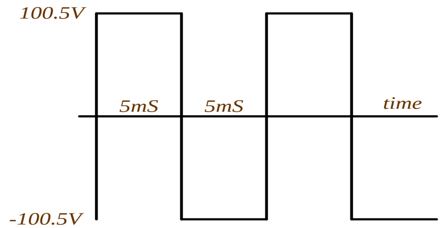
C. Calculate the average load voltage and average load current as a function of α

D. Find the RMS value of the load current.

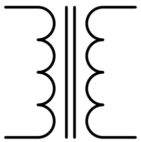
Rectifiers - Homework Problem # 9

Given the following:

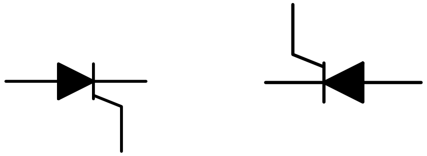
- *Input voltage waveform*



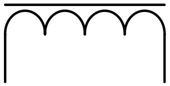
- *Losses transformer*



- *Two SCRs, each with conducting voltage drop of 1V.*



- *Inductor, lossless, with very large inductance*



- *Resistor, 10 ohms, capable of very large power dissipation*

- *Circuit operating under steady-state conditions (i.e. all transients have subsided)*

Problem

A. With the SCRs triggering retard angle at zero degrees, arrange the circuit to provide a full-wave, rectified, and properly low-pass filtered DC output of 200V into the 10ohm load resistor.

B. Calculate the load current and power

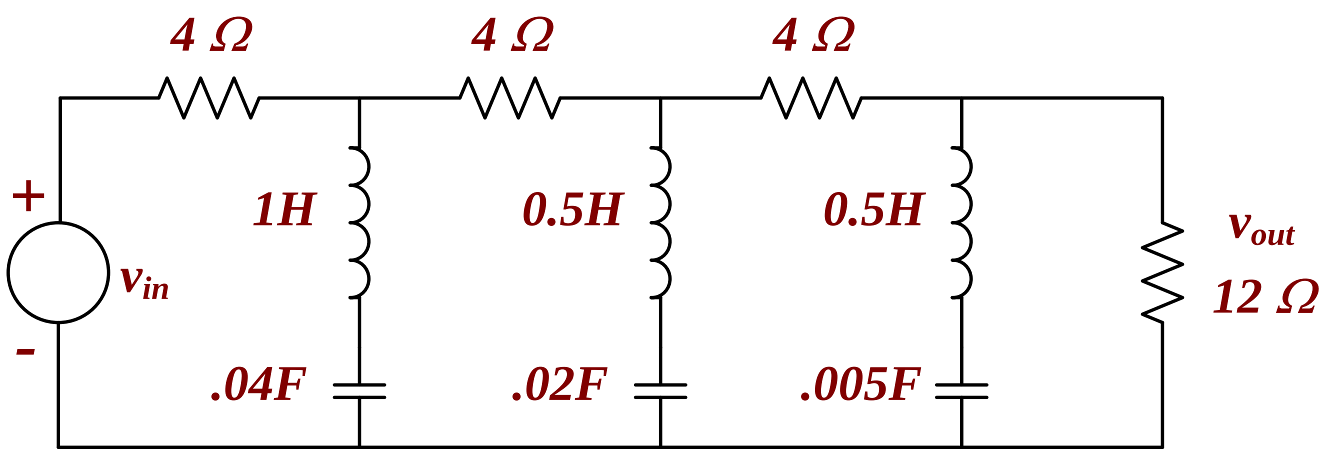
C. Determine the needed transformer turns ratio.

D. Calculate the circuit efficiency

Increase the SCRs trigger retard angle to 90 degrees and
F. Calculate the new output voltage, current, and power

G. Determine the new circuit efficiency

Given the circuit below:



$$h(t) = \frac{v_{out}(t)}{v_{in}(t)} \qquad H(j\omega) = \frac{V_{out}(j\omega)}{V_{in}(j\omega)}$$

Sketch $|H(j\omega)|$ versus ω

Homework Problem # 11

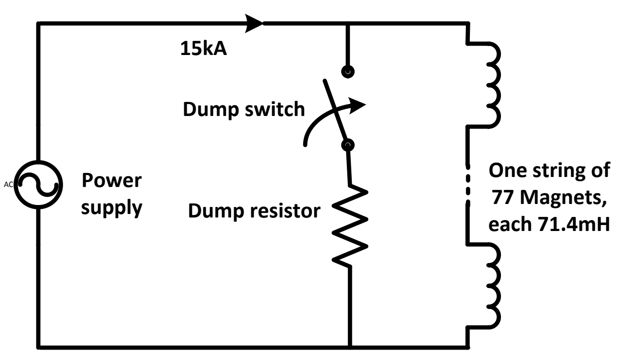
A 100kW power supply is 80% efficient. Approximately 50% of the power supply heat loss is removed by cooling water.

