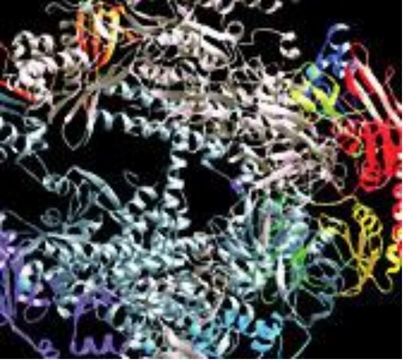
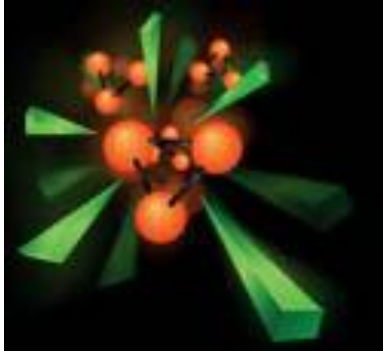




US Particle Accelerator School

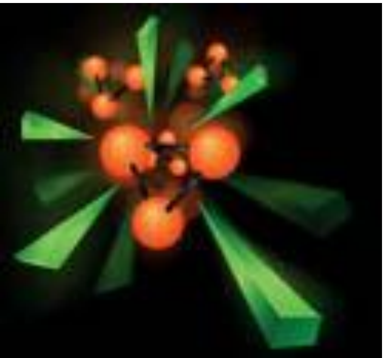
Michigan State University

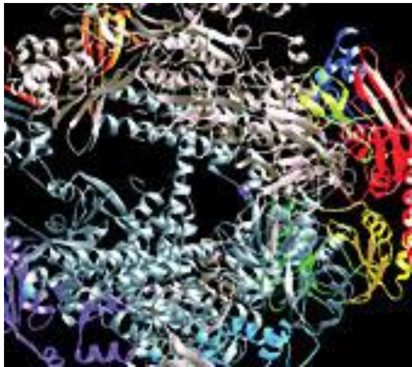
Accelerator Power Electronics Engineering

June 2012

Paul Bellomo and Fernando Rafael

SLAC National Accelerator Laboratory (SLAC)

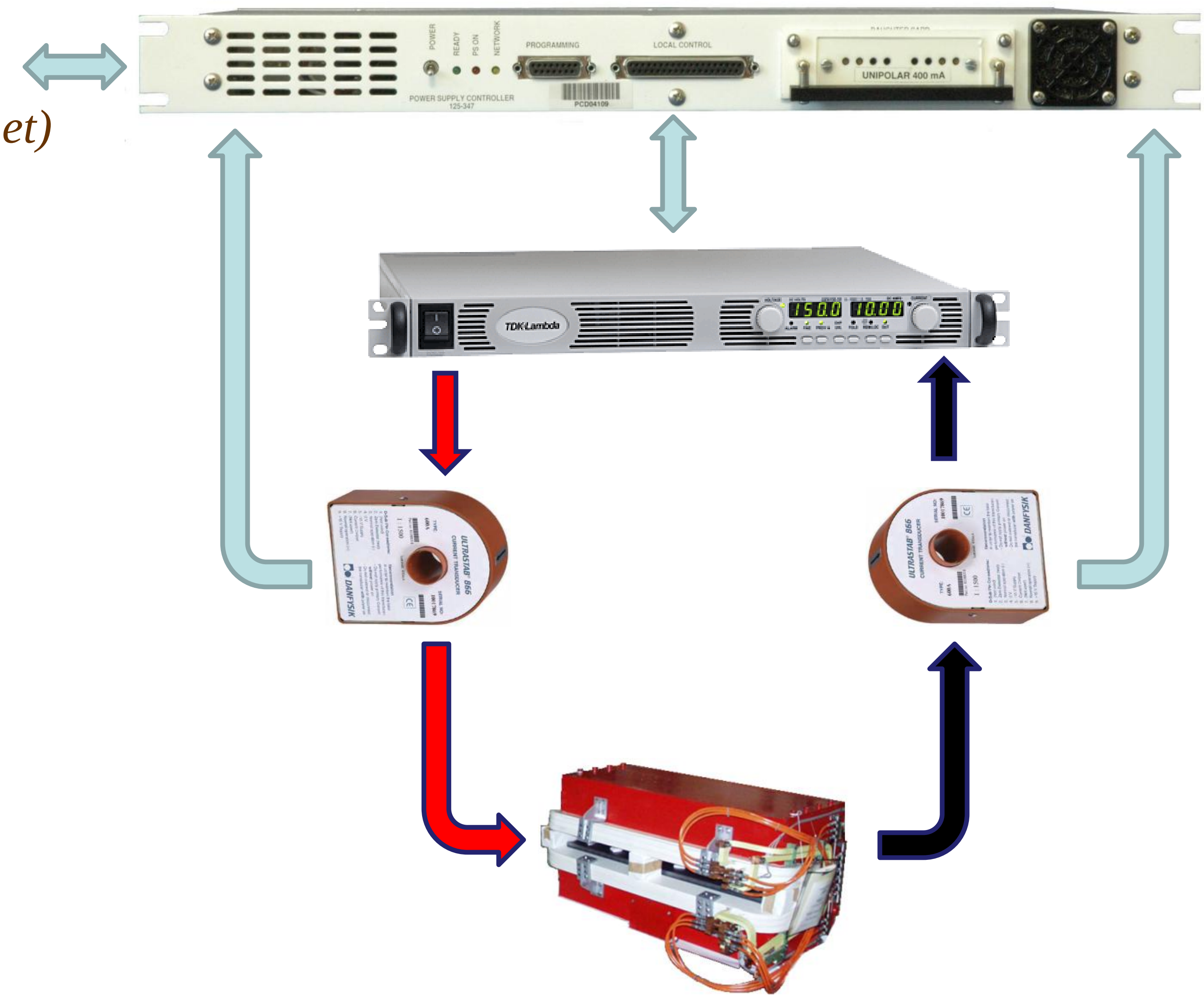




Sections

A Typical DC Magnet Power System

- 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 pulsed power supplies*

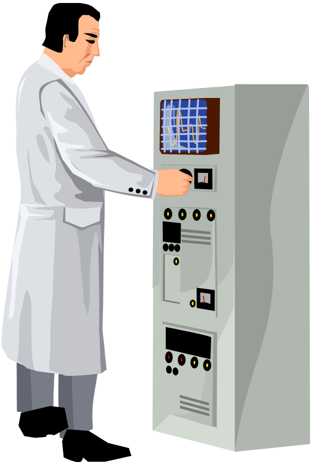
Goals

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

Intended Audience

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

- ***Control Designers*** *– 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

- ***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*

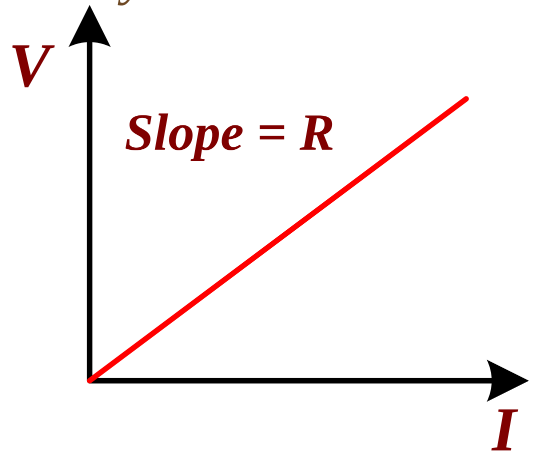
Section 3

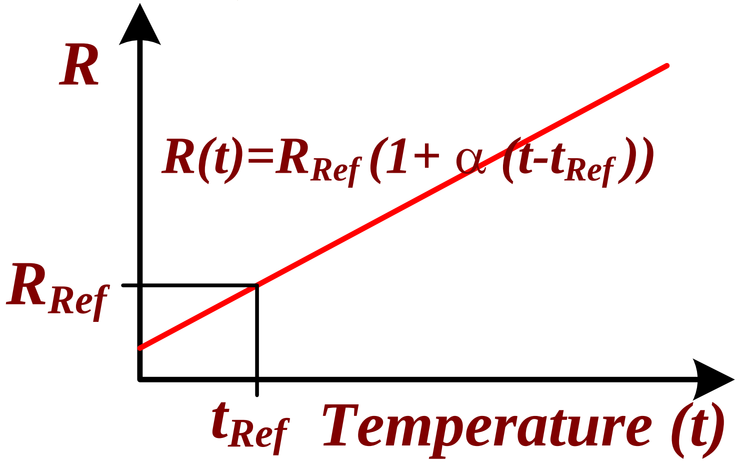
- *Typical Load Types*
  - *Resistive – Filament*
  - *Resistive - Titanium Sublimation Pumps (TSPs)*
  - *DC Magnets*
  - *Klystrons*
  - *Linear Accelerators*
  - *Electron Beam Gun*
  - *Pulsed Magnets*
  - *Flash lamp*

Resistive Load Characteristics

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, 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*

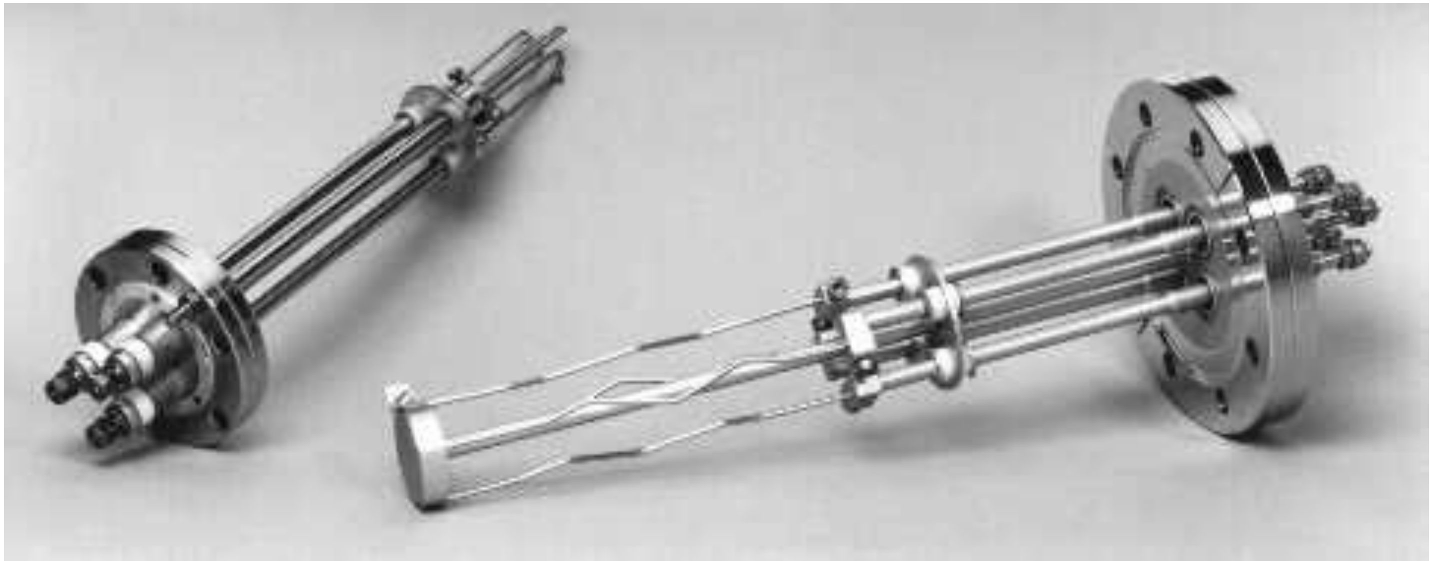
Work function *- the minimum energy which must be supplied to extract an electron from a solid; symbol* ϕ*, units J (joule), or more often eV (electron-volt). It is a measure of how tightly electrons are bound to a material. The work function of several metals is given below:*

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 (TSP s)

- *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*

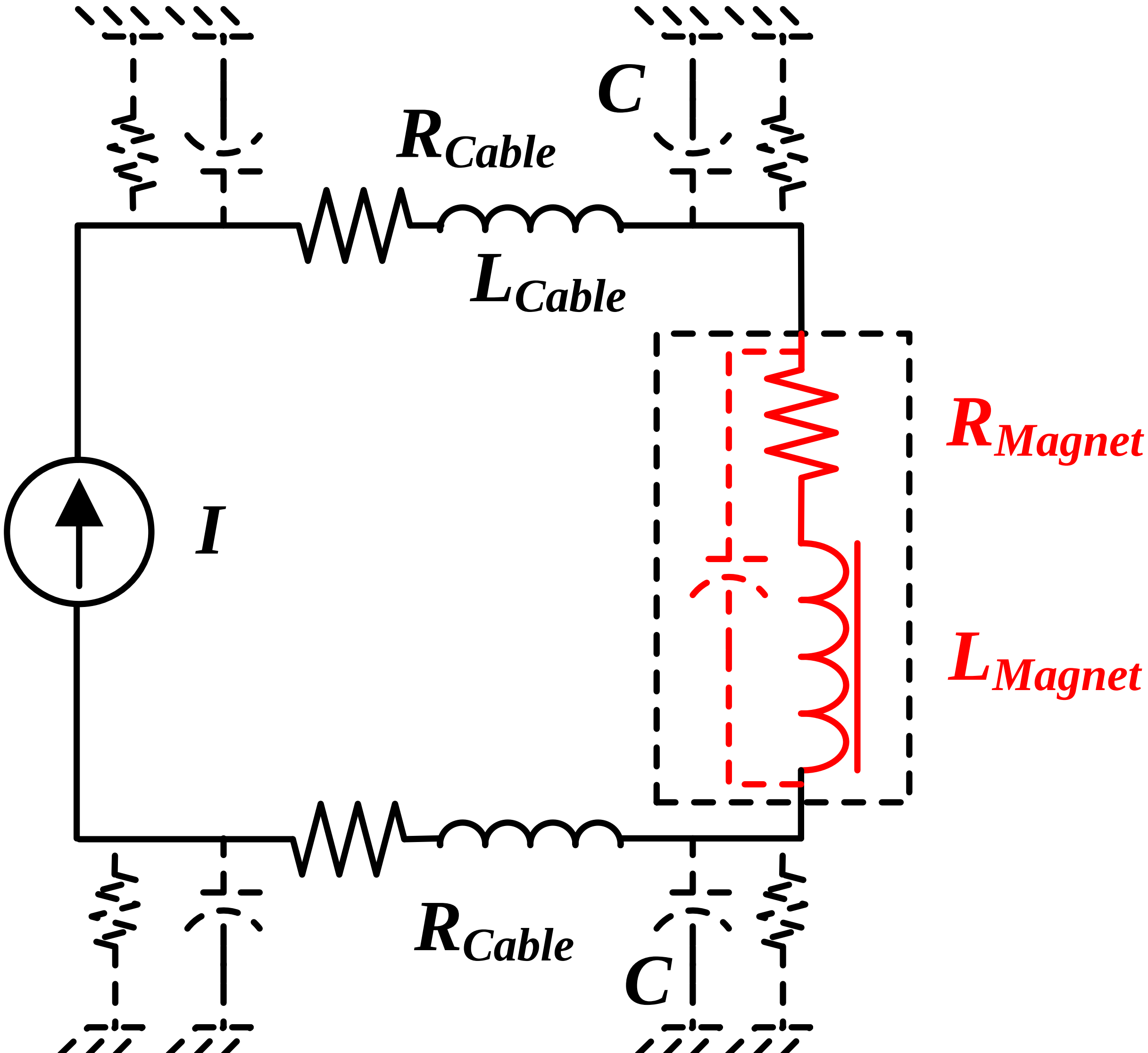


Sublimate *- To transform directly from the solid to the gaseous state or from the gaseous to the solid state without becoming a liquid.*

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



Representation

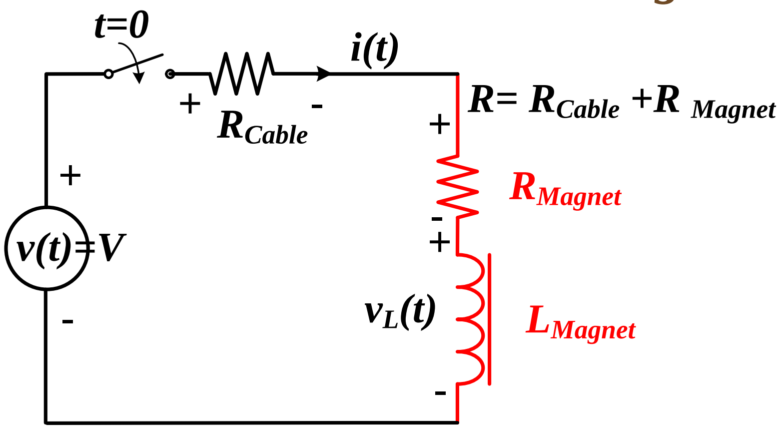
Ampere's Law

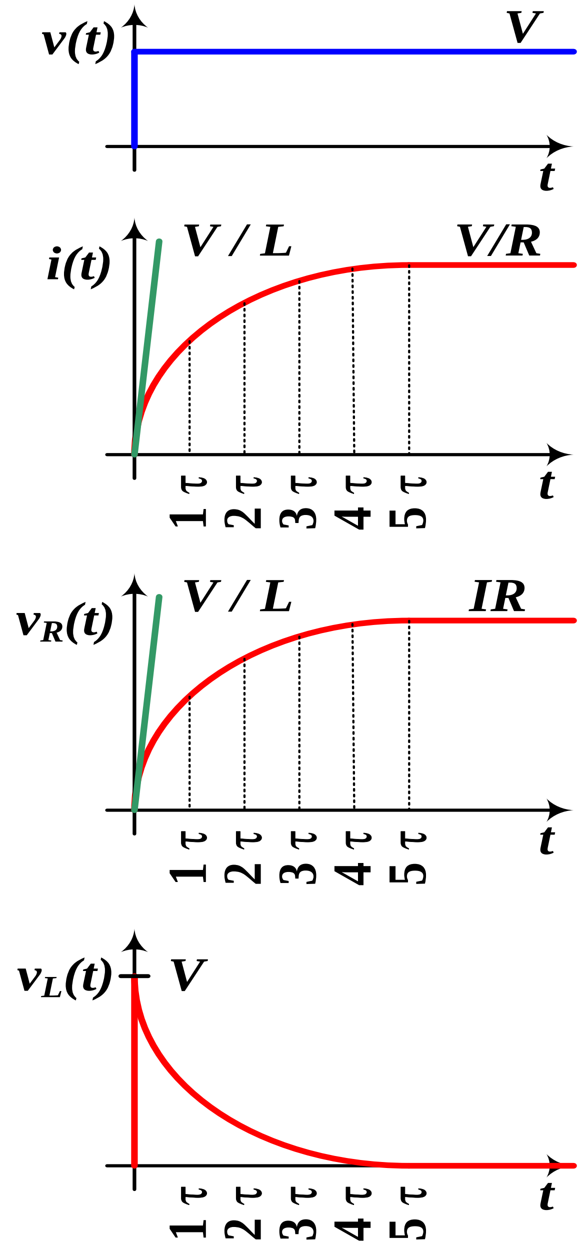
$$B = \mu H = \frac{\mu_r \mu_0 NI}{l}$$

Lorentz Force Law

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

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

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

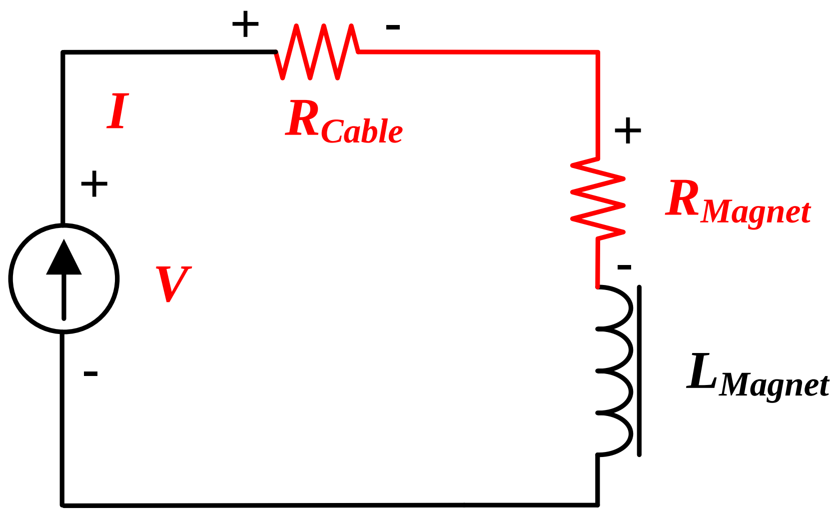
Rearranging gives

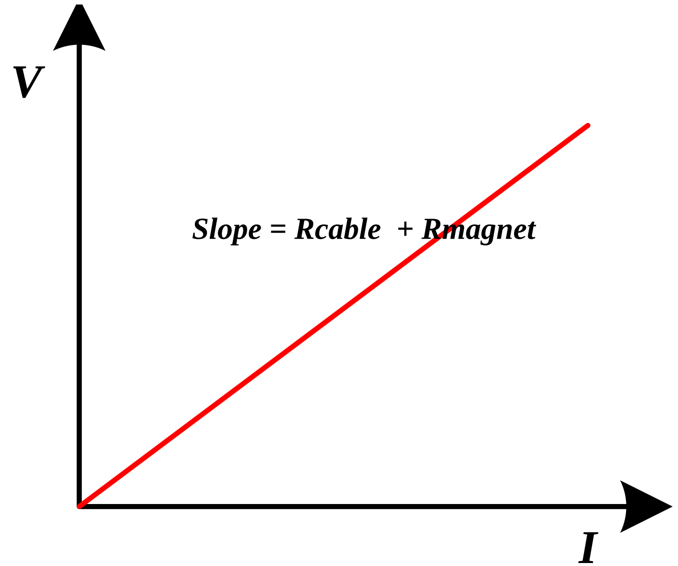
$$I(s)\frac{L}{R}\left(s+\frac{R}{L}\right)=\frac{V}{R}\frac{1}{s} \qquad \text{let } \frac{R}{L}=\alpha \text{ and } \frac{L}{R}=\frac{1}{\alpha}=\tau$$

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

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

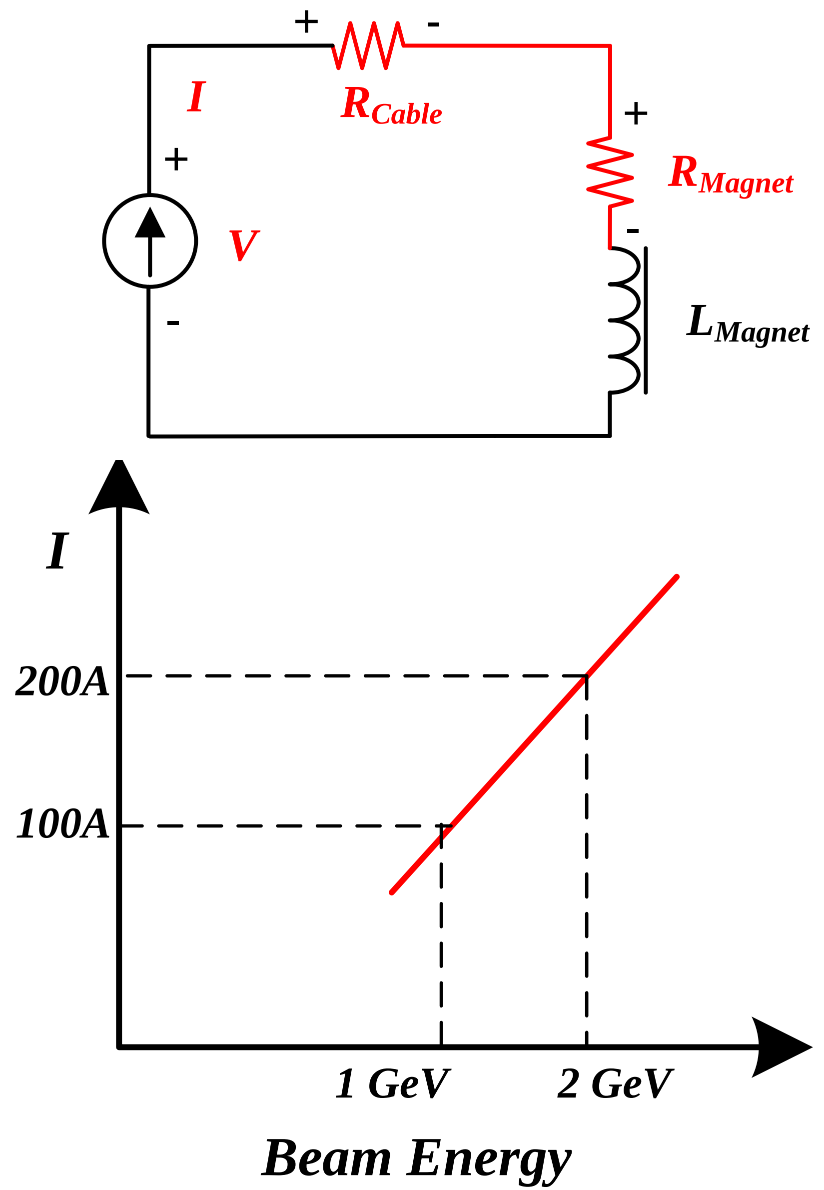
DC Magnet Loads – Characteristics



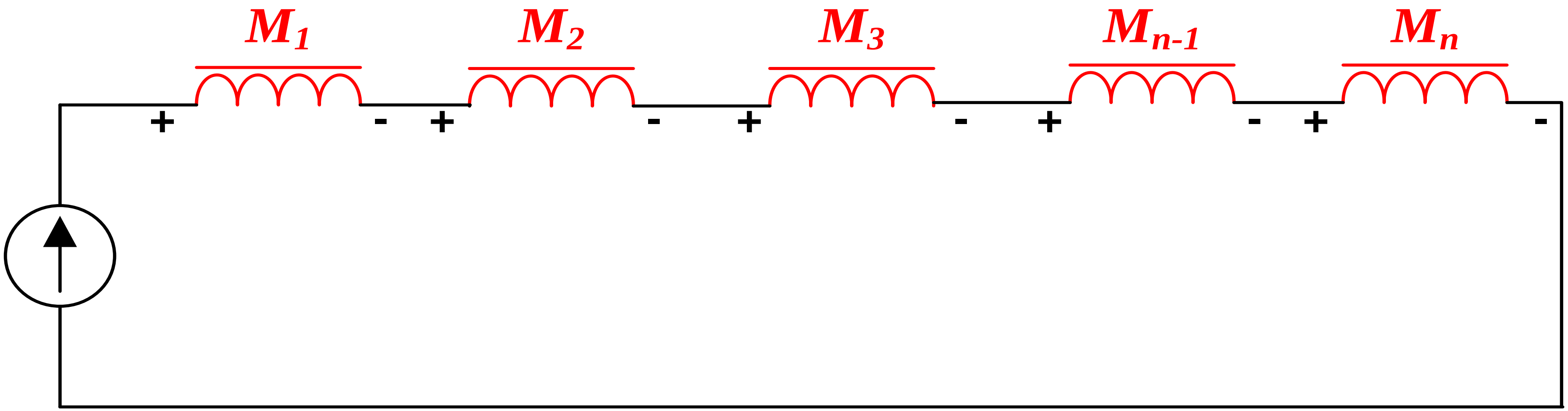


DC V-I Characteristic

DC Magnet Loads – Characteristics



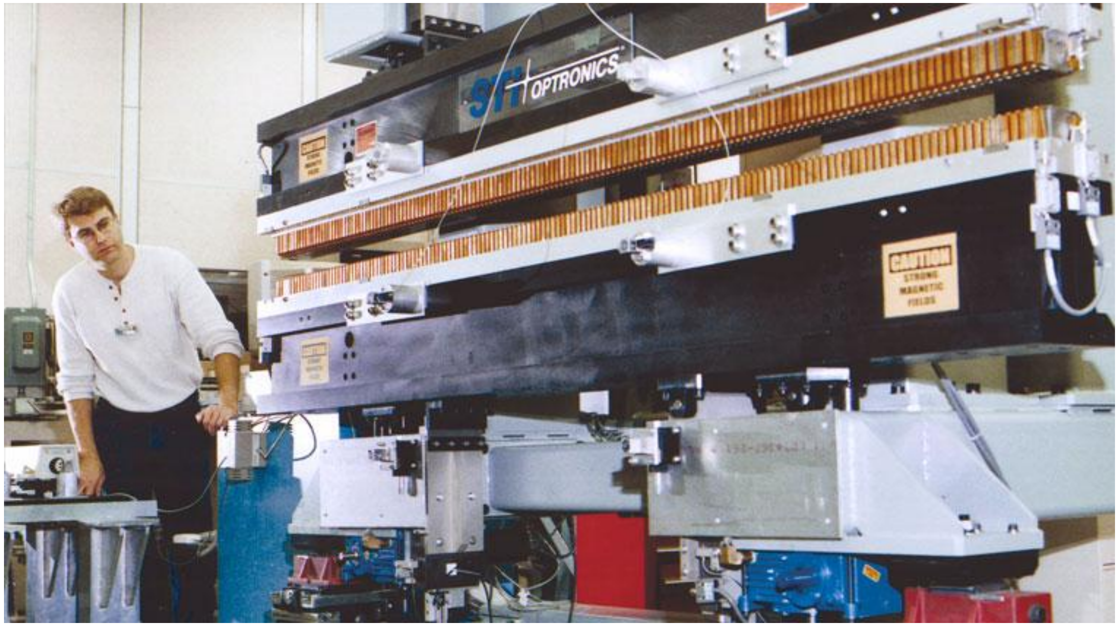
DC Magnet Loads – Characteristics

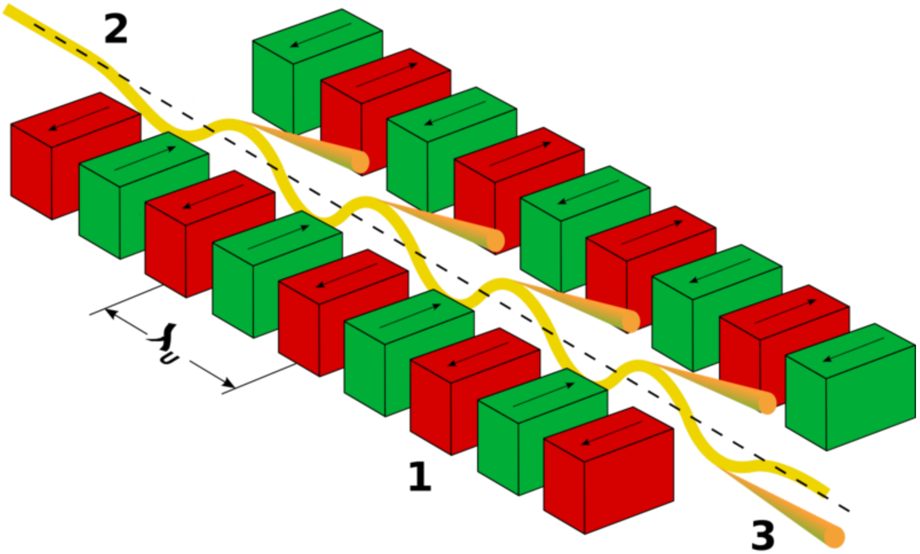


*String (series-connect) magnets for economy when magnets are not adjacent to **insertion devices** or when there are no special optics requirements. The current in each series-connected magnet is the same.*

*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*

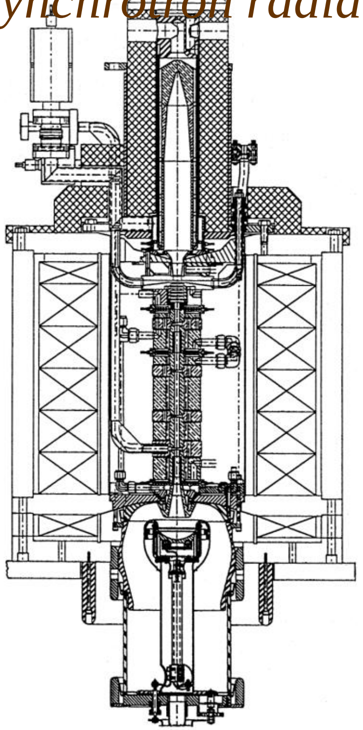
Photograph of an Insertion Device at the APS

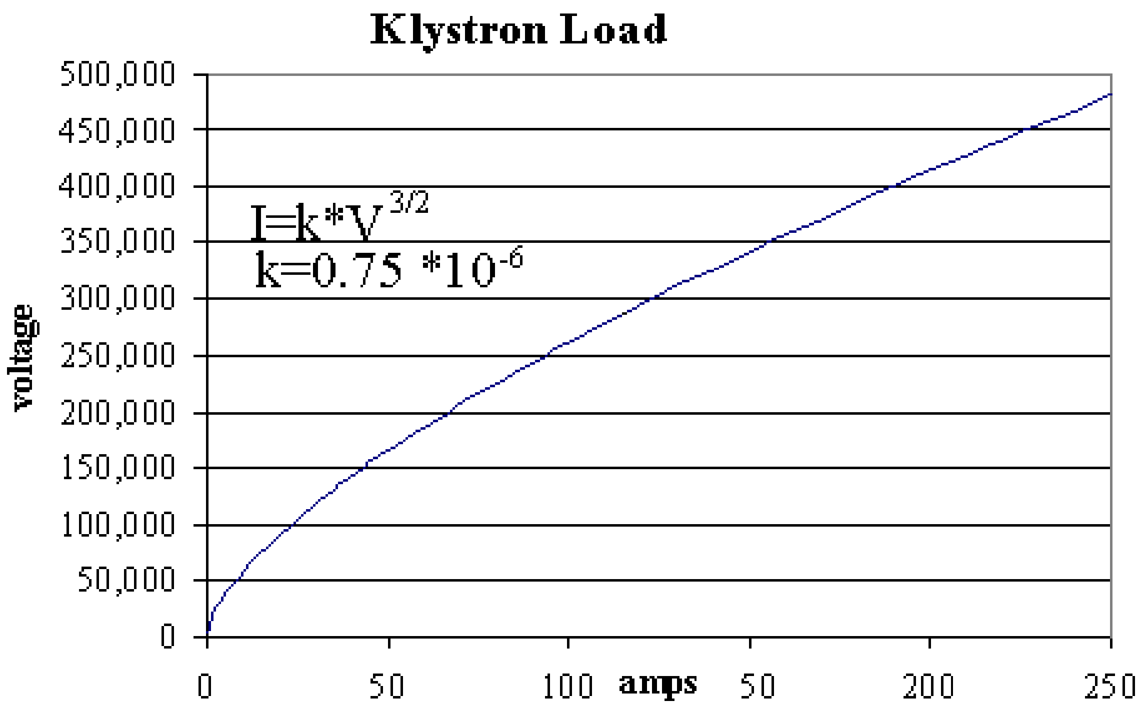




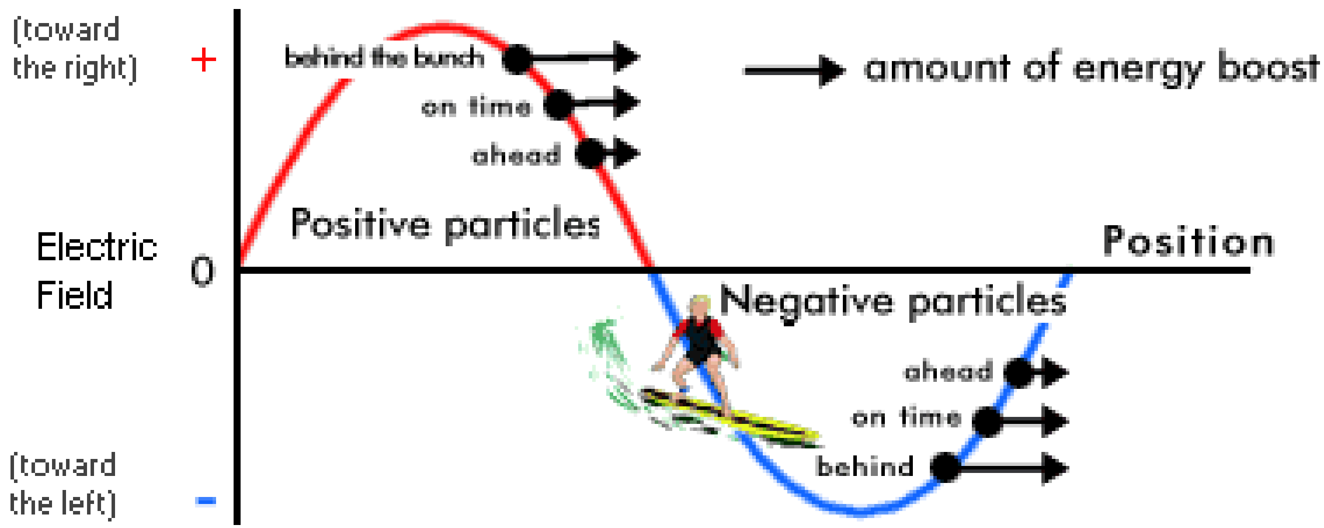
Klystron Load

- Klystrons are used in RF and microwave systems to accelerate electron beams
- Their transfer function is called perveance (k) which is the ratio between beam current and accelerating voltage. Perveance is usually expressed in µp.
- In LINACs they are used in a pulsed mode to accelerate the electron beam
- In boosters and storage rings they are used as continuous-mode to supply make-up energy to the electron beam to compensate for the energy lost by synchrotron radiation



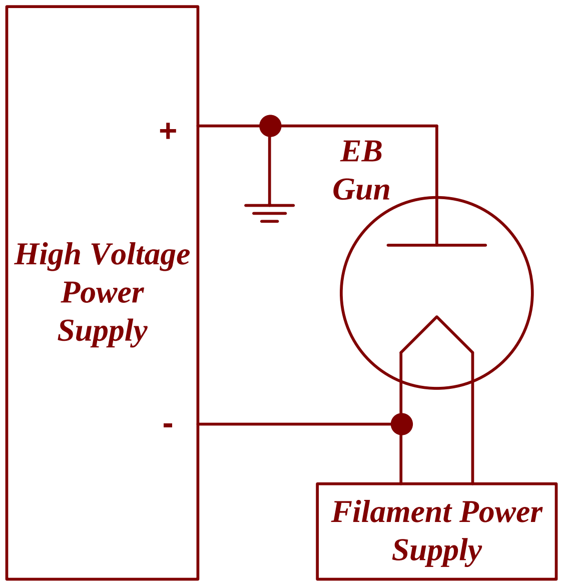


- *Electrons and positrons may be accelerated by injecting them into structures with traveling electromagnetic waves*
- *The microwaves from klystrons in the are fed into the accelerator structure via waveguides. This creates a pattern of electric and magnetic fields, which form an electromagnetic wave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

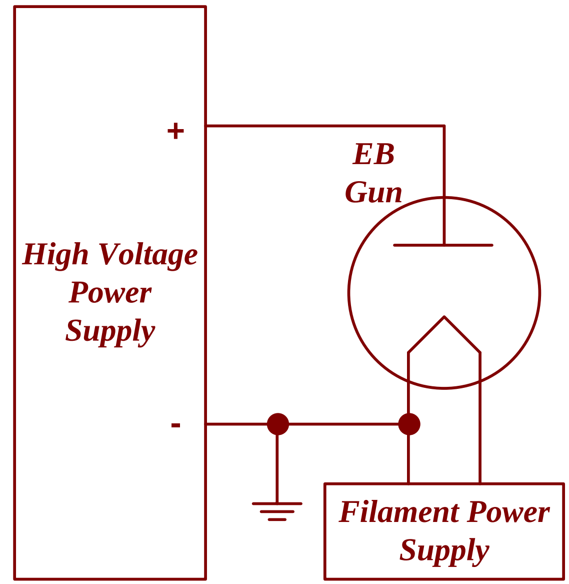


Electron Beam Gun Electrical Load Characteristics

- *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

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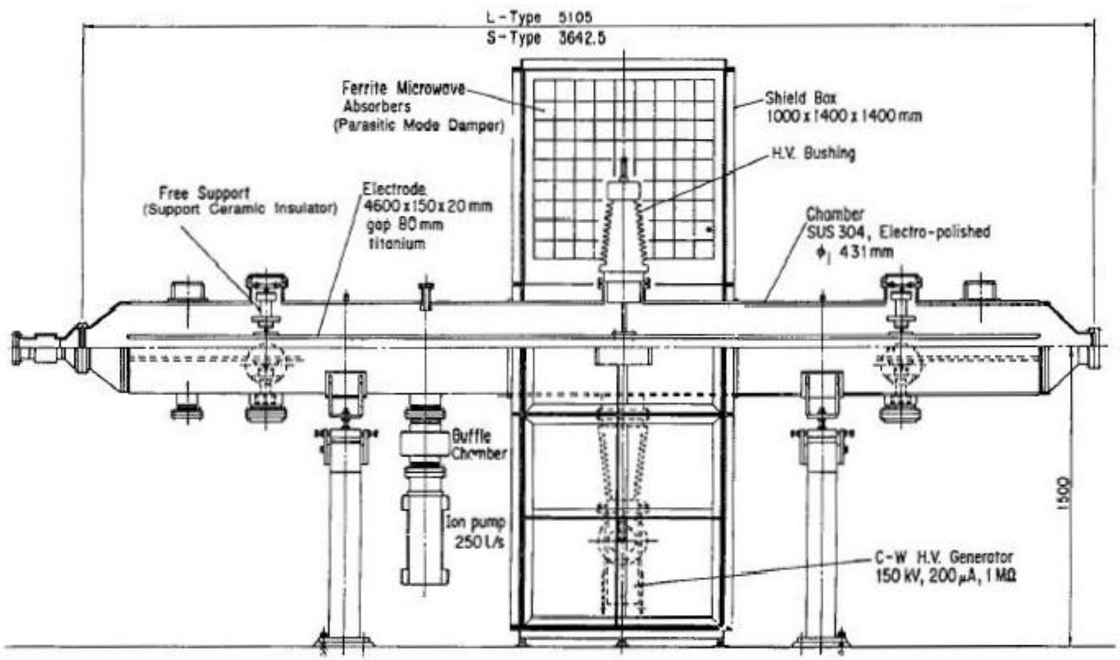
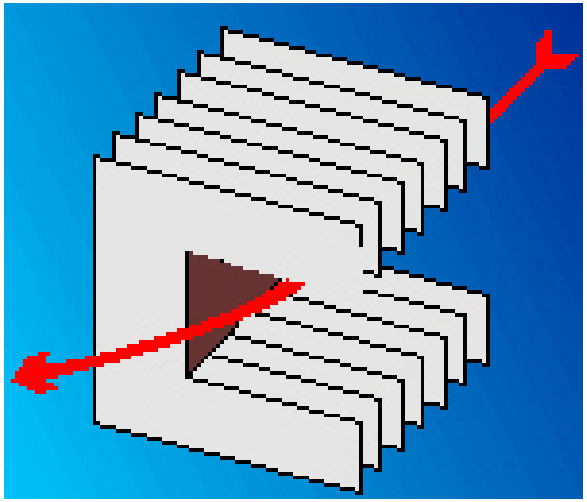


Fig.2 Separator chamber.

- *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 linear section (LINAC) into a storage ring*

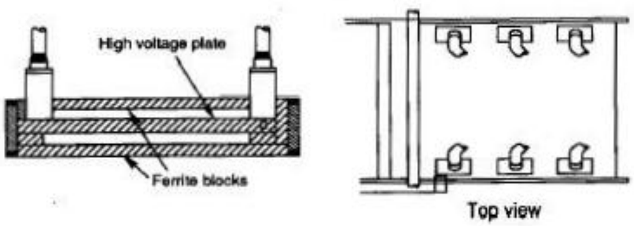
- *An ejection kicker will do the inverse, that is, kick a particle beam from a storage ring into a working beamline.*



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.



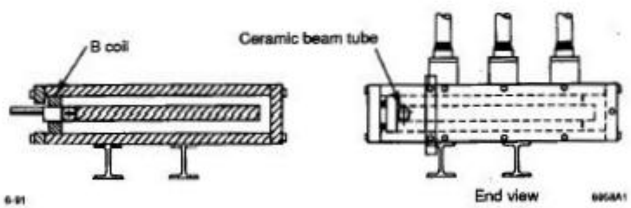
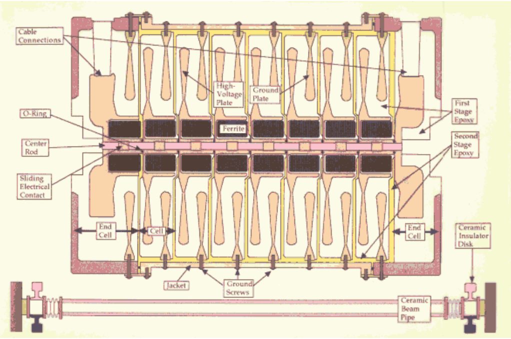
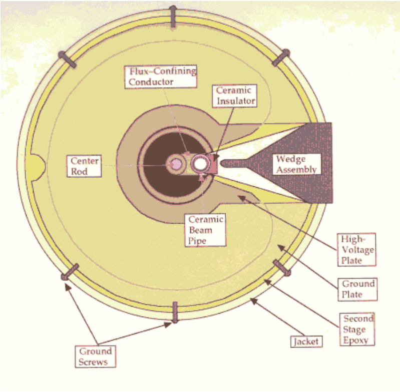
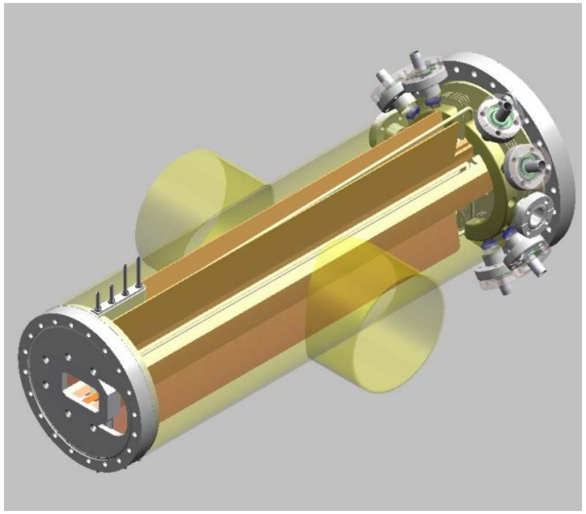
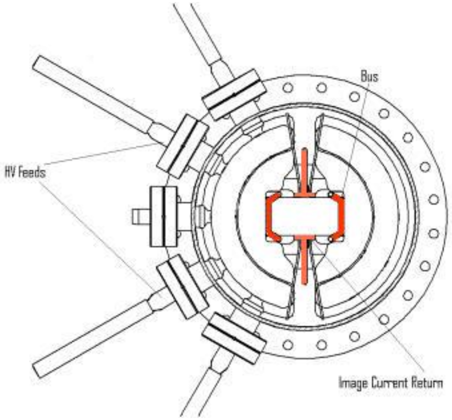


Fig. 6. SLAC-style kicker magnet.







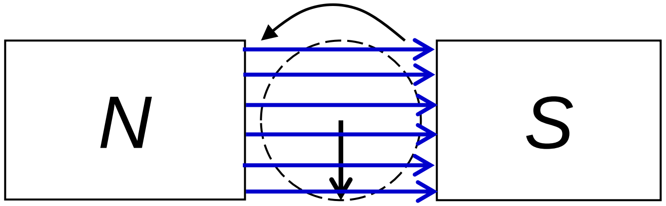


Section 4

- *Power Line and Other Considerations*

Fundamental Quantities - Characteristics of Sinusoidal Waves

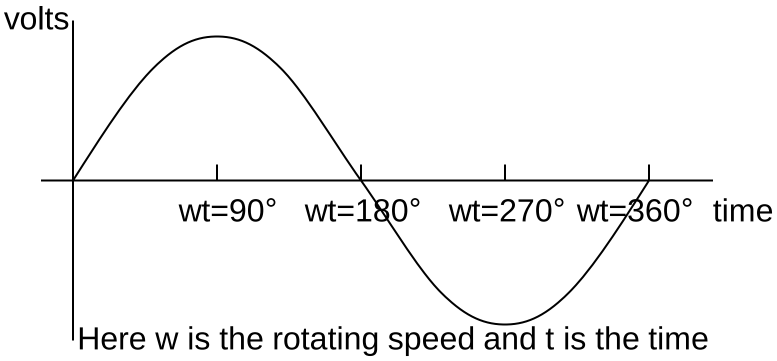
- *Generation of sine waves*



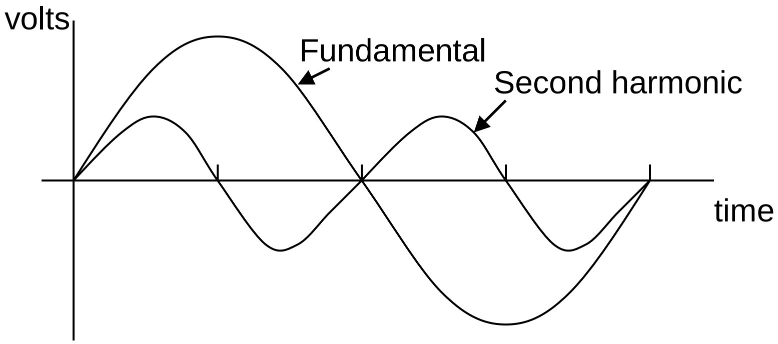
- *Expression of sine waves*

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

- *Plotting of sine waves*



- *Harmonics between sine waves*



- *Average value:*

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

for AC sine system

$$v(t) = V_m \sin(\omega t), \text{then} \quad V_{ave} = \frac{1}{T}\int_0^T V_m \sin(\omega t)dt = 0.636 * V_m$$

- *RMS value:*

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

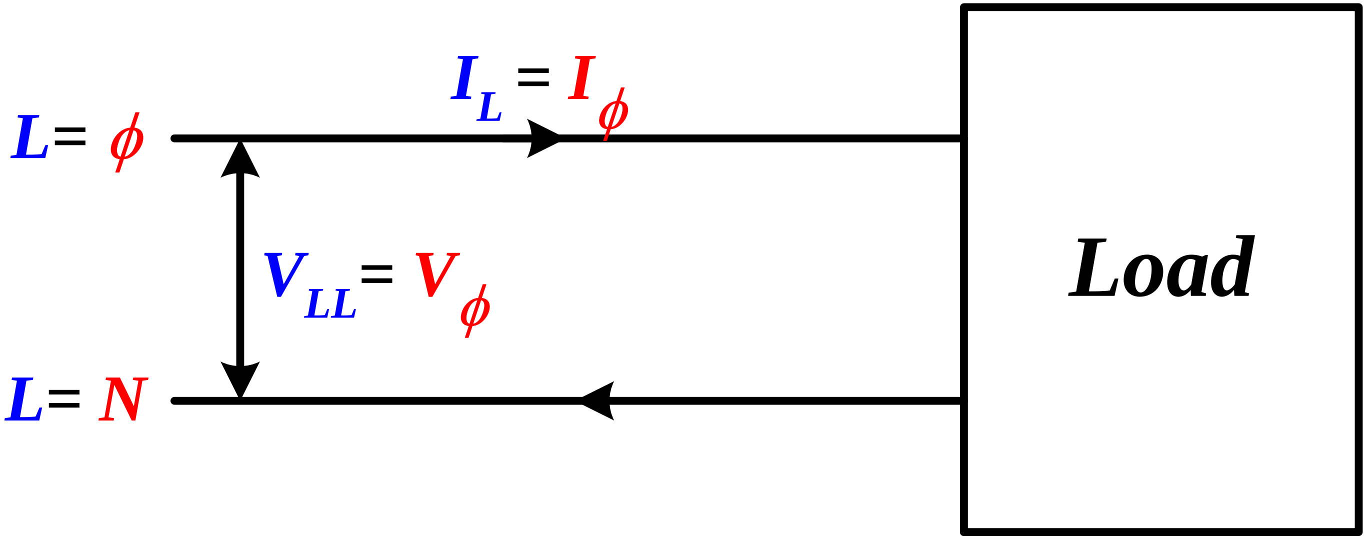
for AC sine system

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

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
	208 V	3ϕ	120 V, 1ϕ
	120 V	1ϕ	None

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

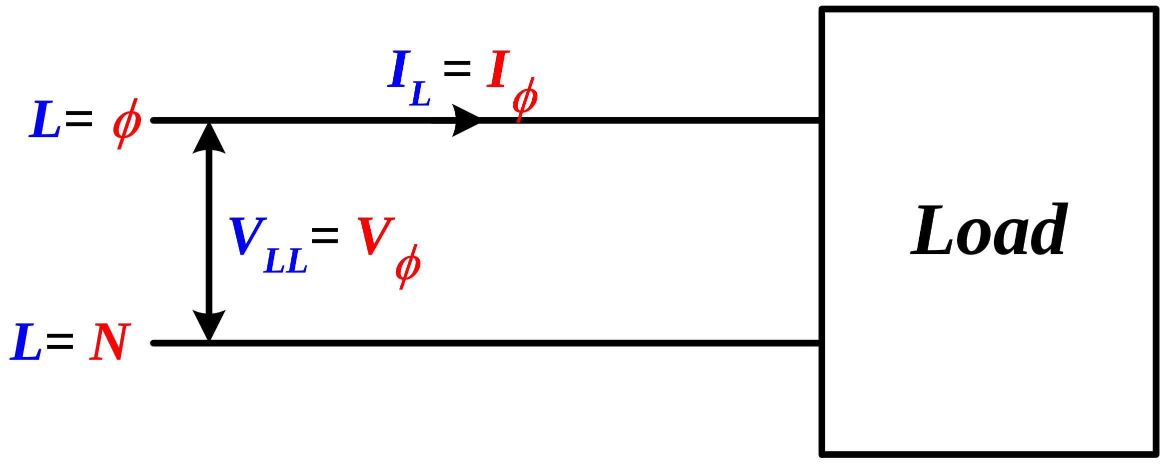


For 1ϕ AC input

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

$I_\phi = I_L$ *where* V_ϕ *and* I_ϕ *are RMS values*

Single Phase Systems



The Apparent, Real and Reactive "powers" are:

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

$$\text{Real} \qquad P_{1\phi} = V_{LL}\ I_L \cos\left(\alpha_{I_L} - \beta_{V_{LL}}\right) \qquad Watt \qquad \cos\left(\alpha_{I_L} - \beta_{V_{LL}}\right) = \text{power factor}$$

$$\text{Reactive} \qquad Q_{1\phi} = V_{LL}\ I_L \sin\left(\alpha_{I_L} - \beta_{V_{LL}}\right) \qquad VAR$$

All "powers" are average "powers"

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

Single Phase Systems

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 $v(t) = \sqrt{2}V\sin(\omega t)$

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

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

Identity

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

Substituting

$$p(t) = V\,I\,[\cos(\omega t - \omega t - \phi) - \cos(\omega t + \omega t + \phi)]$$

$$p(t) = V\,I\,[\cos(-\phi) - \cos(2\omega t + \phi)]$$

recognizing that $\cos(-\phi) = \cos(\phi)$

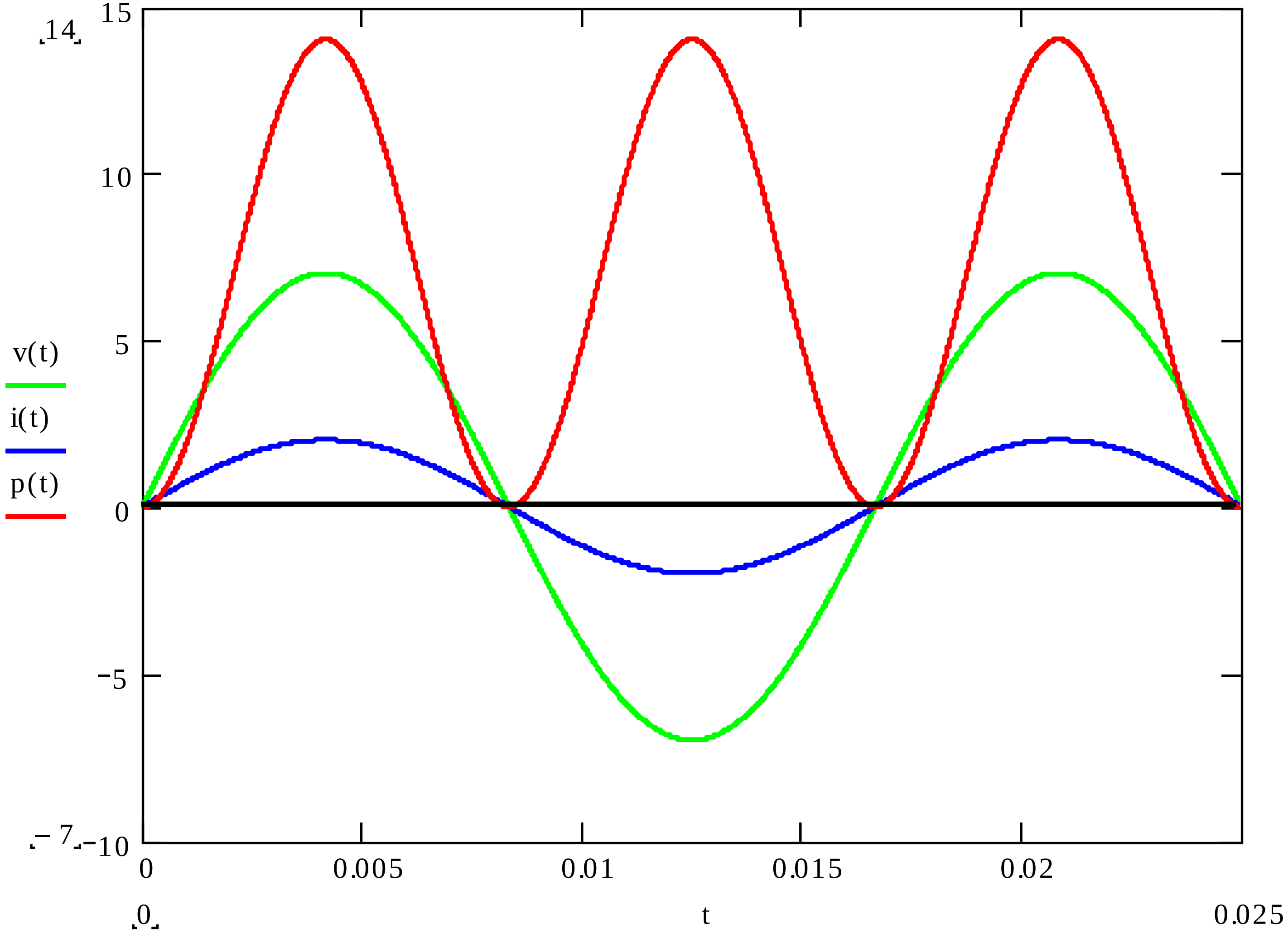
$$p(t) = V\,I\cos(\phi) - V\,I\cos(2\omega t + \phi)$$

It is seen that

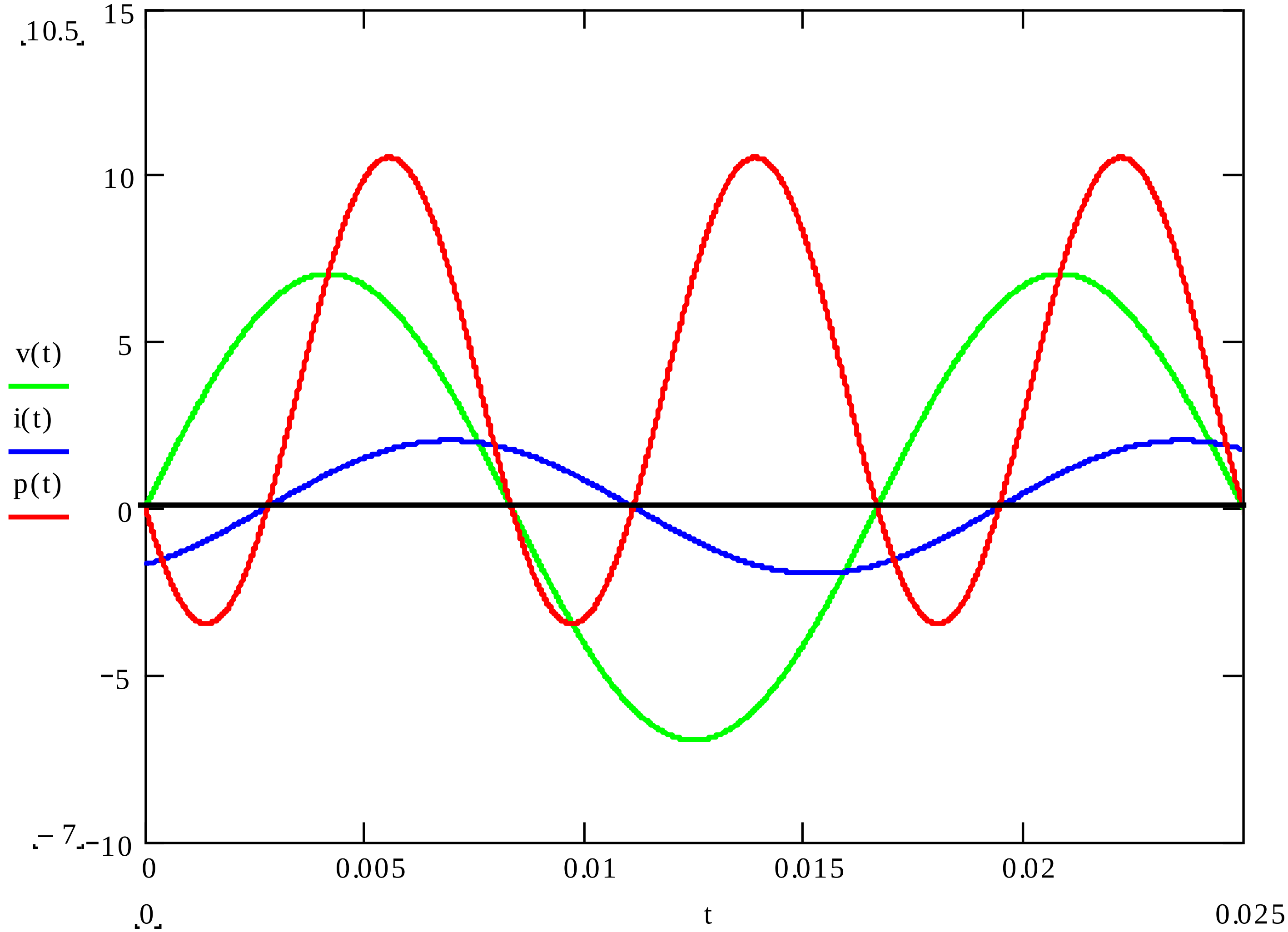
$p(t) =$ DC component + AC component with twice the frequency of the voltage or current

The DC component is a max imum 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

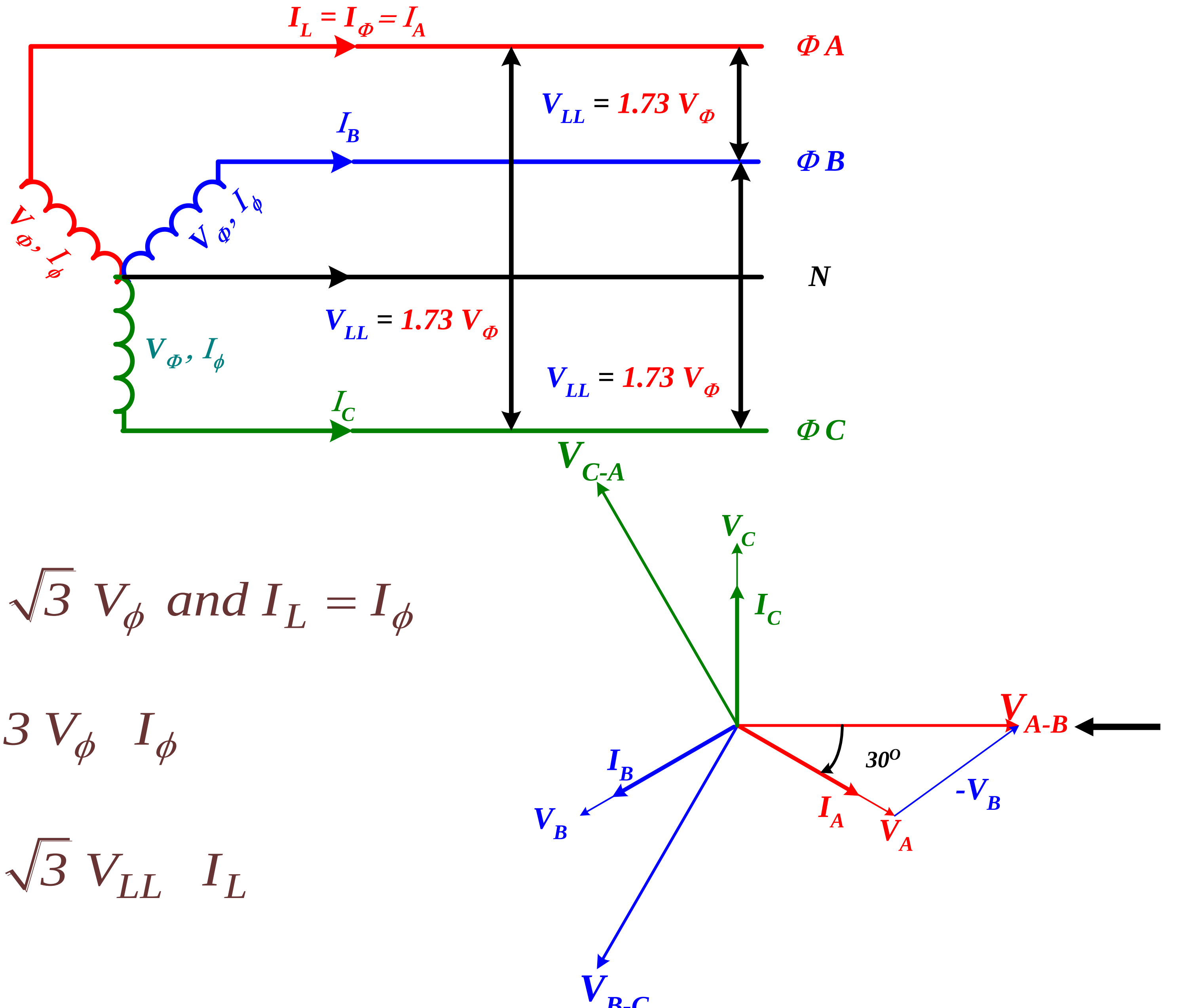


- *Voltage and current are in phase at 60 Hz*
- *Power is + (delivered to load) at 120 Hz*



- Voltage leads current by 60^{O} at 60 Hz
- 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

Three Phase Systems - Wye

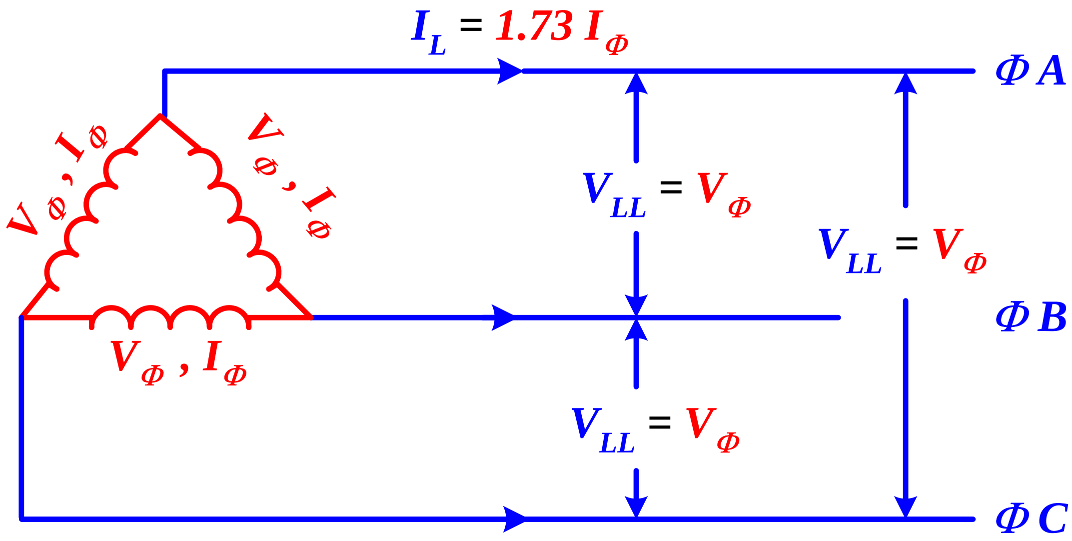


$$V_{LL} = \sqrt{3}\ V_\phi \text{ and } I_L = I_\phi$$

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

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

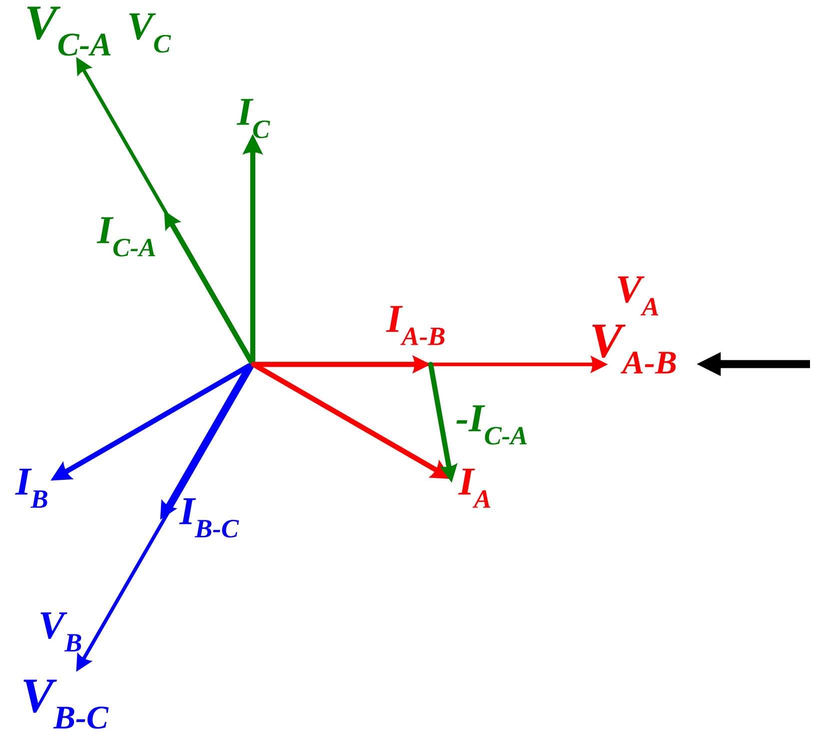
Three Phase Systems - Delta

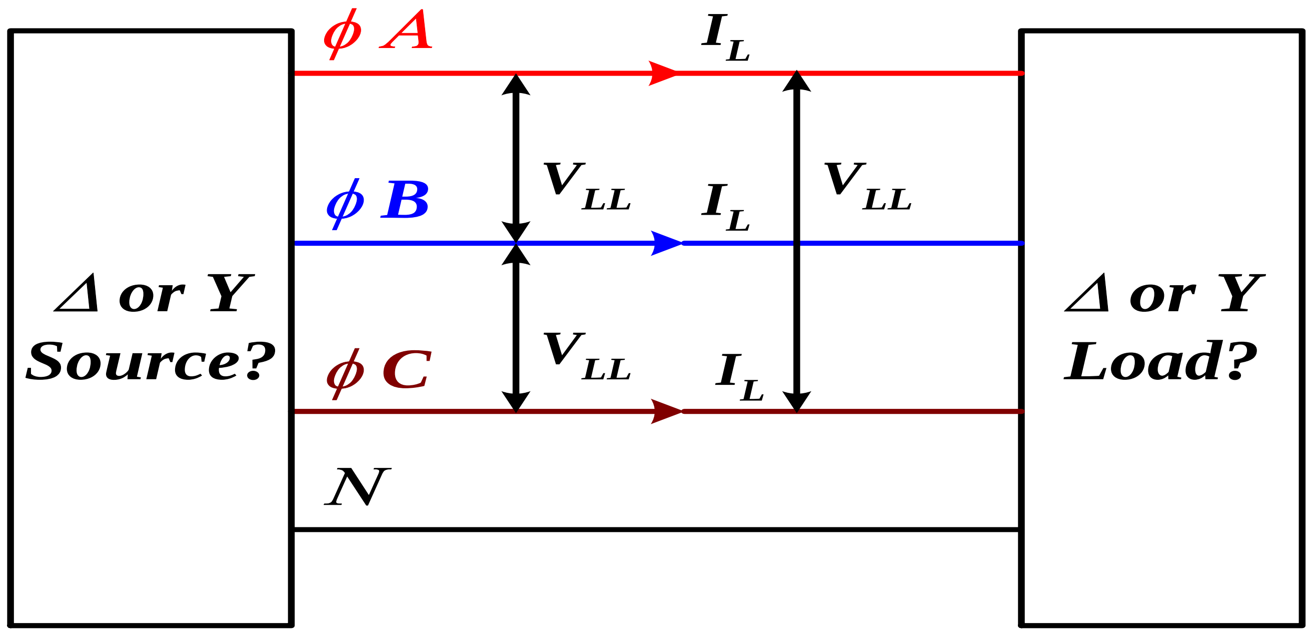


$$V_{LL} = V_{\phi} \quad \text{and } I_L = \sqrt{3}\, I_{\phi}$$

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

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





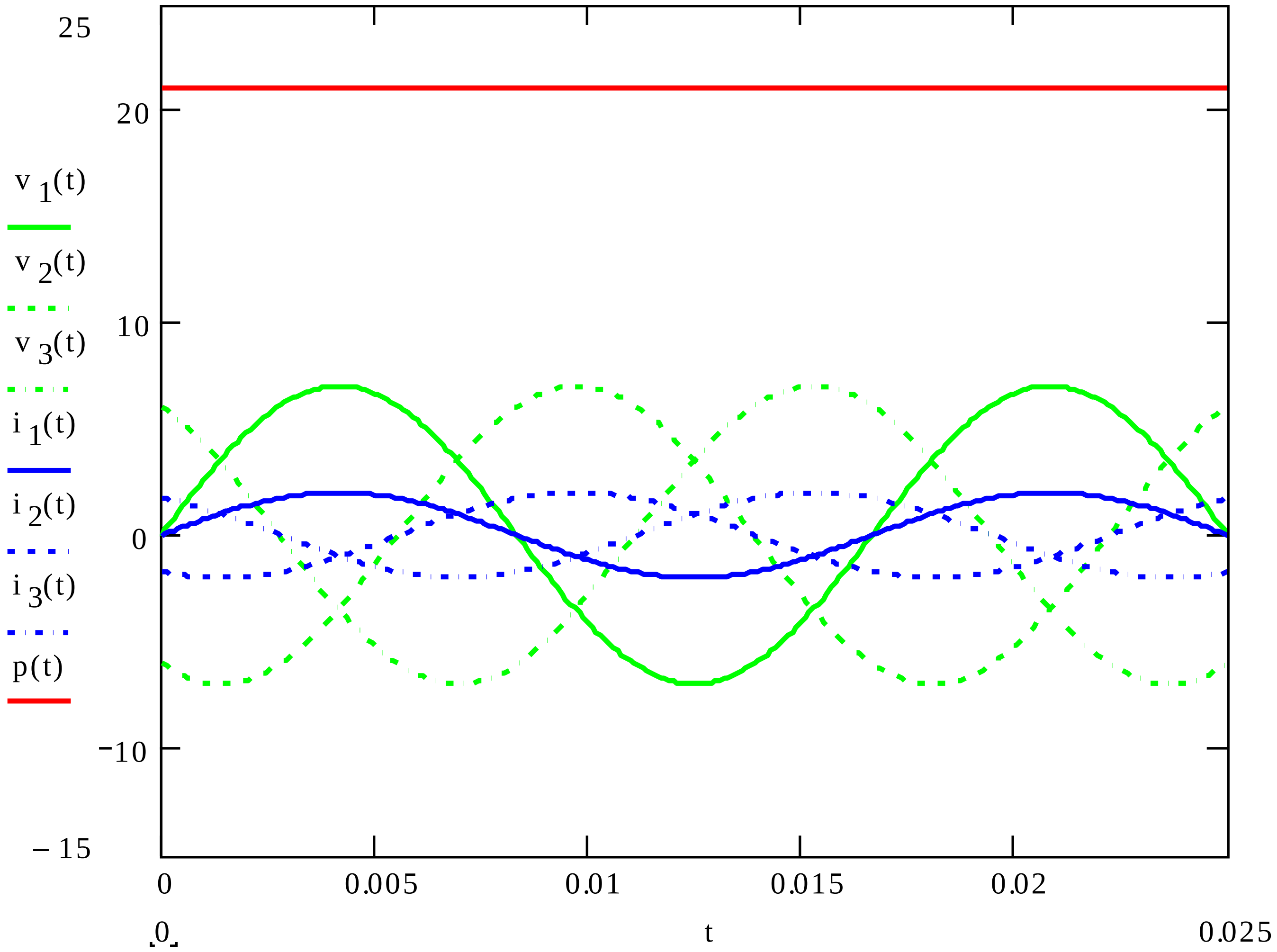
For Wye

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

For Delta

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

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



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

Three Phase Systems

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

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

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

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

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

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

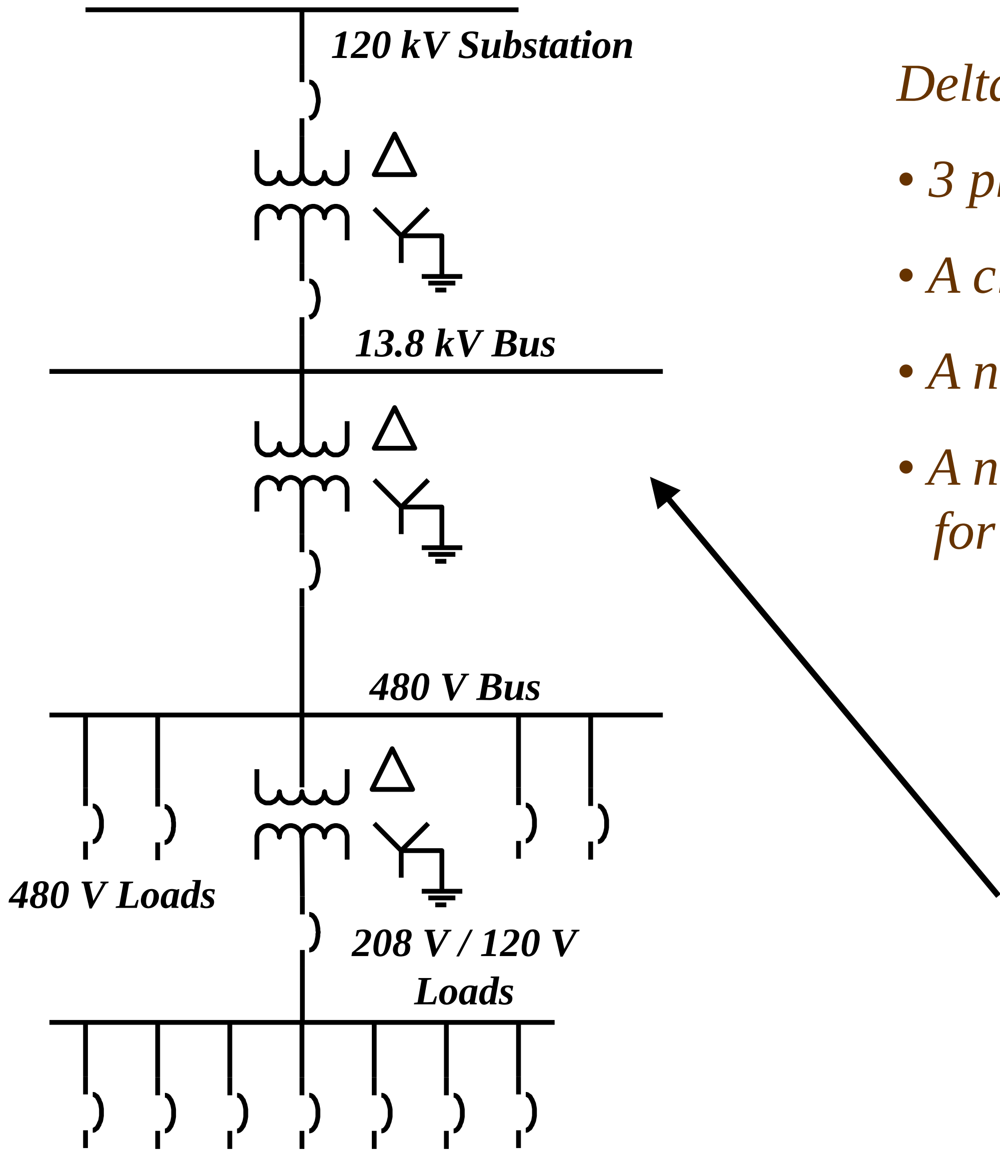
$$s(t) = VI[\cos(\phi) - \cos(2\omega t - \phi) + \cos(\phi) - \cos(2\omega t - 240^o - \phi) + \cos(\phi) - \cos(2\omega t - 120^o - \phi)]$$

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

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*

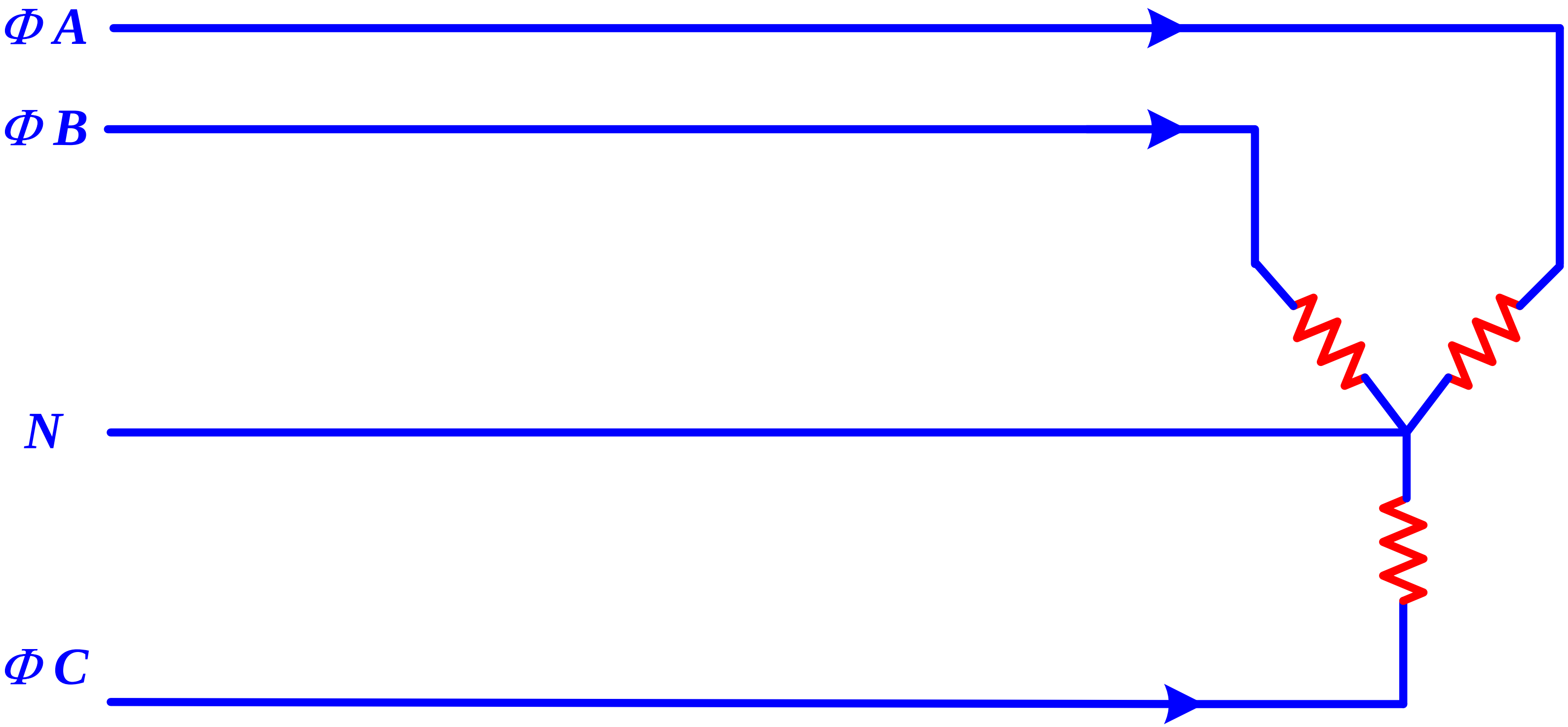


Delta - Wye Provides

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

Single or One-Line Diagram

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



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

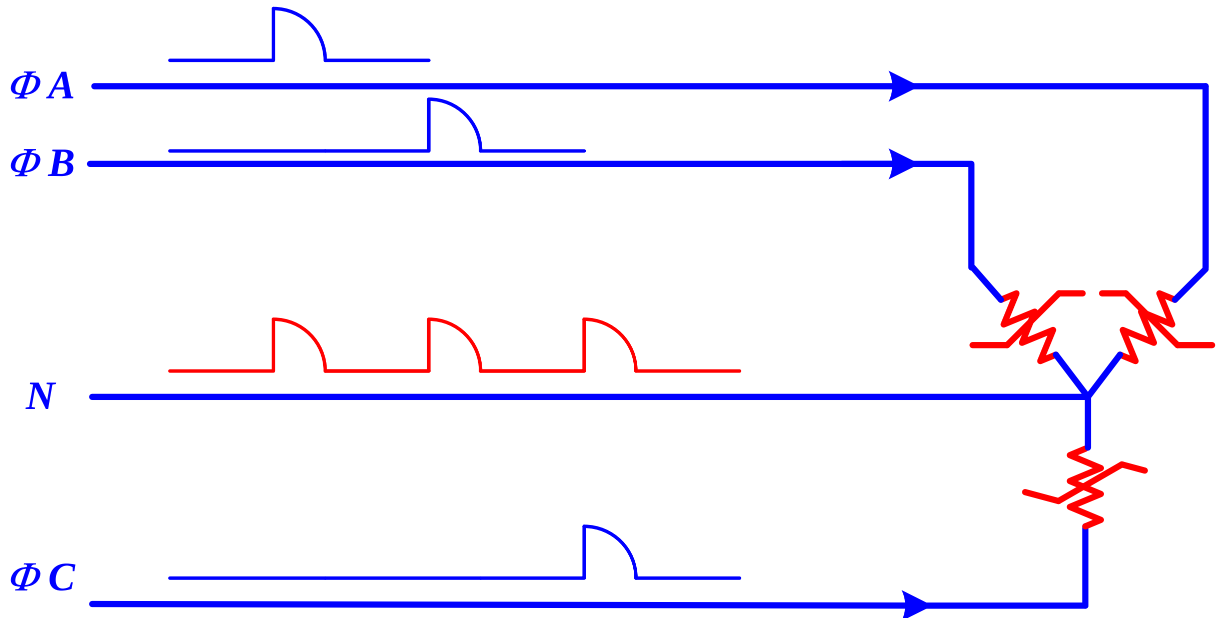
$$|I_A| = |I_B| = |I_C|$$

$$I_N = I_A + I_B + I_C$$

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

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 $\sqrt{3} * MAX(I_A, I_B, I_C)$

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

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

Establish 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 per ϕ Z Base = 3 ϕ Z Base

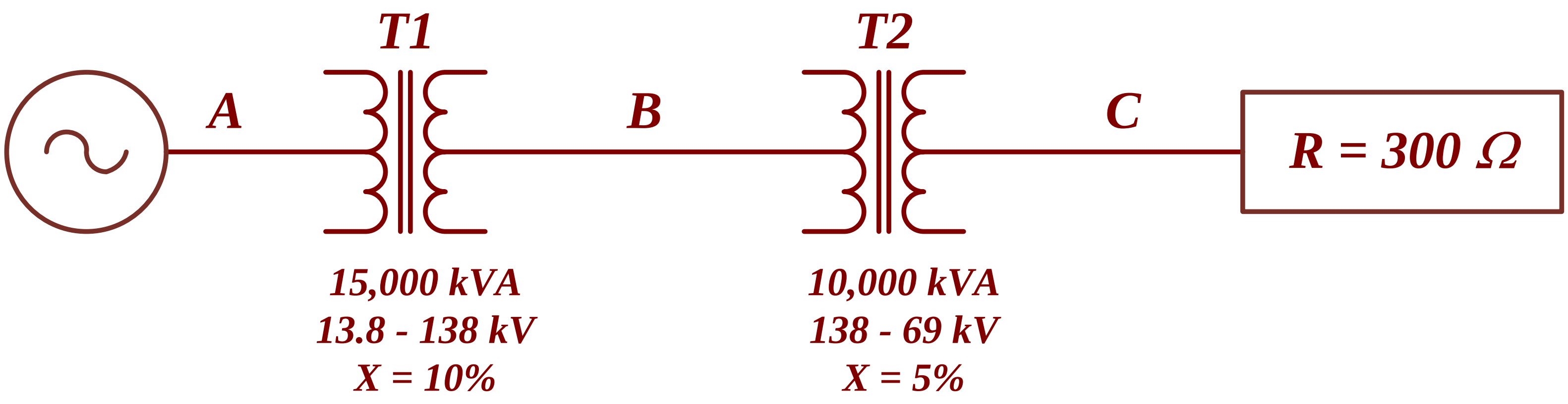
- *p.u. = actual value / Base value*

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

- *% = p.u. * 100 %*

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

The Per Unit Calculation System - 1ϕ Example to Calculate Line Currents



Establish Bases

In Section A

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

$$Base\ V = 13.8\ kV$$

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

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

Section B

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

$$V = 138\,kV$$

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

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

Section C

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

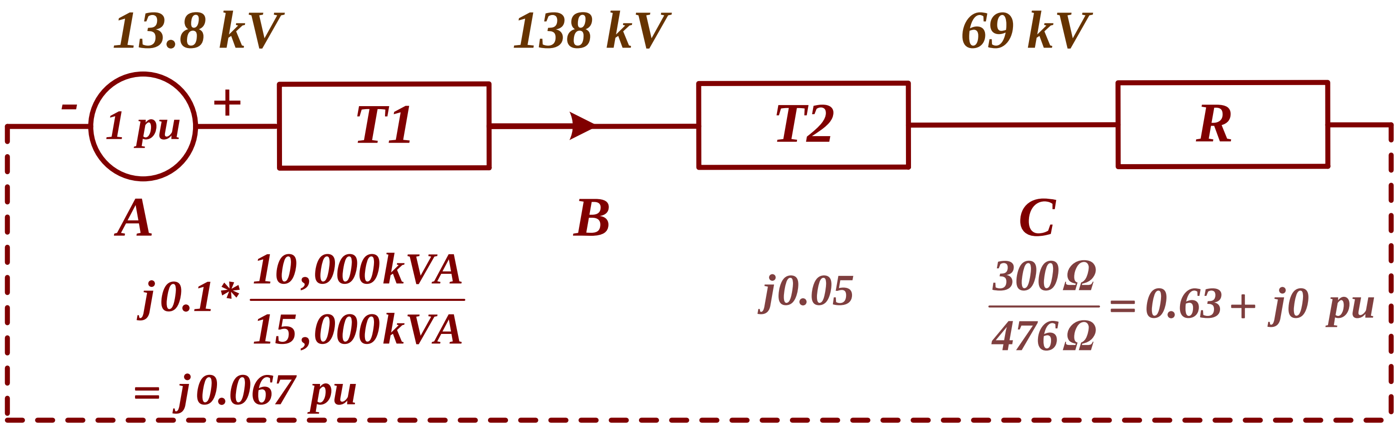
$$V = 69\,kV$$

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

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

The Per Unit Calculation System – 1 ϕ Example (Continued)

Obtain pu values

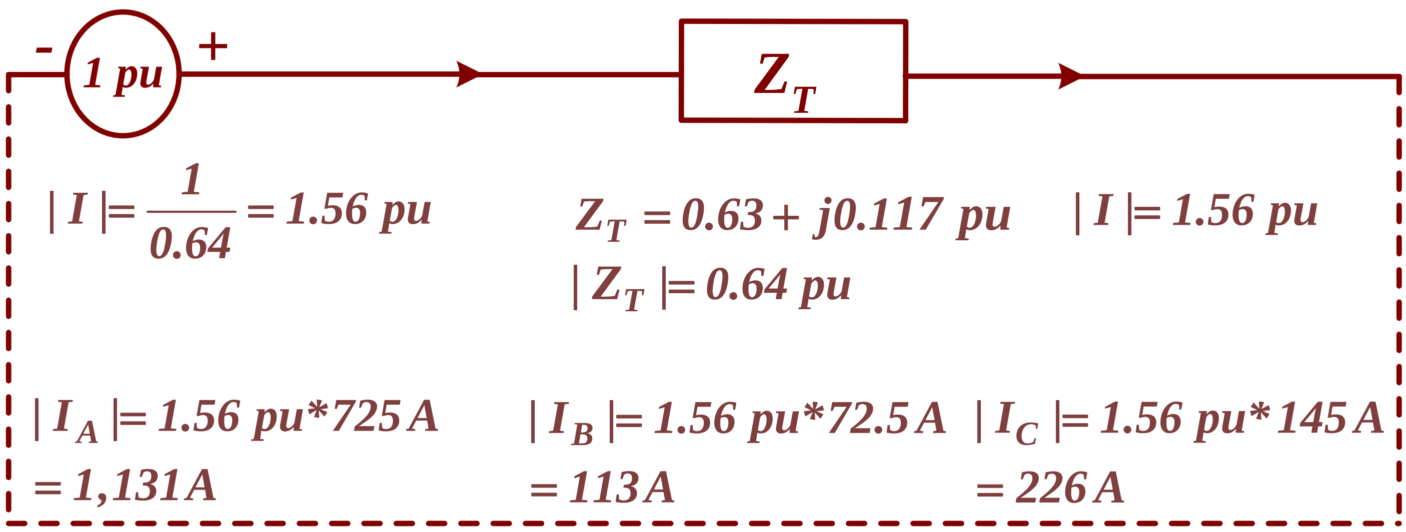


$$j0.1*\frac{10{,}000kVA}{15{,}000kVA} = j0.067\ pu$$

$$j0.05$$

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

Combine impedances – Solve for I



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

$$Z_T = 0.63 + j0.117\ pu$$
$$|Z_T| = 0.64\ pu$$

$$|I| = 1.56\ pu$$

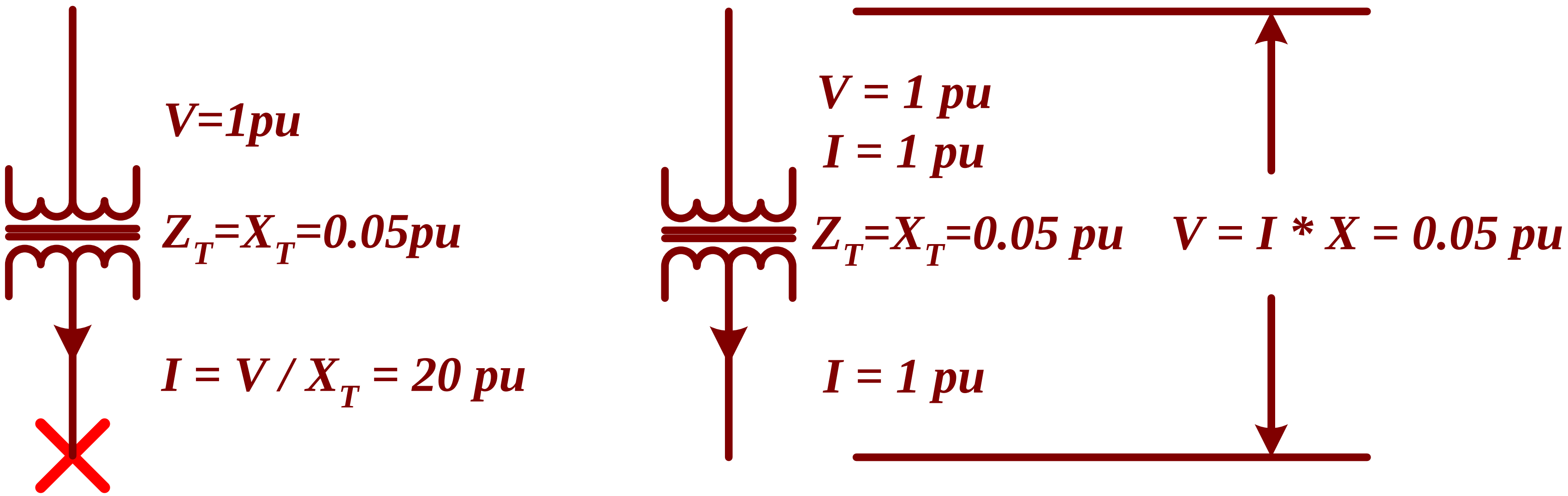
$$|I_A| = 1.56\ pu*725\,A = 1{,}131\,A$$

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

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

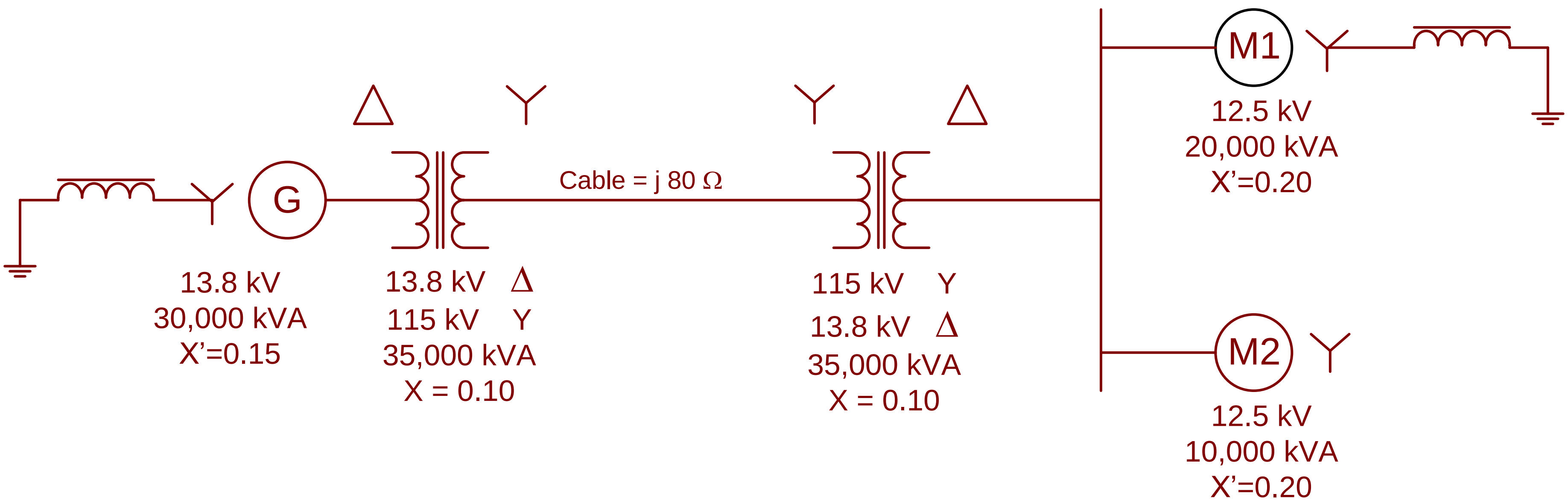
A transformer impedance of 5% means:

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

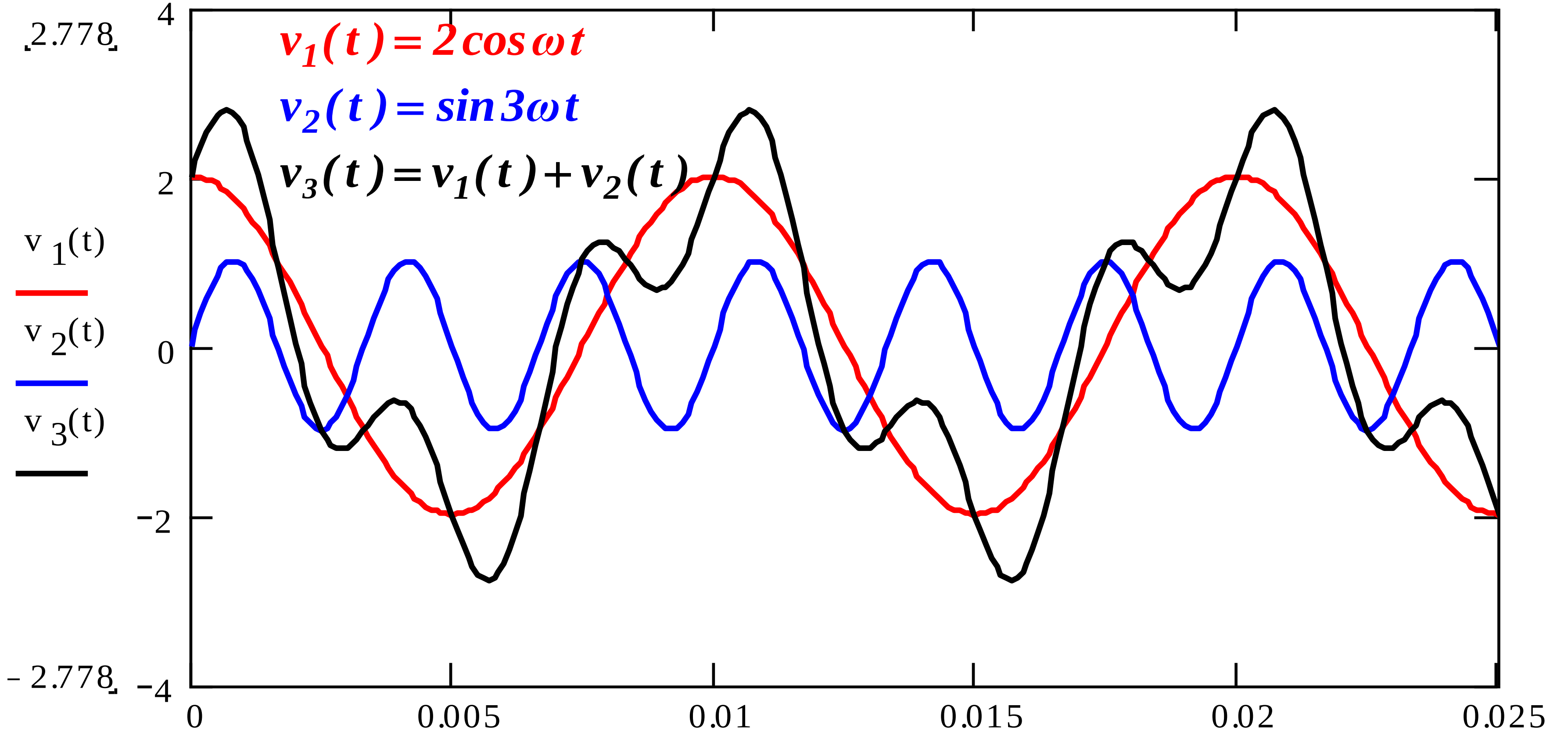


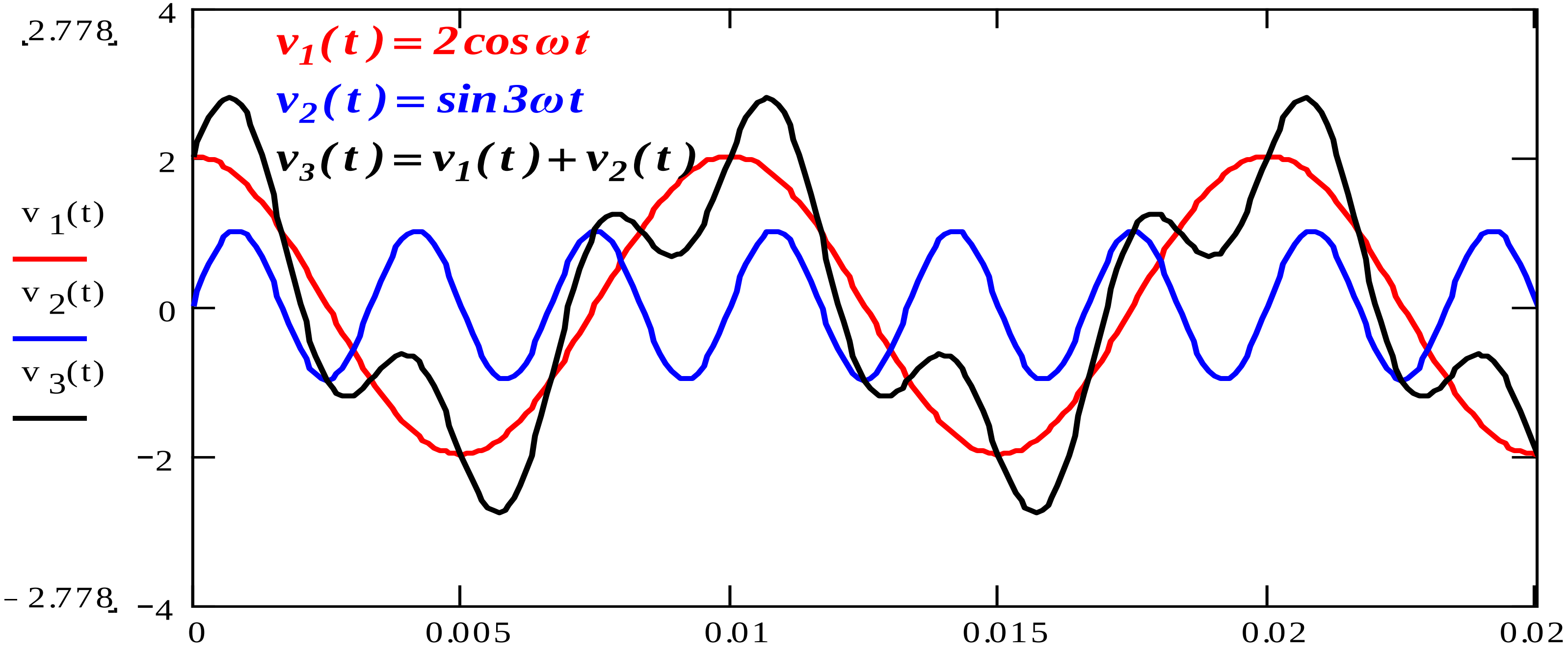
Referring to the one-line diagram below, determine the line currents in the:

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



- *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.*





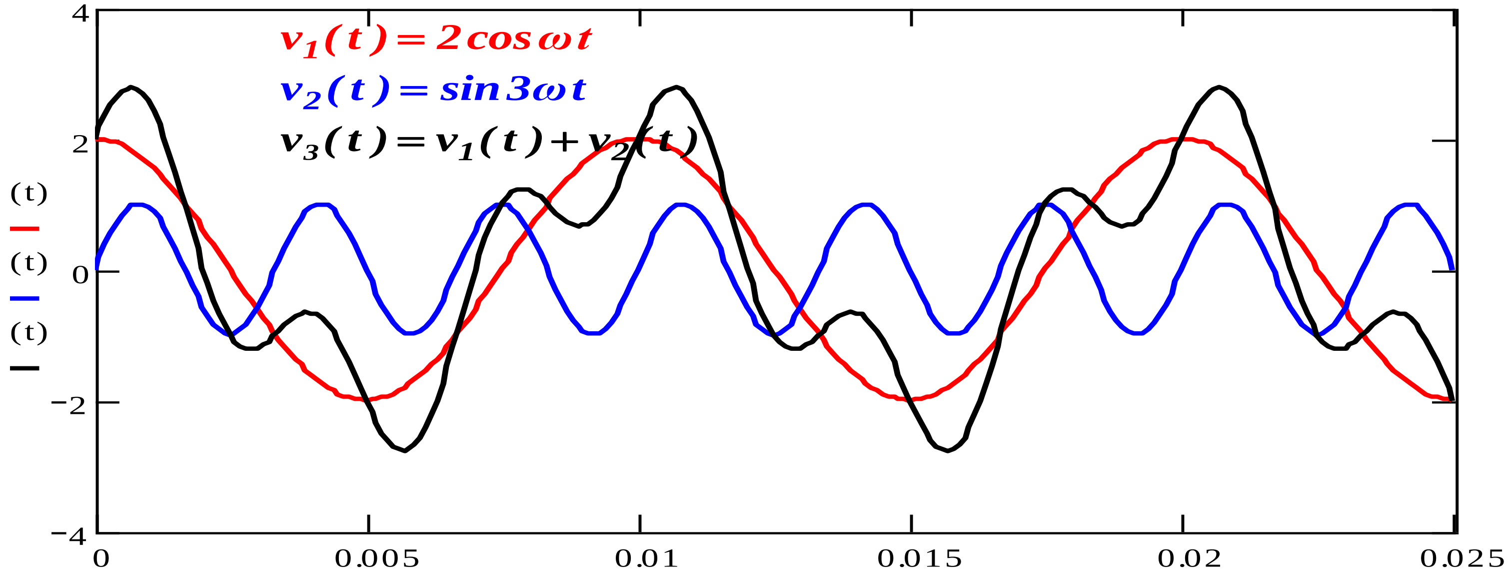
Trigonometric form of the Fourier Series

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

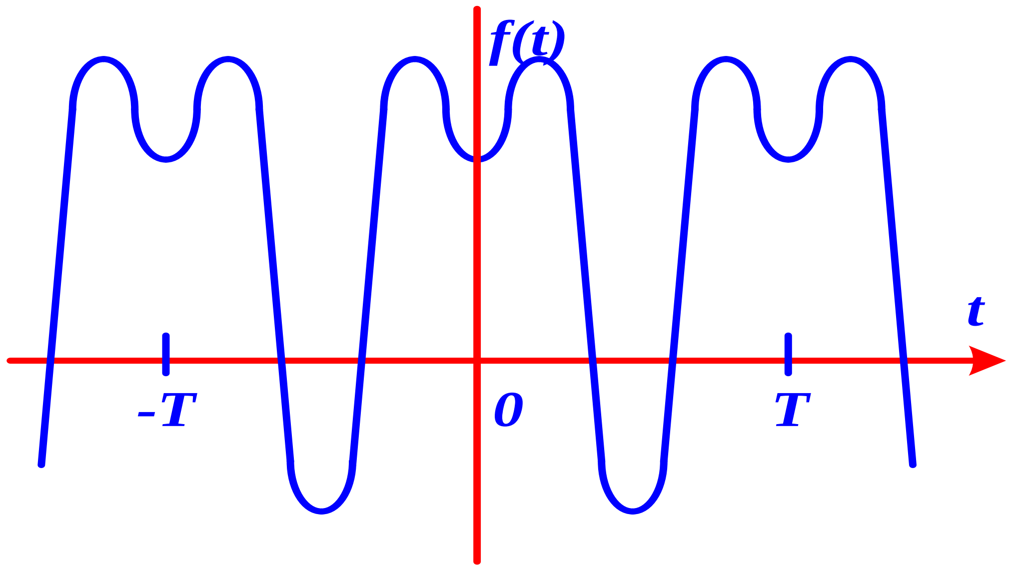
Complex form from Euler $e^{jx} = \cos x + j\sin x$

$$c_k = \frac{1}{T}\int_0^T f(t)e^{-jk\omega t}\,dt$$

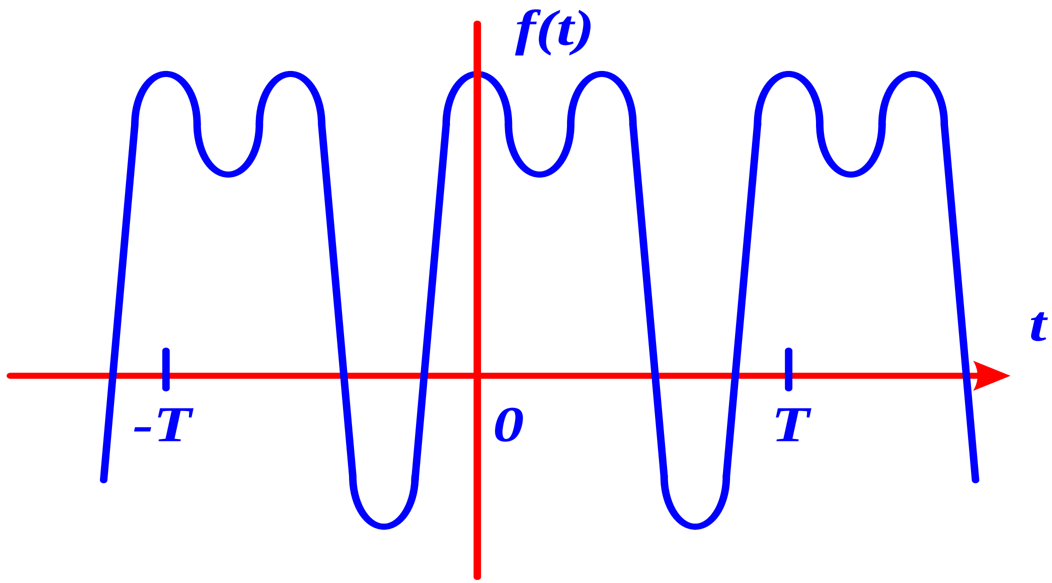
Harmonics, Complex Waveforms and Fourier Series - Coefficient Facilitators



Half-wave symmetry	*f (t) = - f (t -1/2T)*	*Have sines and cosines but only odd harmonics*	*No DC component*
Even function symmetry	*f (t) = f (-t)*	*No cosine terms*	*Has DC component if no half-wave symmetry*
Odd function symmetry	*f (t) = - f (-t)*	*No sine terms*	*No DC component*

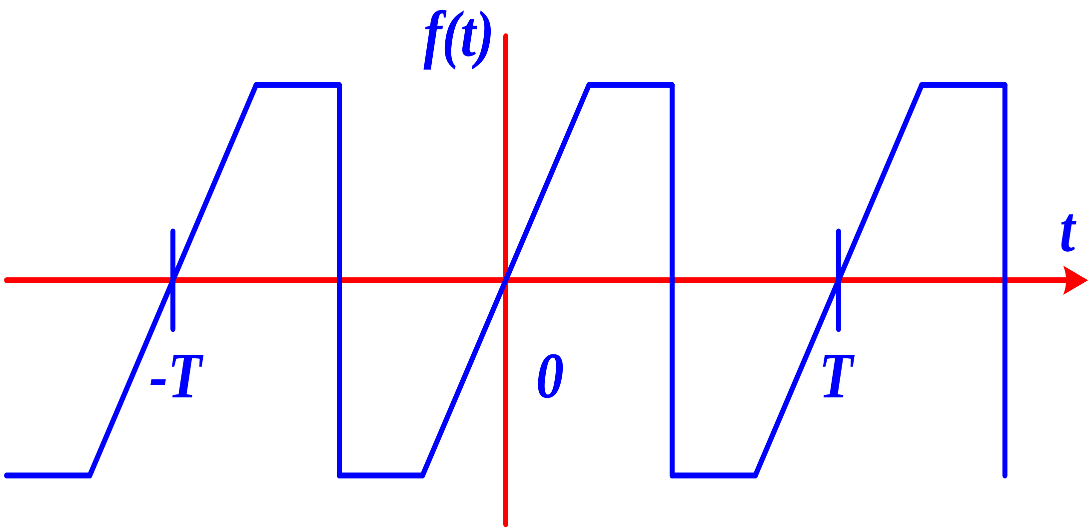


- $f(t)= f(-t)$ even function
- No cosine terms
- No half-wave symmetry
- DC component, a_o
- $a_k = \frac{2}{T}\int_0^T f(t)\cos k\omega_o t\, dt$

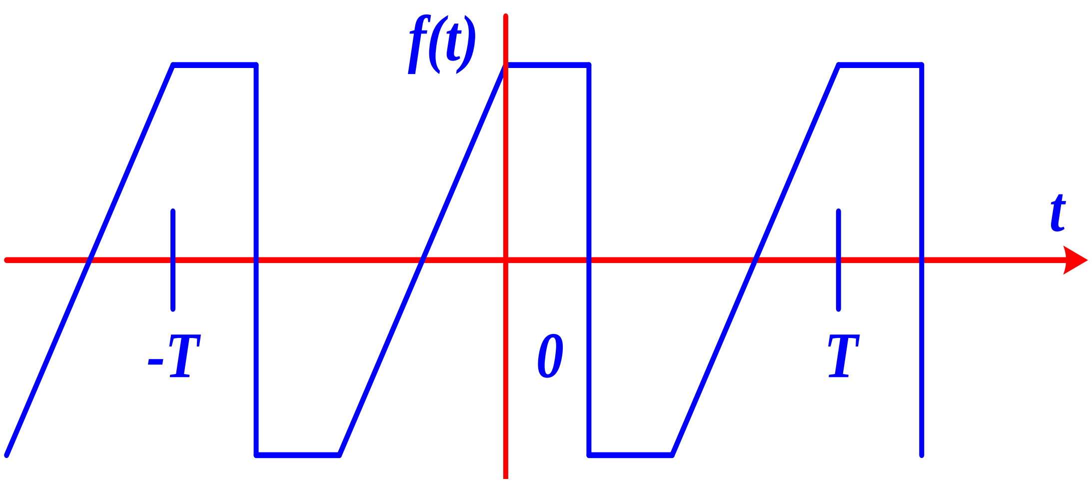


- No even or odd function symmetry
- Have sine and cosine terms
- No half-wave symmetry
- DC component, a_o
- a_o, a_k , b_k terms

Fourier Series - Example of Odd Function Symmetry

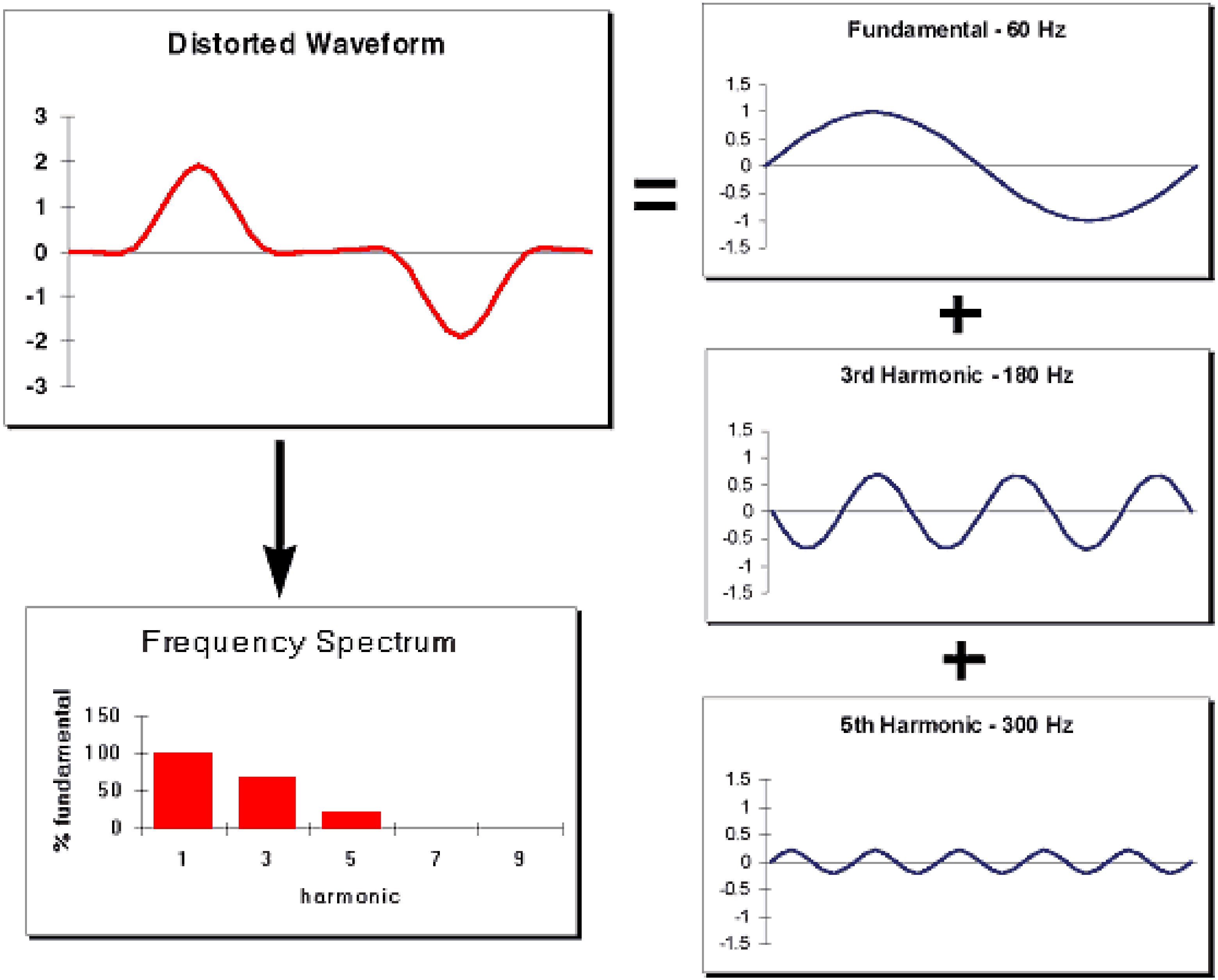


- f(t)=-f(-t) odd function
- No sine terms
- Half-wave symmetry
- No DC component
- $b_k = \frac{2}{T}\int_0^T f(t)\sin k\omega_o t\,dt$



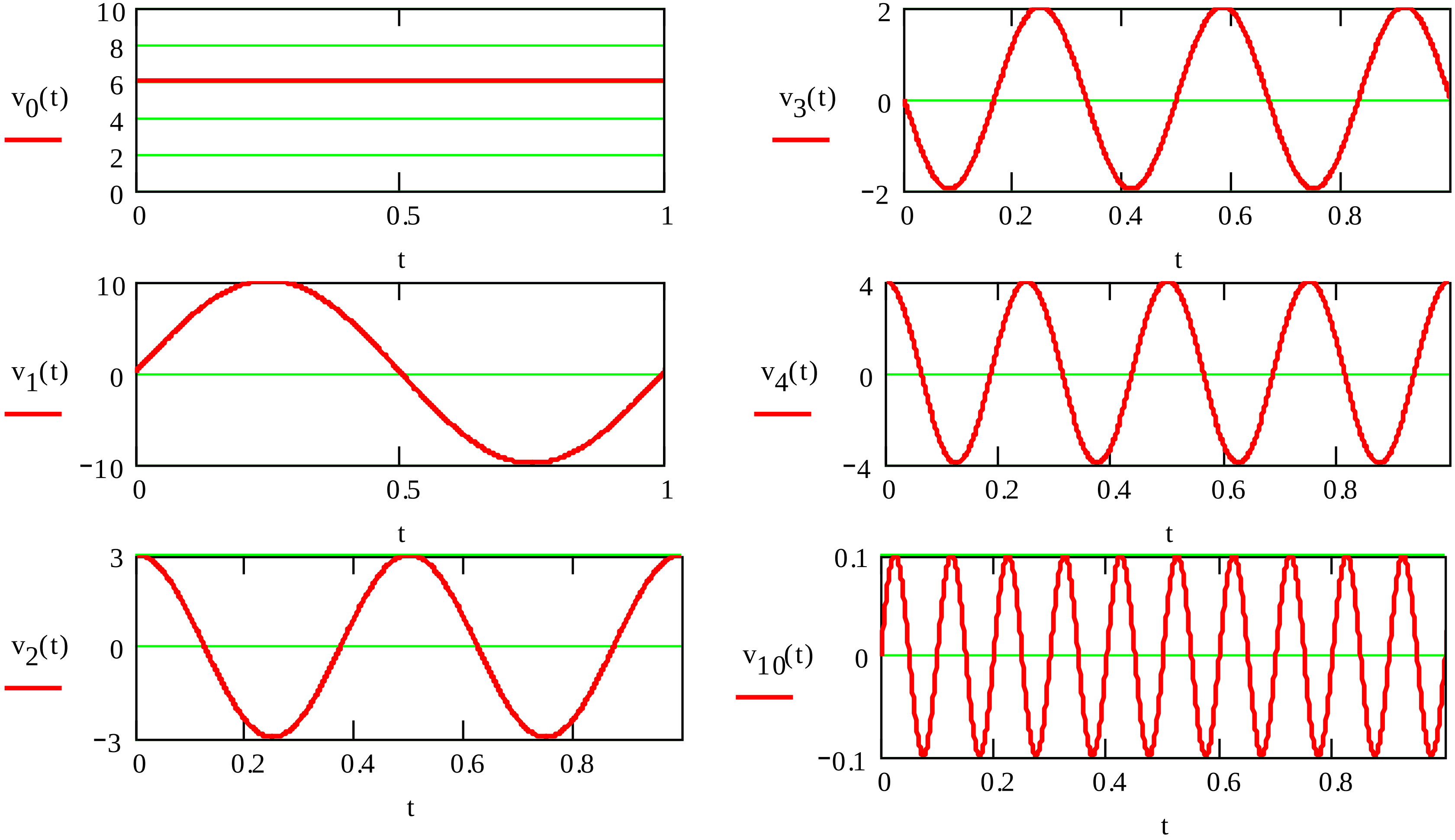
- No even or odd function symmetry
- Have sine and cosine terms
- No half-wave symmetry
- DC component exists
- a_o , a_k , b_k

Fourier Series - Distorted (Complex) Waveforms



Fourier Series - Homework Problem #2

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



a. Write the Fourier series for v(t) in terms of ωt

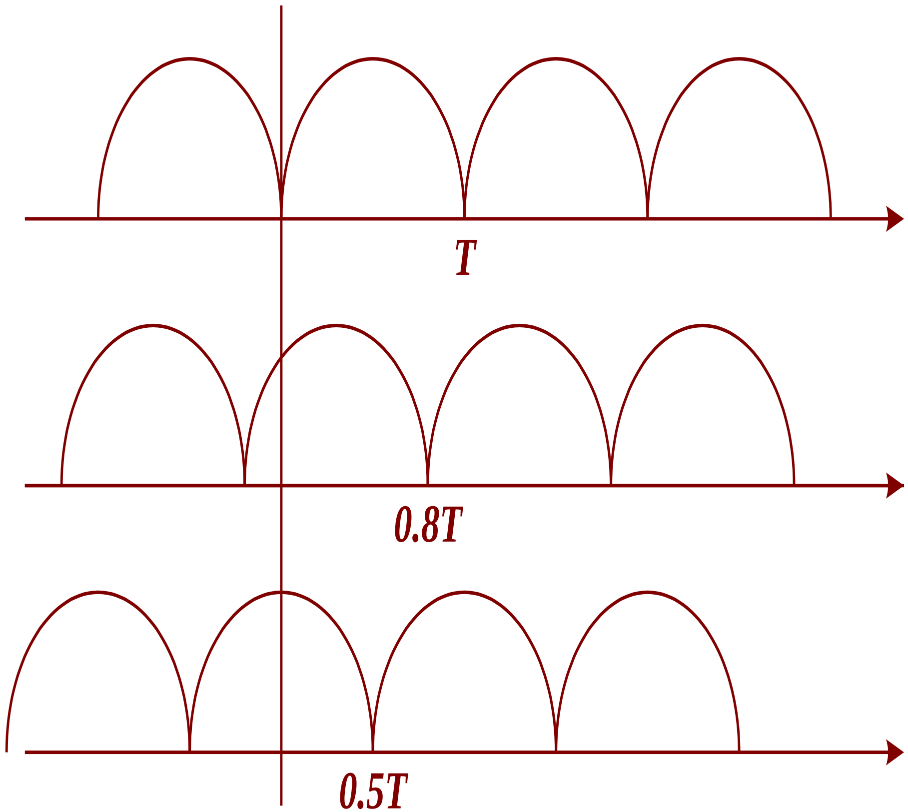
b. Show the harmonic content graphically by plotting the frequency spectrum

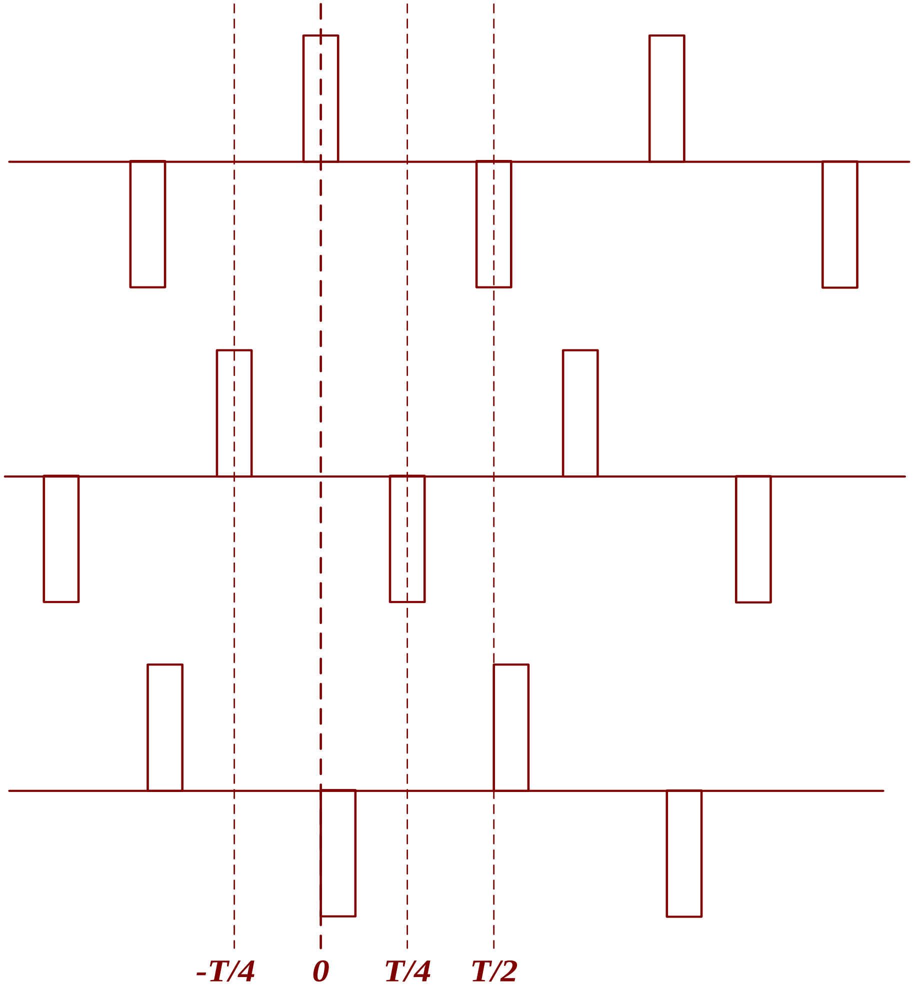
c. Give the numerical result of

$$b_3 = \frac{2}{T}\int_0^T v(t)\sin 3\omega t\,dt \qquad \text{Help}: \int \sin^2(3\omega t)\,dt = \frac{1}{3} * \frac{\frac{1}{2}\cos(3\omega t)\sin(3\omega t) + \frac{3}{2}\omega t}{\omega}$$

$$b_4 = \frac{2}{T}\int_0^T v(t)\sin 4\omega t\,dt \qquad \text{Help}: \int \cos(4\omega t)\sin(4\omega t)\,dt = \frac{-1}{8}\,\frac{\cos^2(4\omega t)}{\omega}$$

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.





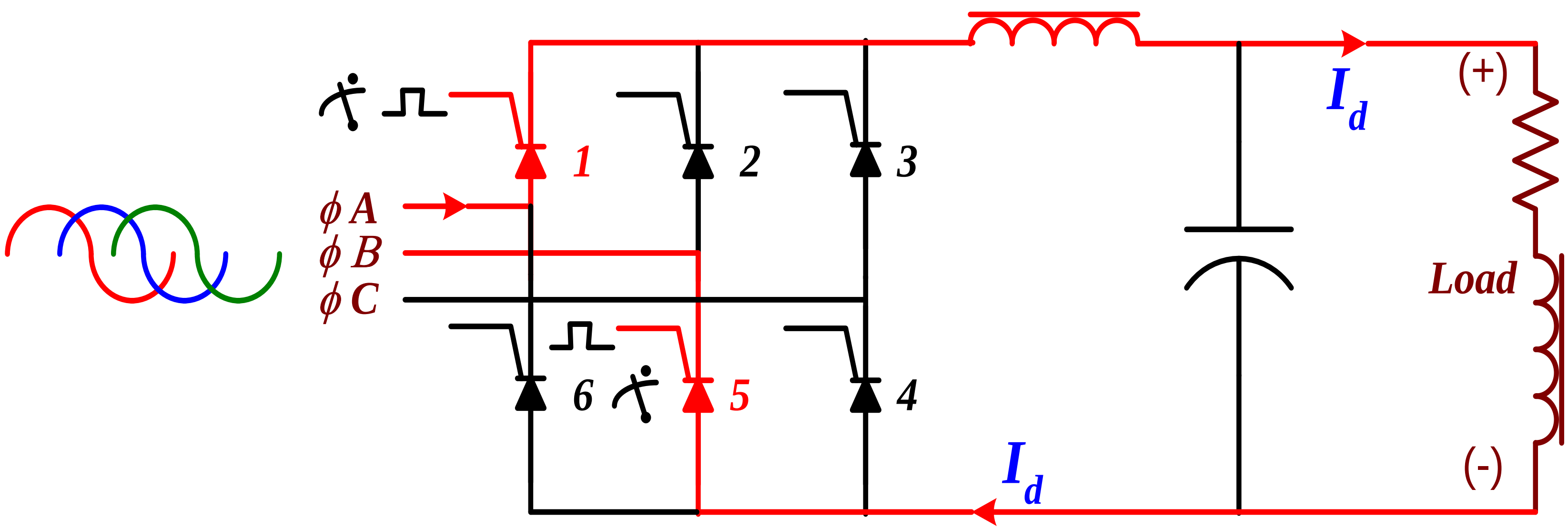
Signal Total Harmonic Distortion (THD): *The ratio of the square root of the summed squares of the amplitudes of all harmonic frequencies above the fundamental frequency to the fundamental frequency*

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

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

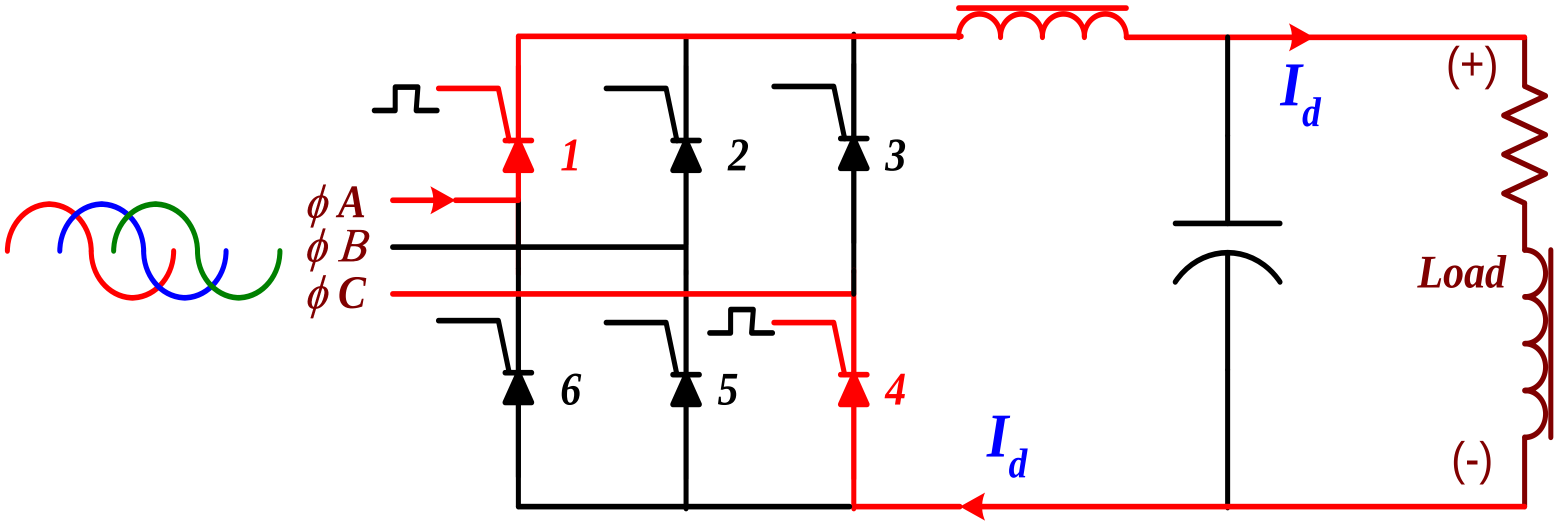
- *Unbalanced 3-phase, non-linear loads*
- *SCR or diode commutation*

SCR Commutation as Distortion Cause



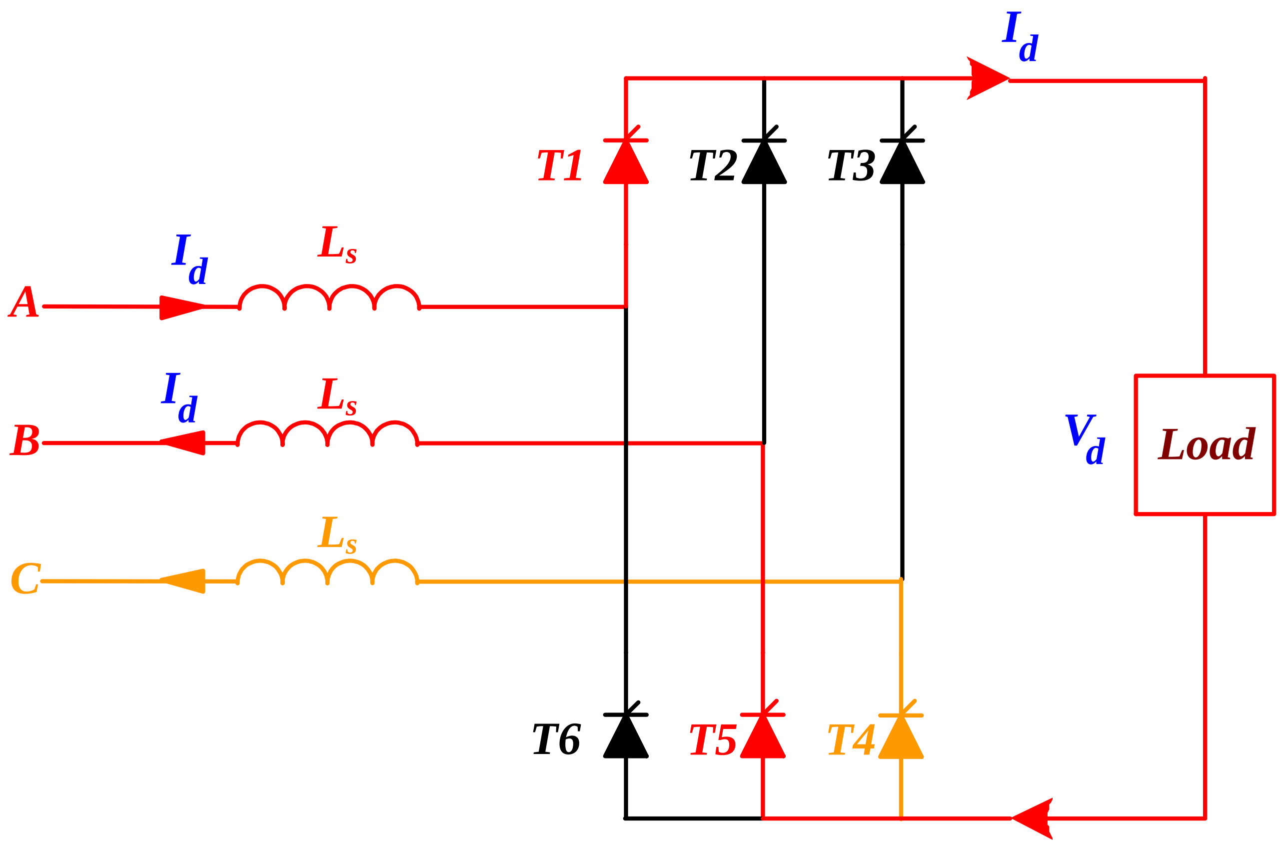
State 1: A-B (+) SCR s 1 – 5 On

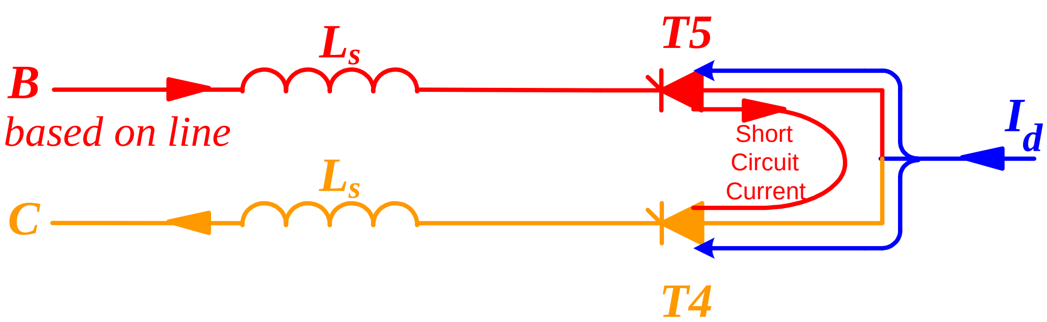
SCR Commutation as Distortion Cause



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

SCR Commutation as Distortion Cause





Line current is based on line voltage B to C

SCR Commutation Voltage Drop

$$V_d = V_{AB} - 2V_{Ls} \qquad V_{Ls} = L_s \frac{d\,i_A}{dt}$$

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

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

Commutation voltage drop

$$V_d = \frac{3\sqrt{2}}{\pi} V_{LL}\cos\alpha - \frac{q\,\omega L_s}{\pi} I_d$$

V_{AB} = Line-line voltage, V_u = commutation drop, V_{Ls} = Line impedance

I_d = Load current, V_{do} = Theoretical output, V_d = reduced output, i_A = phase current

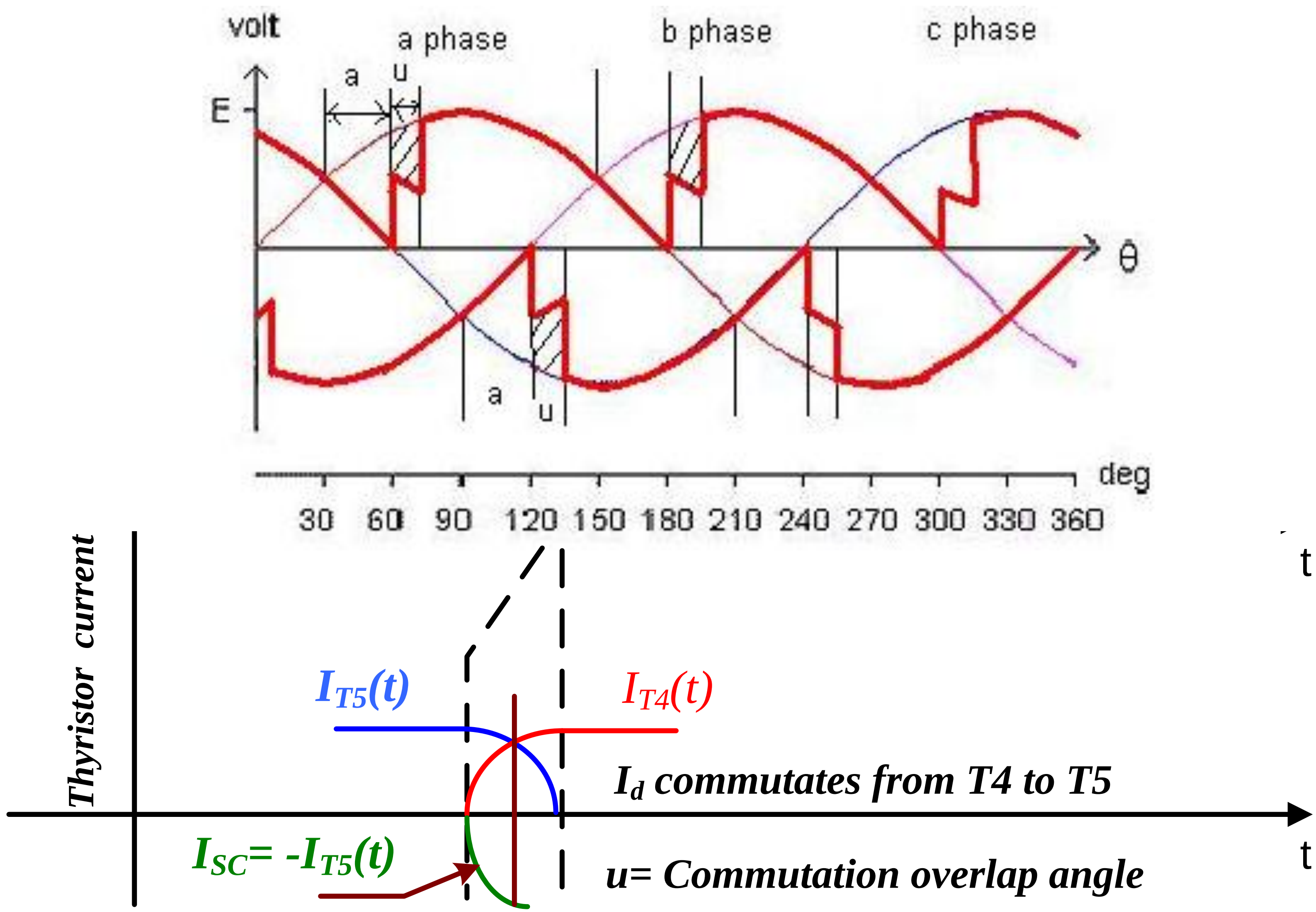
q = number of possible rectifier states, α = SCR gate trigger retard angle

μ = commutation overlap angle, ω = operating frequency in radians

Conclusions

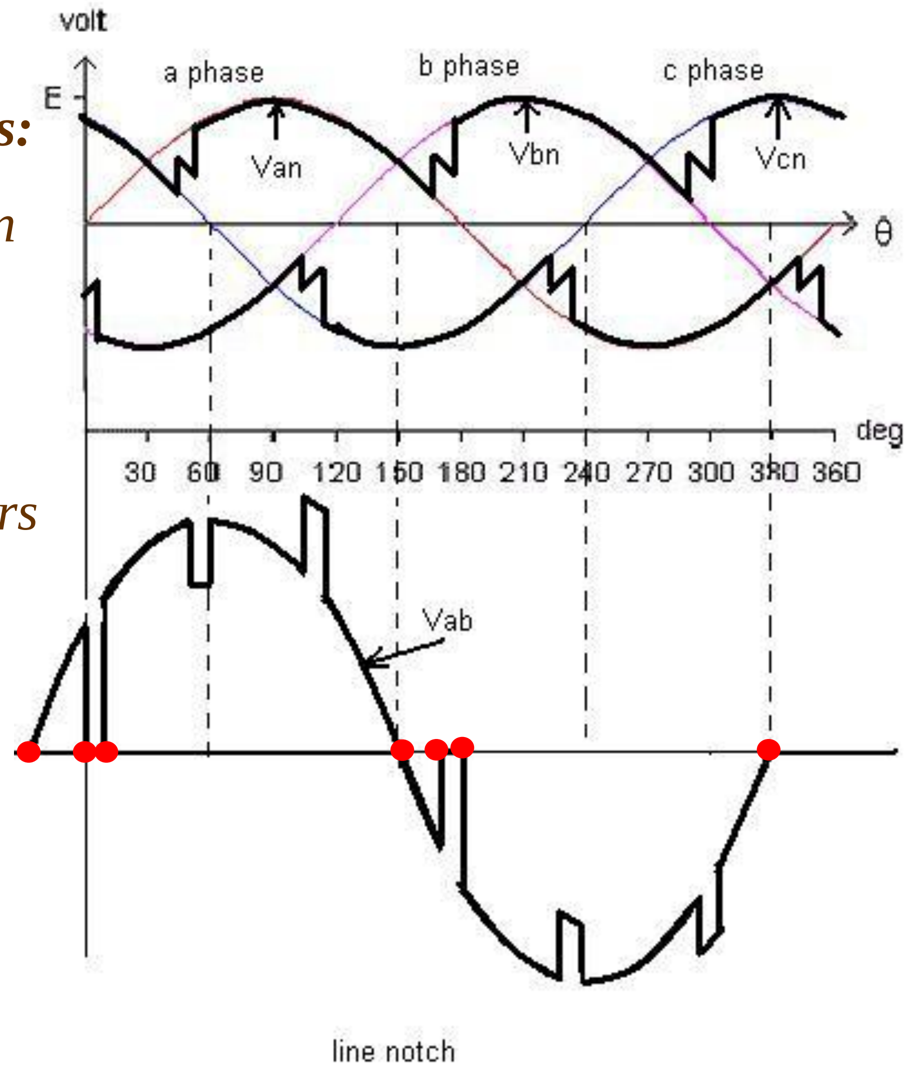
- The current commutation takes a finite commutation interval u.
- During the commutation interval, three SCRs conduct.
- Vu (and line voltage distortion) is directly proportional to the inductive reactance of the input AC line or transformer and the DC current flowing in the load

SCR Commutation as Distortion Cause



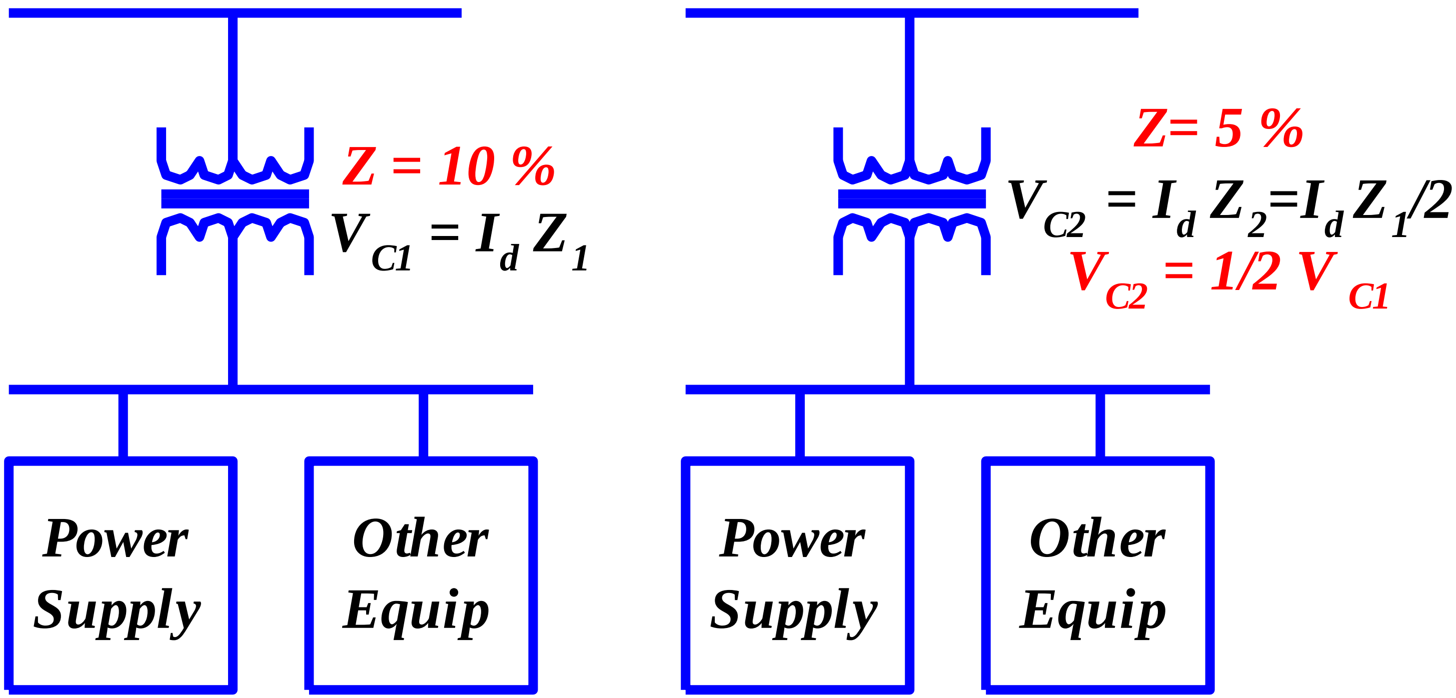
SCR / diode commutation line notches:

- *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.*



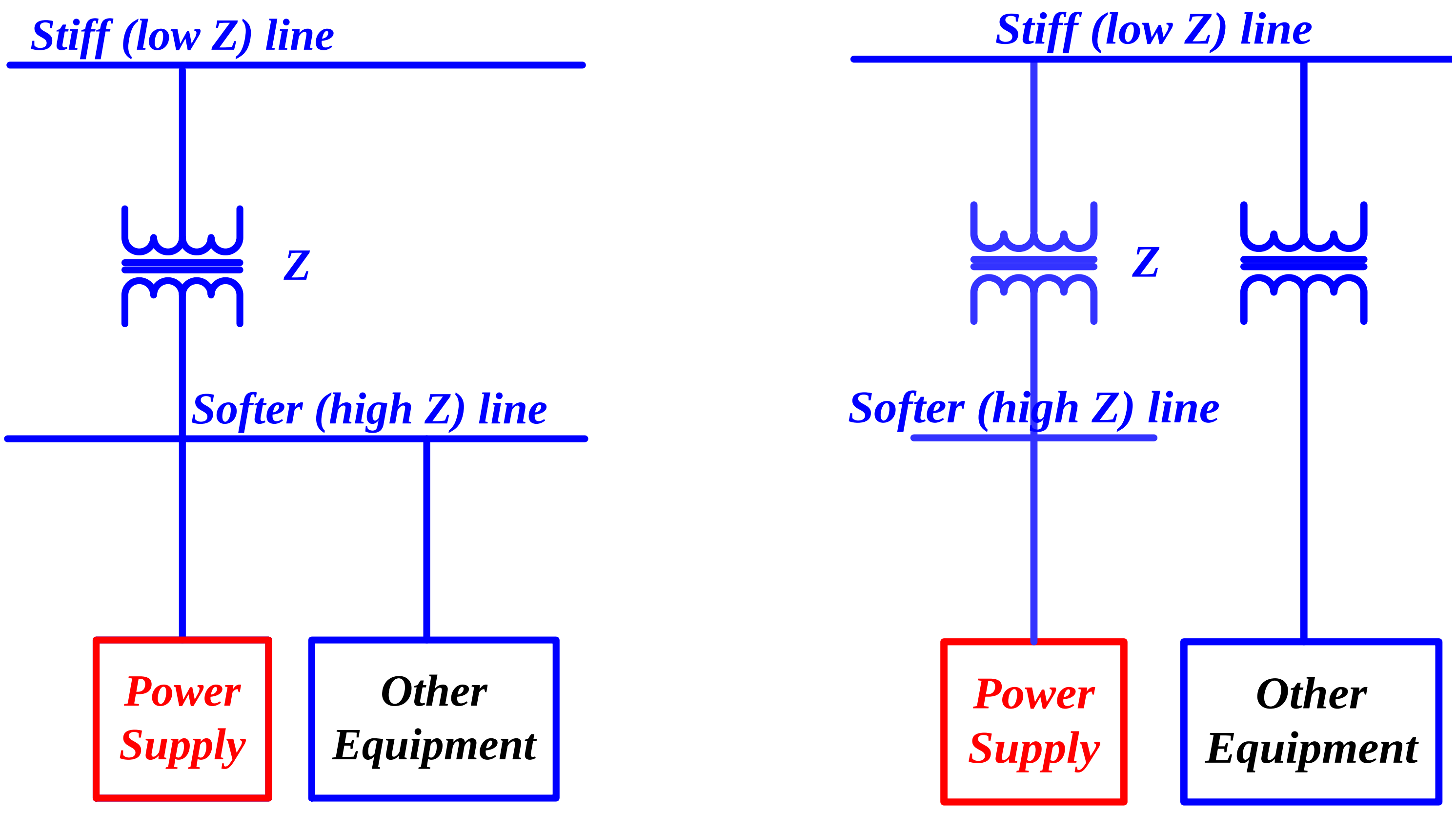
Reducing SCR commutation effects

• *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*



SCR Commutation Effects - International Harmonic Distortion Standards

Australia	AS 2279 - "Disturbances in Mains Supply Networks"
Britain	G5/3 - "Standard for Harmonic Control in Power Systems"
Europe	International Electrotechnical Commission IEC 555 Series for harmonic current distortion limits for small devices (extended by IEC 1000 standards)
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 - μ S	22,800 V - μ S	36,500 V - μ S

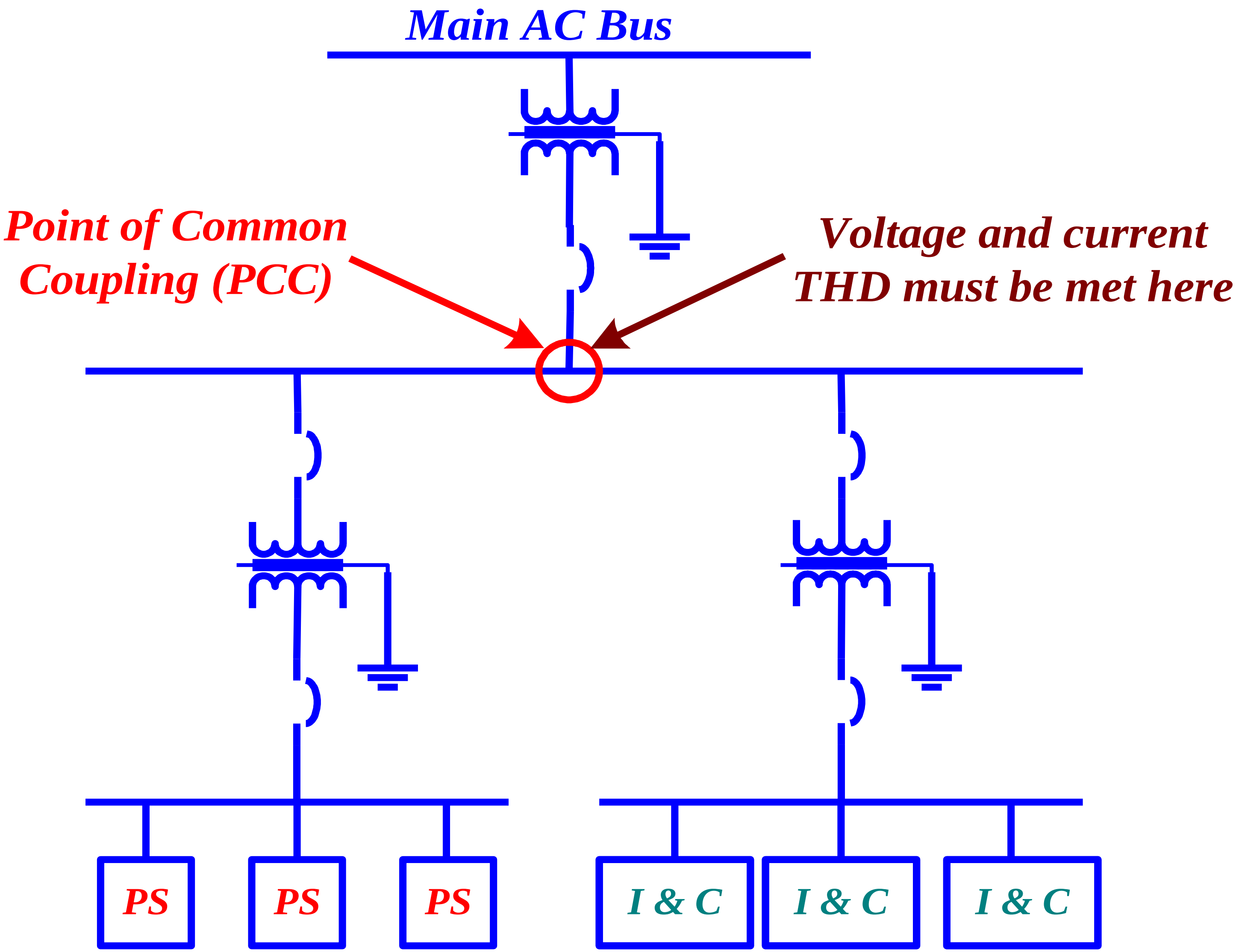
1. Airports and hospitals
2. Exclusive use converters
3. Multiply by V / 480 for other than 480 V systems

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

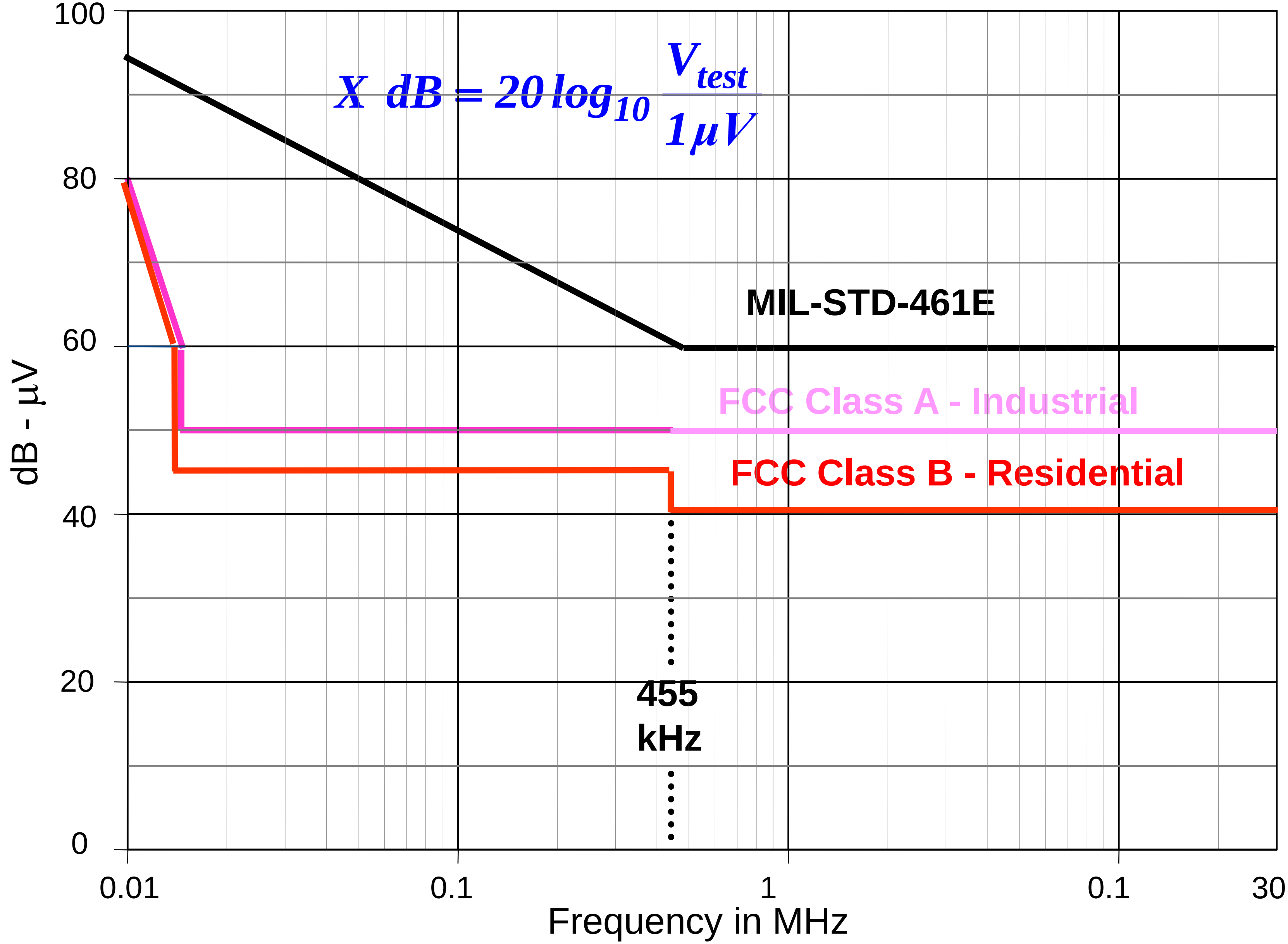
EMC Directives of 1996

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 μV = 0 dB)*

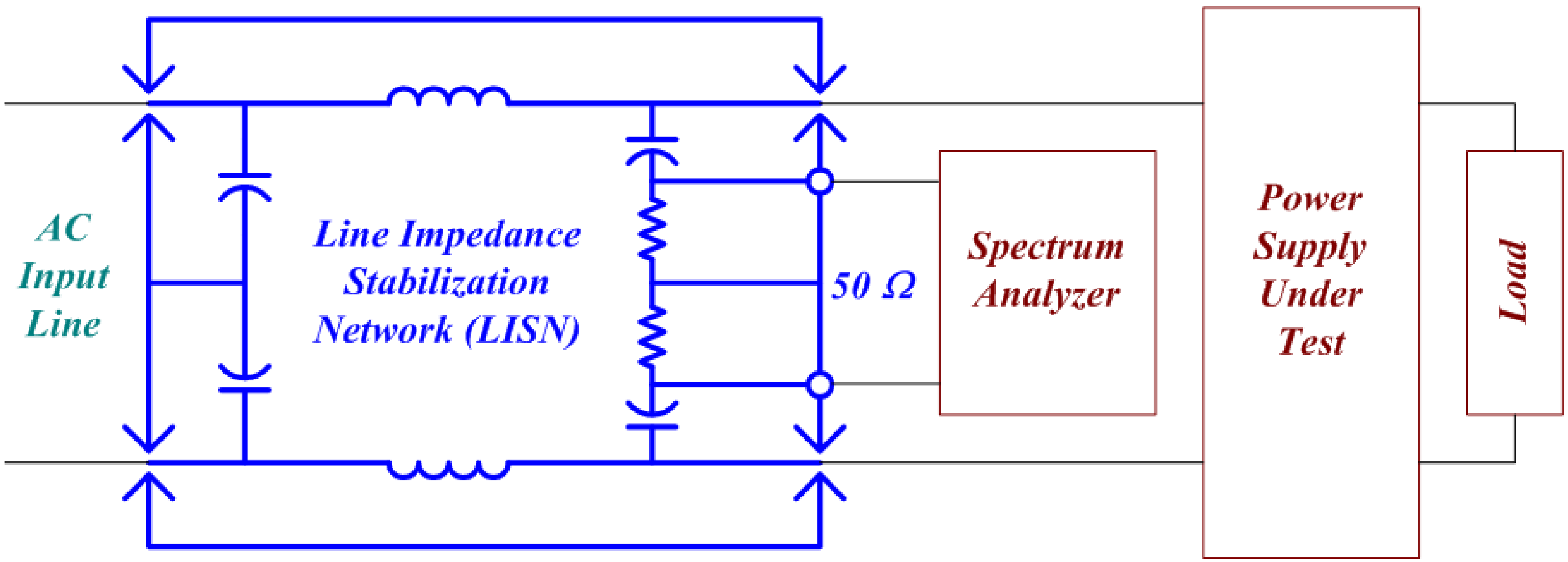
$$dB = 20 * \log_{10} \frac{measured\ \mu V}{1\ \mu V}$$



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

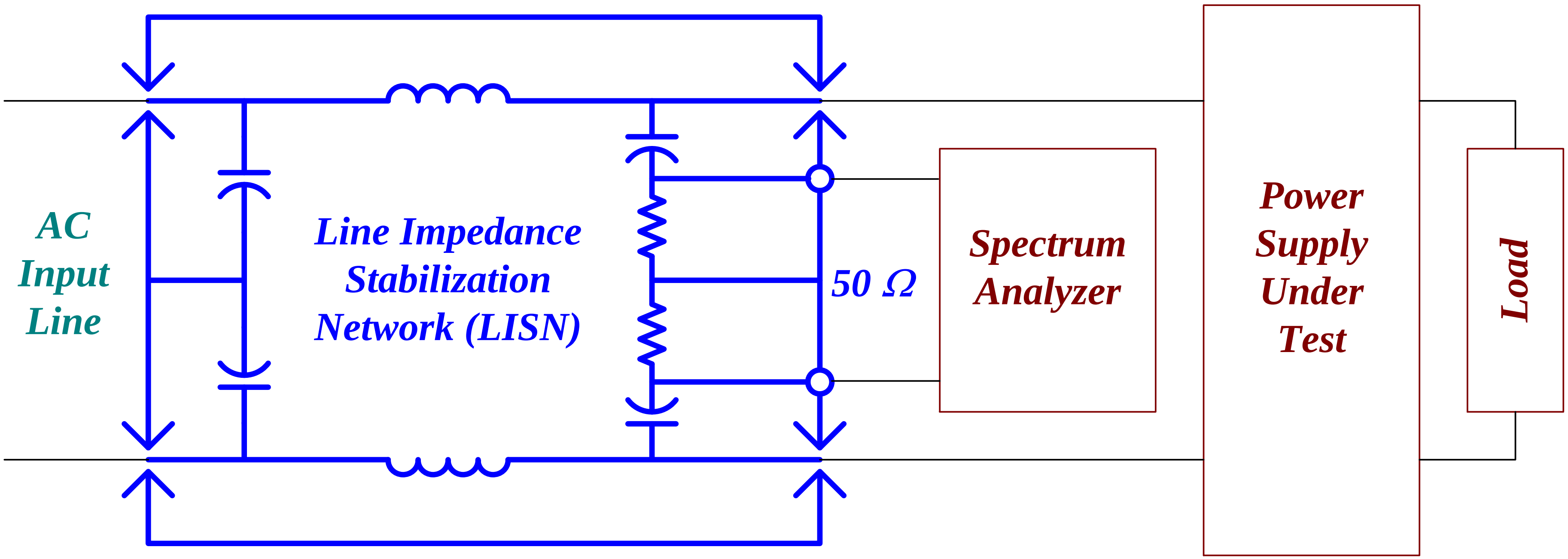
***Test equipment used** – Spectrum analyzers with Line Impedance Stabilization Networks (LISNs) that*

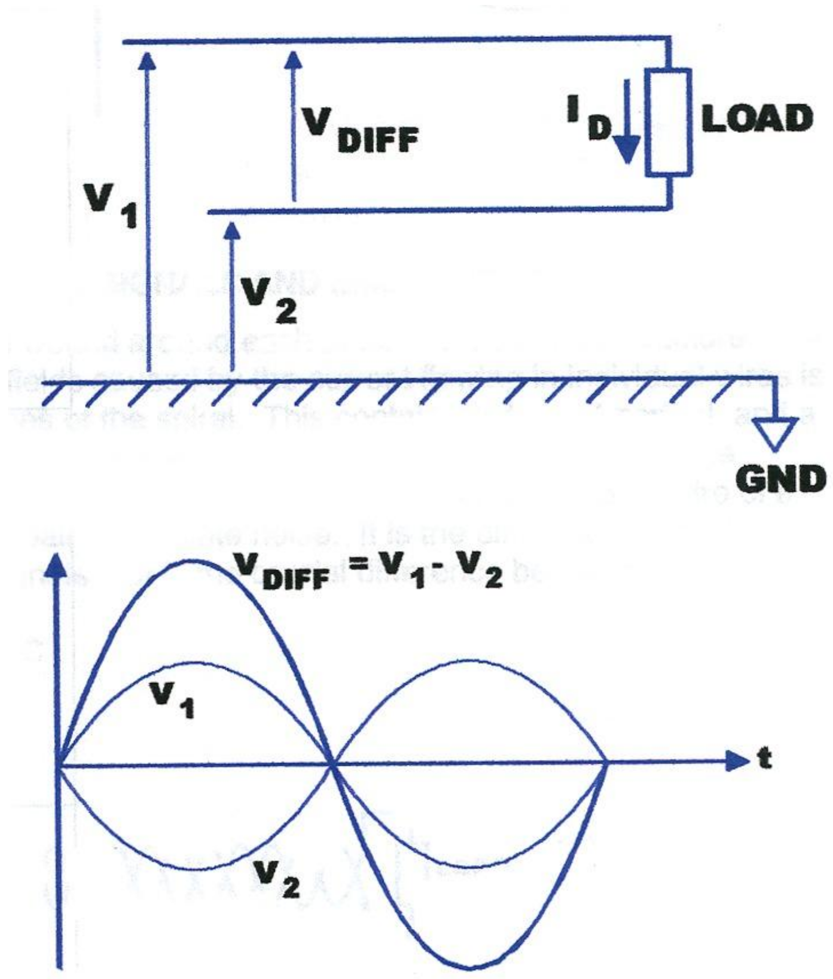
- *Filter and divert external AC line intrinsic noise from the EMI measurements*
- *Isolate and decouple the AC line high voltage and prevent line transients from damaging spectrum analyzers and other sensitive test equipment*
- *Present a known, fixed impedance at RF frequencies to the power supply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



LISN considerations:

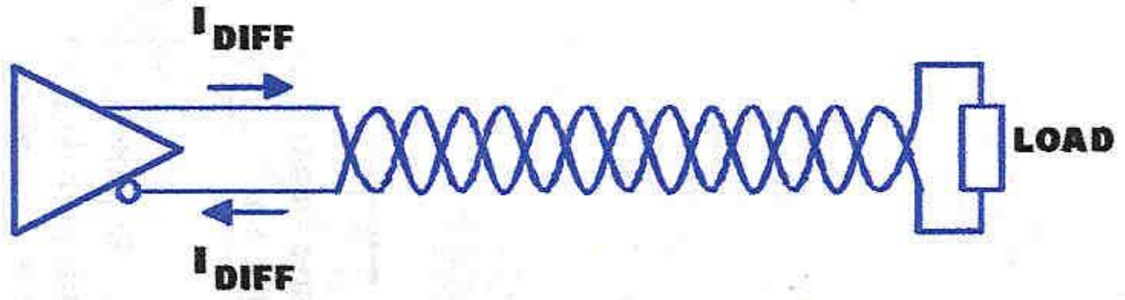
- Desired impedance (typically 50 Ω)
- Bandwidth (typically victims are susceptible to 10 kHz to 30 MHz)
- Line type (DC, Single phase, 3 ϕ delta, 3 phase wye)
- Line voltage (120 V, 208 V, 480 V, etc)
- Power supply input current when under load





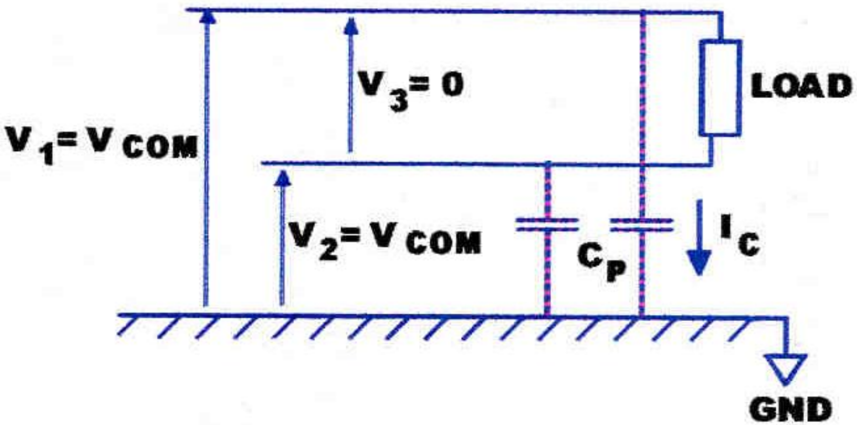
- *Produced as a natural result of complex, high frequency switching V and I*
- $V_1 = - V_2$
- *Magnitudes are equal*
- *Phase difference is* 180^O
- $V_{DIFF} = V_1 – V_2$ = *unwanted signal*
- $I_D = (V_1 – V_2) / R_{Load}$

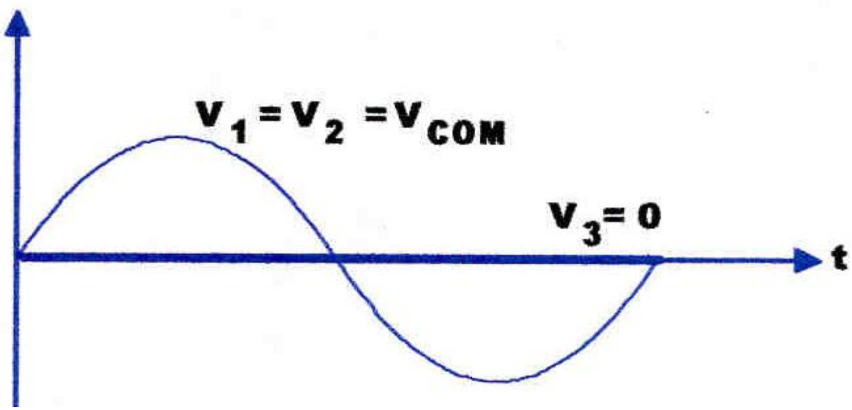
EMC/EMI - Differential Mode Electromagnetic Compatibility



- *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*

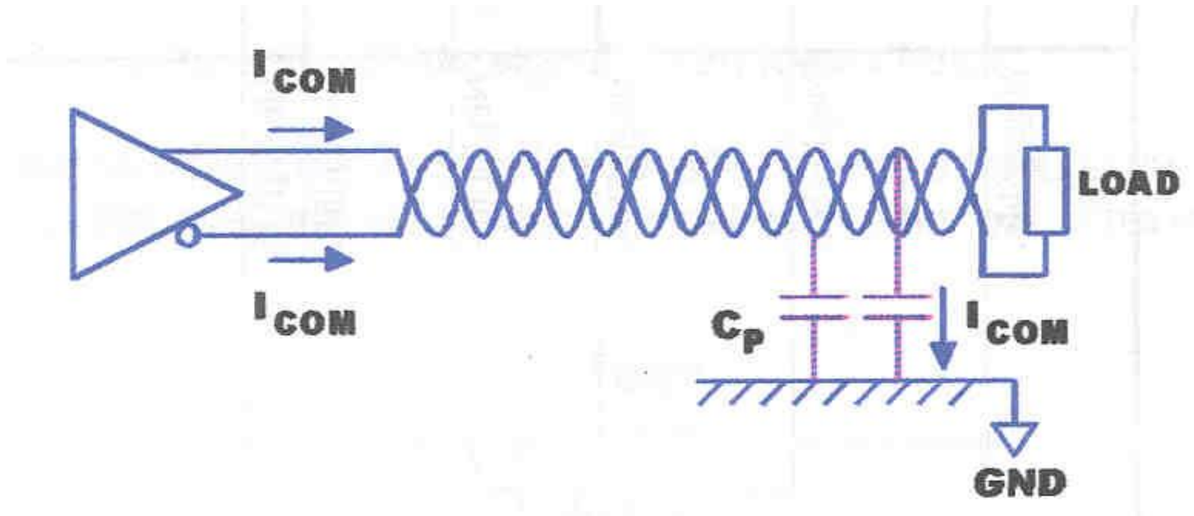
EMC/EMI - Common Mode Noise





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

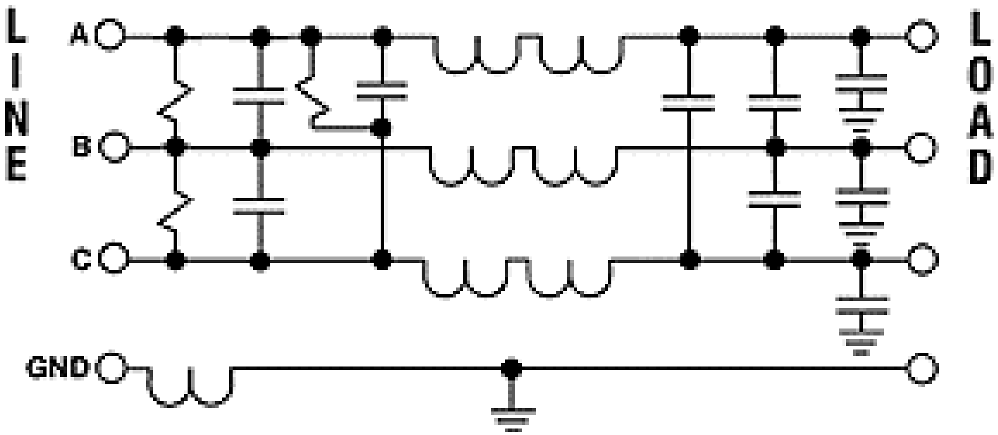
EMC/EMI - Common Mode Compatibility

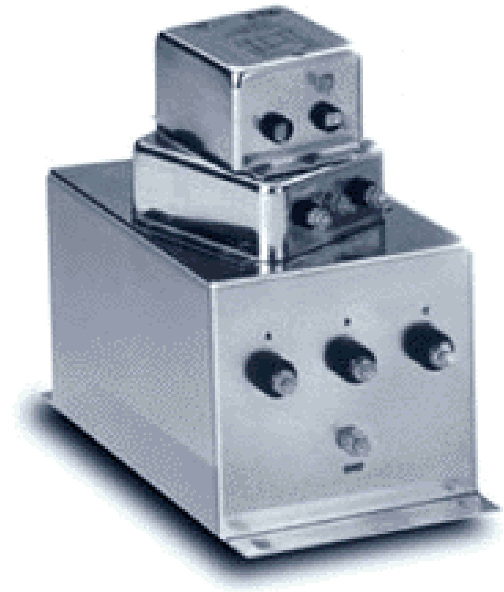


- *Common mode current generated by common mode voltages impressed across parasitic capacitances to ground*
- *Current flows are the same magnitude and in the same direction so that the spirals have no effect on containing the magnetic fields*
- *The pair must be shielded and the shield tied to ground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

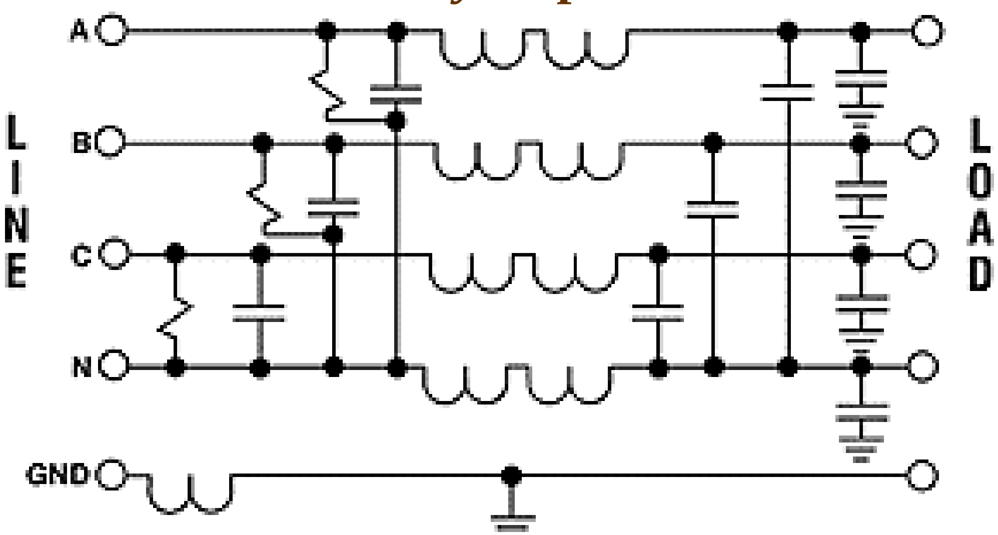
EMC/EMI - Input Conducted Line Noise Filters

Delta input





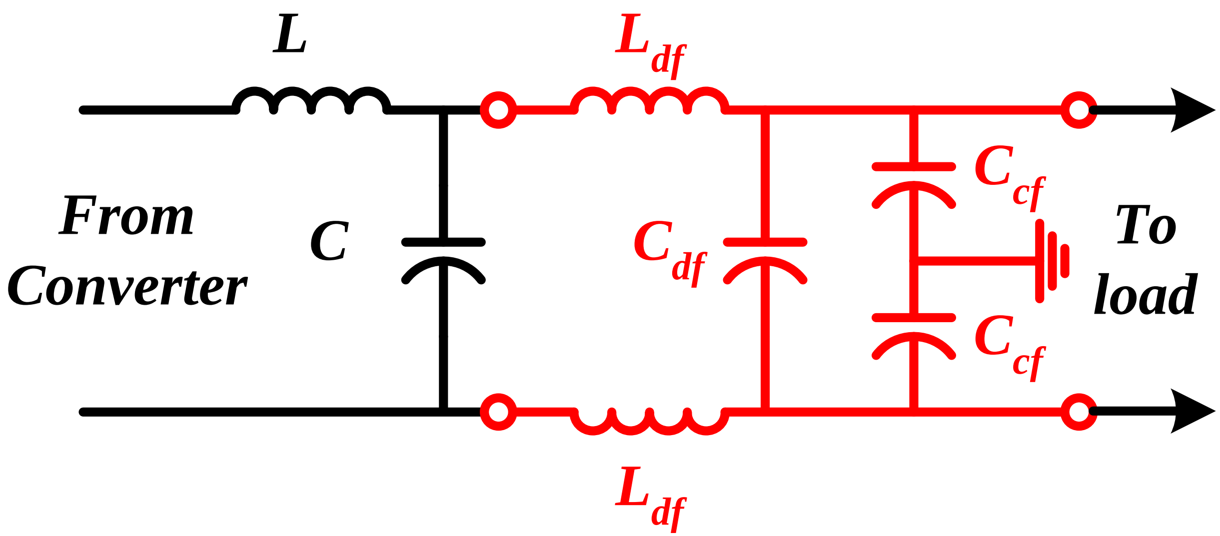
Wye input



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

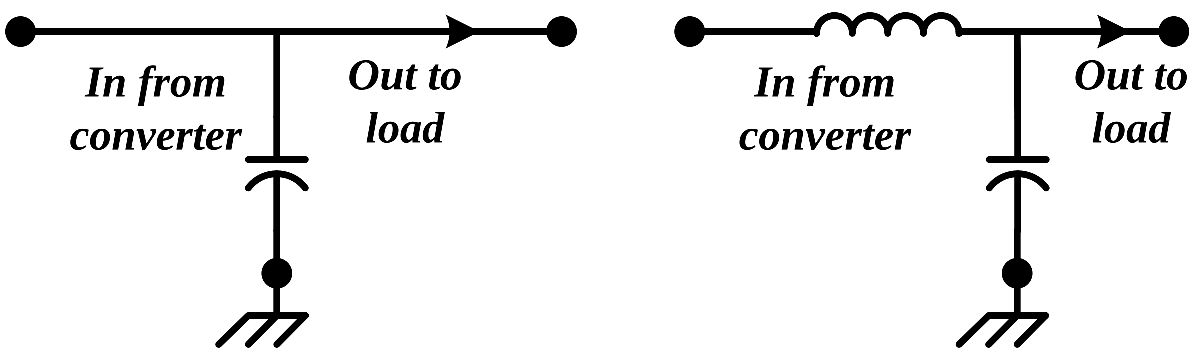
http://www.filterconcepts.com/three_phase/3v_series.html

EMC/EMI - Input / Output Line Noise Filters



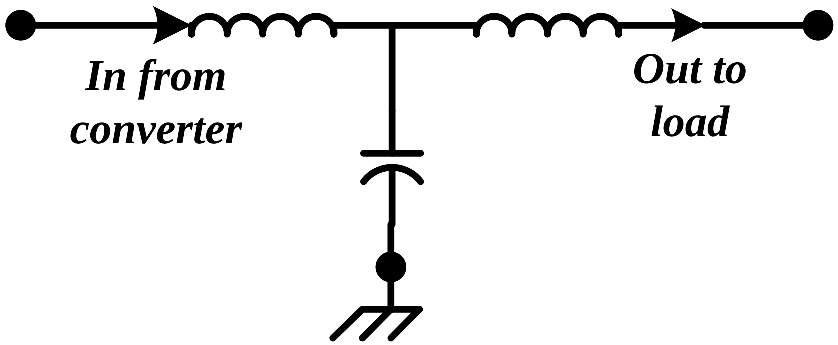
- L and C are not good noise ($f > f_{sw}$) filters
- L looks capacitive at $f > f_{sw}$, C looks inductive at $f > f_{sw}$
- $L_{d\,f}$ is a differential / common mode noise filter inductor and might be a real inductance or the intrinsic inductance of the bus
- $C_{d\,f}$ is a differential mode noise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

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

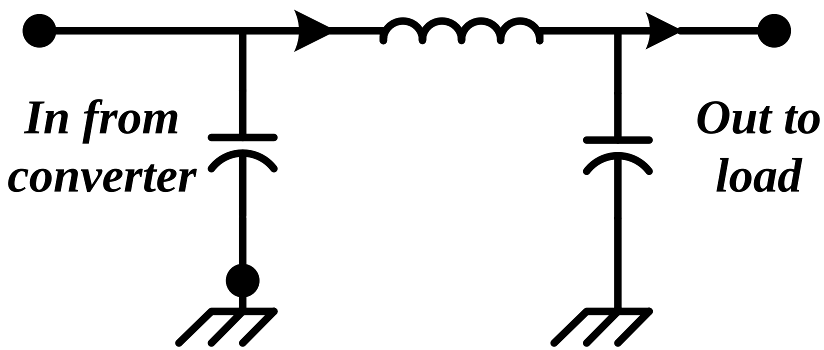


- ***L filters** consist of one inductive element and one capacitor. One disadvantage is that the inductor element in smaller filters consists of a ferrite bead that will saturate and lose effectiveness at larger load currents*

- ***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*

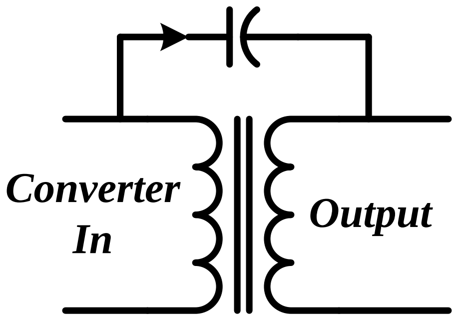


- ***Pi*** *filters consist of two capacitors and one inductor. They present a low impedance to both source and load. The additional capacitor element, provides better high frequency attenuation than the C or L filters*

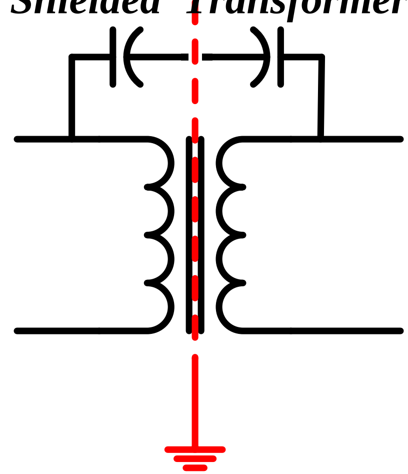


EMC/EMI - Other Conducted Noise Filters

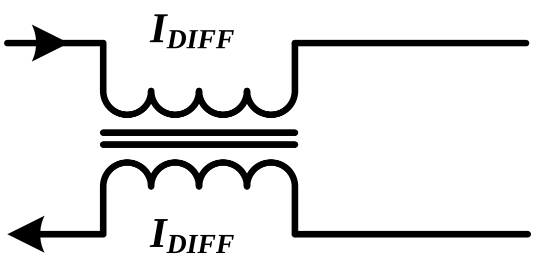
Plain Transformer

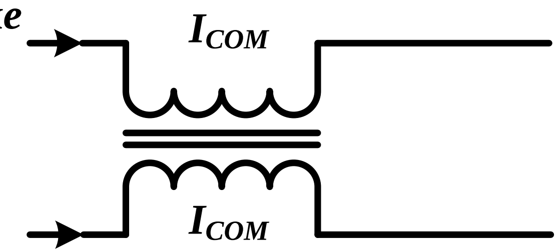


Electrostatic (Faraday) Shielded Transformer



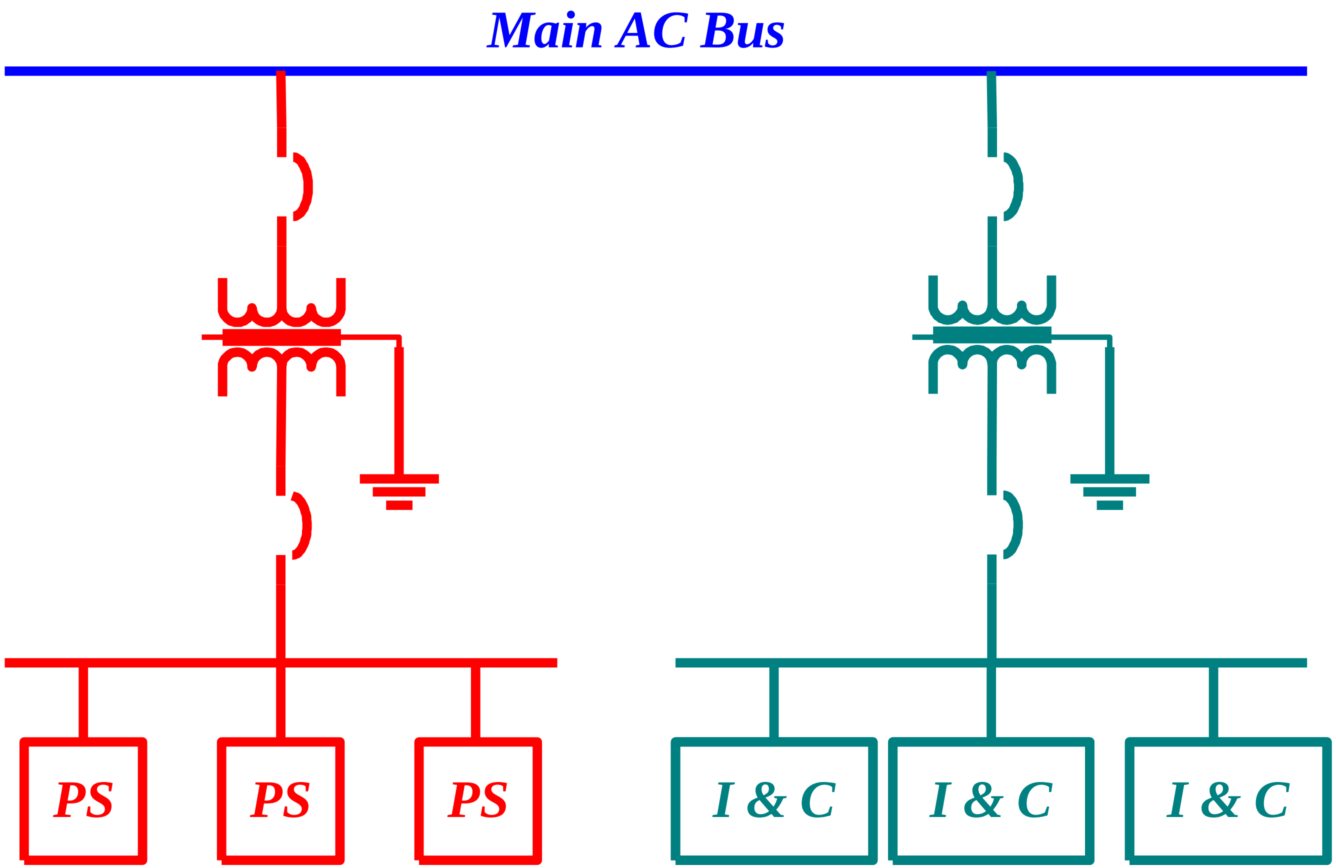
Common Mode Choke





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*

EMC/EMI - Radiated Emissions

Radiated emissions

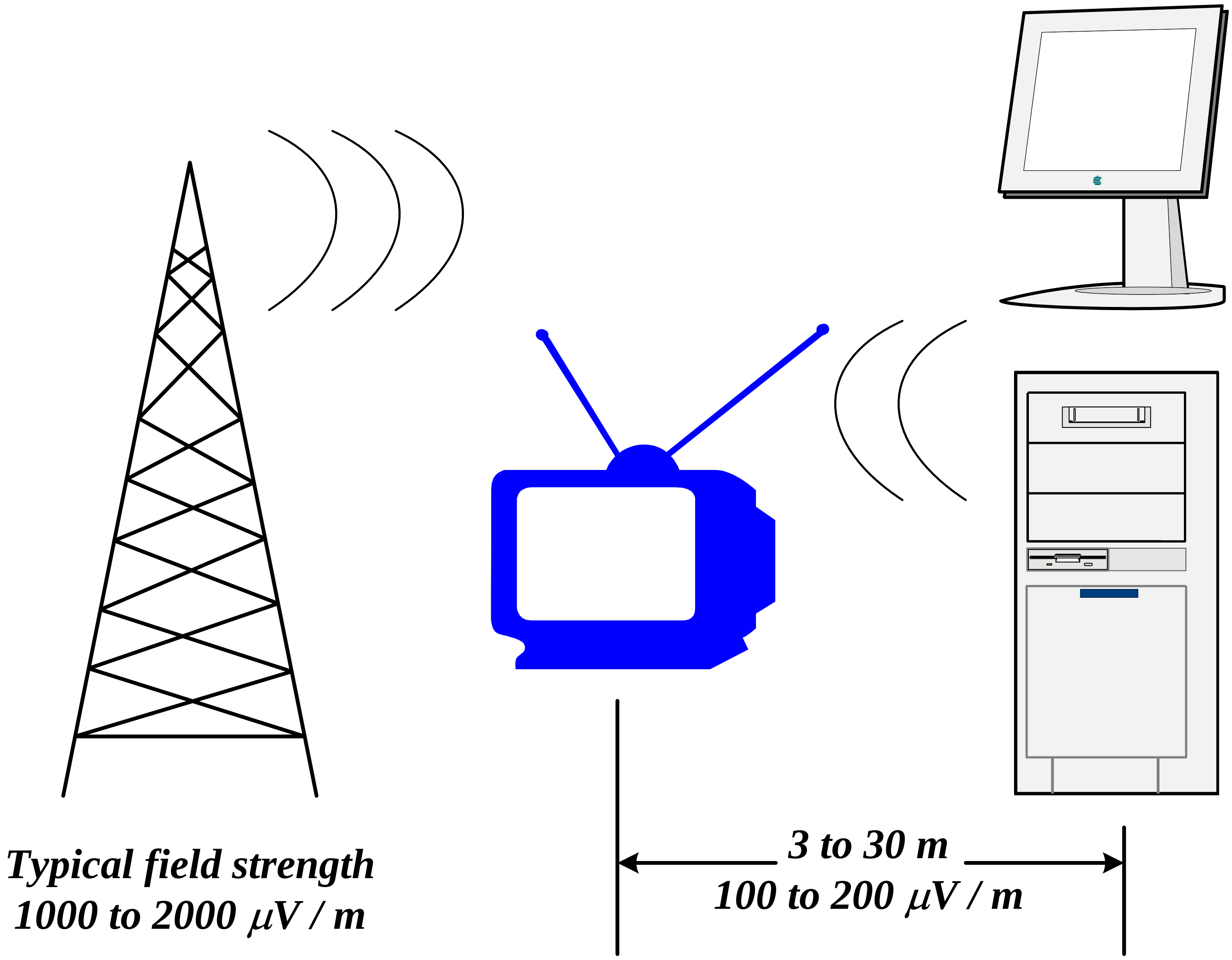
- EMI radiated from cables, transformers, other components.
- Typically 30 MHz to > 1GHz. 30 MHz start because cables and other equipment are effective radiators of frequencies above 30 MHz
- Measured in $\mu V/m$ or dB - $\mu V/m$ (Reference: 1 $\mu V/m = 0$ dB)
- Measured 3 m (residential) or 30 m (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) because it is assumed that there will be an intervening wall between culprit and victim that will provide some shielding

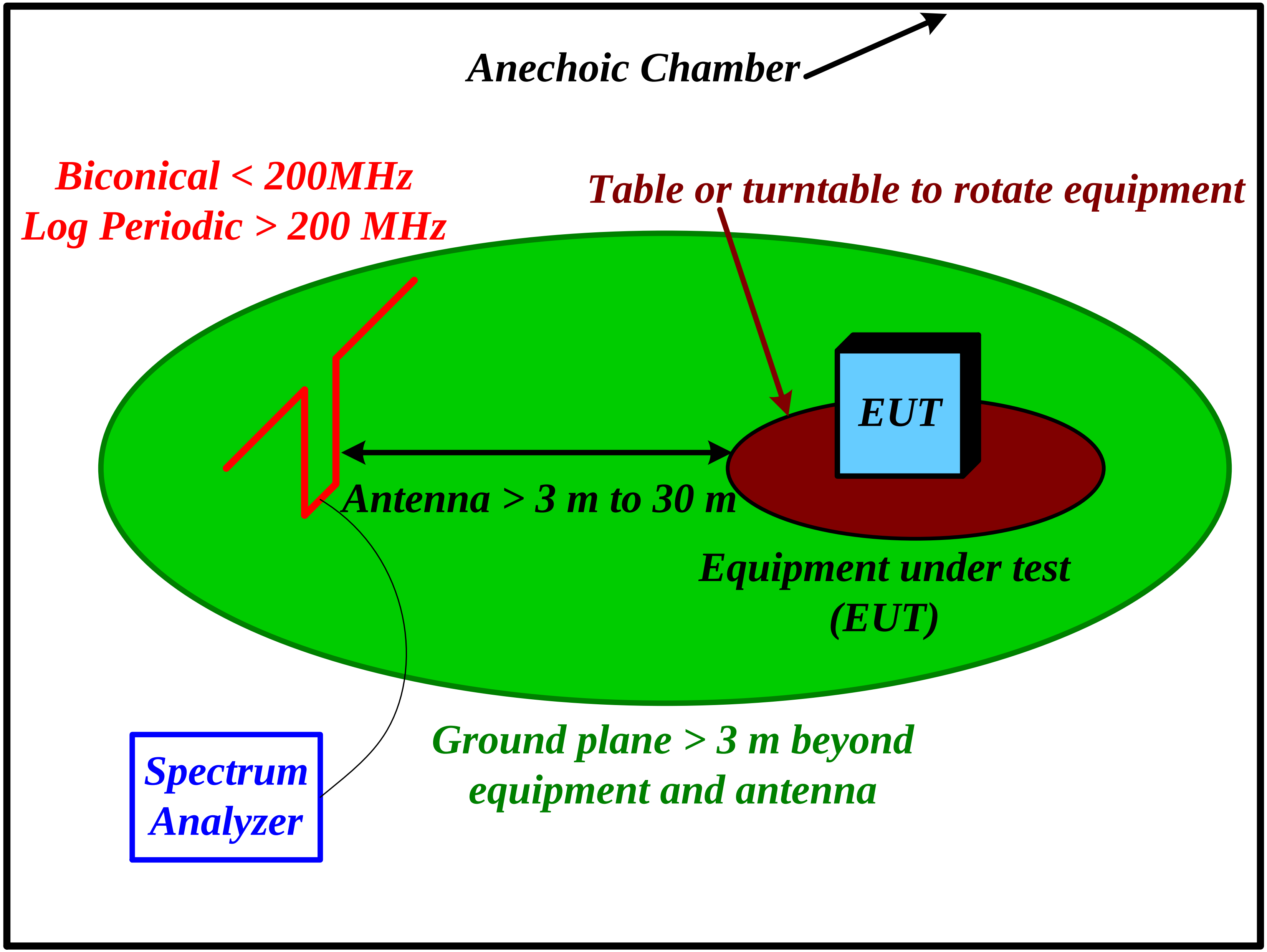
Test equipment used

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

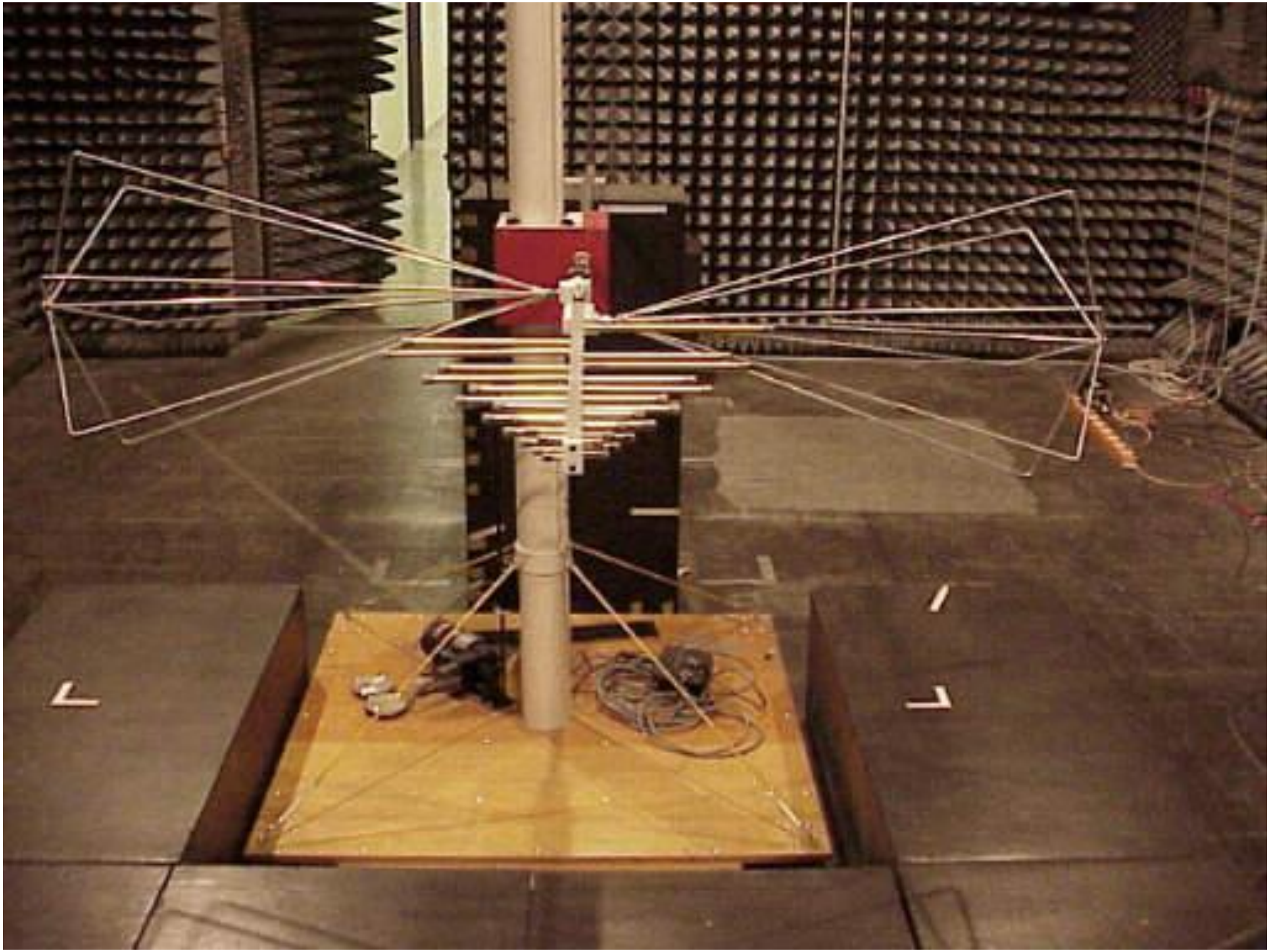
Any component or cable > 1/2 wavelength (λ) will be an efficient radiating or receiving antenna

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


Typical field strength
1000 to 2000 $\mu V / m$
3 to 30 m
100 to 200 $\mu V / m$


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

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

Hint: Homework problem

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

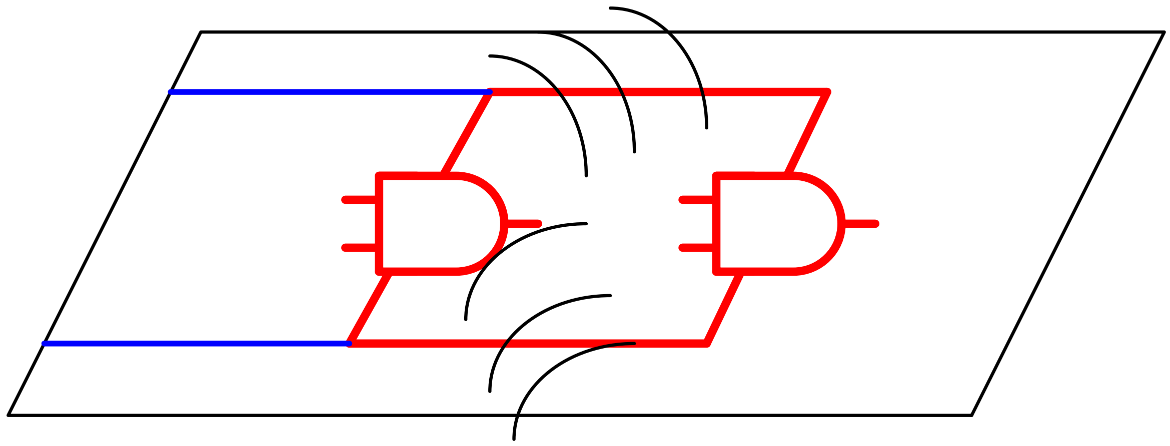
$V \propto A$ *the area of the loop cut by flux*

Moral - minimize loop areas by:

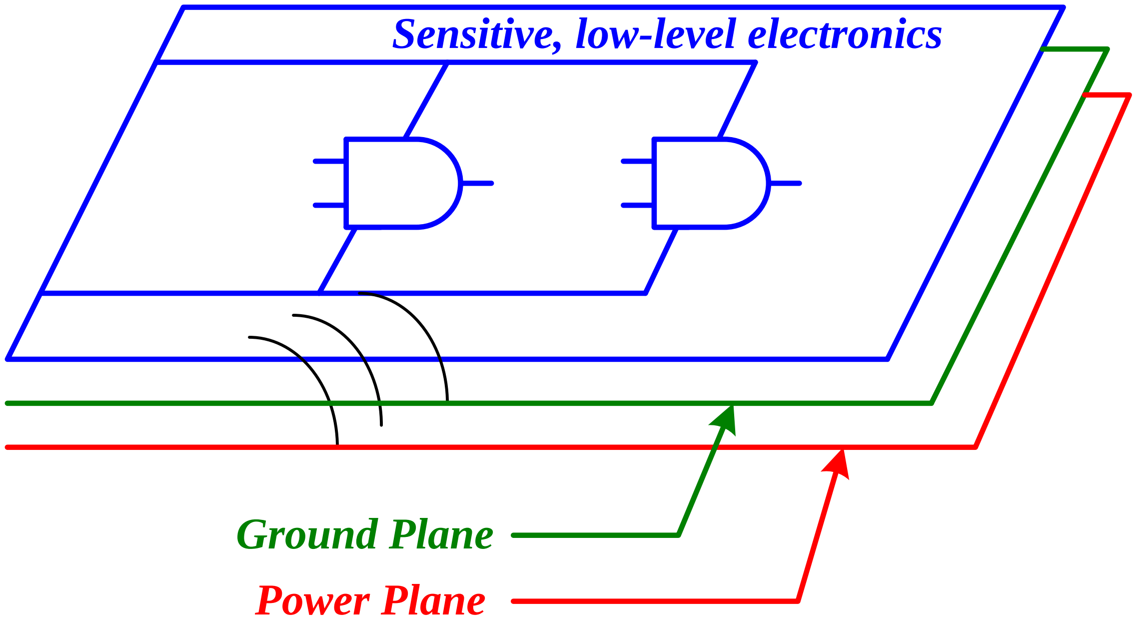
running supply and return bus or cable conductors together

twisting cables whenever possible

EMC/EMI - Radiated Noise Reduction By PCB Small Loops

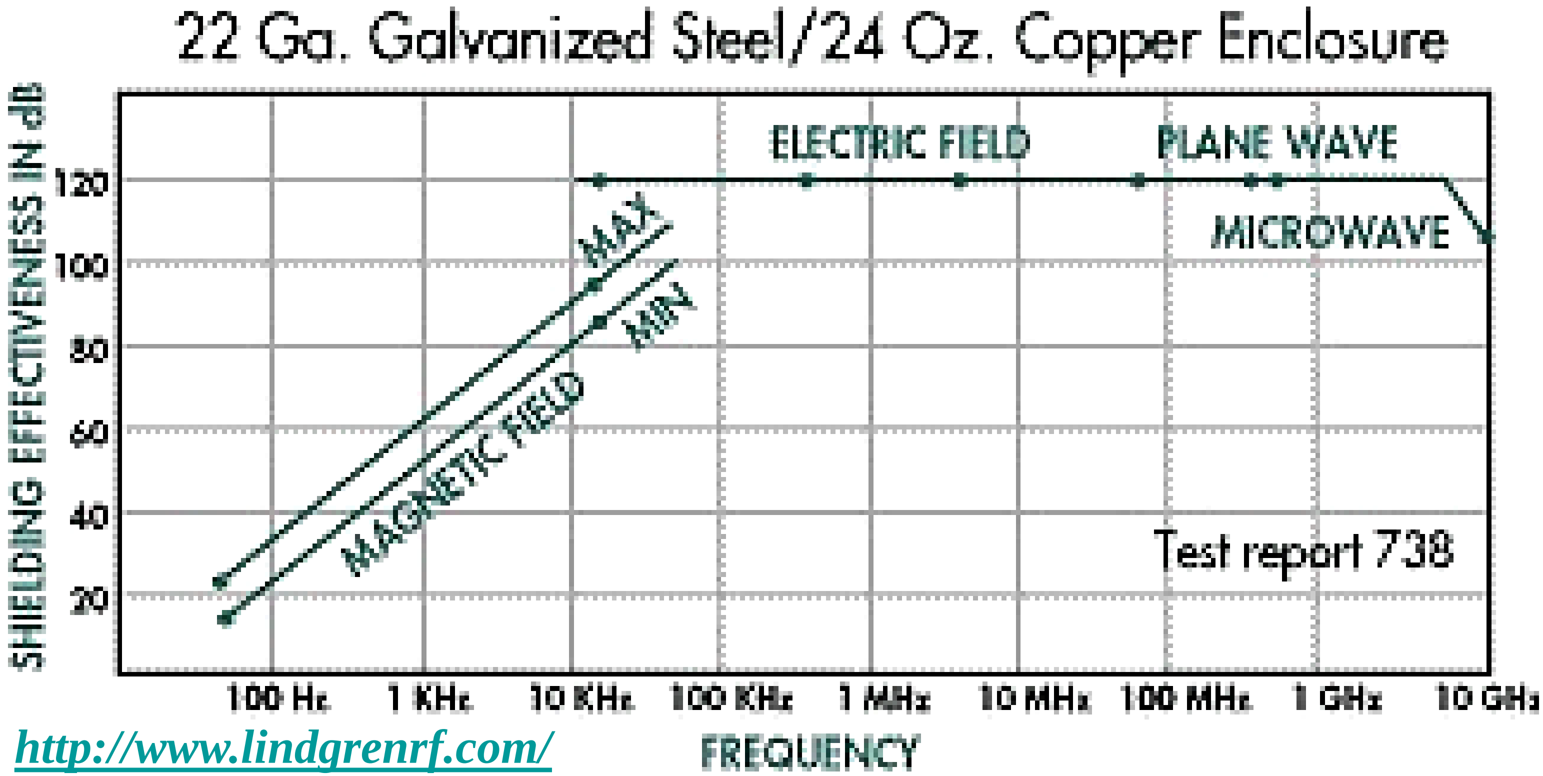


Radiated Noise Reduction By PCB Ground Planes



Use shielded cables

Use shielded enclosures (if necessary for interior controls)



http://www.lindgrenrf.com/

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 # 4

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 $\mu\,\Omega * \mathrm{cm}$.