- *How much heat is dissipated to building air and how much heat is removed by the water system.*
- *Calculate the water flow rate needed to limit the water temperature rise to 8^{O}C maximum.*

Homework Problem # 12

A collider has several equal strings of 77 superconducting magnets, each with 71.4mH inductance, carrying 15kA of current. If one, or more quenches, all the energy from the other magnets will dissipate their energies into the quenched magnet, thus destroying it. Design a switched dump resistor to discharge the current at a maximum rate, dI/dt, of 300A/s to prevent damage to the superconducting magnet in the event of a quench. Refer to the circuit diagram below.

1. *What is the energy stored in each magnet and in the string when running at its design value?*
2. *What is the total inductance of the string?*
3. *Write the equation that describes the resistor current after closing the switch.*
4. *Find the resistor value to limit the maximum rate of decrease of current in the magnets to 150A/s*
5. *What is the maximum voltage generated across the resistor?*
6. *What is the time constant of this circuit?*
7. *Design a steel dump resistor that has little thermal conductance to the outside world (adiabatic system). Calculate how much steel mass (weight) will limit the temperature increase of the resistor to 500°K.*



Help

$Q = M\ C_p\ \Delta T$

$Q =$ *heat (energy) into the system expressed in joules*

$M =$ *mass or weight of the resistor*

$C_p = \text{specific heat of material} = 0.466 \dfrac{J}{gm * {}^oK}$ *for steel*

$\Delta T = \text{Temperature rise of the resistor}$

Based on "LHC Magnet Quench Protection System, L.Coull, et.al, 13th International Conference on Magnet Technology, Victoria, Canada, 1993

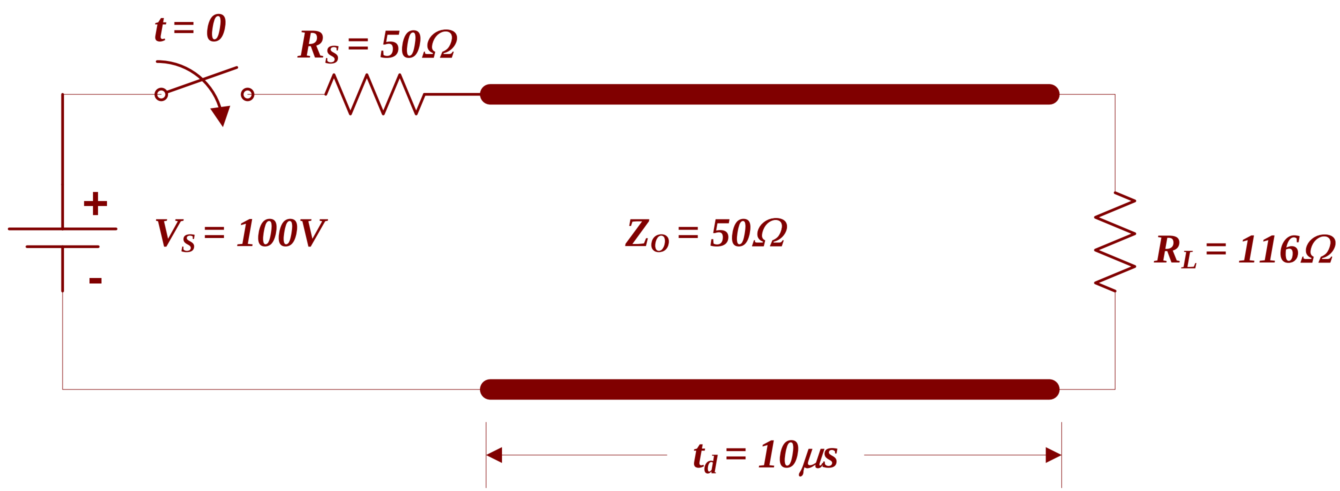
Homework Problem #13

A. A transmission line can be formed using lumped Ls and Cs. Calculate the delay of a line composed of 8 sections of inductances L=4mH per section and capacitance C=40pF per section.