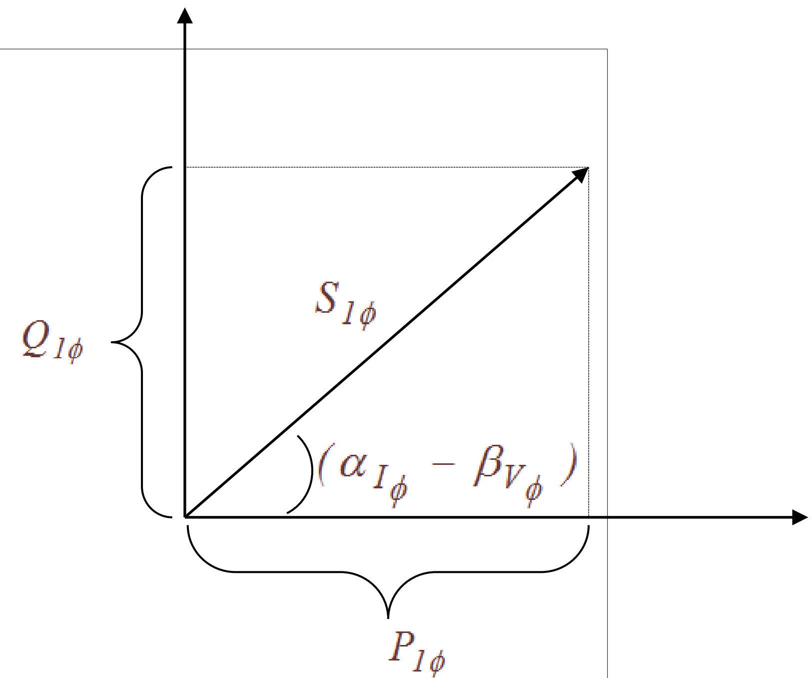
Single Phase

$$S_{1\phi} = V_{\phi}\ I_{\phi} = P_{1\phi} + Q_{1\phi}$$

$$P_{1\phi} = V_{\phi}\ I_{\phi} \cos(\alpha_{I_{\phi}} - \beta_{V_{\phi}})$$

$$Q_{1\phi} = V_{\phi}\ I_{\phi} \sin(\alpha_{I_{\phi}} - \beta_{V_{\phi}})$$

$$PF = \frac{P_{1\phi}}{S_{1\phi}} = \cos(\alpha_{I_{\phi}} - \beta_{V_{\phi}})$$



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

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

Balanced three Phase

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

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

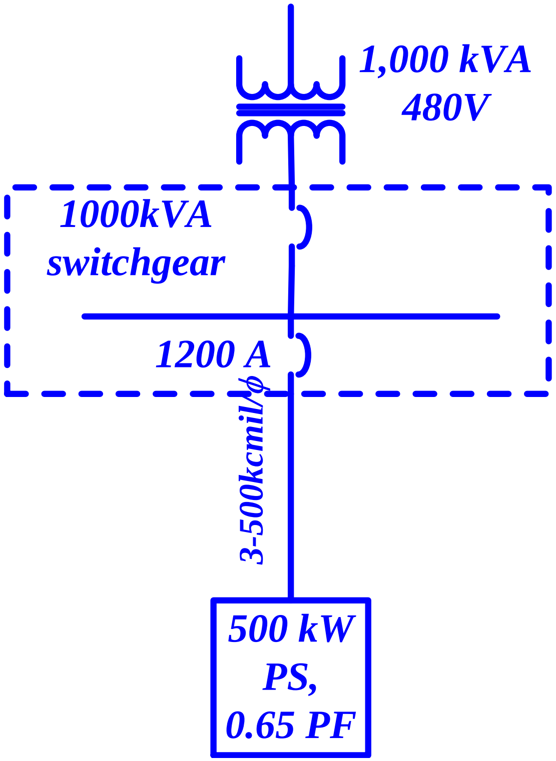
$$PF_{3\phi} = \frac{P_{3\phi}}{S_{3\phi}} = \cos(\alpha_{I_{\phi}} - \beta_{V_{\phi}})$$

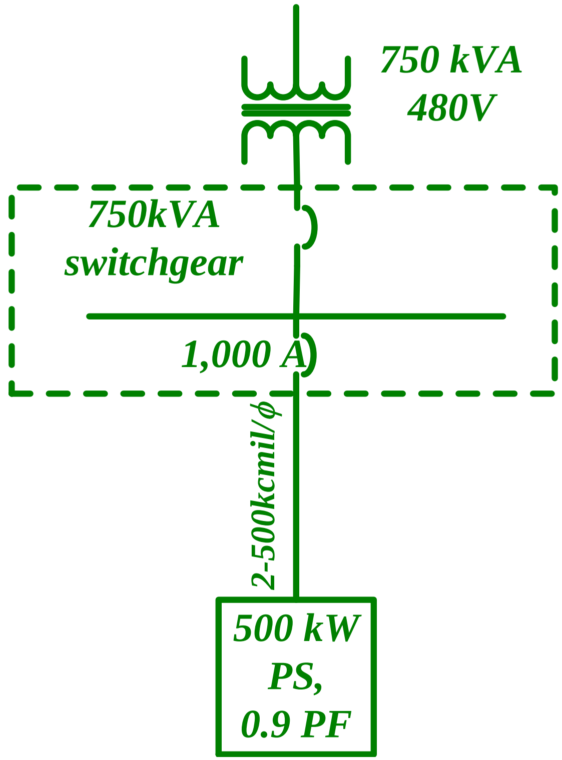
Unbalanced three phase power

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

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

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





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

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

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

Buy 1000kVA switchgear/transformer

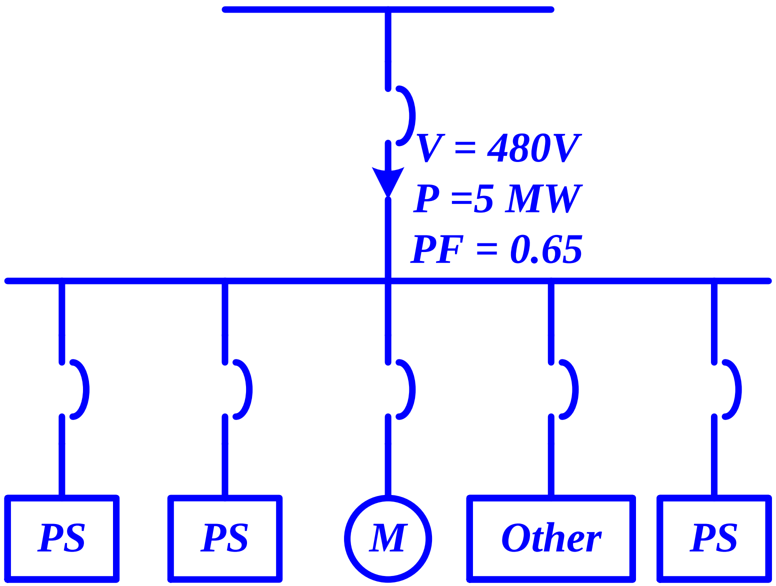
$$S = \frac{P}{PF} = \frac{500kW}{0.9} = 555kVA$$

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

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

Buy 750kVA switchgear/transformer

Power Factor is Important – Energy Cost



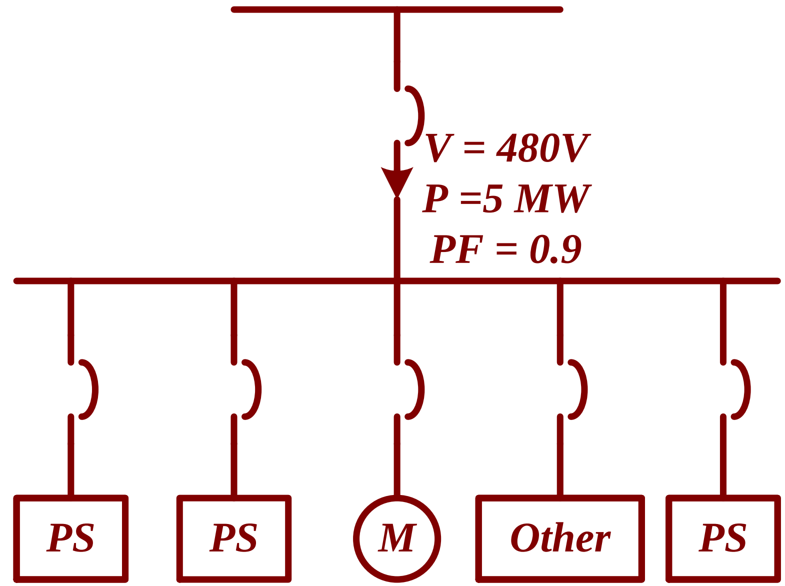
$$S = \frac{P}{PF} = \frac{5MW}{0.65} = 7.7MVA$$

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

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

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

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



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

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

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

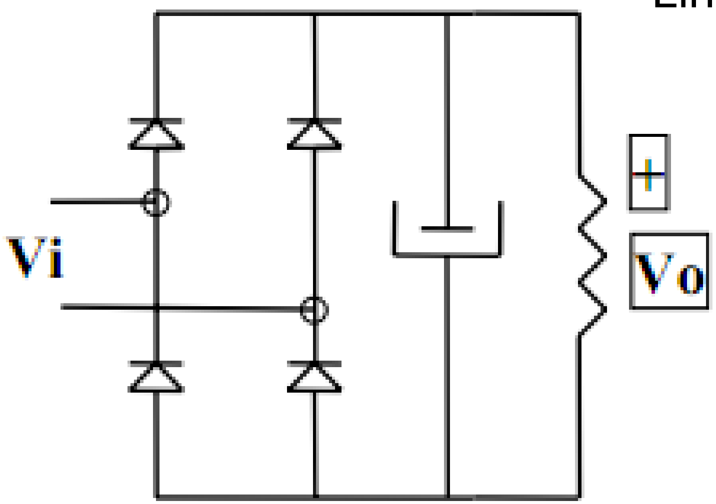
$$5.6MVA * \frac{\$0.06}{kW - Hr} * \frac{6480hr}{yr} = \frac{\$2.2M}{yr}$$

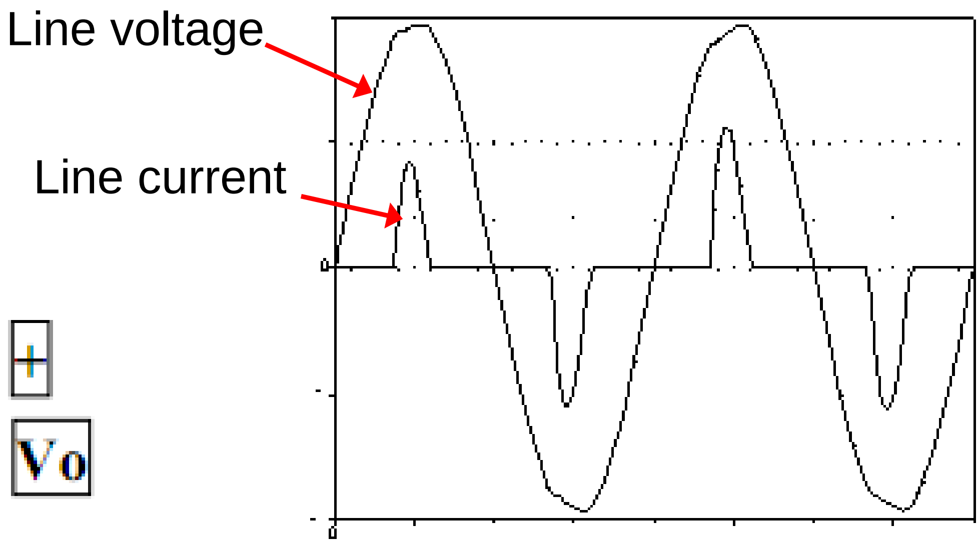
$$\frac{\$2.2M}{yr} * 20yr = \$44M$$

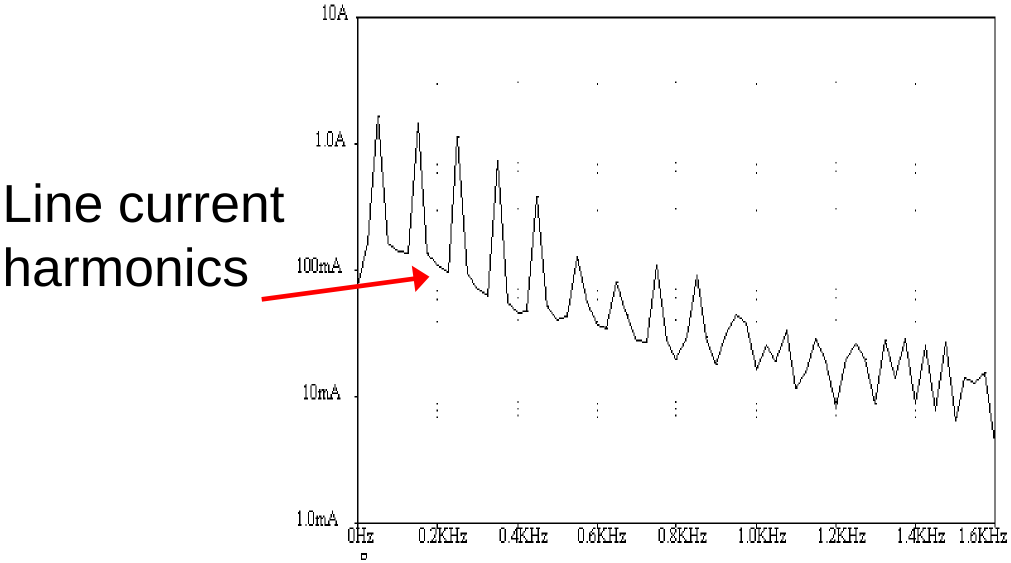
Power Factor Improvement

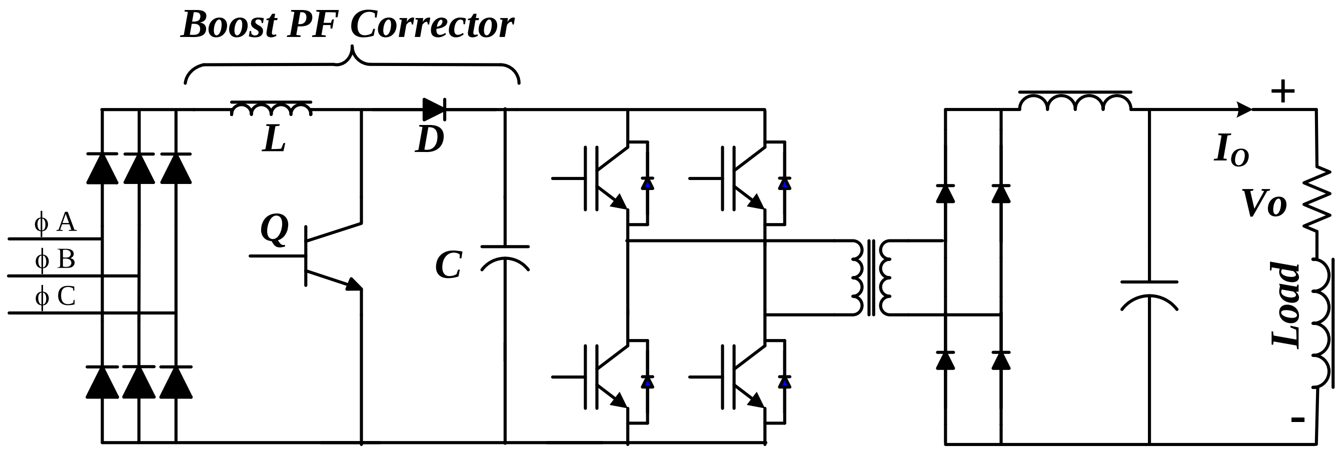
Higher Power Factor Translates to:

- *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*

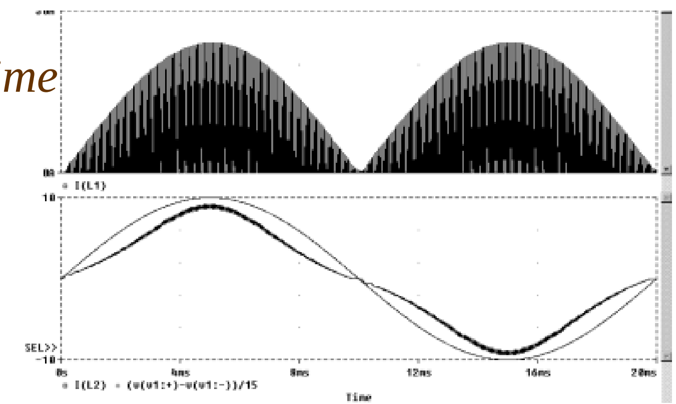

Vi
+
Vo


Line voltage
Line current

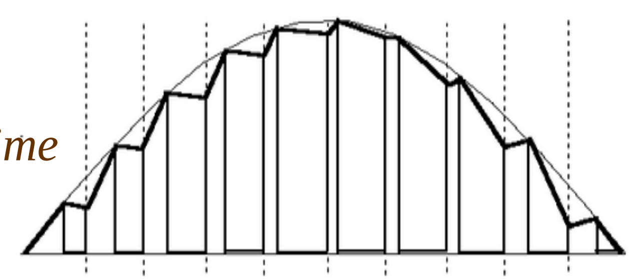

Line current harmonics
10A
1.0A
100mA
10mA
1.0mA
0Hz
0.2KHz
0.4KHz
0.6KHz
0.8KHz
1.0KHz
1.2KHz
1.4KHz
1.6KHz

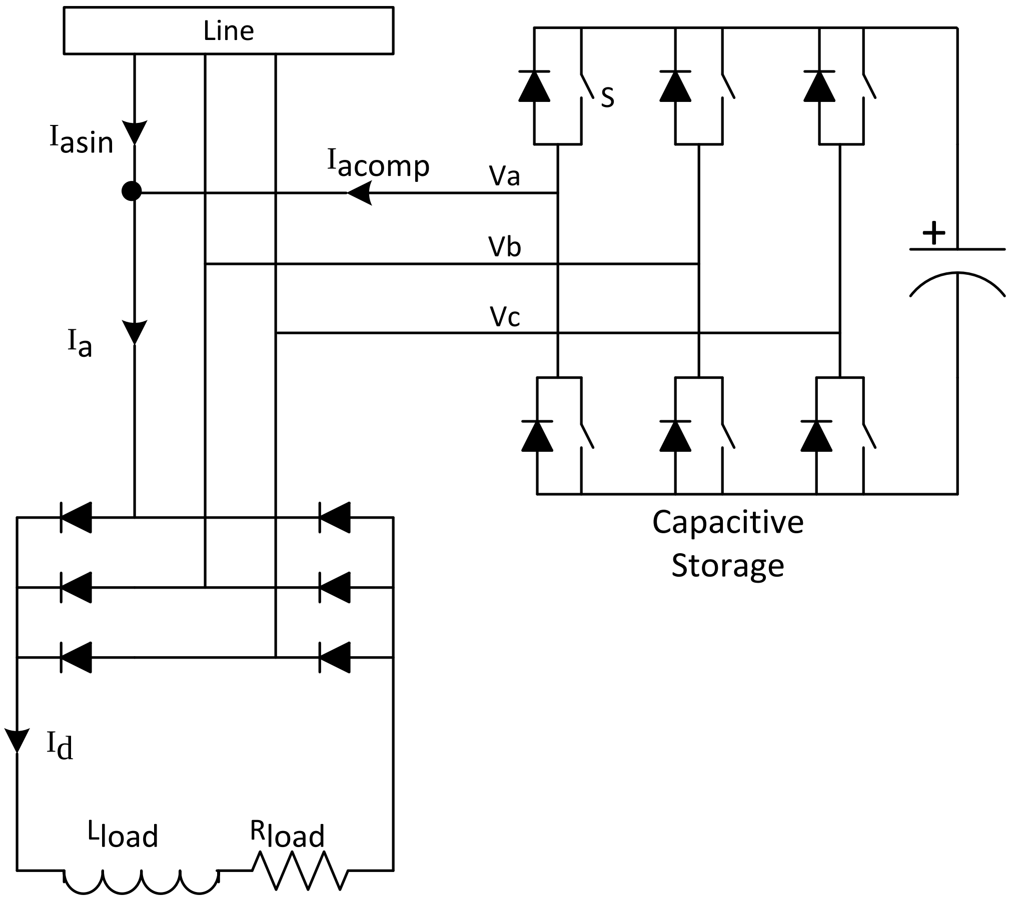


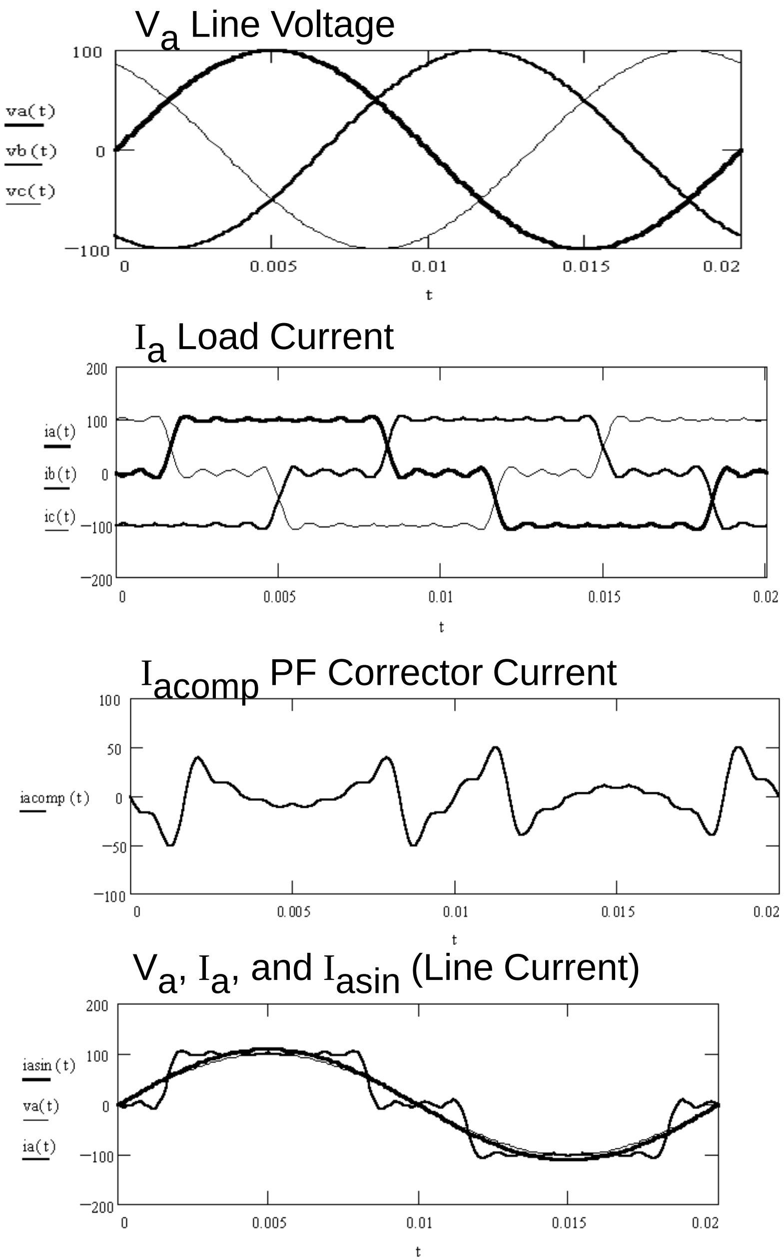
I_c v. time



V_{ab}, I_L, I_Q v. time

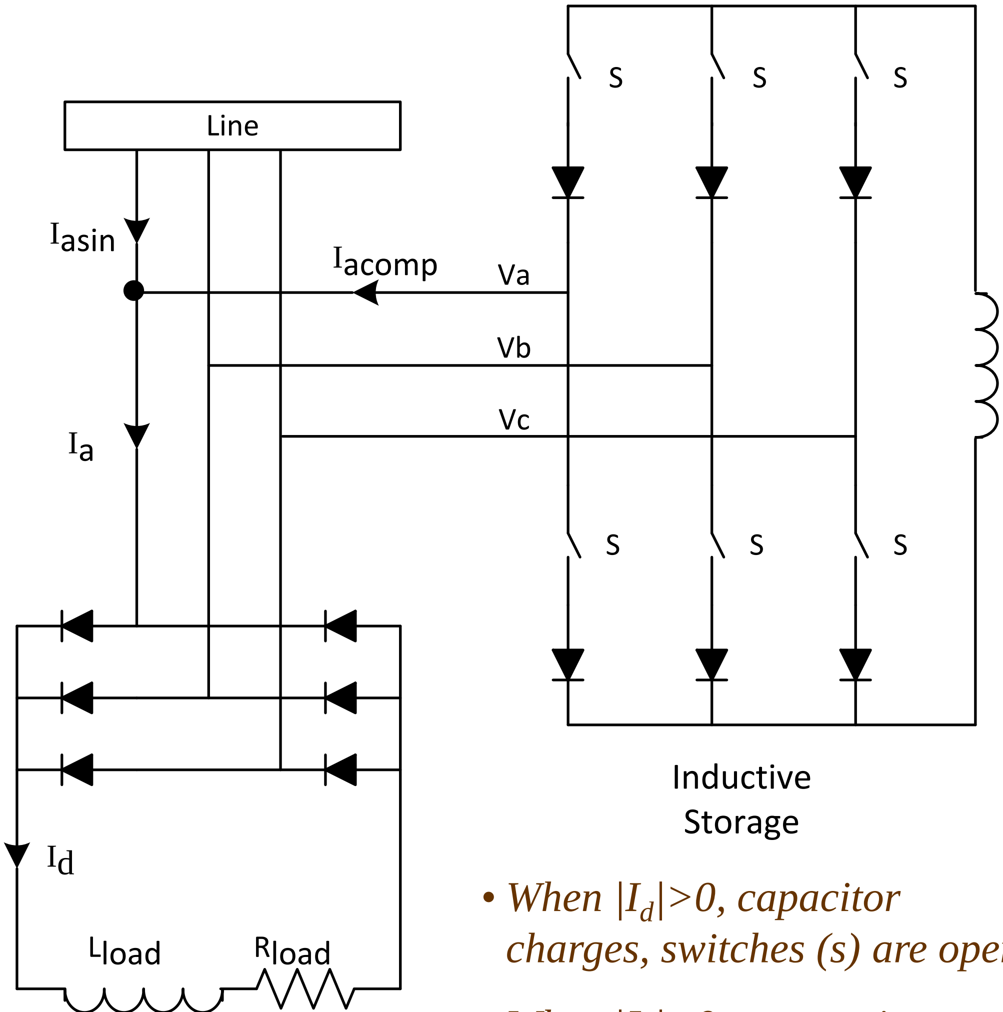






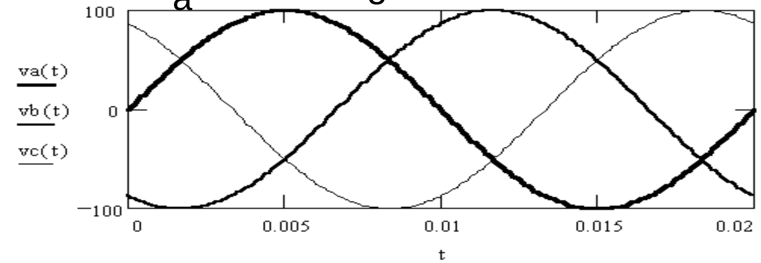
- *Appropriate switches (s) are rapidly opened and closed to control charging and discharging of the capacitor (I_{acomp})*
- *From KCL, $I_{asin}=I_a - I_{acomp}$*

Active Power Factor Correction - 3 Phase Systems

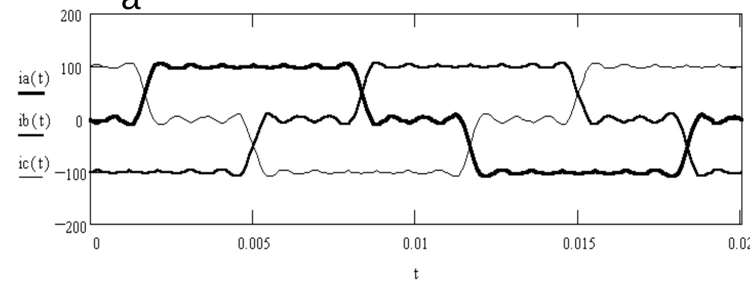


- *When $|I_d|>0$, capacitor charges, switches (s) are open*
- *When $|I_d|=0$, appropriate switches (s) are closed to rapidly discharge the capacitor*
- *From KCL, $I_{asin}=I_a-I_{acomp}$*

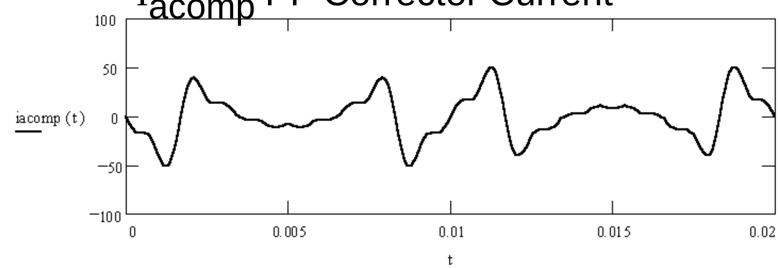
V_a Line Voltage



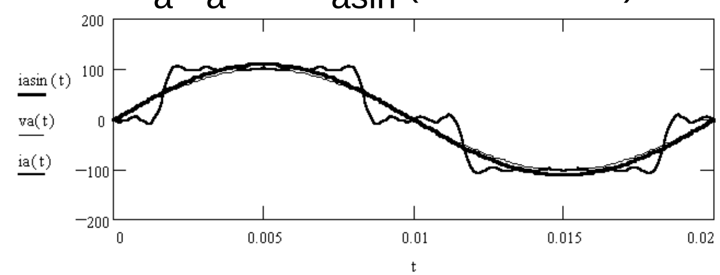
I_a Load Current



I_{acomp} PF Corrector Current

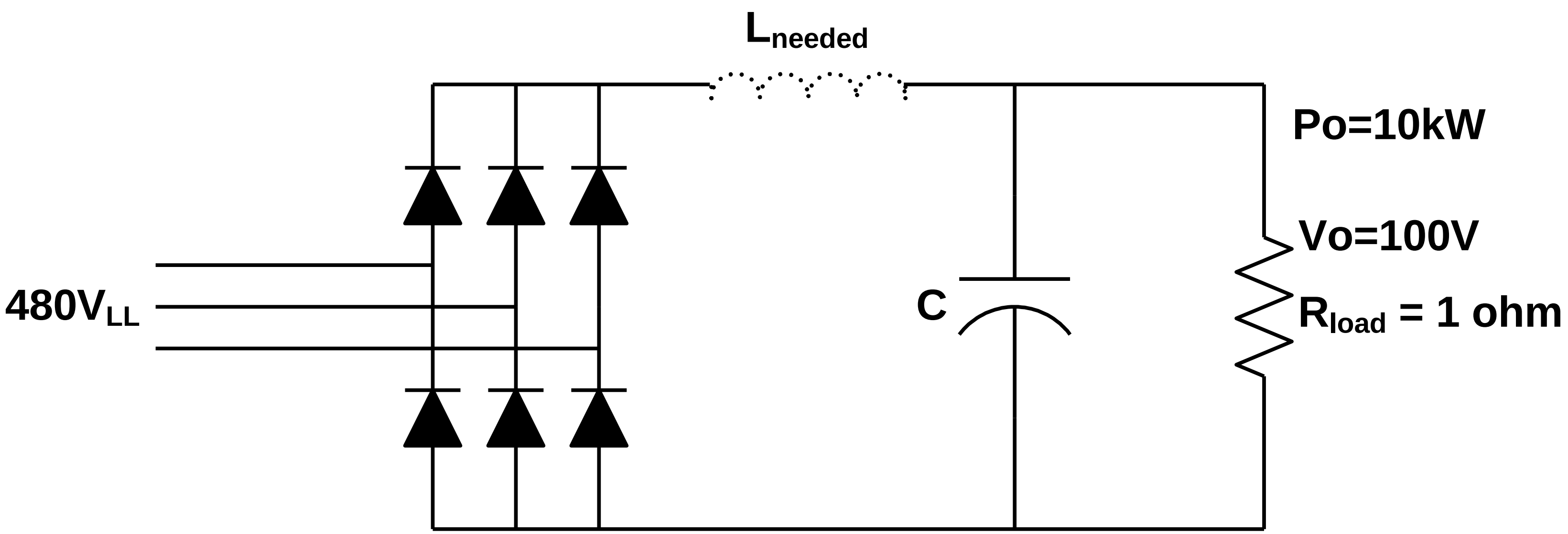


V_a, I_a, and I_{asin} (Line Current)



Homework Problem # 5

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 leading 0.95. Hint: the ripple frequency of the rectifier output is 360Hz.



Section 5

- Power Supplies
  - Power Supply Definition, Purpose, and Scope
  - Transformer Primer
  - Rectifiers
  - Voltage and Current Sources
  - Linear Systems Disadvantage
  - Switchmode DC Power Supplies
    - Advantages
    - Switch Candidates
    - Converter Topologies
    - Pulse Width Modulation
    - Conducting and Switching Losses
    - Resonant Switching
  - High Frequency Transformers and Inductors
  - Ripple Filters
  - Other Design Considerations
  - Power Supplies in Particle Accelerators

Definition

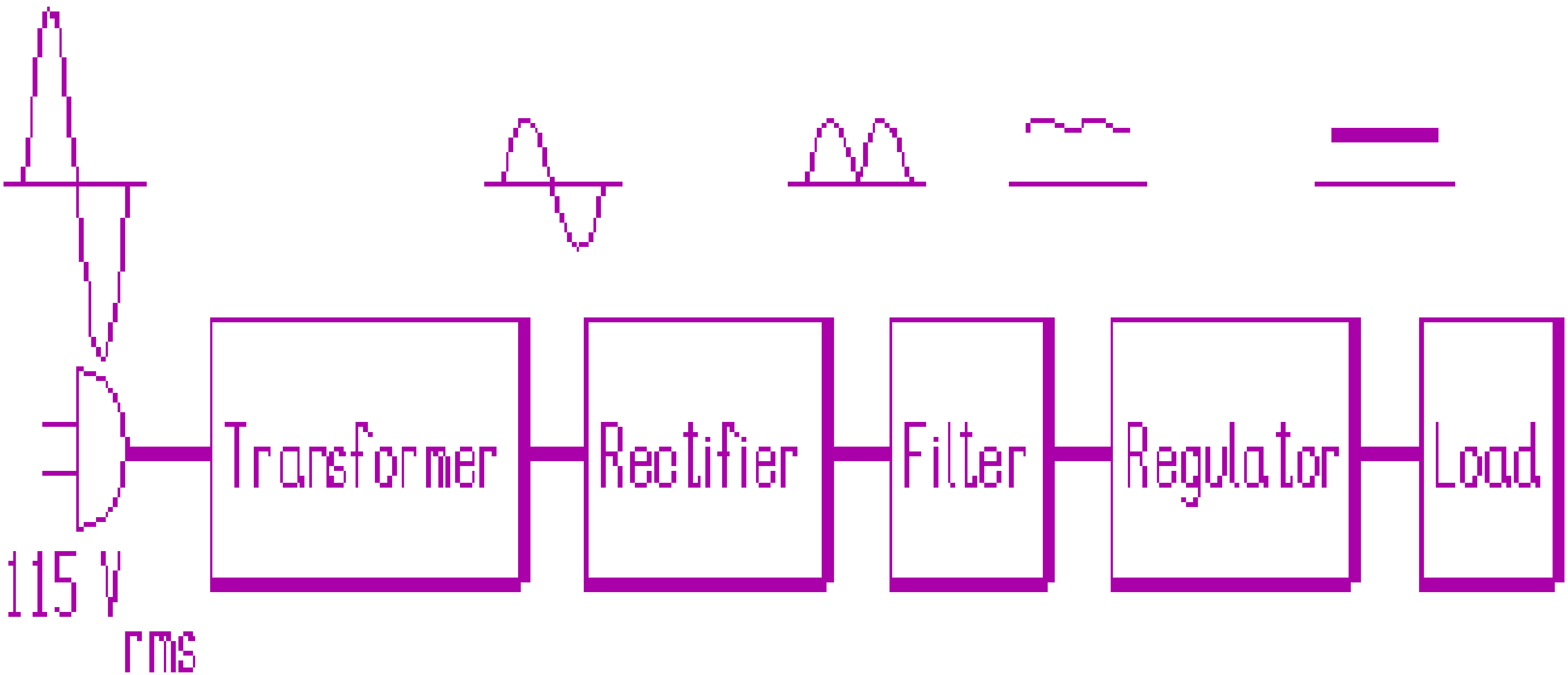
- *A "DC power supply" is a device or system that draws uncontrolled, unregulated input AC or DC power at one voltage level and converts it to controlled and precisely regulated DC power at its output in a form required by the load*

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*



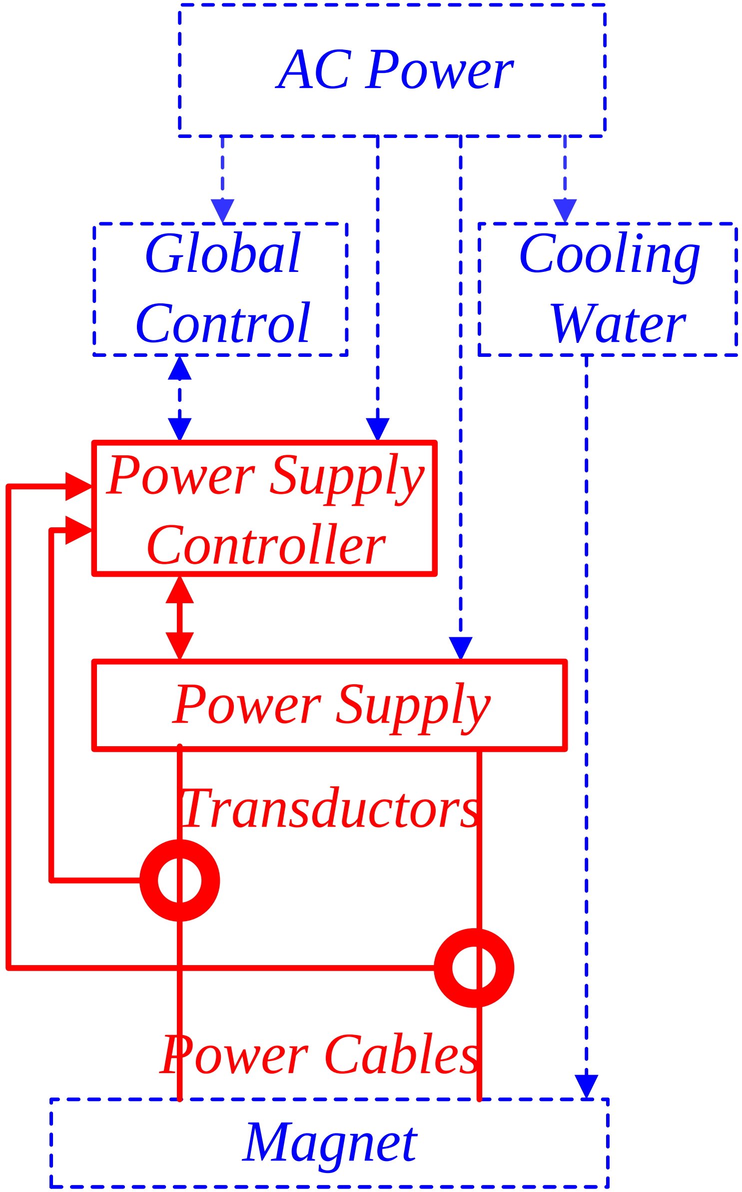
Power Line EMI/EMC

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 can be DC-DC converters

•They are voltage or current sources that use the AC mains (off-line) as their source of energy. 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 are not AC controllers.

• 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

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

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

•Typical loads are magnets or capacitor banks

Transformer Primer - Why Needed

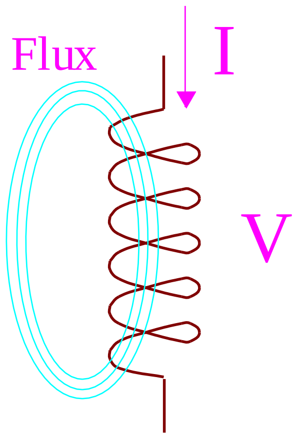
- *Needed to match the load voltage to the line voltage*

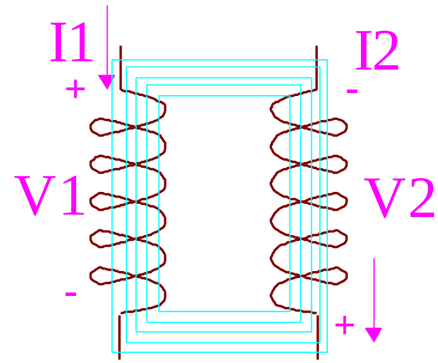
- *Needed to isolate the load from the line better ground fault immuniyty and to reduce the magnitude of fault currents*

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

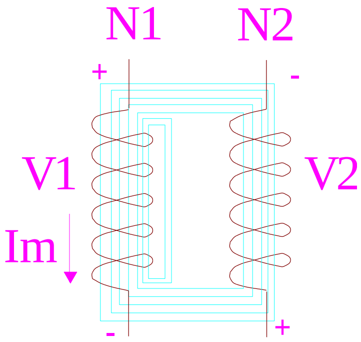
- The current required to magnetize the core with flux is called the magnetizing current and is made up of two parts:

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

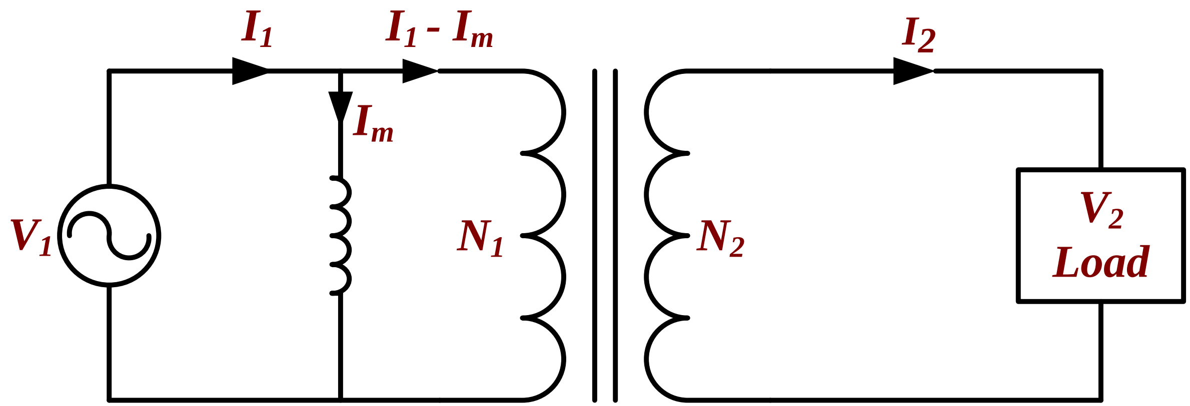
  2. A component in phase with the induced voltage from losses due to eddy current and hysteresis losses.

- 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

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

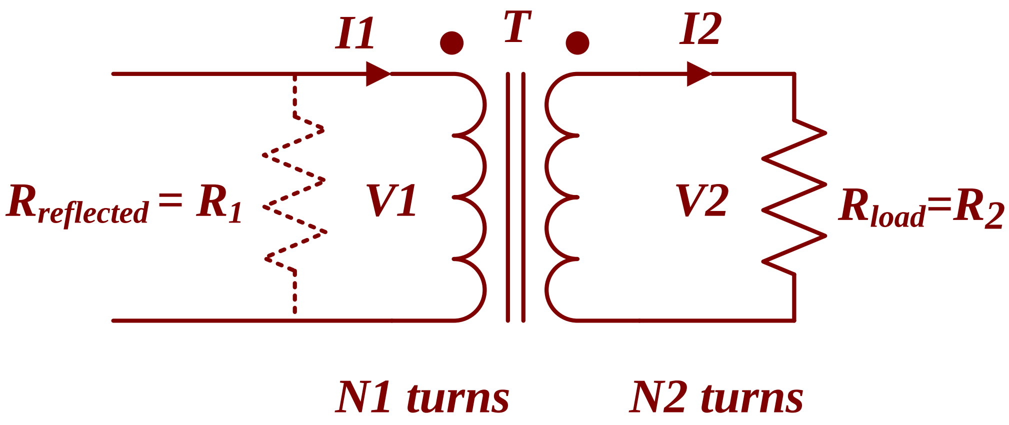
Where N_1 and N_2 are the number of turns cut by the same flux

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

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

If $I_m << I_1$ then

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



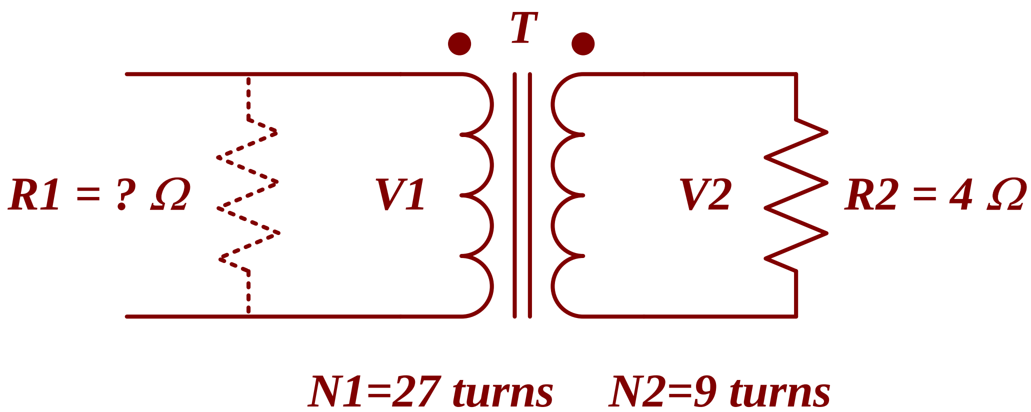
$$R_1 = \frac{V_1}{I_1} = \frac{\frac{N_1}{N_2} V_2}{\frac{N_2}{N_1} I_2} = \frac{N_1 V_2}{N_2} * \frac{N_1}{N_2 I_2}$$

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

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

Example

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

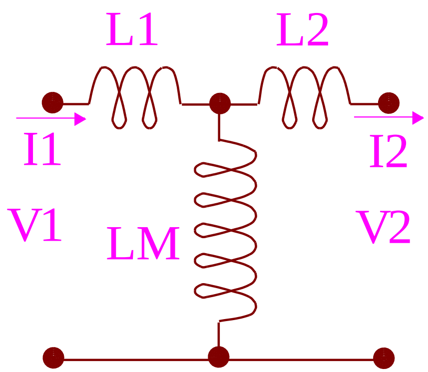


$$R_1 = \frac{N_1^2}{N_2^2} * R_2 = \frac{27^2}{9^2} * 4\Omega$$

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

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)*



$$I_1 = \frac{V_1}{(X_1 + X_2)} = \frac{V_1}{2\pi f\,(L_1 + L_2)}$$

$$L_1 + L_2 = \frac{V_1}{2\pi f\; I_1}$$

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

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

Transformer Primer - Homework Problem #6

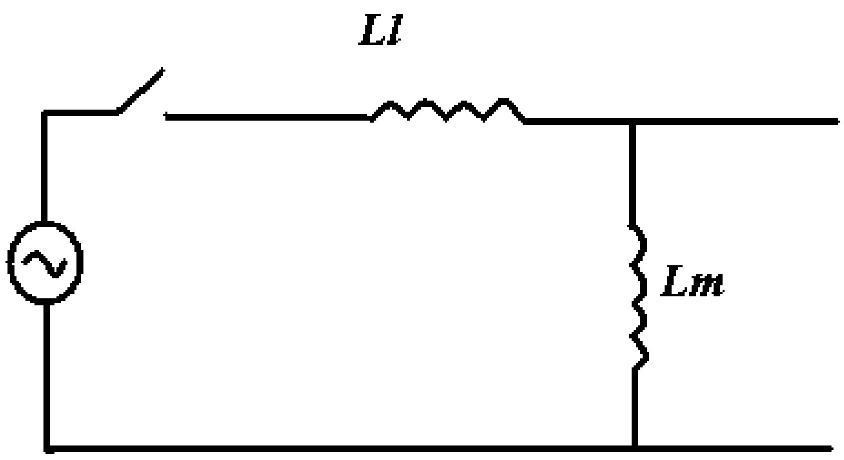
A 1000kVA, 12.47kV to 480V, 60Hz three-phase transformer has an impedance of 5%. Calculate:

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

Transformer Primer - Model

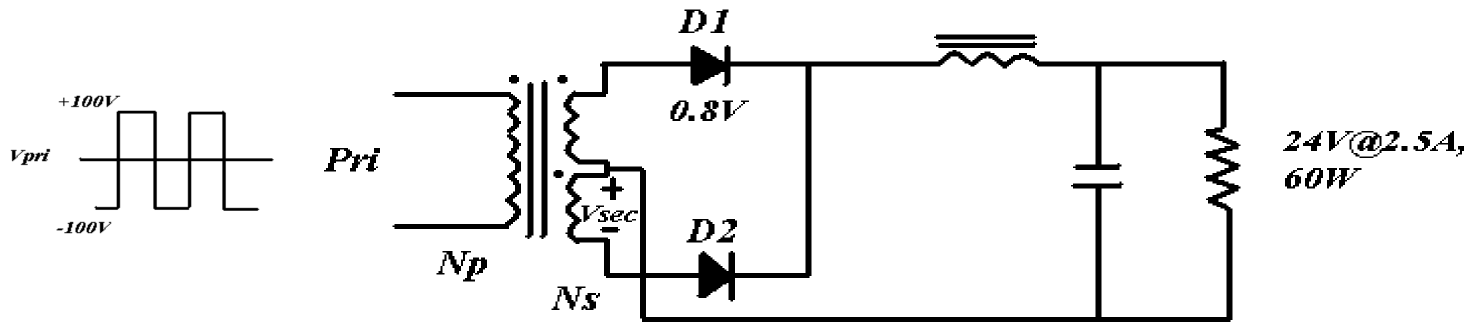


transformer model

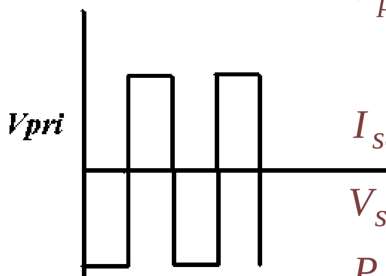
An air gap is undesirable in a transformer because:

- *it reduces L_m , and a large L_m is desired to reduce the magnetizing and inrush current*
- *a small L_l is desired to lower energy and other losses*

Transformer Primer - Example



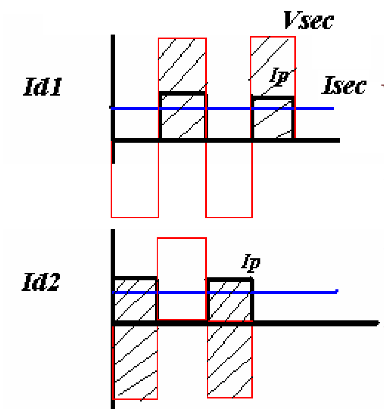
$V_{pripeak} = 100V \quad V_o = 24V \quad V_d = 0.8V \quad V_{secpeak} = 24.8V \quad I_o = 2.5A \qquad D = 0.5$



$I_{secrms} = I_{secavg} * \sqrt{D} = I_o * \sqrt{D} = 2.5 * \sqrt{0.5} = 1.77A$ *rms on each side* *where D is duty ratio*

$V_{secrms} = V_{sec\ peak} * \sqrt{D} = 24.8V * \sqrt{0.5} = 17.5V$

$P_{secavg} = V_{secrms} * I_{secrms} = 17.5V * 1.77A = 31W$ *each secondary*



$V_{pripeak} / V_{secpeak} = 100V / 24.8V = 4.03$ *transformer turns ratio - each secondary*

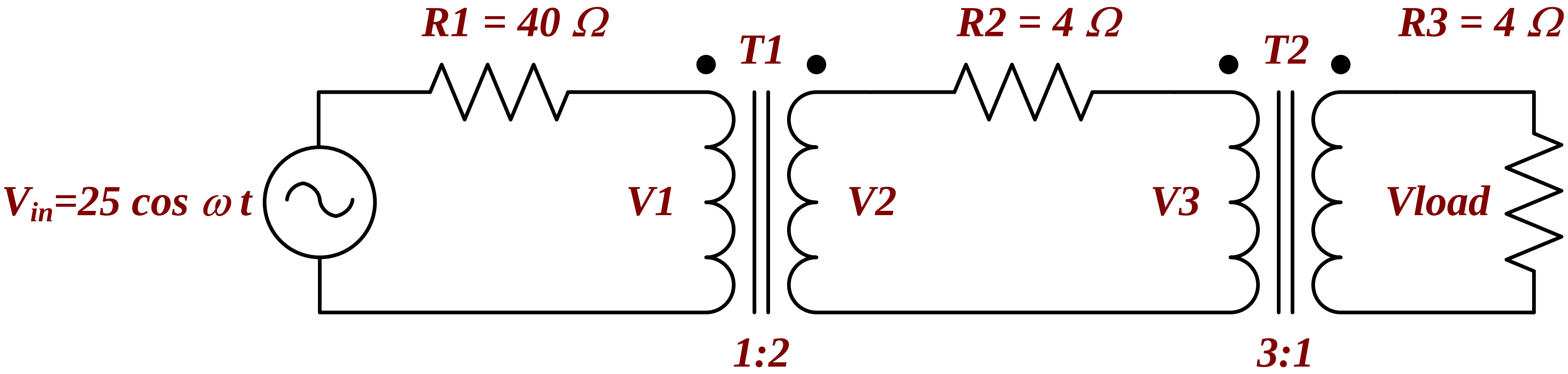
$I_{prirms} = I_{secrms} / N = 1.77A / 4.03 = 0.439A$ *Contribution from each secondary*

$I_{totalprirms} = 0.439A * 2 = 0.878A$

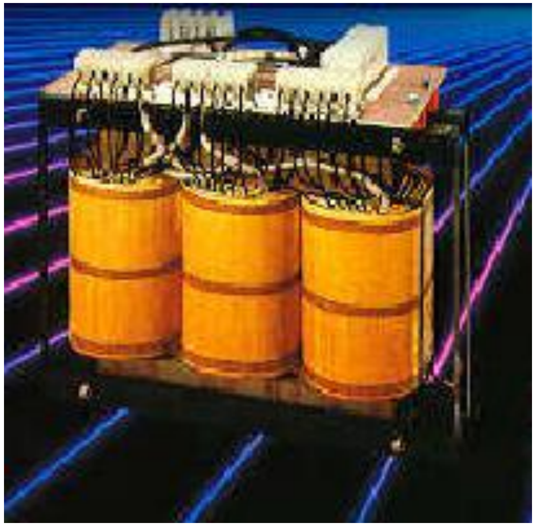
$P_{totalpriavg} = V_{prirms} * I_{totalprirms} = 100V * \sqrt{0.5} * 0.878A = 62W$

$\eta = P_o / P_{totalpriavg} = 60W / 62W = 96.8\%$

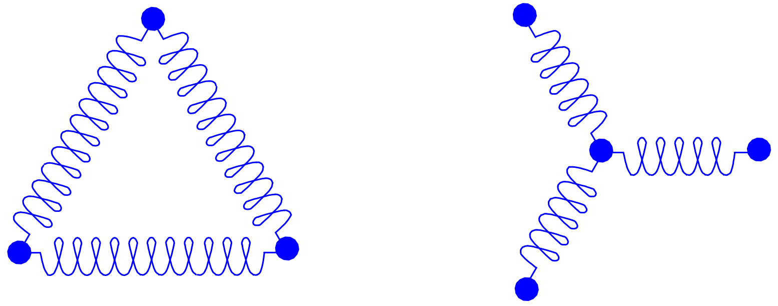
Calculate the output voltage in the circuit shown below.



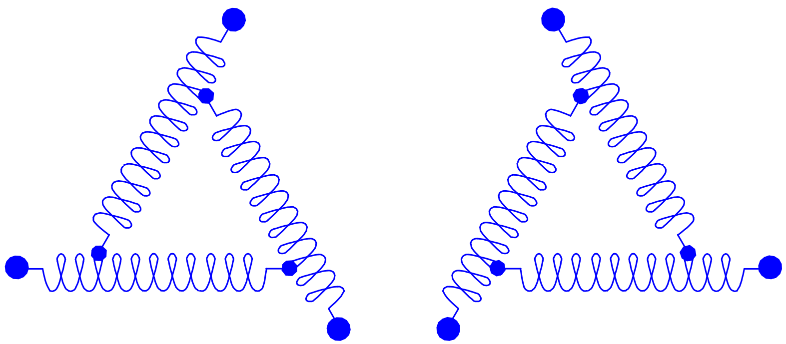
- Low frequency, 60 Hz, transformers almost always use laminated iron cores to direct the flux to tightly couple the windings to reduce the size, cost, leakage reactance and magnetizing current (large magnetizing inductance) of a transformer
- For low power applications < 2.5 kW single phase transformers 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



Delta –wye and extended delta produce 6 phase outputs



Delta-Wye

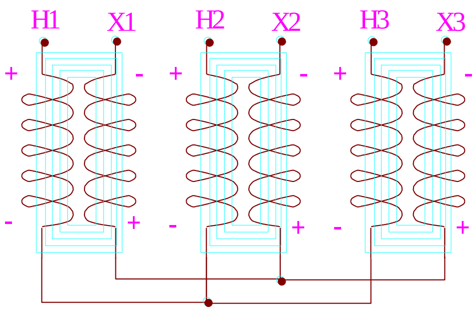


Extended delta

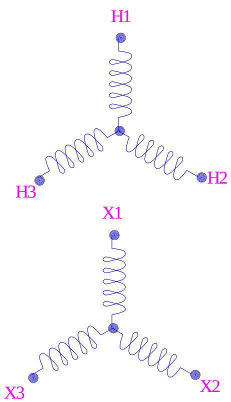
Transformer Primer - Three Phase Most Common Types

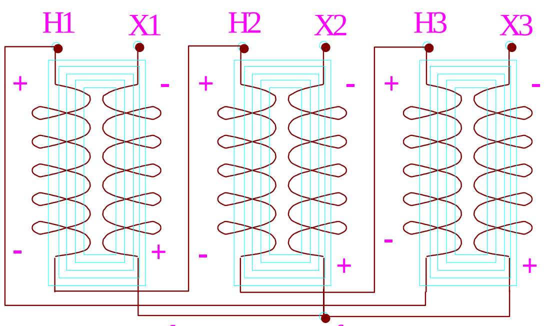
Three phase Transformers

- *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*

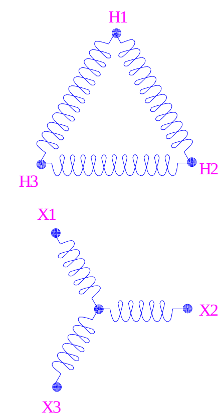


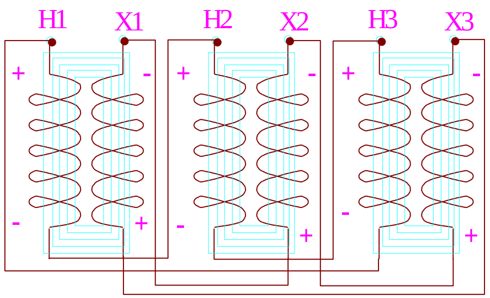
Wye-Wye Transformer



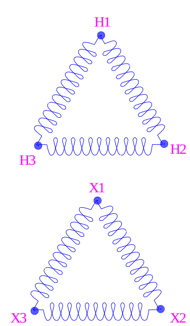


Delta -Wye Transformer

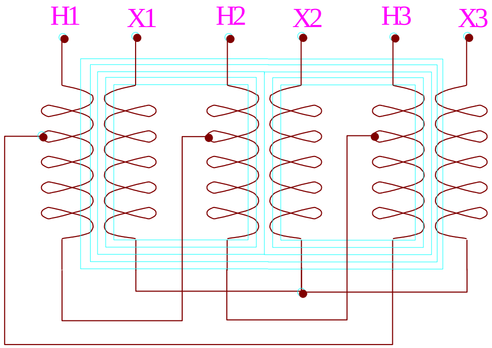




Delta - Delta Transformer

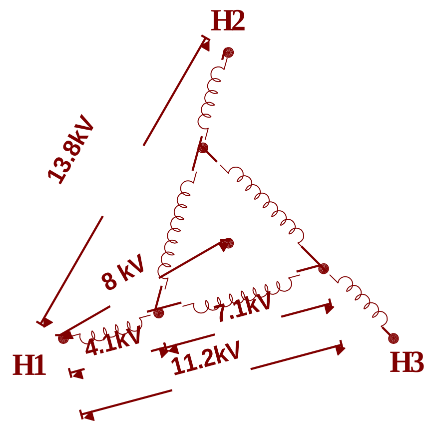


Extended Delta Phase shifting transformer

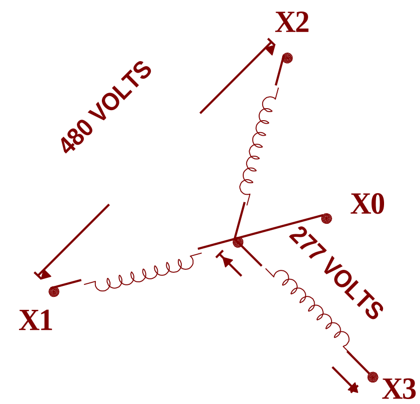


Extended Delta-Wye Transformer 3 core

EXTENDED DELTA 13.8kV to 480 V 7.5 ⁰

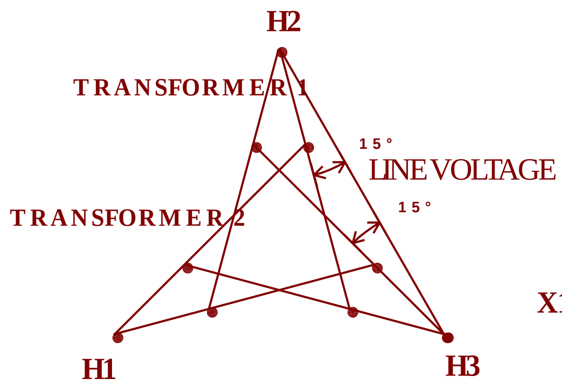


PRIMARY VOLTAGE RELATIONSHIP

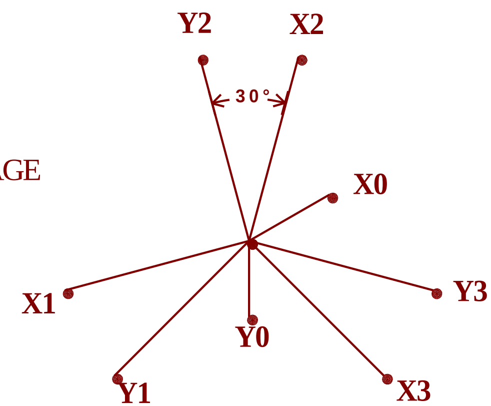


SECONDARY VOLTAGE RELATIONSHIP

PHASE RELATIONSHIP



PRIMARY PHASE RELATIONSHIP

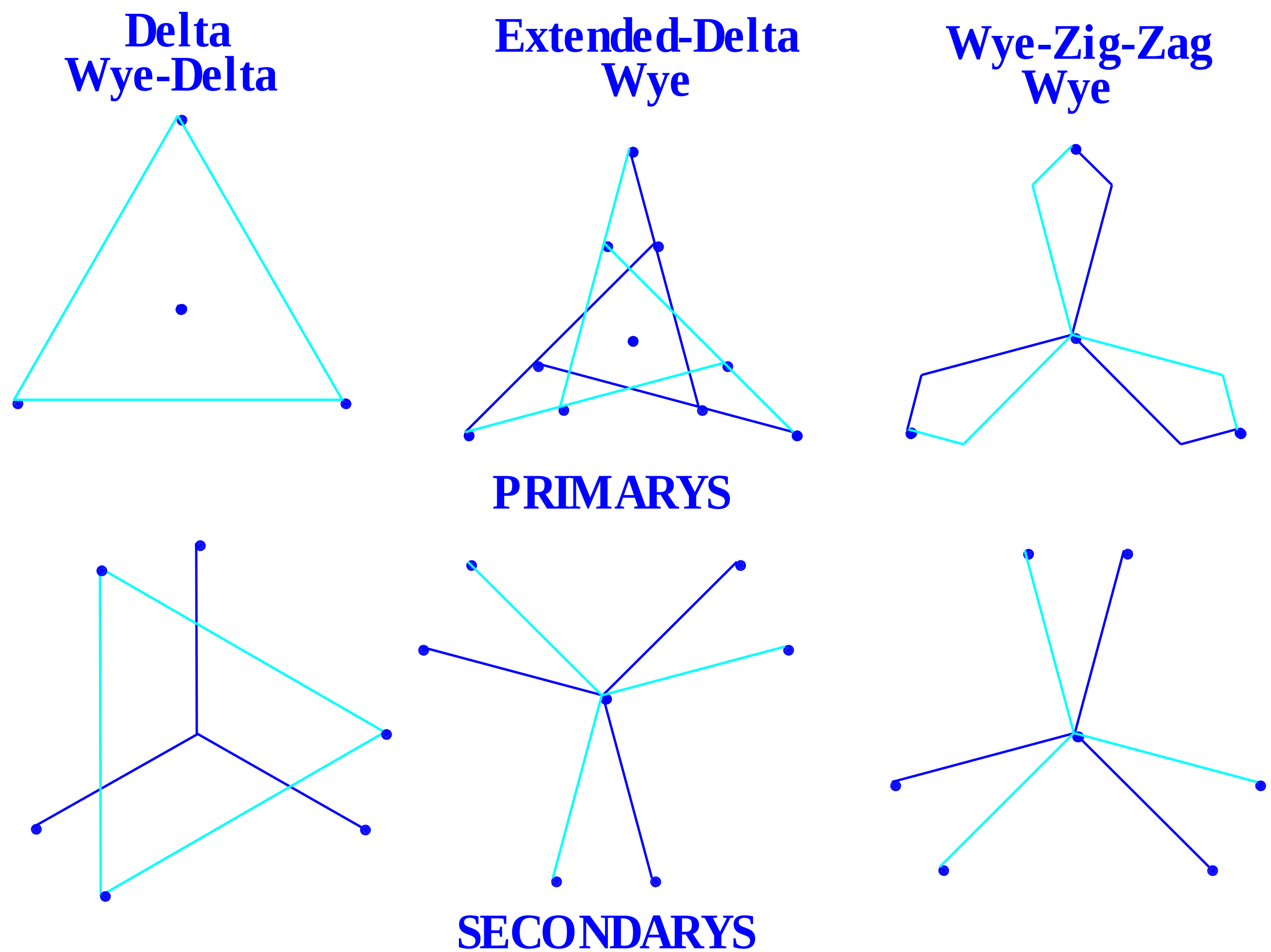


SECONDARY PHASE RELATIONSHIP

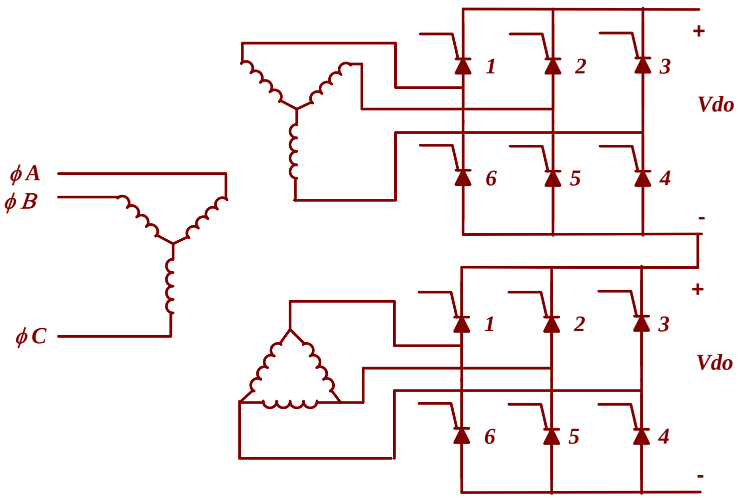
Two transformers Phase rotation change on input produces a 30º phase shift Leakage inductance is the same on all phases

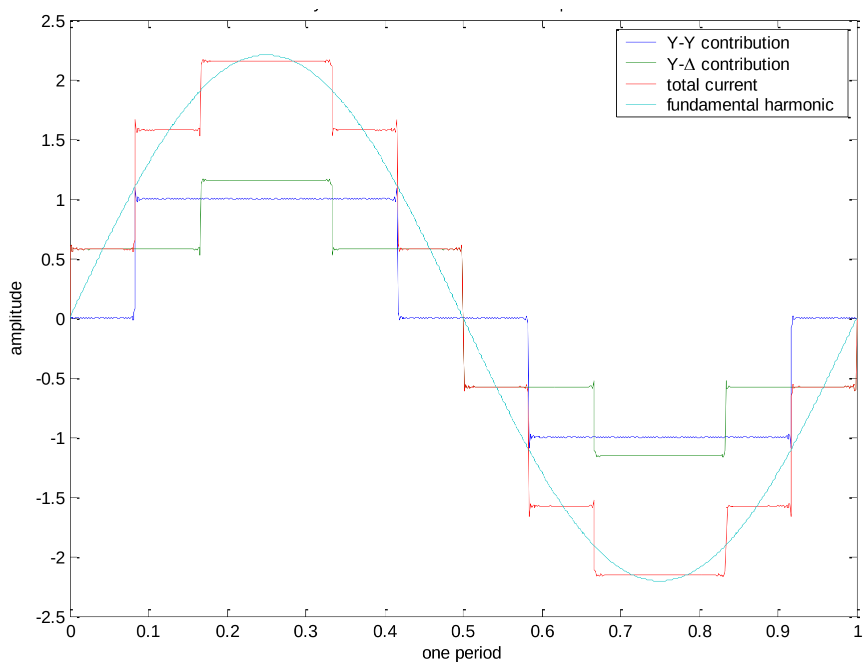
Transformer Primer - Three Phase Phase Shifting Transformer

Phase shifting transformer for 12 Pulse operation

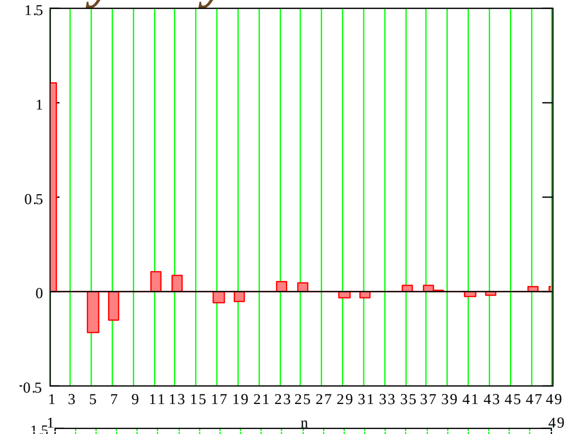


Transformer Primer - Total Primary Current in Wye-Wye-Delta

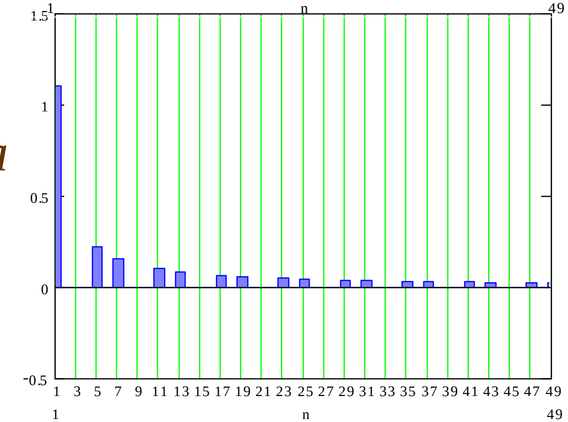




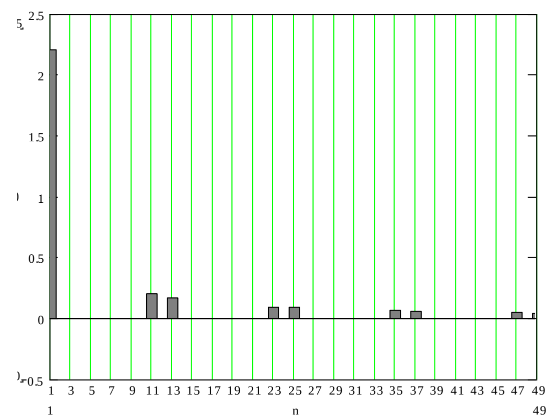
Wye-Wye



Wye-Delta



Wye-Wye-Delta



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

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

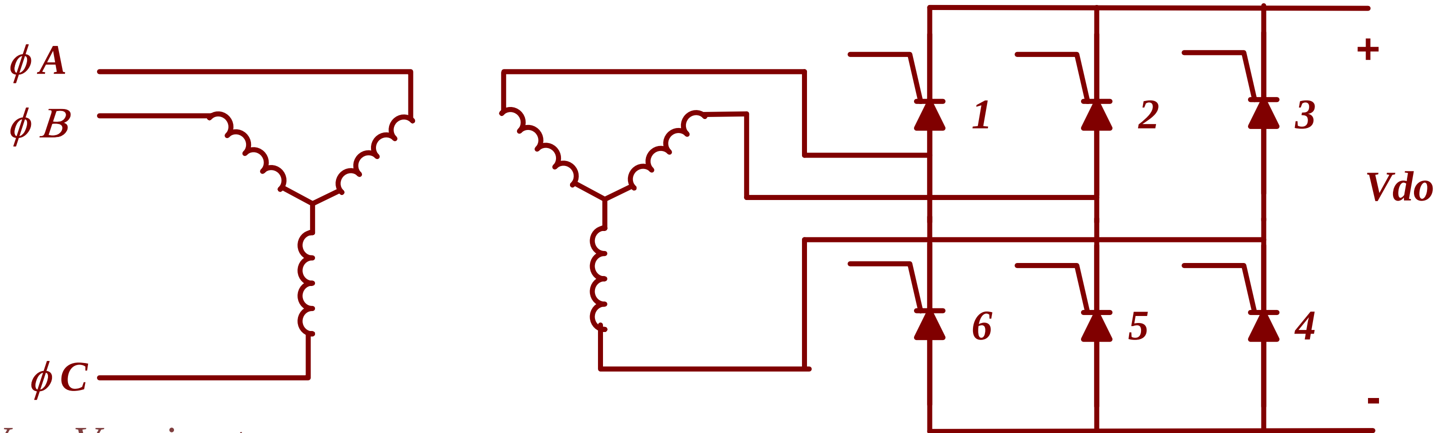
$$\sin a - \sin b = 2\sin\frac{a-b}{2}\cos\frac{a+b}{2}$$

Similarly, since

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

$$\cos a + \cos b = 2\cos\frac{a+b}{2}\cos\frac{a-b}{2}$$

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



$$V_A = V_{LN} \sin \omega t$$

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

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

$$\begin{aligned} V_{AB} &= V_A - V_B \\ &= V_{LN}\left[\sin \omega t - \sin\left(\omega t - 2\pi/3\right)\right] \\ &= 2V_{LN} \sin\frac{\pi}{3}\cos\left(\omega t - \pi/3\right) \\ &= \sqrt{3}V_{LN} \sin\left(\omega t - \pi/3 + \pi/2\right) \\ &= \sqrt{3}V_{LN} \sin\left(\omega t + \pi/6\right) \end{aligned}$$

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

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

For a transformer ratio, N_{YY}

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

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

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

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

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

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

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

Transformer Primer - 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

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

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,

$$a_0 = a_n = 0$$

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

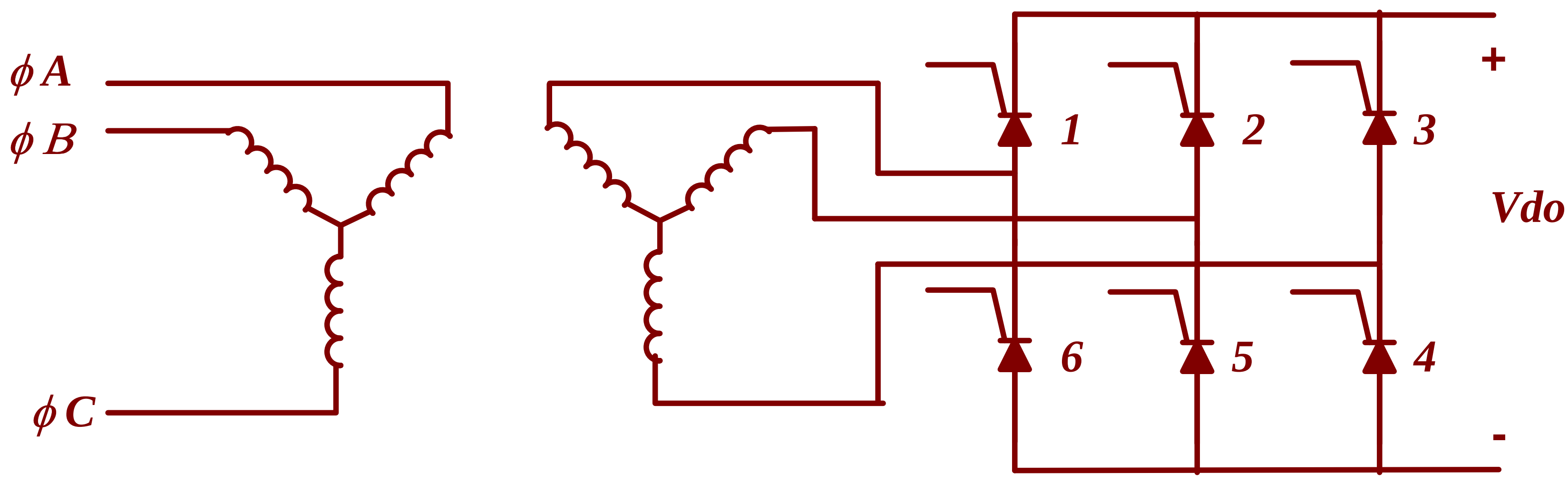
$$= \frac{2I_L}{T}\left[\int_{T/12}^{5T/12} \sin\frac{2\pi nt}{T}\,dt - \int_{7T/12}^{11T/12} \sin\frac{2\pi nt}{T}\,dt\right]$$

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

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

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

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

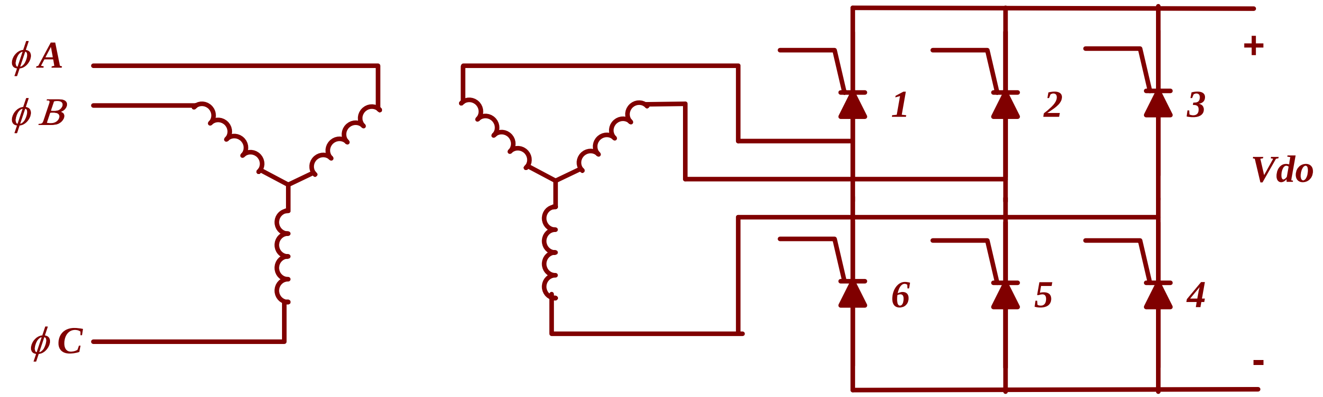


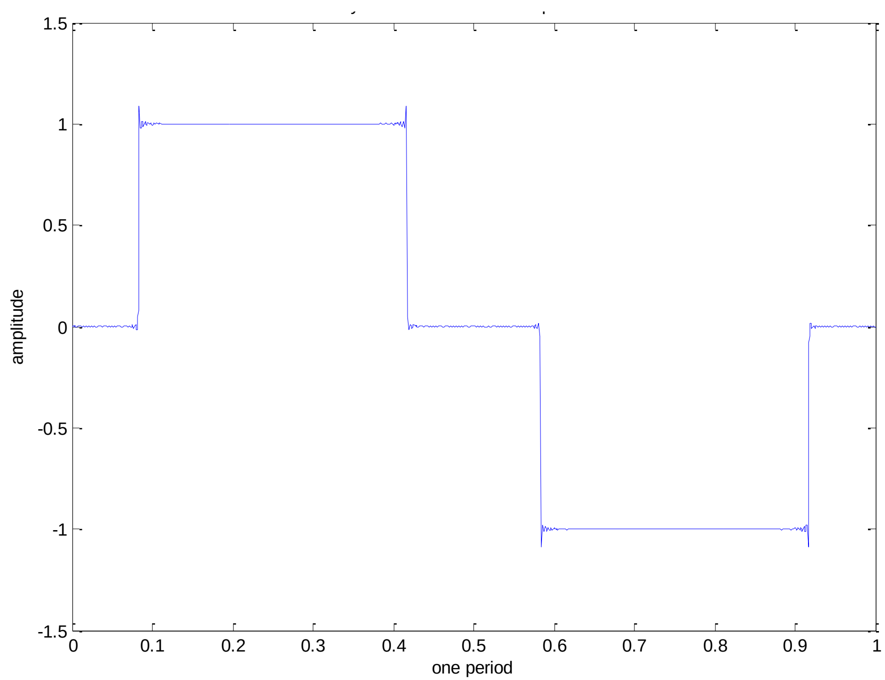
The current on the primary leg of the transformer, due to the YY winding is

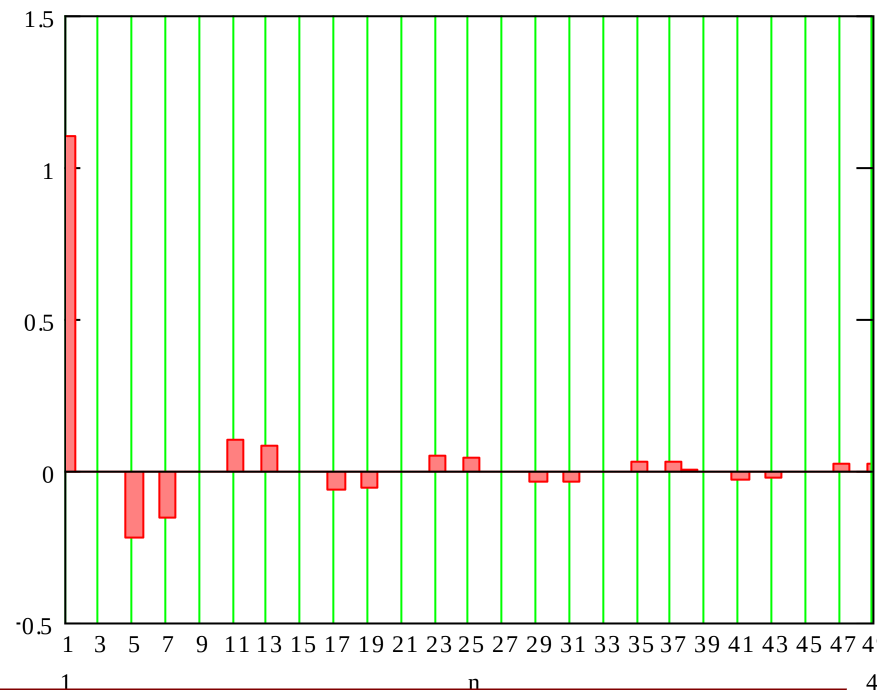
$$I_{ANYp}(t) = N_{YY} \frac{4I_L}{n\pi} \sum_{n=1}^{\infty} \sin\frac{n\pi}{2} \sin\frac{n\pi}{3} \sin\frac{2\pi n t}{T}$$

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

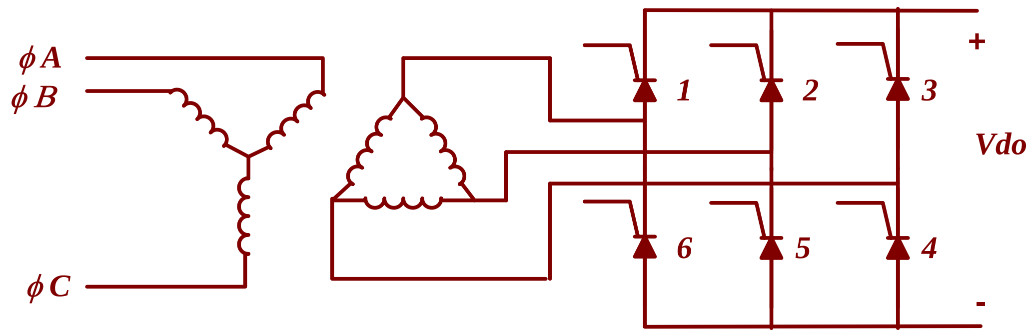
Transformer Primer - Wye-Wye Primary Current







Harmonic	1	3	5	7	9	11	13	15	17	19
Frequency	60	180	300	420	540	660	780	900	1020	1140
Amplitude	1.103	0	-0.221	-0.158	0	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 $N_{Y\Delta}$

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

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

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

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

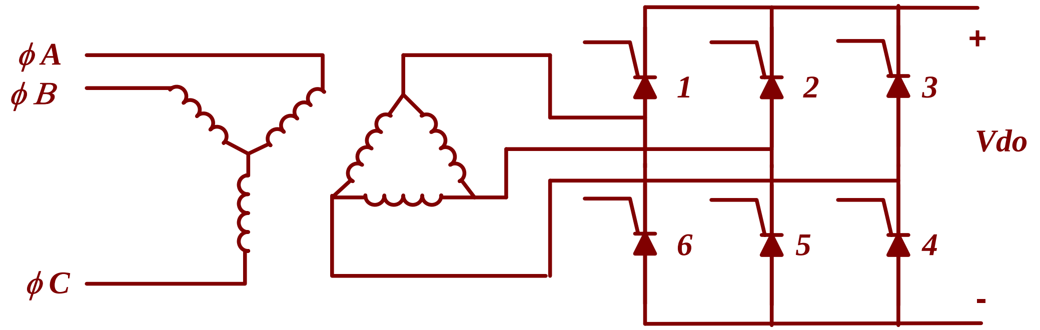
$$I_{BC\Delta s} = (V_{LNp}/N_{Y\Delta}) \sin(\omega t - 2\pi/3 + \phi_Z)$$

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

For equal secondary voltages

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

Transformer Primer - 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

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

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

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

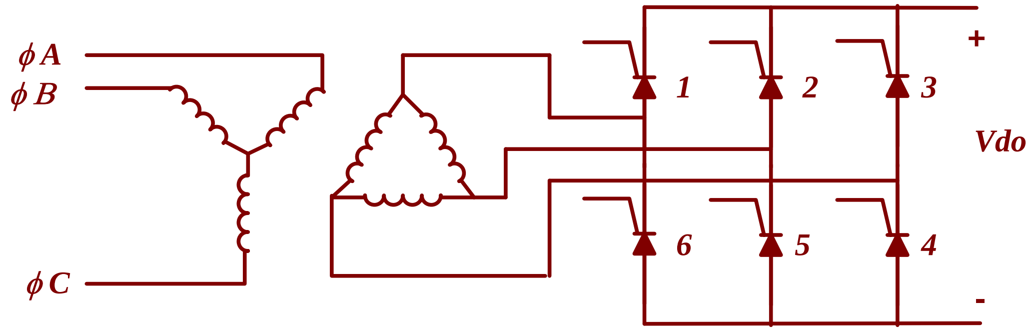
$$= \frac{2I_L}{3n\pi}\left[\left(\cos 0 + \cos\frac{\pi n}{3}\right) - \left(\cos\frac{2\pi n}{3} + \cos\pi n\right)\right]$$

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

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

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

Transformer Primer - 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.*

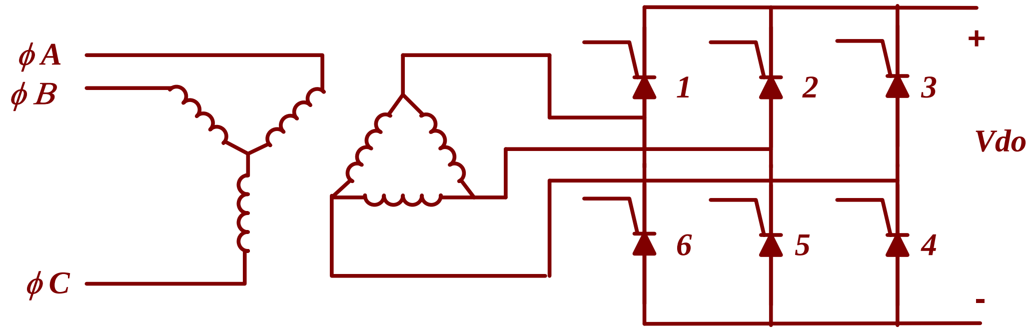
The non-vanishing terms are $n = 1,5,7,11,\cdots$, *for which the magnitude is* $\sqrt{3}/2$.

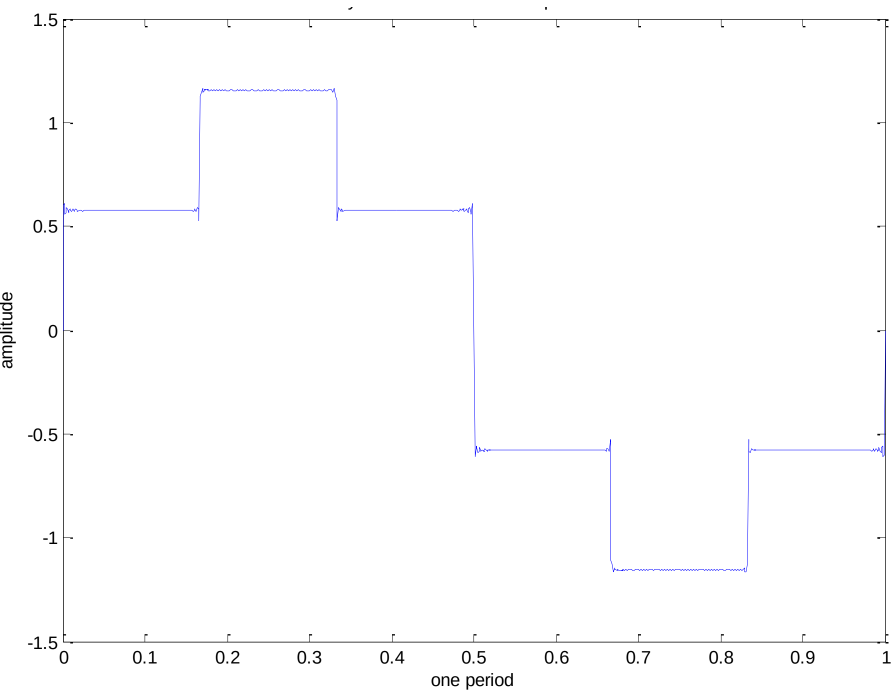
Referred back to the primary, the current is

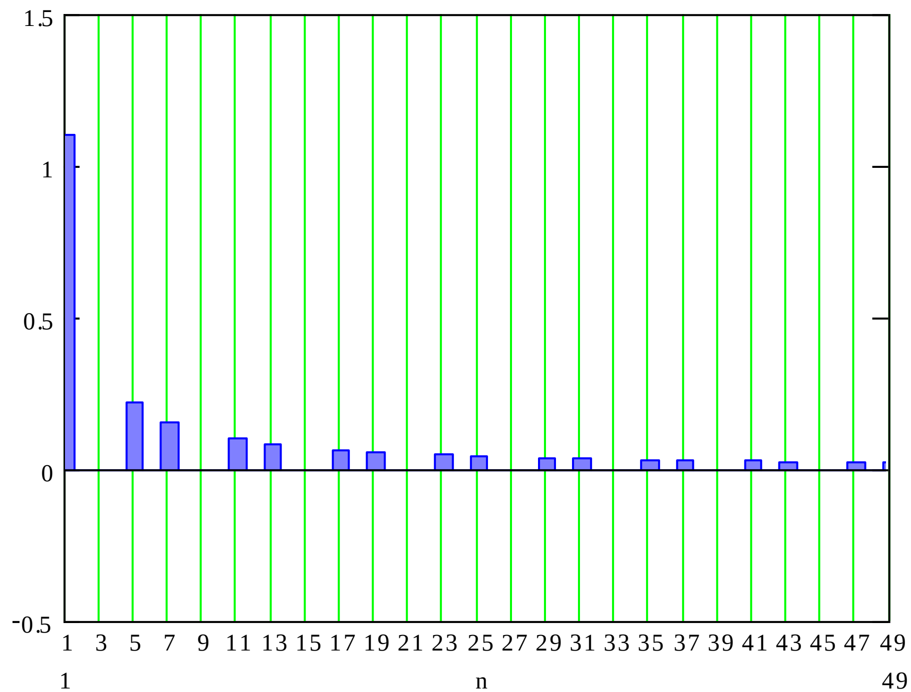
$$I_{A\Delta p}(t) = N_{Y\Delta}\frac{8I_L}{3n\pi}\sum_{n=1}^{\infty} cos\frac{n\pi}{6}\,sin\frac{n\pi}{2}\,sin\frac{n\pi}{3}\,sin\frac{2\pi nt}{T}$$

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

Transformer Primer - Primary Current in the Wye-Delta

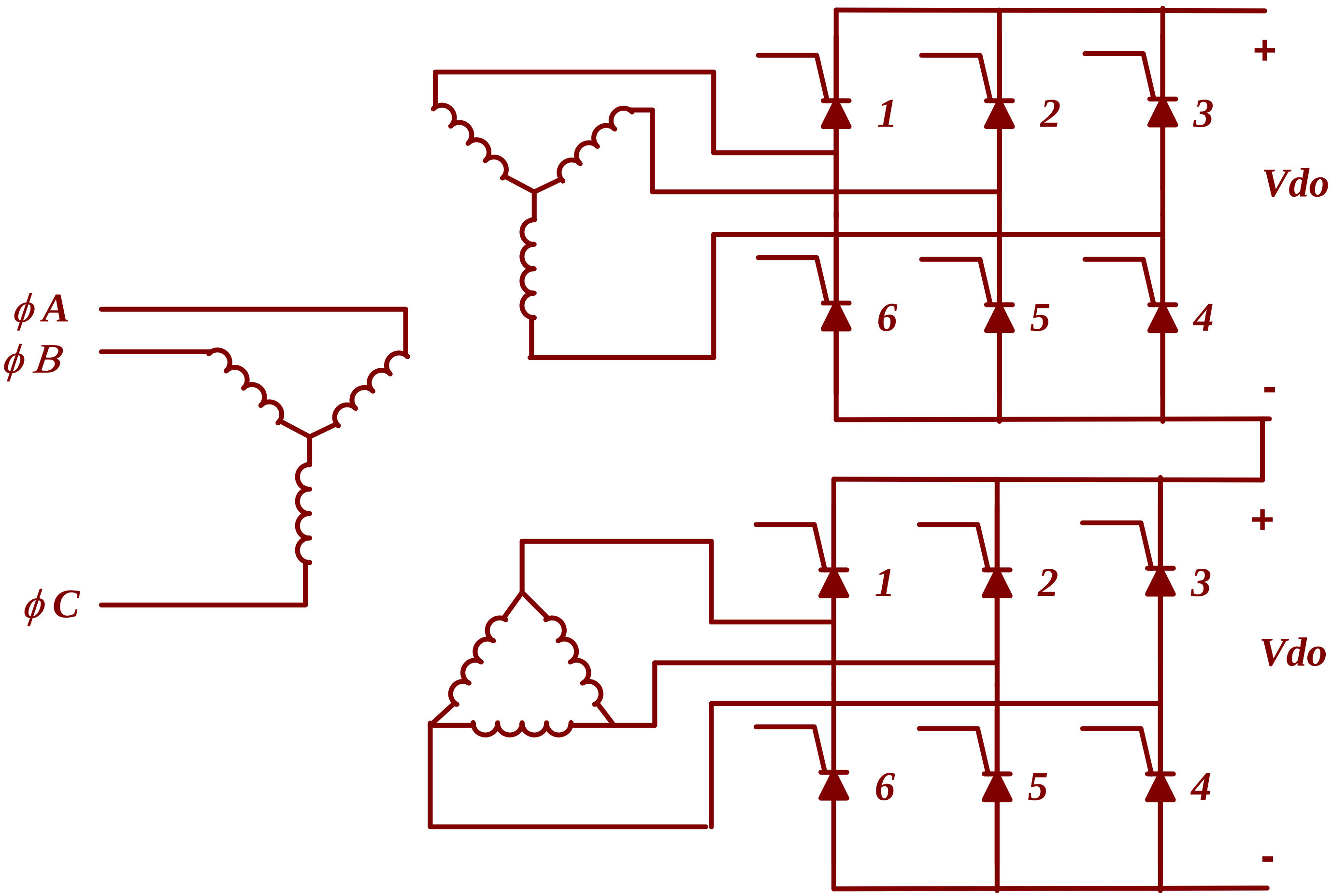






Harmonic	*1*	*3*	*5*	*7*	*9*	*11*	*13*	*15*	*17*	*19*
Frequency	*60*	*180*	*300*	*420*	*540*	*660*	*780*	*900*	*1020*	*1140*
Amplitude	*1.103*	*0*	*0.221*	*0.158*	*0*	*0.100*	*0.085*	*0*	*0.065*	*0.058*

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



Transformer Primer - Total Primary Current in Wye-Wye-Delta

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

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

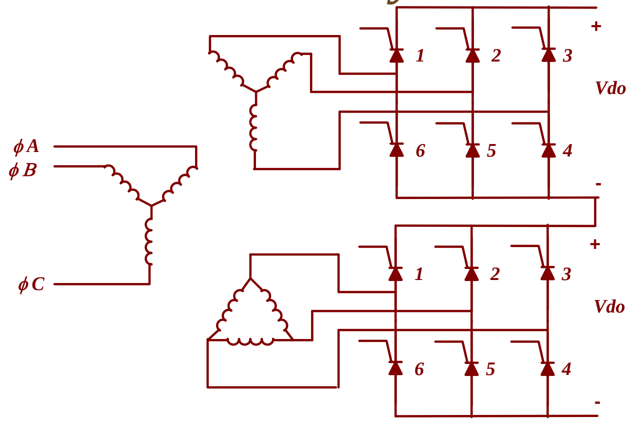
The only non-vanishing terms in both of these series are $n = 1,5,7,11$

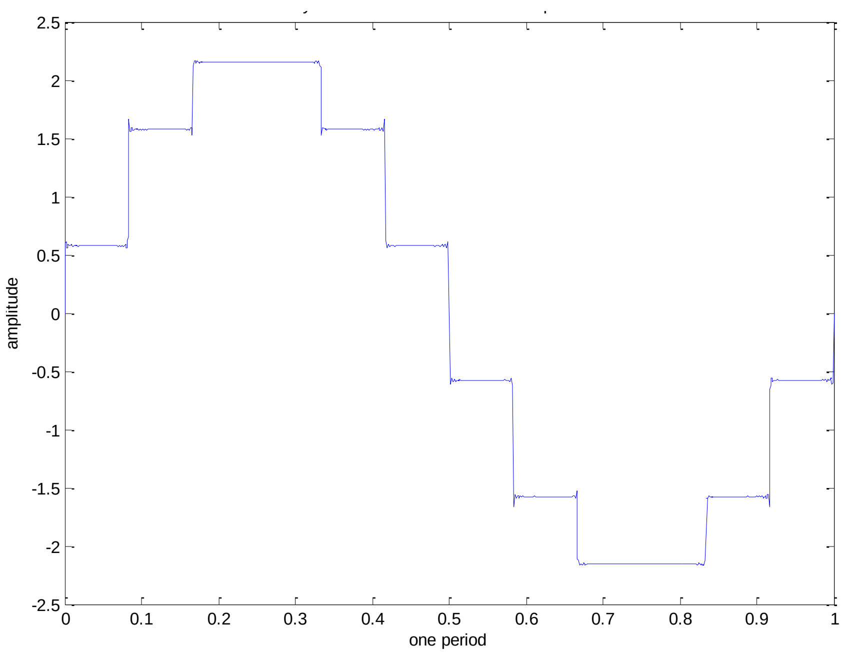
and all other values of n which have the same phase

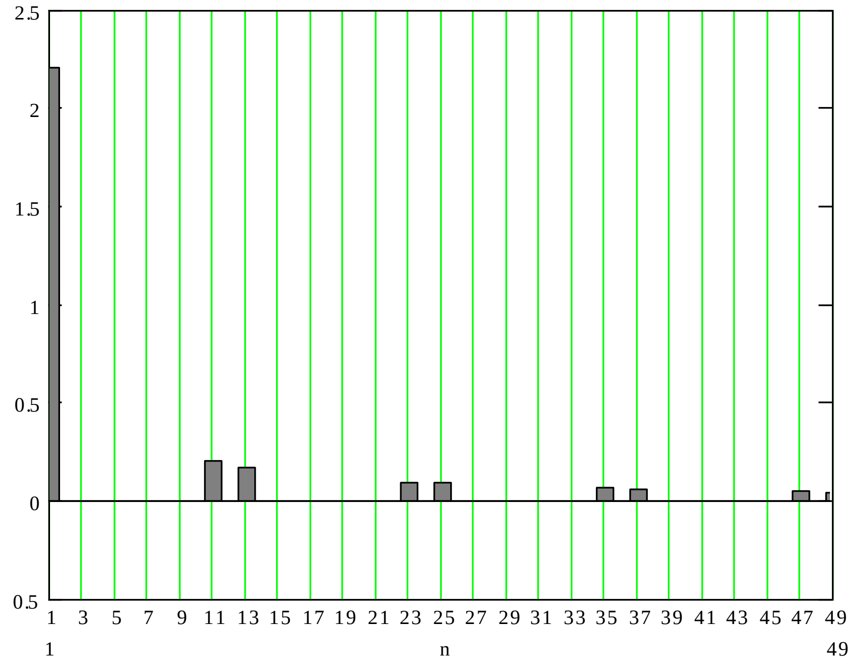
The values of $\cos\frac{n\pi}{6}$ *for these n are* $\frac{\sqrt{3}}{2}, -\frac{\sqrt{3}}{2}, -\frac{\sqrt{3}}{2}, \frac{\sqrt{3}}{2}$

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* $N_{YY}\frac{4I_L}{n\pi}$

Transformer Primer - Total Primary Current in Wye-Wye-Delta

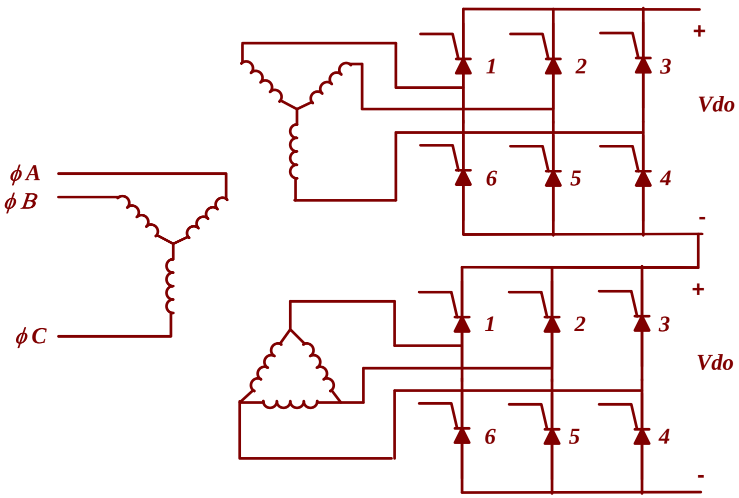


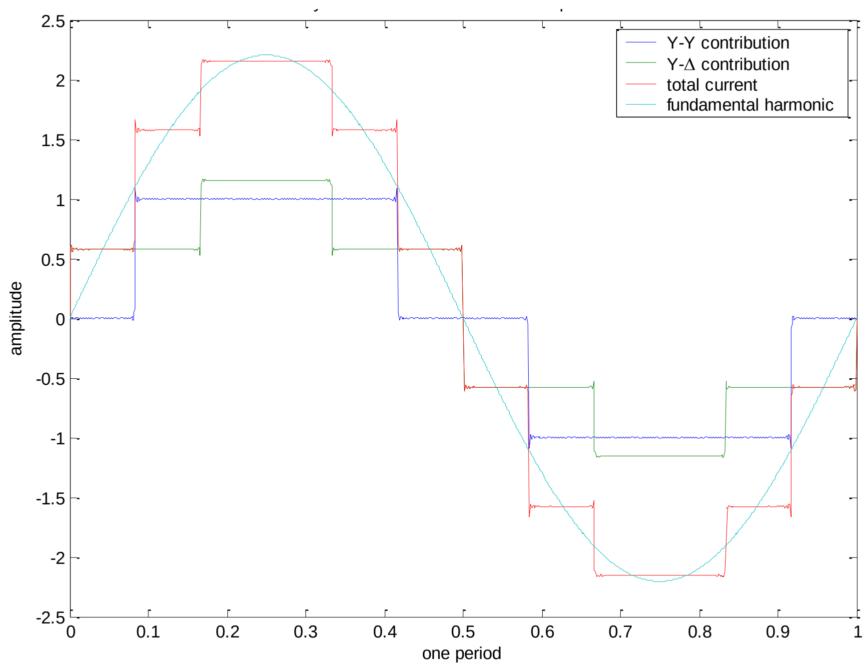




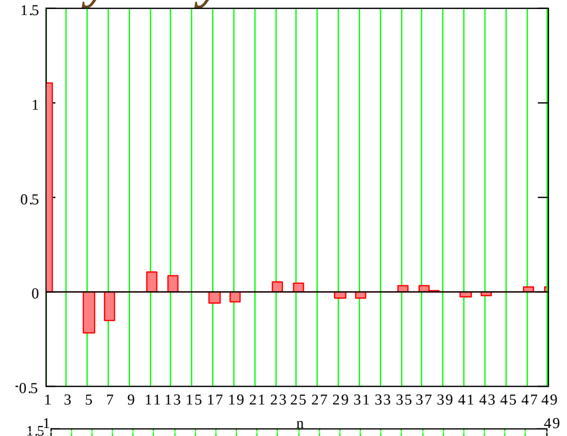
Harmonic	1	3	5	7	9	11	13	15	17	19
Frequency	60	180	300	420	540	660	780	900	1020	1140
Amplitude	2.205	0	0	0	0	0.200	0.085	0.170	0	0

Transformer Primer - Total Primary Current in Wye-Wye-Delta

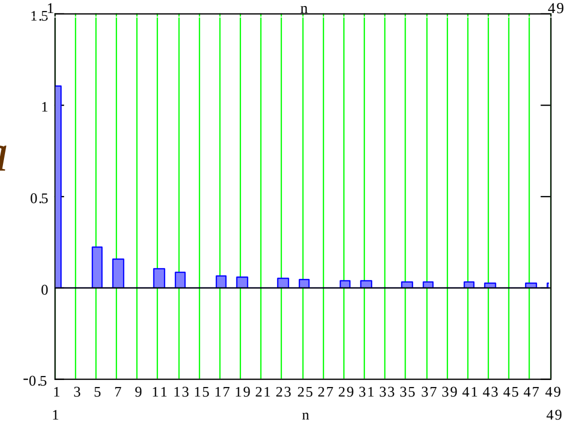




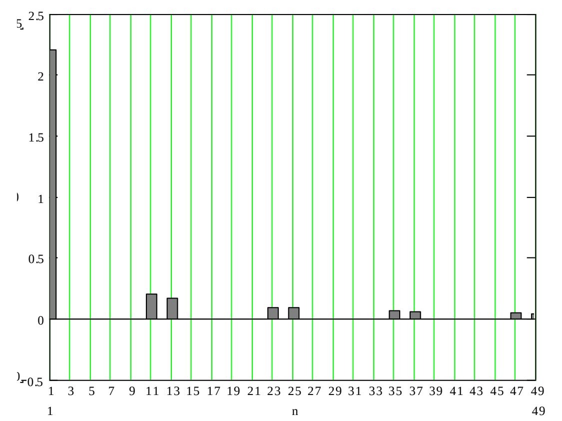
Wye-Wye



Wye-Delta



Wye-Wye-Delta



Standards for Power Rectifier Transformer

1) *Pool-Cathode Mercury-Arc Rectifier Transformer ASA C57.18-1964*
2) *Practice for Semiconductor Power Rectifiers ANSI C34.2-1973*
3) *IEEE standards for Transformer and Inductors for Electronic power conversion Equipment ANSI/IEEE std 388-1992*

Insulation Class Recommended for Rectifier Transformer.

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.*

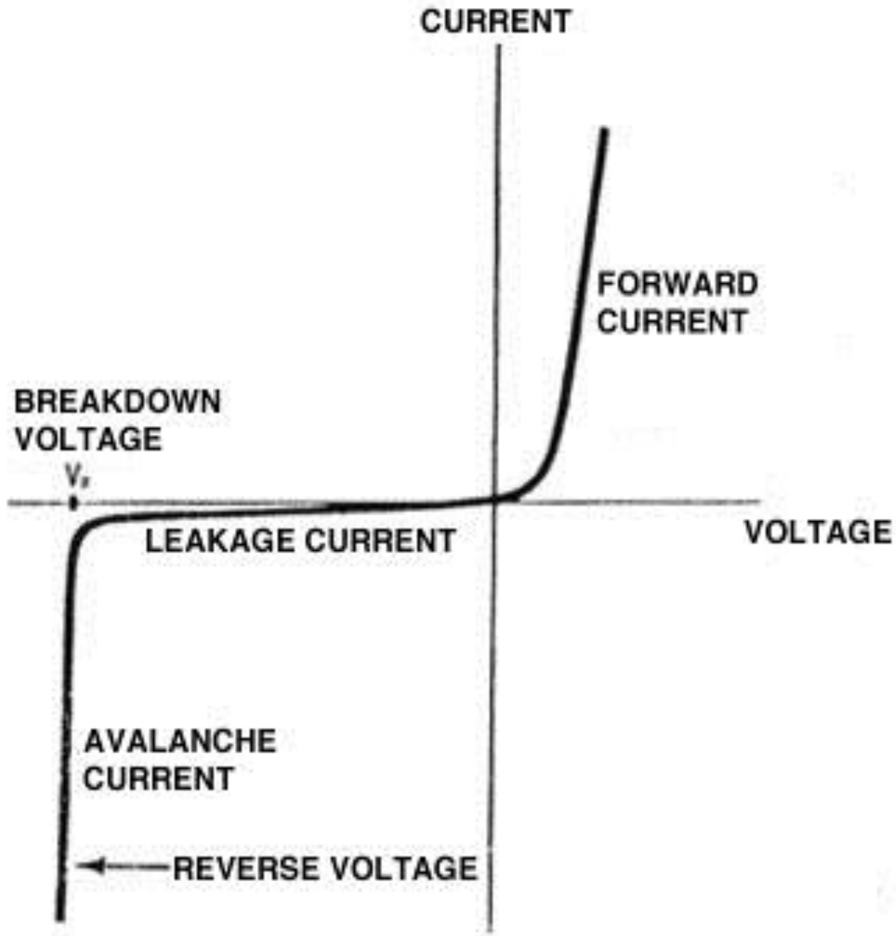
*2) Presence of DC and/or **second harmonic** currents/ voltage can saturate the core resulting in more harmonics and excessive core hysteresis loss.*

*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.*

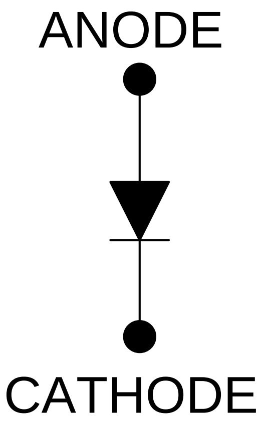
Rectifiers - Diode Characteristics



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 conduct in forward direction up to a threshold voltage, 0.3V for germanium and 0.7V for silicon

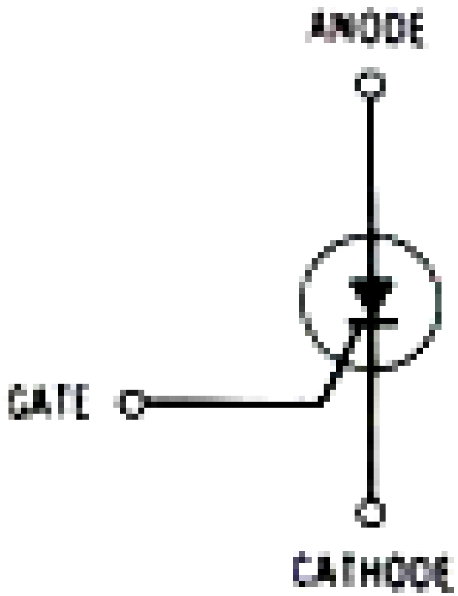
Rectifiers - Diode Considerations



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, $I_{R(AV)}$*
- *Reverse recovery time, t_{rr}*
- *Peak surge current, I_{surge}*
- *Cooling (air, water, oil, other)*
- *Package style*

Rectifiers - Thyristors - Silicon Controlled Rectifier (SCR)

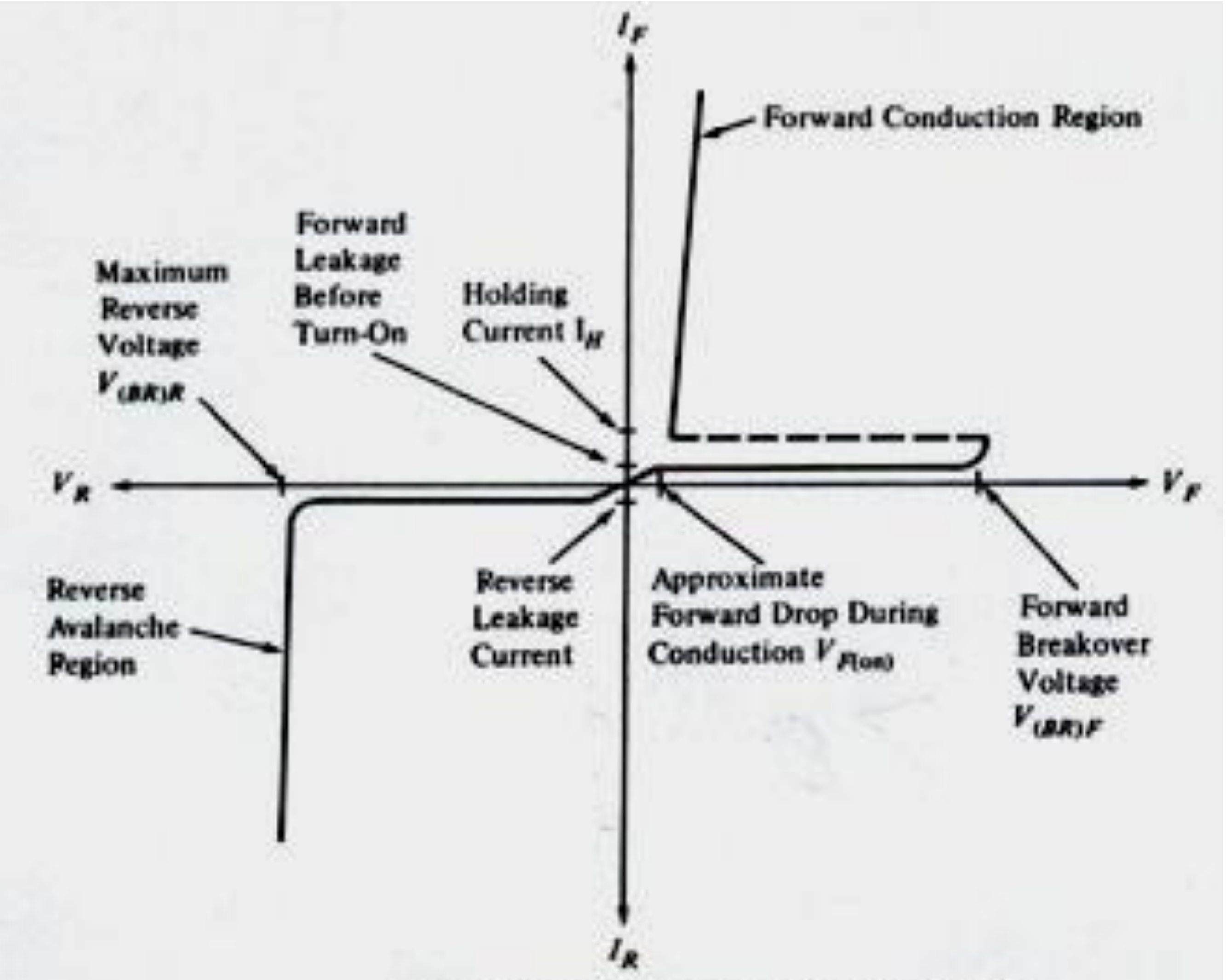


Schematic representation

SCR properties

- *It is simply a conventional rectifier controlled by a gate signal*
- *It is controlled from the off to on states by a signal applied to the gate*
- *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

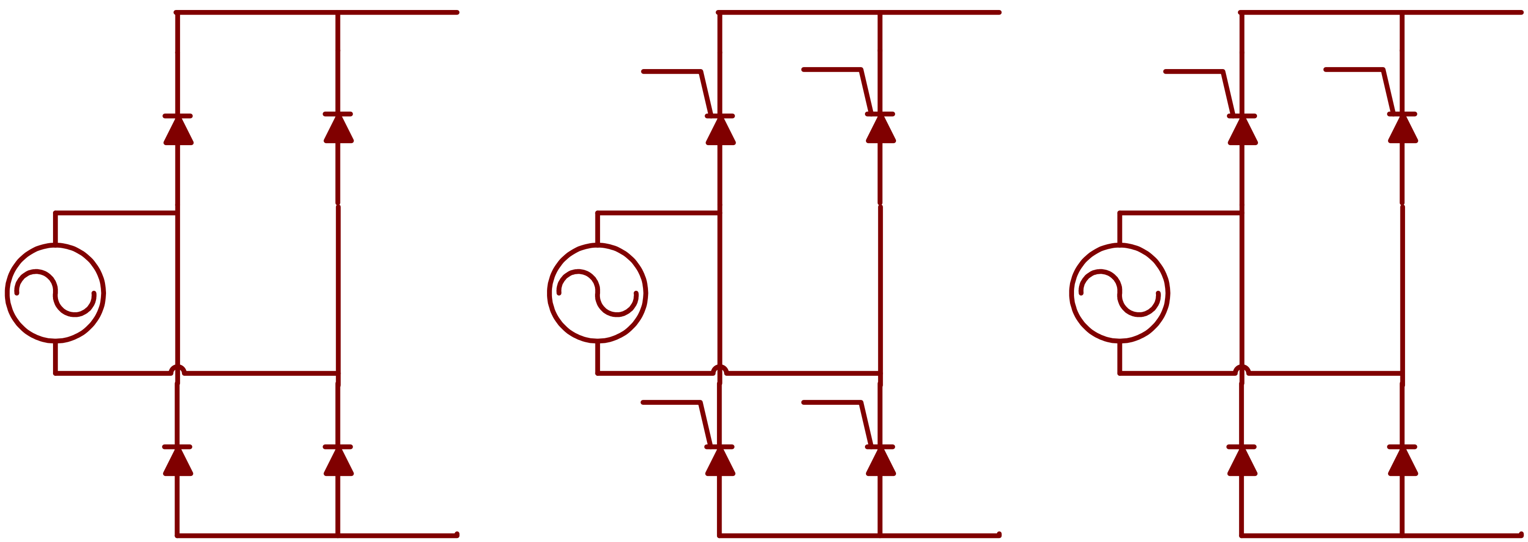
- *Maximum forward current*
- *Reverse breakdown voltage*
- *Gate trigger voltage and current*
- *Minimum holding current, I_h*
- *Power dissipation*
- *Maximum reverse dv/dt*
- *Peak forward voltage*

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

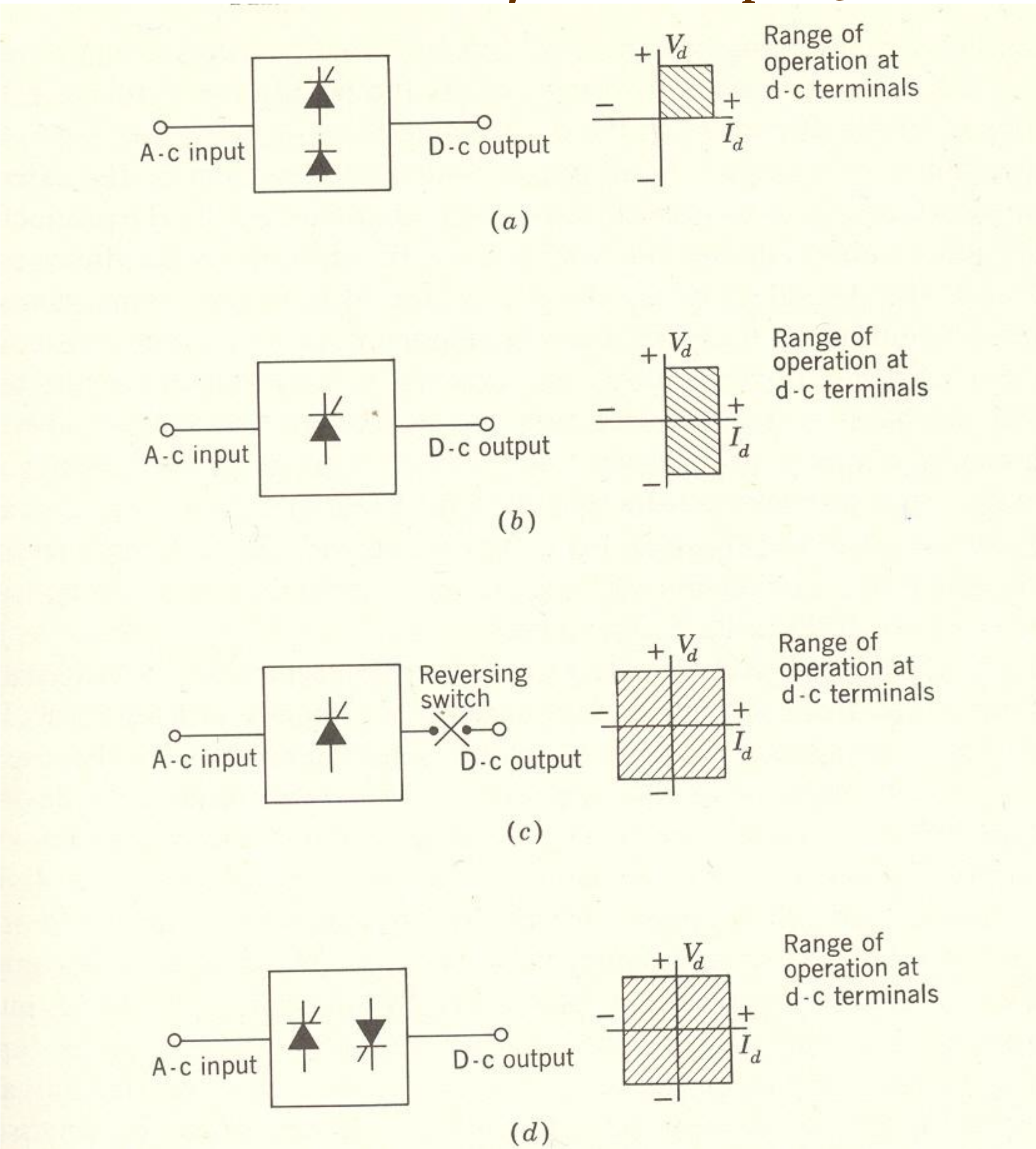
  Uncontrolled rectifiers (diodes)

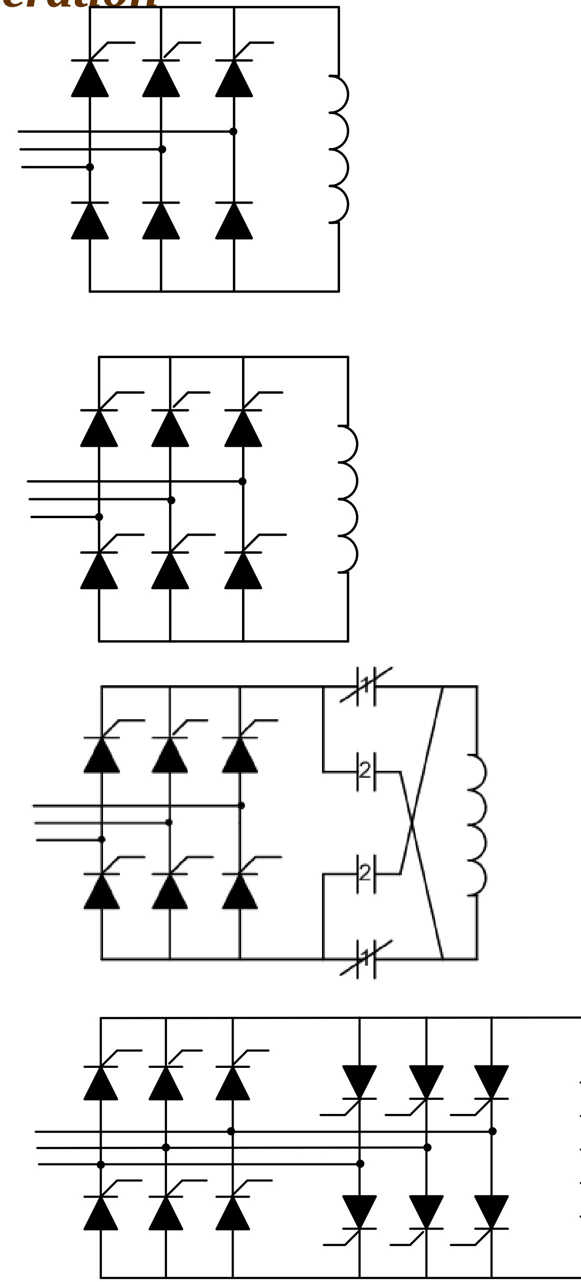
  Fully Controlled rectifiers (all SCRs)

  Semi-controlled rectifiers (SCRs and diodes)

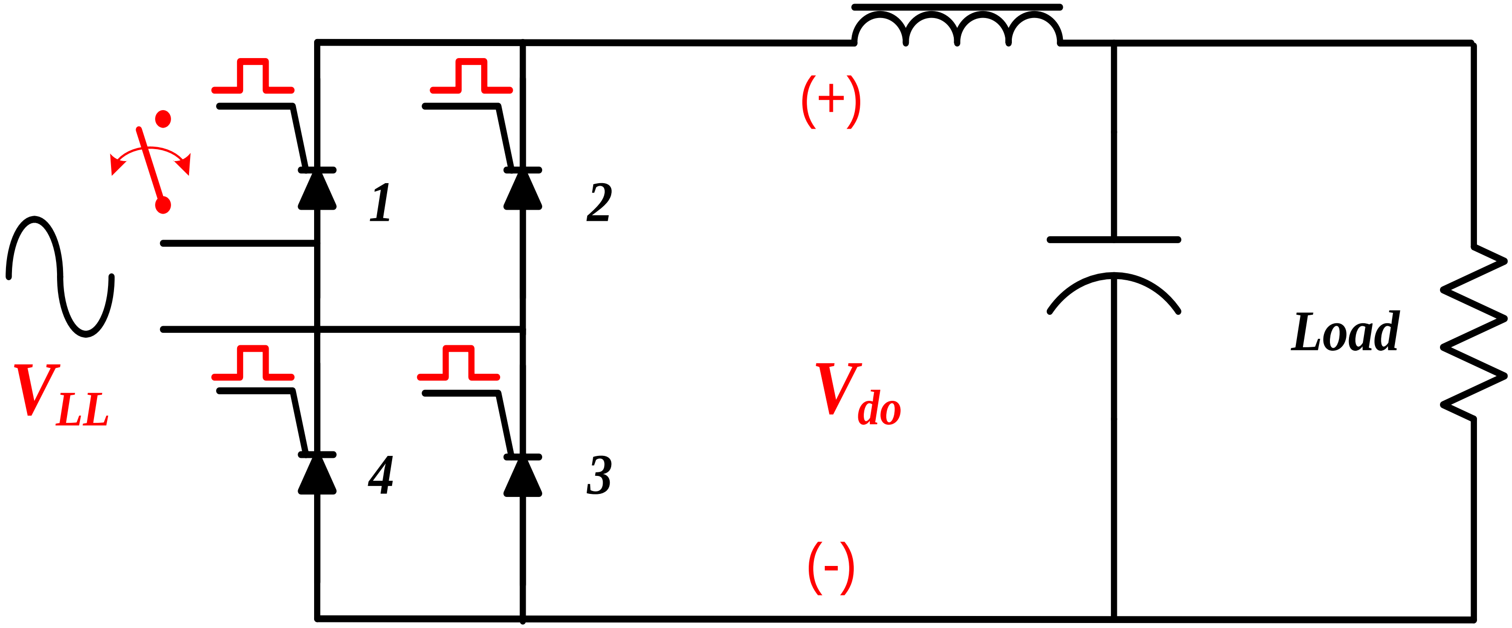


Rectifiers - Multiple Quadrant Operation

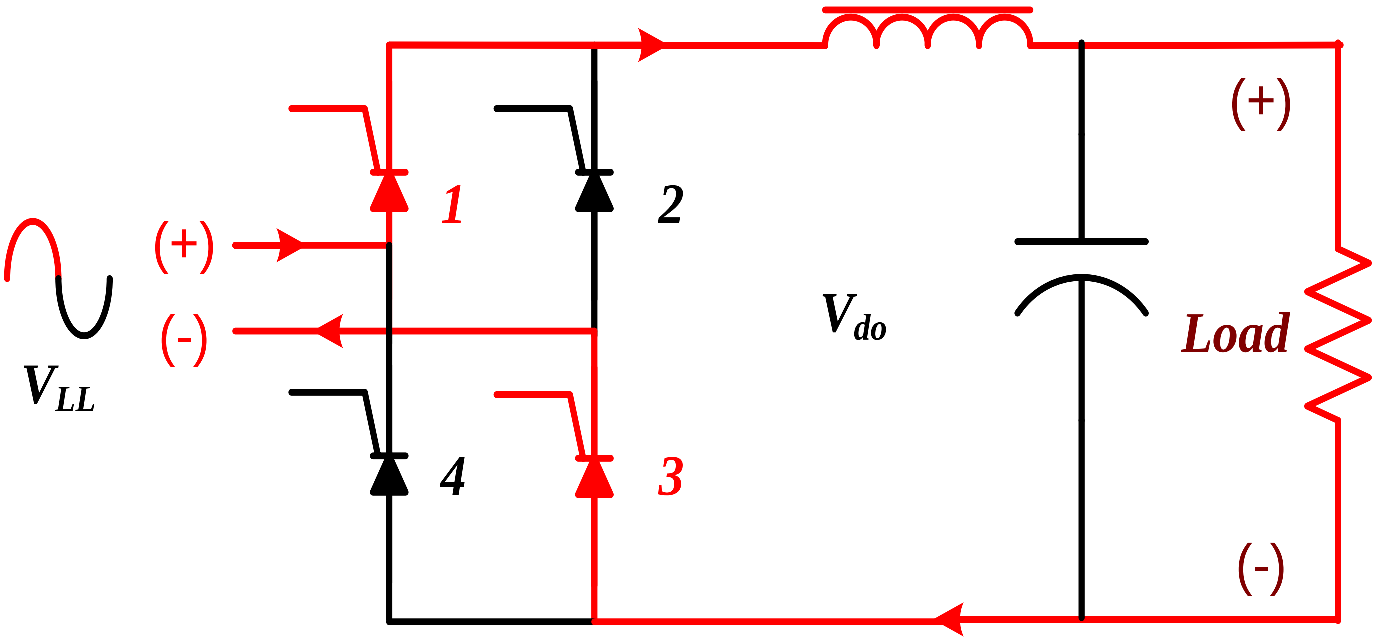




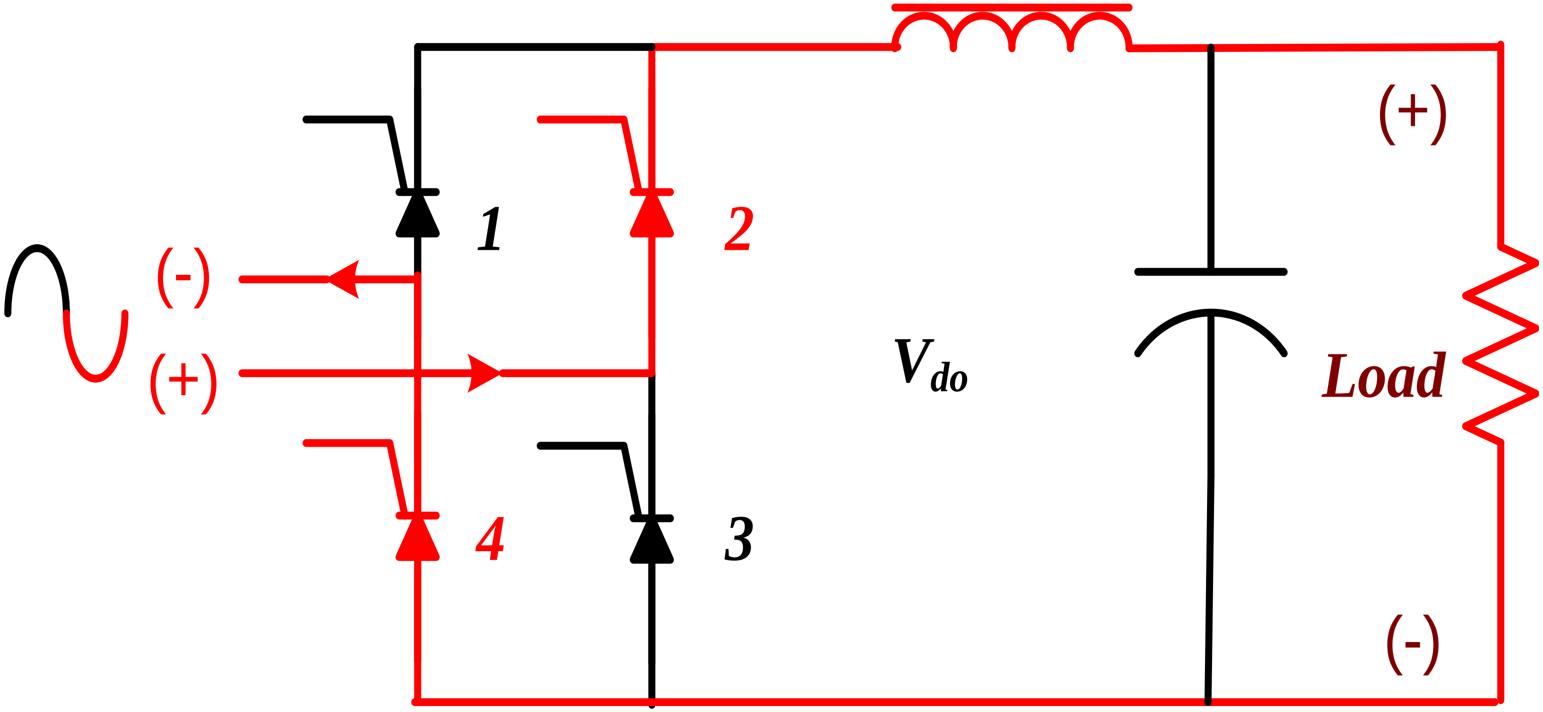
Rectifiers - 1 ϕ Full Wave (q = 2 Pulse)



- $q \equiv$ *the number of possible rectifier states*
- *SCR s are electronic switches*

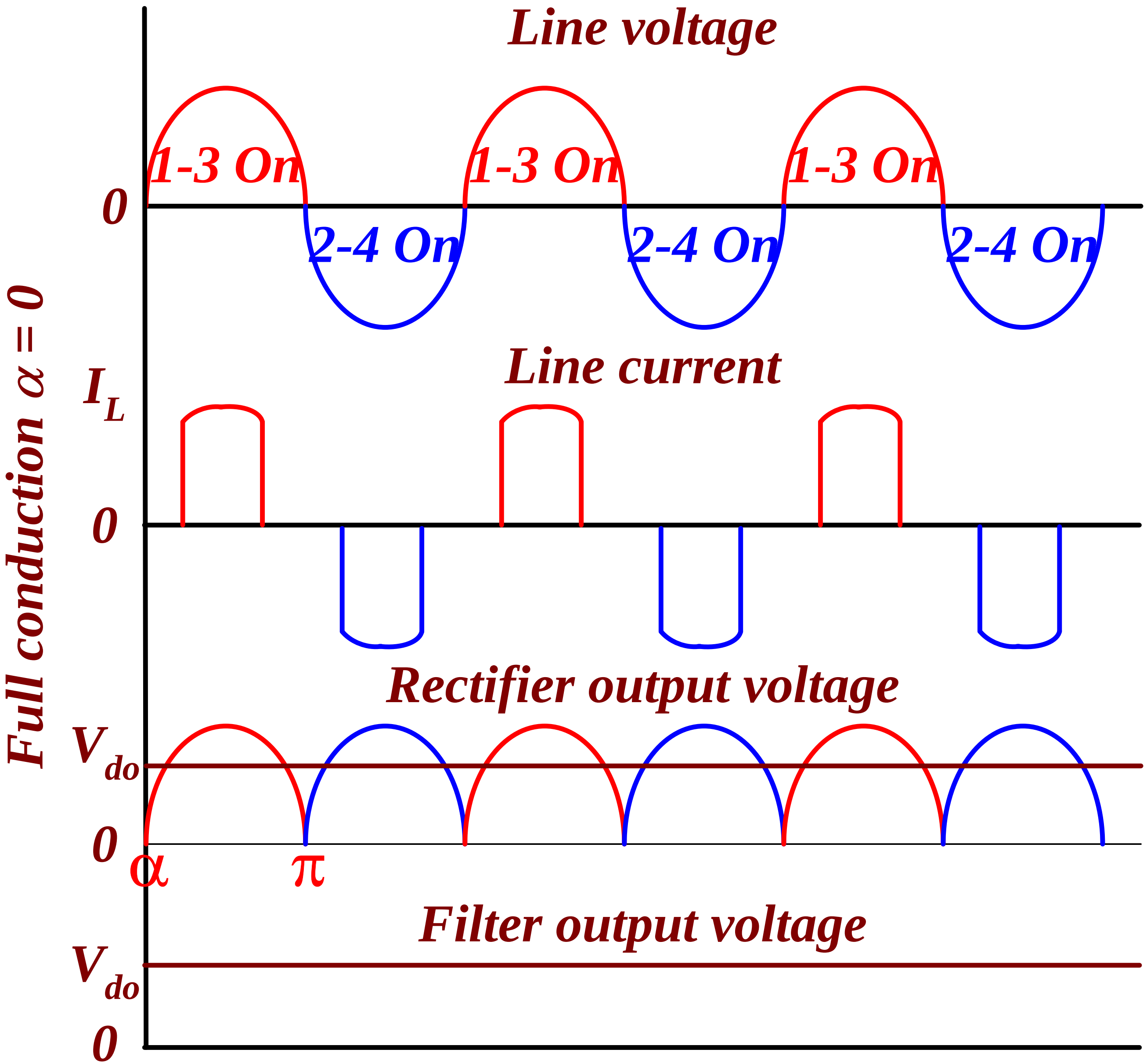


State 1 : SCR s 1 – 3 On

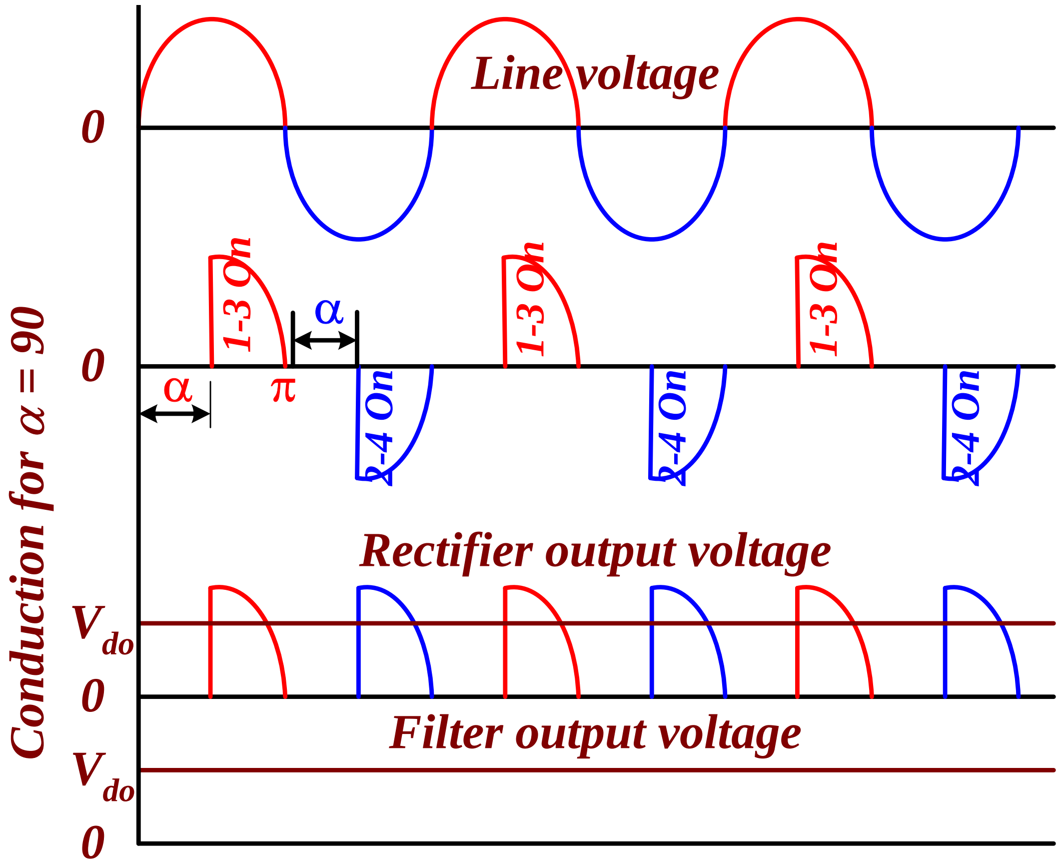


State 2 : SCR s 2 – 4 On

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



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



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

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

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

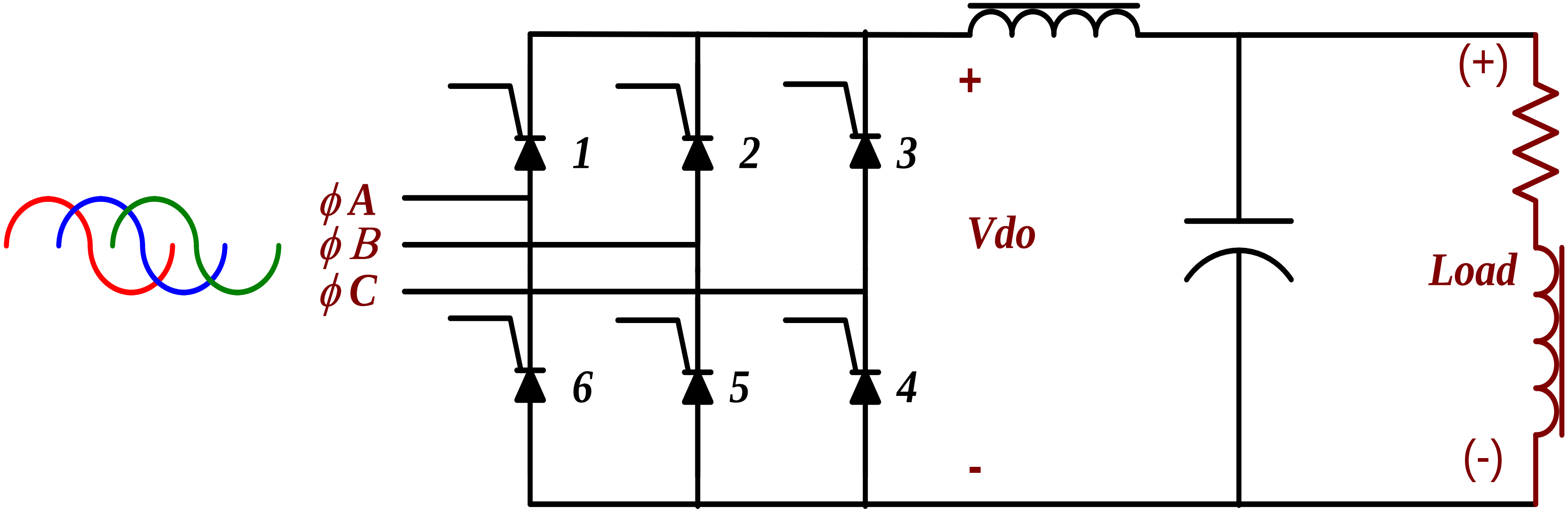
- 2 pulse rectifier – low input power factor, high output ripple
- Ripple frequency is 120 Hz (if input is 60 Hz)
- Large filter needed
- Limited in use to power supplies < 2.5 kW

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

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

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

Rectifiers - 3 ϕ, q = 6 Pulse

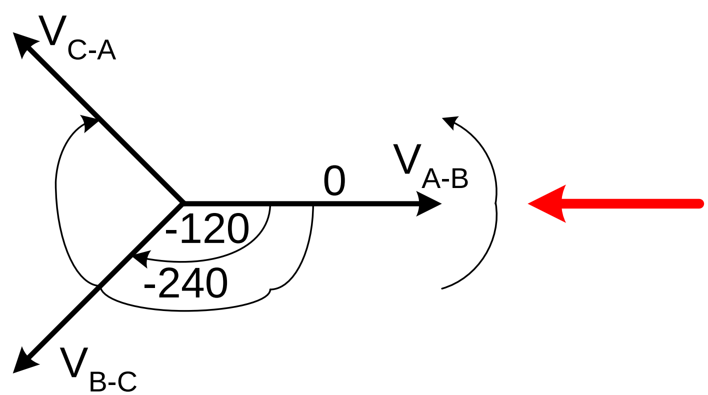


Assuming the American standard phase rotation of

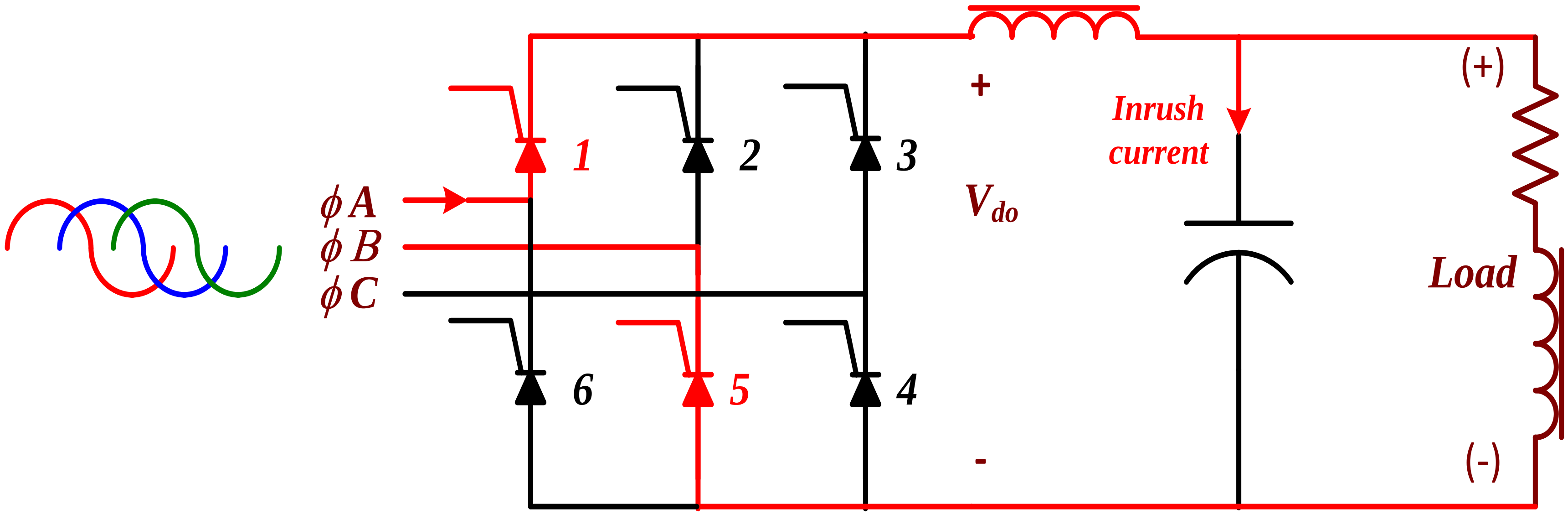
$V_{A-B} = |V|\,e^{j0}$ $\qquad$ $V_{B-C} = |V|\,e^{-j120}$ $\qquad$ $V_{C-A} = |V|\,e^{-j240}$

The thyristor firing sequence is:

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

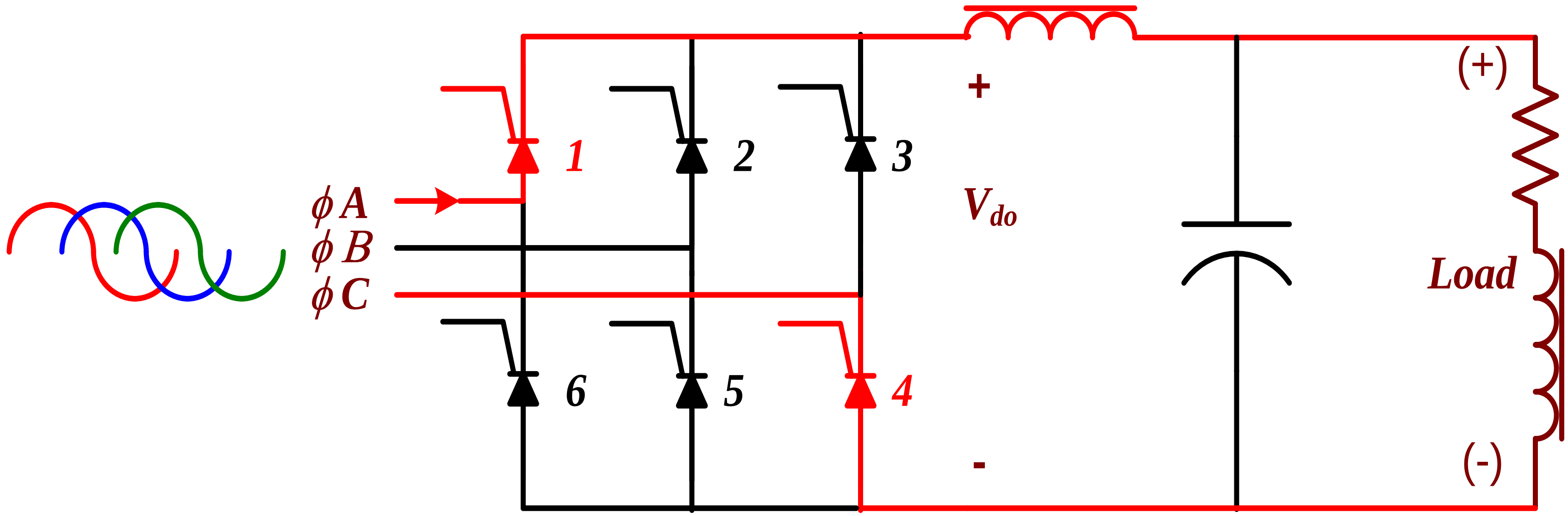


Rectifiers - 3 ϕ, $q = 6$ Pulse

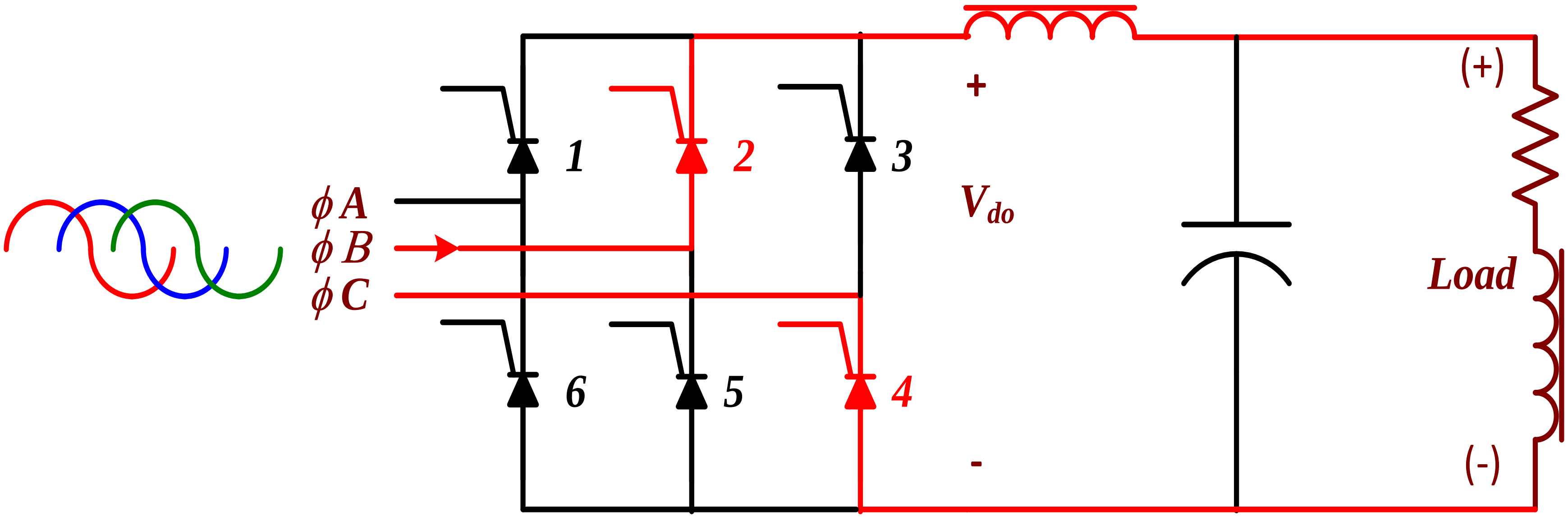


State 1: A-B (+) SCR s 1 – 5 On

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

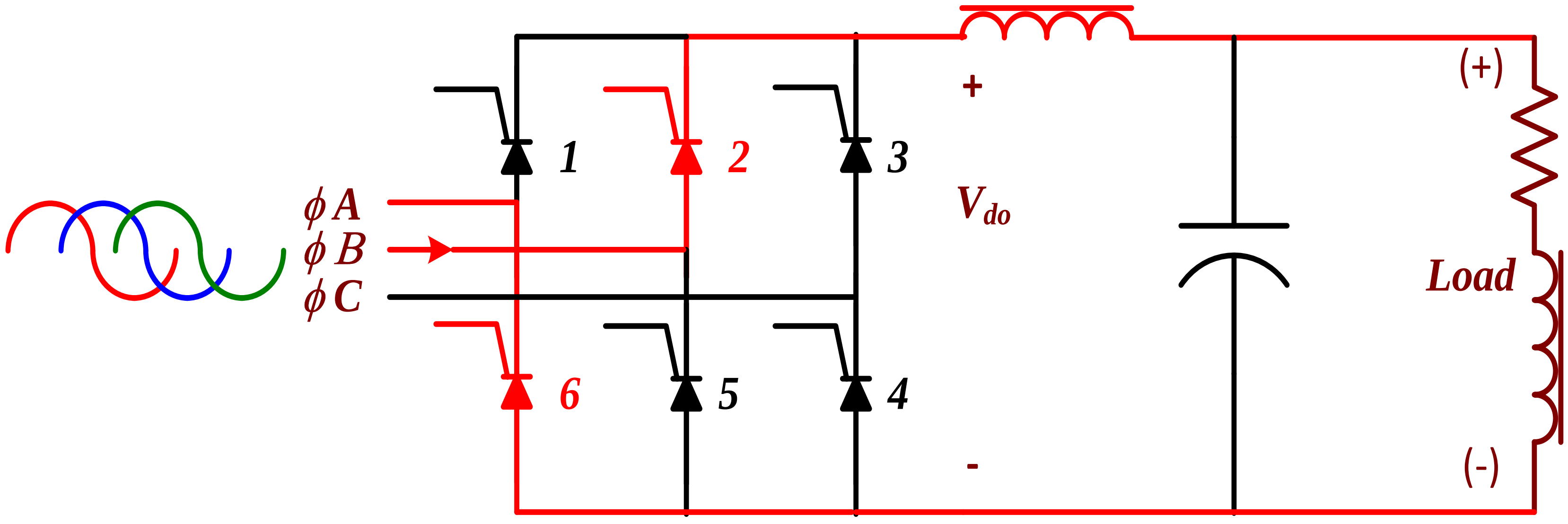


State 2 : C-A (-), 5 off, SCR s 1 – 4 On



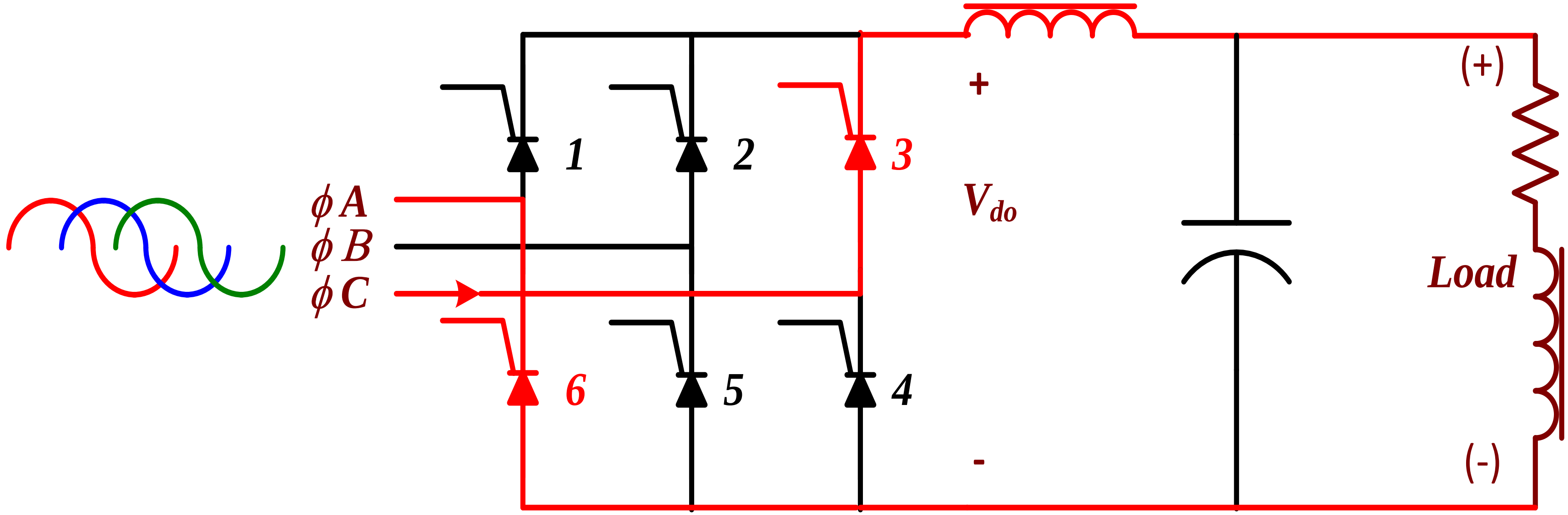
State 3 : B-C (+), 1 off, SCR s 2 – 4 On

3 ϕ, q = 6 Pulse Rectifier



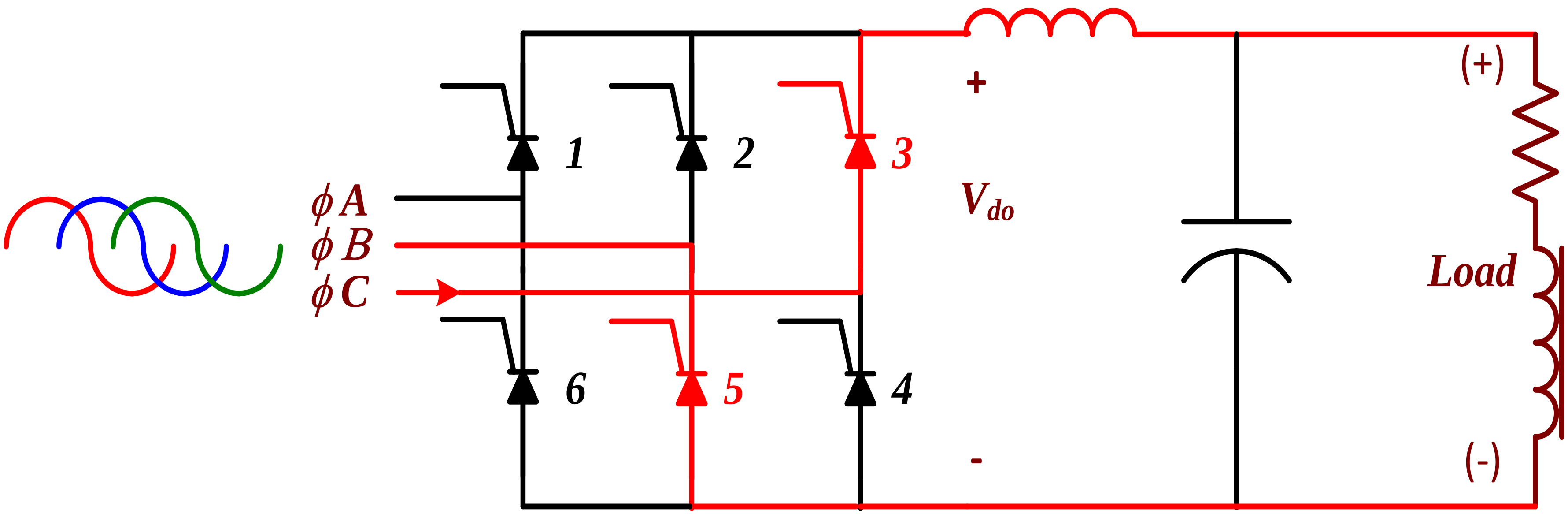
State 4 : A-B (-), 4 off, SCR s 2 – 6 On

3 ϕ, $q = 6$ Pulse Rectifier



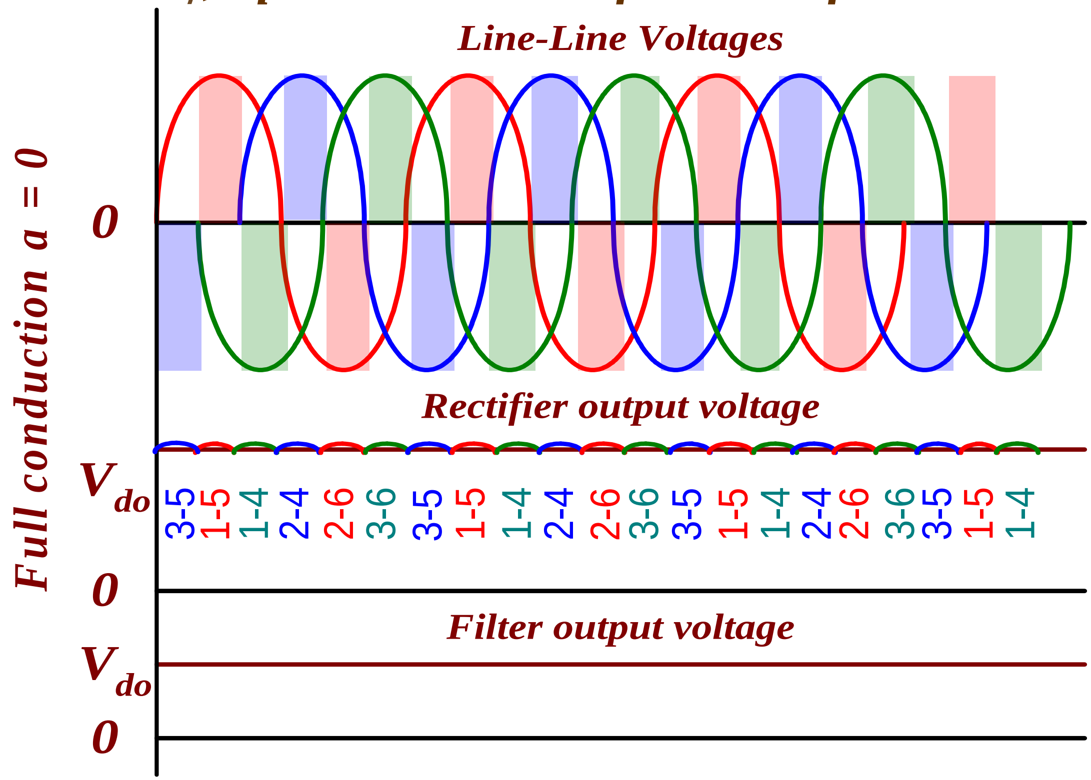
State 5 : C-A (+), 2 off, SCR s 3 – 6 On

3 ϕ, q = 6 Pulse Rectifier



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

3 ϕ, q = 6 Pulse Rectifier Waveforms



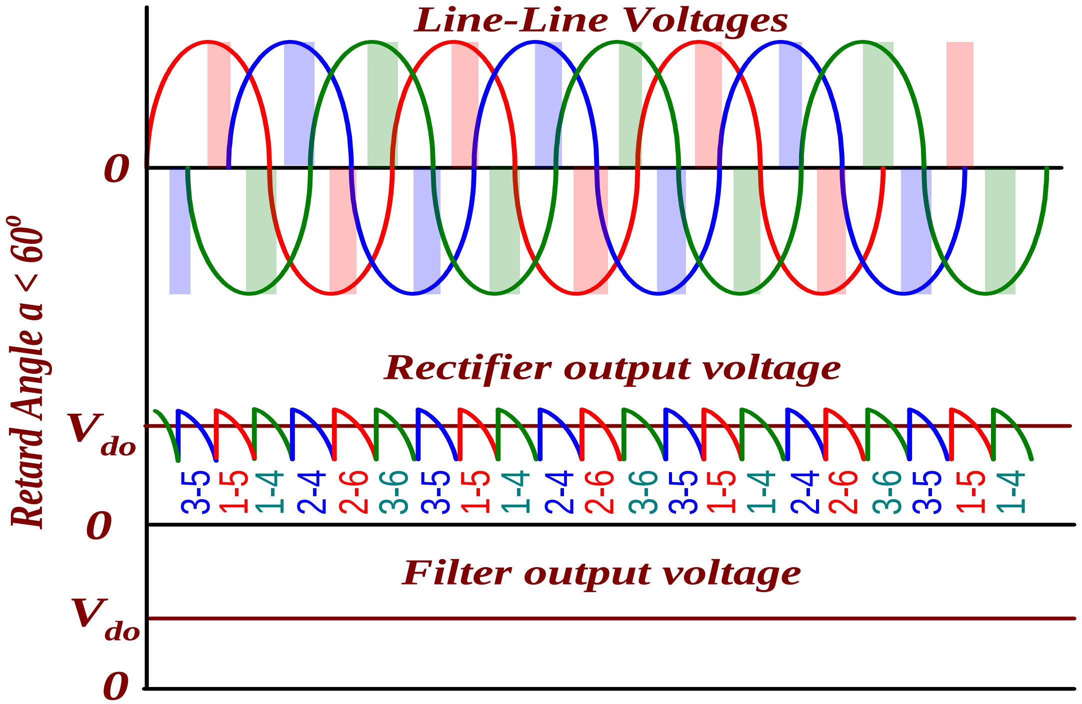
For $0 \le \alpha \le \frac{\pi}{3}$ where α is the gate trigger retard angle and conduction is continuous

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

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

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

3 ϕ, q = 6 Pulse Rectifier Waveforms



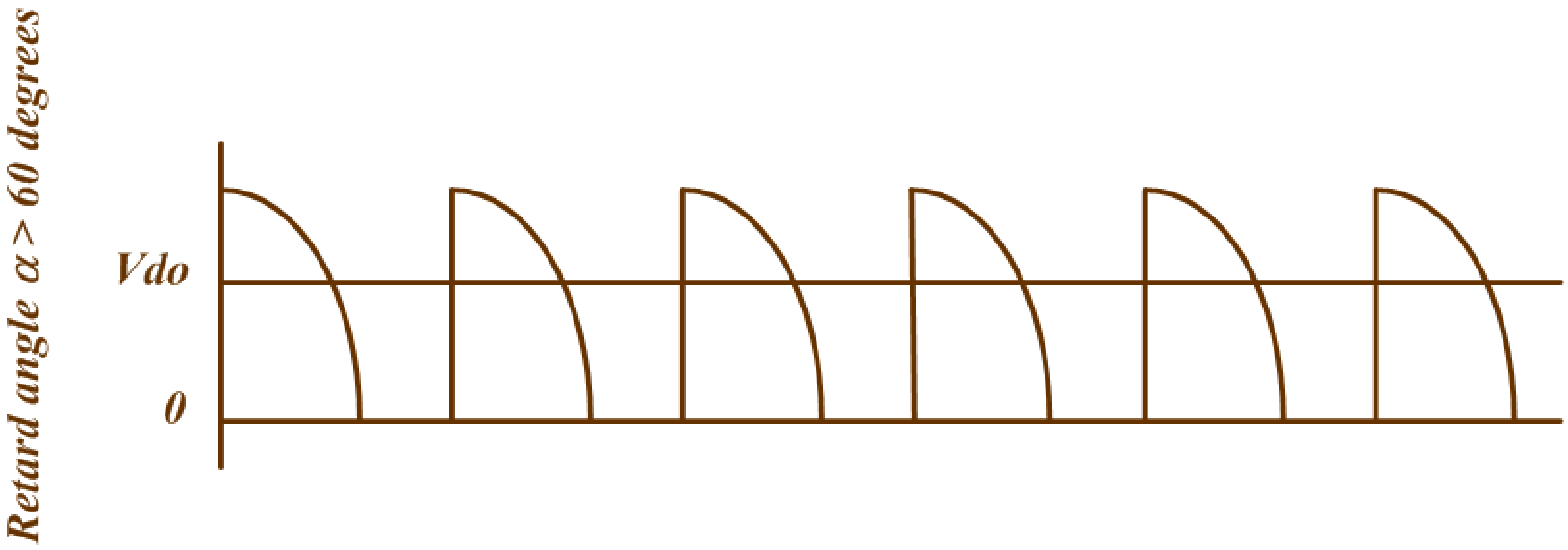
For $0 \le \alpha \le \frac{\pi}{3}$ where α is the gate trigger retard angle and conduction is continuous

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

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

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

3 ϕ, q = 6 Pulse Rectifier Waveforms



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

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

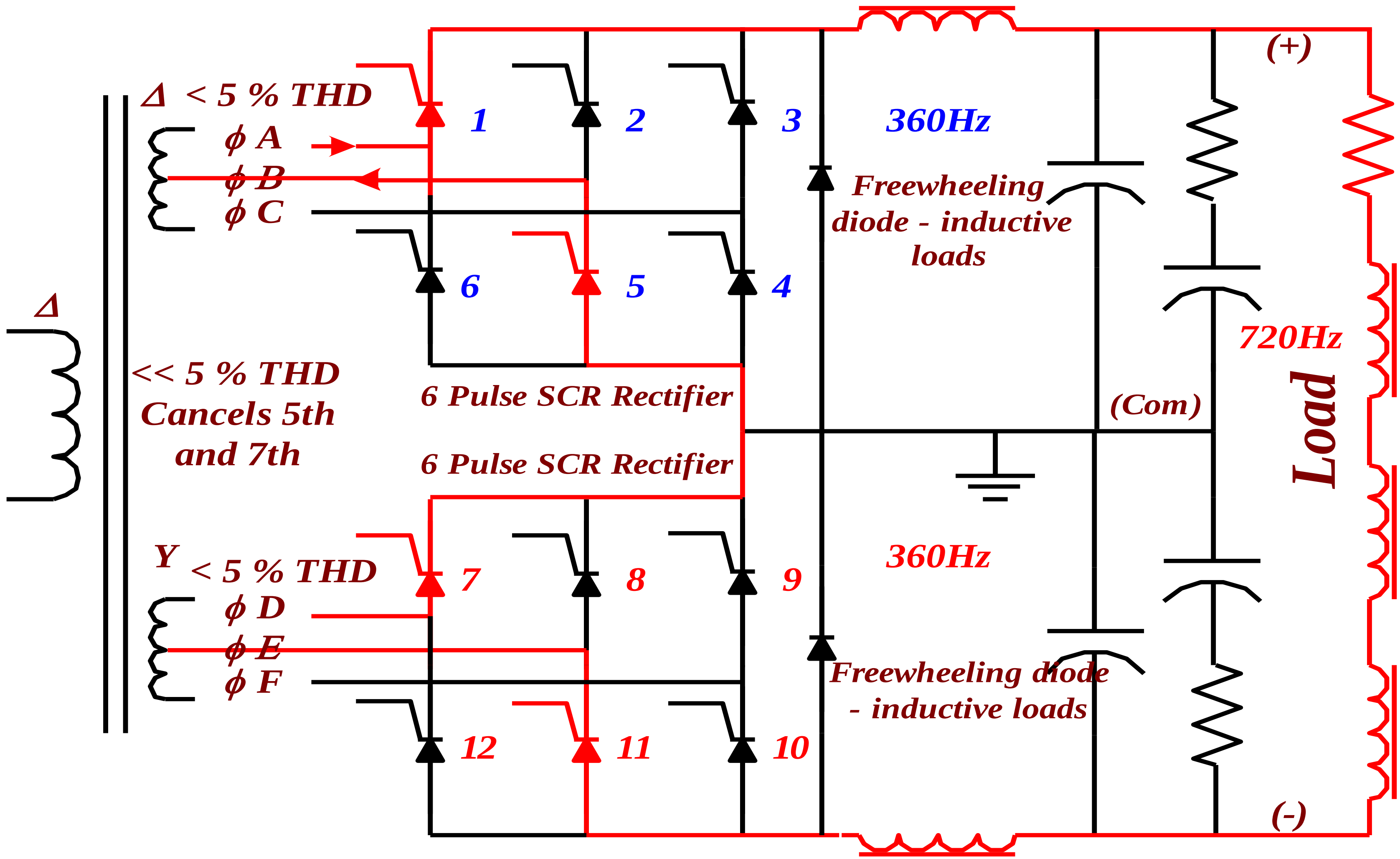
For $\frac{\pi}{3} \le \alpha \le \frac{2\pi}{3}$ where conduction can be discontinuous

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

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

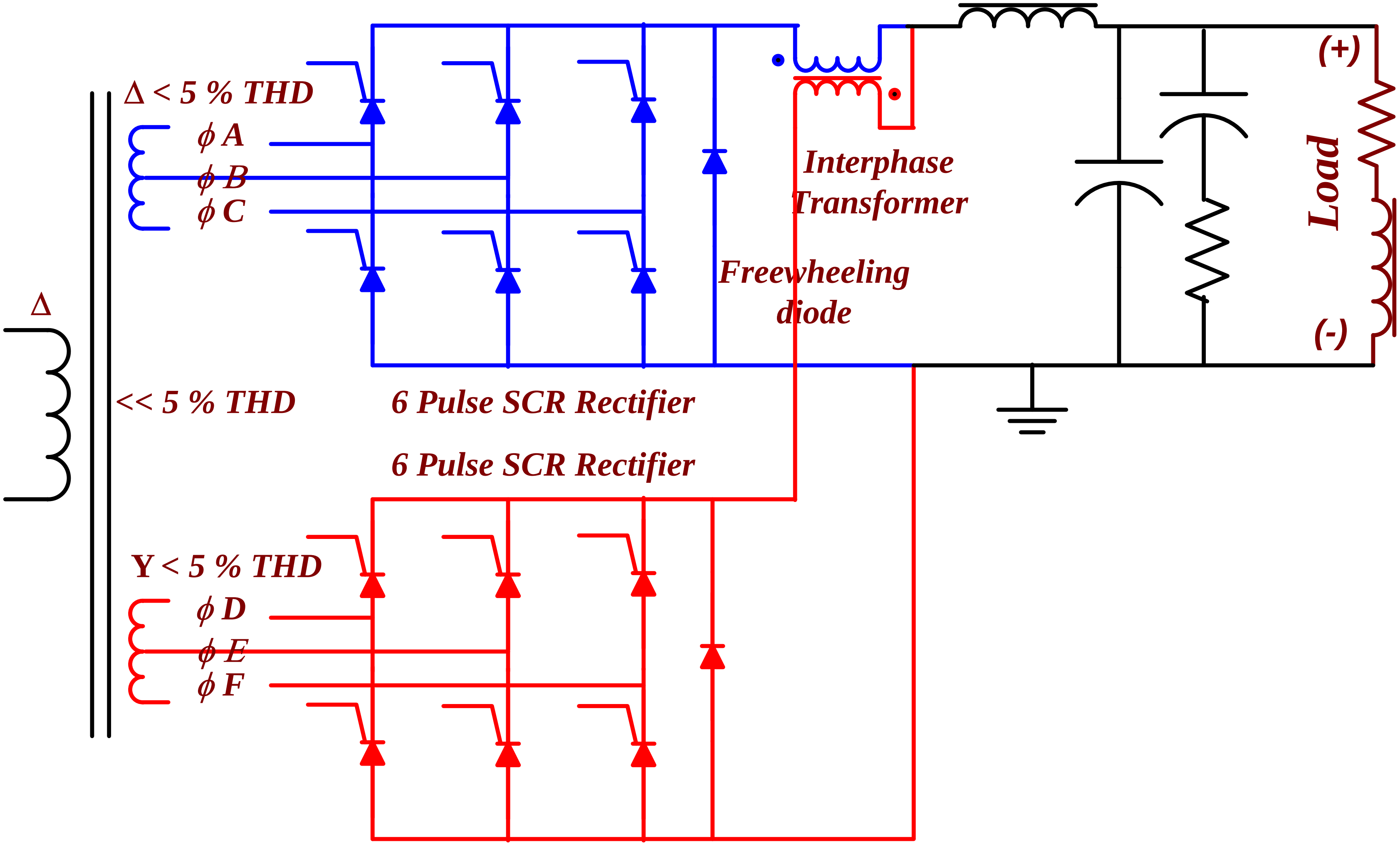
6 ϕ, q = 12 Pulse By Series Bridges



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 ϕ, 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

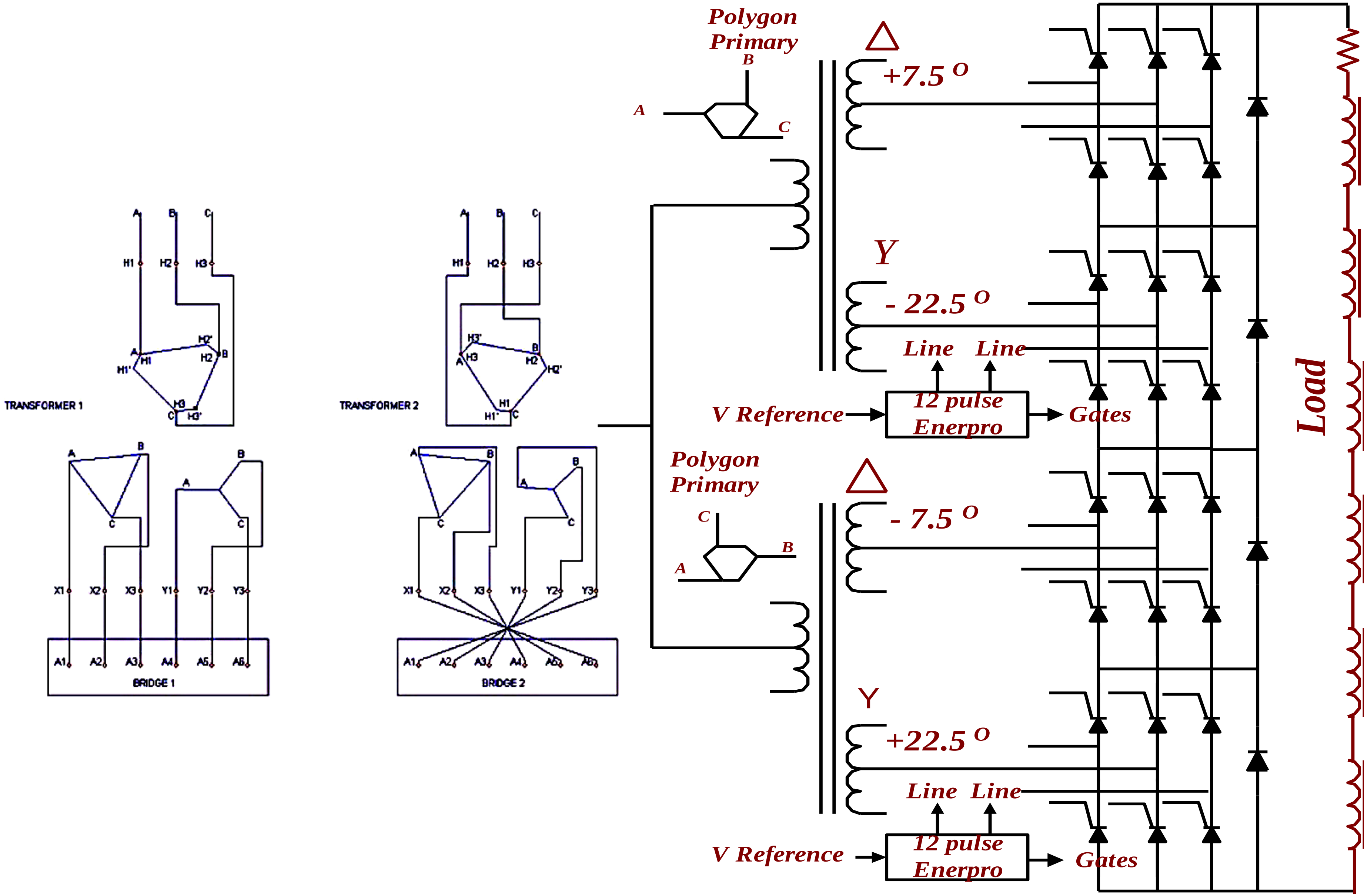
Series-connected bridges

- *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*

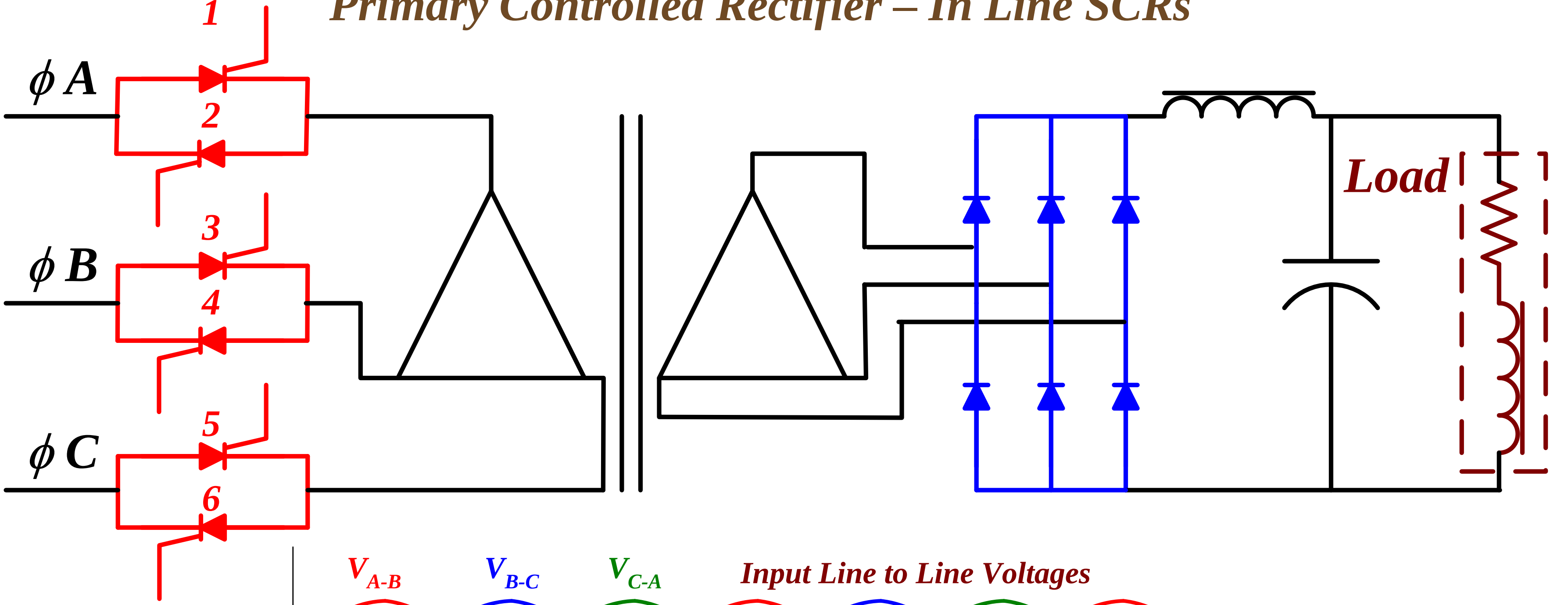
12 ϕ, q = 24 Pulse Rectifier

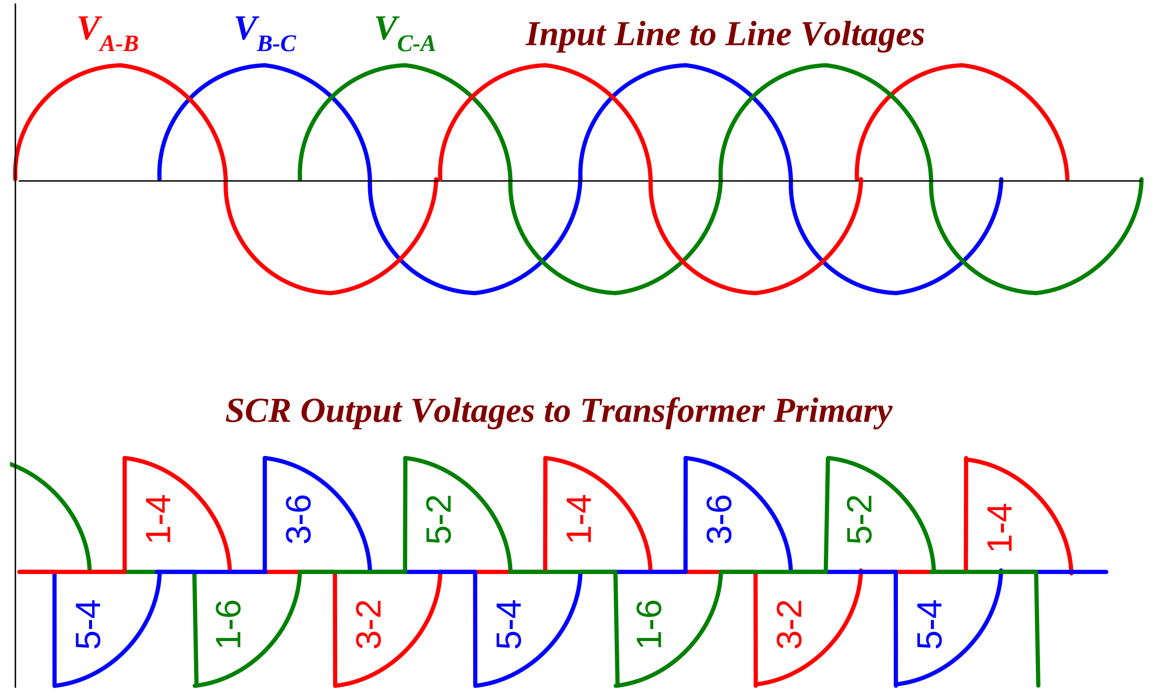


12 ϕ, q = 24 Pulse Rectifier Summary

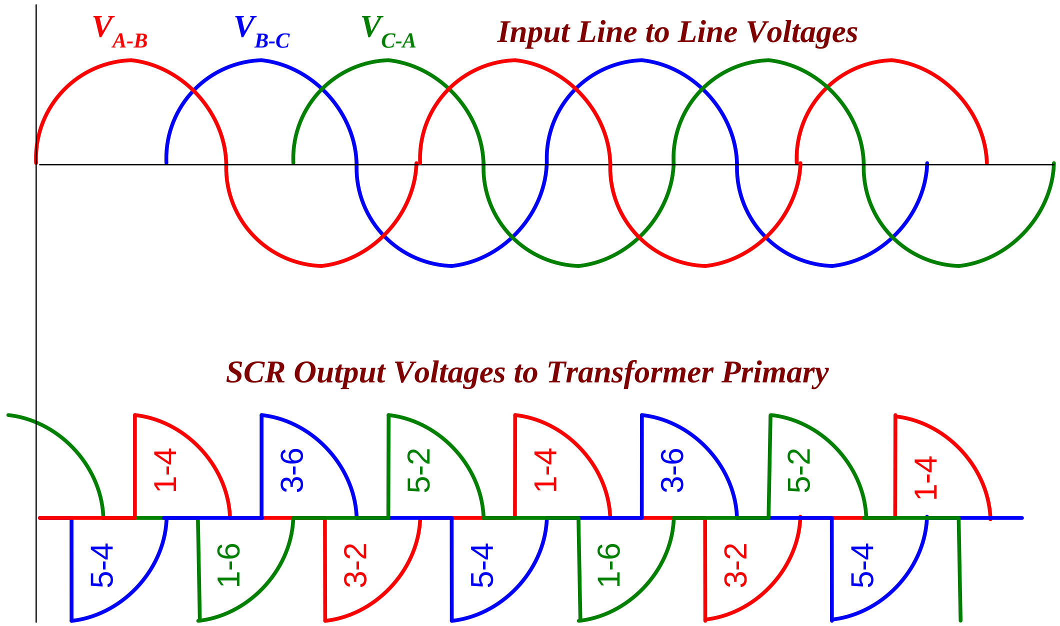
- *Input transformer polygon primary to + 7.5^O Δ – Y secondaries for -30^O shift*
- *Input transformer polygon primary to - 7.5^O Δ – Y secondaries for +30^O shift*
- *15^O shift between the 4 sets of bridges*
- *For loads $\geq$ 1 MW DC or Pulsed*

Primary Controlled Rectifier – In Line SCRs





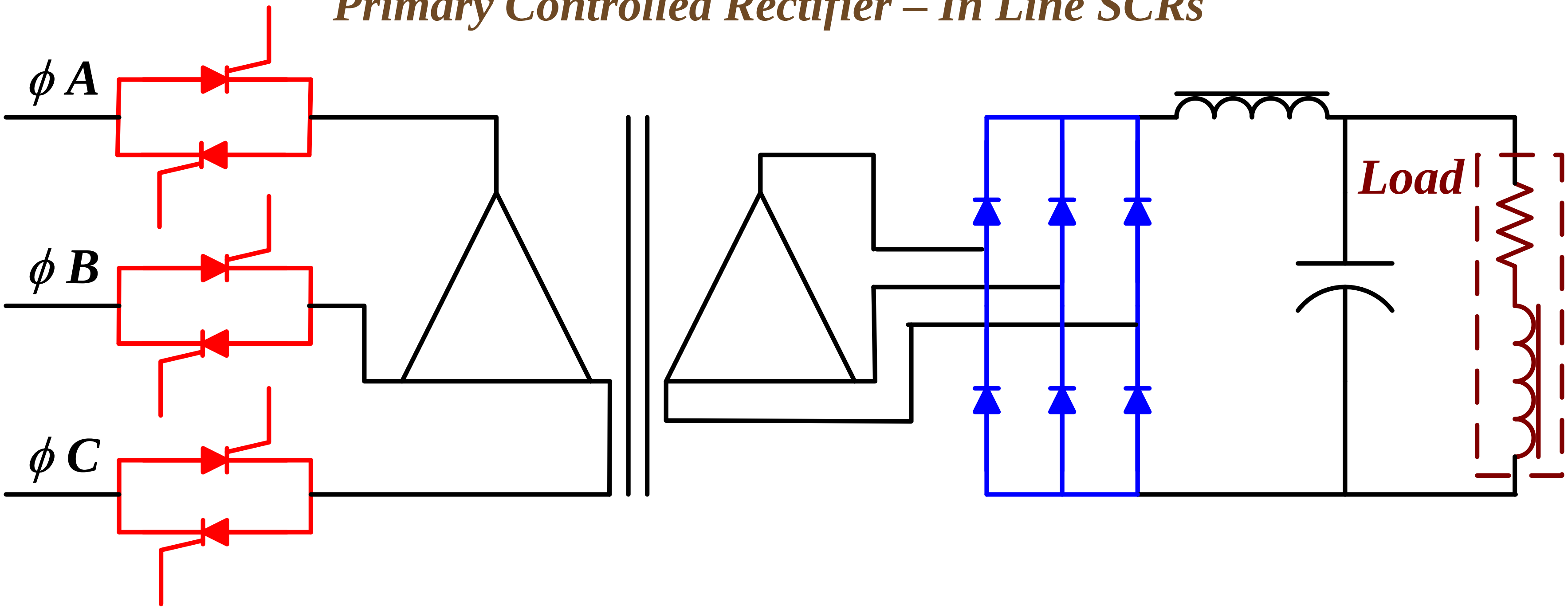
Primary Controlled Rectifier – In Line SCRs



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

$$V_{do} = \frac{3\sqrt{2}\,V_{RMS}}{\pi} * N$$ *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

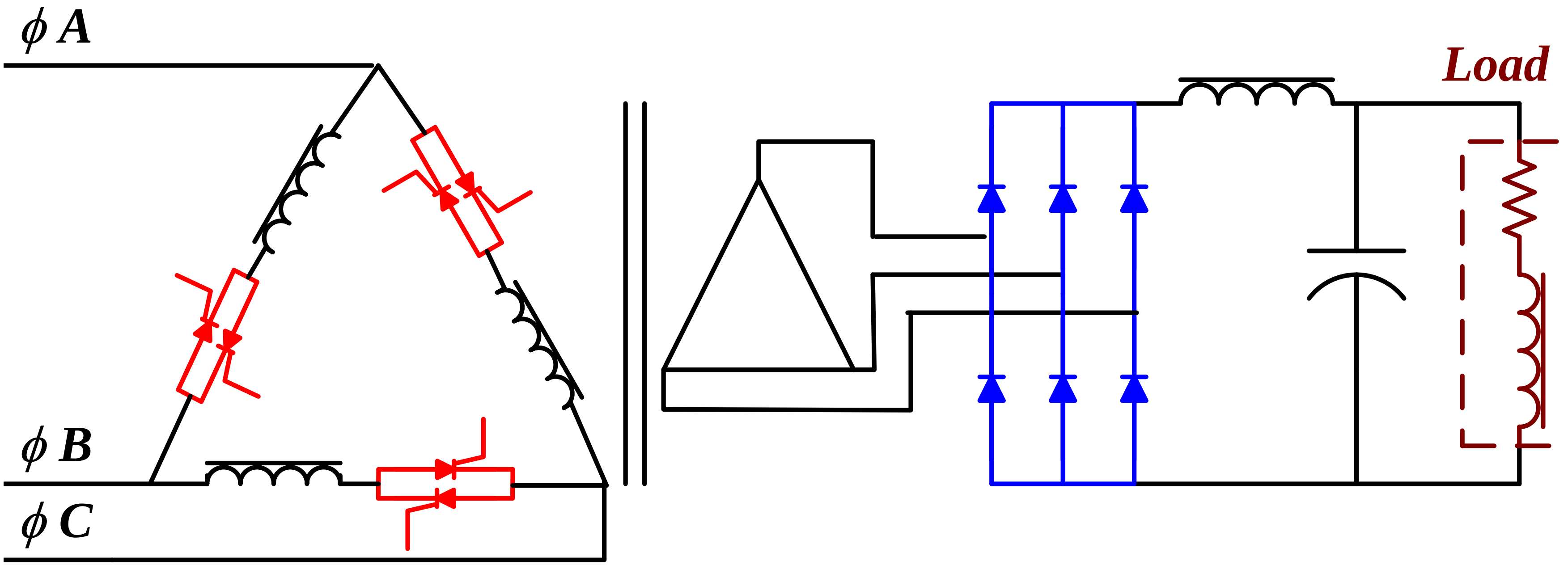
Disadvantage Compared To secondary Control

- 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)*

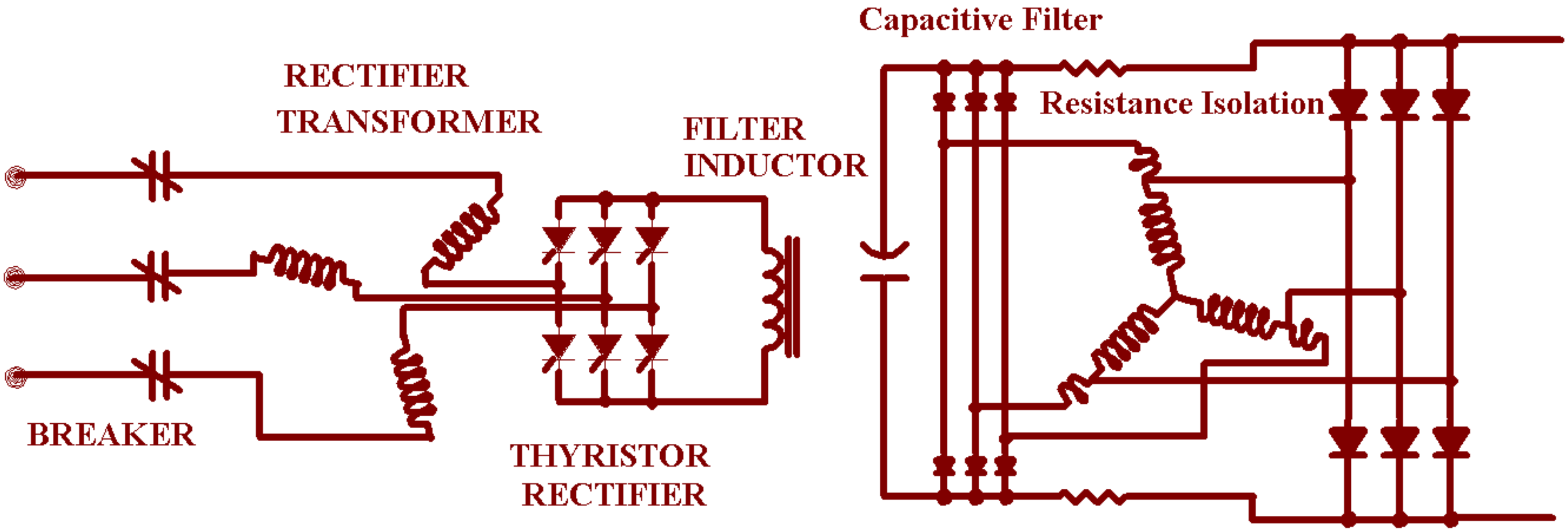
Disadvantage

- *Transformer wiring more complex*

Similarities

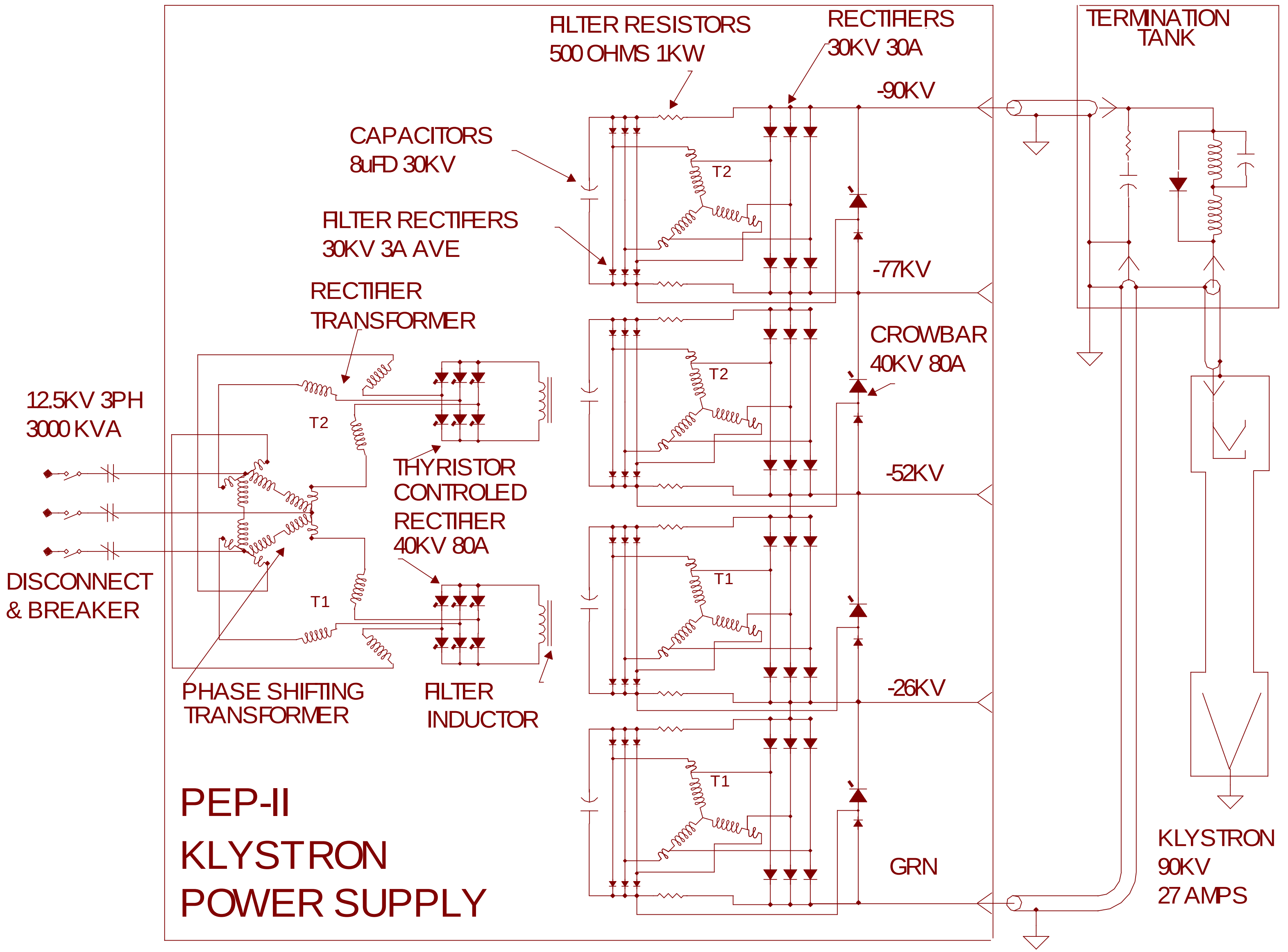
- *Other characteristics similar to In Line SCR controller*

6 Pulse SCR Star Point Rectifier



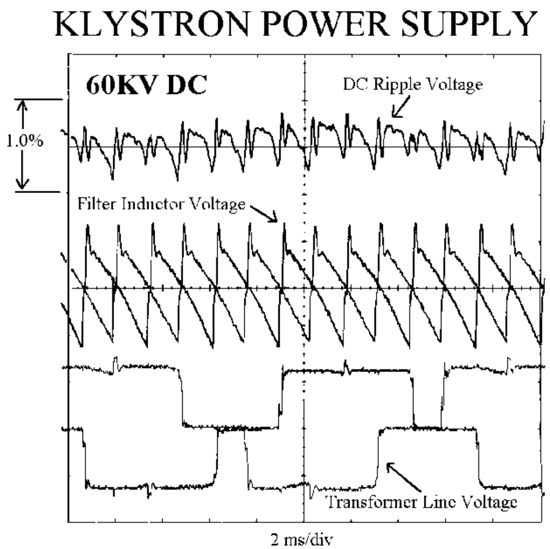
- *Primary SCR in open wye with filter inductor in lower voltage primary*
- *High voltage secondary with diodes and filter capacitor isolated from main load*
- *Protected against secondary faults. High output impedance, capacitor bank isolated from load*
- *Secondary uses diodes only.*

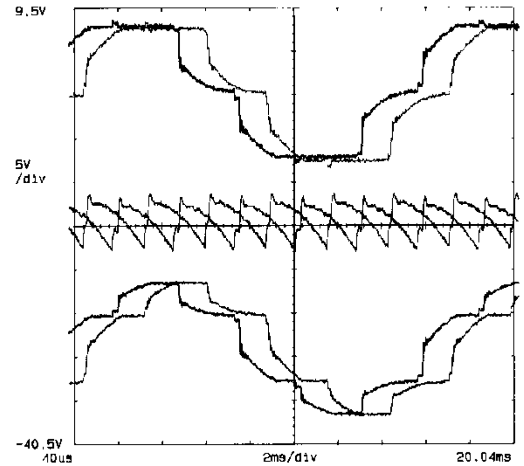
6 Phase SCR Star Point Rectifier with Isolated filter



6 Phase SCR Star Point Rectifier

•Large Joule under Load with Fault from filter Capacitor an Inductor

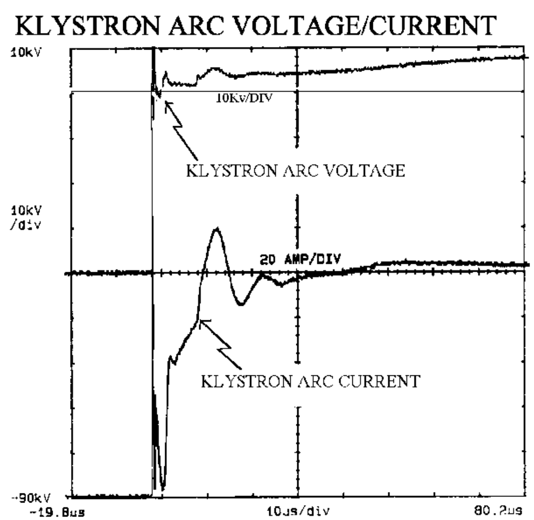


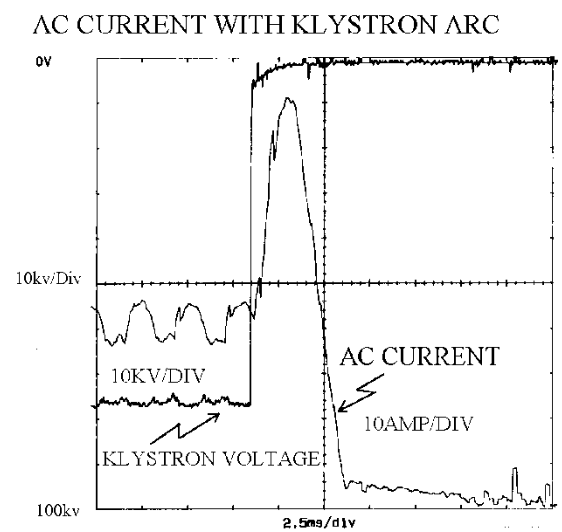


•Large Joules under Load Fault from filter Capacitor

•Low Joules under Fault

•Filter Loss $V_{max} * I_{ripple}$ or ~ 5% of Load





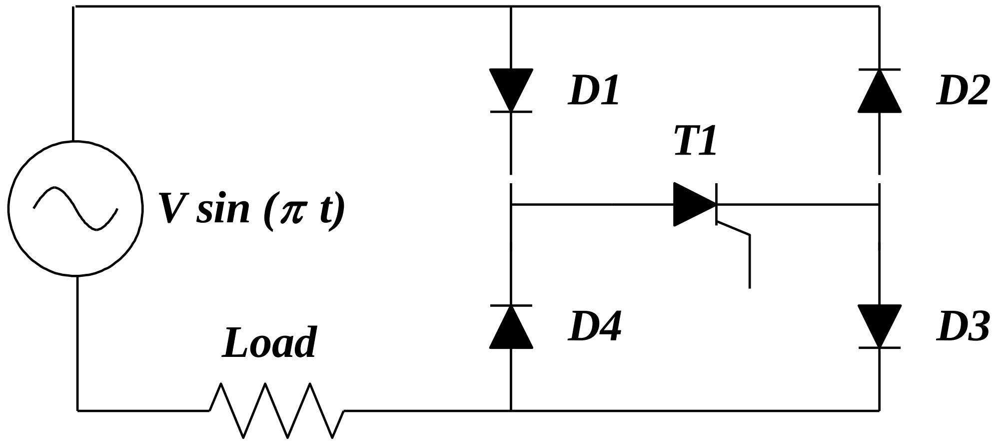
•Low Joules under Fault

•Filter Loss 5% Vmax Iripple or ~0.03% of Load*

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



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

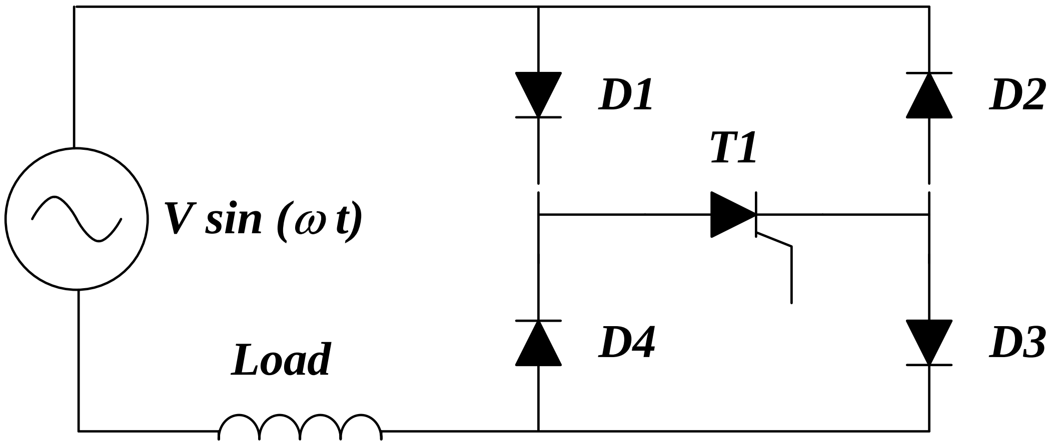
A. Explain how the circuit operates

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



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

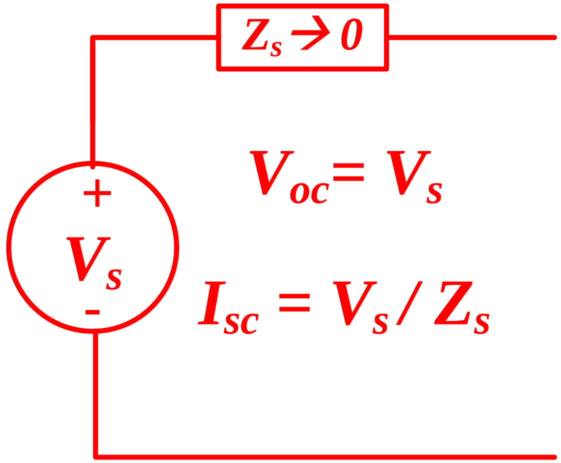
A. Explain how the circuit operates.

B. Draw the load voltage and load current waveforms 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

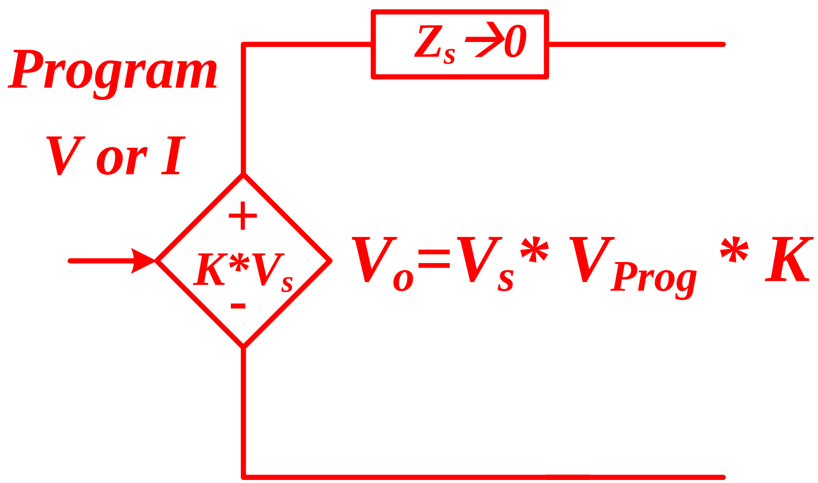
D. Find the RMS value of the load current.