B. The frequency of a signal applied to a two-wire transmission cable is 3GHz. What is the signal wavelength if the cable dielectric is air? Hint – relative permittivity of air is 1

C. What is the signal wavelength if the cable dielectric has a relative permittivity of 3.6?

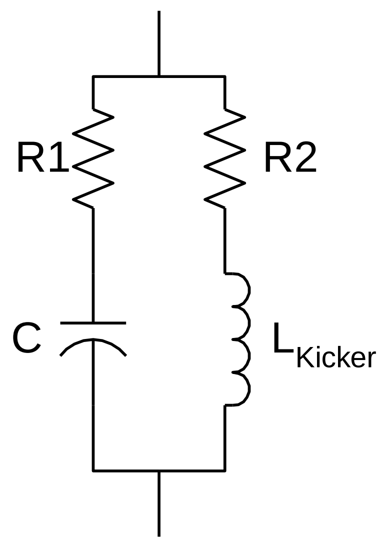
For the transmission line shown below, calculate the Reflection Coefficients Γ, the reflected voltages and the voltage and current along the line versus time.



Homework Problem # 15

A controlled impedance transmission line often drives a kicker. The kicker is usually well modeled as an inductor. A matching circuit can be built around the kicker and its inductance so that this circuit, including the kicker magnet, has constant, frequency independent, impedance which is matched to the transmission line.

Assuming that the transmission line impedance is Z_0 and the kicker inductance is L_{Kicker} derive the values of R1, R2, and C necessary to make a frequency independent (constant) impedance Z_0.



Homework Problem #16

A. What is the significance of the value $\sqrt{\dfrac{\mu_o}{\varepsilon_o}}$?

B. What is the significance of the values $\dfrac{1}{\sqrt{\mu_o \varepsilon_o}}$ *and* $\sqrt{L*C}$?

C. Calculate the speed of light in mediums with dielectric constants of:
$\varepsilon_r = 1$ $\varepsilon_r = 2$ $\varepsilon_r = 4$ $\varepsilon_r = 8$ $\varepsilon_r = 16$

Homework Problem # 17

A. At least 1 of 4 parallel identical power supplies in an accelerator must continue to operate for the system to be successful. Let $R_i = 0.9$. Find the probability of success.

B. Repeat for at least 2 out of 4 succes

C. Repeat for at least 3 out of 4 success

D. Repeat for 4 out of 4 success

Solution:

Homework Problem # 18

Calculate the MTBF of a "typically commercial" 5 kW, switchmode power supply with EMI filter and appropriate electromechanical safety features amounting to 10% of the total number of components. The power supply operates at 50C ambient temperature. The power supply consists of the following components with the listed failure rates.:

- *2 each ICs, plastic linear, l = 3.64*
- *1 each opto-isolator, l = 1.32*
- *2 each hermetic sealed power switch transistors, l = 0.033*
- *2 each plastic power transistors, l = 0.026*
- *4 each plastic signal transistors, l = 0.0052*
- *2 each hermetic sealed power diodes, l = 0.064*
- *8 each plastic power diodes, l = 0.019*
- *6 each hermetic sealed switch diodes, l = 0.0024*
- *32 each composition resistors, l = 0.0032*
- *3 each potentiometers, commercial, l = 0.3*
- *8 each pulse type magnets, 130C rated, l = 0.044*
- *12 each ceramic capacitors, commercial, l = 0.042*
- *3 each film capacitors, commercial, l = 0.2*
- *9 each Al electrolytics, commercial, l = 0.48*

Homework Problem # 19

Two inverter stages in an uninterruptible power supply are to be connected in parallel. each is capable of full-load capability. The calculated failure rate of each stage is l = 200 failures per million hours. A. What is the probability that each inverter will remain failure free for a mission time of 1000 hours and B) What is the probability that the system will operate failure free for 1000 hours?

Solution:

Homework Problem # 20

For a critical mission, 3 power supplies, each capable of supplying the total required output, are to be paralleled. The power supplies are also decoupled such that a failure of any power supply will not affect the output. The calculated failure rate of each power supply is 4 per million hours.

A. What is the probability that each power supply will operate failure free for 5 years?

B. What is the probability that the system will operate failure free for 5 years? Solution below.