Independent



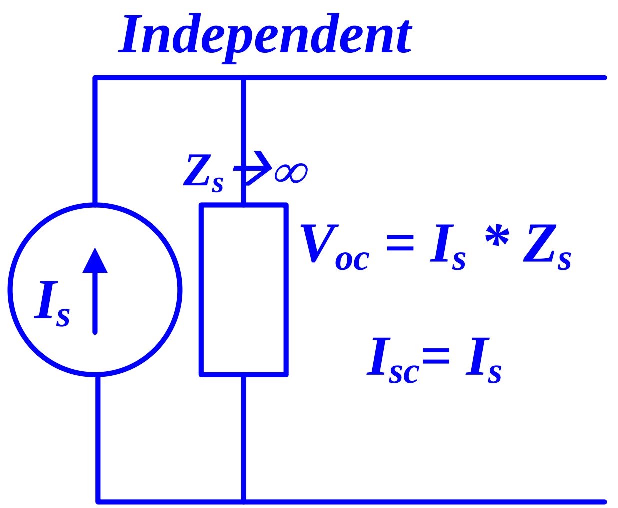
- *Provides a constant output voltage regardless of the output current*
- *Fixed DC output voltage*

Dependent

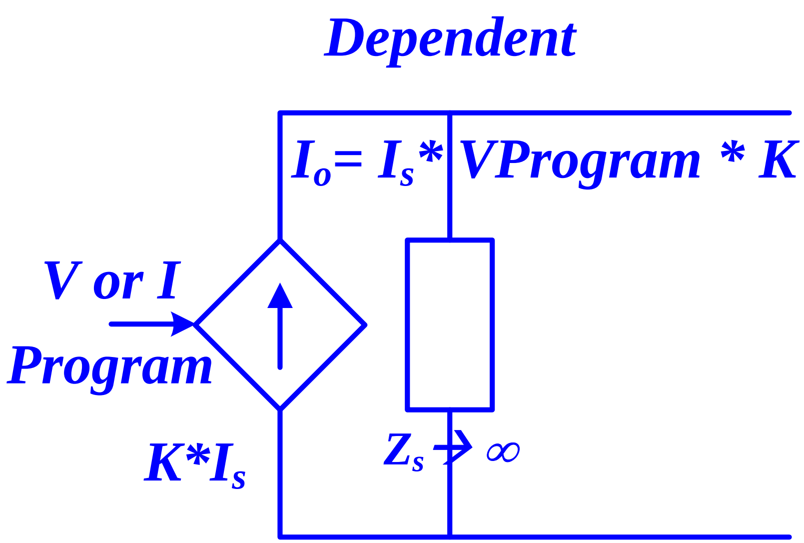


- *Provides a constant output voltage regardless of the output current*
- *Continuously adjustable*
- V_o *dependent on* V_{Prog} (V_{Ref})

Norton Current Sources



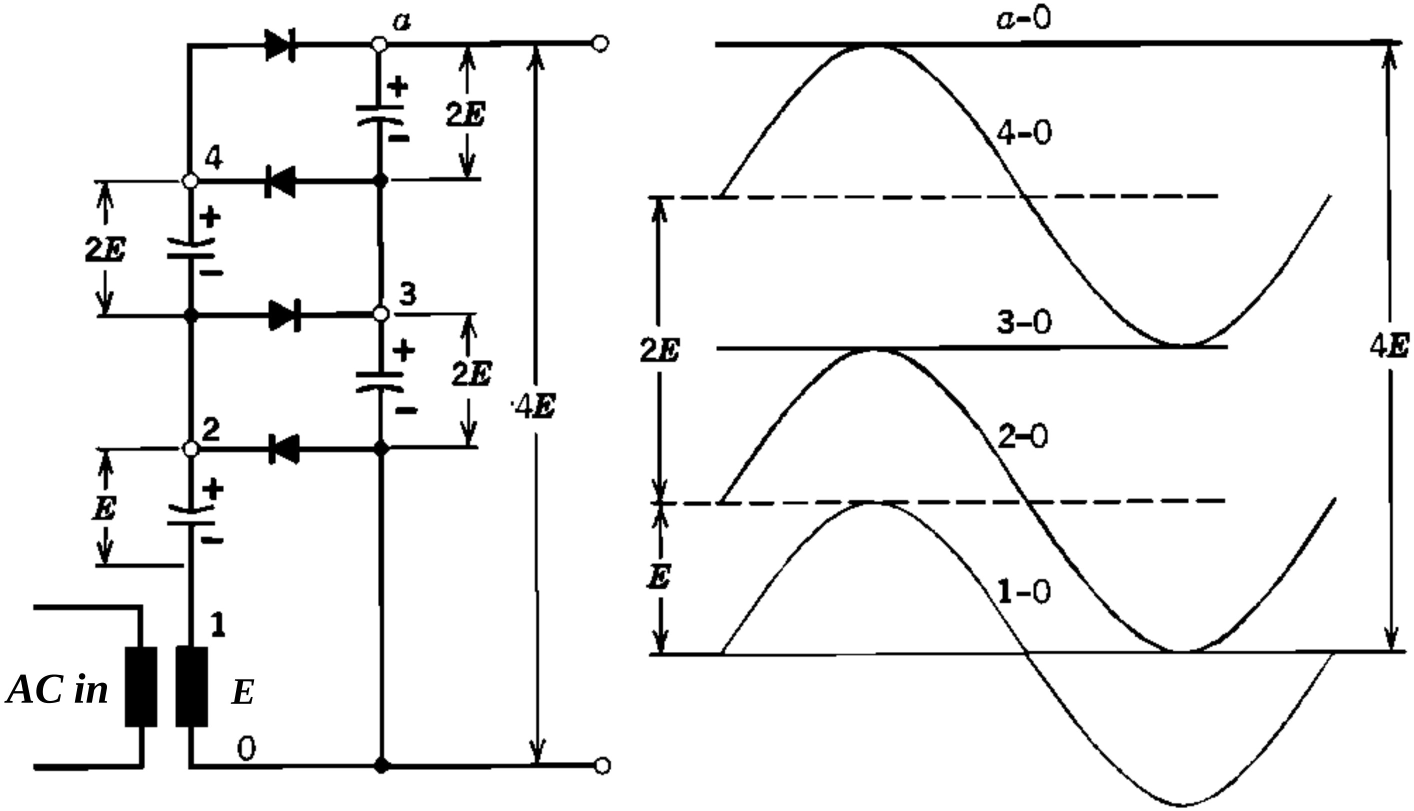
- *Provides a constant output current regardless of the output voltage*
- *Fixed DC output current*



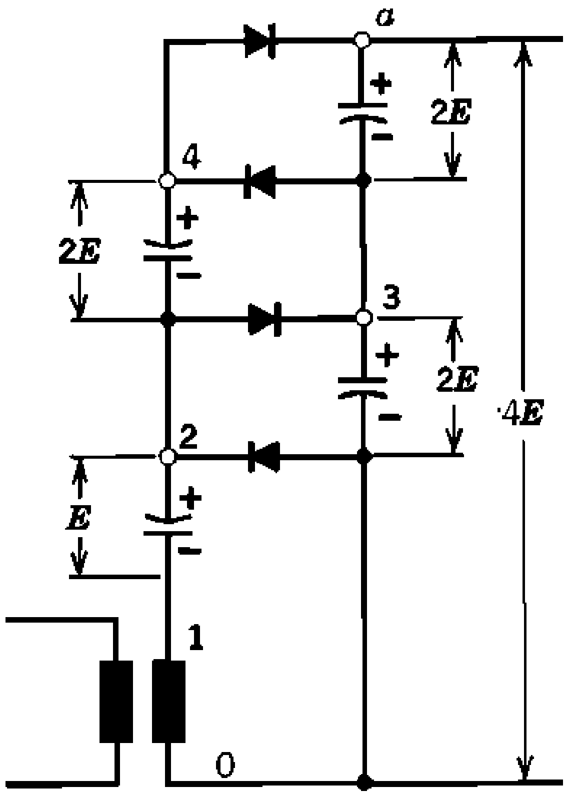
- *Provides a constant output current regardless of the output voltage*
- *Continuously adjustable*
- *I_o dependent on V_{Prog} (V_{Ref})*

High Voltage Low Current DC supplies

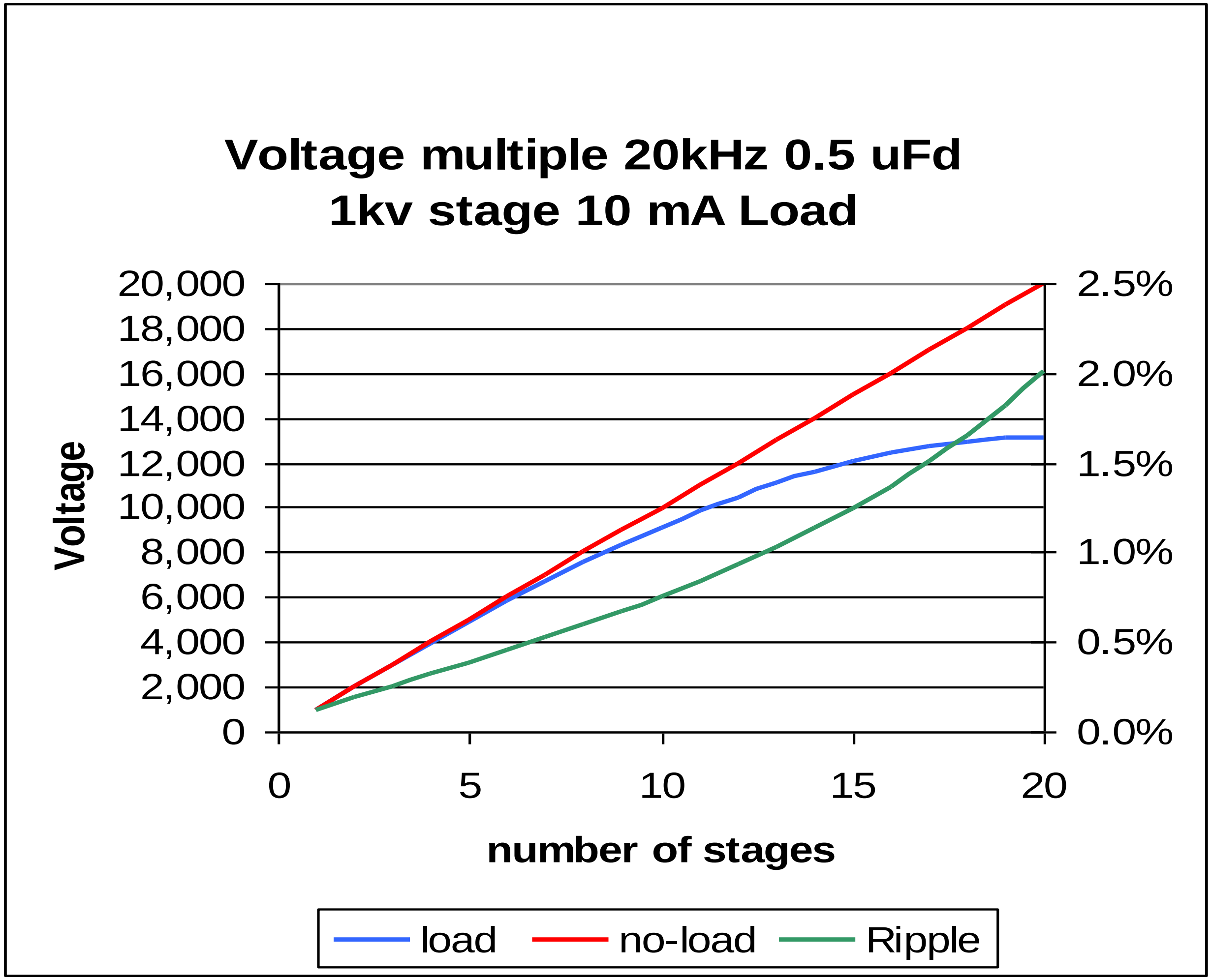
Voltage Multipliers, Cockroft Walton or Cascade Supplies



High Voltage Low Current DC supplies



- Voltage multipliers or cascaded supplies
- Electron beam gun supplies and deflector supplies
- Half-wave, full-wave, three-phase, or six phase
- Capacitor / rectifier arranged to couple AC voltage through the capacitor after being charged by DC from the rectifier
- 20kV to 1,000 kV, 0 to 10 mA DC
- AC high frequency drive ~ 5 kHz to 50 kHz
- Advantages – simple, reliable, inexpensive
- Disadvantages- low output power, poor regulation high output ripple, high output Z, 1st stage draws high current

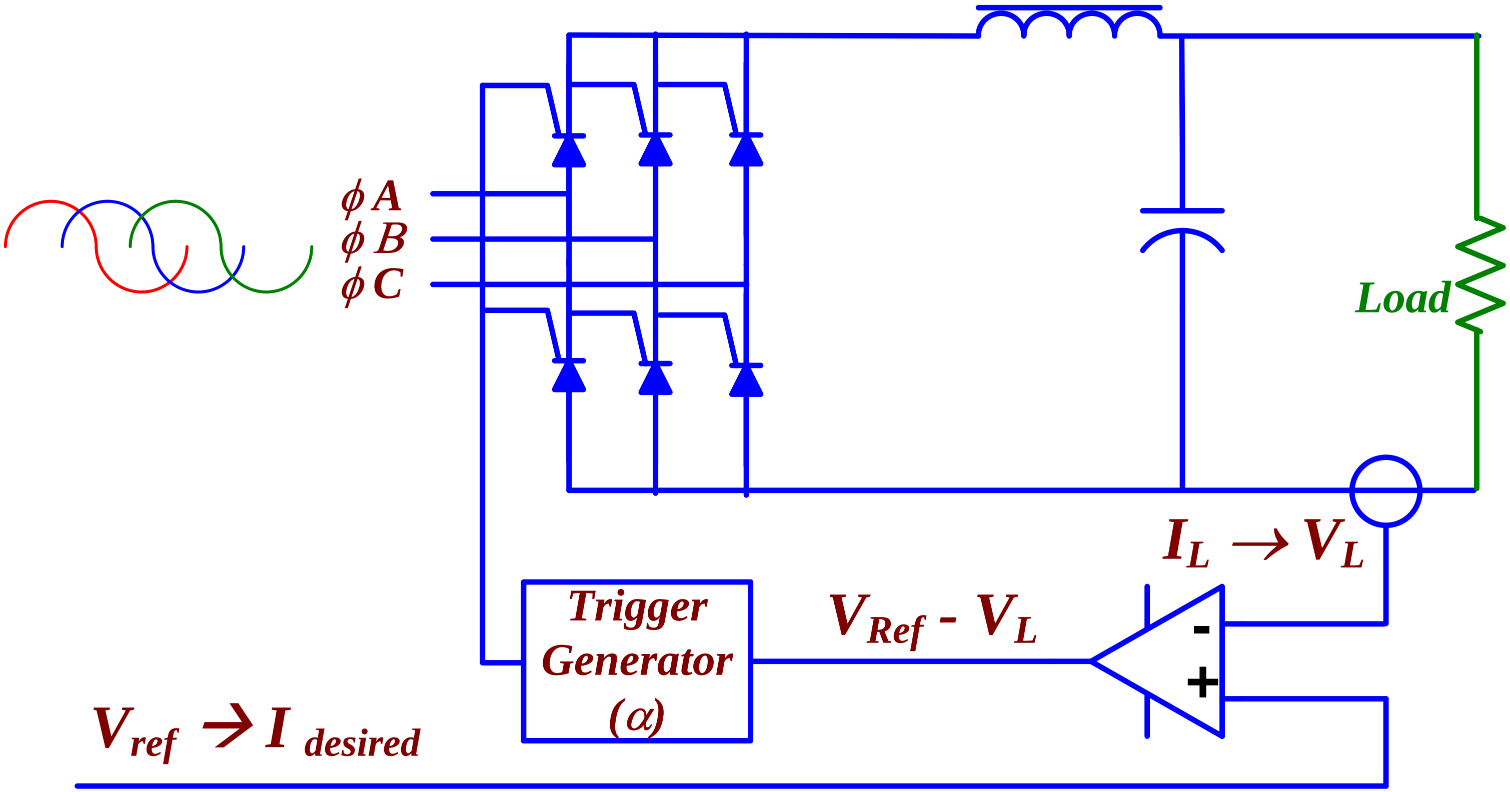


• *Disadvantages:*

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

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

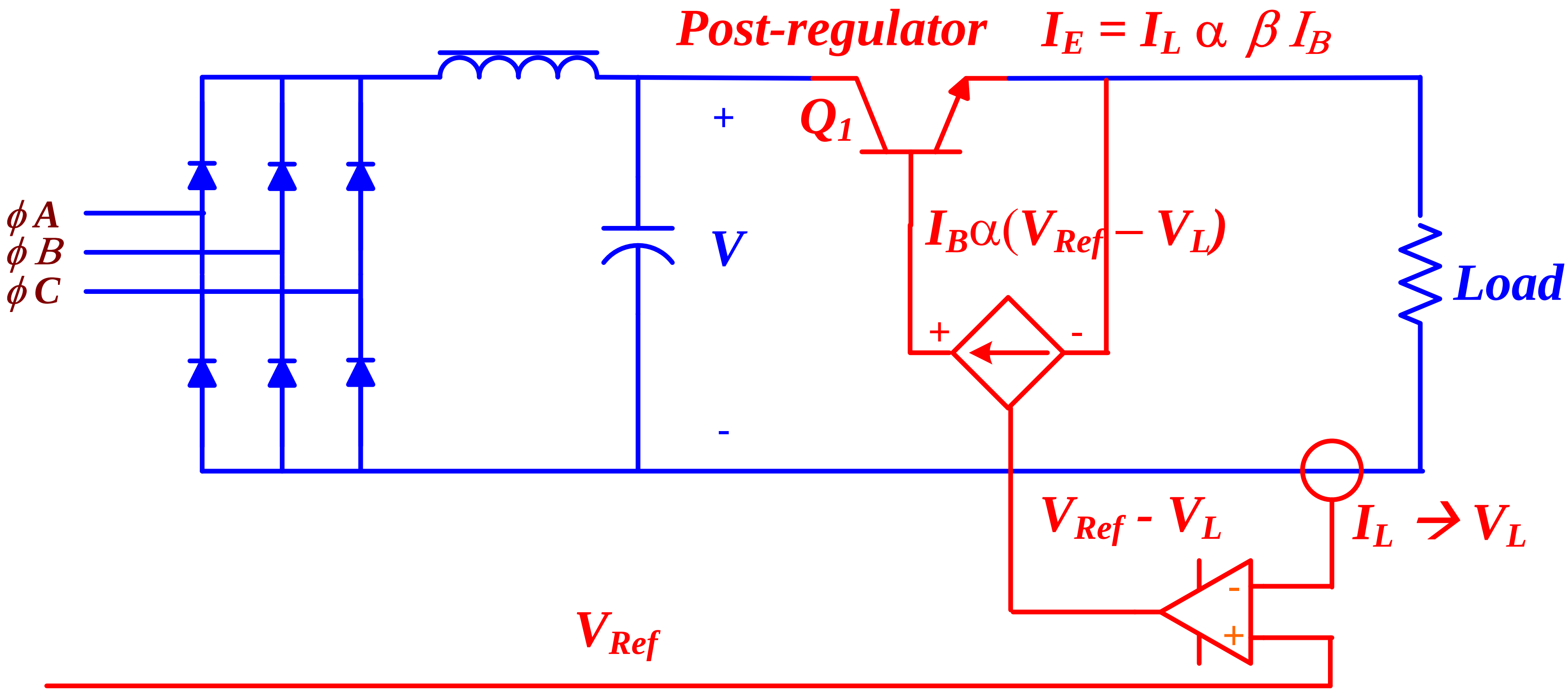
SCR Rectifier / Regulator Current Source



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

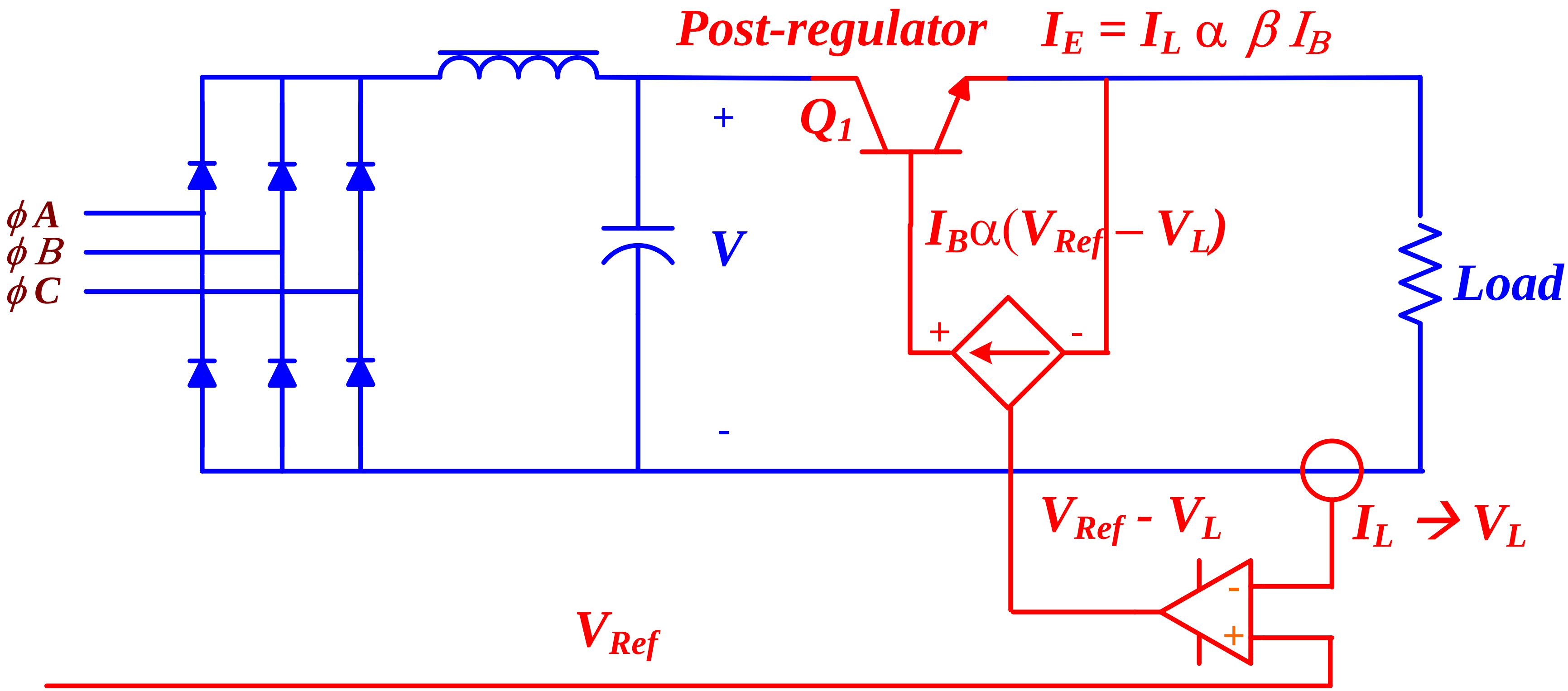
Disadvantage: *Line commutated, low bandwidth, some fast changes not regulated*

Diode Rectifier With Linear Post-Regulator To Improve Response



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

Diode Rectifier With Linear Post-Regulator To Improve Response



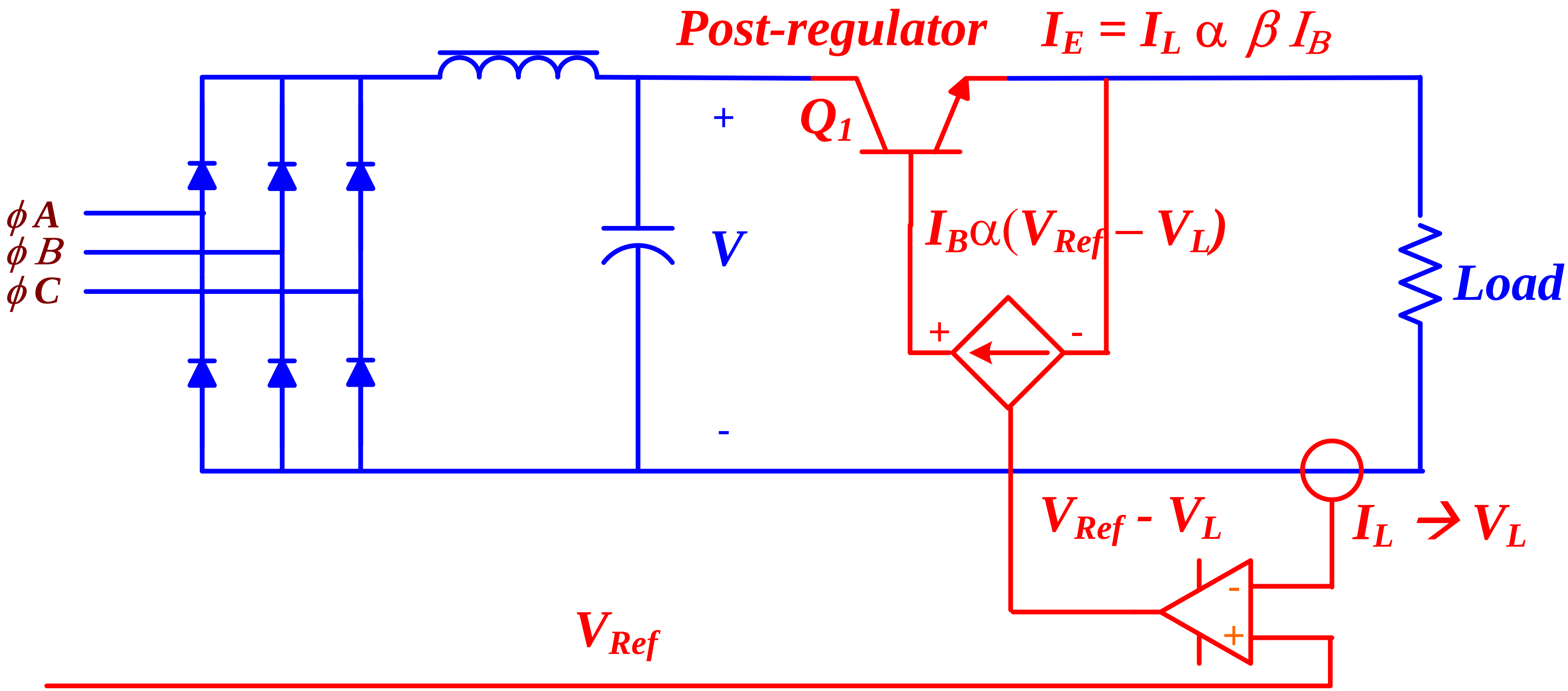
Regulation occurs by changing the transistor Q1 resistance

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

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

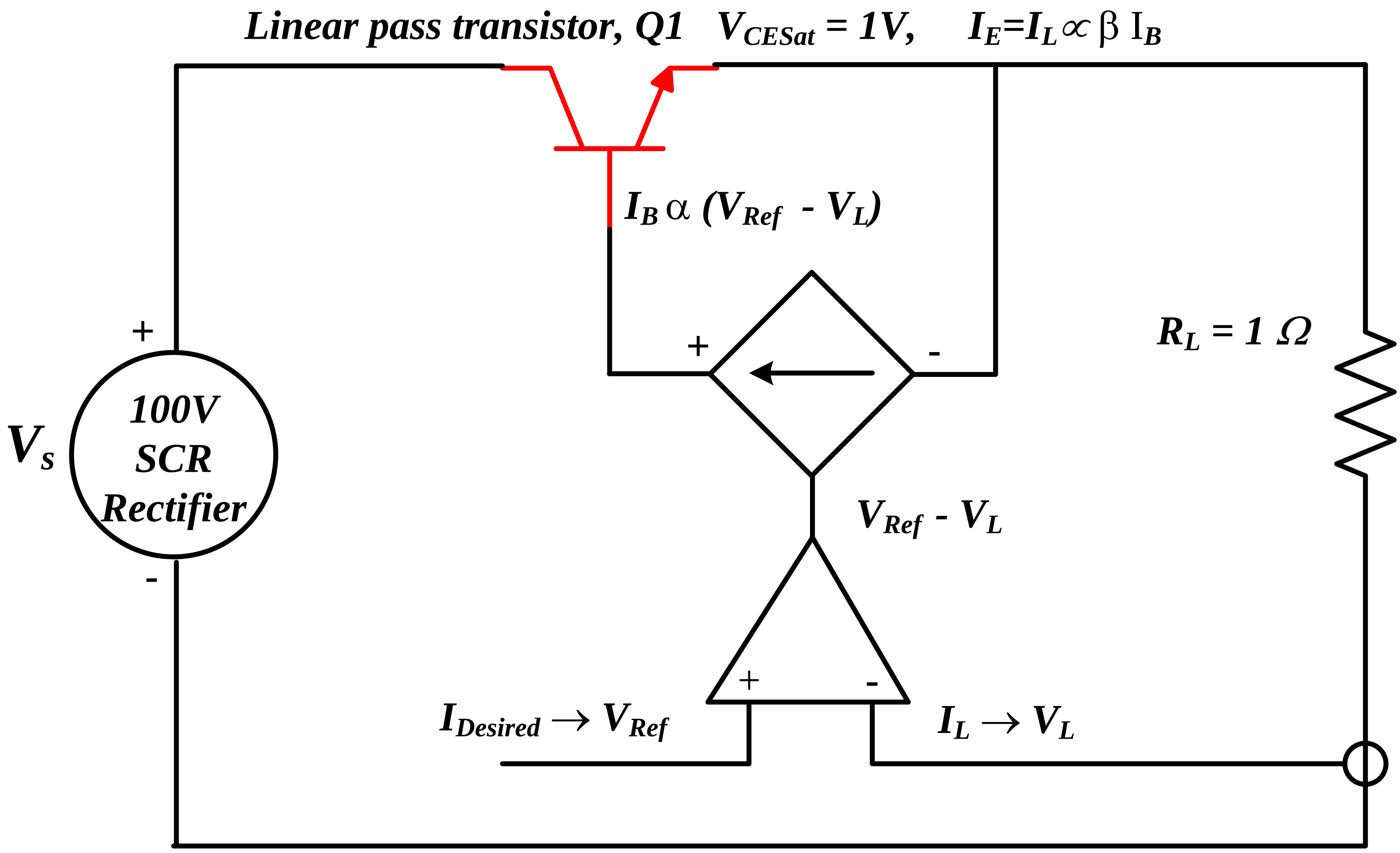
if $I_L \downarrow, V_L \downarrow, \; V - V_L \uparrow, \; R_{Q1} \uparrow$

Diode Rectifier With Linear Post-Regulator To Improve Response



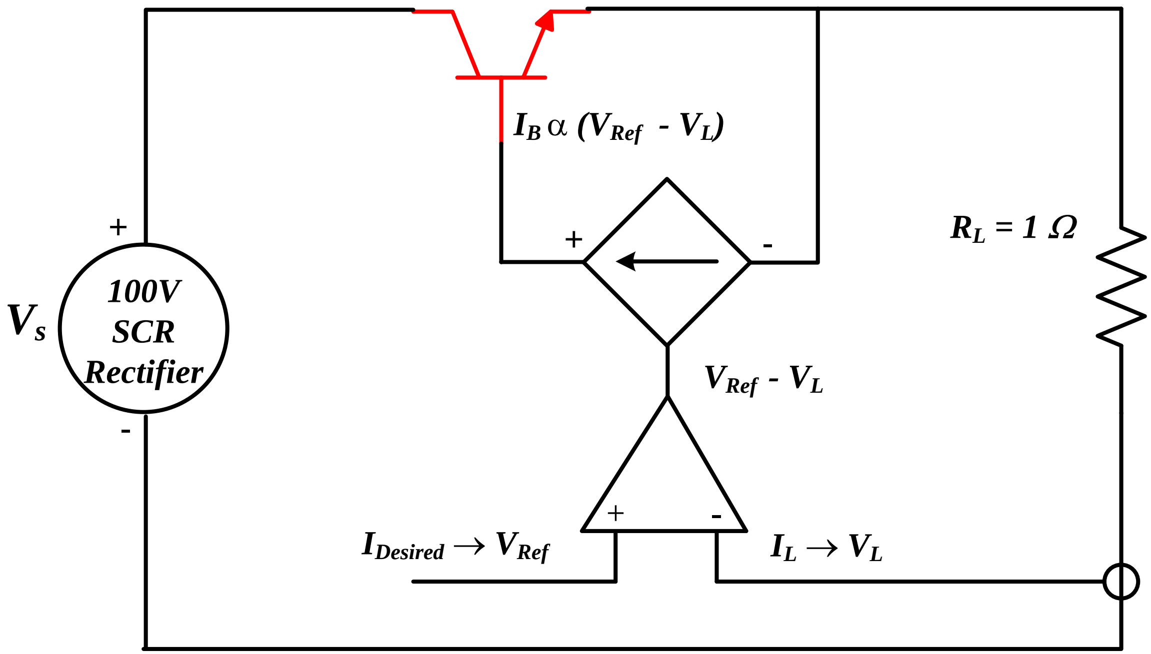
- Output I sensed and deviations due to programming, load or other changes are corrected by changing the resistance of the post-regulator.
- Broader bandwidth than line-commutated type
- Very inefficient topology, except when full output is required

Linear Regulator Disadvantage



Linear Regulator Disadvantage

Linear pass transistor, Q1 $V_{CESat} = 1V$, $I_E = I_L \propto \beta I_B$



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

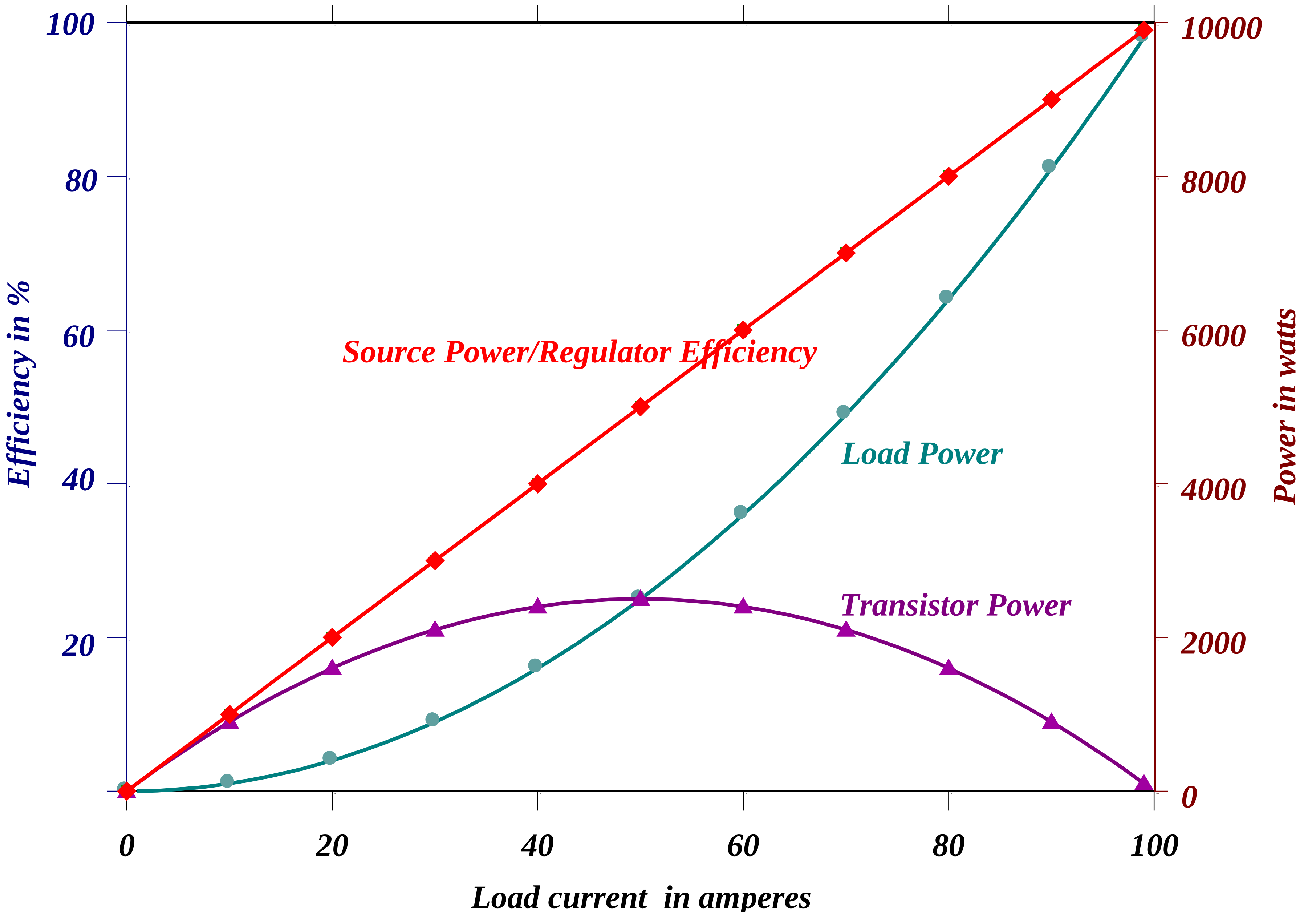
$$I_S = I_L \qquad V_L = I_L * R_L \qquad P_{Q1} = V_{Q1} * I_{Q1}$$

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

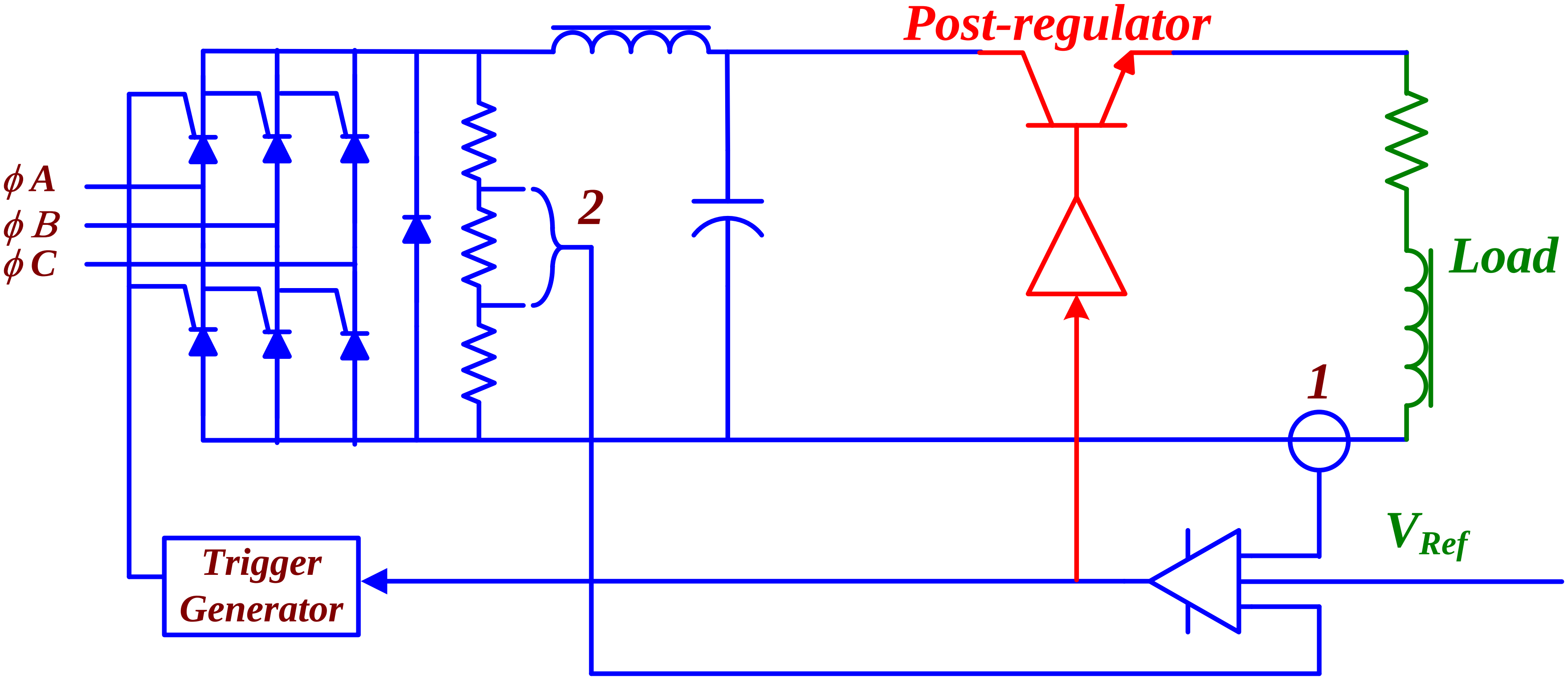
Linear Regulator Disadvantage

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

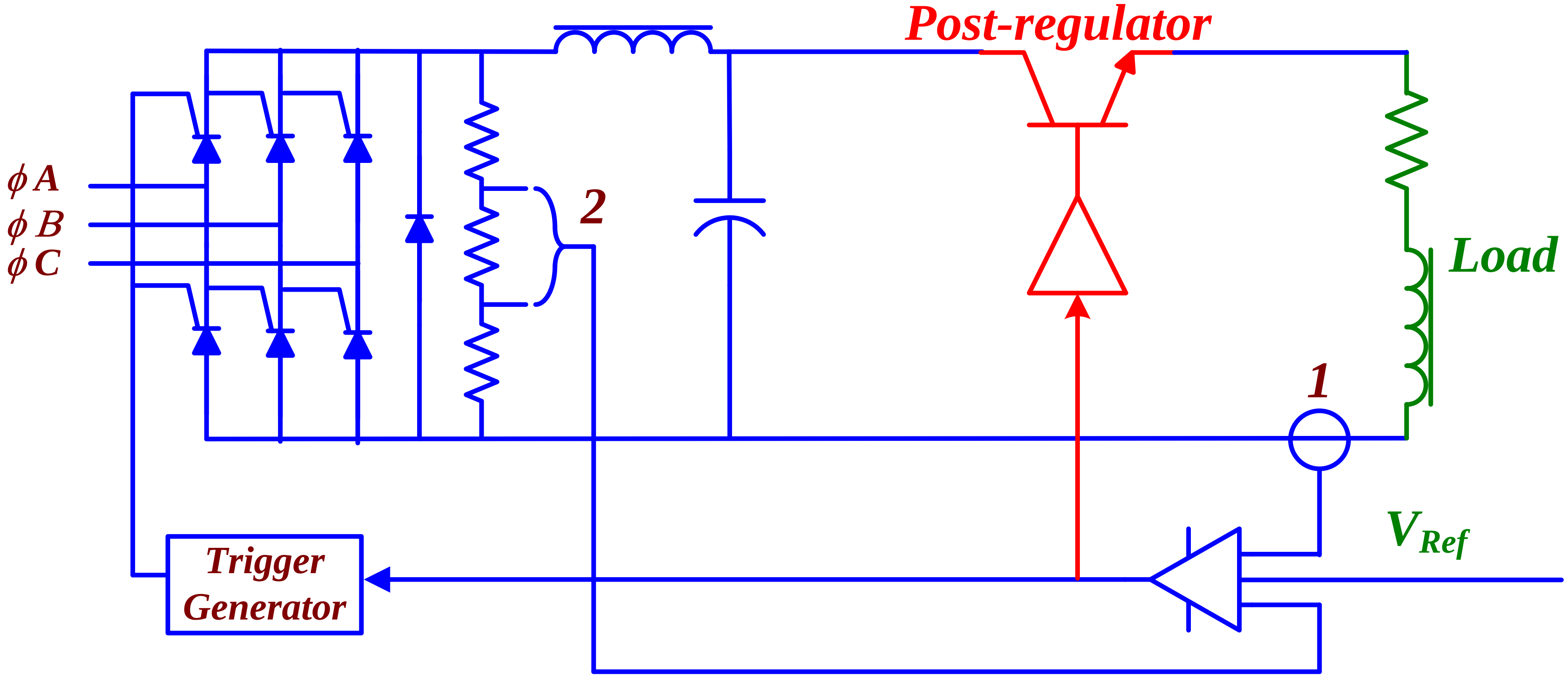


SCR Rectifier With Linear Post-Regulator To Improve Efficiency / Response



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

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

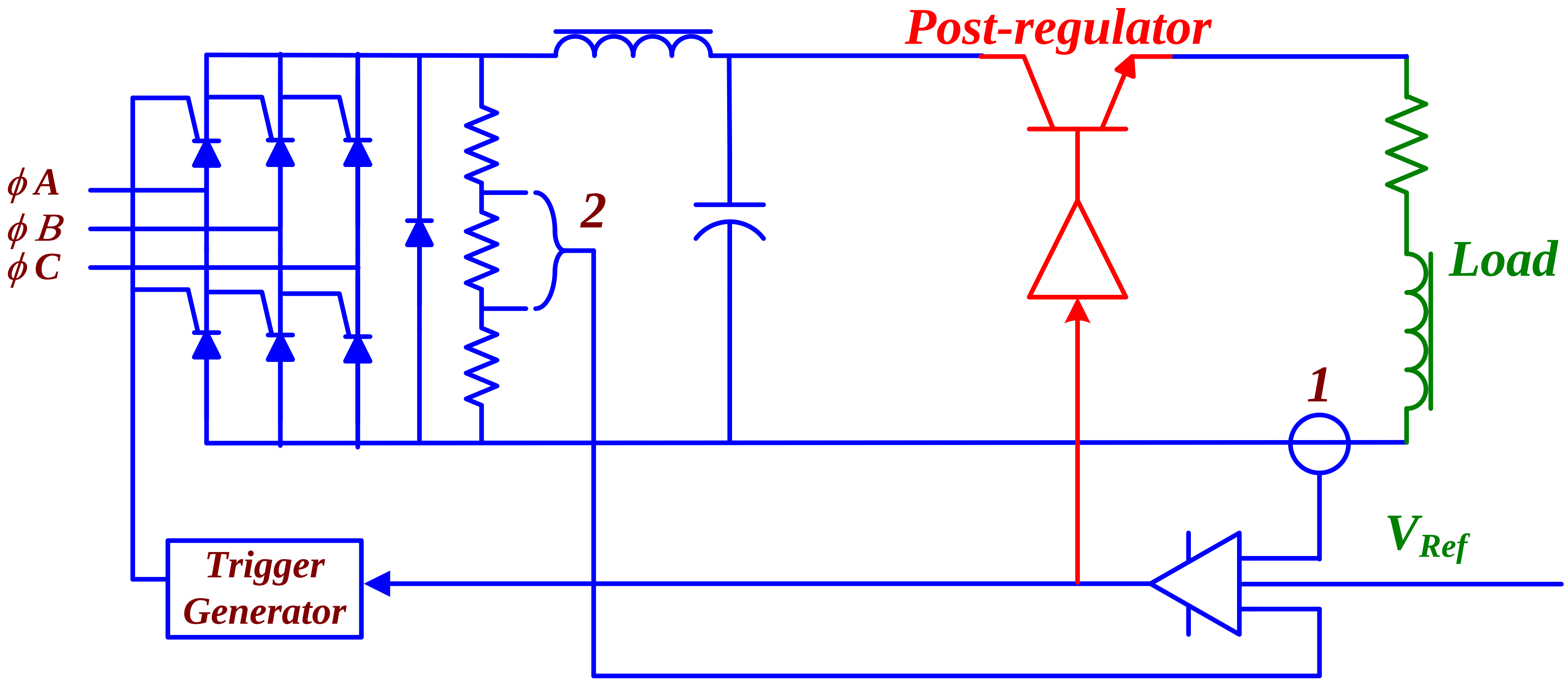


1. Output I sensed. Deviations due to load or other changes are corrected by SCR rectifier and post-regulator.

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*

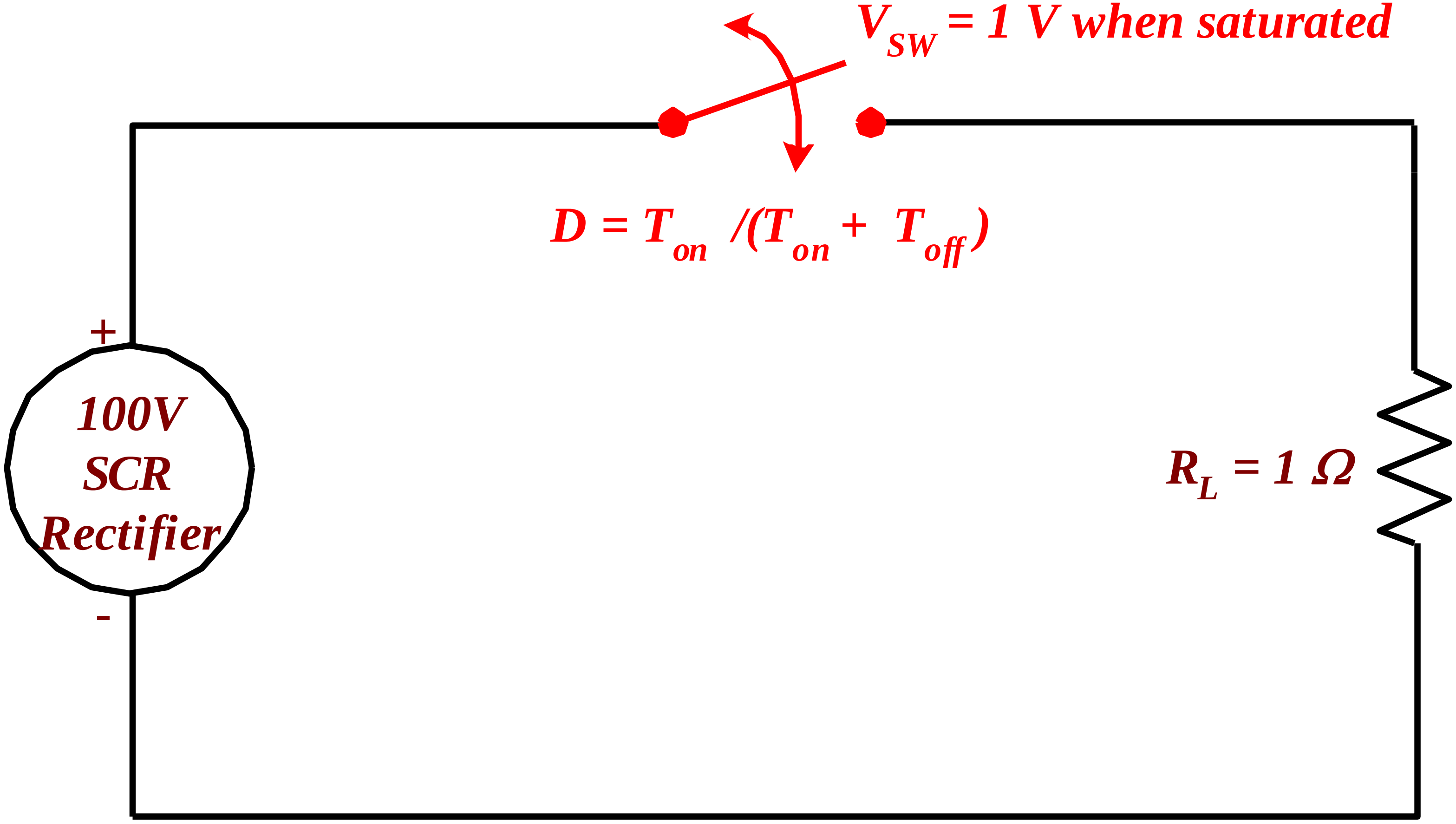
The Present – Switchmode Power Supplies
Circa 1990 - Present

Recalling The Recent Past

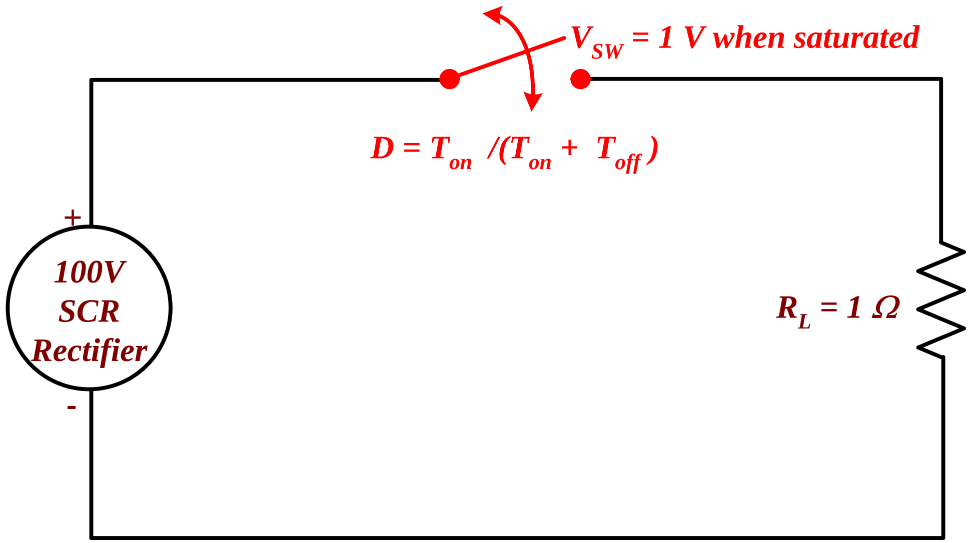
Topology	*Disadvantages*
• *SCRs for rectification and regulation*	• *Low power factor* • *High AC line harmonic distortion* • *Narrow bandwidth* • *Slow transient response*
• *SCRs for rectification and gross regulation* • *Fine regulation by post linear transistors*	• *Low power factor when line V $\neq$ 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 Ω

The Switchmode Advantage



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

$$V_S = 100V$$

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

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

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

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

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

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

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

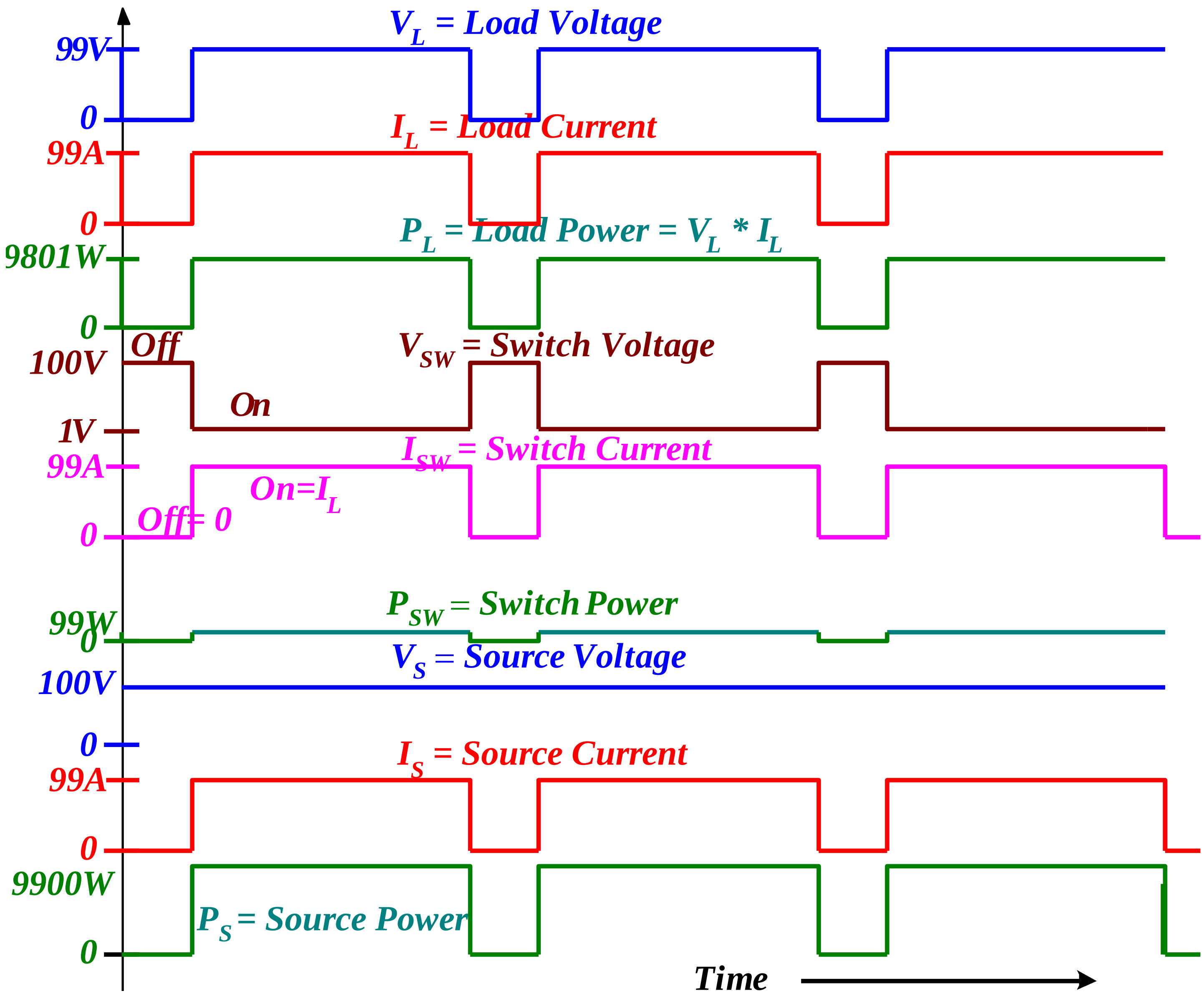
$$P_{SW} = V_{SWRMS} * I_{SWRMS}$$

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

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

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

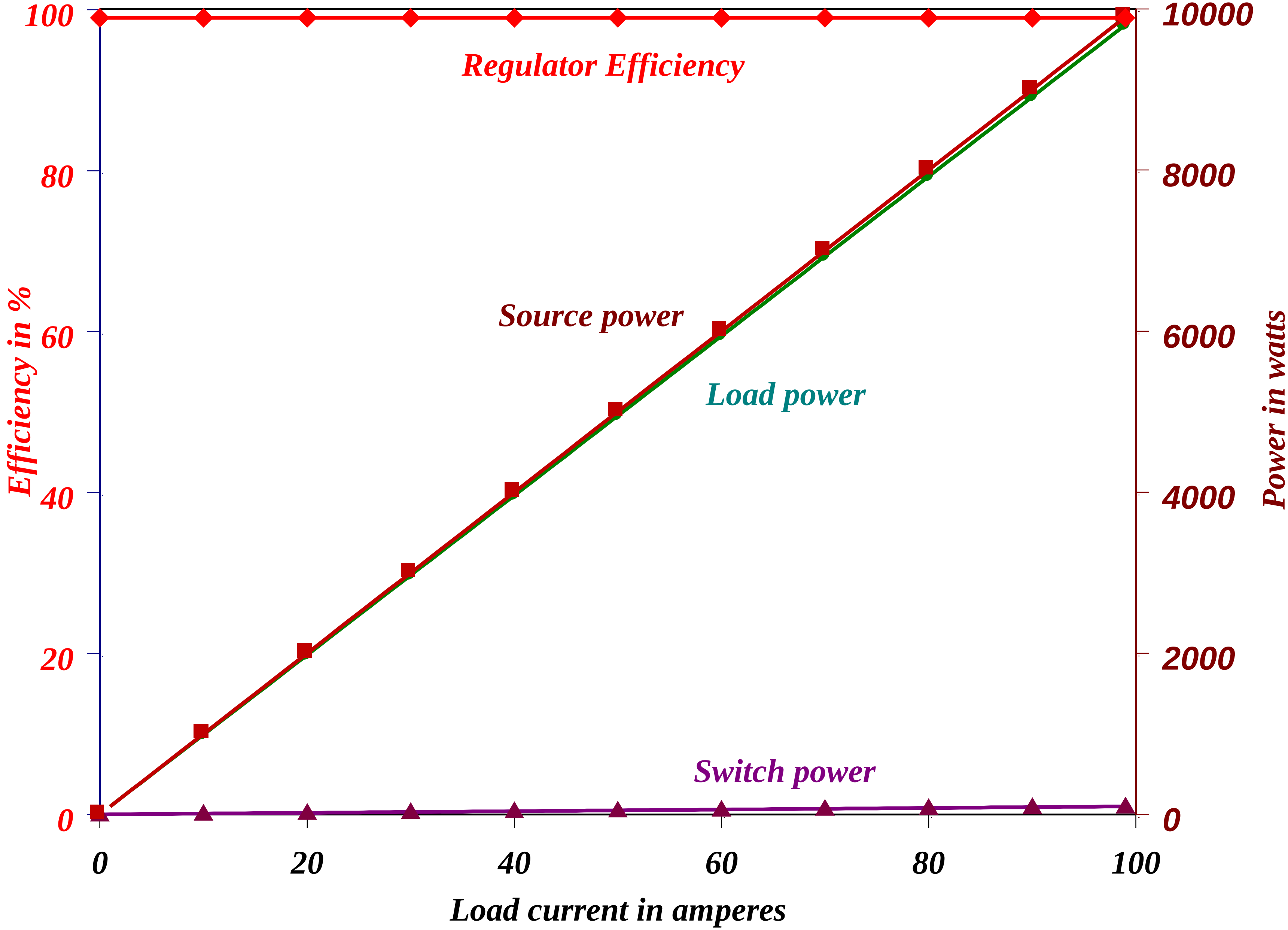
The Switchmode Advantage - Waveshapes



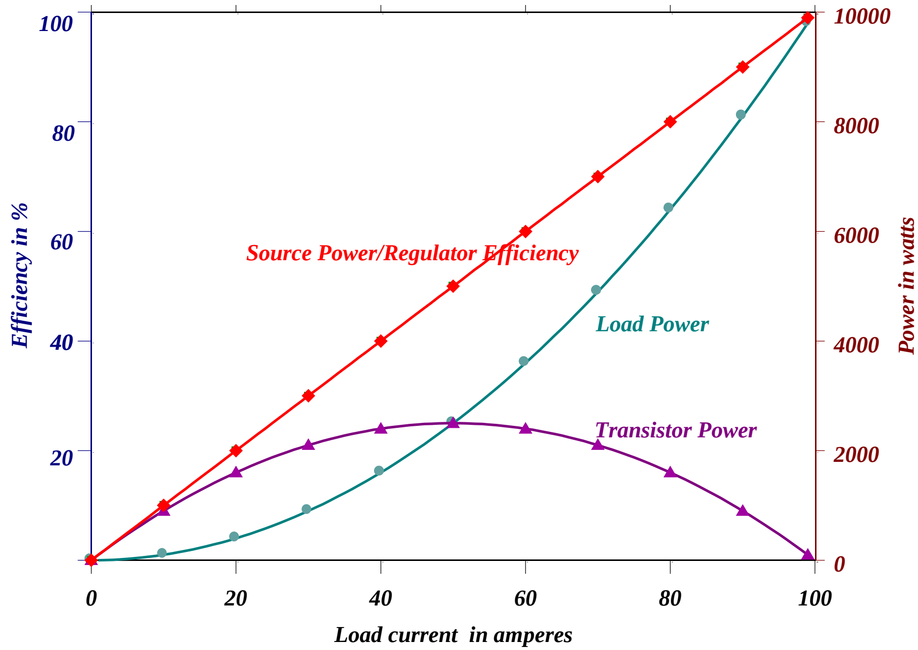
The Switchmode Advantage - Calculations

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

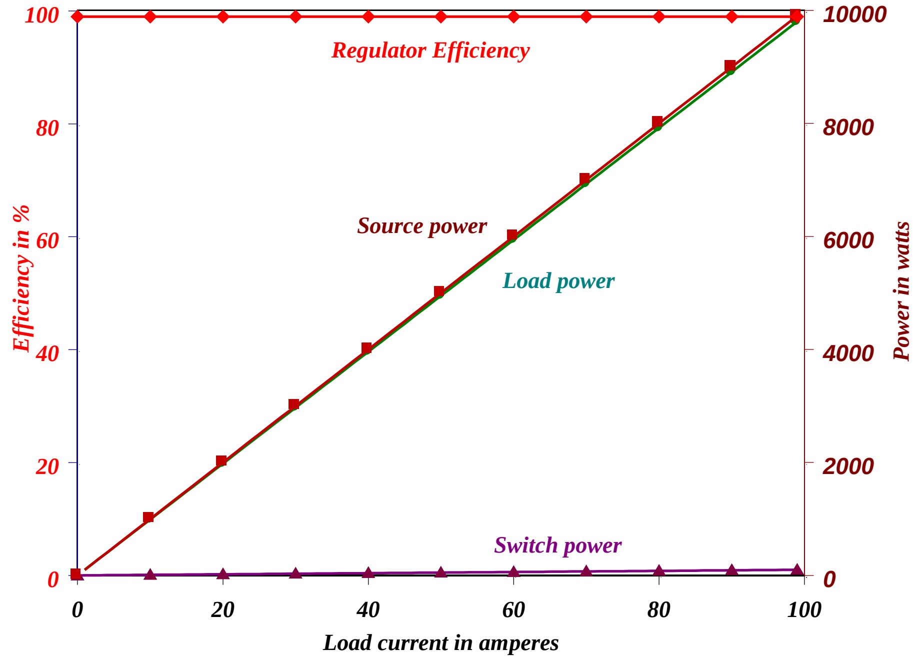
The Switchmode Advantage - Plots



Linear regulator



Switchmode regulator



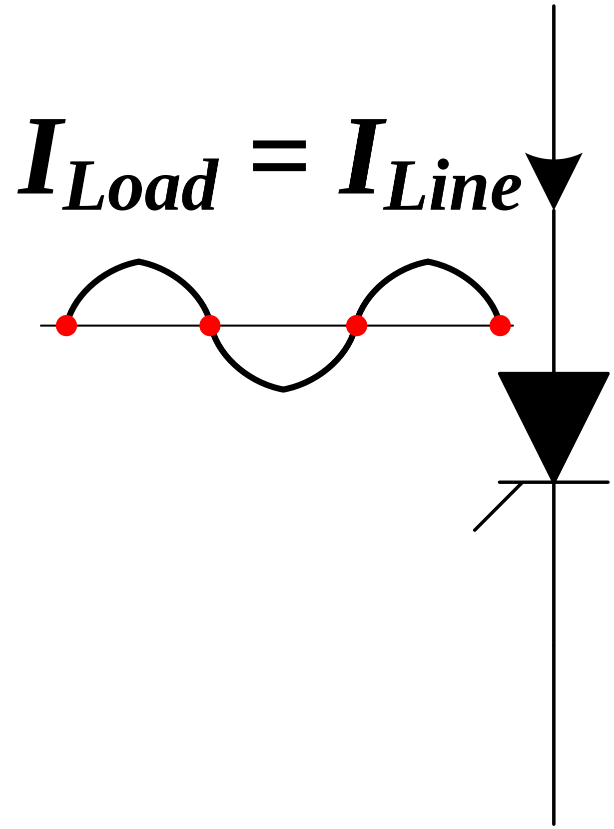
SCR Regulation Vs Switchmode Regulation

	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*

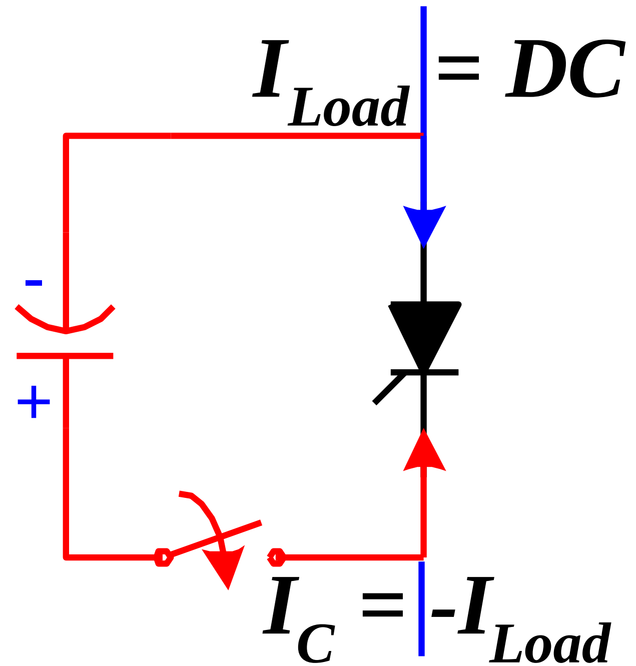
- *Employ natural current zero occurs each 1/2 cycle for turnoff*

- *Slow, tied to 60Hz line and no turnoff control*

- *Not suitable as fast switch*

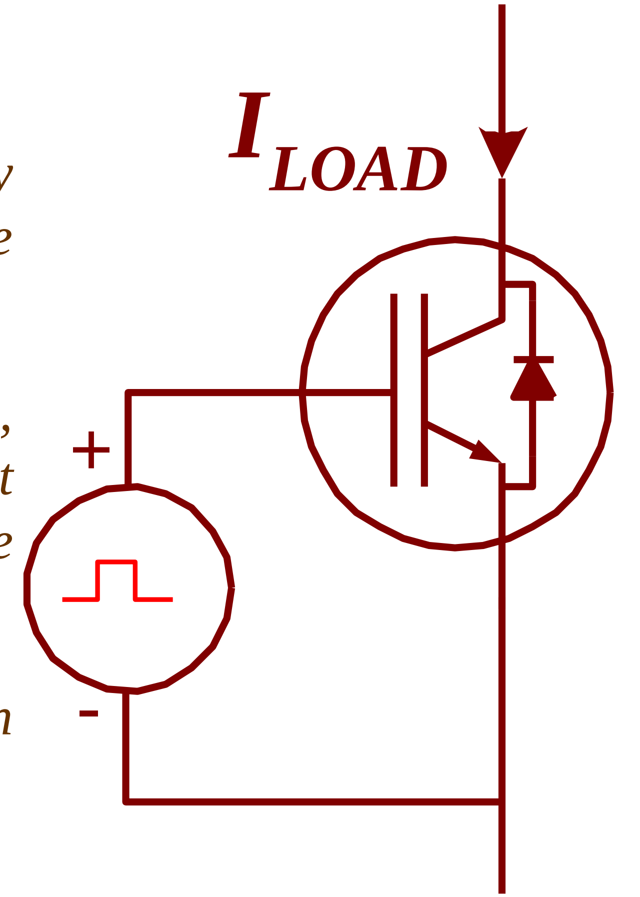
Force Commutated

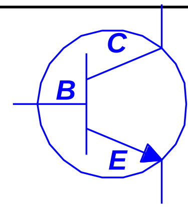
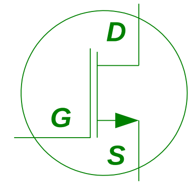
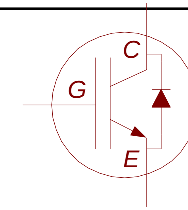
- *Typically SCRs, Triacs*
- *Artificial current zero is manufactured by pre-charged capacitor $I_c = - I_{Load}$*
- *Complex and power-consuming charging and discharging circuits for capacitor*
- *Not suitable approach for fast switches*



Self Commutated

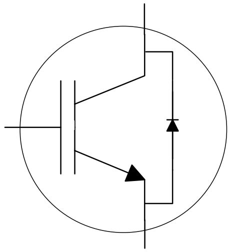
- *Devices have the ability to turn on or turn off by the application of a forward or reverse bias to the control elements (gate – emitter)*
- *Typically Bipolar Junction Transistors (BJTs), Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) or Insulated Gate Bipolar Junction Transistors (IGBTs)*
- *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 $\rightarrow$ 100 A* *1000V, 10 $\rightarrow$ 100A*	*150 V, 10 $\rightarrow$ 600 A* *600 V, 10 $\rightarrow$ 100 A* *1200V, 10 $\rightarrow$ 100A*	*600 V, 10 $\rightarrow$ 800 A* *1200V, 10 $\rightarrow$ 2400A* *1700V, 50 $\rightarrow$ 2400A* *3300V, 200 $\rightarrow$ 1500A* *6500V, 200 $\rightarrow$ 800A*
Switching Speed	$DC \leq fs \leq 2\ kHz$	$DC \leq fs \leq 1{,}000\ kHz$	$DC \leq fs \leq 20\ kHz$
Vce or Vds f(Vge/Vgs, Ic/Id)	*0.5 V $\rightarrow$ 1.5 V*	*1.5 V $\rightarrow$ 6 V*	*1.0 $\rightarrow$ 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

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

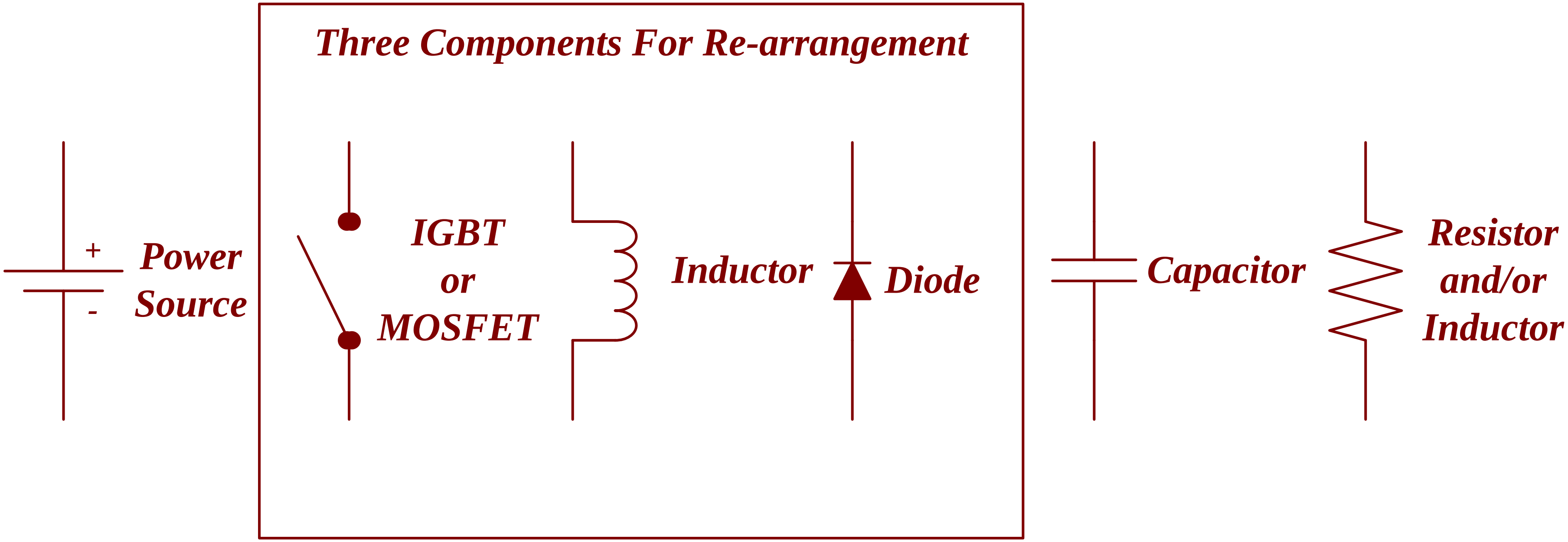
Typical Forward Converters Listed In Order Of Increasing Use

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

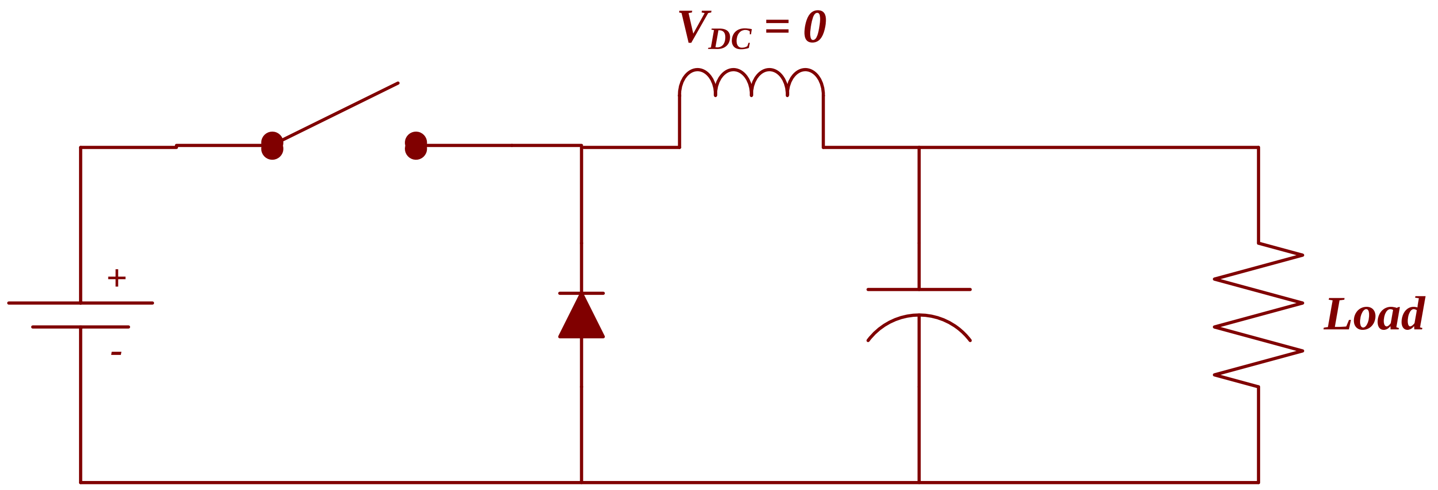
Typical Forward Converters Listed in Order of Increasing Complexity

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

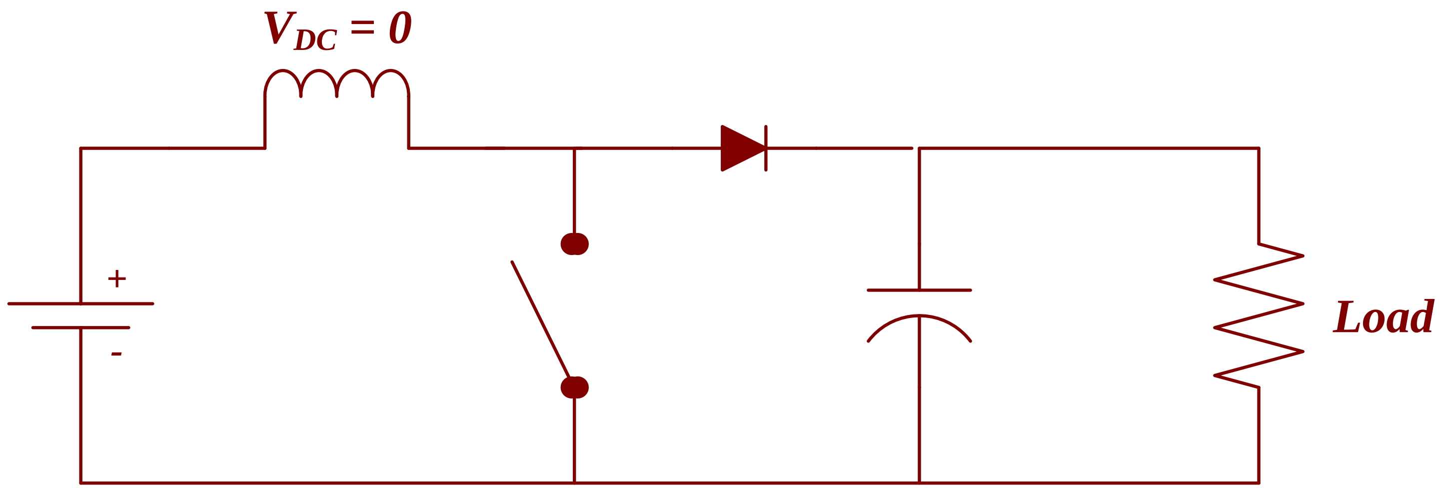
Basic switchmode tool kit



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

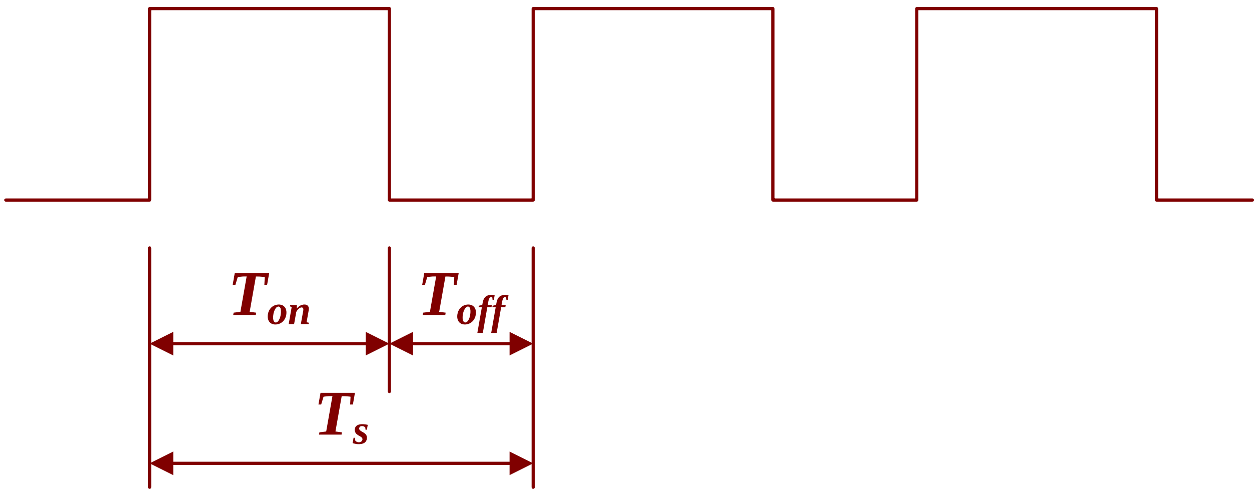


Buck



Boost

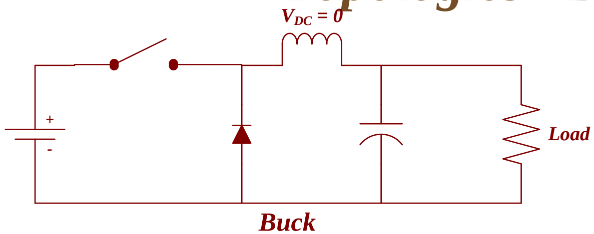
Definition of the Pulse Width Modulated (PWM) Waveform

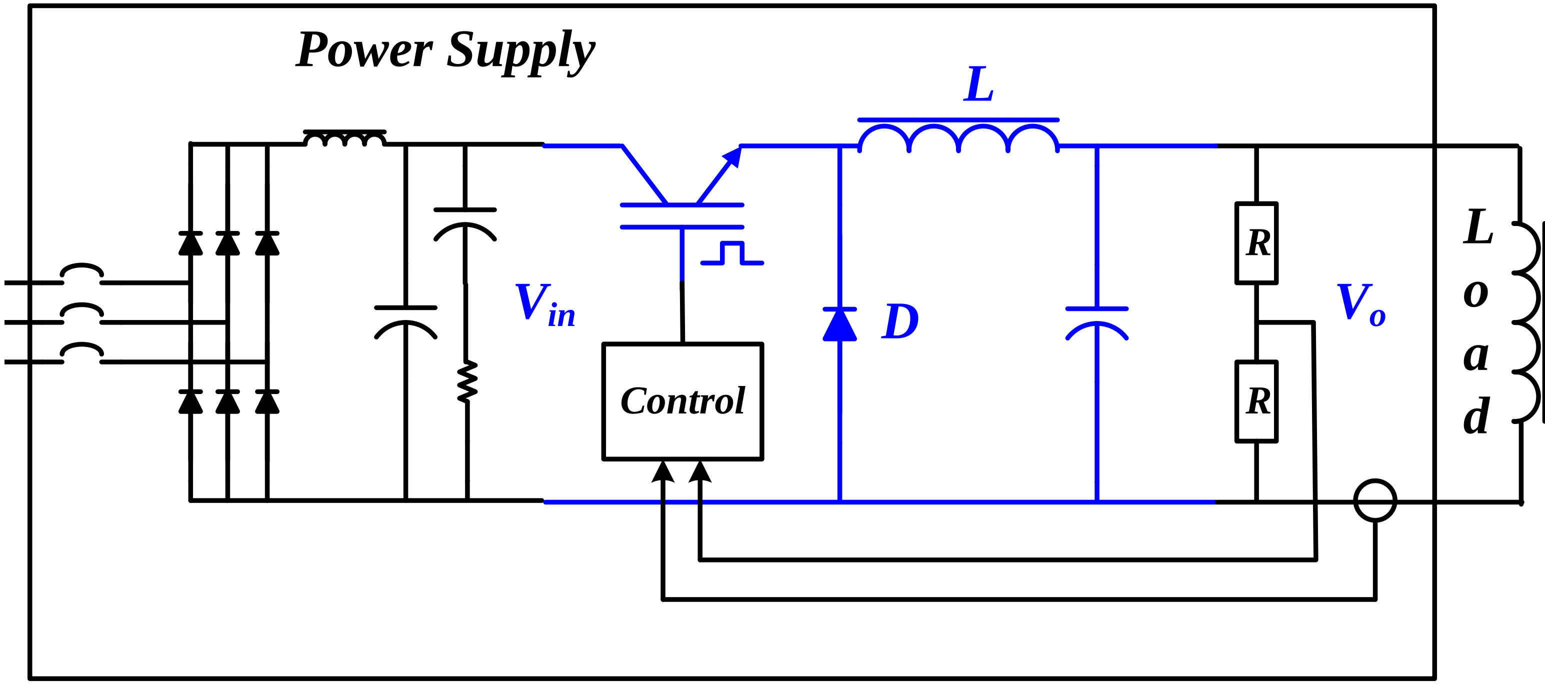


$$Duty\ Cycle = Duty\ \ Ratio = D = \frac{T_{on}}{T_{on} + T_{off}} = \frac{T_{on}}{T_s}$$

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

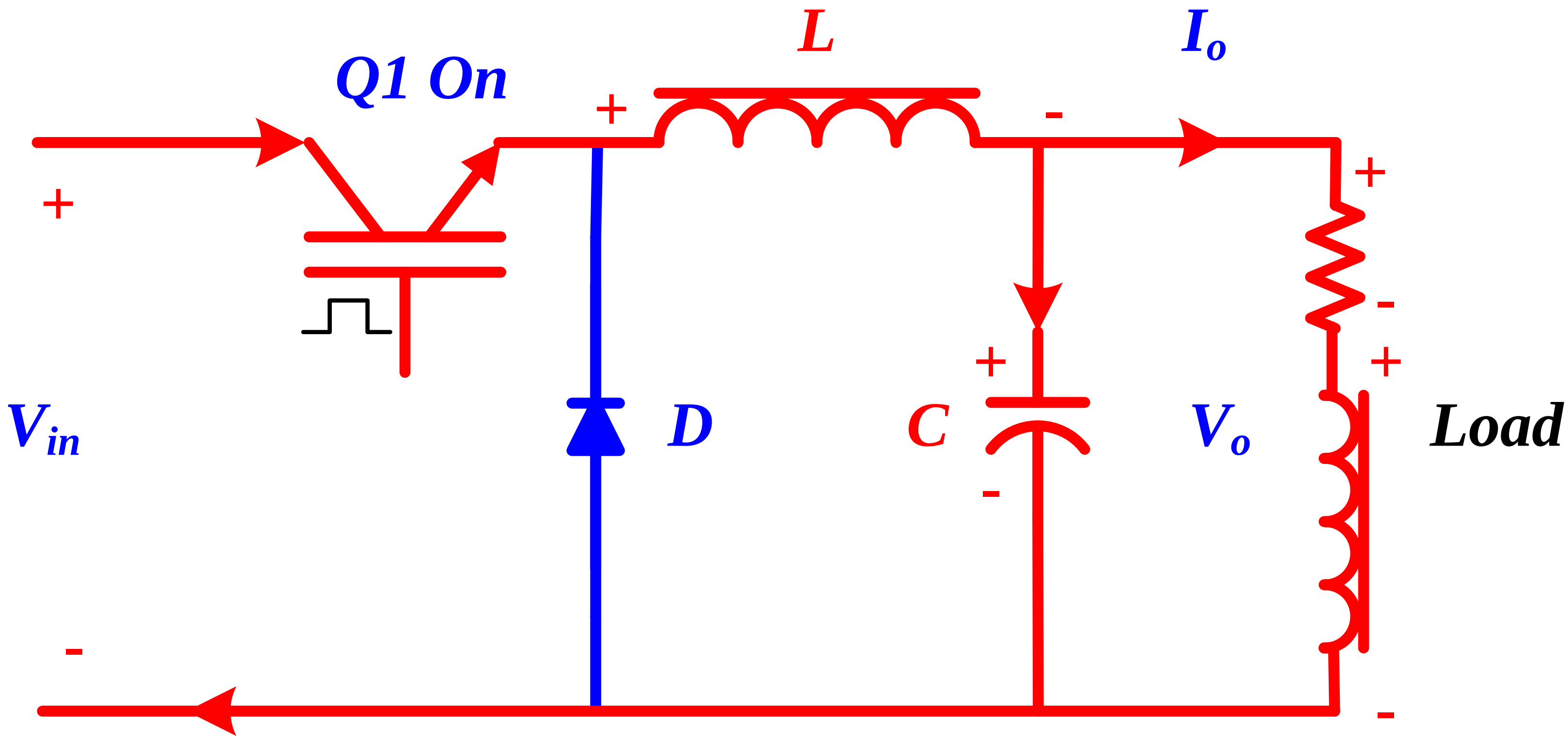
Topologies - Buck Converter (Regulator)





- 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

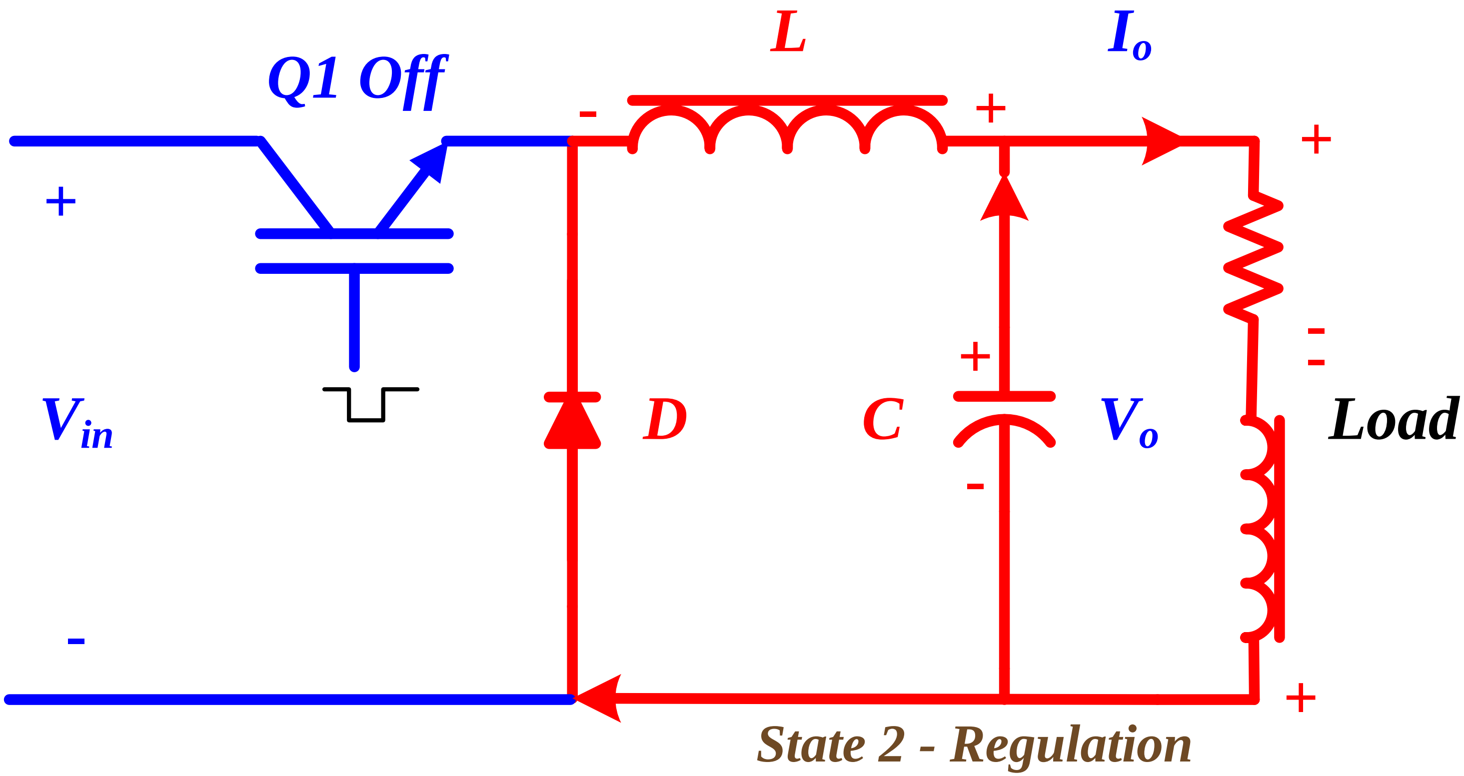
Topologies - Buck Converter



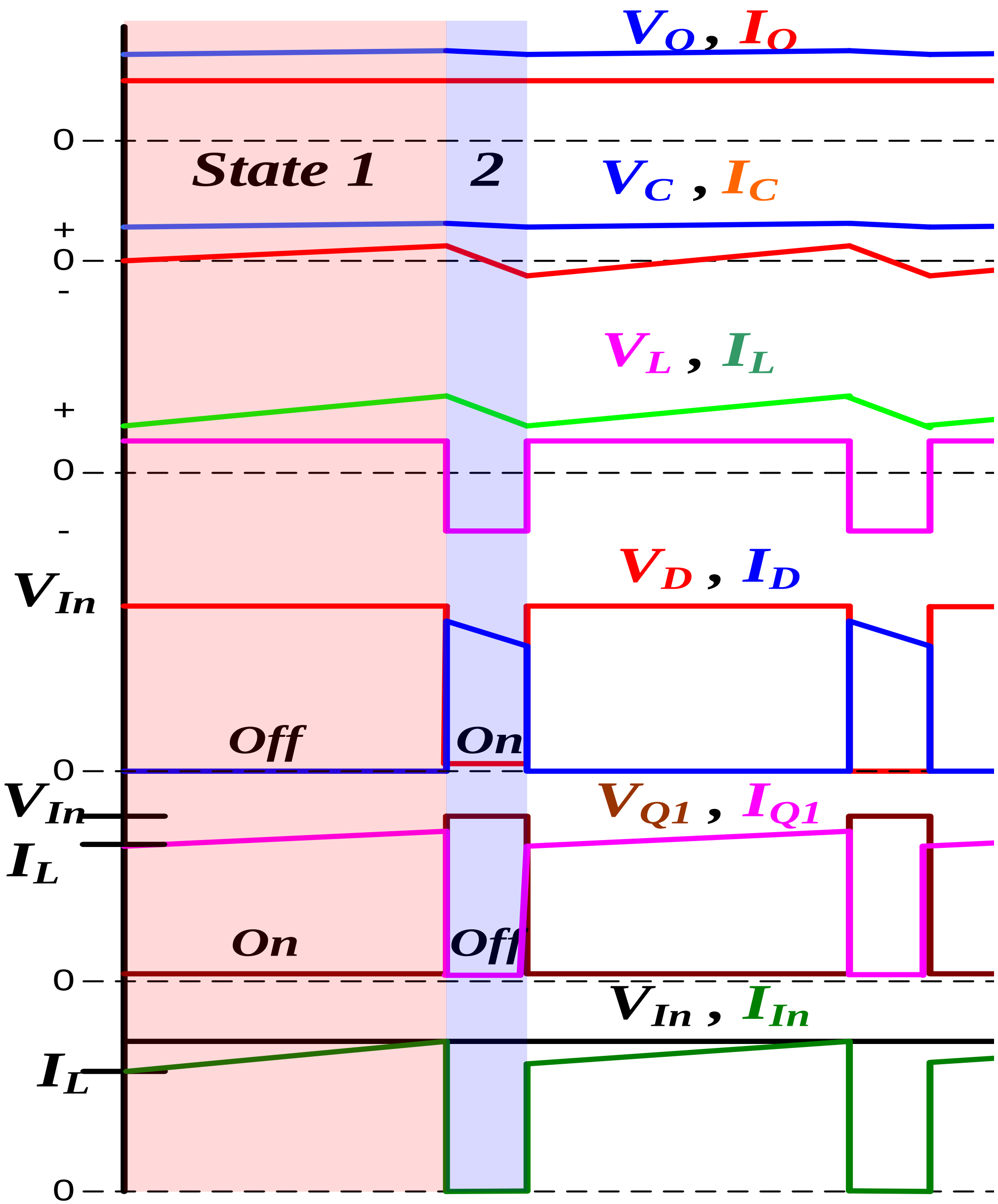
State 1 – Power Transfer

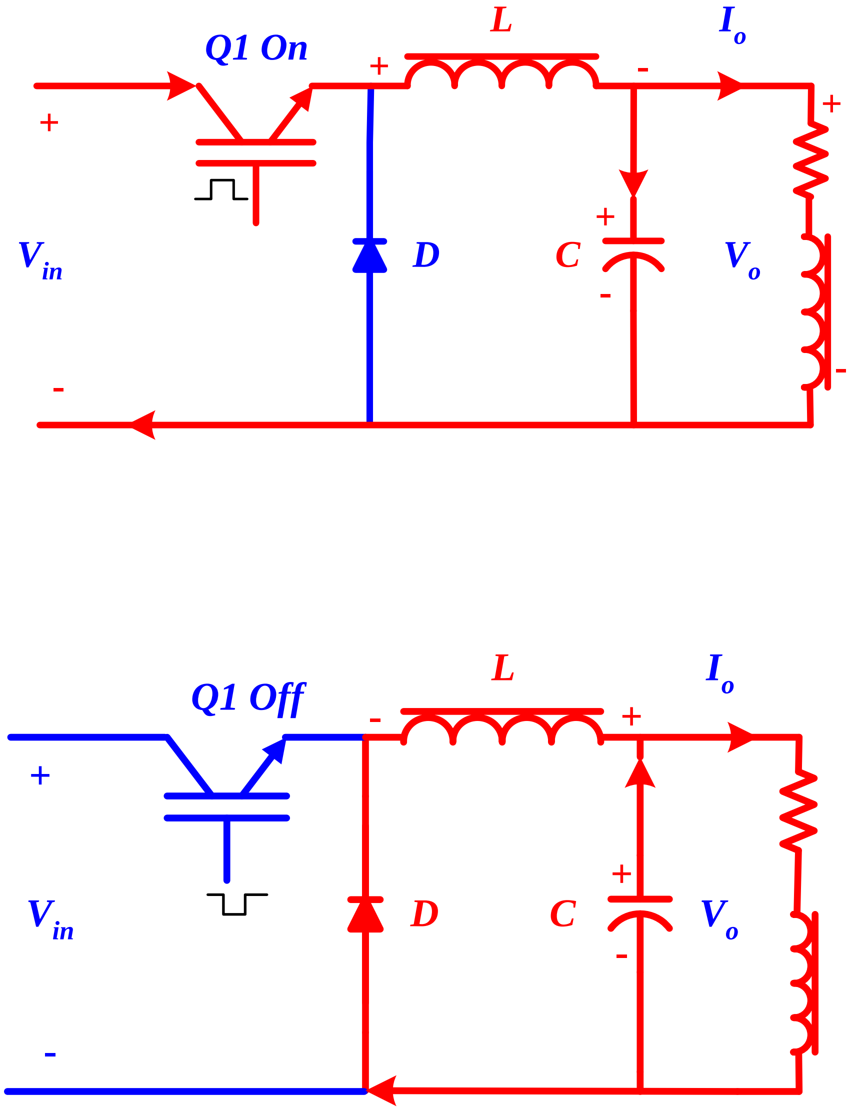
- *Switching device Q1 turned on by square wave drive circuit with controlled on-to-off ratio (duty factor, D)*
- *$V_{in} – V_o$ impressed across L*
- *Current in L increases linearly*
- *Capacitor C charges to Vo*

Topologies - Buck Converter



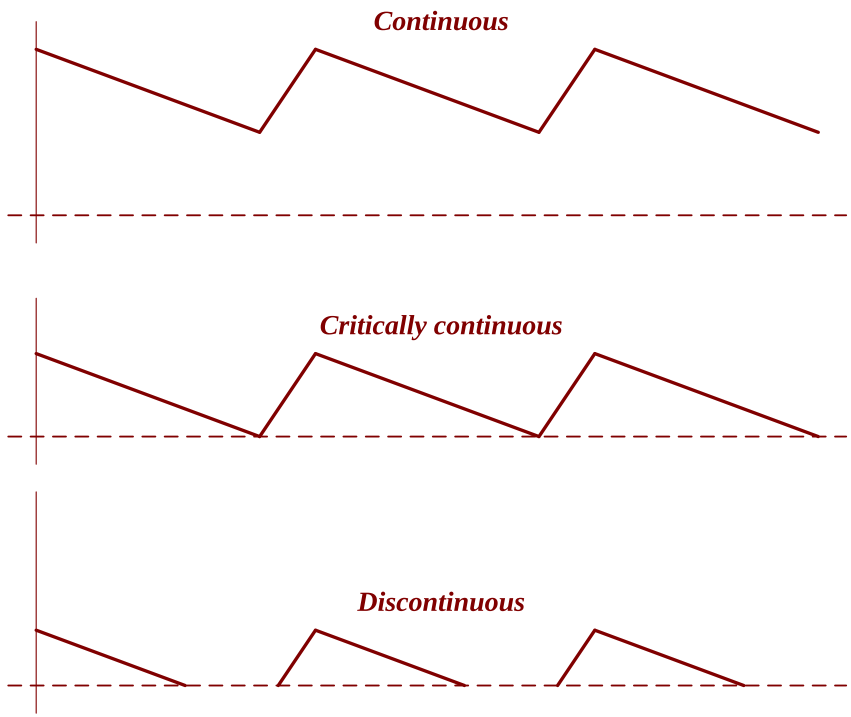
- *Switching device Q1 turns off*
- *Voltage across L reverses: – Vo impressed across L*
- *Diode D turns on*
- *Current in L decreases linearly*
- *C discharges into the Load*


VO , IO
State 1
2
VC , IC
VL , IL
VD , ID
VIn
Off
On
VQ1 , IQ1
VIn
IL
On
Off
VIn , IIn
IL
0
+
-


Q1 On
L
Io
D
C
Vin
Vo
Q1 Off
L
Io
D
C
Vin
Vo

Topologies - Buck Converter Conduction

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 $\neq D^* Vin$*

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 ≤ 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

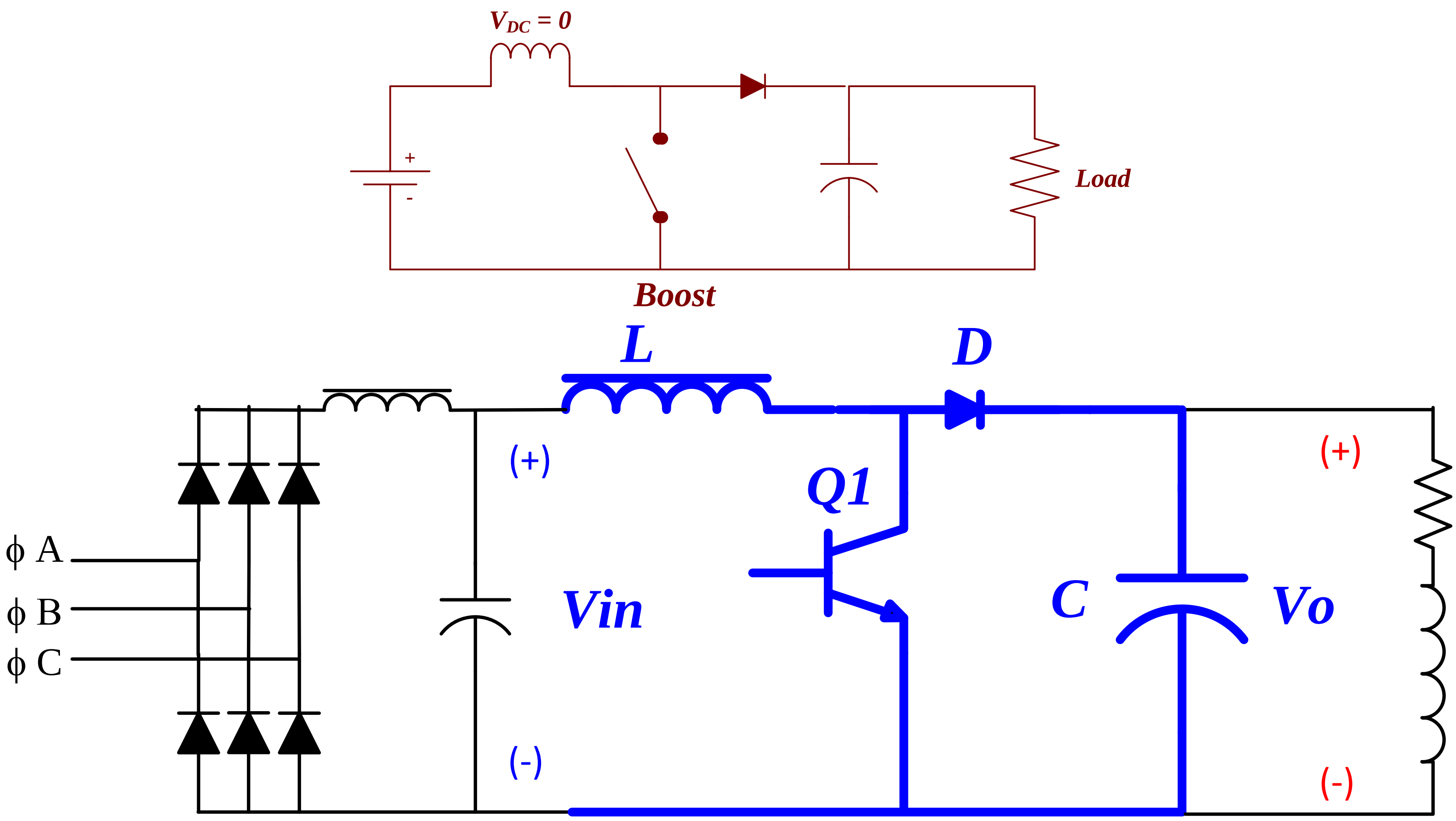
Disadvantages

- 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

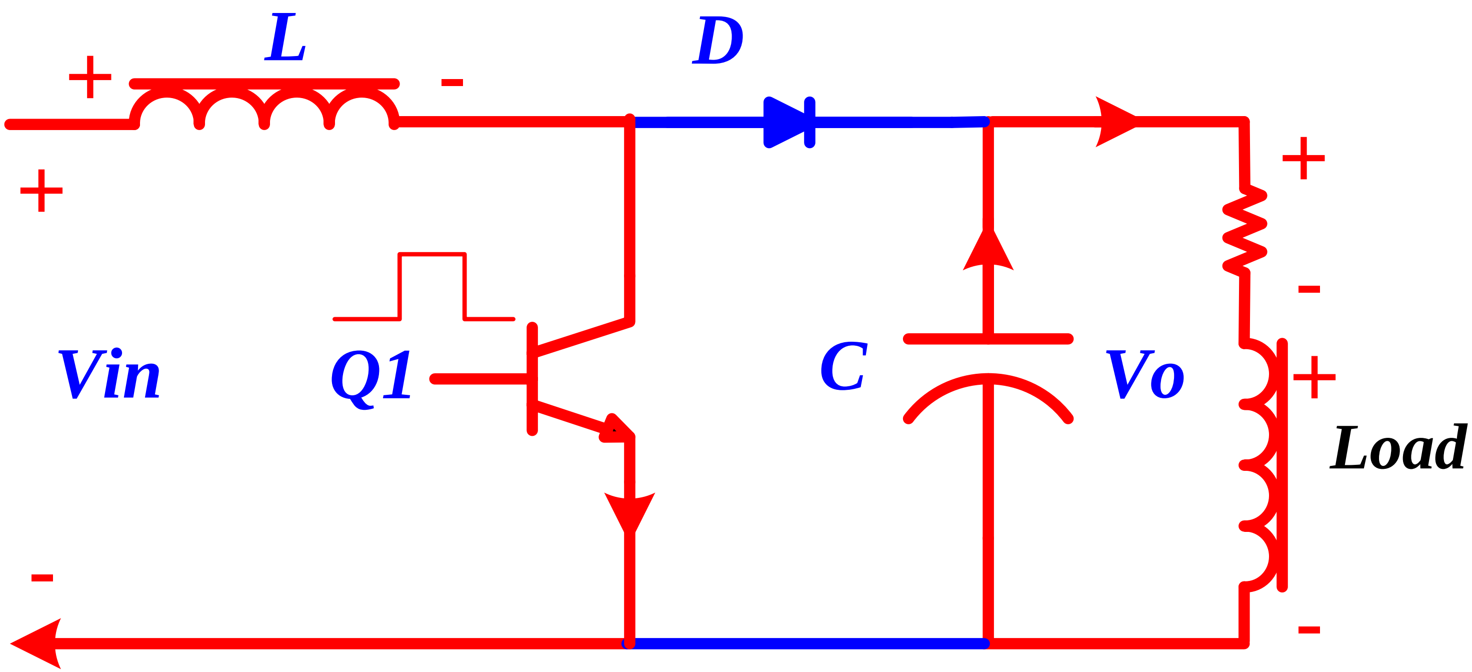
Application

- 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 - Boost Converter

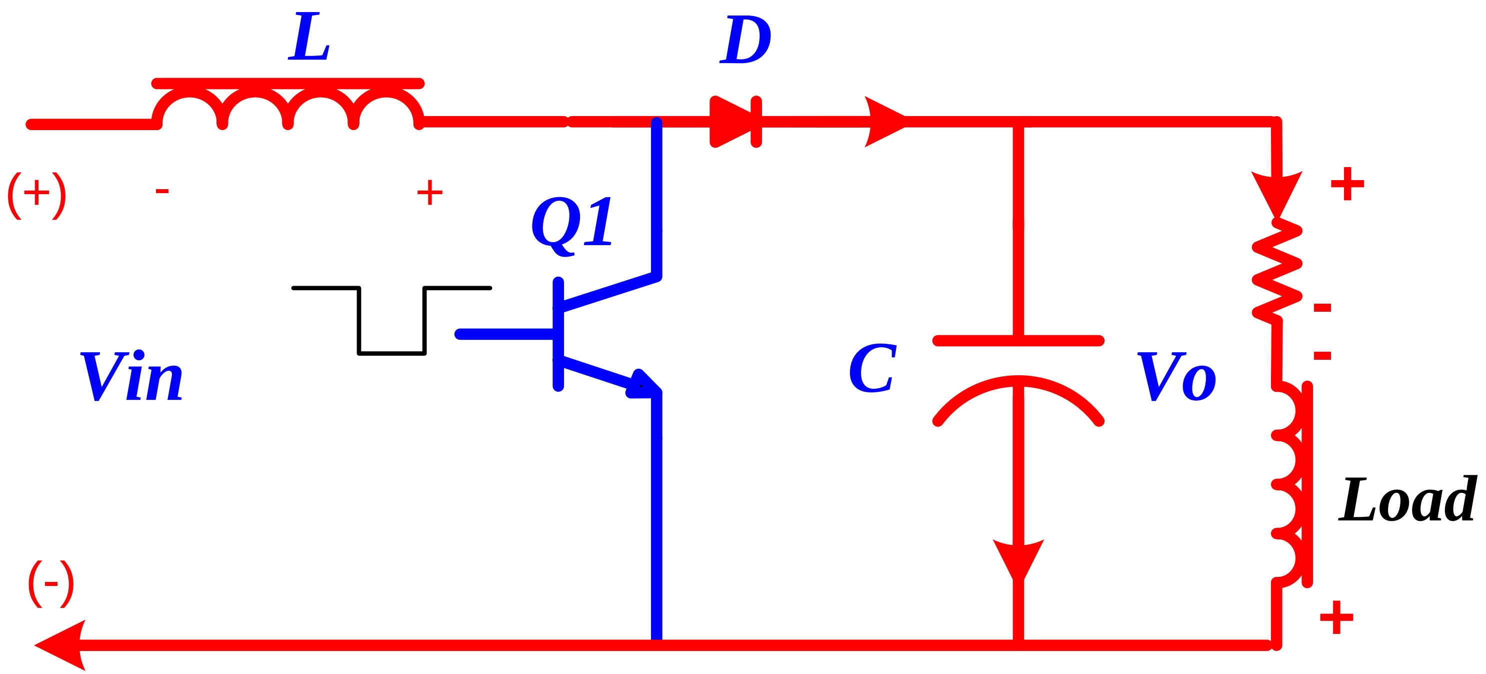


- Boosts the input voltage to a higher output voltage
- Input current is smooth (continuous) – output current is discontinuous (chopped)



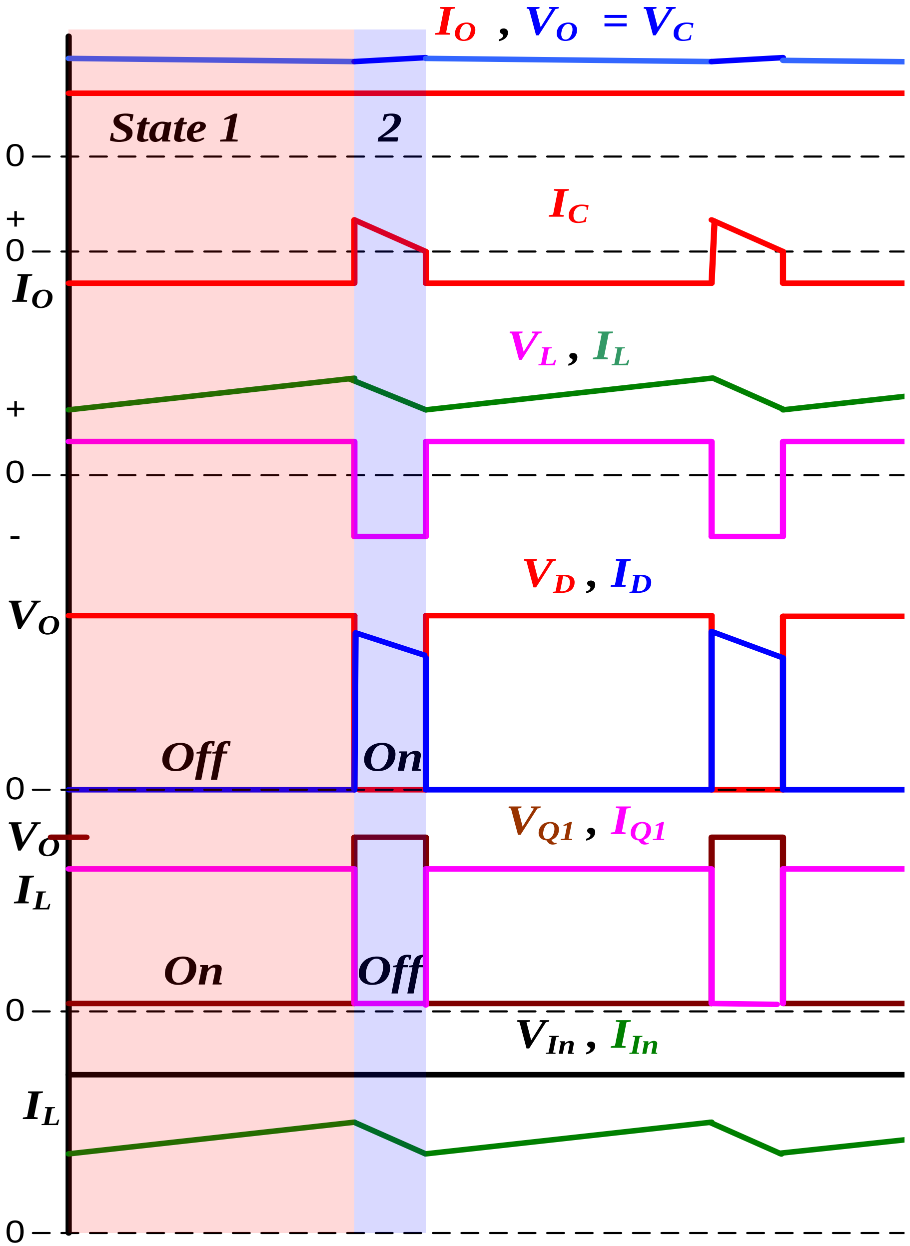
State 1 – Power Transfer

- *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*

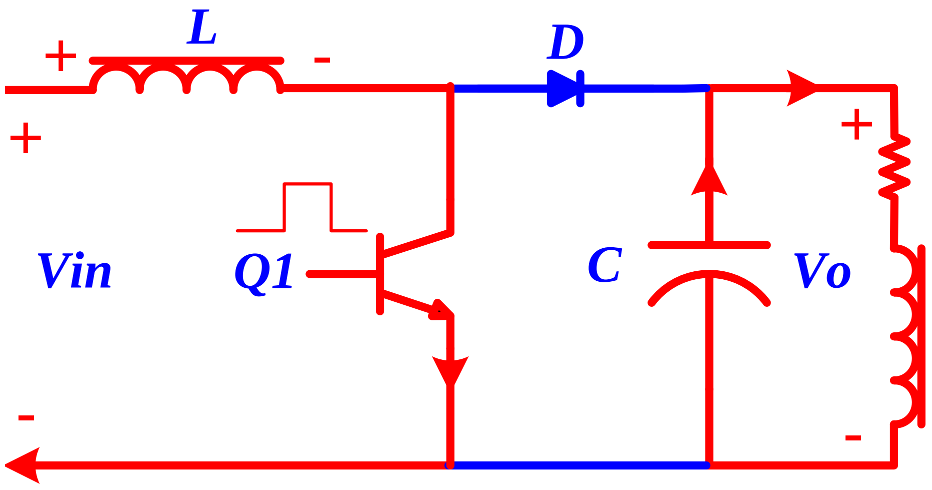


State 2 - Regulation

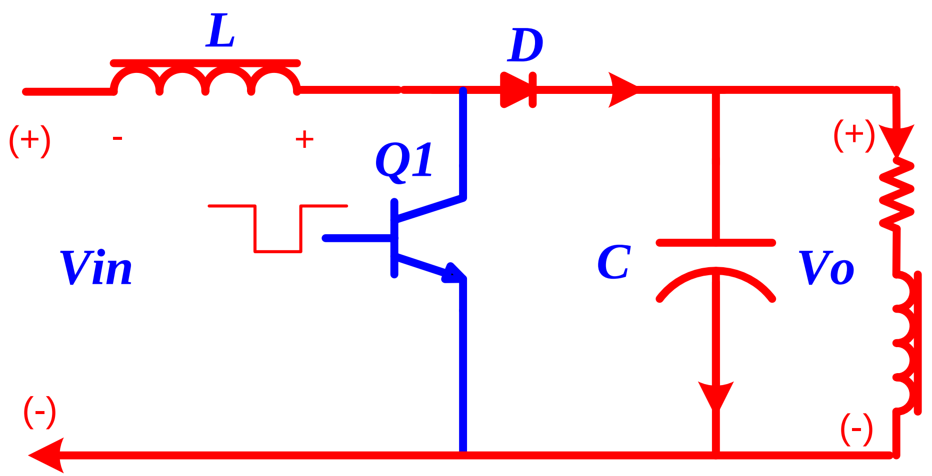
- Q1 turned off. L polarity reverses.
- $V_O = V_{In} + V_L$, $V_L = V_O - V_{In}$
- $V_O > V_{In}$, L current decreases linearly
- Diode D is forward biased (closed)
- Capacitor C is recharged



I_O , V_O = V_C
State 1
2
0
+
0
I_C
I_O
V_L , I_L
+
0
-
V_D , I_D
V_O
Off
On
0
V_{Q1} , I_{Q1}
V_O
I_L
On
Off
0
V_{In} , I_{In}
I_L
0



+
L
-
D
+
+
Vin
Q1
C
Vo
-
-



L
D
(+)
-
+
Q1
(+)
Vin
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).*

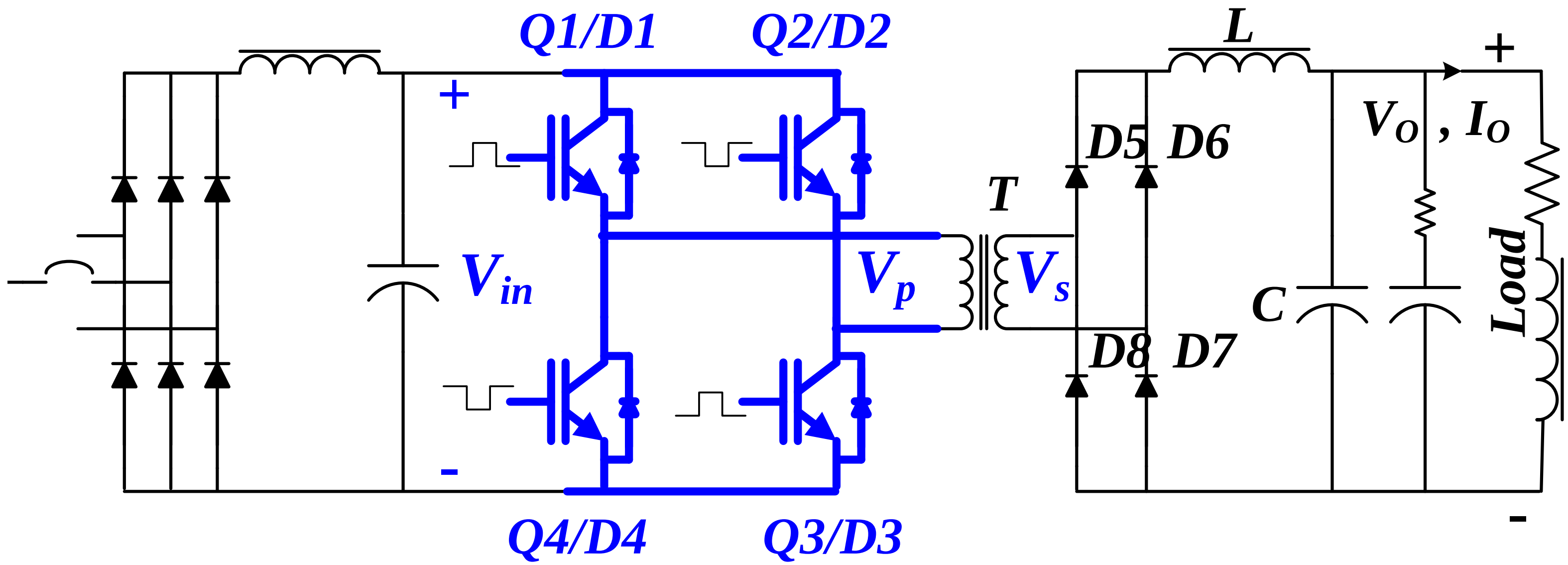
Some Advantages

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

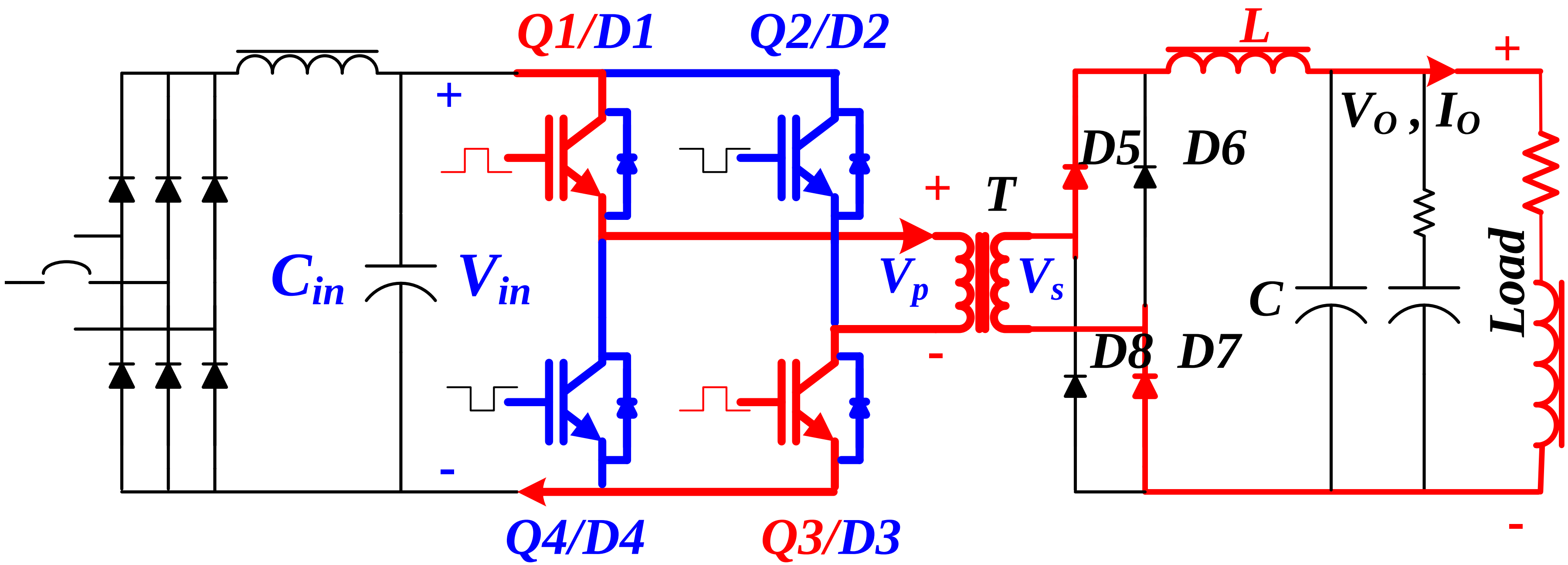
Some Disadvantages

- *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 - Full-Bridge Converter

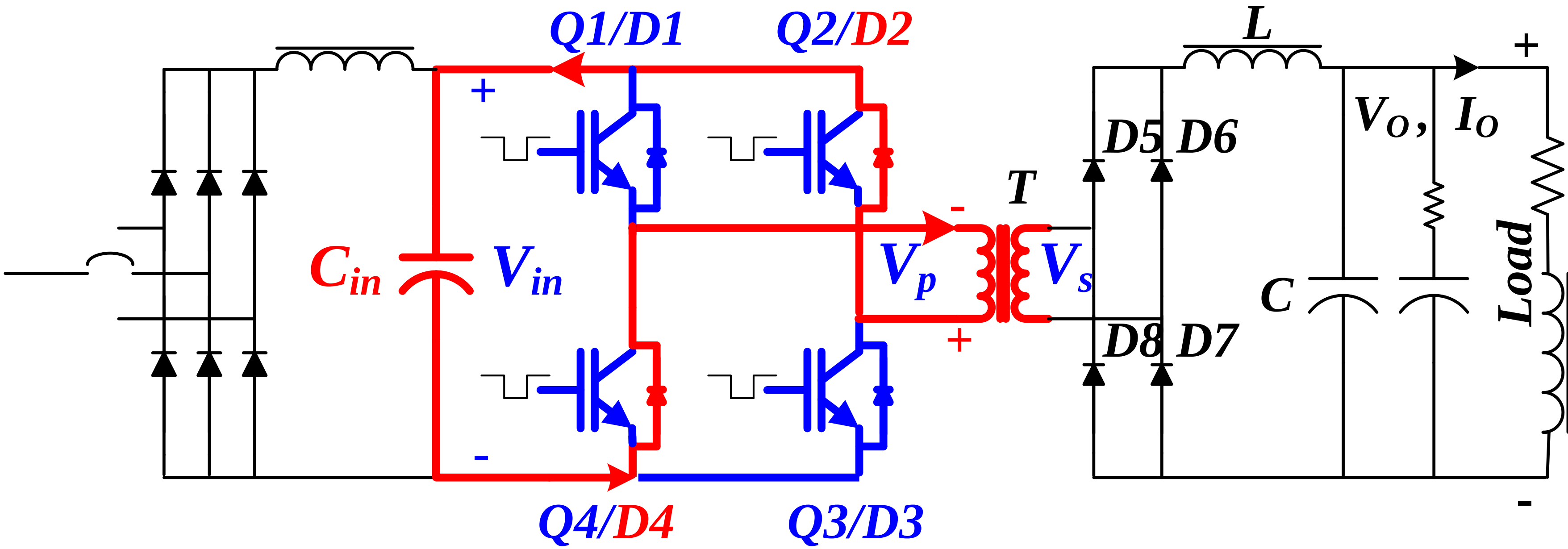


- *Full wave rectifier, output ripple is multiples of the input frequency*
- *Equal in popularity to buck topology for high-power converters*
- *Used when line and load voltages are not matched*
- *Voltage stress on switches = input voltage*
- *Good transformer utilization, power is transmitted on both half-cycles*



State 1 - Power

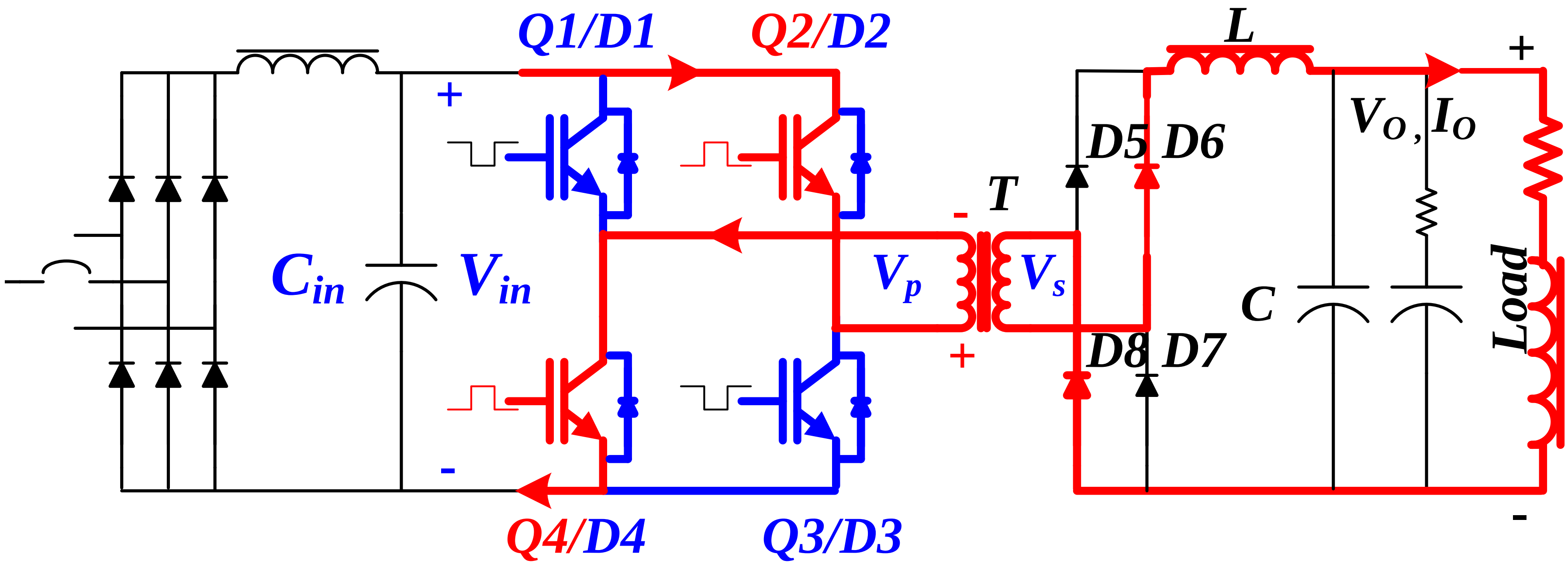
- *Power is derived from the input rectifier and slugs of energy from C_{in}*
- *Q1 and Q3 are closed. Current flows through Q1 and the primary winding of T and Q3*
- *A voltage (V_{in}) is developed across the primary winding of T. A similar voltage is (V_{in} *N) is developed across the secondary winding of T*
- *The secondary voltage causes rectifiers D5 and D7 to conduct current*



State 2 - Power Off

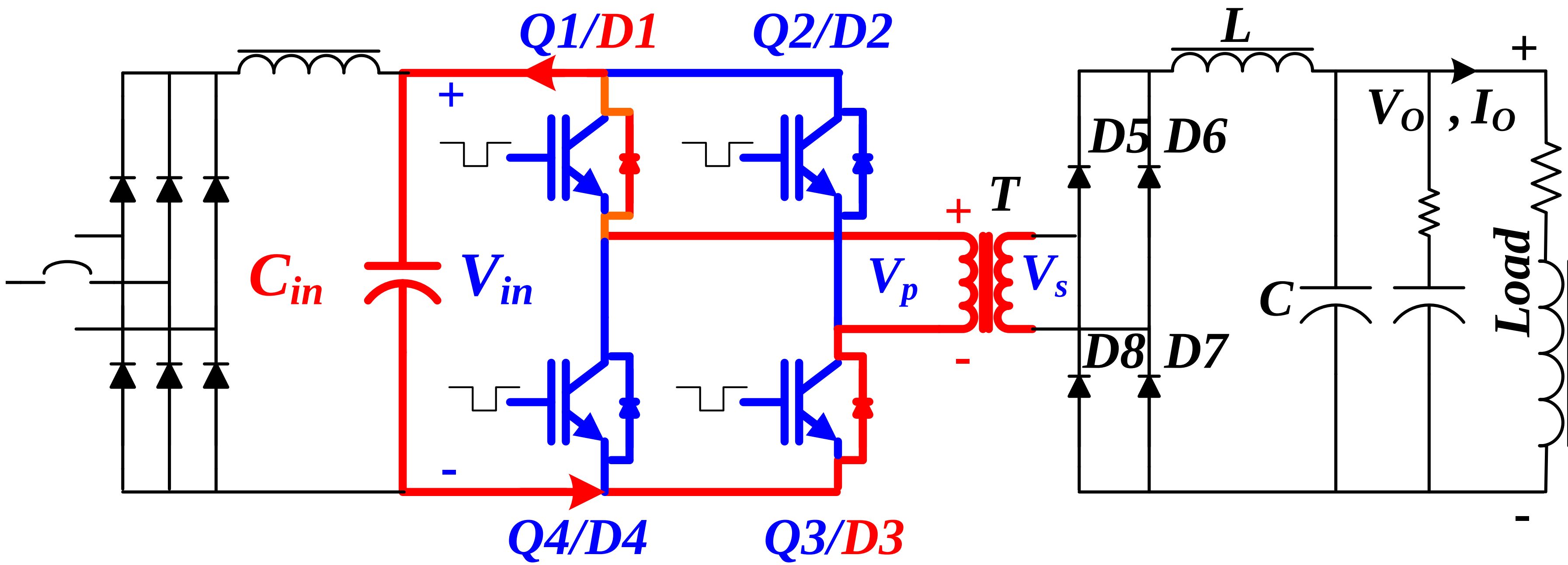
- *Q1 and Q3 are turned off. All switches are off*
- *C_{in} recharges*
- *The transformer primary current flows in the same direction but the voltage reverses polarity. This causes D2 and D4 to conduct. Stored leakage inductance energy is returned to the input filter capacitor. The transformer current 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



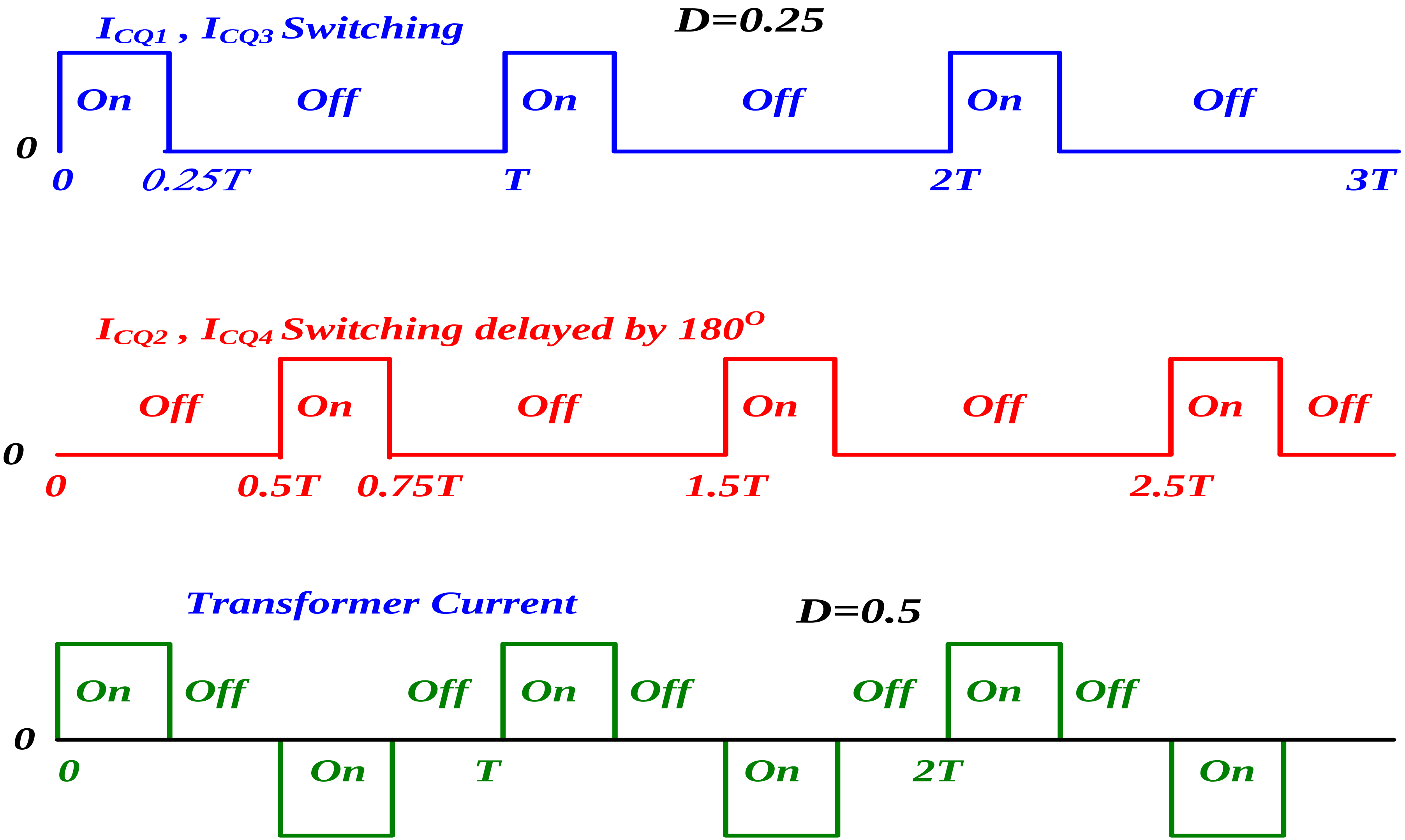
State 3 - Power

- 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

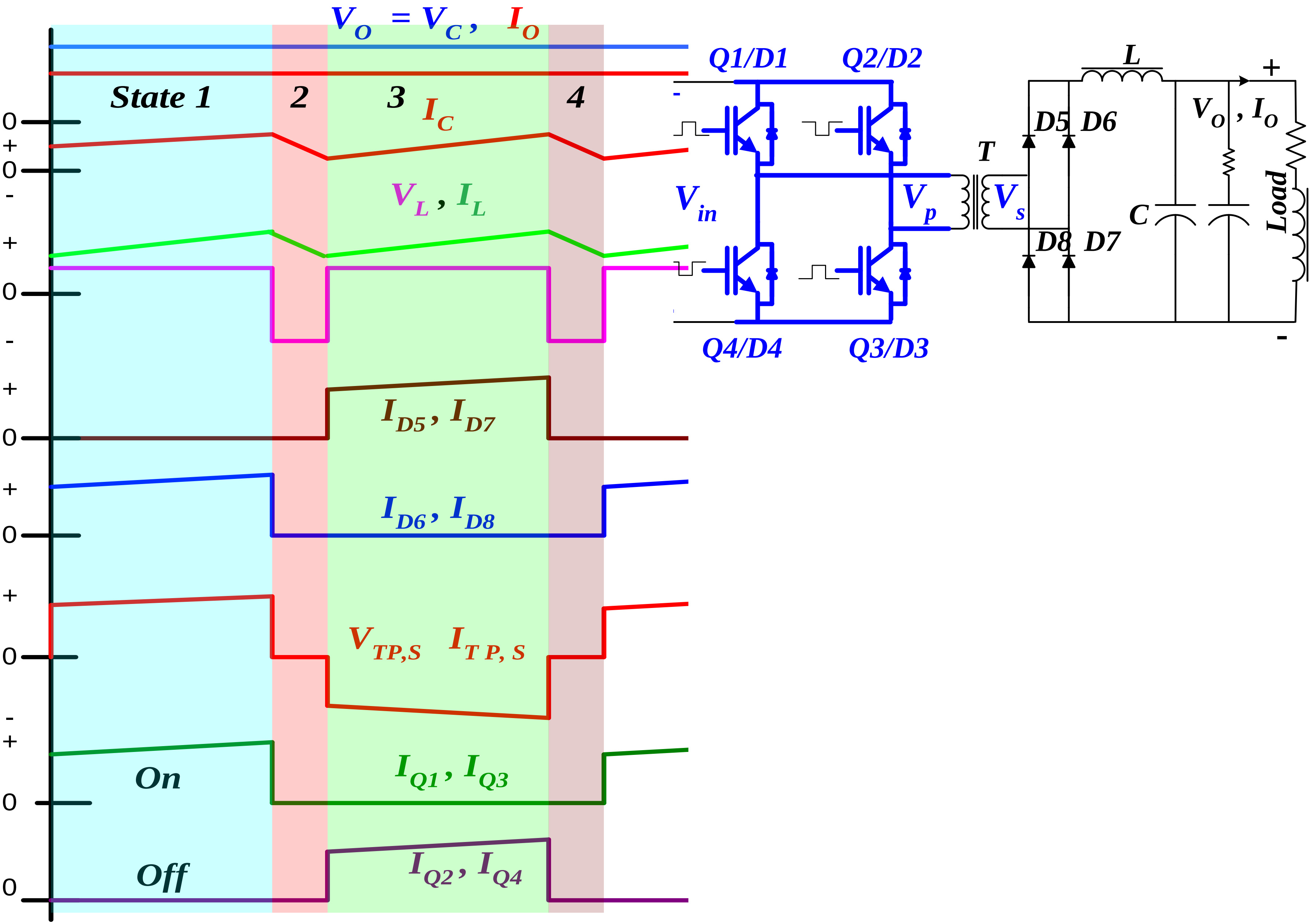


State 4 – Power Off

- *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

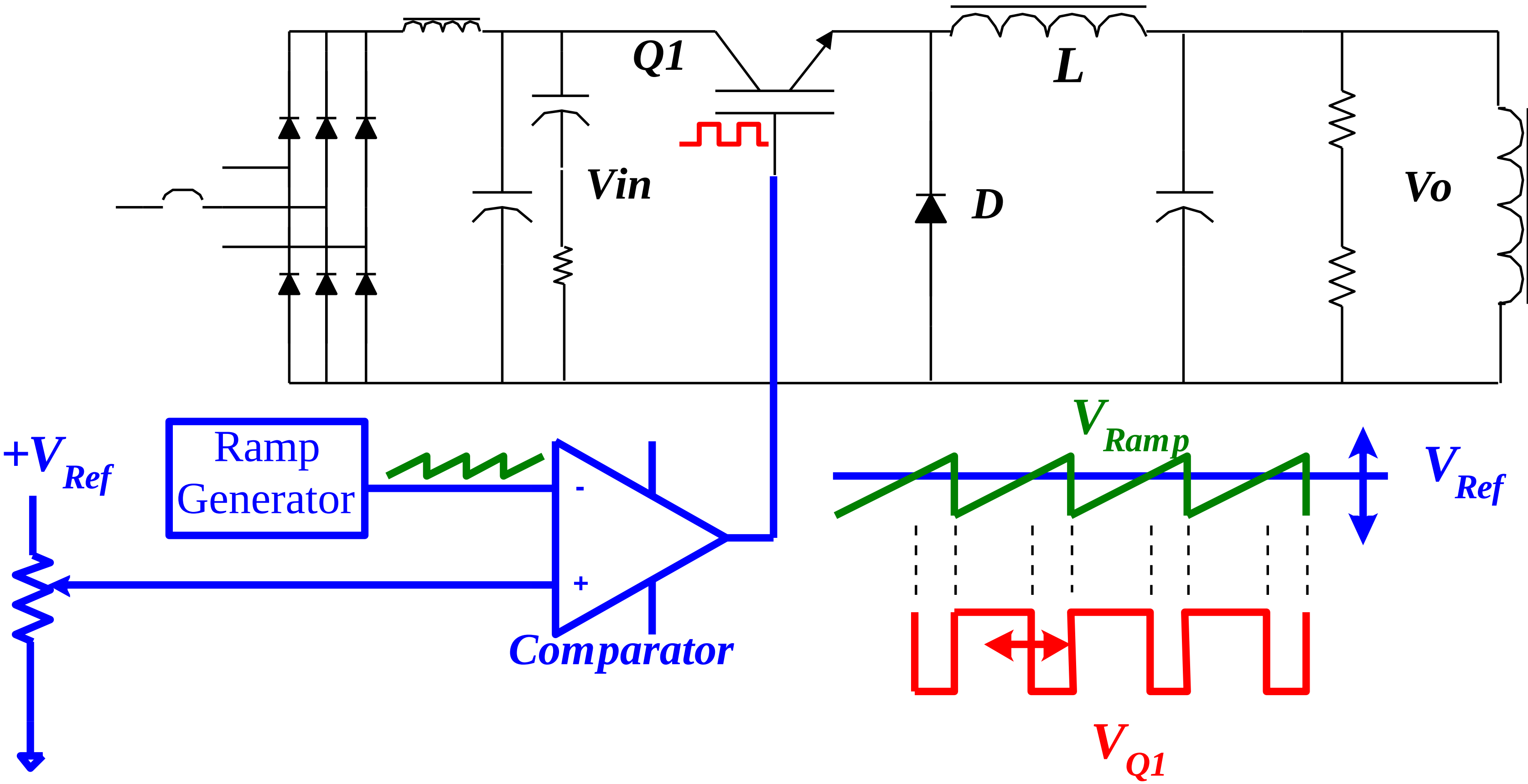
- *Four (4) switches are required, and since 2 switches operate in series, the effective saturated on-state power loss is somewhat greater than in the 2 switch, half-bridge case. In high voltage, off-line switching systems, these losses are acceptably small.*

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*

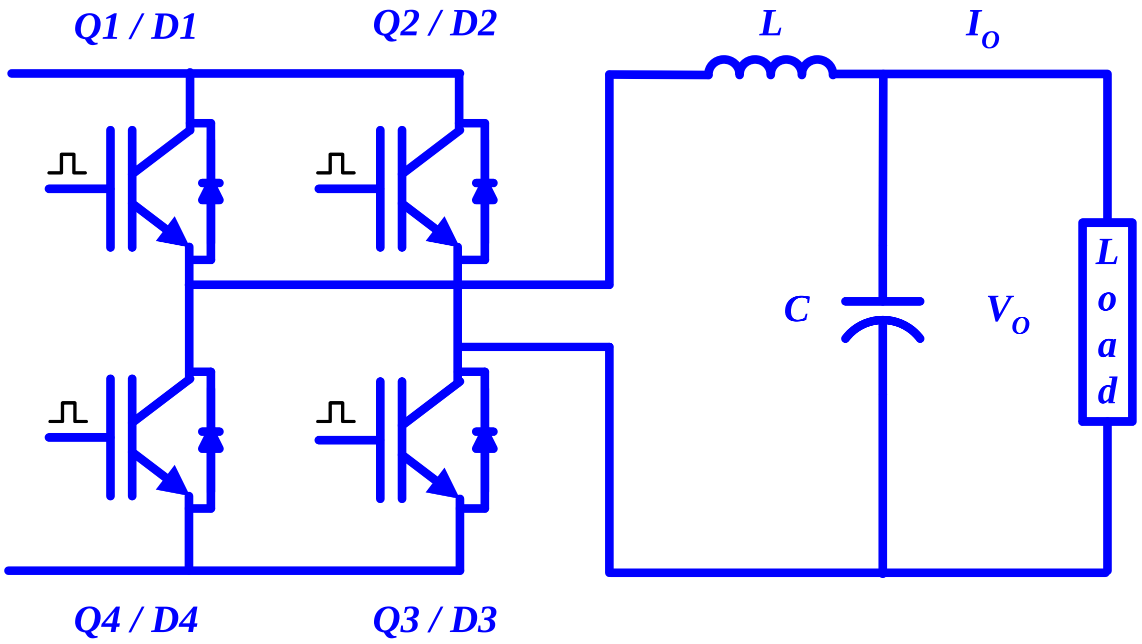
Pulse Width Modulation (PWM) Techniques

Pulse Width Modulation



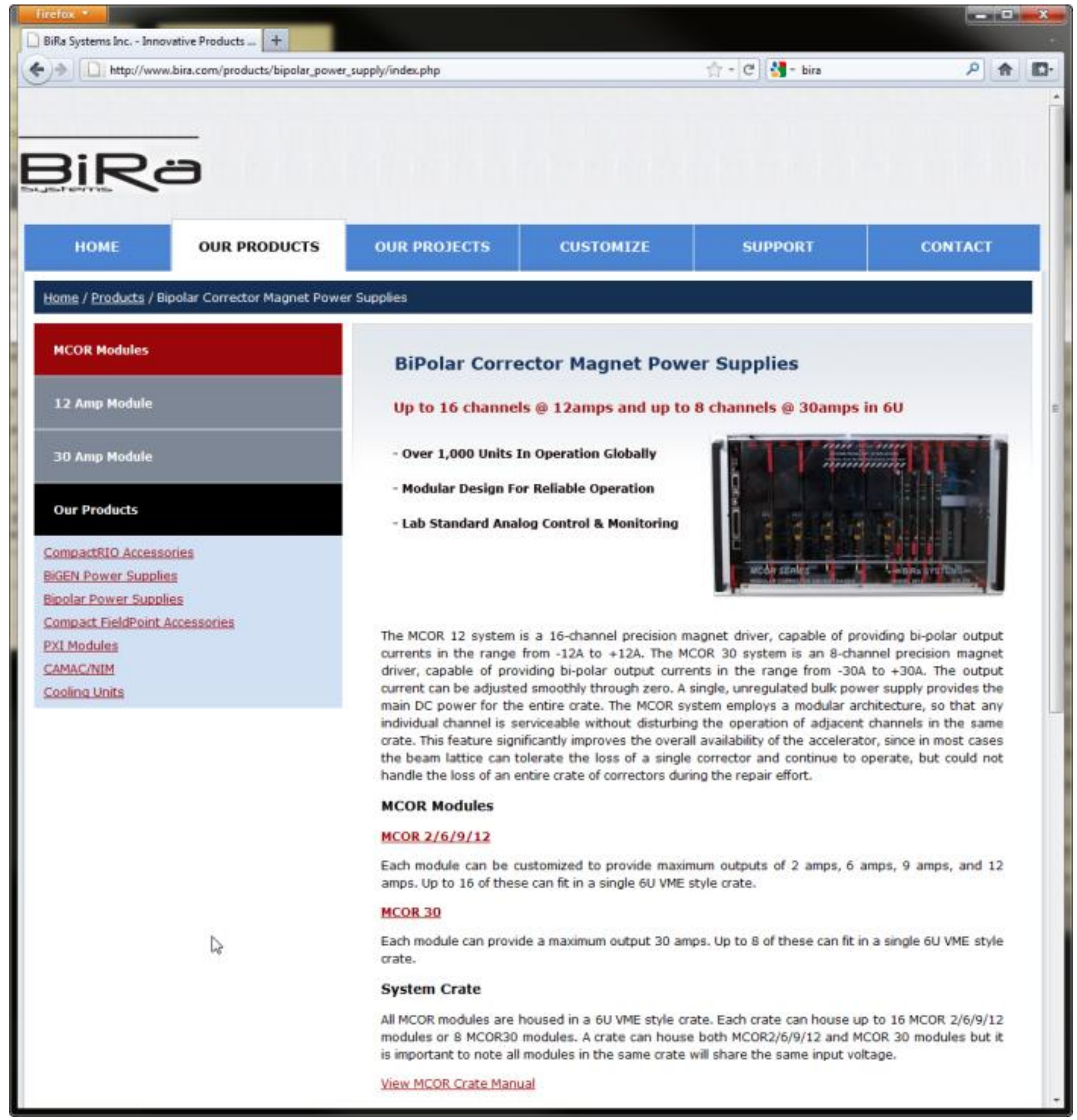
V_{Ref}	$V_{Ref} - V_{Ramp} = V_{Q1}$ pulse width	V_O
$V_{Ref} \downarrow$	$V_{Ref} - V_{Ramp} = V_{Q1}$ pulse width $\downarrow$	$V_O \downarrow$

PWM - Bipolar Bridge



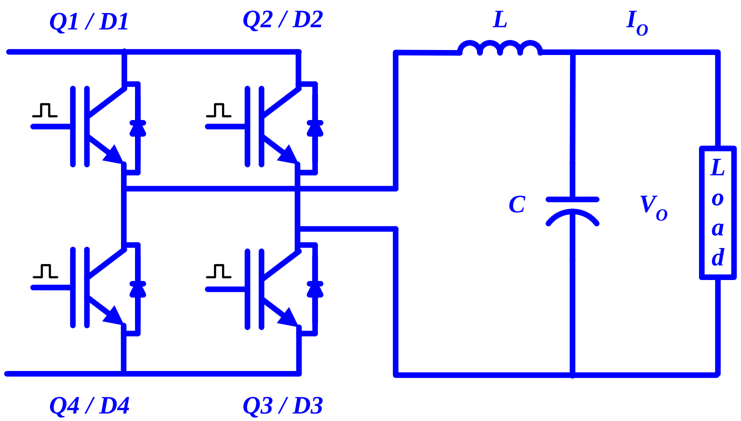
PWM - Bipolar Bridge

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

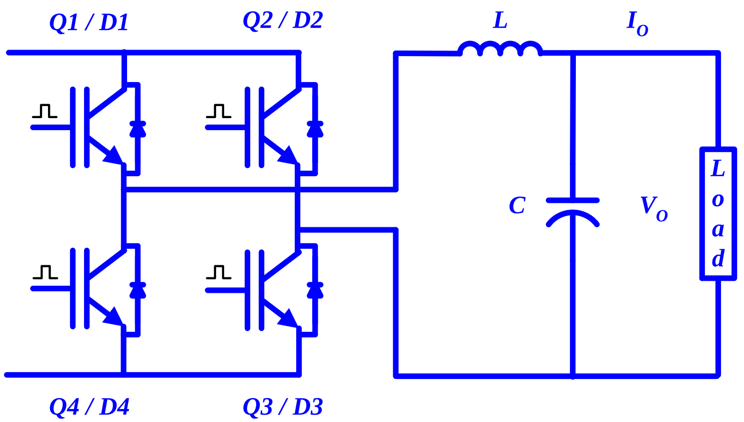
Two types of PWM

- *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*

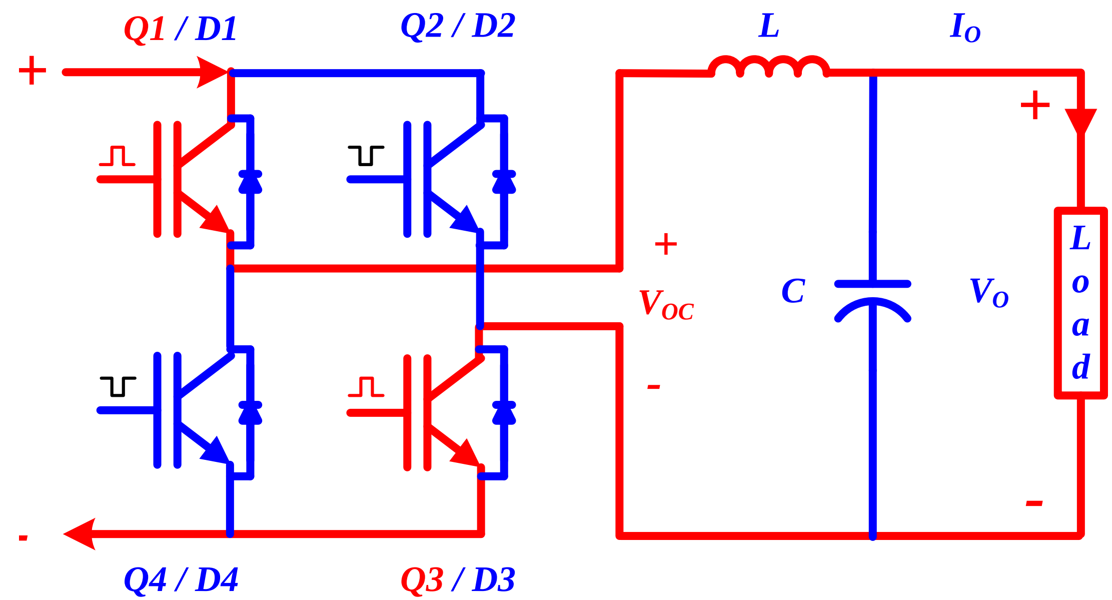
PWM - Bipolar Bridge – Sign / Magnitude PWM

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

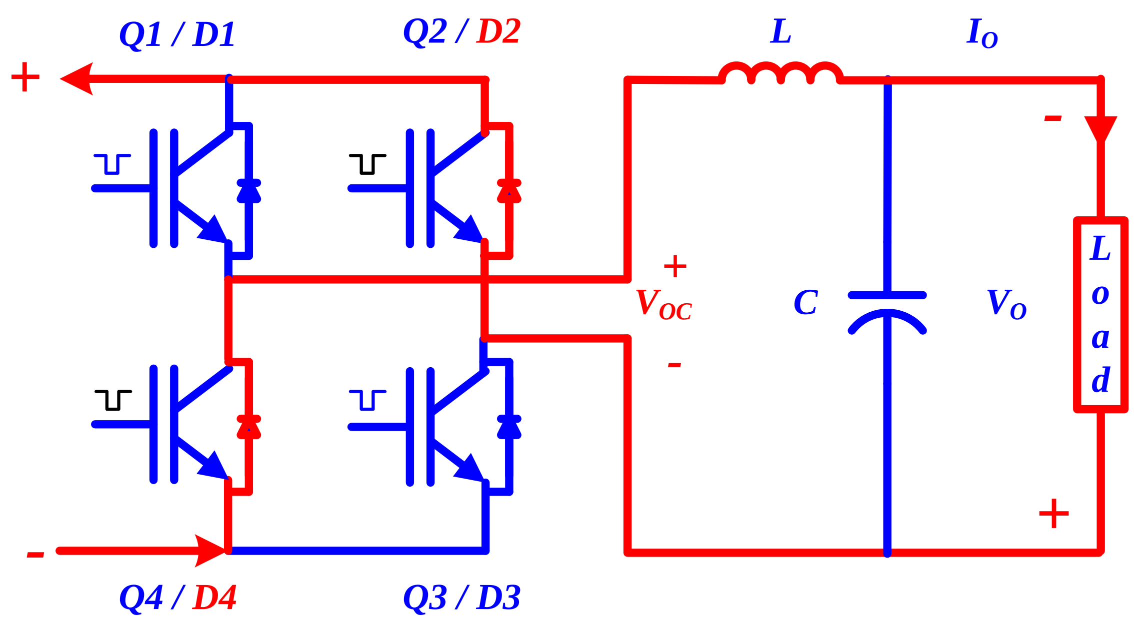


- Switch only one leg at a time
- The 2 switches in the active leg switch on and off together

Bipolar Bridge – Sign / Magnitude PWM – (+) Output

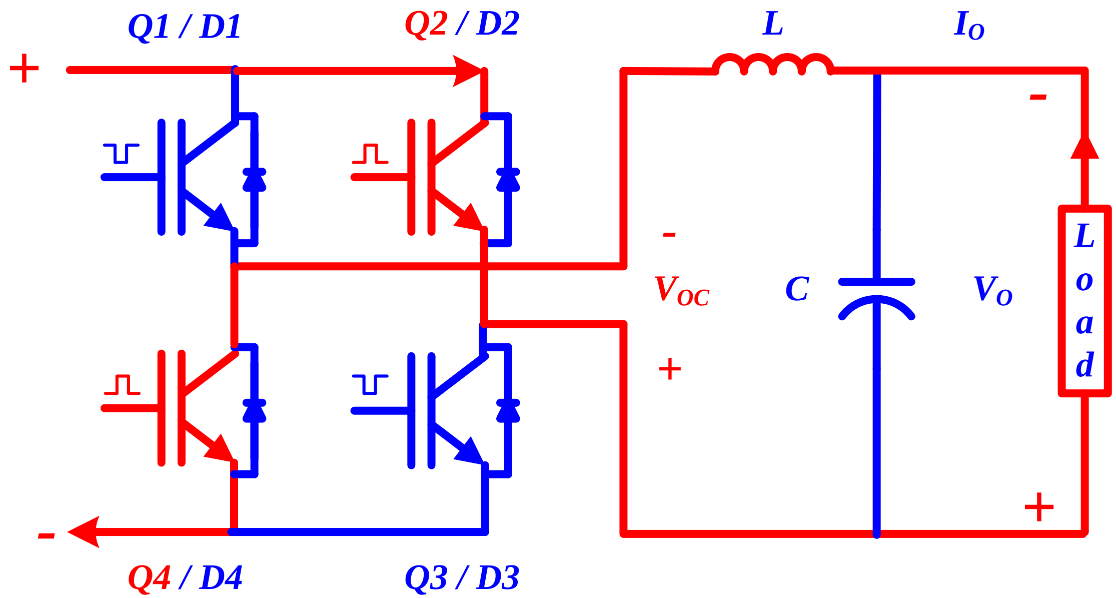


Q1/Q3 closed

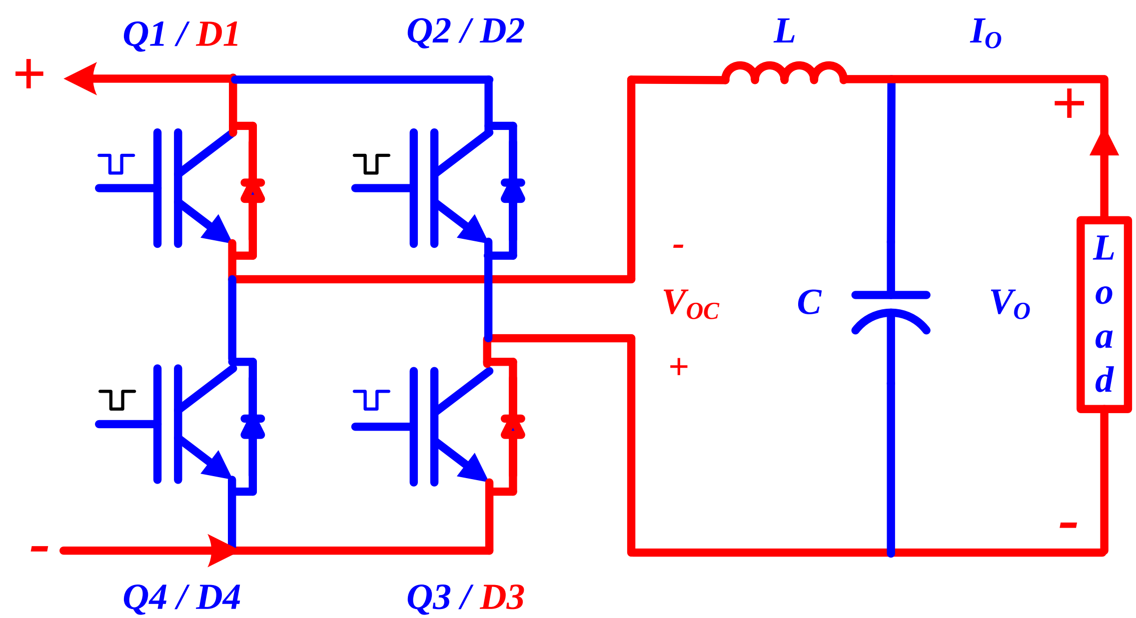


Q1/Q3 opened

Bipolar Bridge – Sign / Magnitude PWM – (-) Output

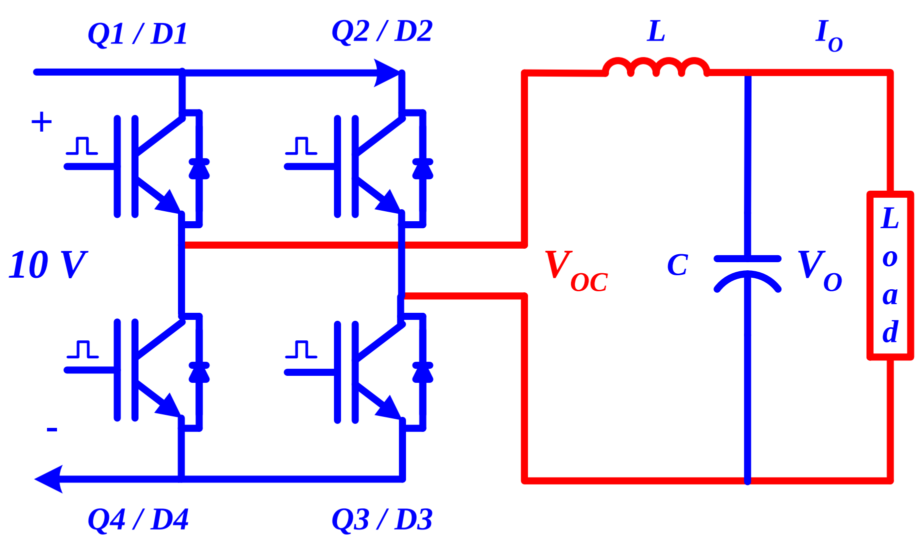


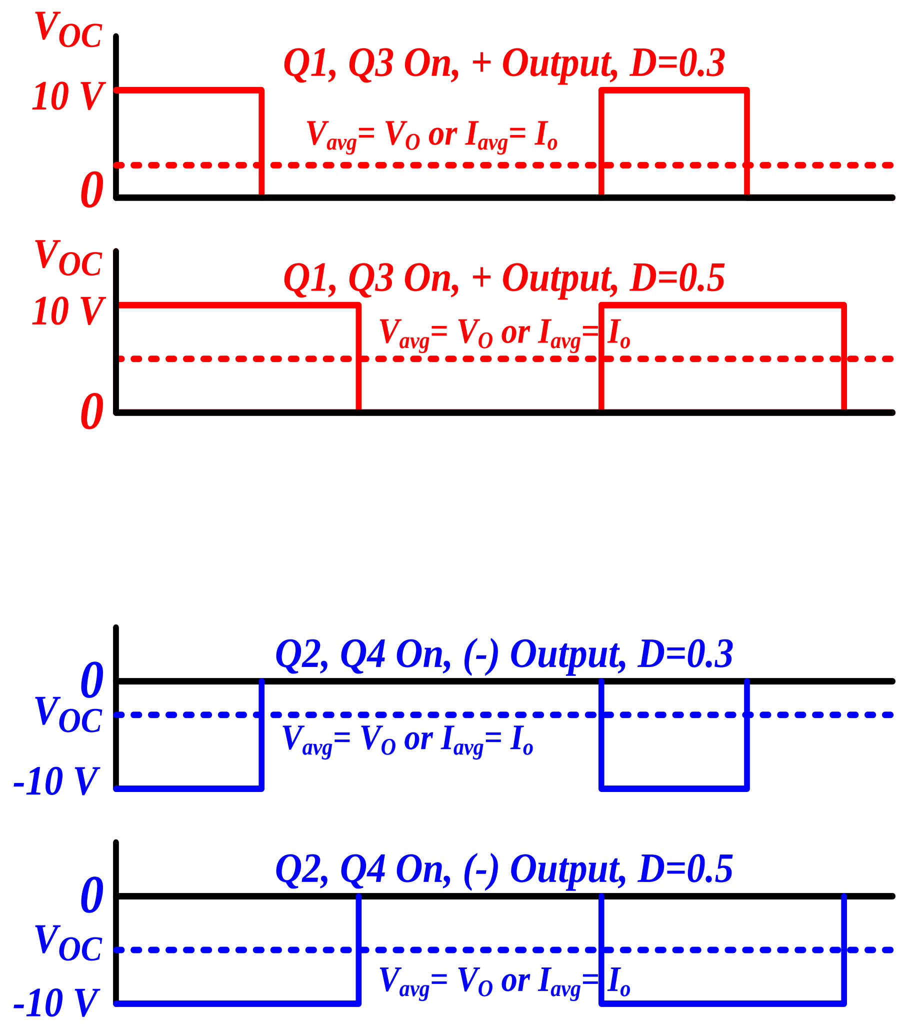
Q2/Q4 closed



Q2/Q4 opened

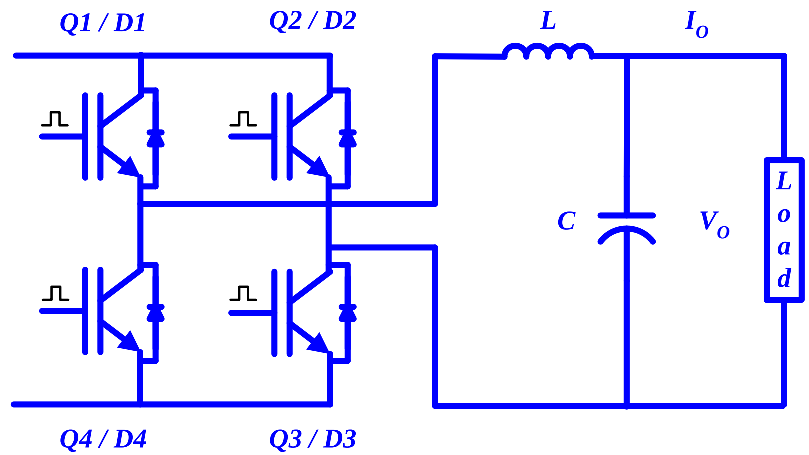
Bipolar Bridge – Sign / Magnitude PWM - Waveforms





“50/50” Bipolar PWM

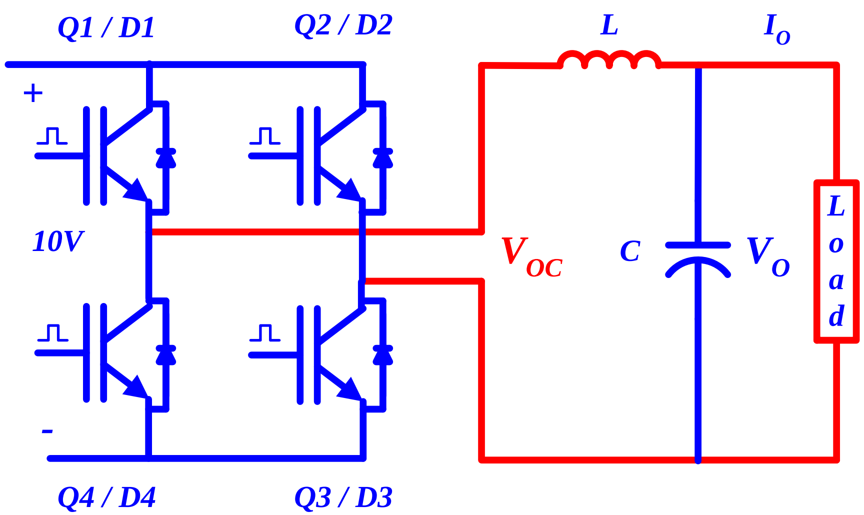
Desired Output Reference Signal	Q1/Q3D	Q2/Q4 D
-100%	0.0%	100.0%
-75%	12.5%	87.5%
-50%	25.0%	75.0%
-25%	37.5%	62.5%
0%	50.0%	50.0%
25%	62.5%	37.5%
50%	75.0%	25.0%
75%	87.5%	12.5%
100%	100.0%	0.0%



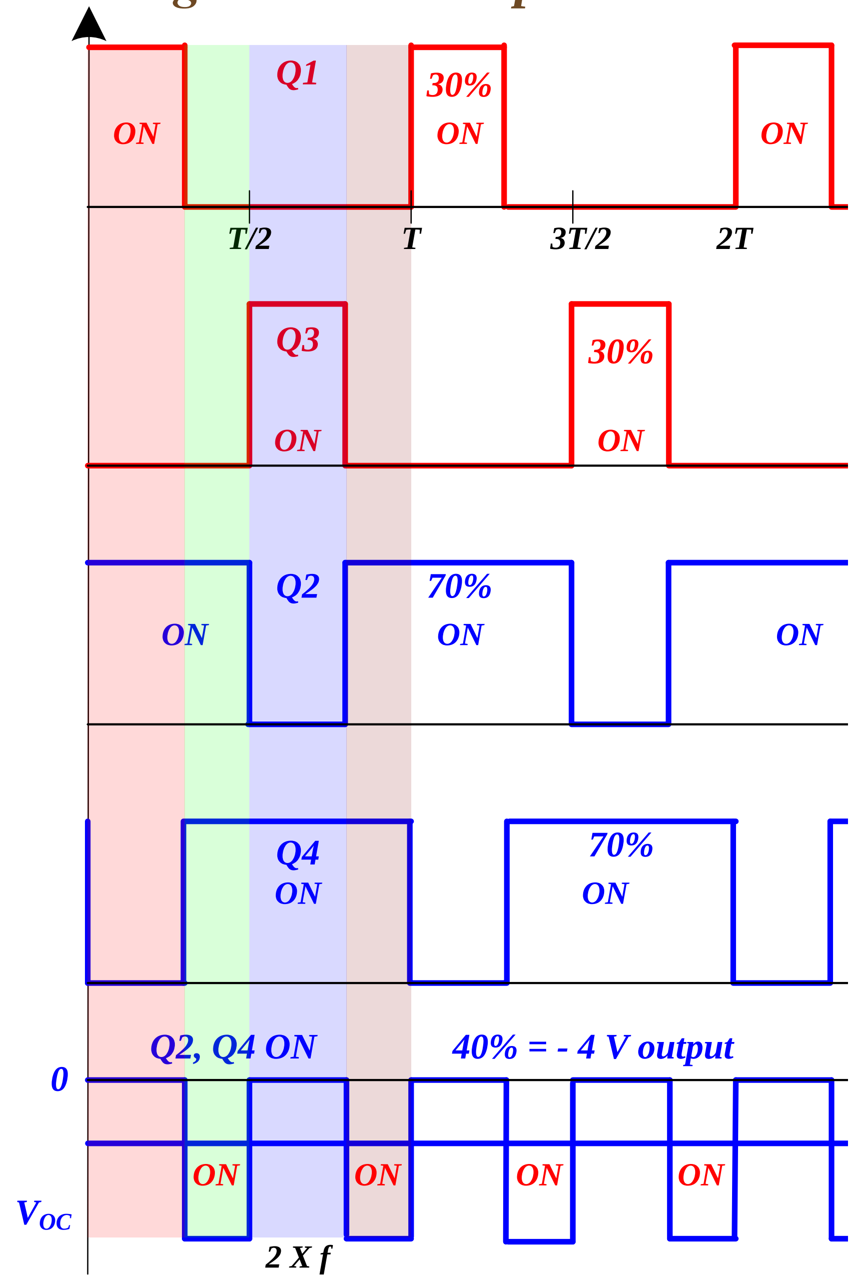
- Both bridge legs are always active
- Q1/Q3 (+) bridge
- Q2/Q4 (-) bridge
- Q1/Q3 180 ^{O} phase shifted
- Q2/Q4 180 ^{O} phase shifted
- Q1 is complement of Q4
- Q2 is complement of Q3

PWM - "50/50" Bipolar Switching For - 4 V Output

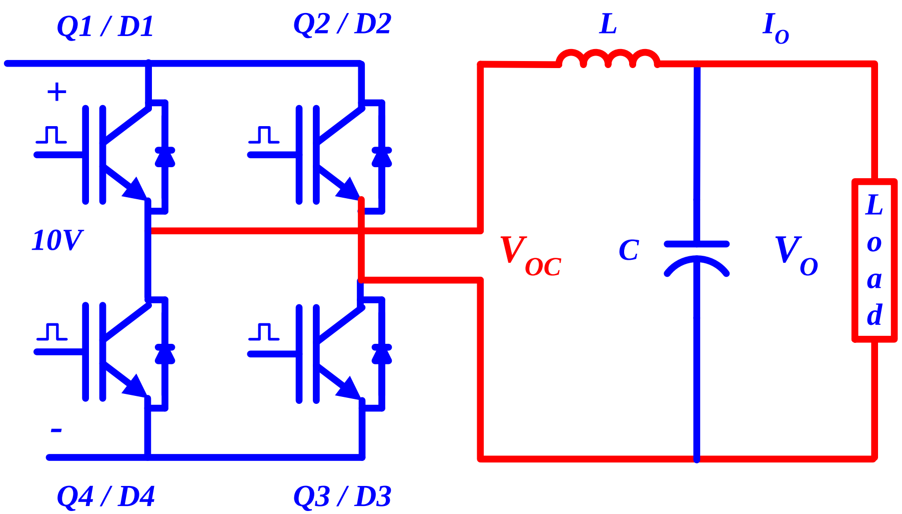
Q1/Q3 on 30%   Q2/Q4 on 70%



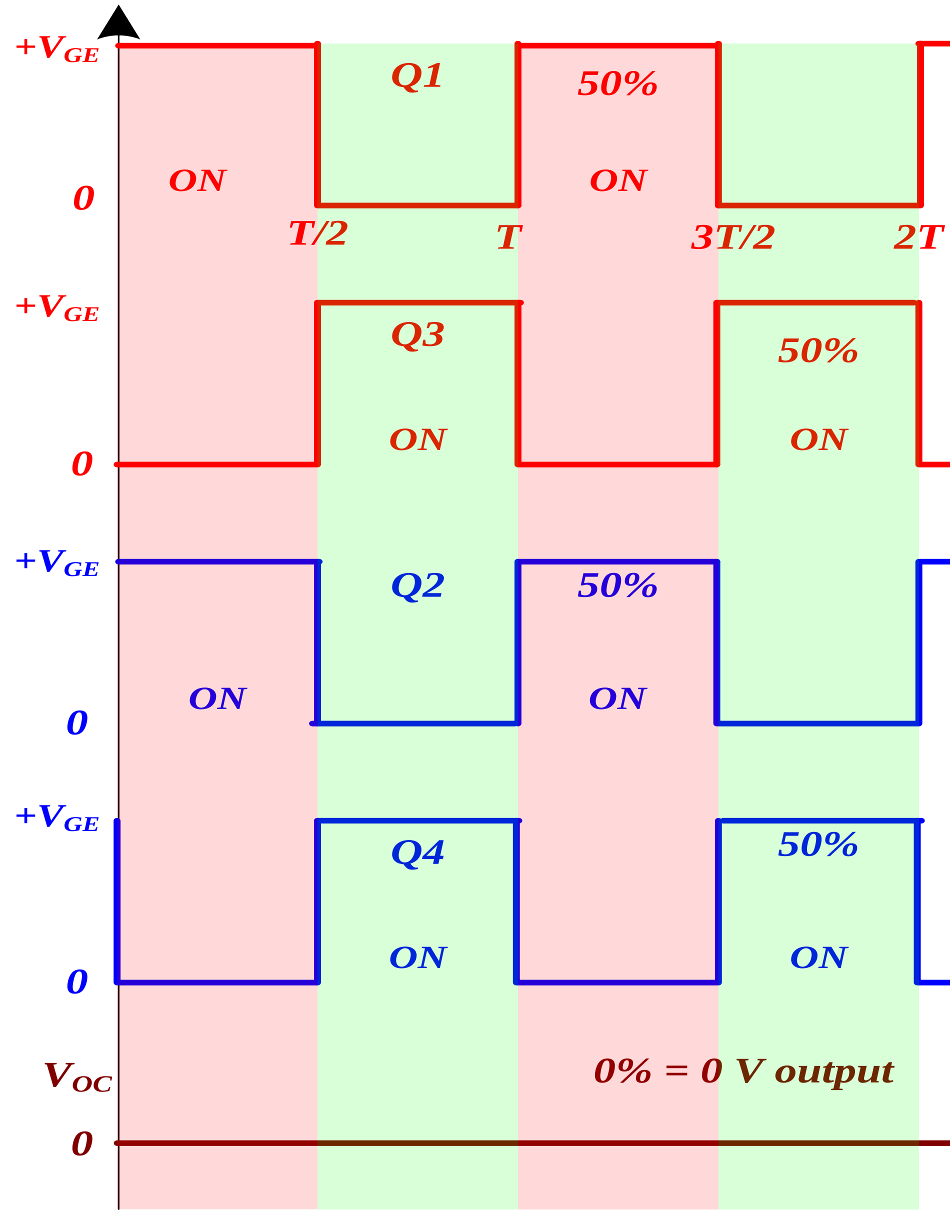
	Q1	Q3	Q2	Q4	V_{OC}
1	On	Off	On	Off	0 V
2	Off	Off	On	On	-10 V
3	Off	On	Off	On	0 V
4	Off	Off	On	On	-10 V



Q1/Q3 on 50% Q2/Q4 on 50%

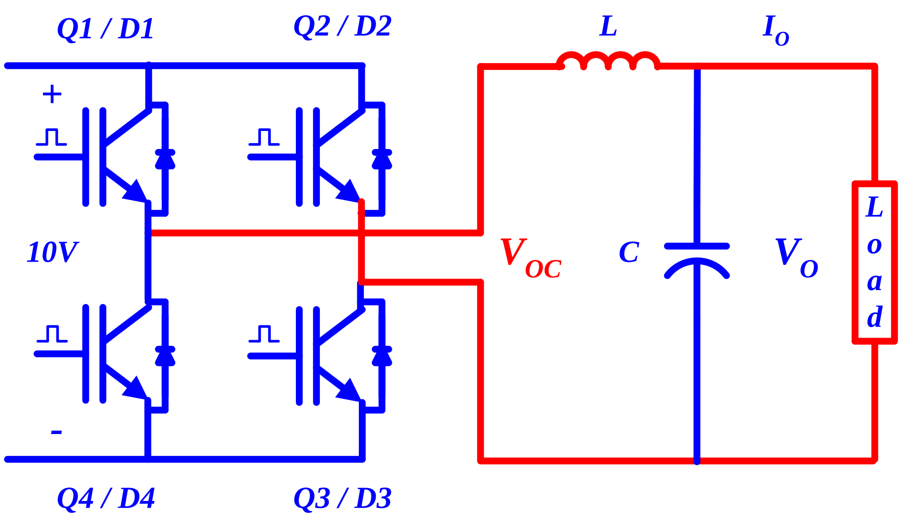


	Q1	Q3	Q2	Q4	VOC
1	On	Off	On	Off	0 V
2	Off	On	Off	On	0 V
3	On	Off	On	Off	0 V
4	Off	On	Off	On	0 V

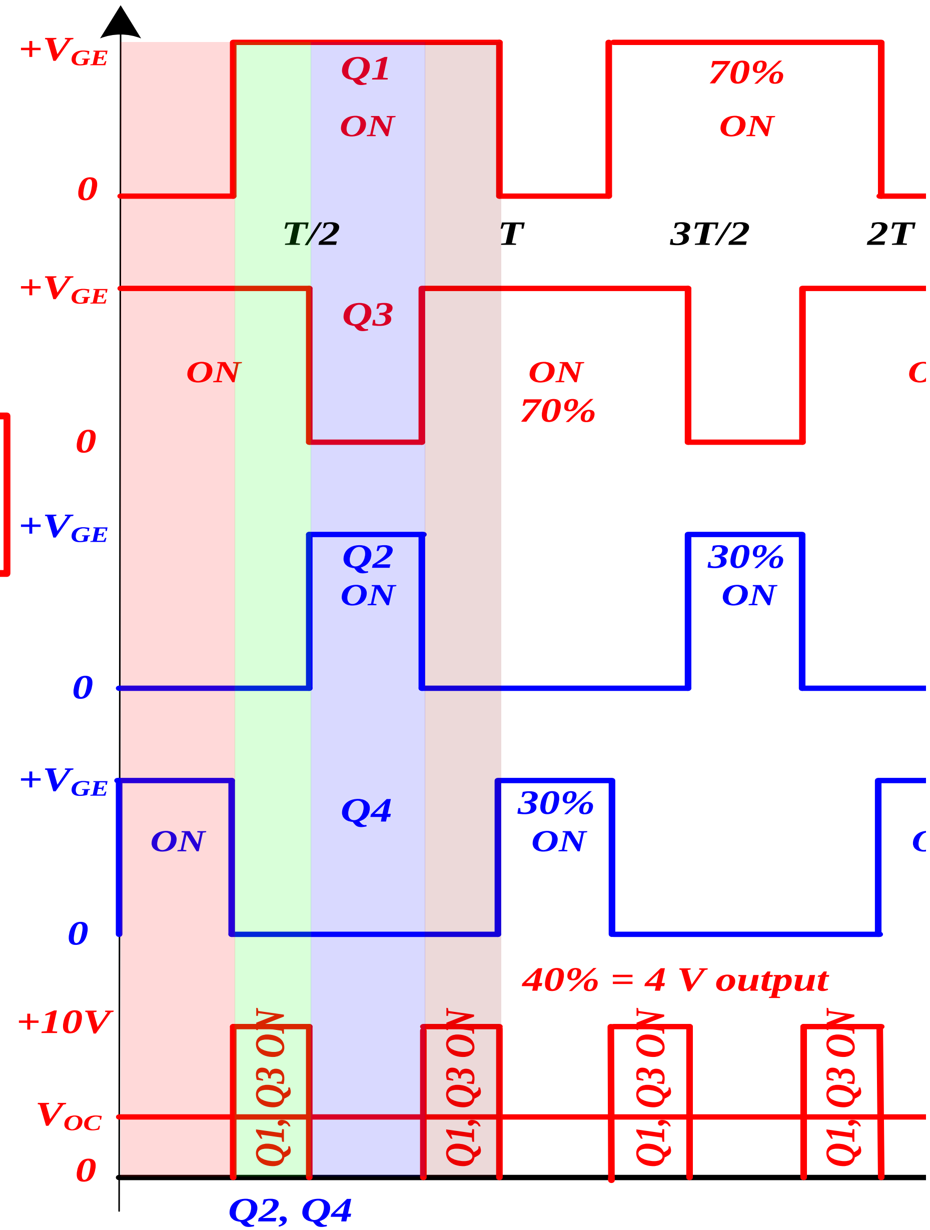


PWM - "50/50" Bipolar Switching For + 4 V Output

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

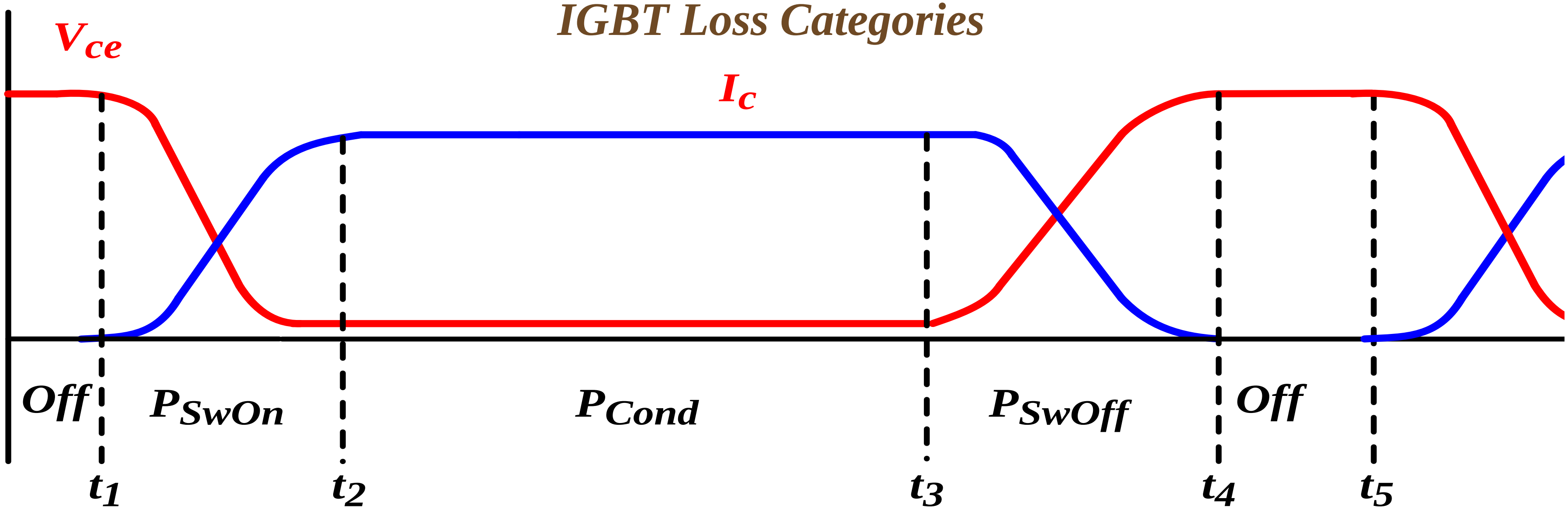


PWM - Bipolar PS PWM Strategies Compared

PWM Type	***Advantages***	***Disadvantages***
Sign/Magnitude		*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 $$P_{Cond} = \frac{1}{t_5 - t_1} * \int_{t_2}^{t_3} V_{CE} * I_C * dt$$

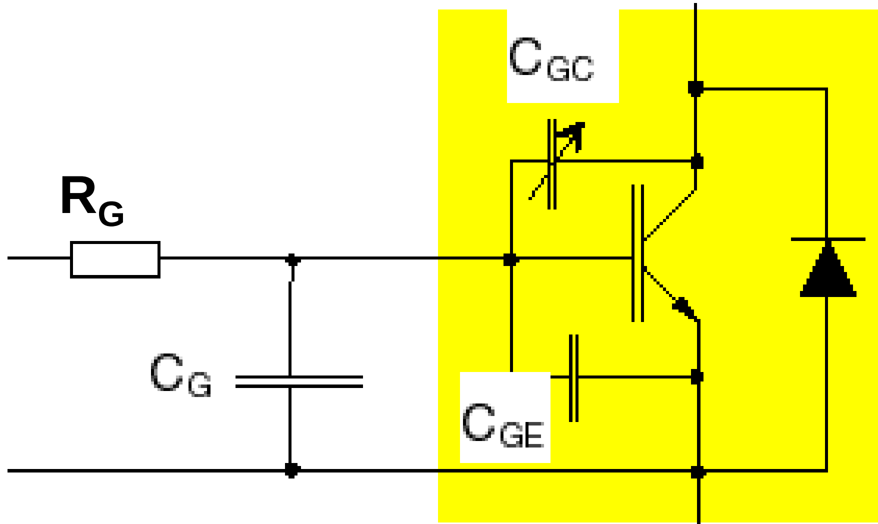
Turnoff losses $$P_{SwOff} = \frac{1}{t_5 - t_1} * \int_{t_3}^{t_4} v_{CE}(t) * i_C(t) * dt$$

Reducing Conducting and Switching Losses

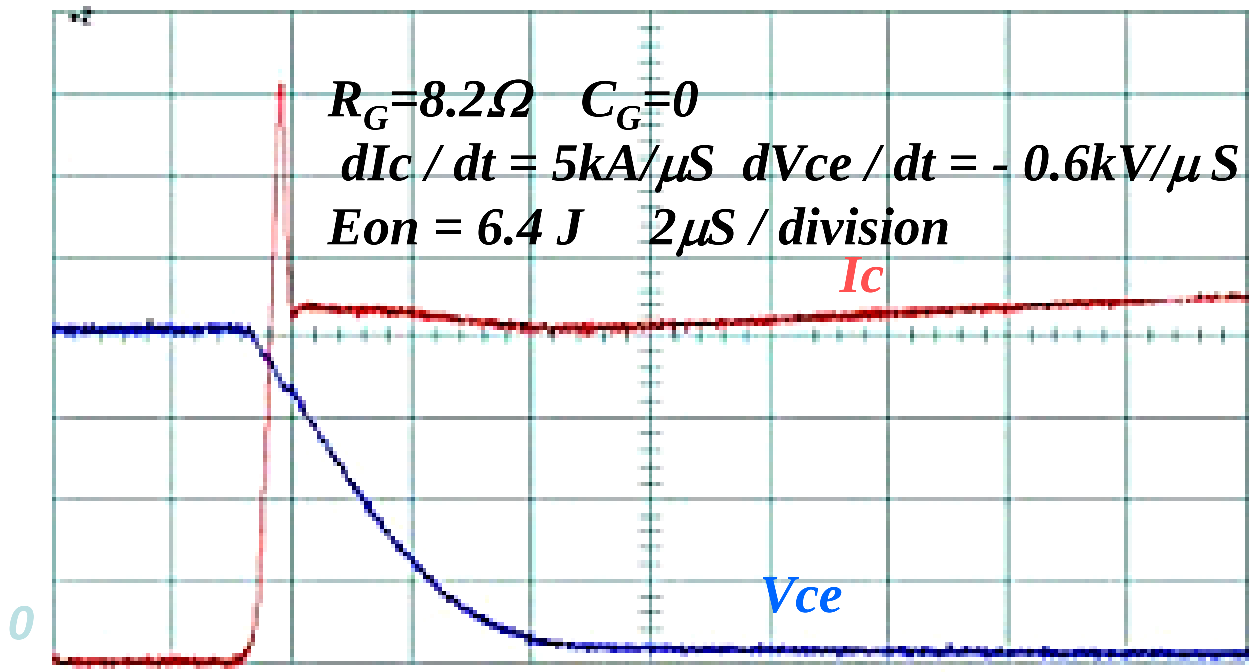
Reduce losses for greater efficiency and:

- *Smaller AC distribution system*
- *Less heat load into cooling water system*
- *Less heat into buildings and building HVAC*
- *Reduce IGBT dissipation*

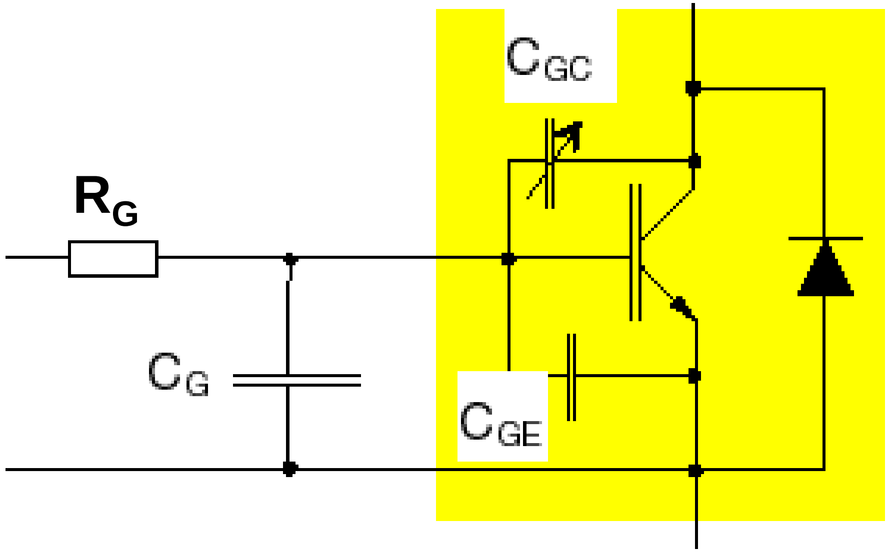
Reducing Turn On Losses By Varying R_G

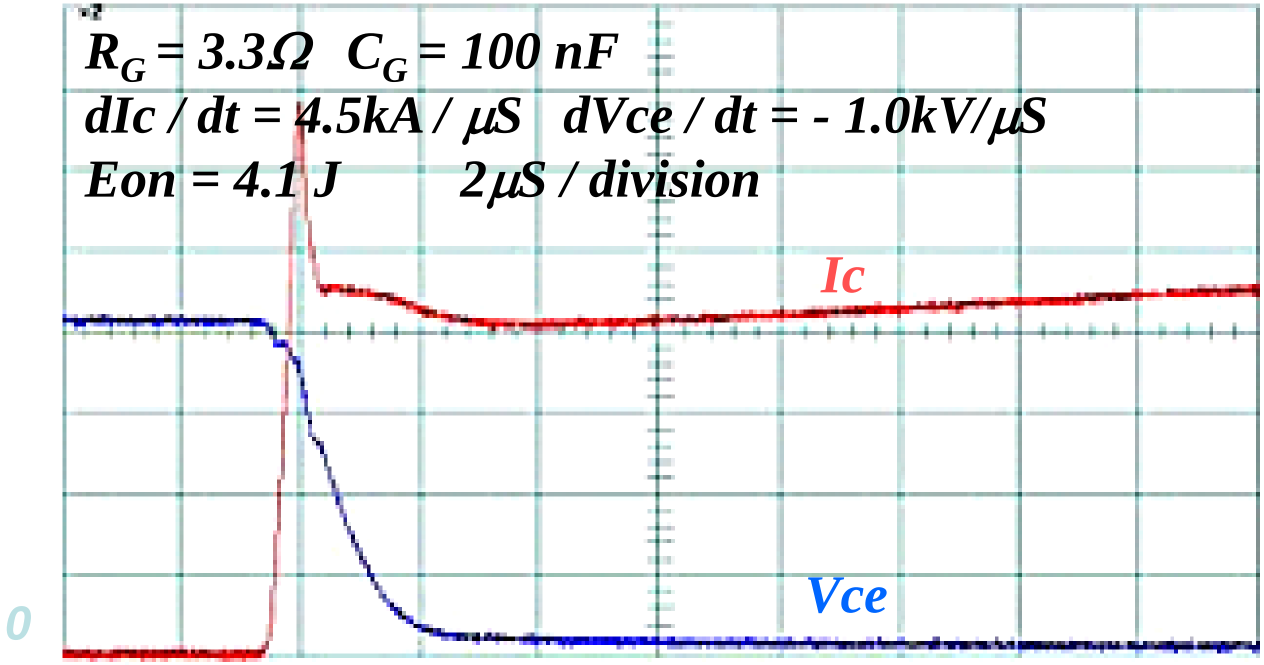


http://www.eupec.com/editorials/effect_cge.htm

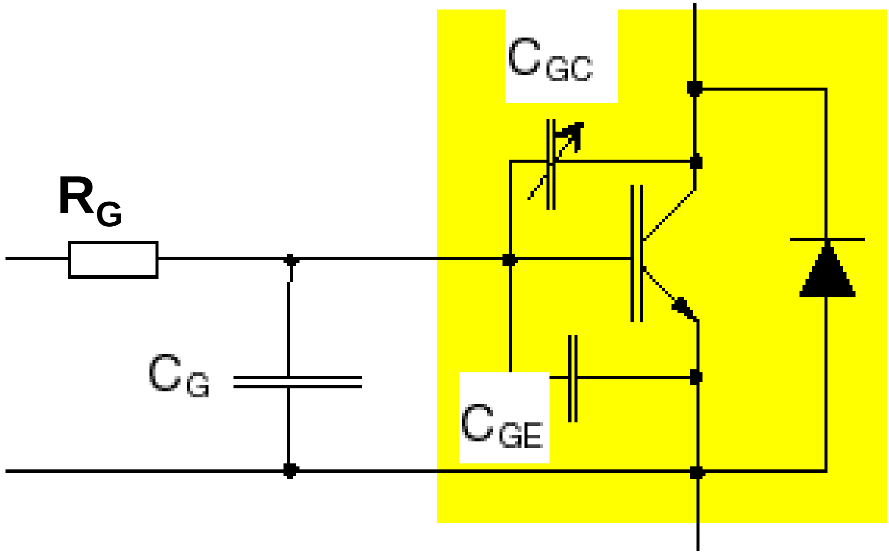


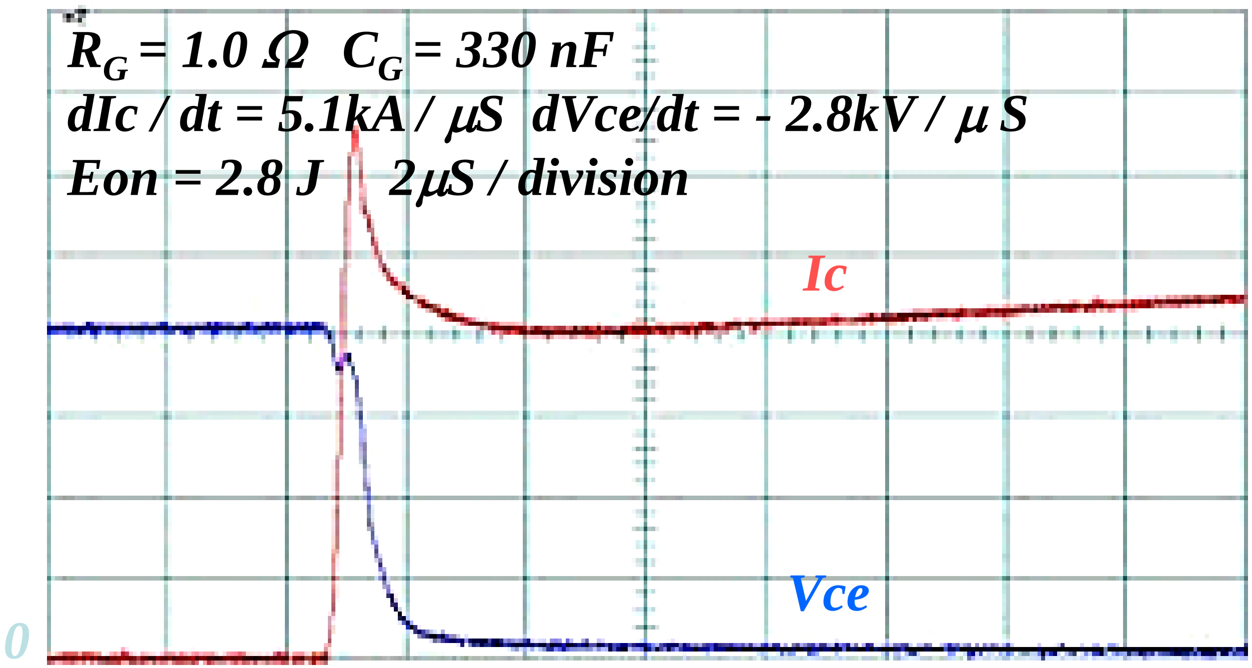
Reducing Turn On Losses By Varying R_G





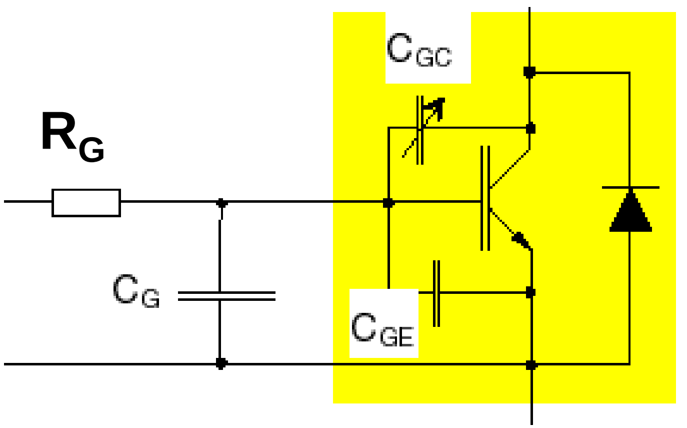
Reducing Turn On Losses By Varying R_G





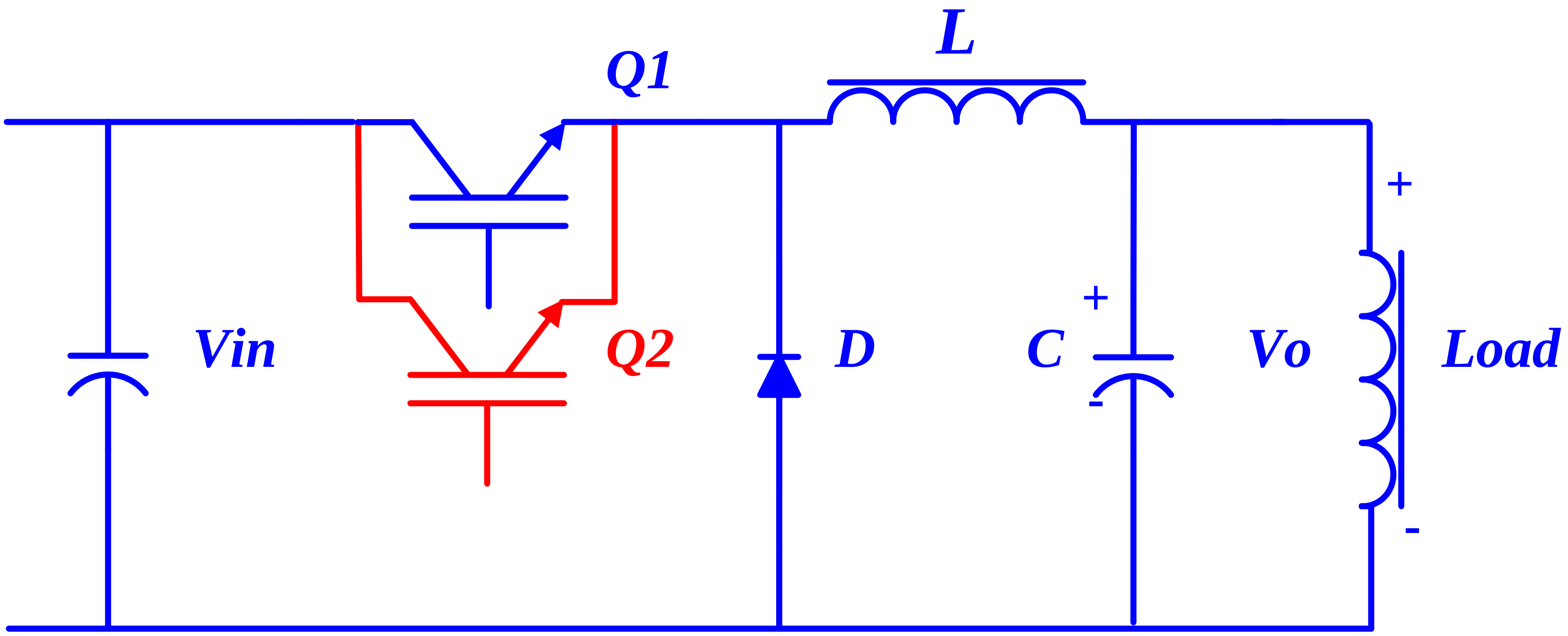
Reducing Turn On Losses By Varying R_G

Case	R_G	dV_{CE} / dt	E_{On}
1	$8.2\ \Omega$	$-0.6\ kV / \mu S$	6.4 J
2	$3.3\ \Omega$	$-1.0\ kV / \mu S$	4.1 J
3	$1.0\ \Omega$	$-2.8\ kV / \mu S$	2.8 J



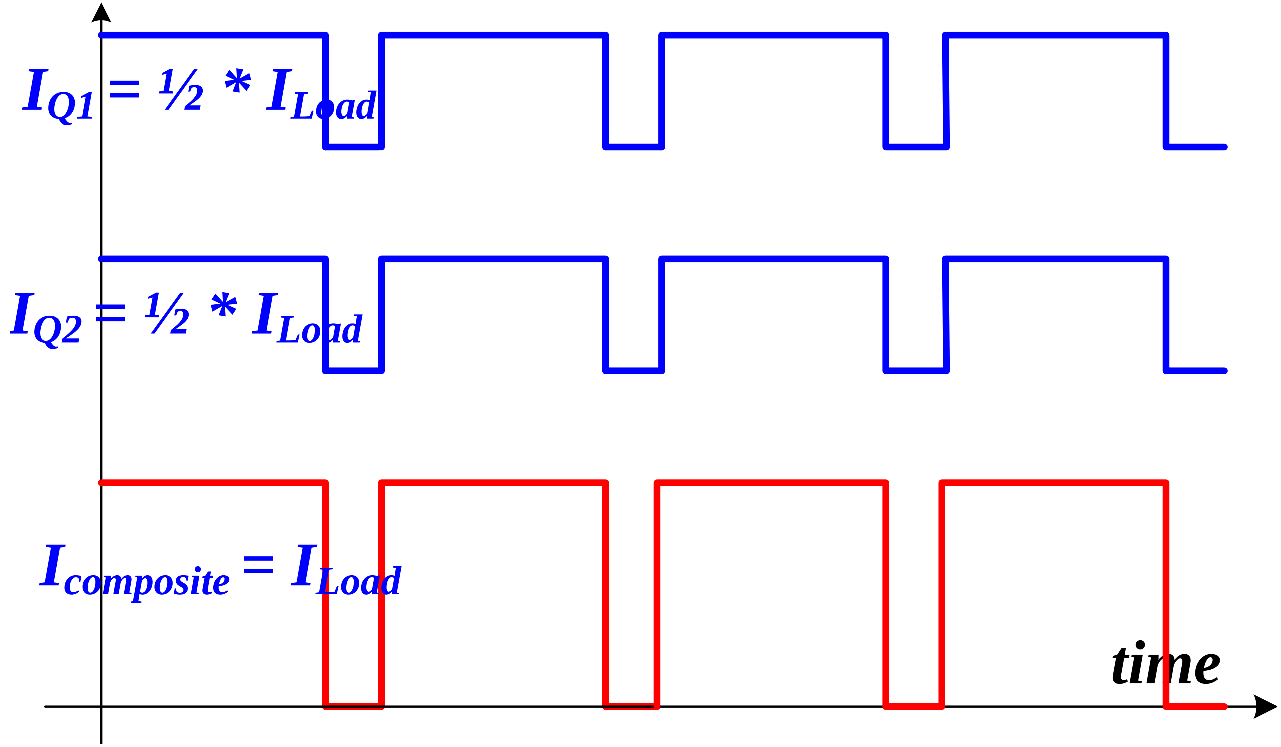
- $P_{Diss} \propto^{-1} -dV_{CE} / dt$
- dV_{CE} / dt is controlled via R_G
- Lower losses but possibly increased EMI because of faster dV_{CE} / dt

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



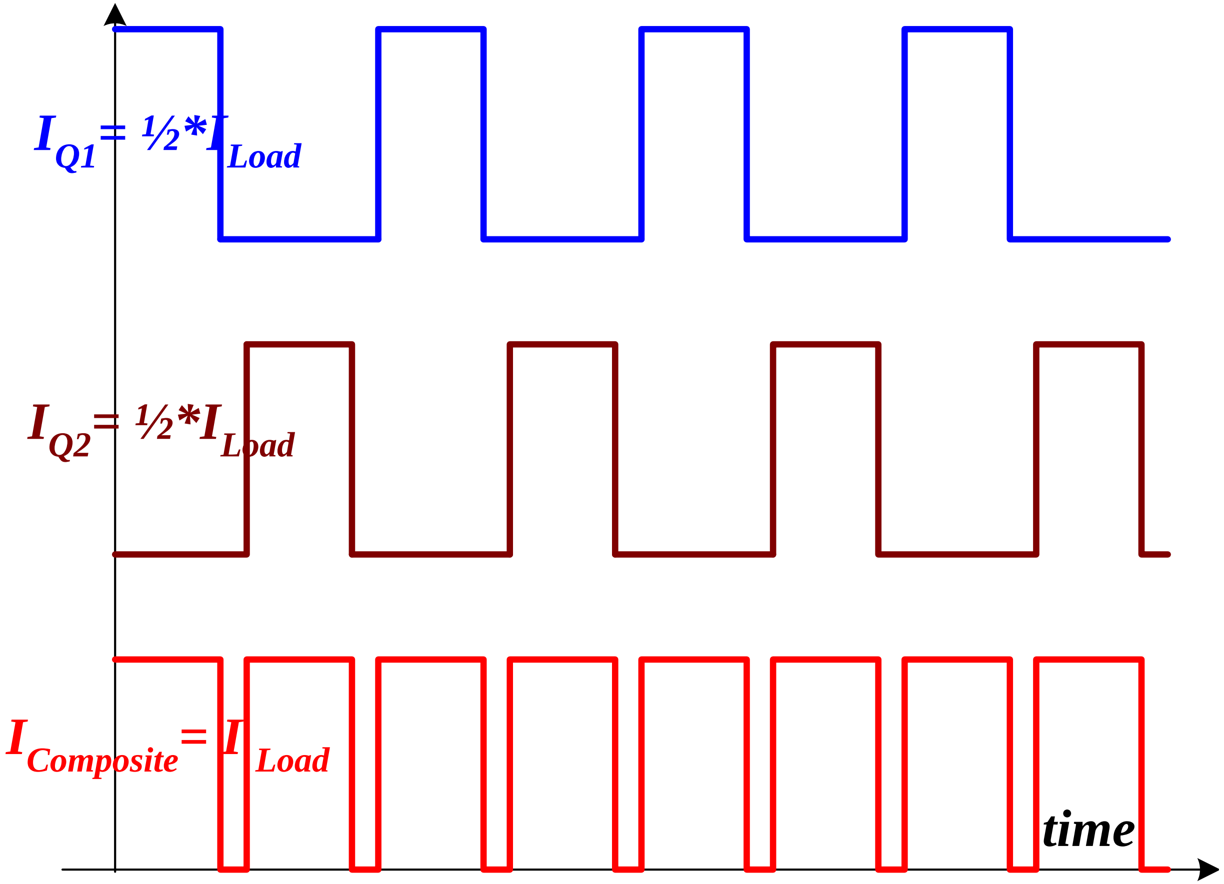
$$V_{RMS\,2Sw-EaSw} = V_{RMS-1Sw} \qquad I_{RMS\,2Sw-EaSw} = \frac{1}{2} * I_{RMS-1Sw}$$

$$P_{Ave1Sw} = V_{RMS1Sw} * I_{RMS1Sw}$$

$$P_{Ave2Sw-EaSw} = V_{RMS1Sw} * \frac{1}{2} I_{RMS1Sw} = \frac{1}{2} * P_{Ave1Sw}$$

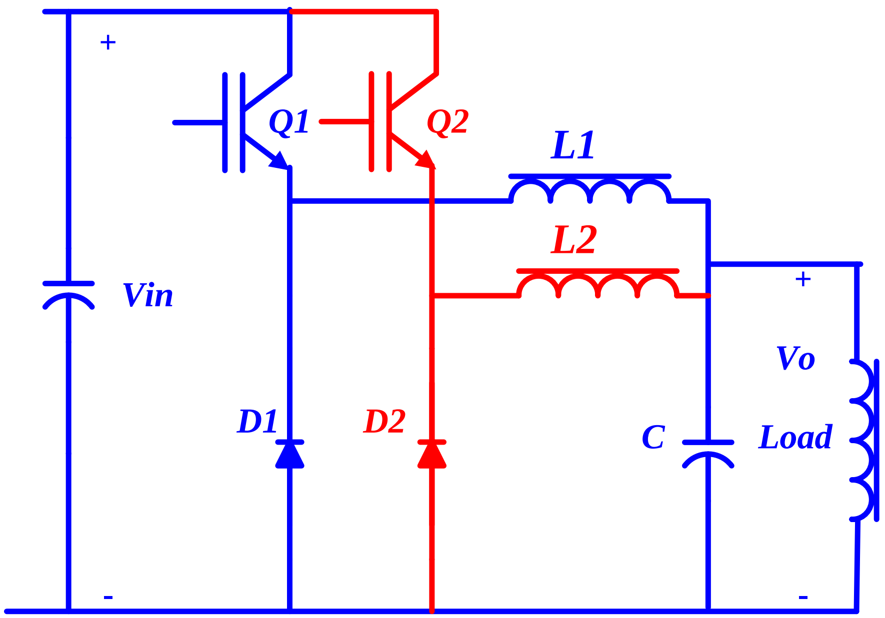
The composite frequency is the same as in Q1 and Q2

Conducted Loss Reduction By Staggered Switching of Q1 and Q2



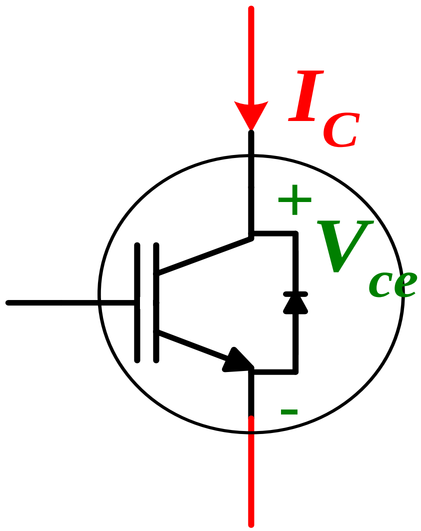
- *Duty factor is each switch is halved*
- *P_{ave} in each switch is 1/2 that of the single switch case*
- *The composite frequency is twice that of Q1 and Q2*

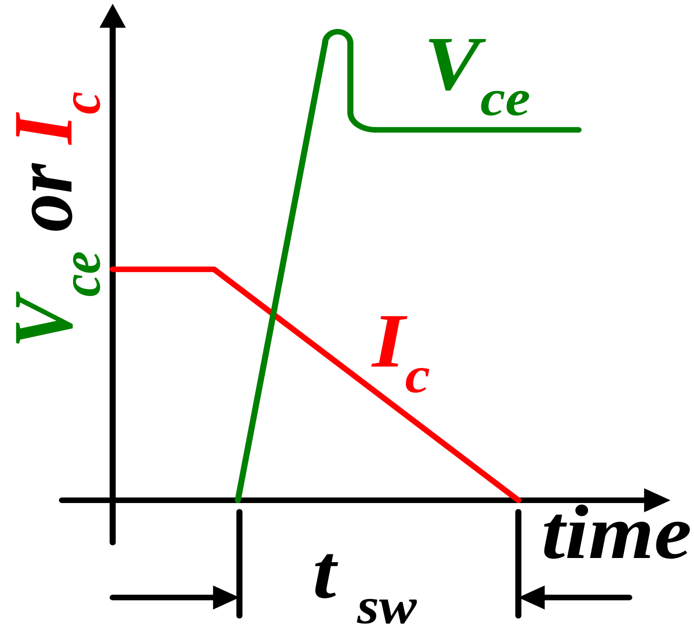
Conducted Loss Reduction By Paralleled Buck Regulators



Features:

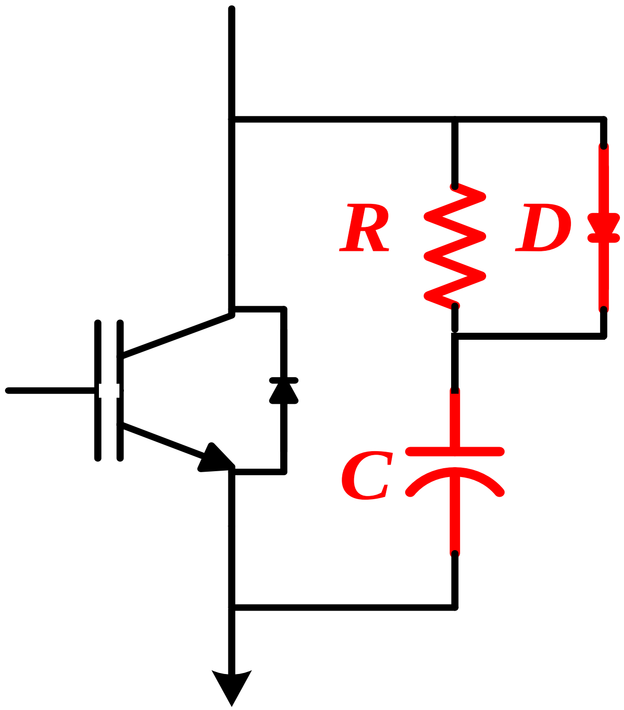
- *A second switch Q1 is added.*
- *Q1 and Q2 are staggered switched*
- *D2 is added, L2 is added*
- *Current in D1, D2 is 1/2 the load current*
- *Current in L1, L2 is 1/2 the load current*
- *L1, L2 energy 1/4 that of single inductor since E=1/2 *L * I* ^{2}

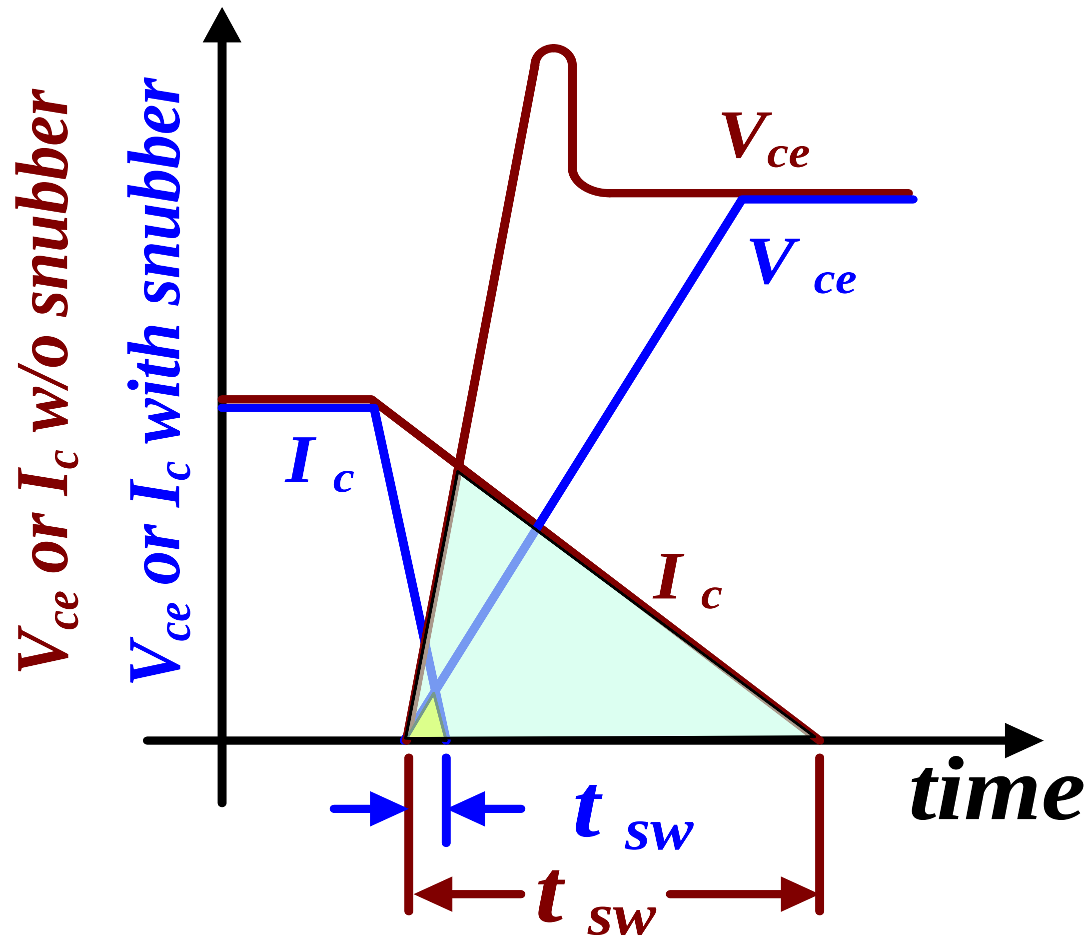




$$P_{SwOff} = \frac{1}{T} \int_0^{t_{Sw}} v_{CE}(t)\, i_C(t)\, dt$$

Switch Turnoff Loss Reduction By RCD Snubber

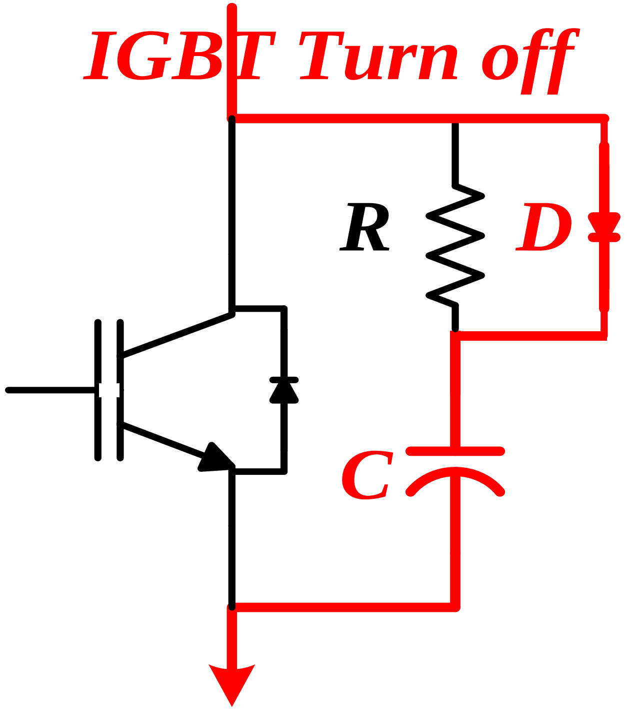




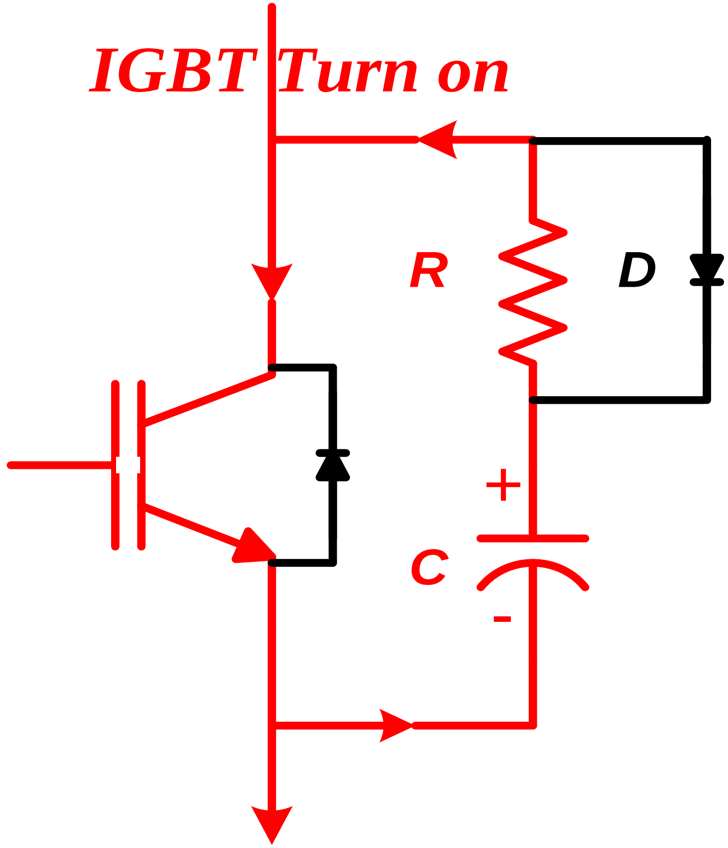
Goal:

- *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

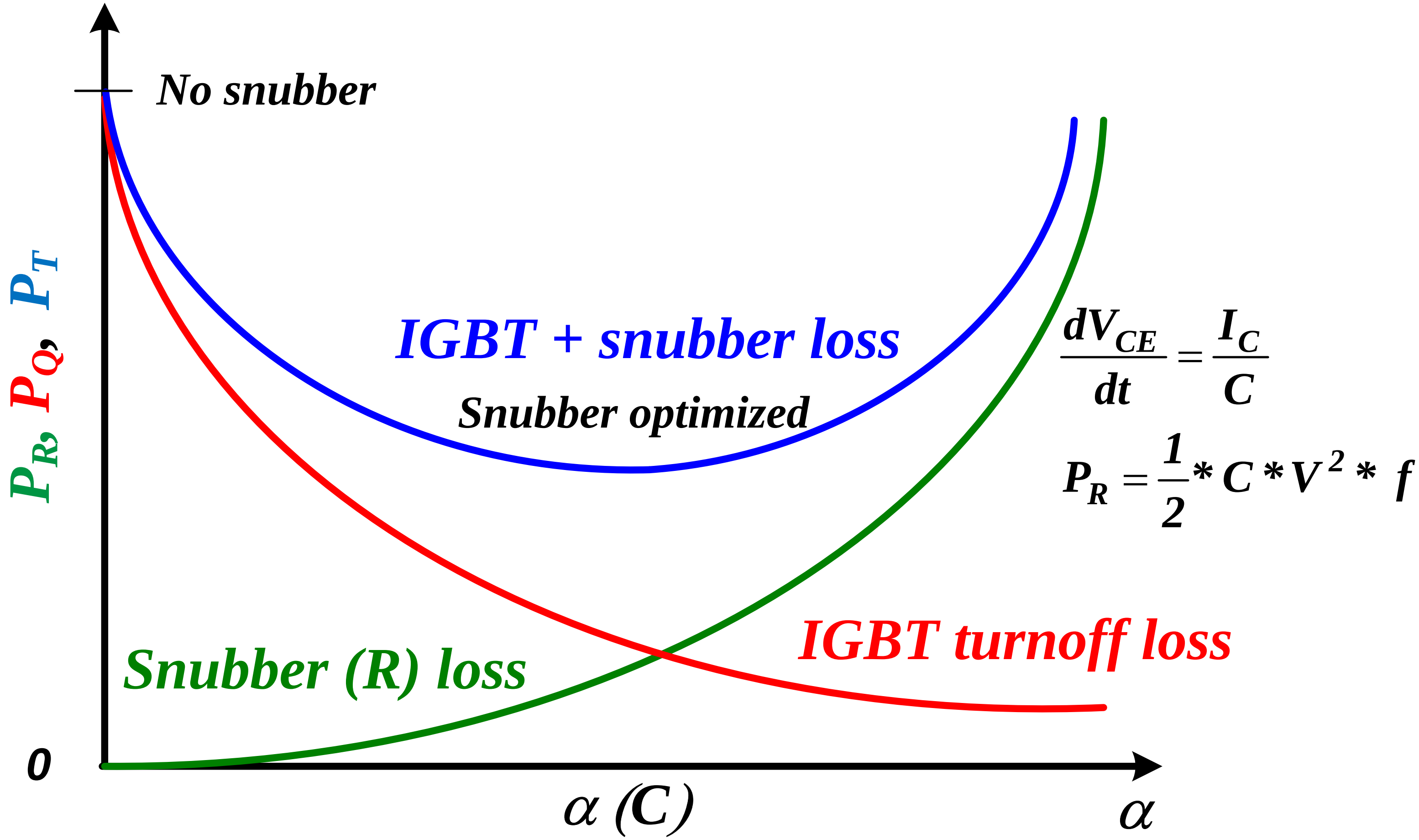


- When the IGBT turns off, current commutates out of the IGBT into the capacitor, C via the diode D
- This aids fast I_C current decay
- C becomes linearly charged to the bus voltage
- dV_{CE} / dt inversely proportional to C – this slows V_{CE} recovery



• *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 !*

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

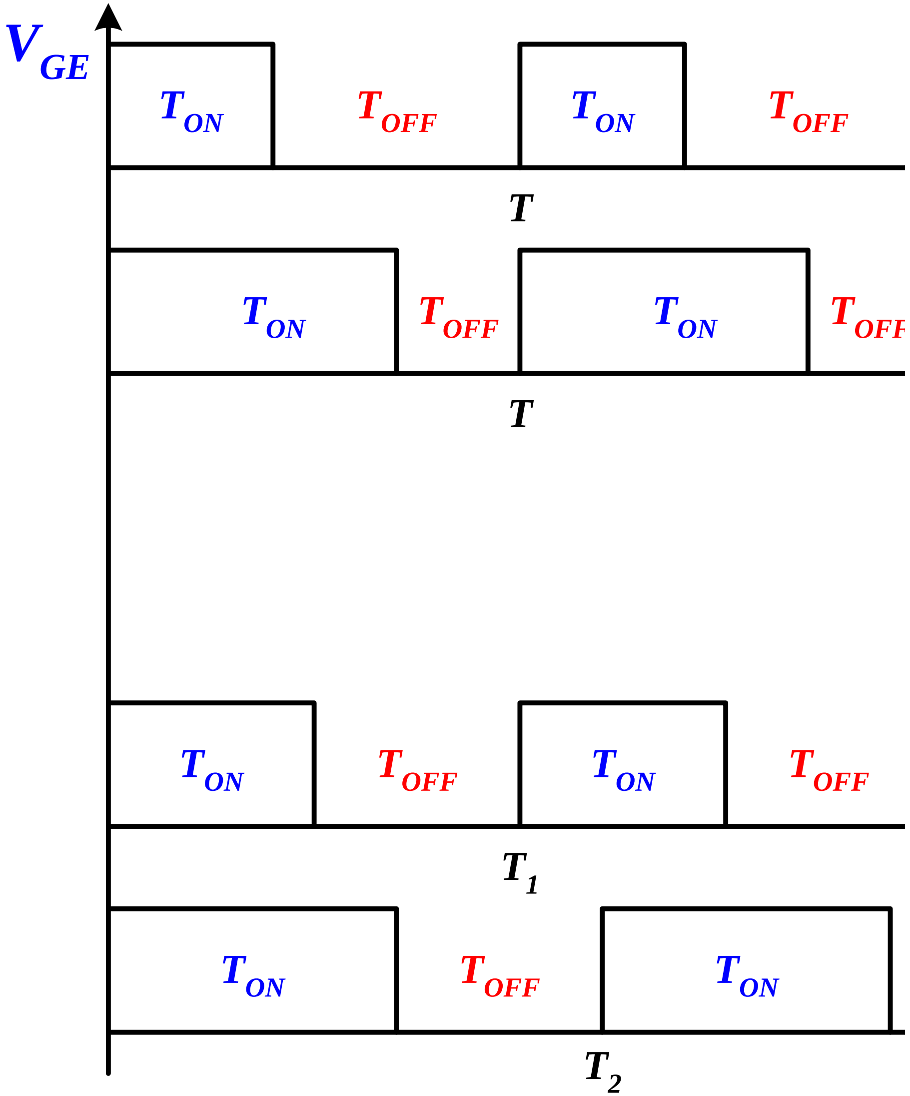
Resonant Switching Attractions

- *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*

Reducing Switch Losses By Resonant Switching



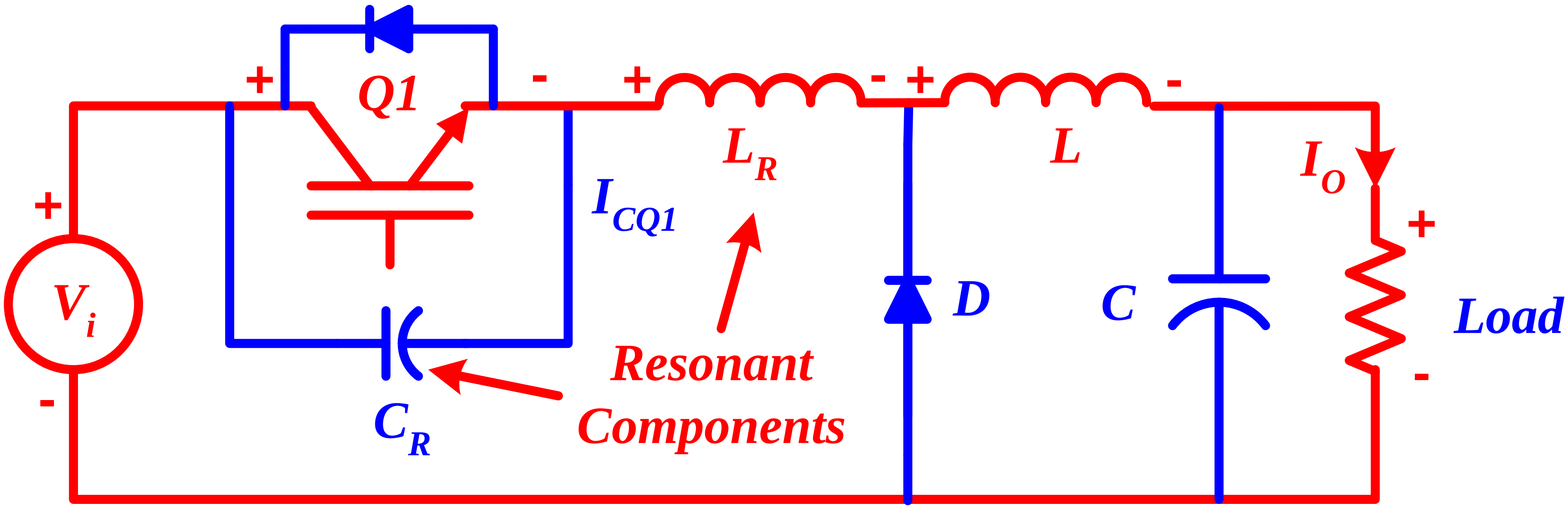
Fixed Frequency Switching

- 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

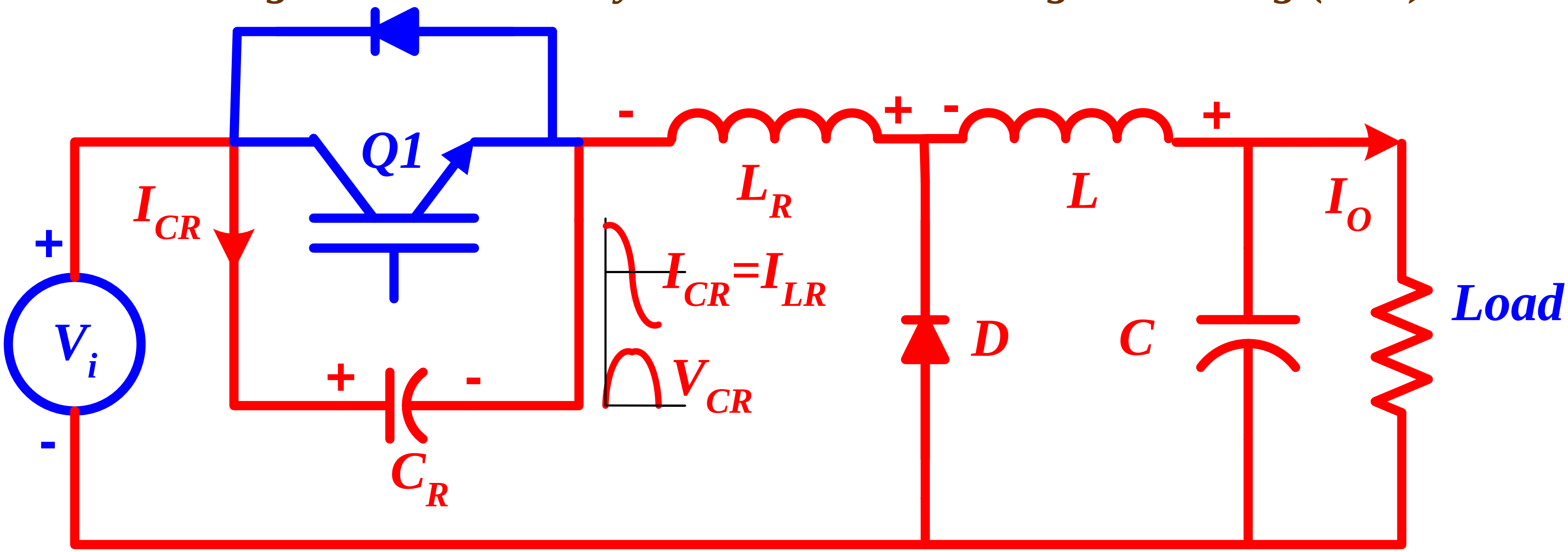
Reducing Switch Losses By Resonant Zero Voltage Switching (ZVS)



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 $I_{CQ1}=I_{LR}$

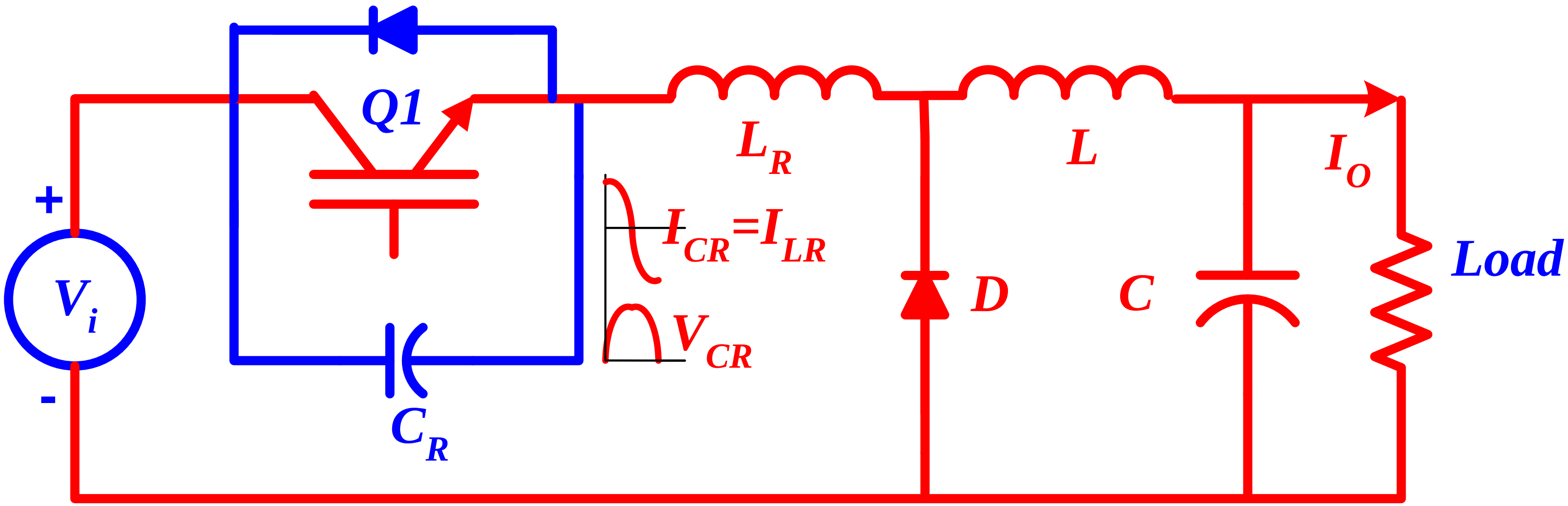
Reducing Switch Losses By Resonant Zero Voltage Switching (ZVS)



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
- $V_{CEQ1} = V_{CR}$
- $I_{CR} = I_{LR}$

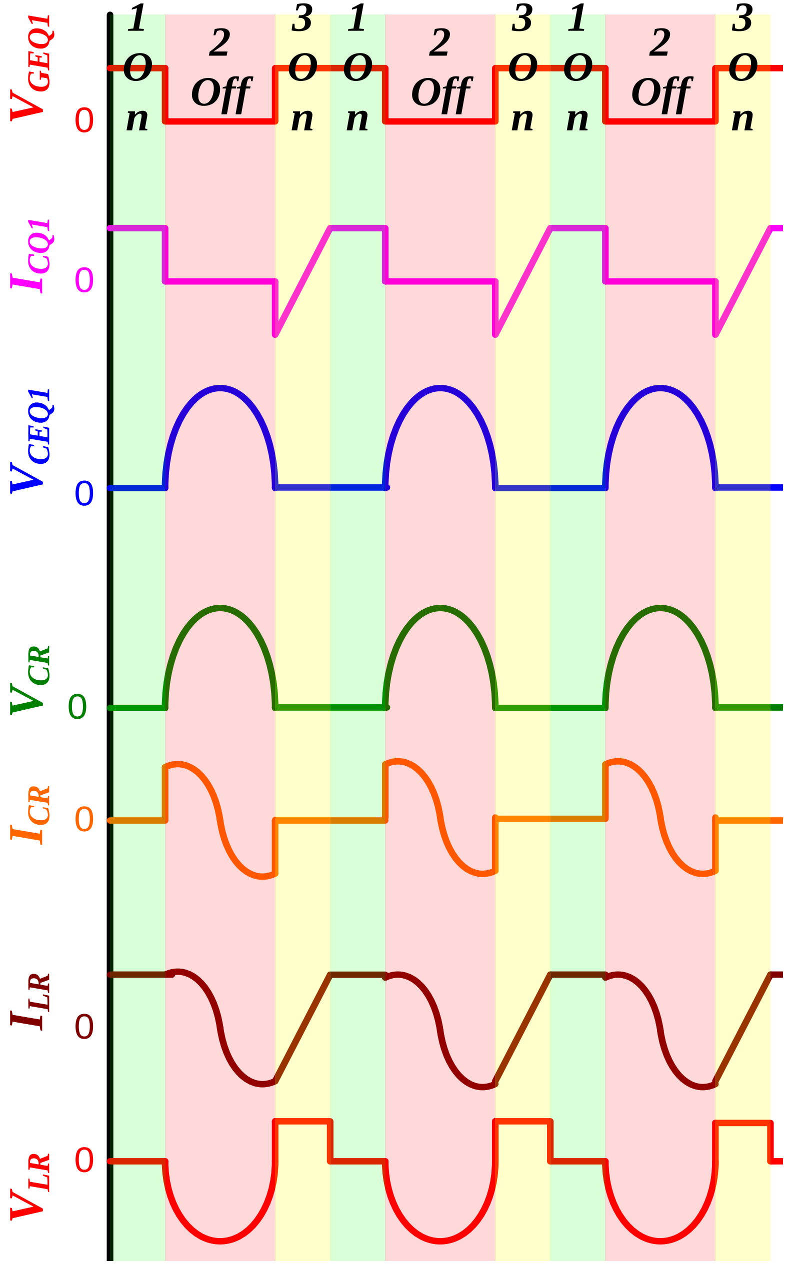
Reducing Switch Losses By Resonant Zero Voltage Switching (ZVS)

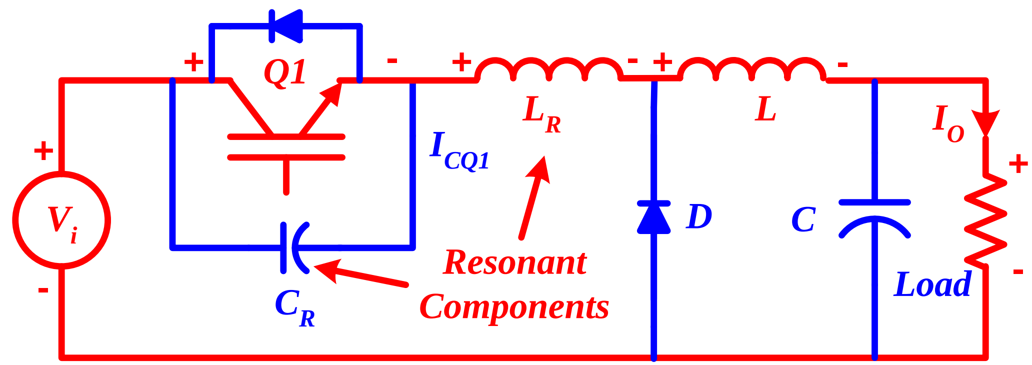


Time Interval 3

- *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





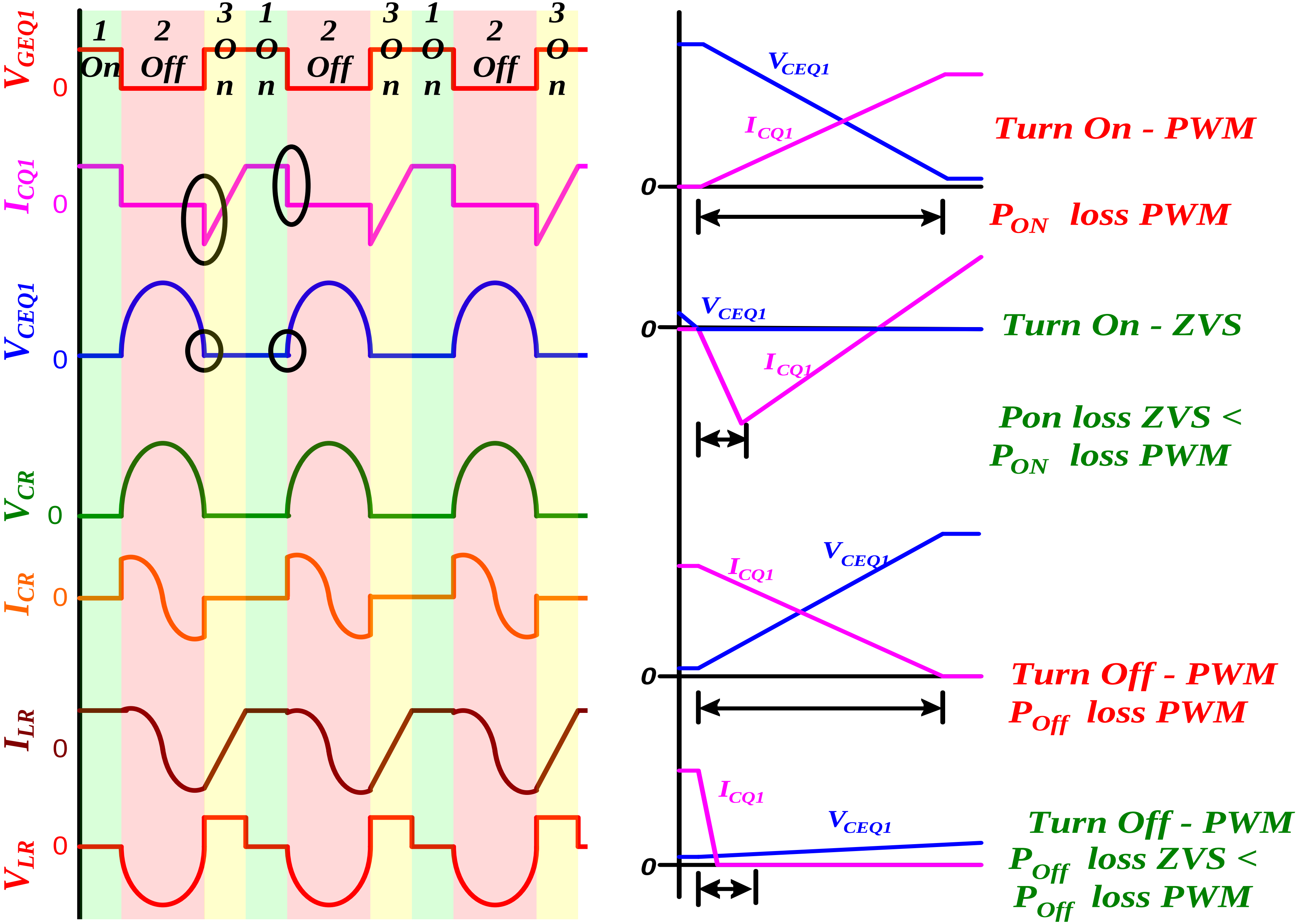
Q1 On

- $V_{CEQ1} = V_{CR} \approx 0$
- $I_{CQ1} = I_{LR}$
- $I_{CR}=0$
- $V_{LR}=L*dI_{LR}/dt=0$

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

Low and High Frequency Transformers Compared

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 $= A_C * A_E \propto \dfrac{V * A}{B_M * f * J}$

Low and High Frequency Transformers Compared

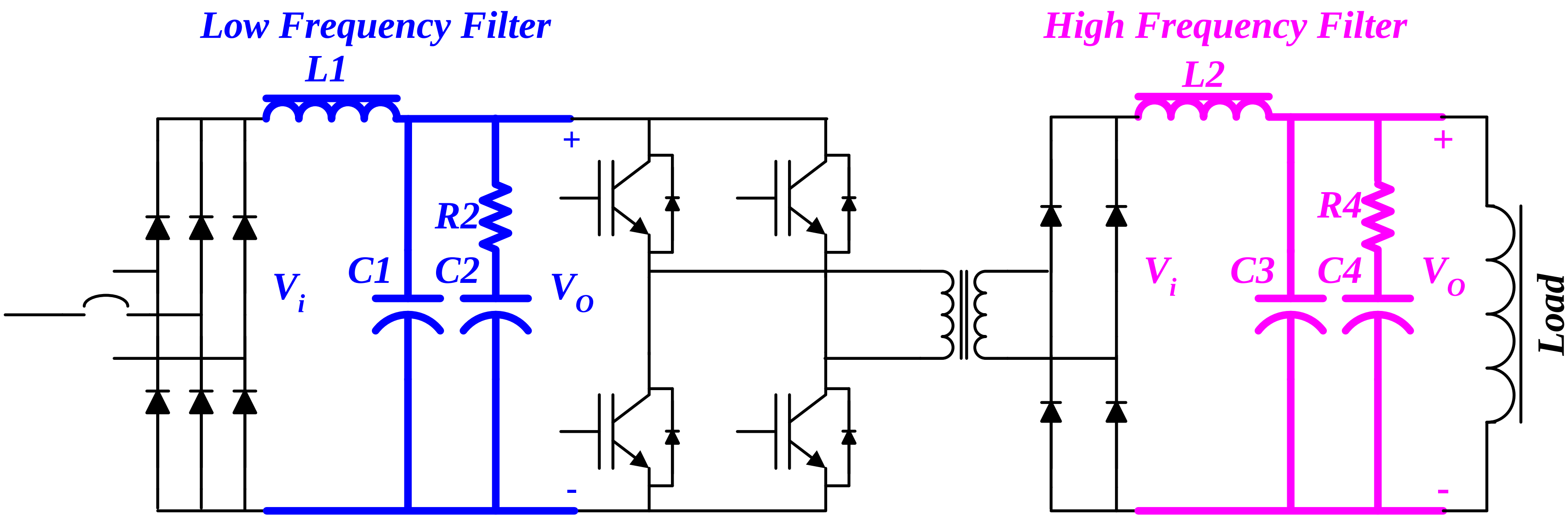
An example of a 10kVA, 480V : 208V Transformer At 60Hz the volume and weight would be					
f	*f* ratio to 60Hz	Volume (in ^{3})	Volume ratio to 60Hz	Weight (lb)	Weight ratio to 60Hz
60 Hz	1	18 X 18 X 18 = 5832 (in ^{3})	1	100	1
20 kHz	333	6H X 5.25W X 3.37D 118 (in ^{3})	1 / 50	5	1 / 20

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* $Y(f) = X(f) * T(f)$

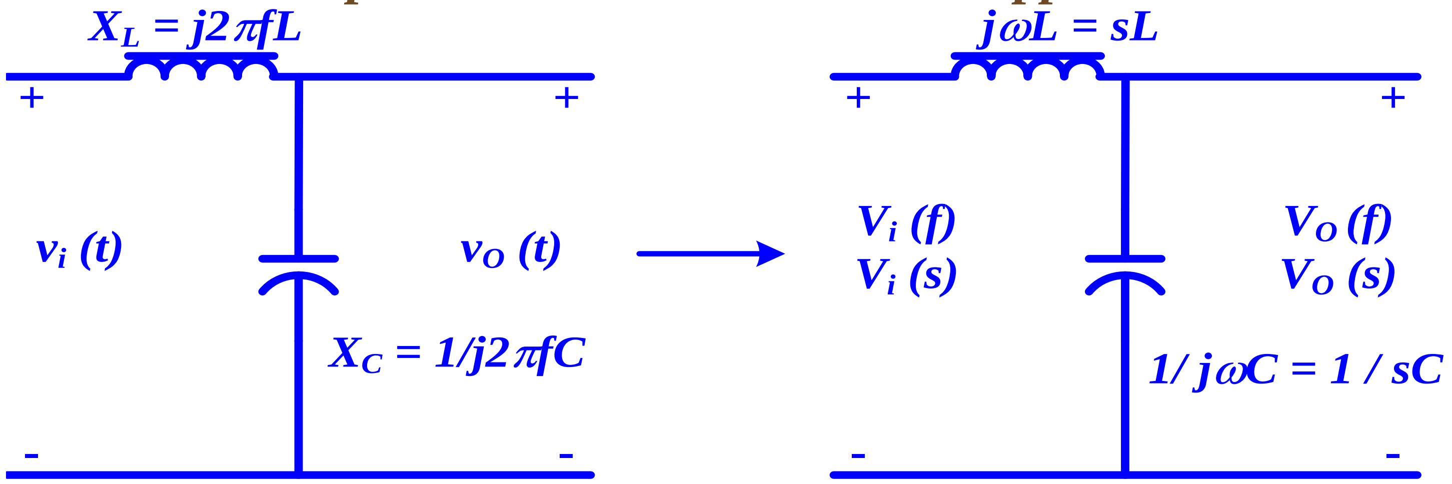
The “s” Operator

- *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 $$V_o = V_i * \frac{\frac{1}{sC}}{\frac{1}{sC} + sL} \qquad T = \frac{1}{s^2 LC + 1}$$

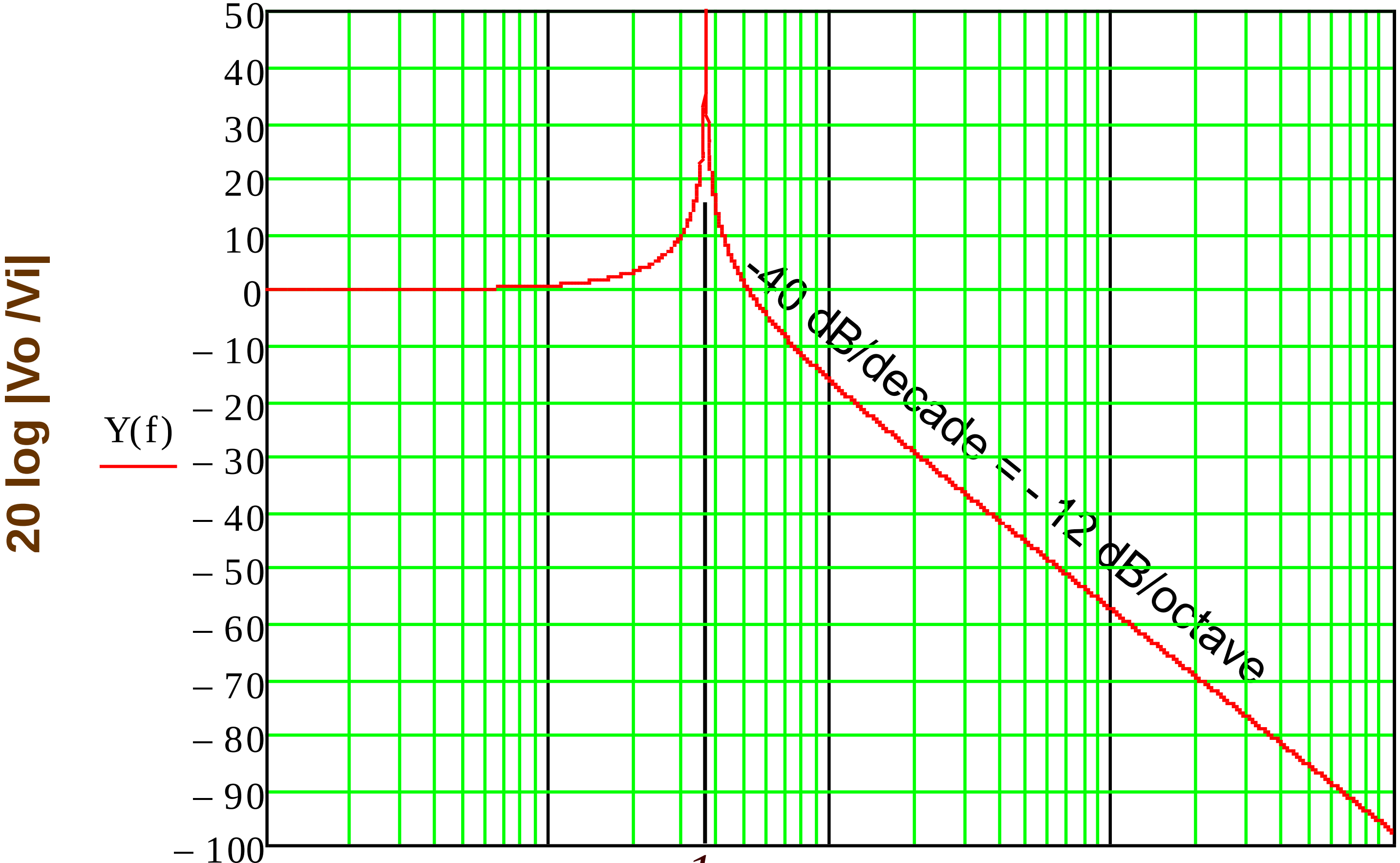
Pole $s^2 LC + 1 = 0$ $$(j2\pi f_p)^2 LC + 1 = 0$$

Resonant frequency (pole) $$f_p = \frac{1}{2\pi\sqrt{LC}}$$

Zero occurs at $$(j2\pi f_p)^2 LC + 1 = \infty$$

Zero frequency at $$f_z = \infty$$

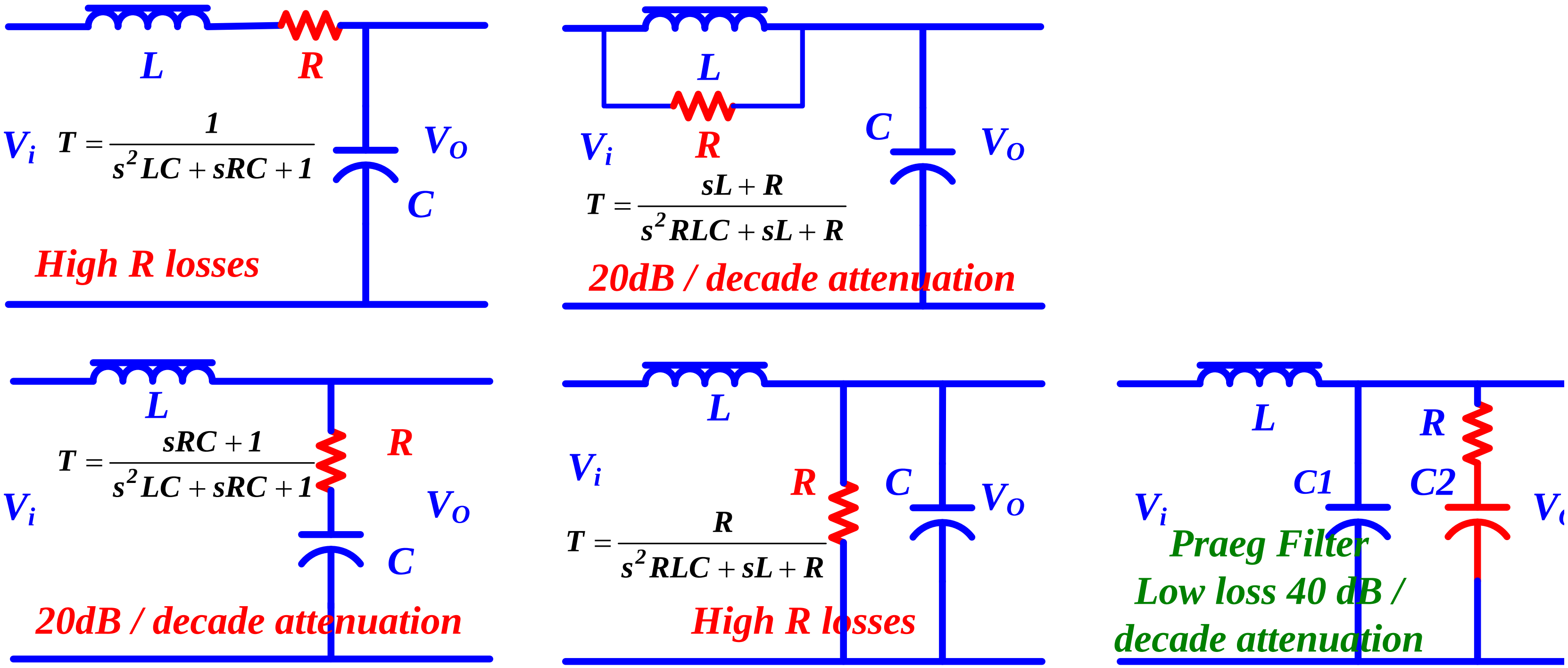
A Simple Low Pass Filter



$$f_p = \frac{1}{2\pi\sqrt{LC}} \longrightarrow f_z = \infty$$

- *Resonant frequency (pole) at f_p will cause problems !*
- *At $f = \infty$, the output goes asymptotically to zero*

The Praeg Low Pass Ripple Filter

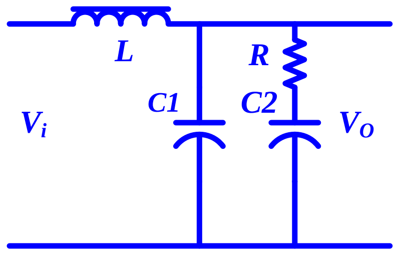


Why important:

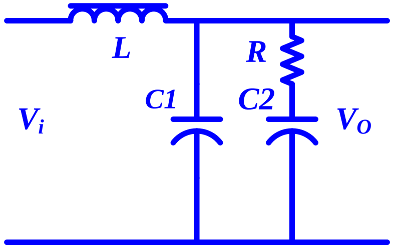
- Used as low and high frequency filters in virtually every power supply
- Provides the filtering of the previous 2^{nd} order filter
- Essentially critical damped
- No DC current in R, C2

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 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*
- $C2 \geq 5 * C1$
- $R = (L / C1)^{1/2}$

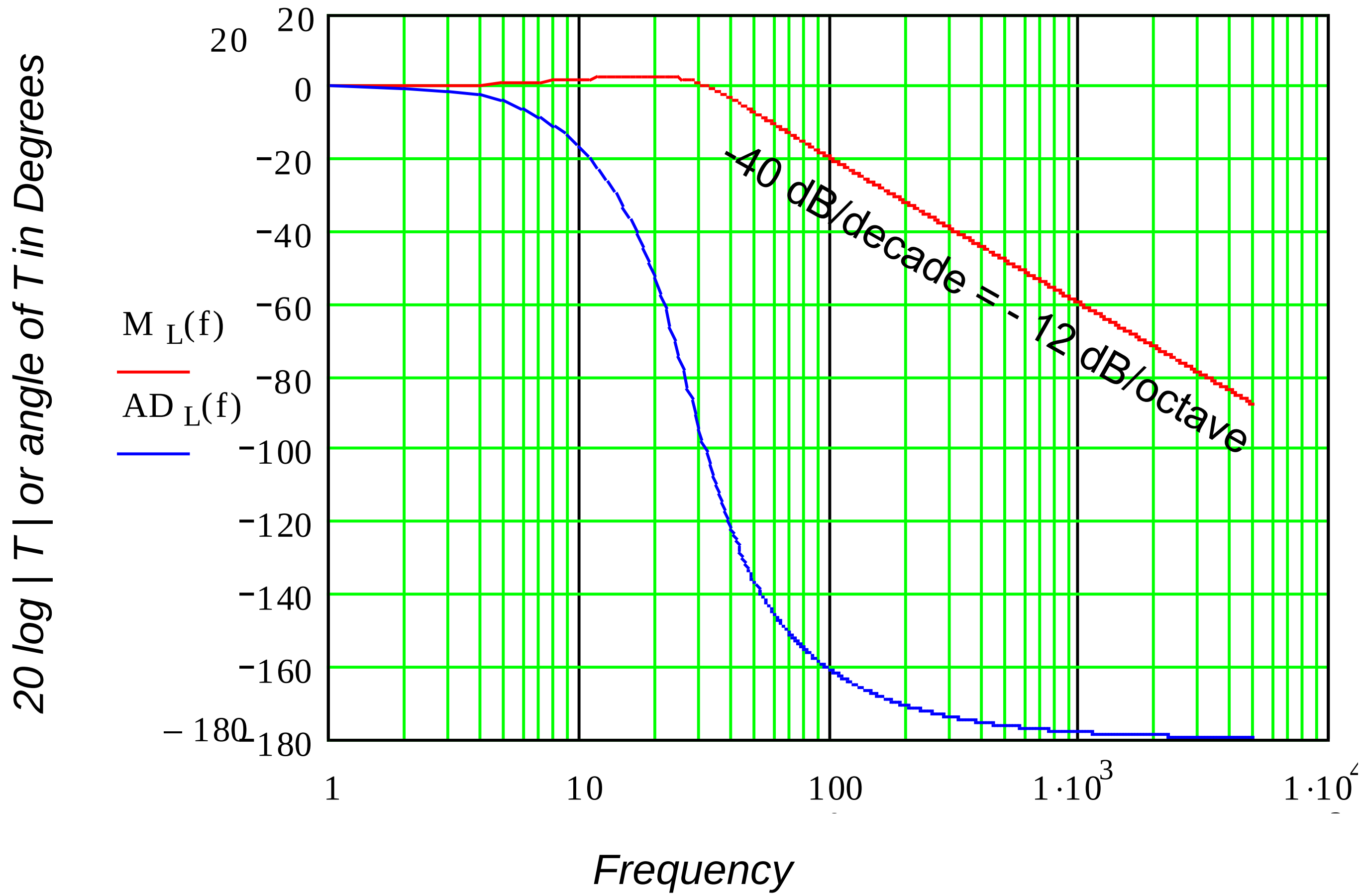


The Praeg Low Pass Ripple Filter



$$T = \frac{s\,R\,C_2 + 1}{s^3 R\,L\,C_1 C_2 + s^2 L(C_1 + C_2) + s\,R\,C_2 + 1}$$

$$C_2 \geq 5 * C_1 \qquad\qquad R = \sqrt{\frac{L}{C_1}}$$



360 Hz Praeg Filter

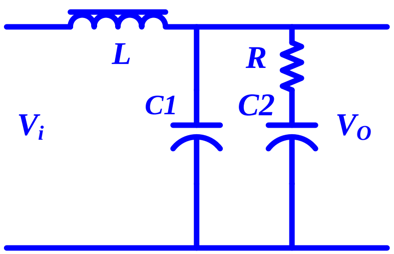
$f := 1\cdot Hz, 2\cdot Hz .. 1000\cdot Hz \qquad s(f) := j\cdot 2\cdot\pi\cdot f \qquad L := 1.5\cdot 10^{-3}\cdot H \qquad f_r := 36\cdot Hz \qquad C_1 := \dfrac{1}{4\pi^2\cdot L\cdot f_r^2} \qquad C_1 = 0.0130\,F$

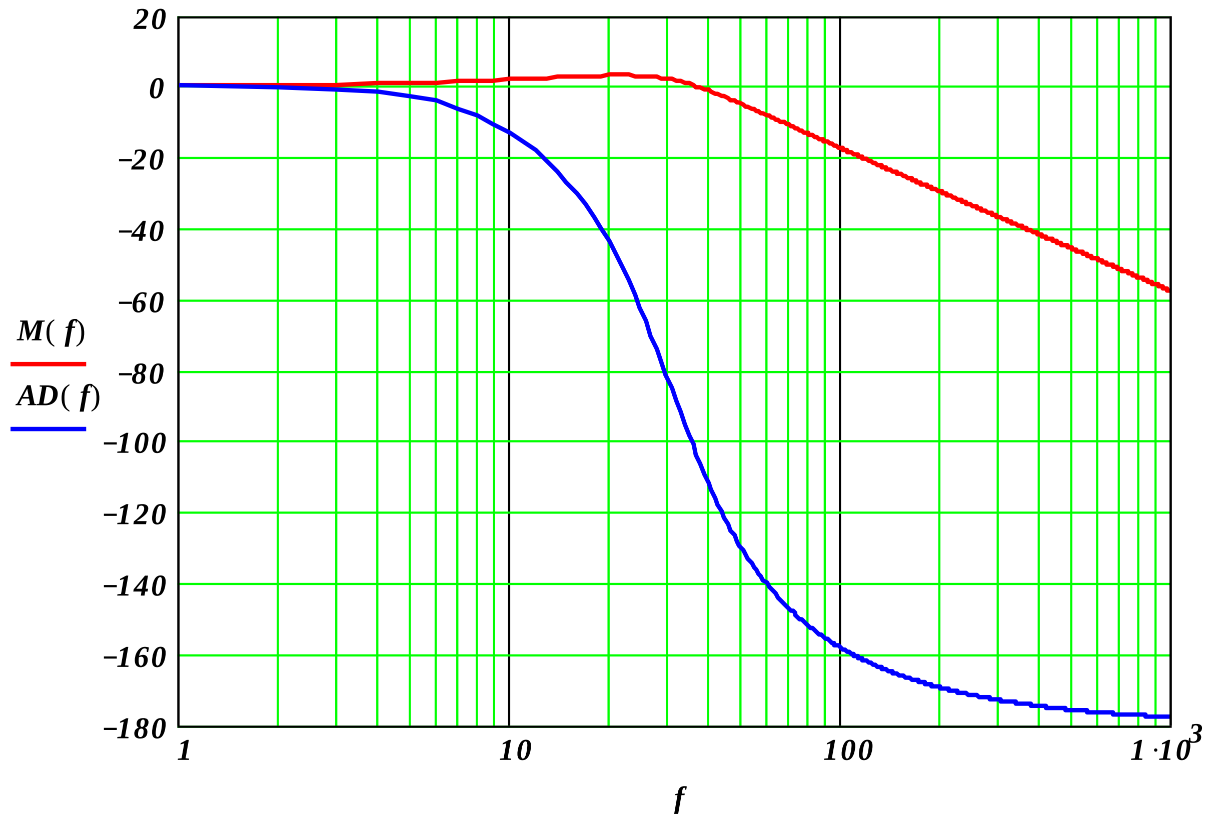
$R := \sqrt{\dfrac{L}{C_1}} \qquad R = 0.34\,\Omega \qquad C_2 := 5\cdot C_1 \qquad C_2 = 0.065\,F$

$$T(f) := \frac{s(f)\cdot R\cdot C_2 + 1}{s(f)^3\cdot R\cdot L\cdot C_1\cdot C_2 + s(f)^2\cdot L\cdot\left(C_1 + C_2\right) + s(f)\cdot R\cdot C_2 + 1}$$

$M(f) := 20\cdot\log\left(\left|T(f)\right|\right) \qquad AR(f) := \arg(T(f))$

$AD(f) := AR(f)\cdot 57.3$





36 kHz Praeg Filter

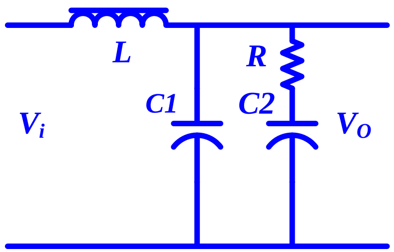
$f := 10 \cdot Hz, 20 \cdot Hz .. 100000 \cdot Hz \quad s(f) := j \cdot 2 \cdot \pi \cdot f$ $\quad L := 1.5 \cdot 10^{-5} \cdot H \quad C_1 := 0.00013 \cdot F \quad f_r := \dfrac{1}{2 \cdot \pi \cdot \sqrt{L \cdot C_1}}$

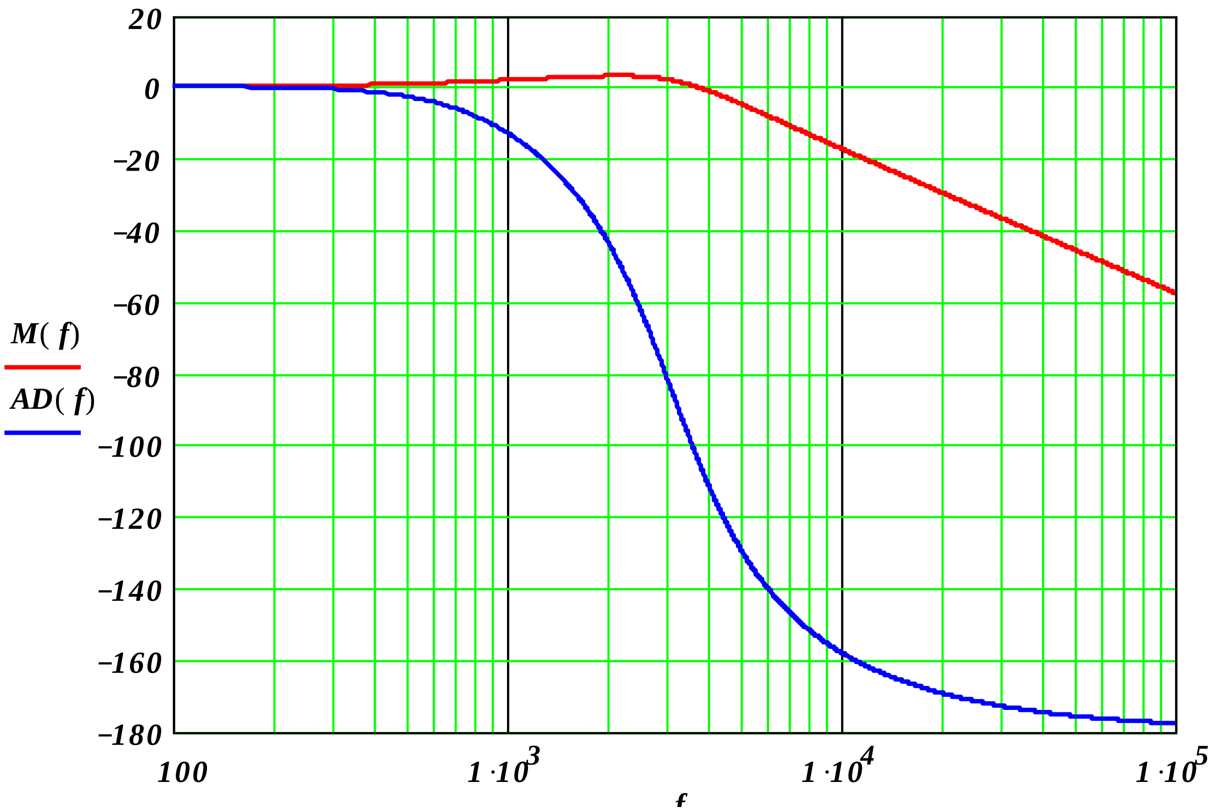
$R := \sqrt{\dfrac{L}{C_1}} \quad R = 0.34\,\Omega \quad C_2 := 5 \cdot C_1 \quad C_2 = 6.5 \times 10^{-4}\,F \quad f_r = 3604\,Hz$

$$T(f) := \frac{s(f) \cdot R \cdot C_2 + 1}{s(f)^3 \cdot R \cdot L \cdot C_1 \cdot C_2 + s(f)^2 \cdot L \cdot (C_1 + C_2) + s(f) \cdot R \cdot C_2 + 1}$$

$M(f) := 20 \cdot \log(|T(f)|) \quad AR(f) := \arg(T(f))$

$AD(f) := AR(f) \cdot 57.3$





Higher Frequency Operation Means a Smaller Filter

$$f_{r1} = \frac{1}{2\pi\sqrt{LC}}$$

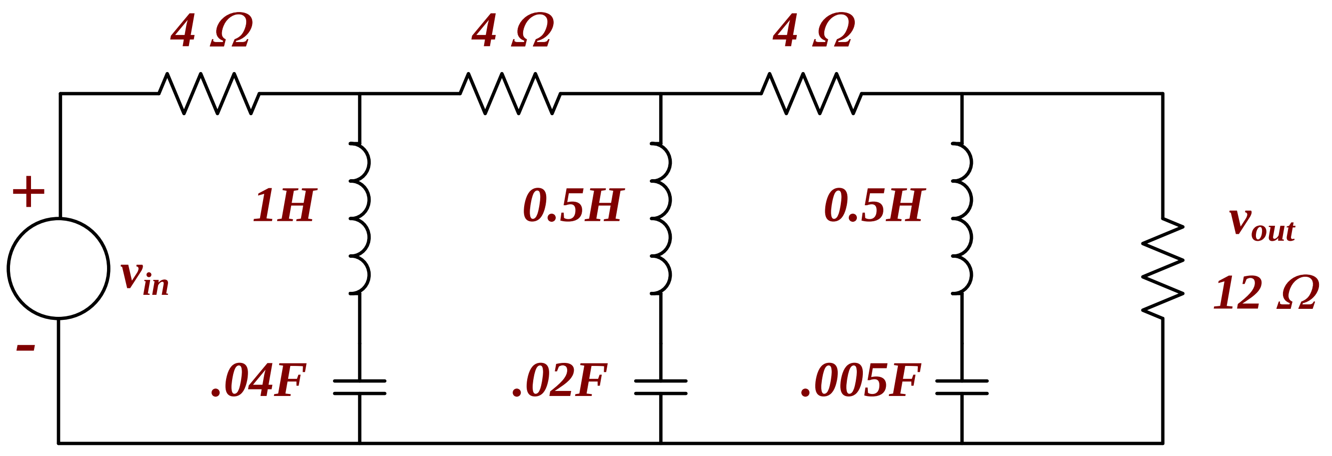
$$Let\ f_{r2} = nf_{r1} = \frac{n}{2\pi\sqrt{LC}}$$

$$nf_{r1} = \frac{1}{2\pi\sqrt{\frac{L}{n}\frac{C}{n}}}$$

L is smaller by the factor n

C is smaller by the factor n

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

$$All\ equipment = \sum P_{switchgear} + P_{transformer} + P_{AC\,cables} + P_{PS} + P_{DC\,cables}$$

- $Switchgear\ effiency \geq 98\%$ $\quad Switchgear\ losses = P_O * (\frac{1-Eff}{Eff})$

- $Transformer\ efficiency \geq 97\%$ $\quad Transformer\ losses = P_O * (\frac{1-Eff}{Eff})$

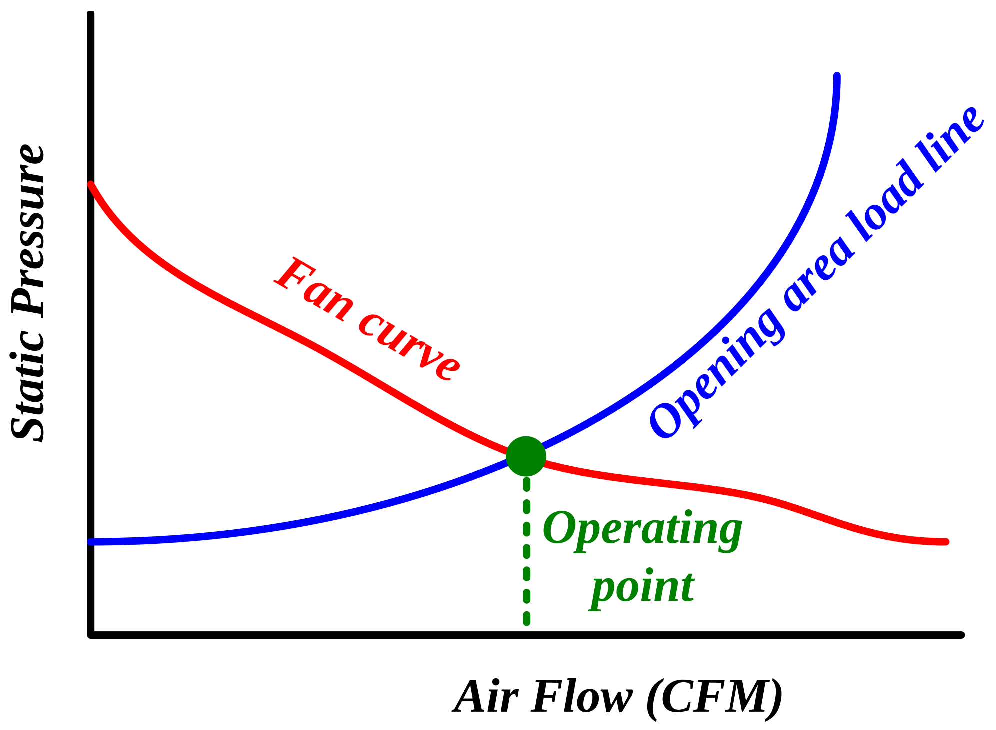
- $P_{AC\,cables} = \sum_j i_{RMS}^2 * \frac{R}{ft} * Length$

- $Power\ supply\ losses = \sum_j (P_{in\ j} - P_{out\ j})$

- $P_{DC\ output\ cable} = \sum_i i_{DC}^2 * \frac{R}{ft} * Length$

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



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

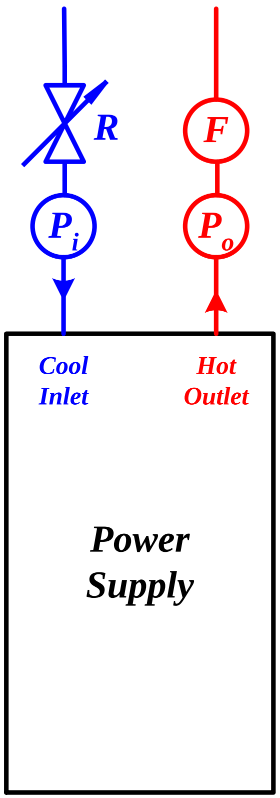
$$Q = M * c * \Delta T \qquad cal = gm * \frac{cal}{gm * {}^{O}C} * \left({}^{O}C_{Outlet} - {}^{O}C_{Inlet}\right)$$

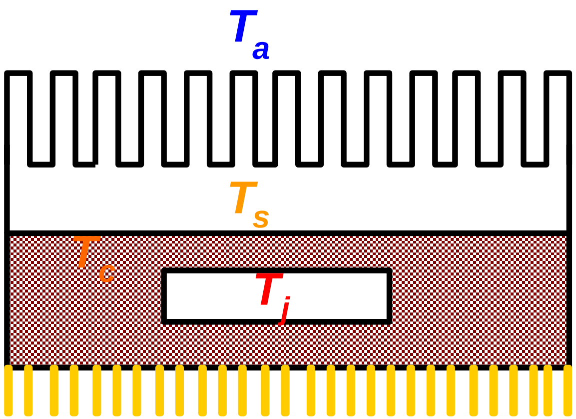
$$q = m * c * \Delta T \qquad watt = gpm * \frac{264\,watt}{gpm * {}^{O}C} * \left({}^{O}C_{Outlet} - {}^{O}C_{Inlet}\right)$$

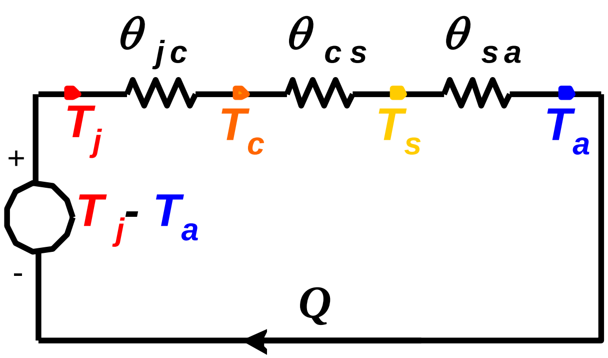
Usually the power loss and the inlet and maximum allowable outlet temperatures are known. The mechanical group will usually ask for an estimate of the water flow requirements. So solving for the flow yields

$$m = \frac{q}{c * \Delta T} = \frac{watt}{\frac{264\,watt}{gpm * {}^{O}C} * \left({}^{O}C_{Outlet} - {}^{O}C_{Inlet}\right)}$$

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 (^OC)

T_c = Device case temperature (^OC)

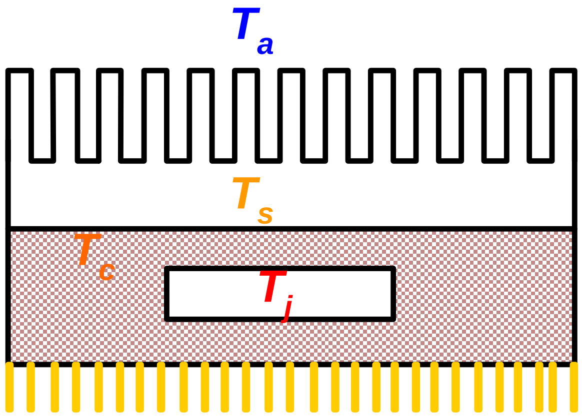
T_s = Heatsink temperature (^OC)

T_a = Ambient air or cooling water inlet temperature (^OC)

θ_{jc} = junction to case thermal resistance (^OC / W)

θ_{cs} = case to heatsink thermal resistance (^OC / W)

θ_{sa} = Heatsink to ambient air or cooling water thermal resistance (^OC / W)

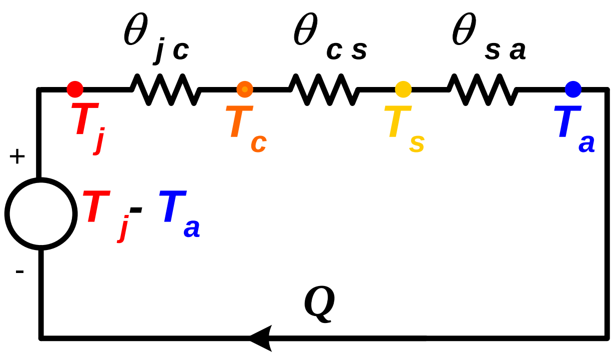


Calculate $Q = \dfrac{T_j - T_a}{\theta_{jc} + \theta_{cs} + \theta_{sa}}$

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 $q = m*c*\Delta T$

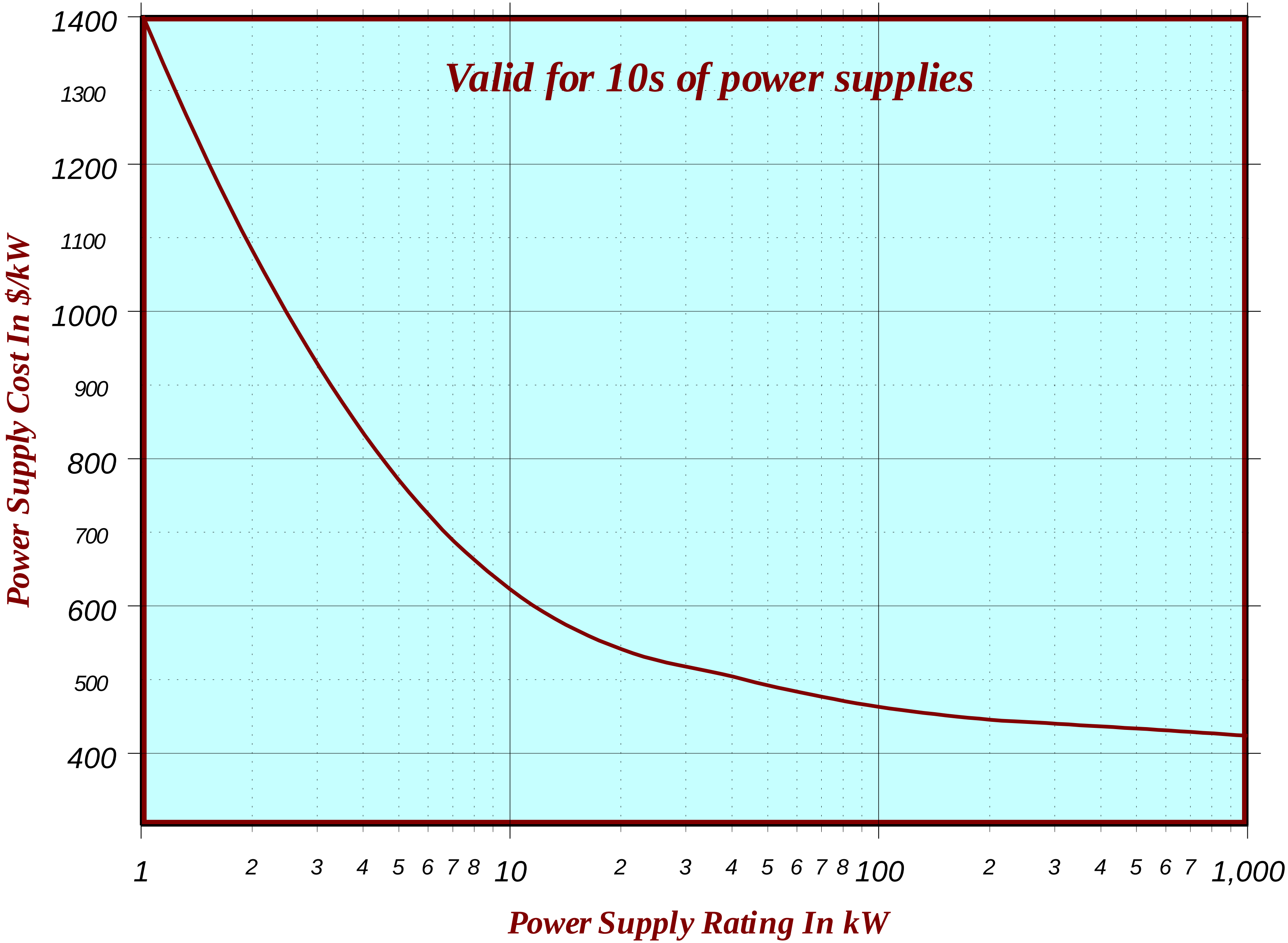
$$\Delta T = \frac{q}{m*c} = \frac{watts}{gpm * \dfrac{264 watt}{gpm * {}^{O}C}}$$

$\Delta T \leq$ 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



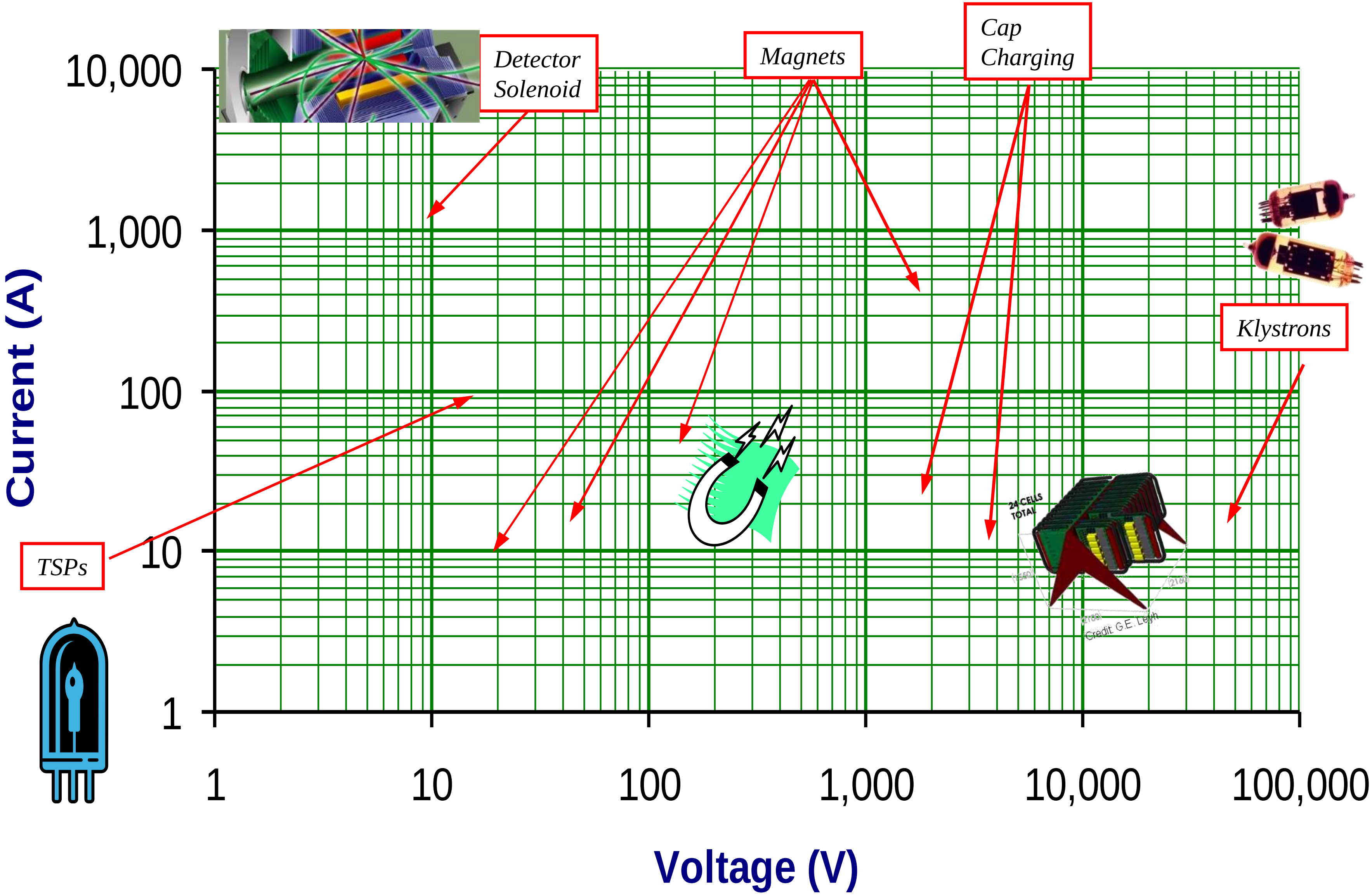
Valid for 10s of power supplies
Power Supply Cost In $/kW
1400
1300
1200
1100
1000
900
800
700
600
500
400
1
2
3
4
5
6
7
8
10
2
3
4
5
6
7
8
100
2
3
4
5
6
7
1,000
Power Supply Rating In kW

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.

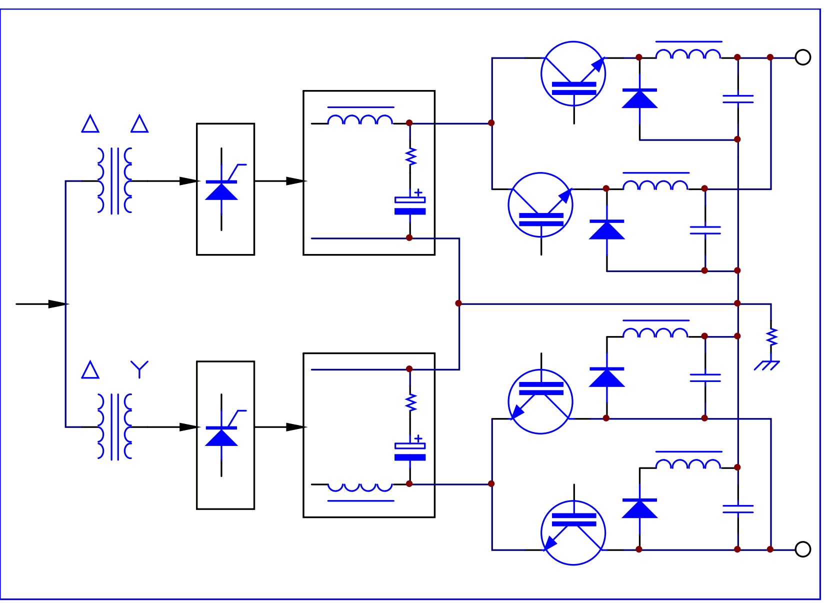
- *How much heat is dissipated to building air and how much heat is removed by the water system.*
- *Calculate the water flow rate needed to limit the water temperature rise to $8^{O}C$ maximum.*

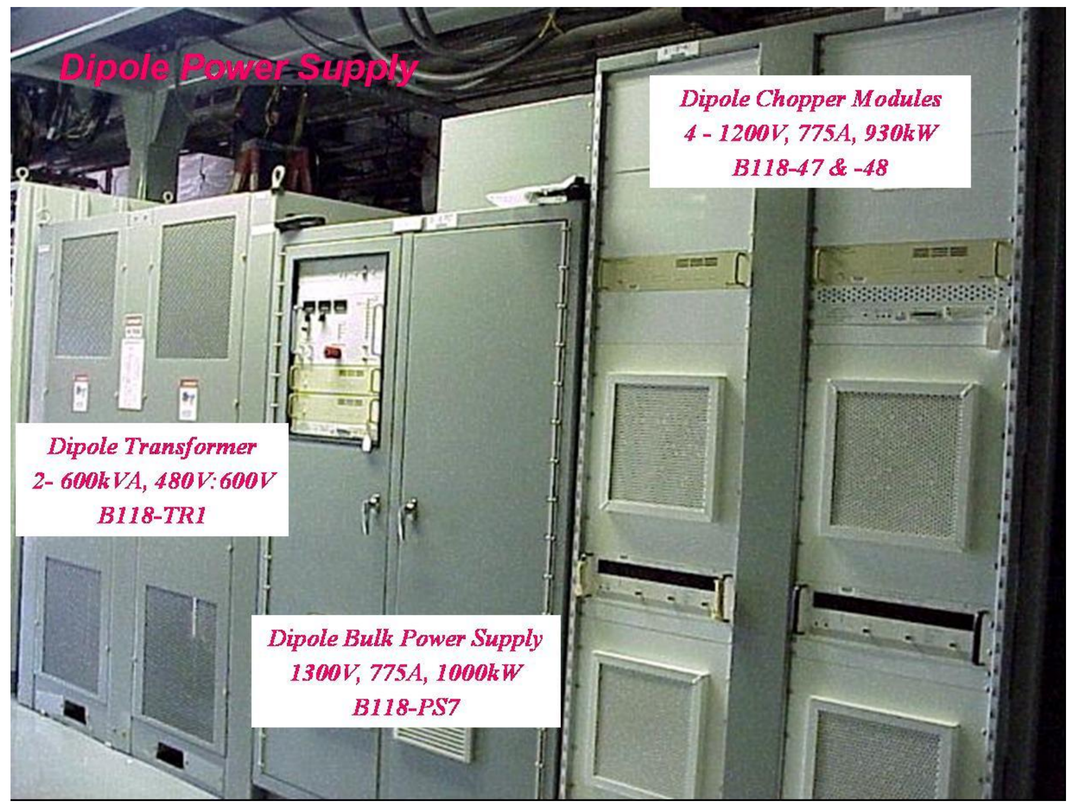
Typical DC Power Supply Ratings for Accelerators



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

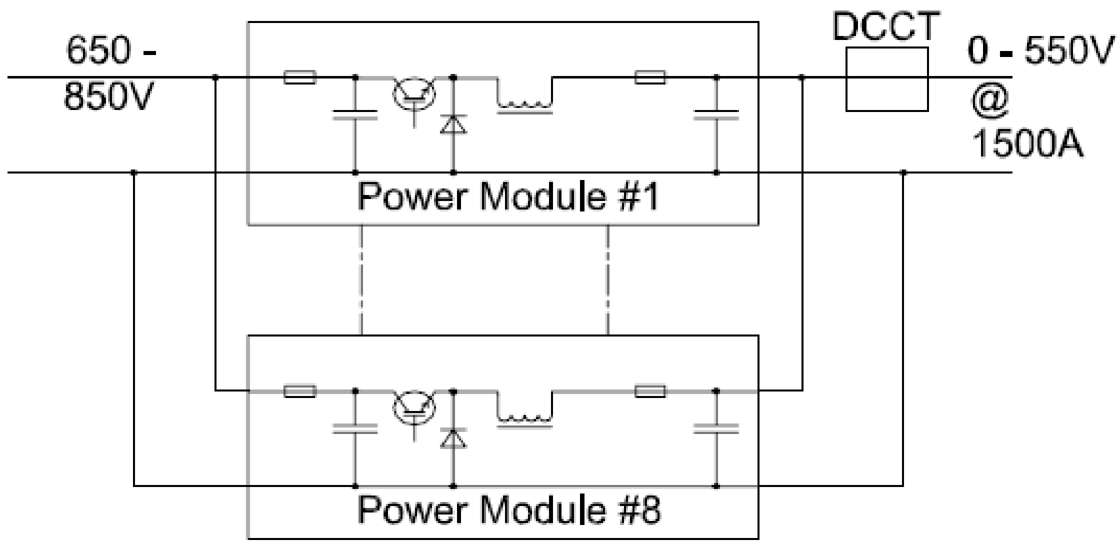


Figure 1: Dipole Converter Topology.

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*

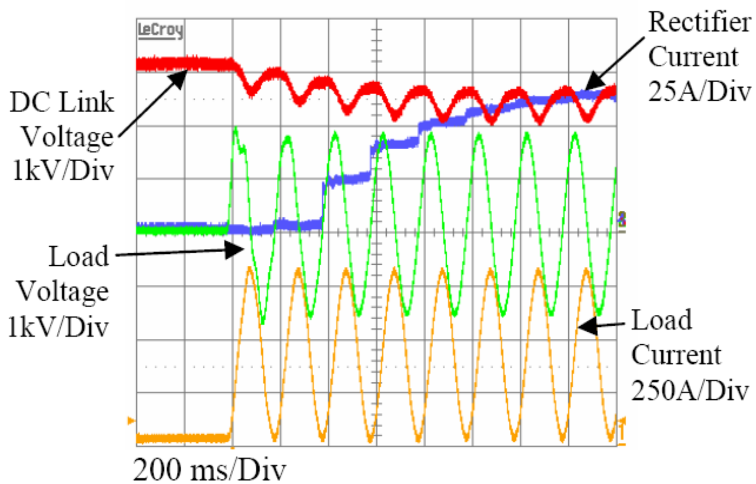


Figure 4: First few cycles after turn on.

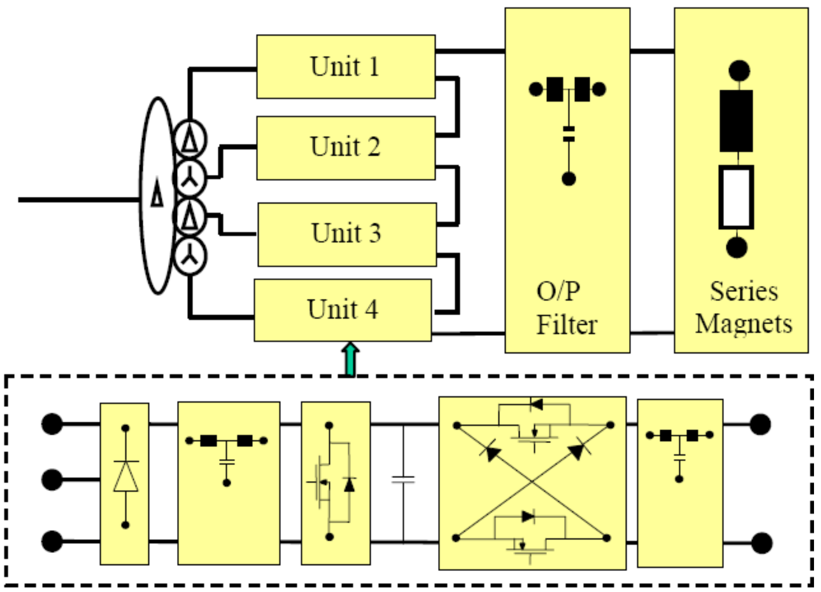
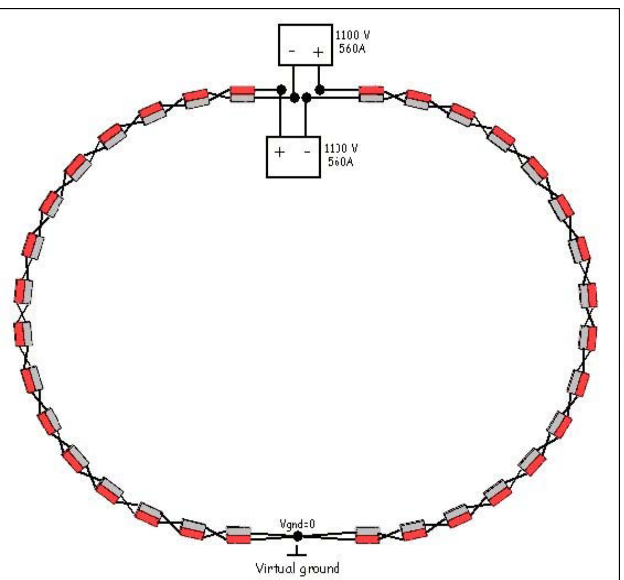


Figure 1: Booster dipole power circuit.

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



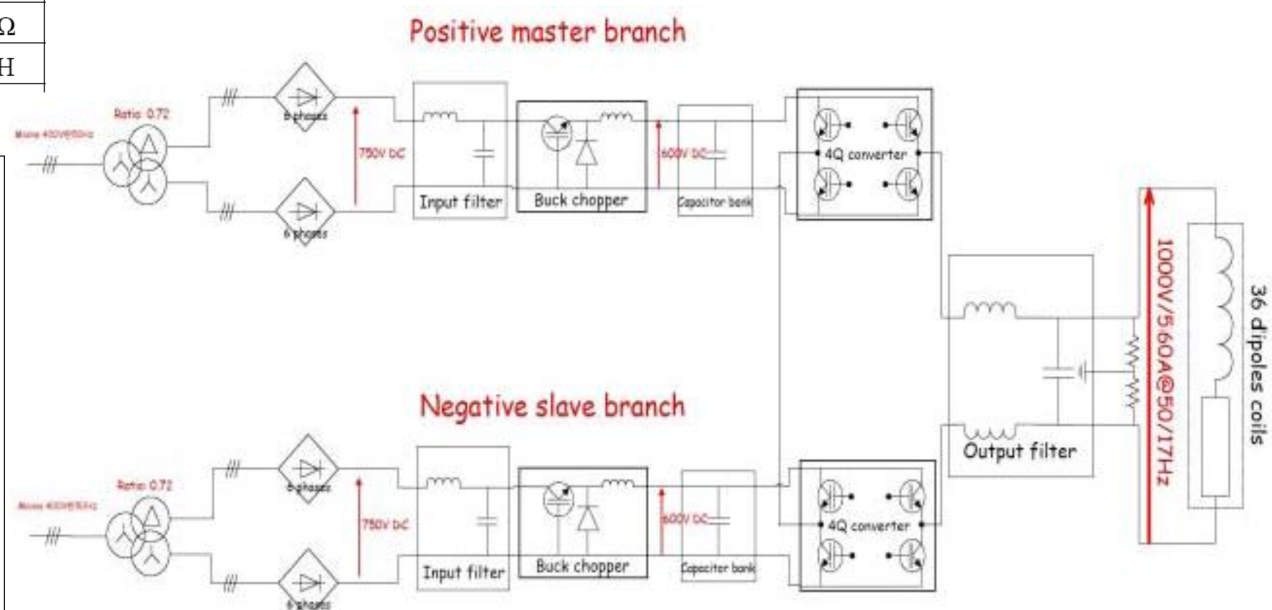
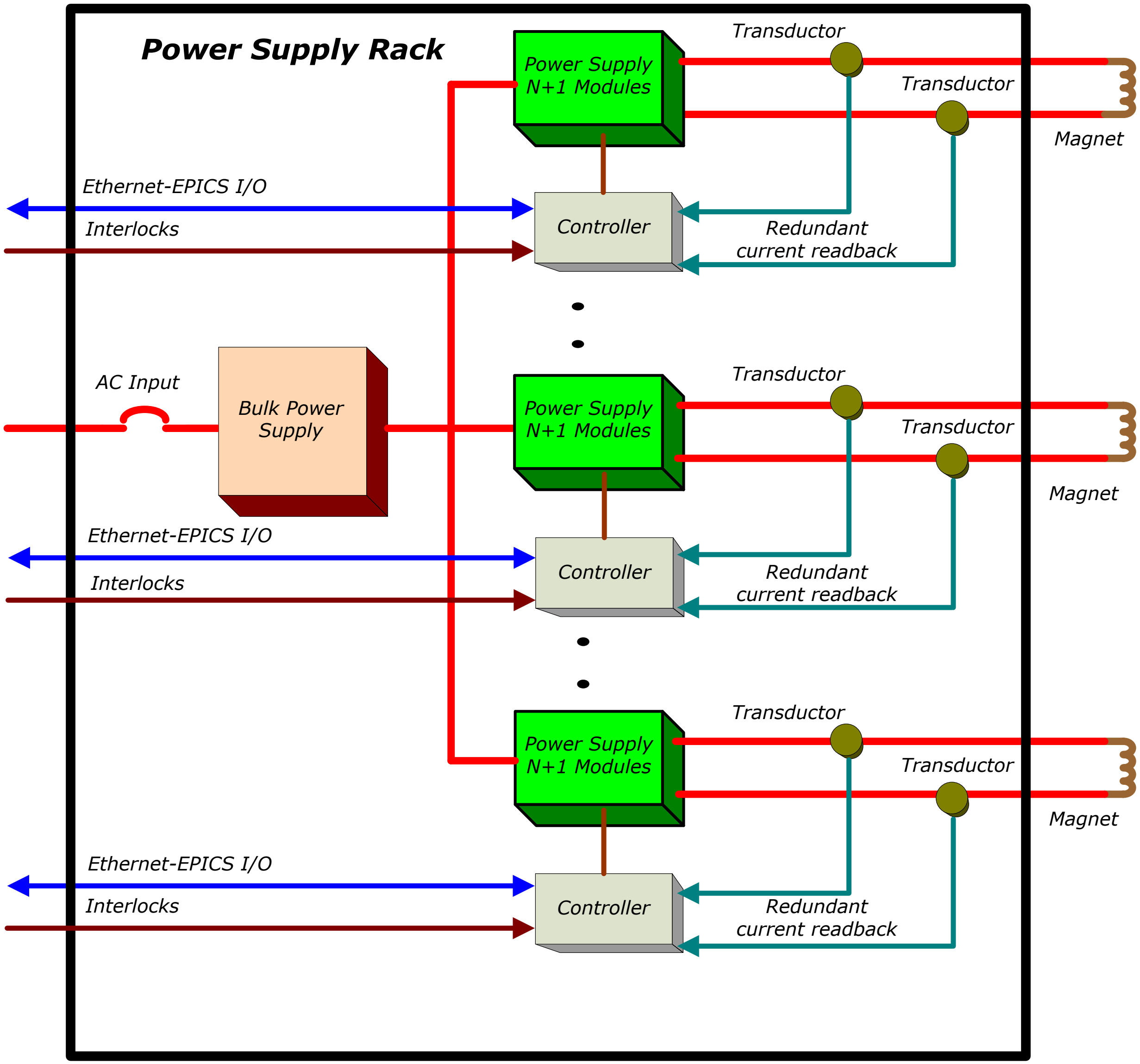


Figure 4: dipoles PS main schematics

Power Supplies for the ATF2



CNAO STORAGE RING DIPOLE MAGNET POWER CONVERTER 3000A / ±1600V

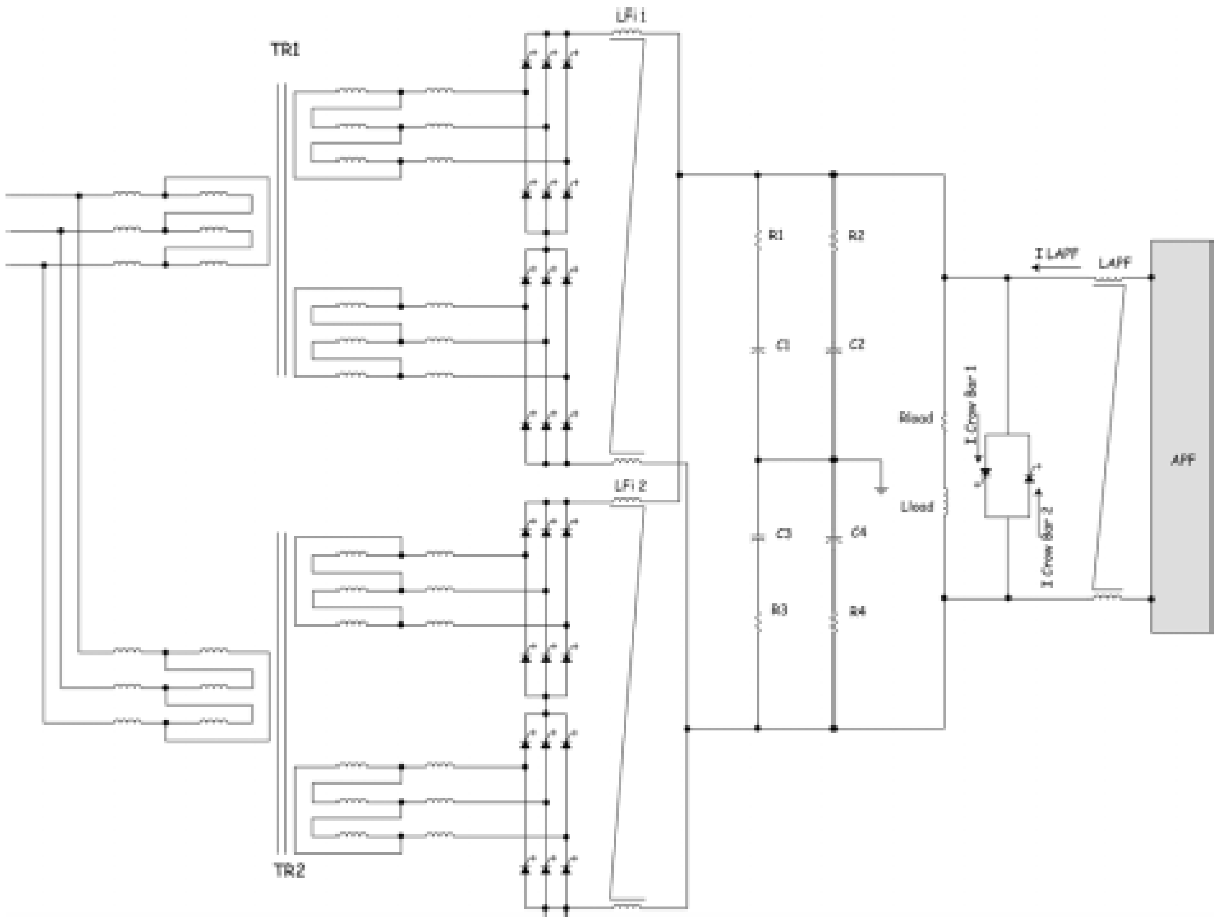


Figure 2: Topology of CNAO synchrotron power supply.

Bipolar Power Supplies at SPEAR3 and LCLS (480W, ±40V, ± 12A)

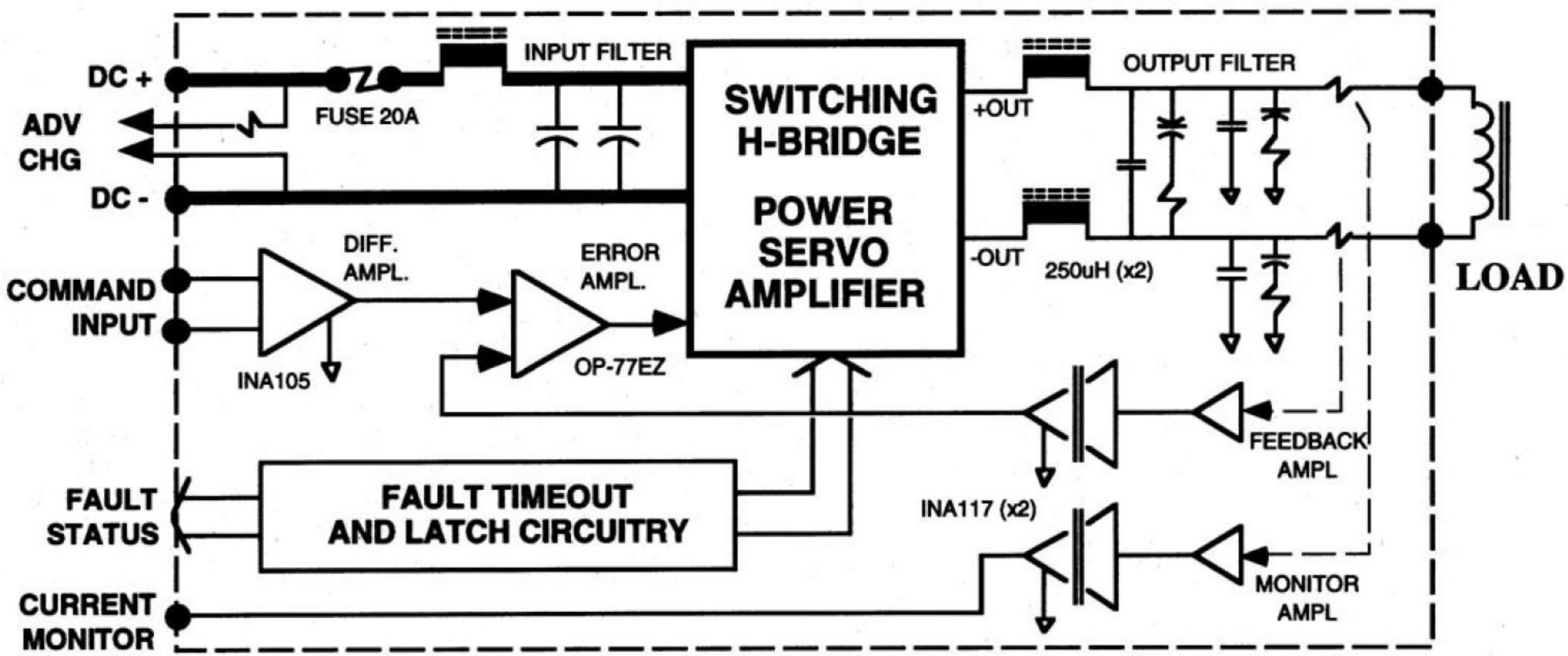


Figure 1.3. MCOR12 Block Diagram.

Bipolar Power Supplies at SPEAR3 and LCLS

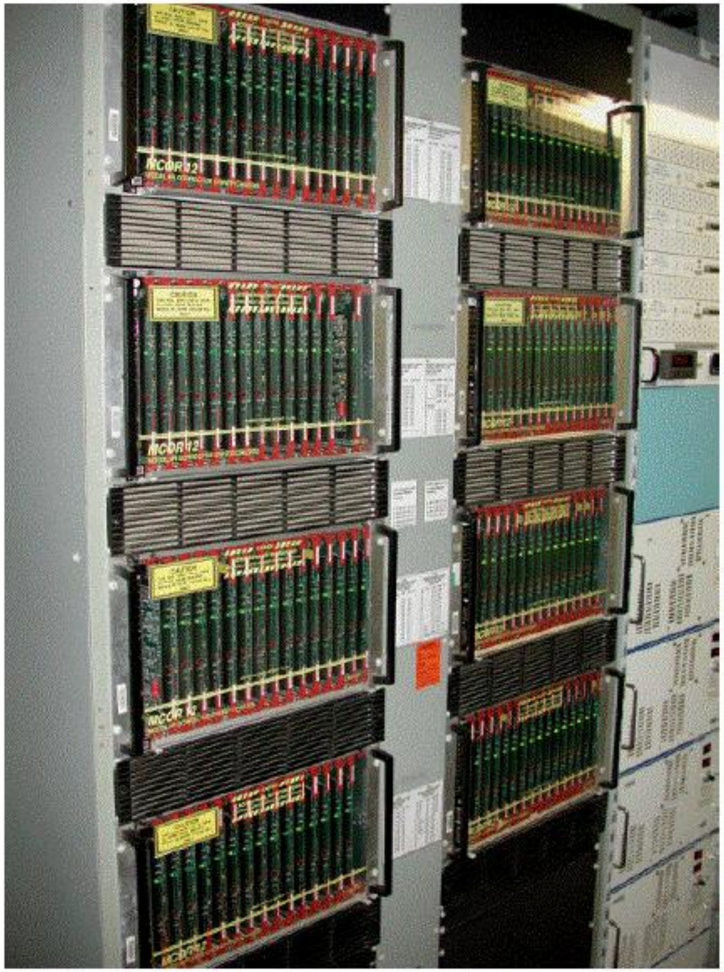
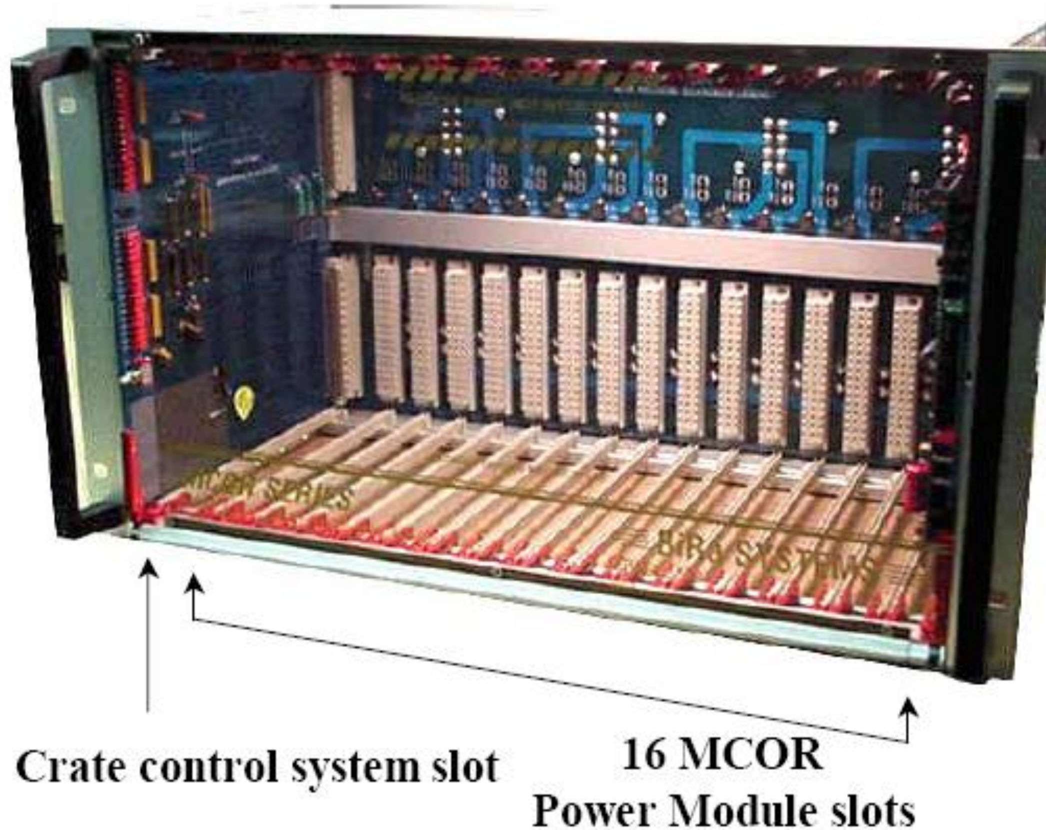


Figure 1.1. A typical MCOR installation



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

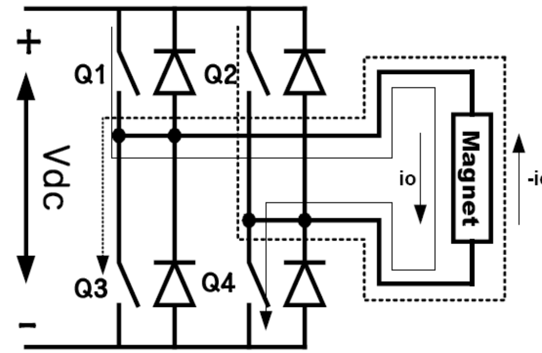


Figure 1: Bipolar MPS operation of full-bridge four-quadrant DC/DC converter.

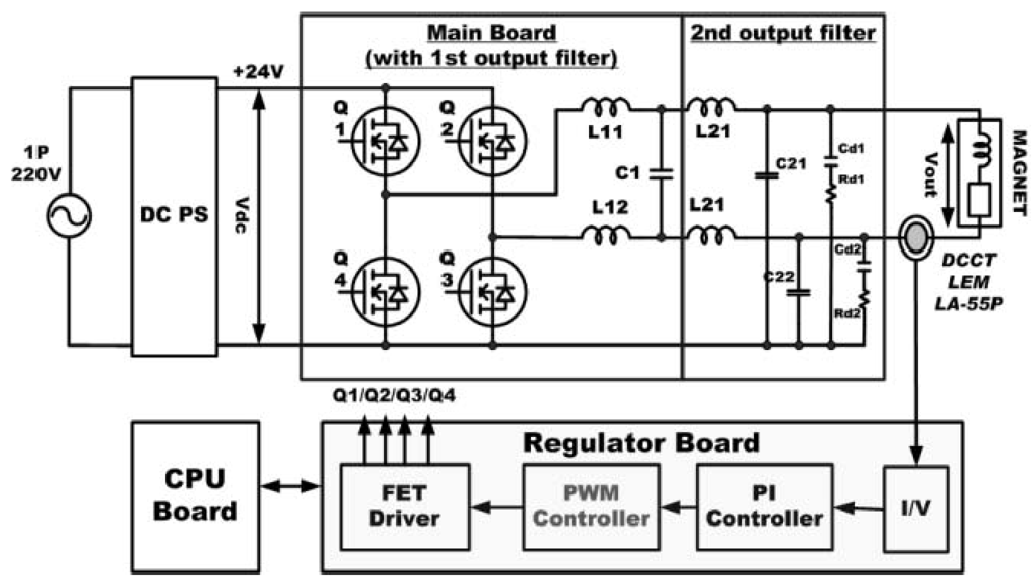
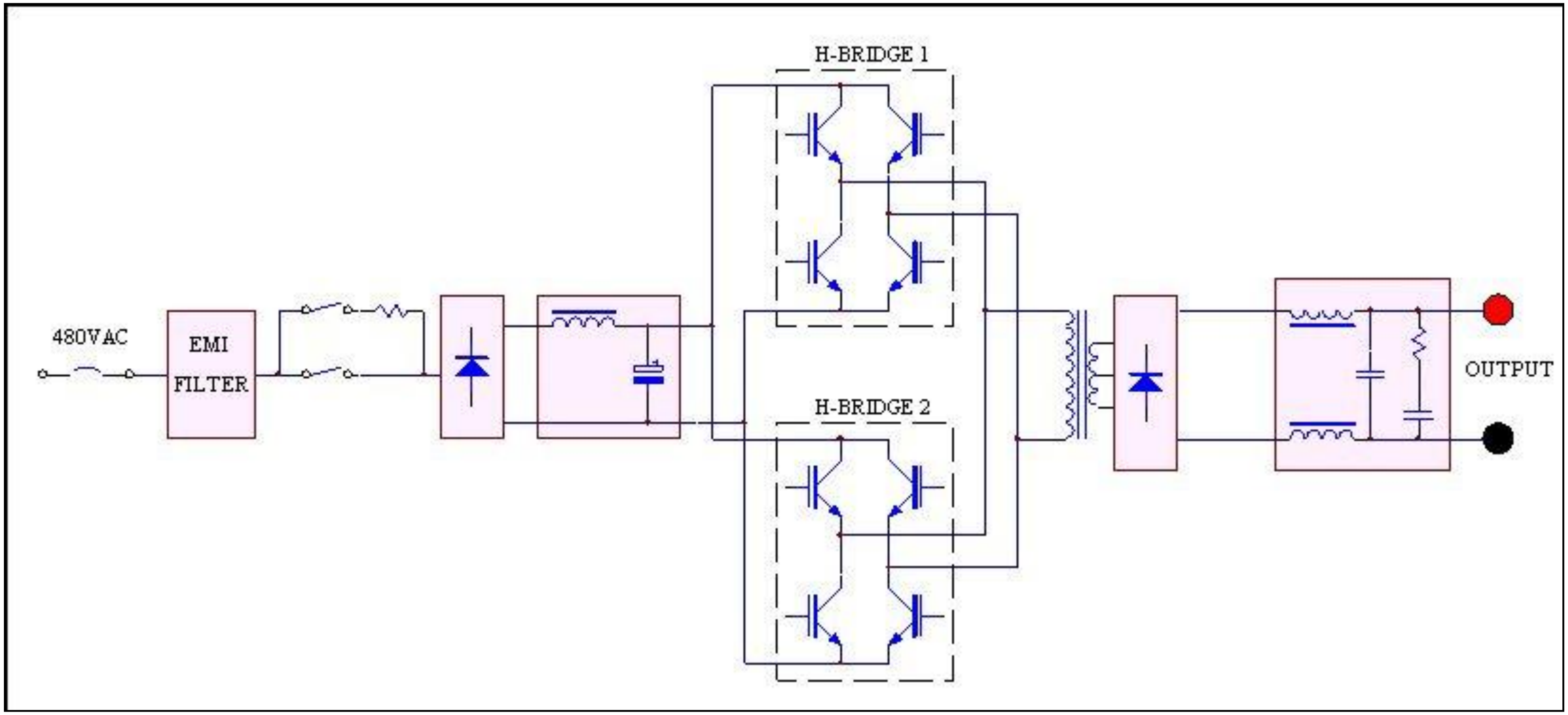


Figure 4: Circuit diagram of bipolar MPS.

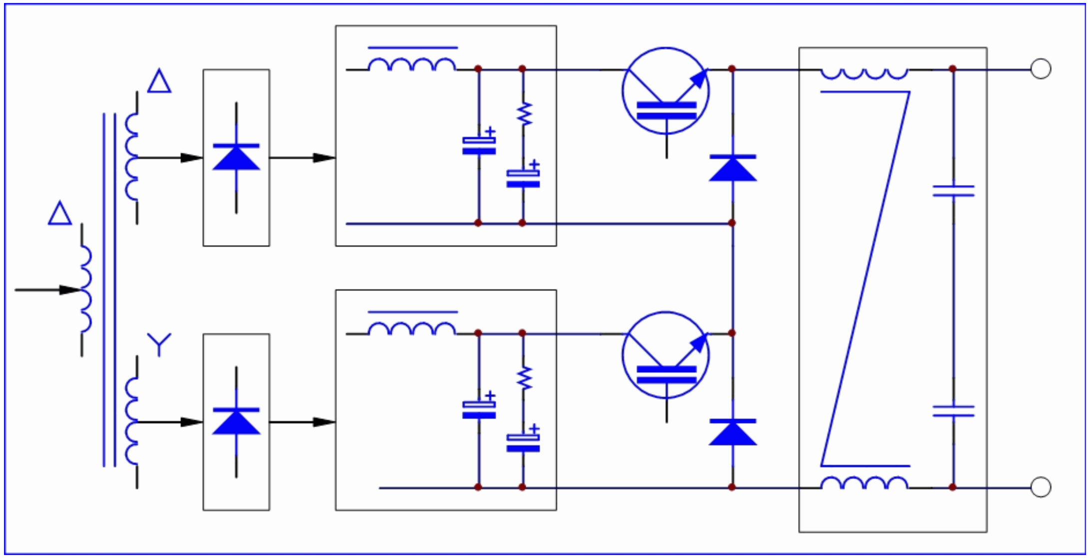
Table 1: LGPS ratings.

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 6 – Pulsed Power Supplies

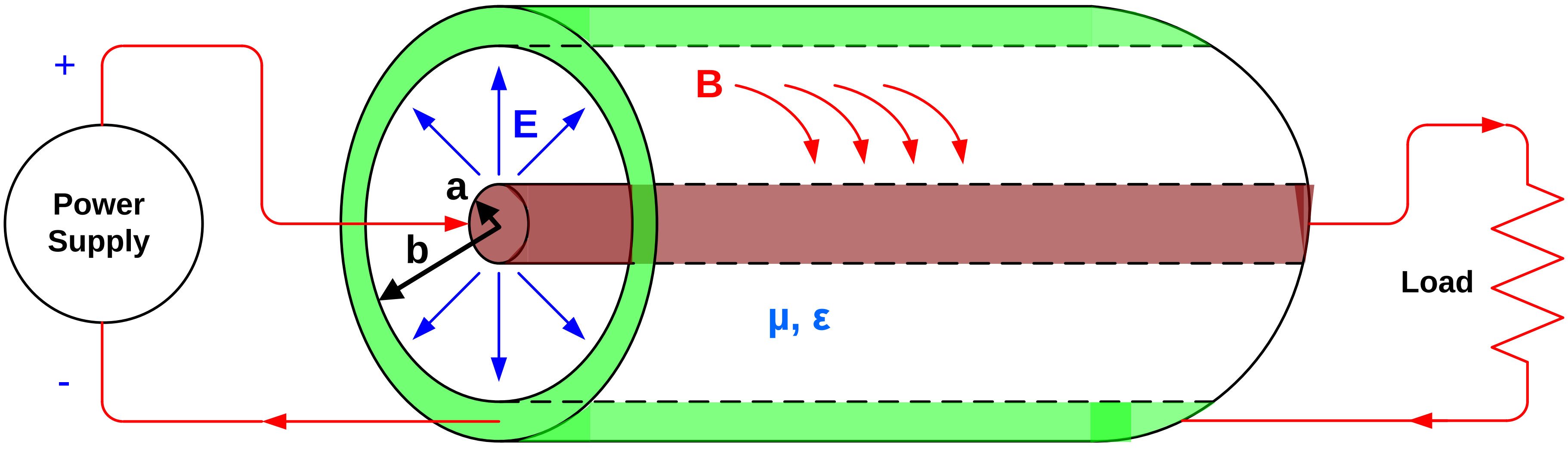
Transmission Line Basics

- *A transmission line is a "controlled impedance" device, usually consisting of two conductors.*
- *Its geometry and dielectric 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 is determined by the integral of the magnetic field on the conductor surfaces.*
- *Transmission lines support the propagation of fixed velocity waves in both directions along the line.*
- *Transmission lines guide transverse electro magnetic (TEM) waves, TE or TM waves are guided by waveguides*

Transmission Line Types

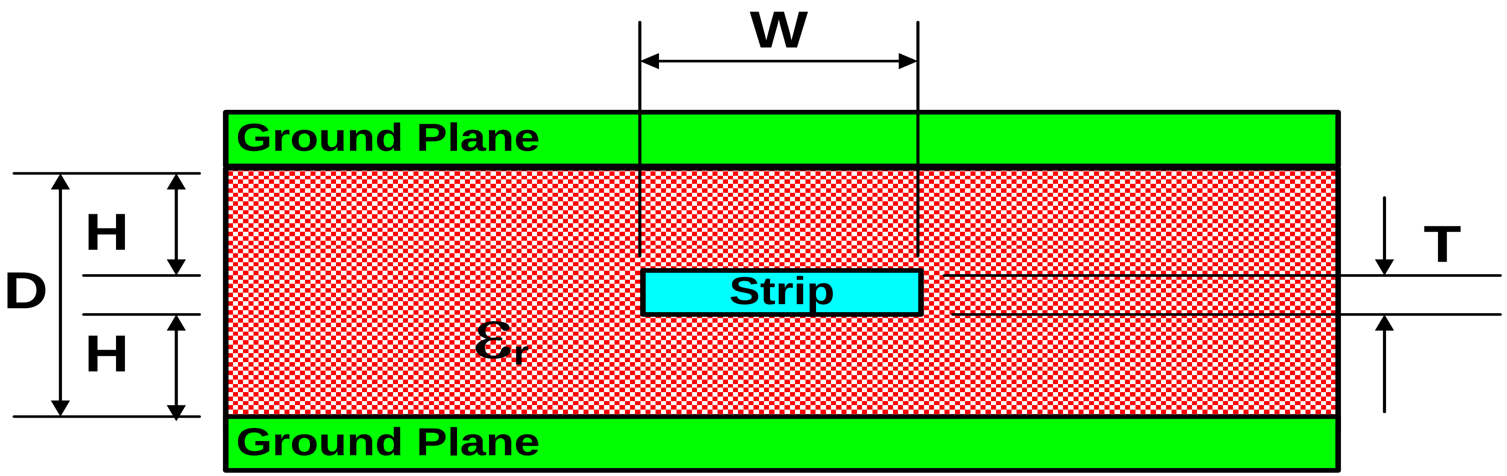
- *Coaxial transmission lines*
  - *Voltage between two coaxial conductors*
  - *Currents of equal magnitude and opposite sign are carried on the conductors*
  - *Conductors separated by air or dielectric*
  - *Transverse electromagnetic (TEM) transmission line media*
  - *Non-dispersive (propagates all frequency components equally), no cutoff frequency*
  - *No external electric or magnetic fields*

- *Coaxial transmission lines and cables*



$$Z_0 = \frac{\ln b/a}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}$$

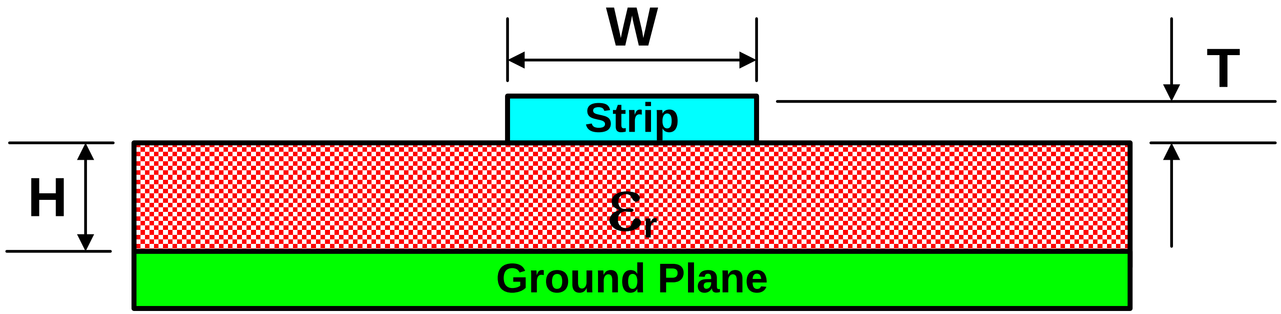
- *Planar transmission line - Stripline consists of a single strip buried in a dielectric separated from two or more ground planes*



Characteristic Impedance

$$Z_O = \frac{60}{\sqrt{\varepsilon_r}} \ln\left[\frac{4H}{0.67\pi W\left(0.8 + \frac{T}{D}\right)}\right] \text{ ohms}$$

- *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 $Z_o = \frac{60}{\sqrt{\varepsilon_e}} \ln\left(8\frac{H}{W} + 0.25\frac{W}{H}\right)$ ohms

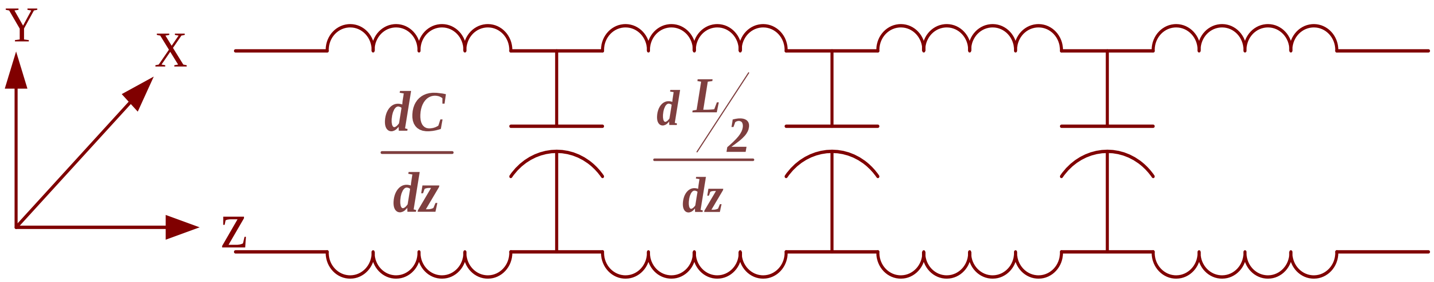
when $\left(\frac{W}{H}\right) \geq 1$ Effective Dielectric Constant $\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\left(1 + 12\left(\frac{H}{W}\right)\right)^{-1/2}\right]$

Characteristic Impedance $Z_o = \frac{120\pi}{\sqrt{\varepsilon_e}\left[\frac{W}{H} + 1.393 + \frac{2}{3}\ln\left(\frac{W}{H} + 1.444\right)\right]}$ 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

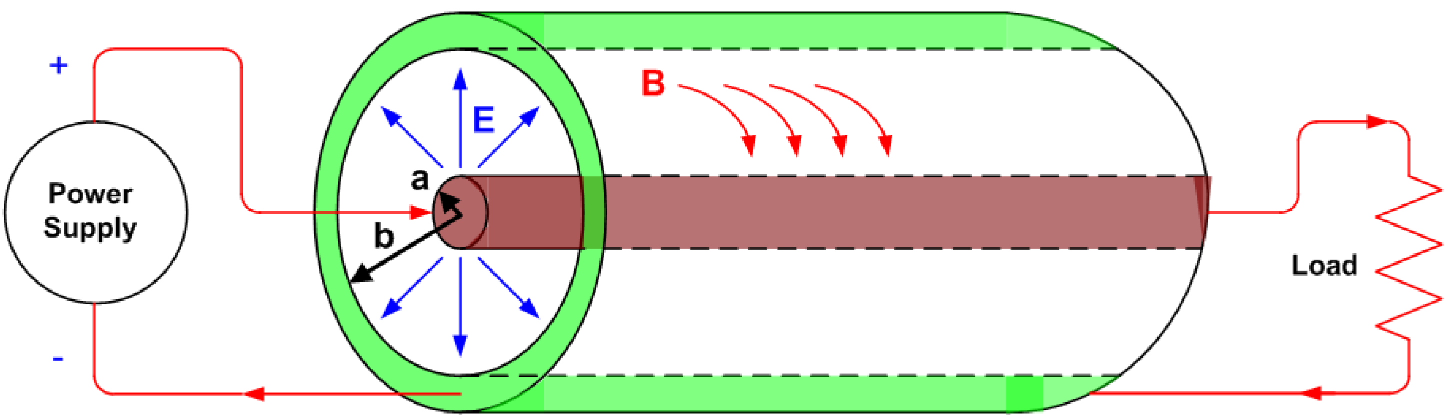


$$E = \hat{y}E_y \quad H = \hat{x}H_x \qquad Z_0 = \sqrt{\frac{L}{C}} \text{ Characteristic impedance - 377 ohms for air (free space)}$$

for air (and most dielectrics) $\mu_r = 1$, for air $\varepsilon_r = 1$ (most other dielectrics $\varepsilon_r > 1$, n = number of sections

$$Z_0 = \frac{\ln b/a}{2\pi}\sqrt{\frac{\mu}{\varepsilon}} \text{ For coaxial line, } 50\Omega \le Z_0 \le 80\Omega$$

$$v = \frac{1}{\sqrt{\mu_0 \mu_r \varepsilon_0 \varepsilon_r}} = \text{wave velocity} \quad \text{wavelength } \lambda = \frac{v}{f} \quad \text{time delay} = t_d = n * \sqrt{LC}$$



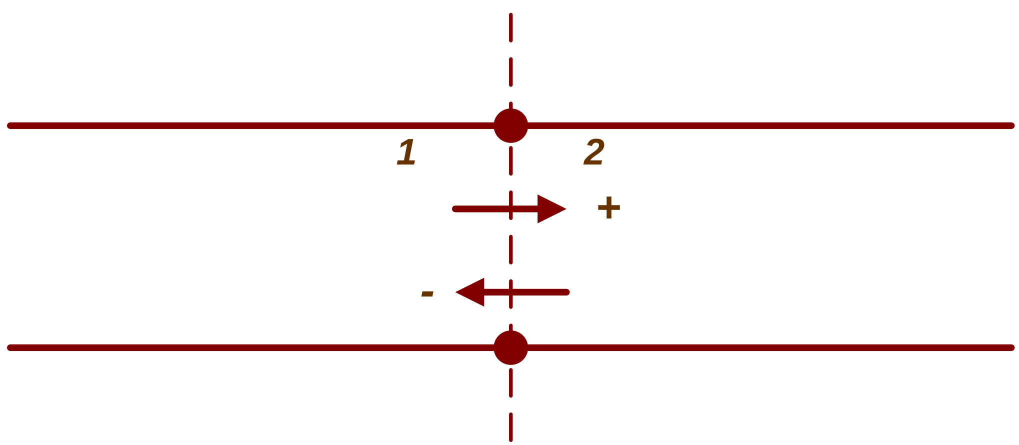
Transmission Line Equations at an Interface

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 also causes a reflected voltage and current, (V_1^-, I_1^-), moving backward on Line 1, with $V_1^- = Z_1 I_1^-$*



Transmission Line Equations at an Interface

The voltages on each side of the interface must be equal.

$$V_1^+ + V_1^- = V_2^+$$

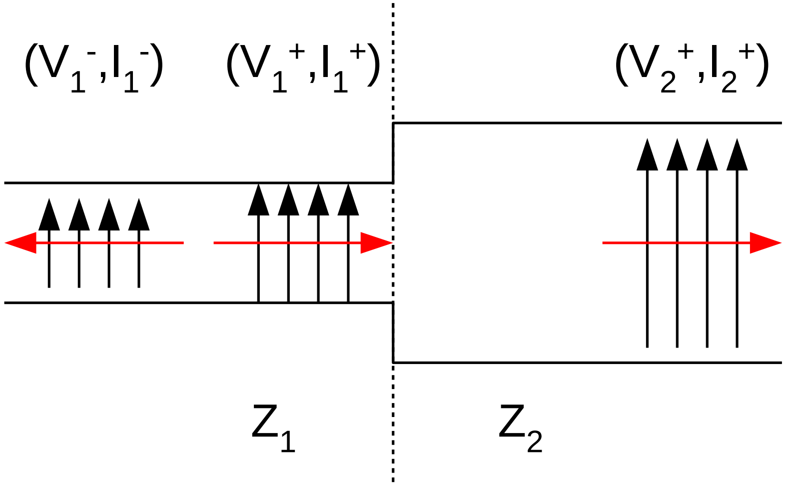
Current must be conserved at the interface.

$$I_1^+ = I_2^+ + I_1^-$$

Expressing the second equation in terms of the voltages and impedances yields the Reflection Coefficient, Gamma

$$\frac{V_1^+}{Z_1} = \frac{V_2^+}{Z_2} + \frac{V_1^-}{Z_1} = \frac{V_1^+}{Z_2} + \frac{V_1^-}{Z_2} + \frac{V_1^-}{Z_1}$$

$$\frac{V_1^-}{V_1^+} = \frac{\frac{1}{Z_1} - \frac{1}{Z_2}}{\frac{1}{Z_1} + \frac{1}{Z_2}} = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \Gamma$$



The transmission coefficient, T, is defined as

$$T \equiv \frac{V_2^+}{V_1^+} = \frac{\left(V_1^+ + V_1^-\right)}{V_1^+}$$

$$= 1 + \Gamma$$

$$= \frac{Z_2 + Z_1 + Z_2 - Z_1}{Z_2 + Z_1} = \frac{2Z_2}{Z_2 + Z_1}$$

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*

The flow of energy (power) is conserved at the interface.

$$P_{IN} = V_1^+ I_1^+ \text{ (assume all voltages and impedances are real)}$$

$$= \frac{(V_1^+)^2}{Z_1}$$

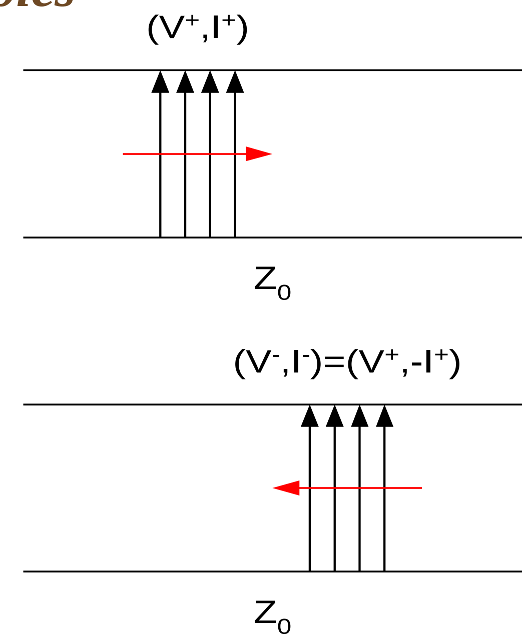
$$P_T = \frac{\left(TV_1^+\right)^2}{Z_2} = \frac{\left(4Z_2\right)}{\left(Z_2 + Z_1\right)^2}\left(V_1^+\right)^2$$

$$P_R = \frac{\left(\Gamma V_1^+\right)^2}{Z_1} = \frac{\left(Z_2 - Z_1\right)^2}{Z_1\left(Z_2 + Z_1\right)^2}\left(V_1^+\right)^2$$

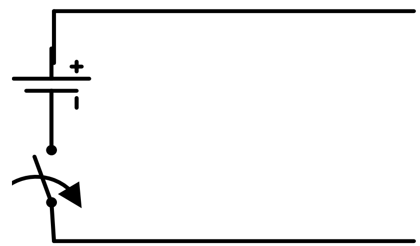
$$P_T + P_R = \frac{\left(4Z_2Z_1 + Z_2^{\,2} - 2Z_2Z_1 + Z_1^{\,2}\right)}{Z_1\left(Z_2 + Z_1\right)^2}\left(V_1^+\right)^2 = \frac{\left(V_1^+\right)^2}{Z_1}$$

$$= P_{IN}$$

Transmission Line Simple Examples

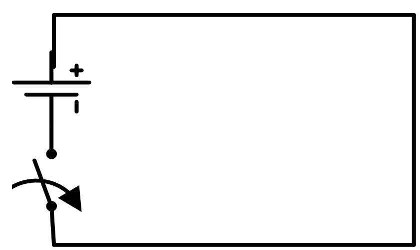


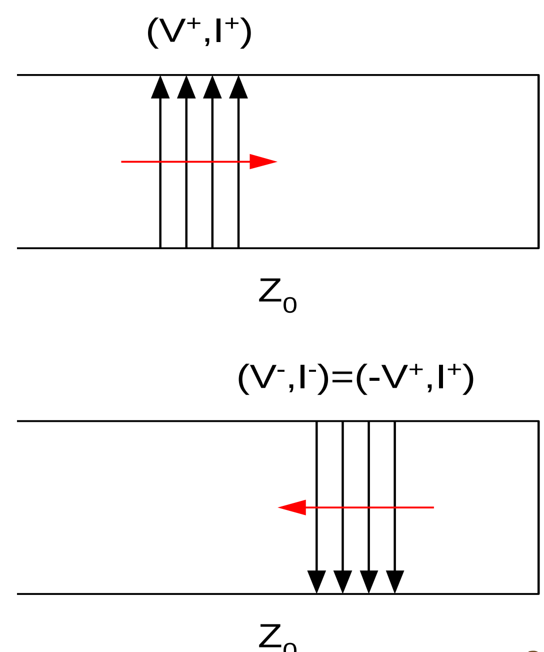
Open Line



- $Z_1 = Z_0$, Z_2 infinite
- $\Gamma = 1$
- $I_2 = 0$
- *Voltage totally reflected without inversion*

Shorted Line

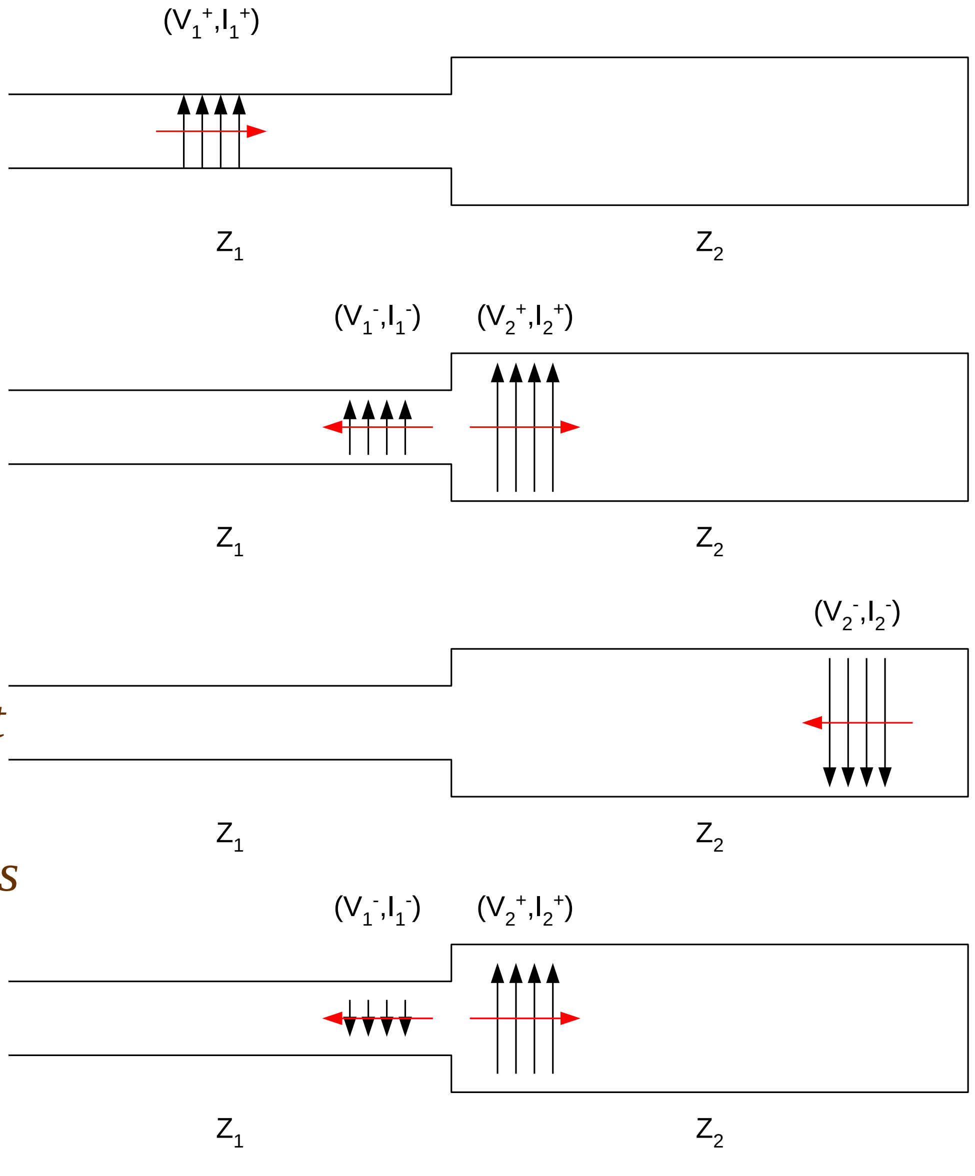




- Z_2 zero
- $\Gamma = -1$
- $V_2 = 0$
- *Voltage totally reflected with inversion*

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*



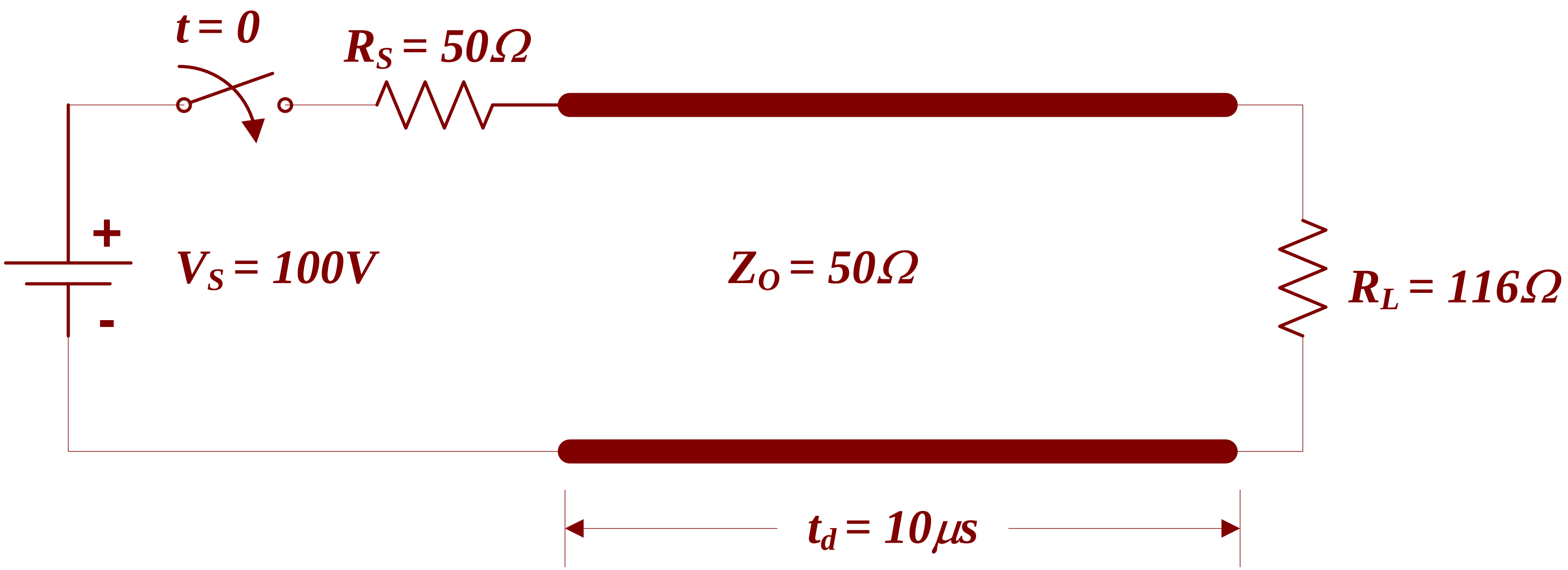
Transmission Line Homework Problem #12

A. *An artificial transmission line can be formed using lumped Ls and Cs. Calculate the delay of an artificial line composed of 8 sections of inductances L=4mH per section and capacitance C=40pF per section.*

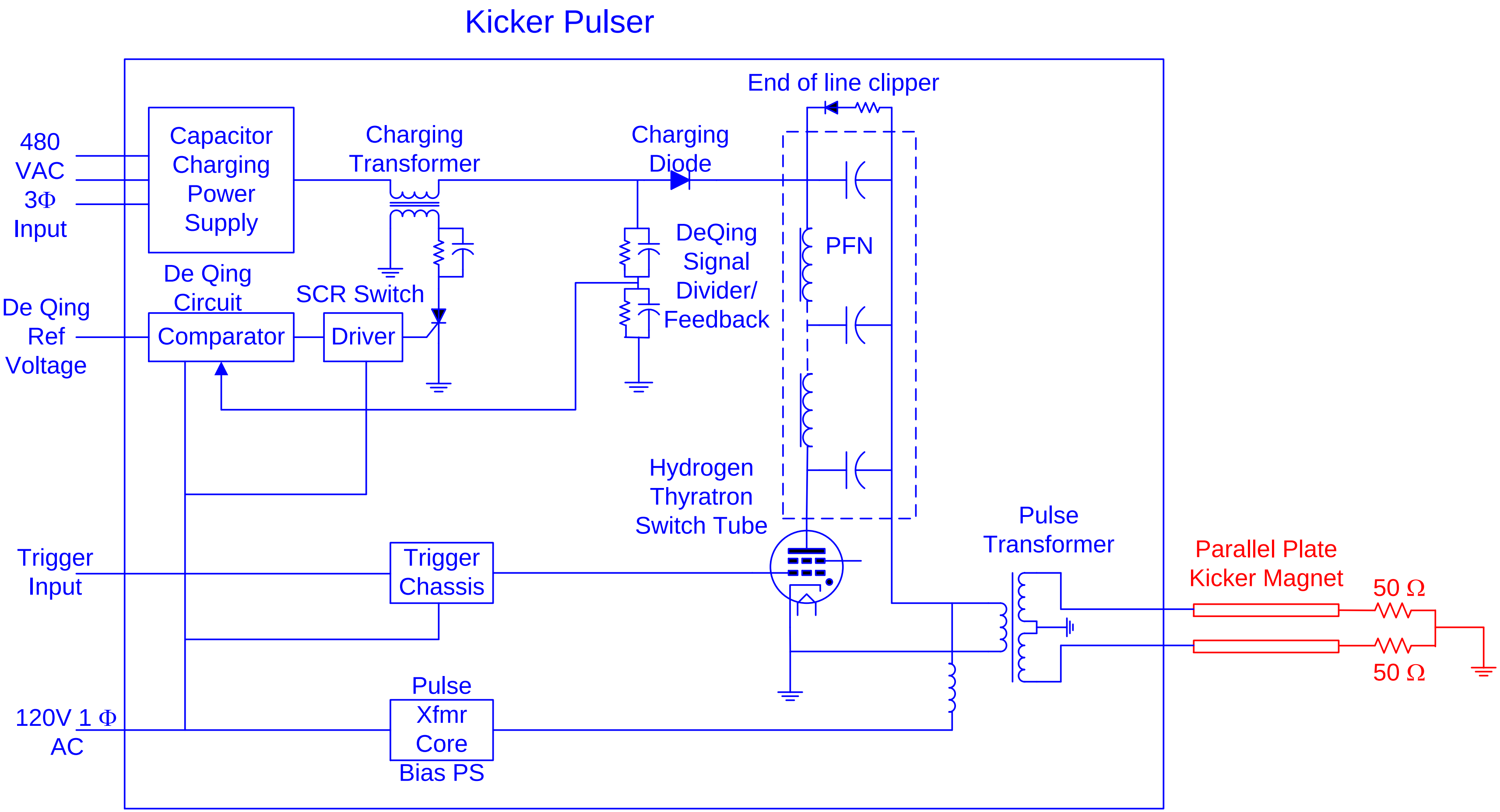
B. *The frequency of a signal applied to a two-wire transmission cable is 3GHz. What is the signal wavelength if the cable dielectric is air? Hint – relative permittivity of air is 1*

C. *What is the signal wavelength if the cable dielectric has a relative permittivity of 3.6?*

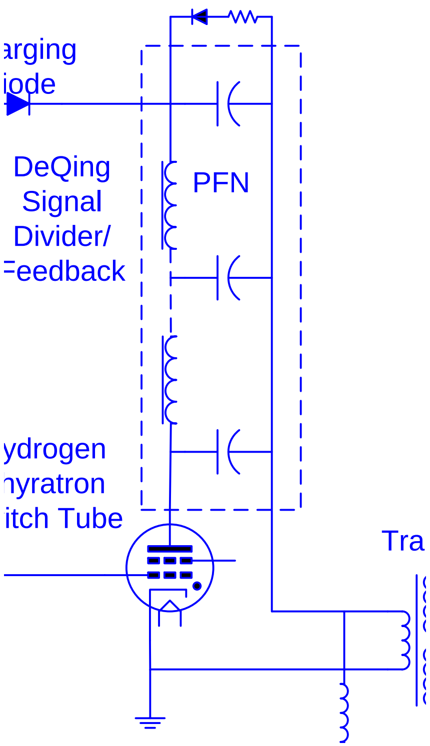
For the transmission line shown below, calculate the Reflection Coefficient Γ, the reflected voltage and the voltage and current along the line versus time.



Conventional Thyratron Pulser - PFN



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.

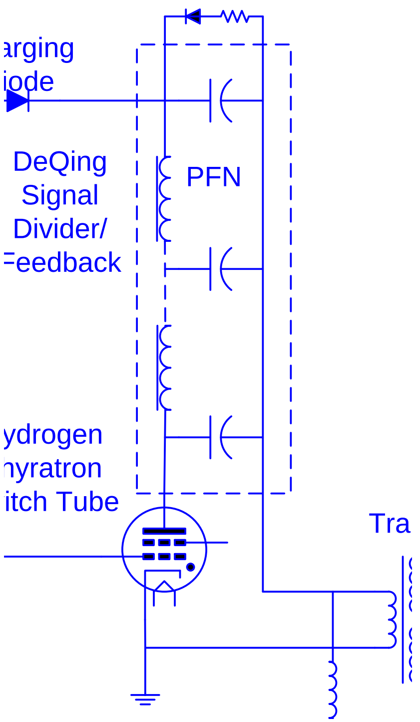
$$Z = \sqrt{\frac{L}{C}}$$

$$T = 2 * Z * C$$

$$C = \frac{T}{2 * Z}$$

$$L = \frac{T * Z}{2}$$

Since the PFN impedance is matched to the load impedance, all the PFN stored energy is dissipated in the load



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,

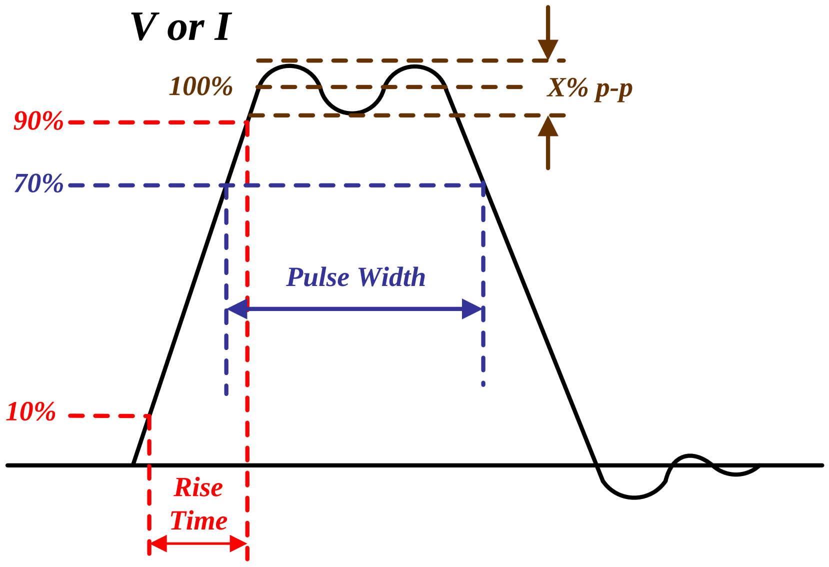
$$V_{pfn} = 2 * V_{load}$$

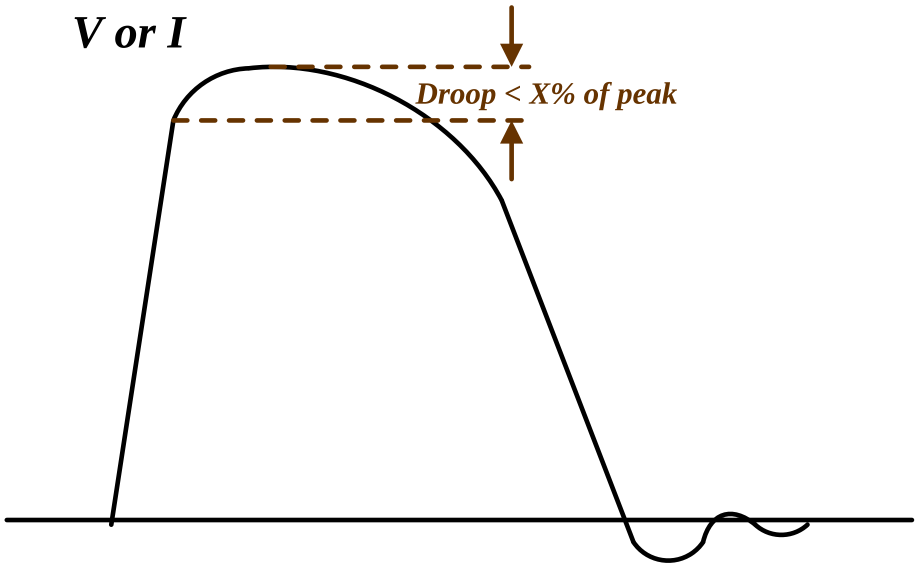
Therefore the PFN must be charged to twice the desired load voltage.

- *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)





Conventional Pulsers - Why Use a 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

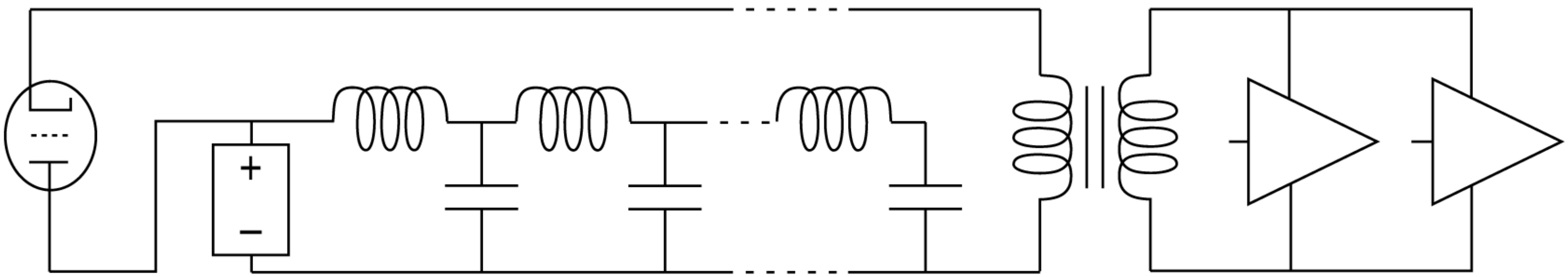
Smaller power source

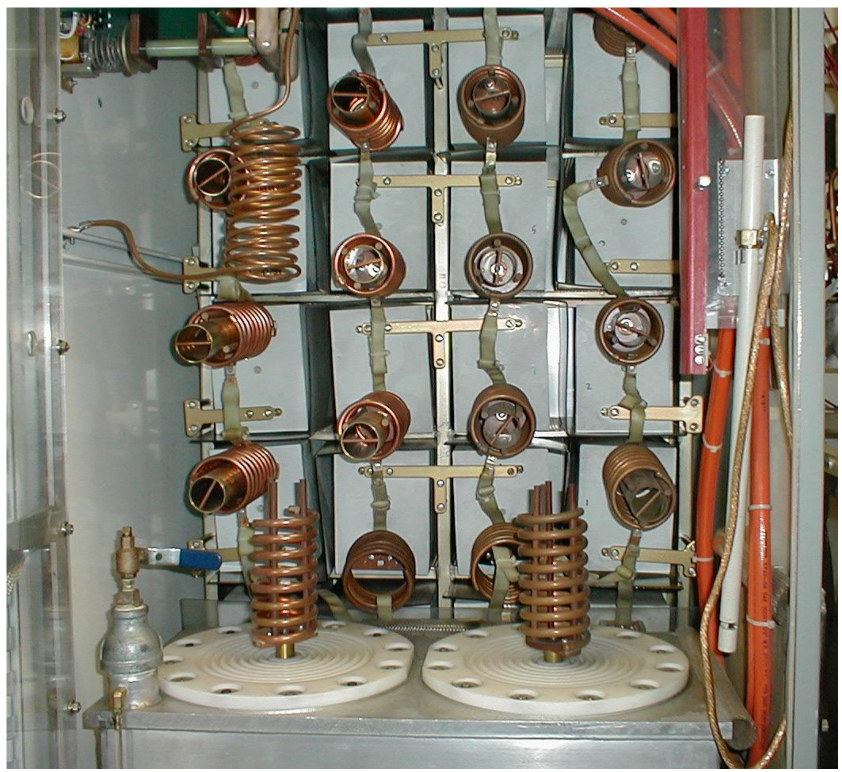
Less cooling required (klystron efficiency is 45%)

*Average power = peak power *duty cycle(on-time*PRR)*

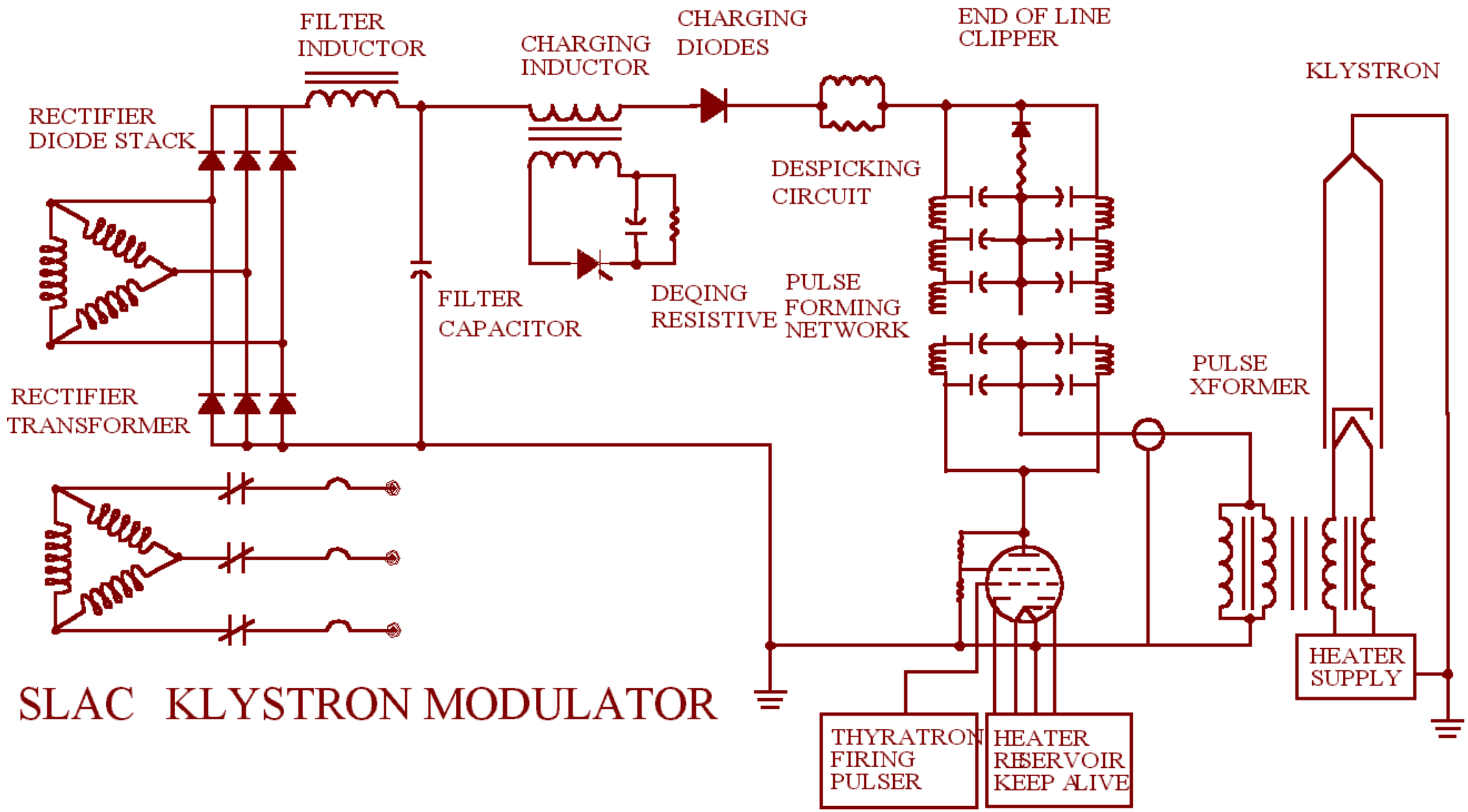
*Average power = 144.9MW *5μS*60Hz=42.4kW much lower power*

Conventional Pulsers - Klystron Modulator with PFN



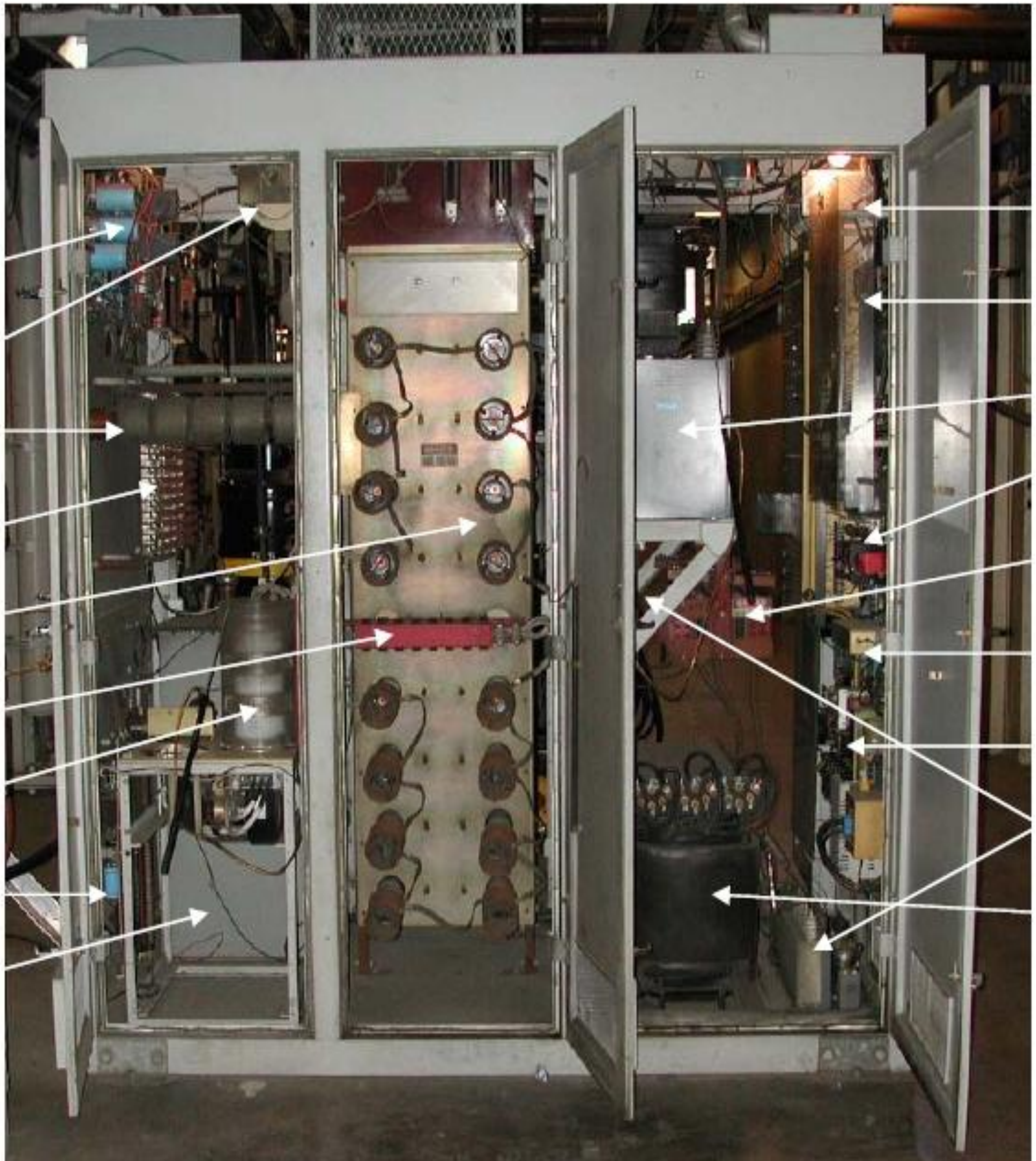


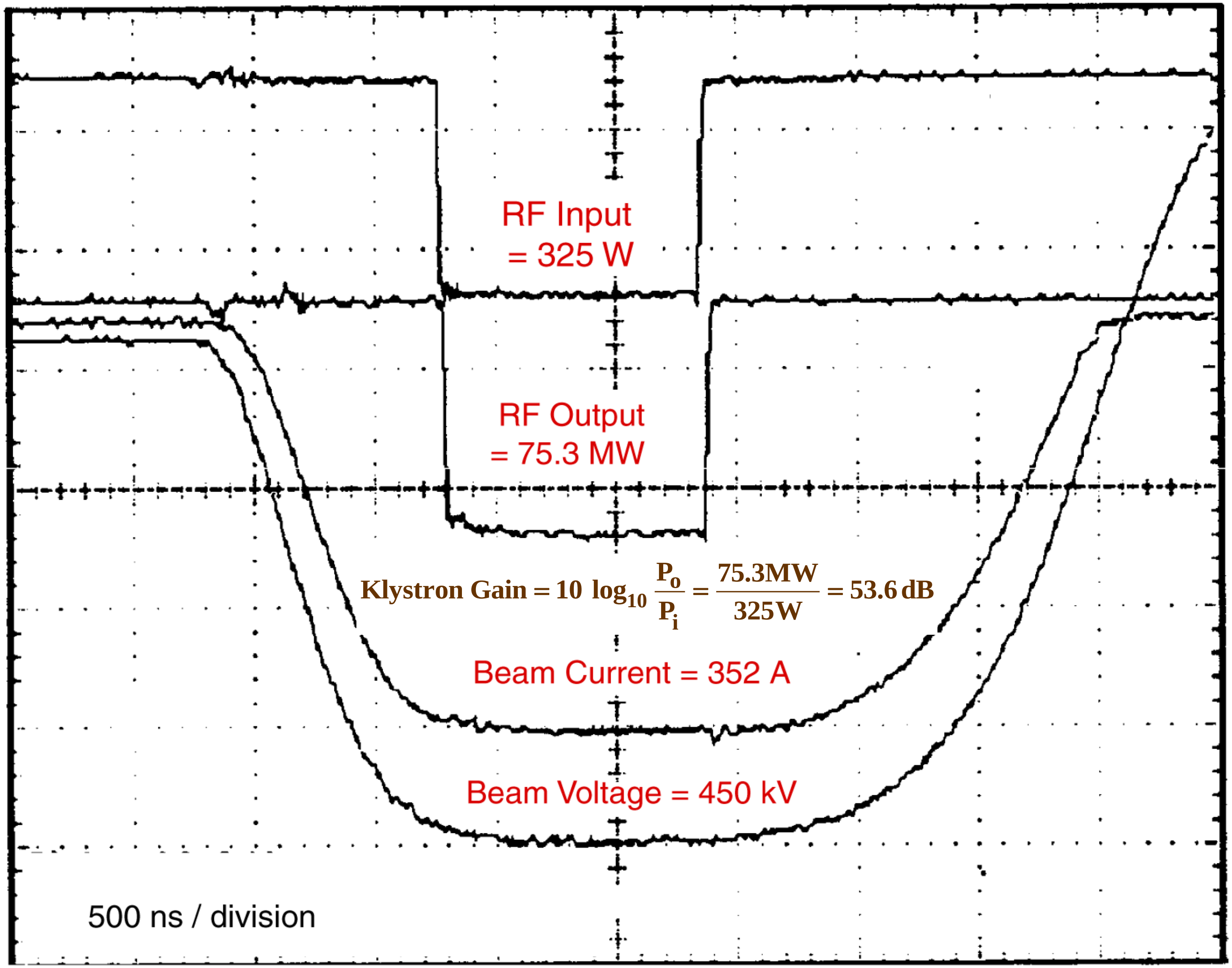
Conventional Pulsers - Present Klystron Modulator Power Supply



- *Primary VVT, with diode rectifier*
- *High voltage secondary with diodes and filter capacitor*
- *Protected against secondary faults*

Conventional Pulsers - Klystron Modulator PS – Cabinet Details



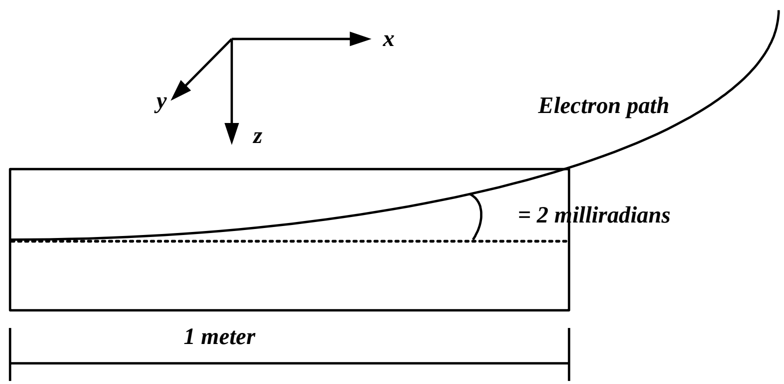

RF Input
= 325 W
RF Output
= 75.3 MW
Klystron Gain = 10 log10 Po/Pi = 75.3MW/325W = 53.6 dB
Beam Current = 352 A
Beam Voltage = 450 kV
500 ns / division

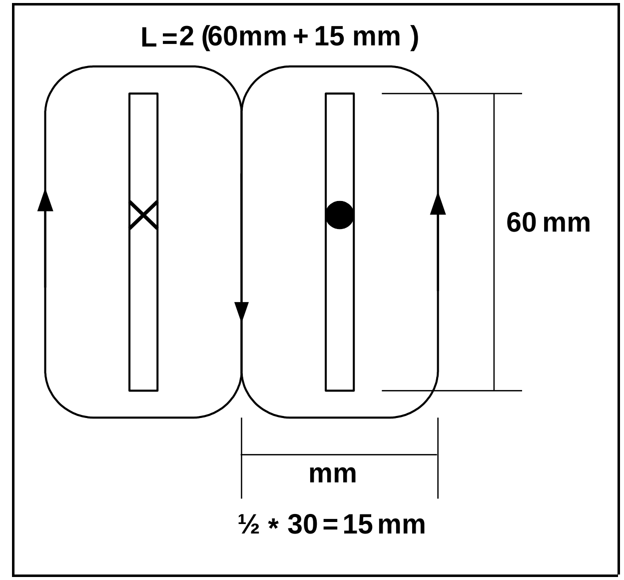
Conventional Pulsers - Kicker or Fast Modulator

- *Improve the rise time of modulator pulse using Cable PFN*
- *In line Switch with PFN*
- *Blumline with Shunt Switch*

Kicker Magnet Calculation

A 3GeV electron moves in a magnetic field as shown below. Calculate the B field and the magnet current needed to provide a 2 milliradian deflection in the electron path. The magnet is 1 meter in length.





magnet aperature 60mm X 34mm

Some definitions and constants needed for conversion

$q := 1.6 10^{-19} C$ Electron charge $v_x := 3 \cdot 10^{8} \cdot \frac{m}{s}$ electron velocity $eV := 1.6 10^{-19} \cdot J$ Electron energy

$electronmass := 9.1095 10^{-31} \cdot kg$ electron rest mass $n_t := 2$ magnet turns (2 plates producing field in same direction)

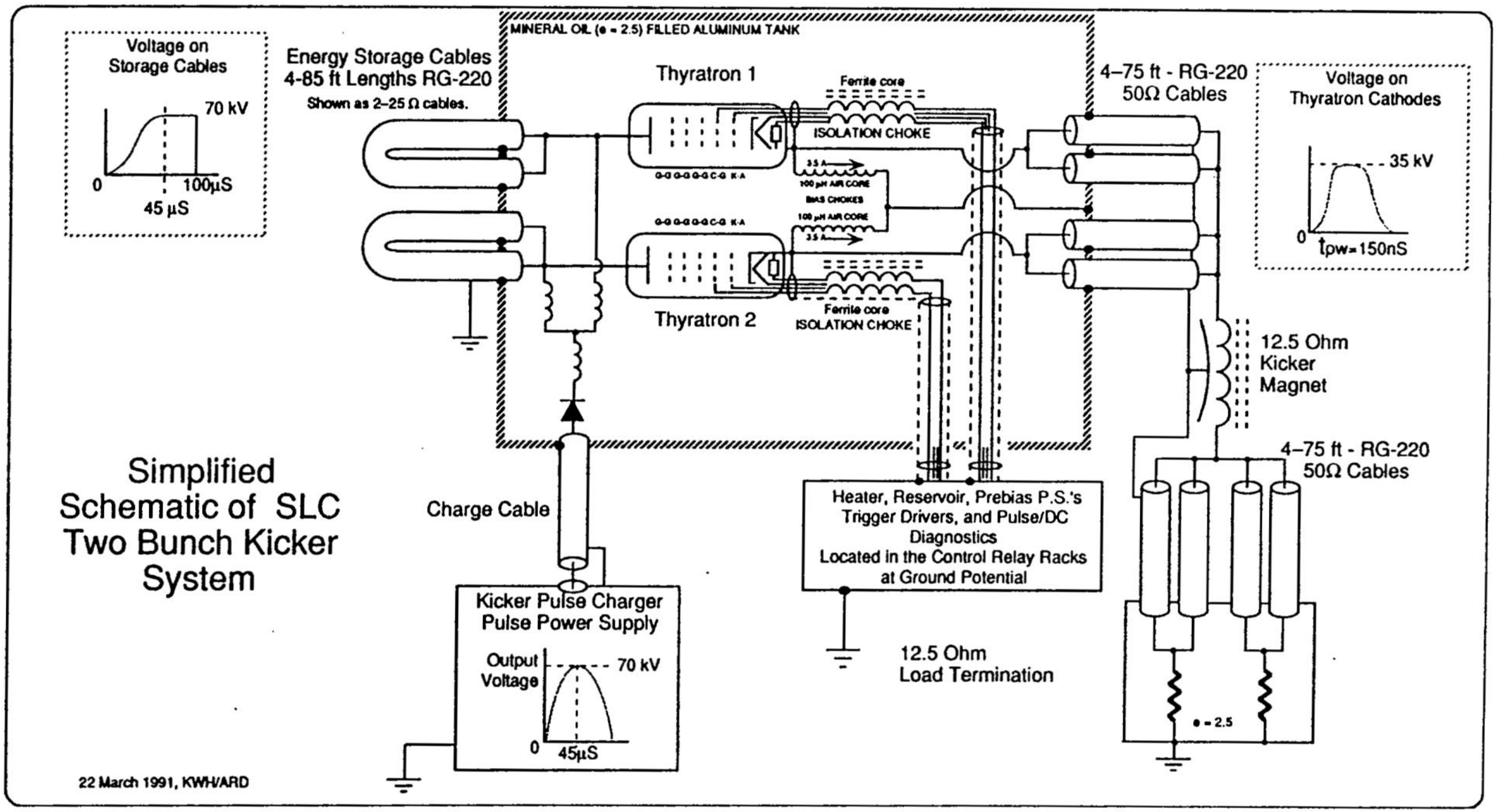
$L_{mag} := 1 \cdot m$ magnet length $\theta := 2 \cdot 10^{-3} rad$ This is the deflection angle $\mu_0 := 4 \cdot \pi \cdot 10^{-7} \cdot \frac{newton}{amp^2}$ $\mu_r := 1$

$E_x := 3 \cdot 10^{9} \cdot eV$ $E_y := E_x \cdot \tan(\theta)$ $E_y = 9.6 \times 10^{-13} J$ $E_y = 6 \times 10^{6} eV$ $F_y := \frac{E_y}{L_{mag}}$ $F_y = 9.6 \times 10^{-13} N$

$L_{field} := 2 \cdot (60 \cdot mm + 15 \cdot mm)$ $L_{field} = 0.15 m$ $B_z := \frac{F_y}{q \cdot v_x}$ $B_z = 0.02 T$ $I := \frac{B_z \cdot L_{field}}{\mu_0 \cdot \mu_r \cdot n_t}$ $I = 1194 A$

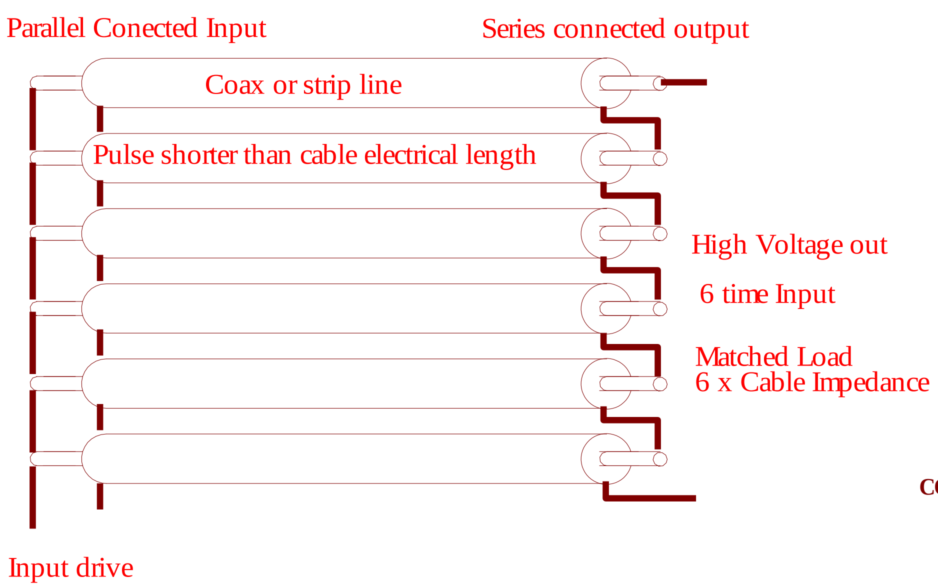
Conventional Pulsers - Kicker Modulator

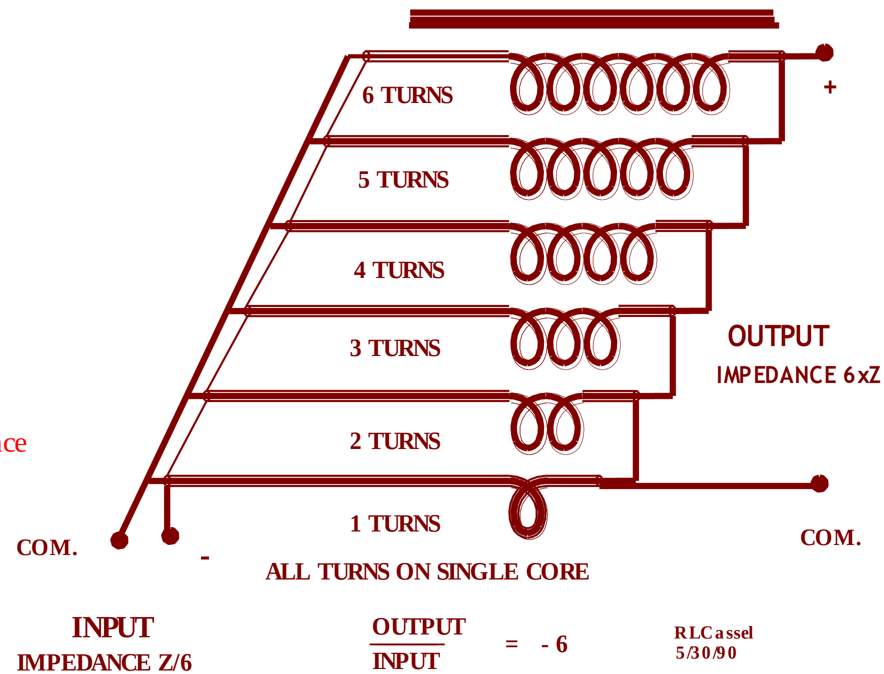
- *Conventional Inline Kicker Modulator*
- *Thyratron for switches*
- *Improve the rise time of modulator pulse using Cable PFN*



Conventional Pulsers - Cable Transformer Modulator

- *Cable Pulse transformer connecting the input of a cable in Parallel and the Output In Series and if the pulse is shorter than twice the electrical length of the cable and driving a matched load cable transformer works.*
- *Fast rise time with simple transformer*
- *Disadvantage stray capacitance and floating cable return limits transformer usage*





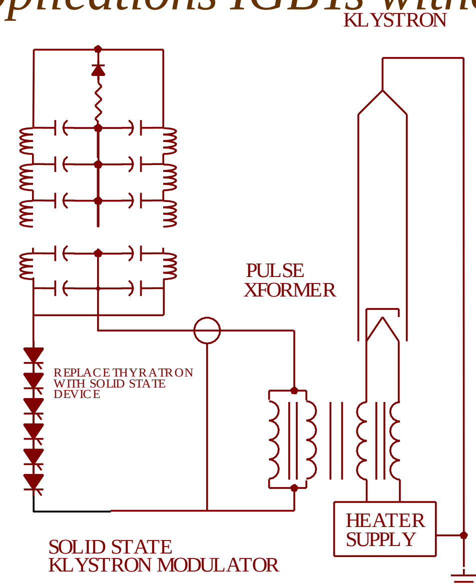
Solid-State Pulsers

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*



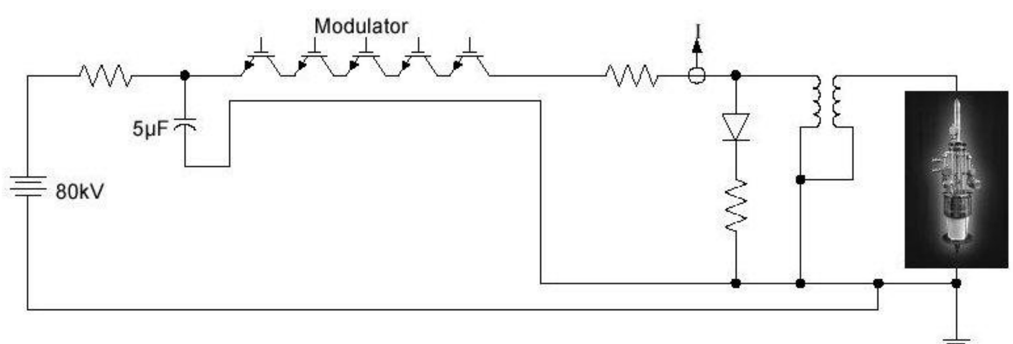


Figure 1 The hybrid modulator block diagram shows the high voltage power supply, the solid state modulator with energy storage capacitor, and the pulse transformer.

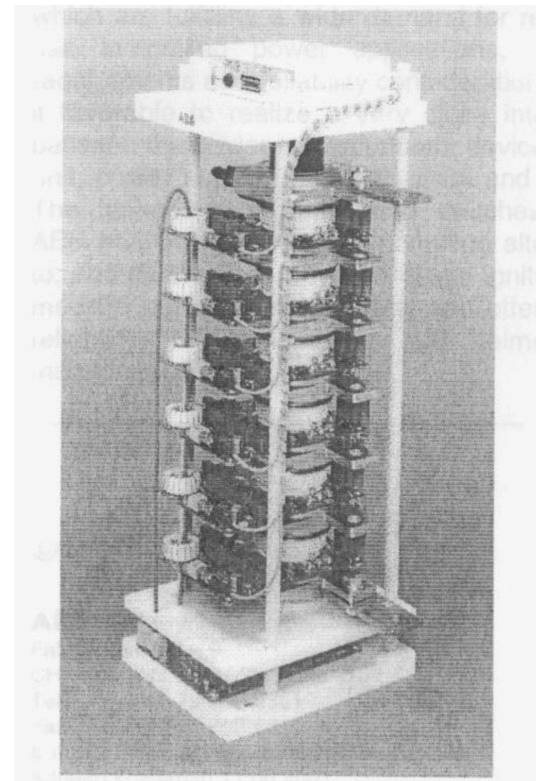
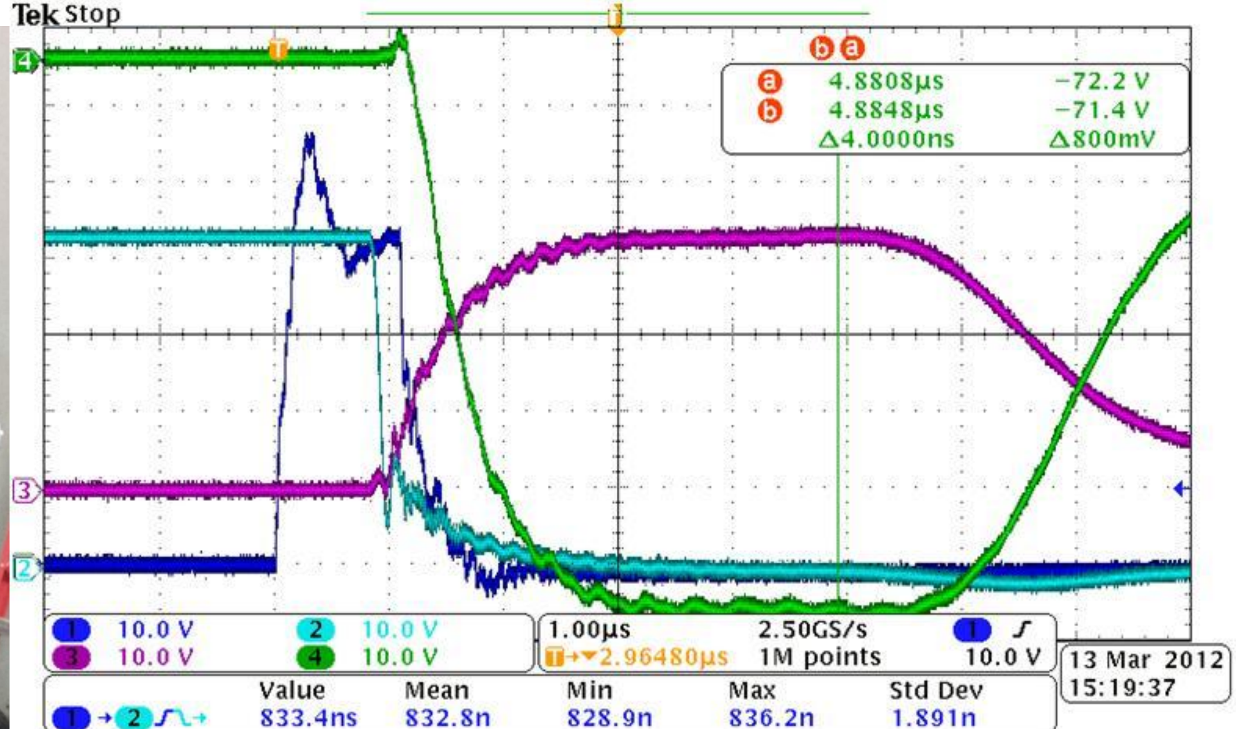


Fig. 11) Switch Assembly SPR-08F45-6-WC

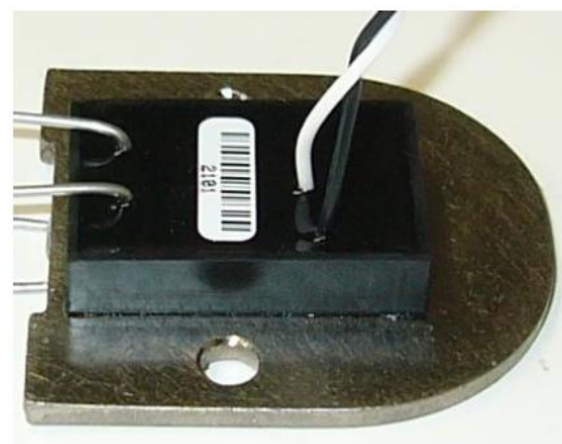
ABB Semiconductor AG



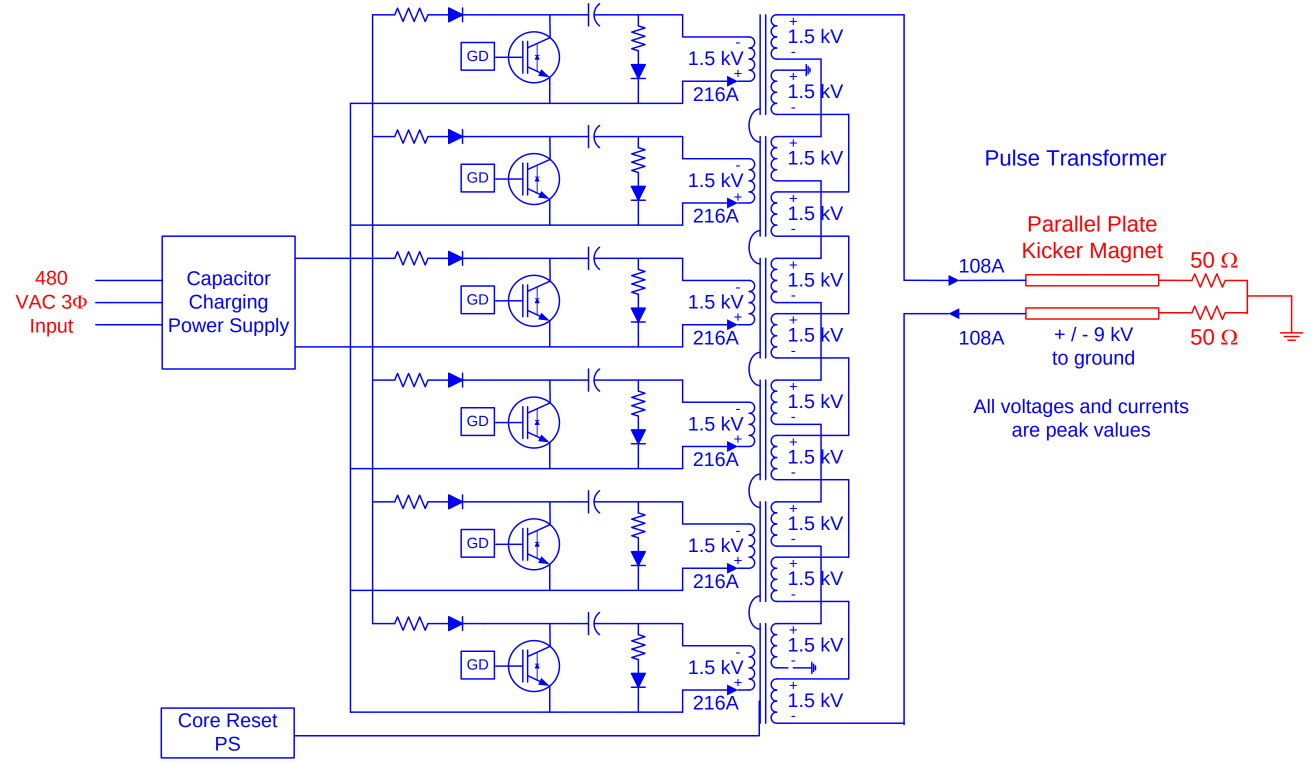
Model S38
Thyristor Module

Features:

- 4700V Peak Off-State Voltage
- 14kA Peak Non-Repetitive Current
- 30kA/µS Maximum di/dt
- 100nS turn-on delay time
- Low Inductance

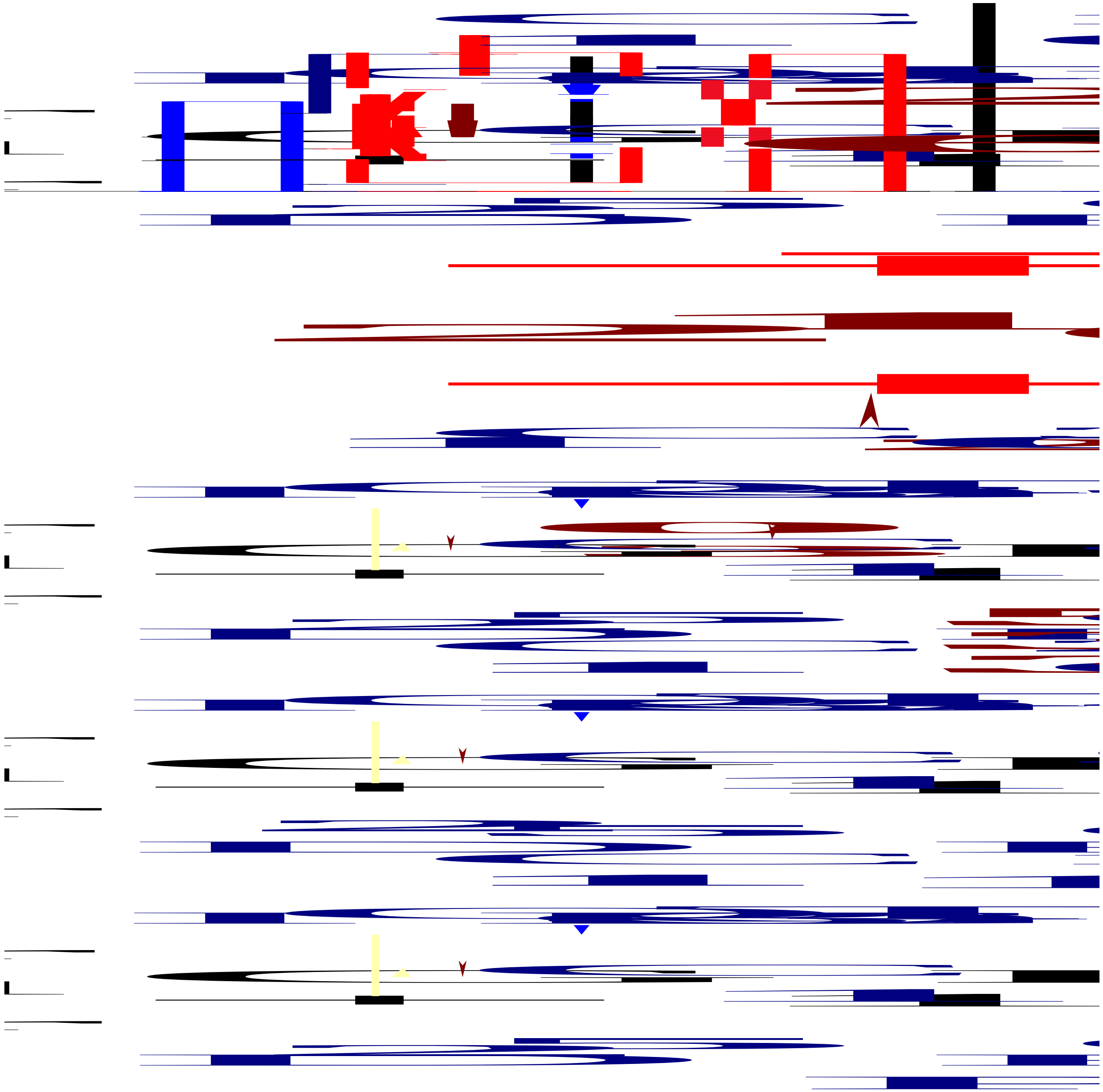


A Solid-State Turn-On Pulser

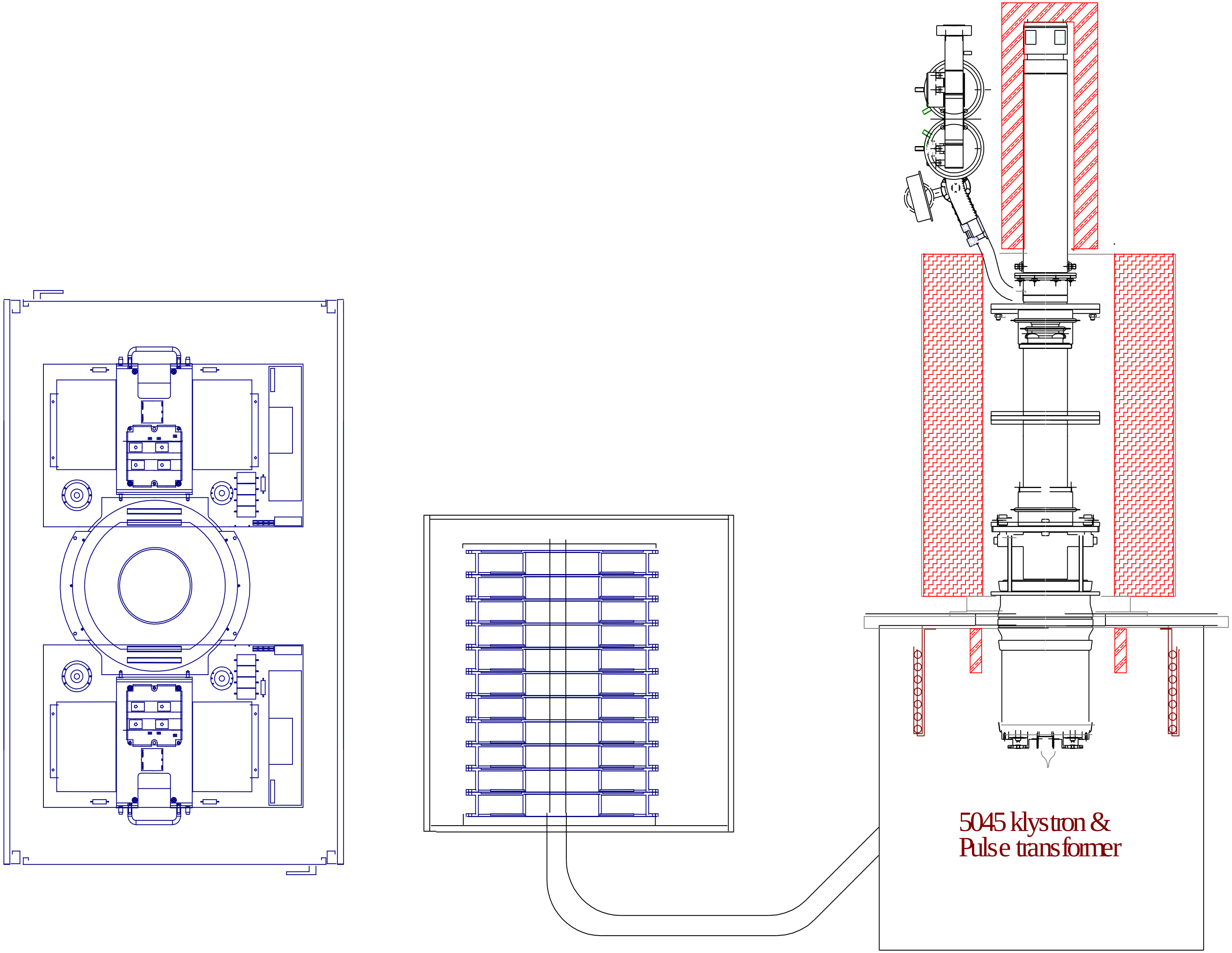


- *All pulse capacitors are pre-charged simultaneously*
- *IGBTs are all switched on together*
- *Capacitors are then simultaneously discharged producing sinusoidal V and I pulses in the pulse transformer and magnet. The secondary winding voltages are additive*
- *At the end of the pulse the IGBT is 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*

Solid-State Induction Klystron Modulator



Solid-State Induction Klystron Modulator

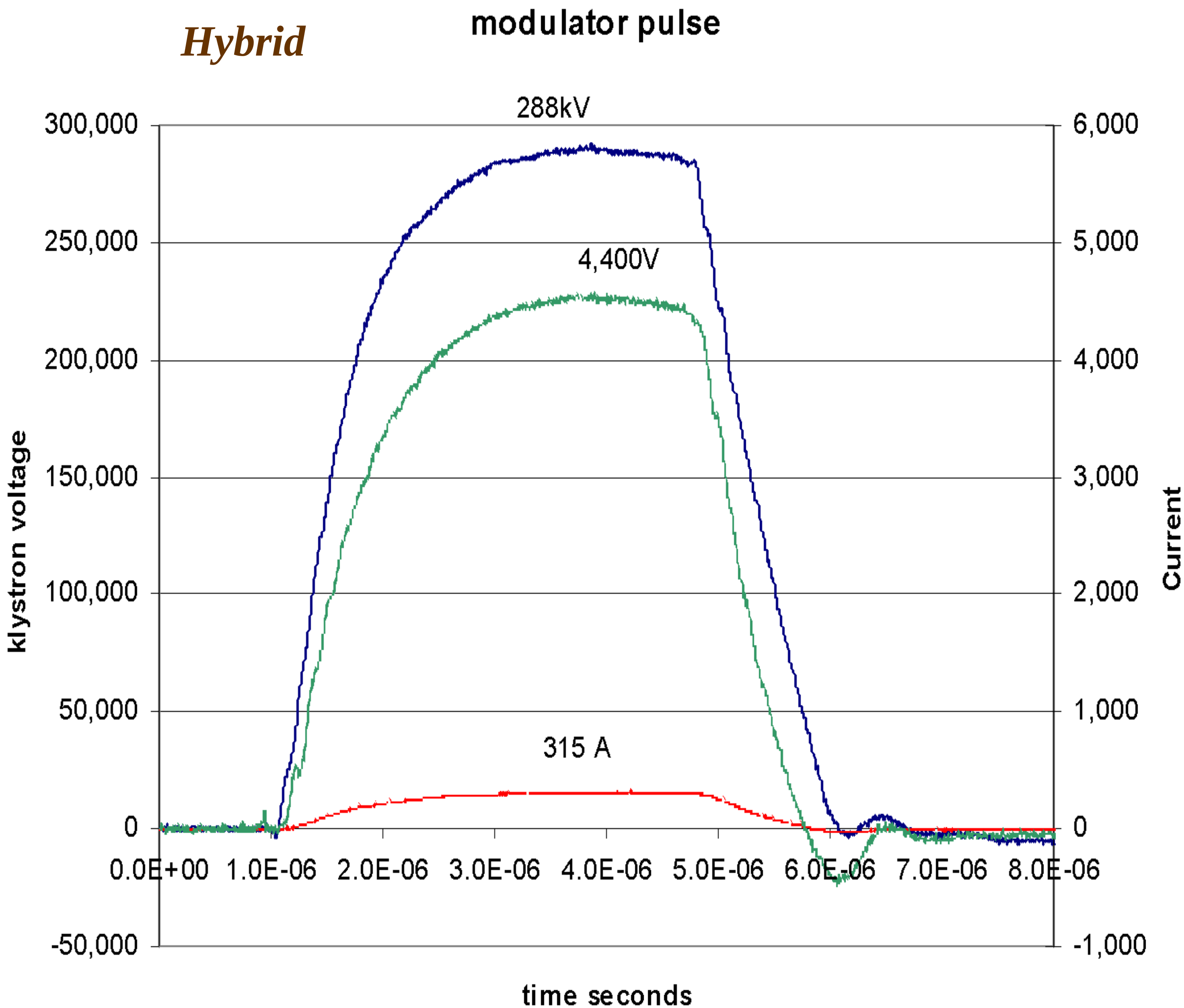


Hybrid

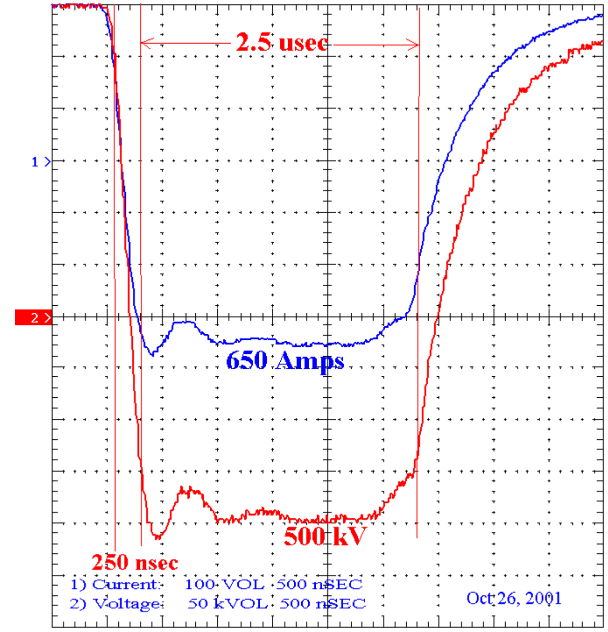
- *Solid-state 10 - stack installed alongside Gallery line-type PFN unit*
- *22 kV => 330 kV via 15:1 xfmr*
- *Prototype currently at 255 kV @ 2.2 μsec @ 120 PPS*

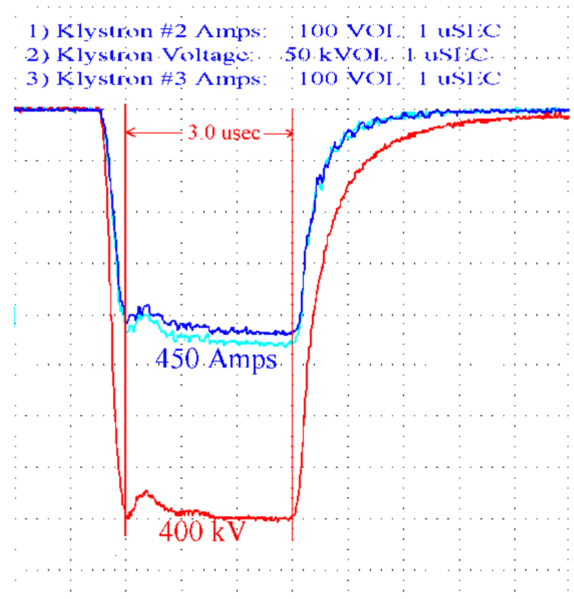
Solid-State Induction Klystron Modulator

Hybrid



Solid-State Induction Klystron Modulator





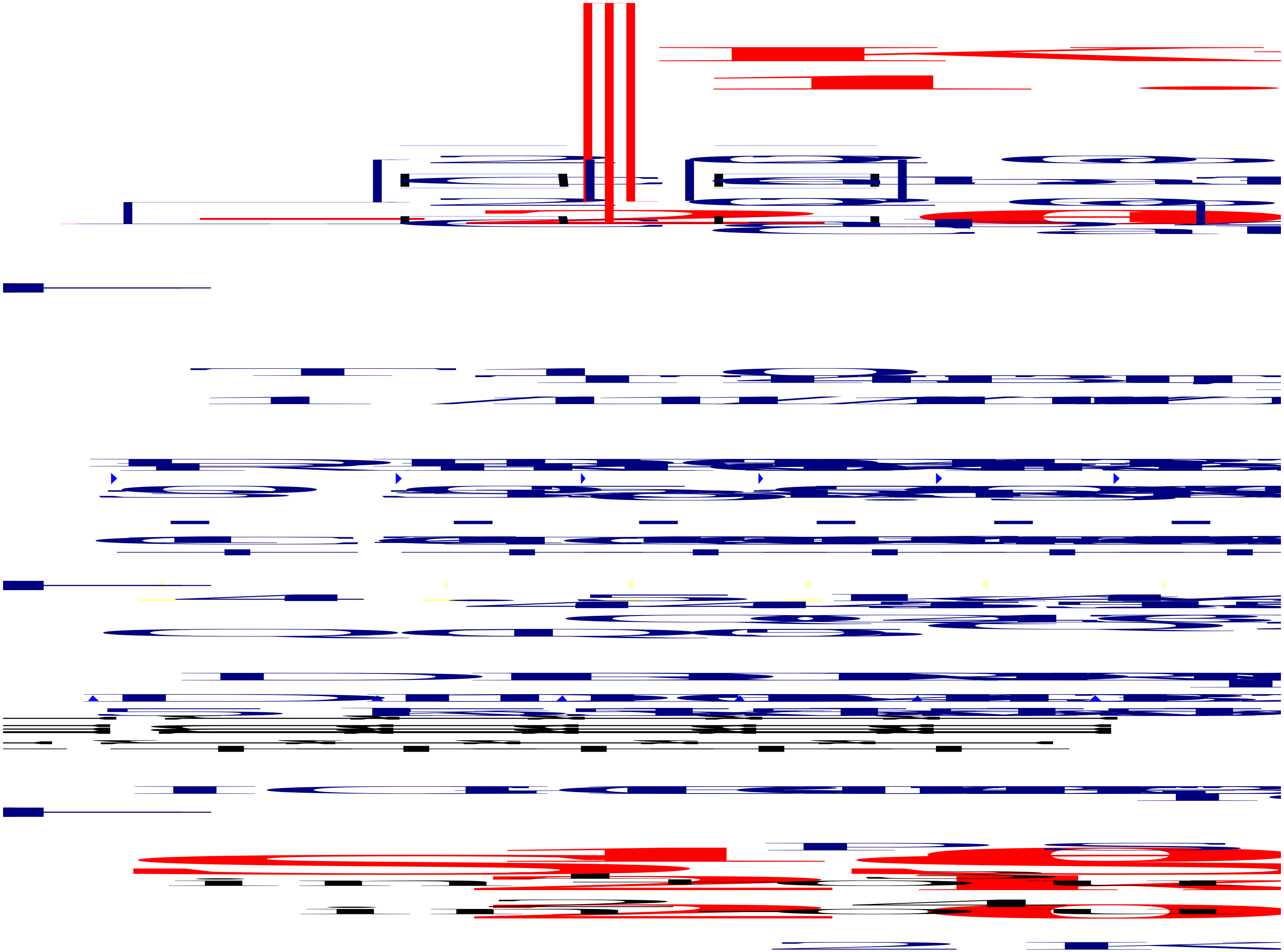
CORES AND SECONDARY

- *76 Primaries @ 5400 A*
- *3-Turns Secondary*
- *400kV @ 1800A, 725MW for 3.2μs, 350kW Ave.*

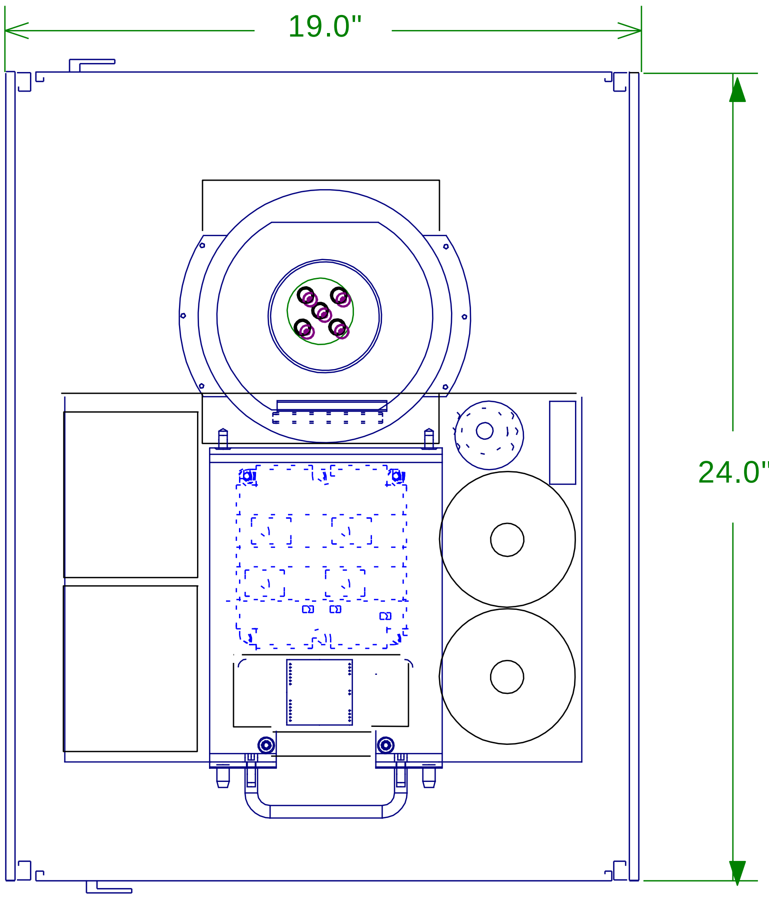
SOLID STATE DRIVERS

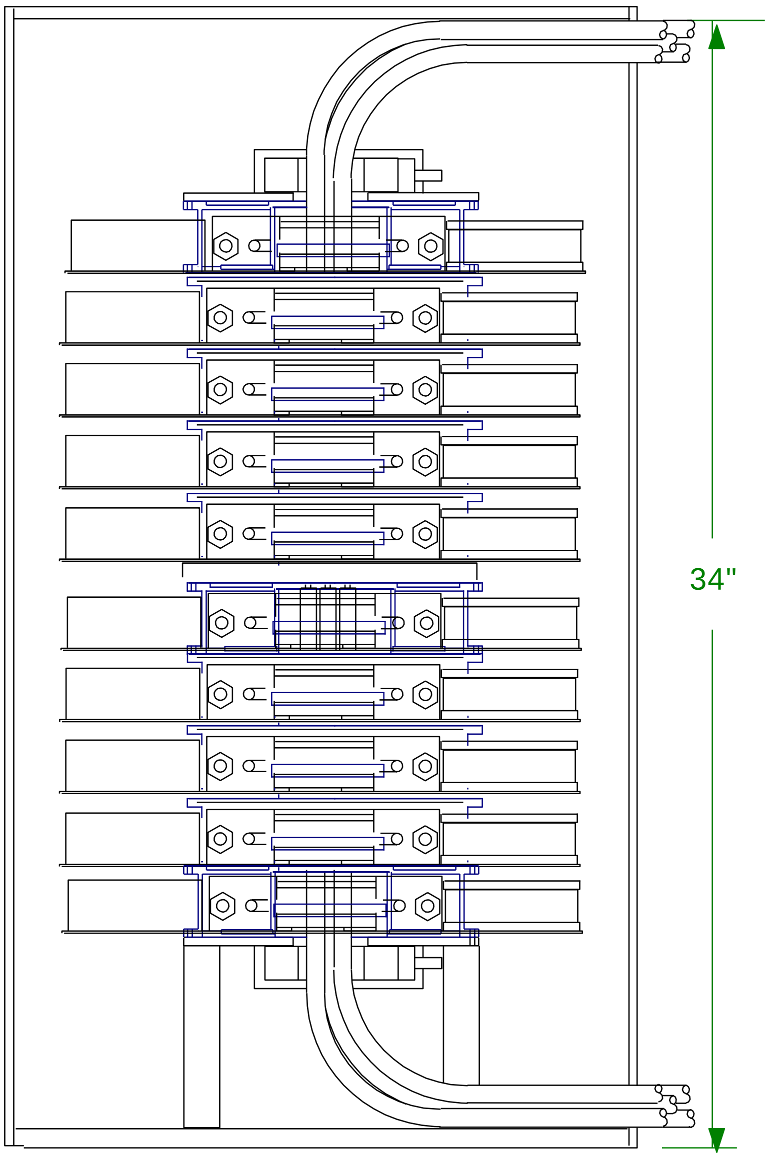
- *152 IGBT Drivers (two per each primary)*
- *1800 Volts per IGBT*
- *2700 Amps per Driver*

Solid-State Induction Kicker Modulator



2 ea. 10 kV 2.5 kA
0.6 meters 1.5 mrad

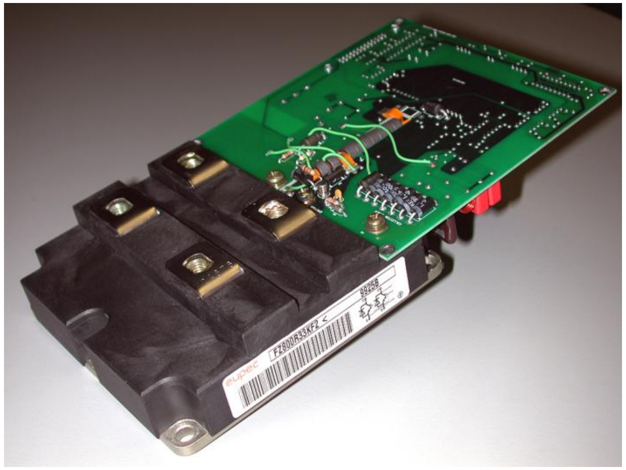


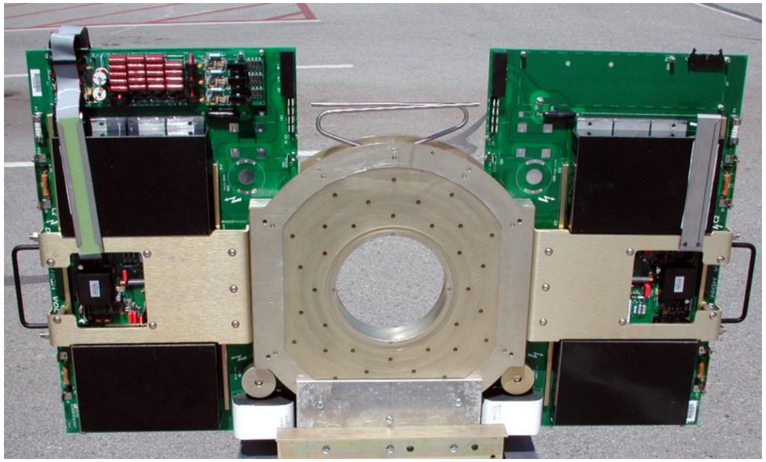


Solid-State Induction Modulators

- *Fractional turn pulse transformer*
  - *–Similar to a induction accelerator*
  - *–Multiple primaries driven in parallel*
  - *–The secondary connected in series*

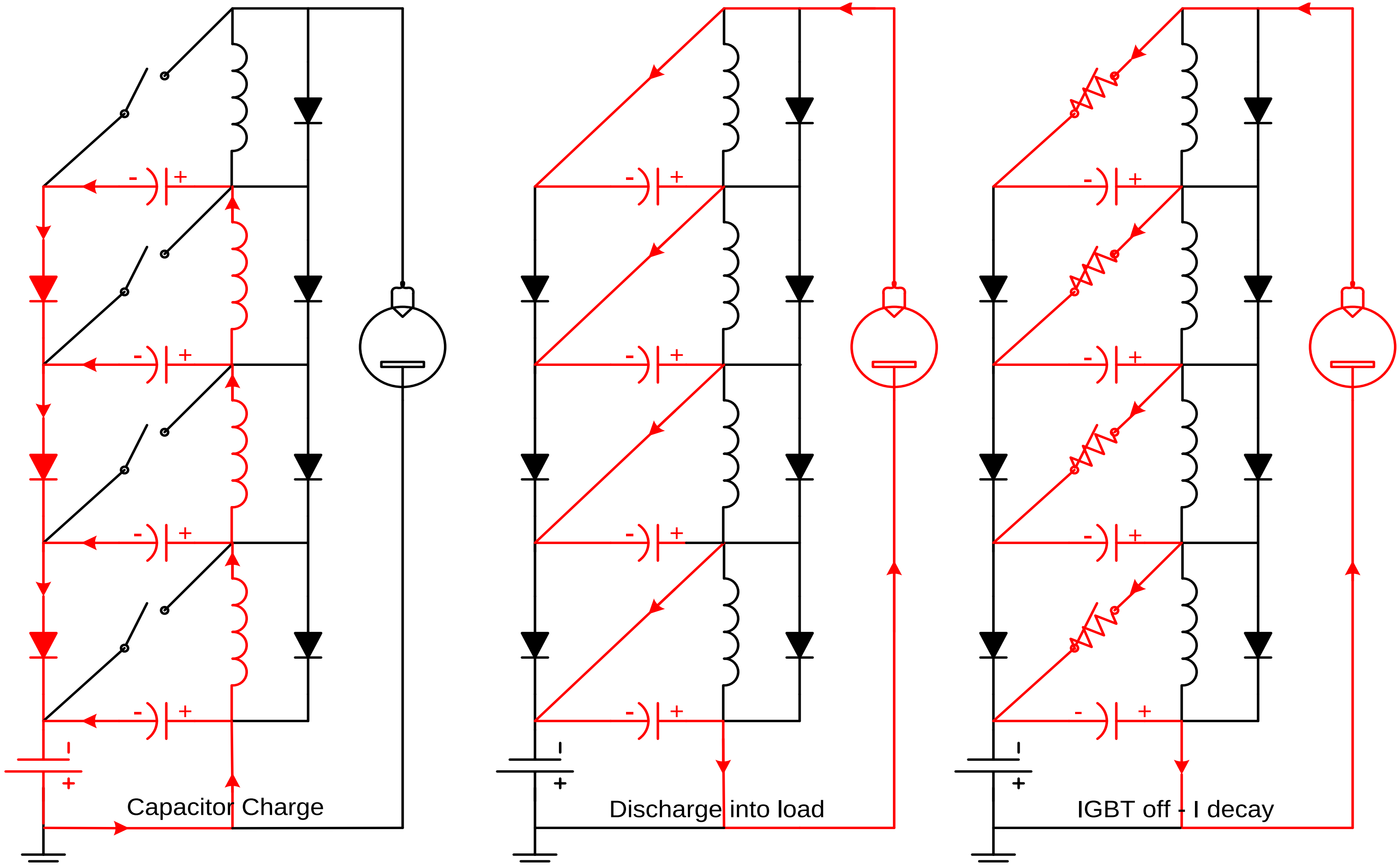
- *Solid-state driver consists of*
  - *– A solid state switch that turns on and off*
  - *– DC capacitor per primary winding*





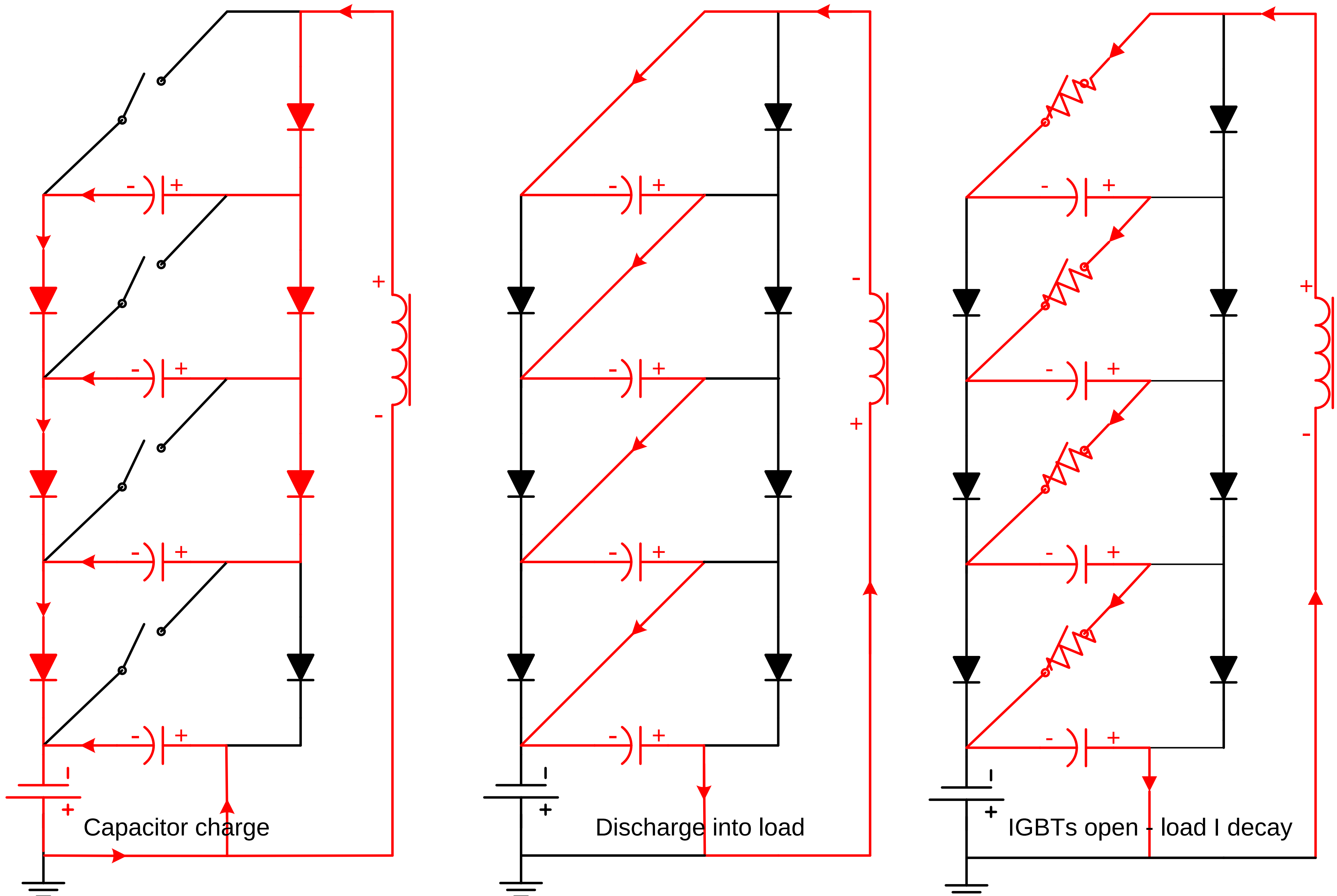
Solid-State Marx Generator for Modulators or Kickers

- *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*



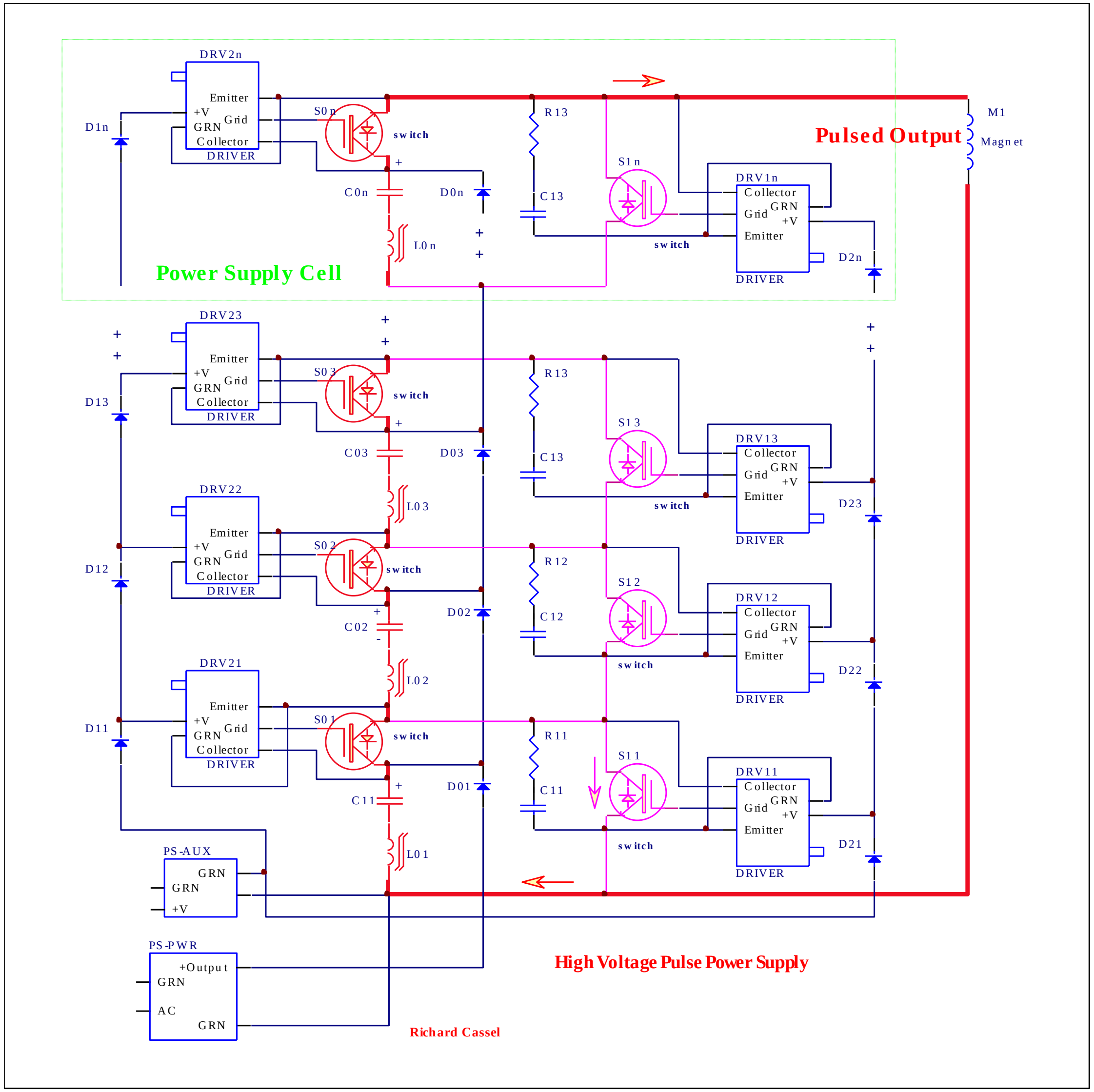
Solid-State Marx Generator for Modulators or Kickers

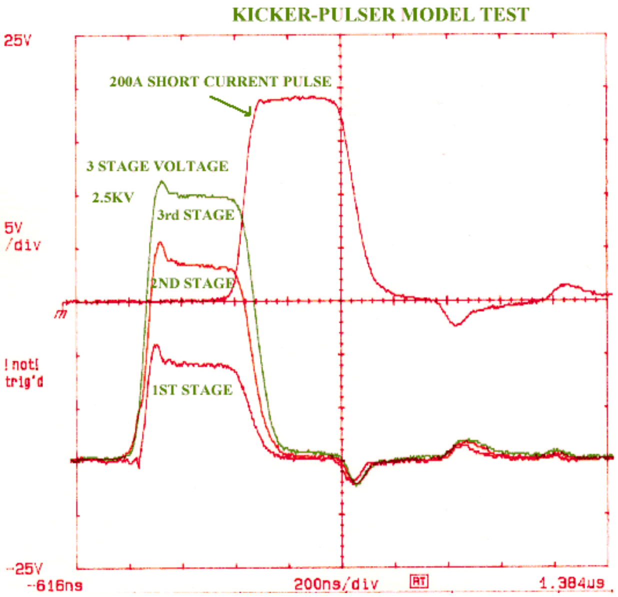
- *If the load is a magnet, the charging inductors are not required*



Solid-State Marx Generator for Modulators or Kickers

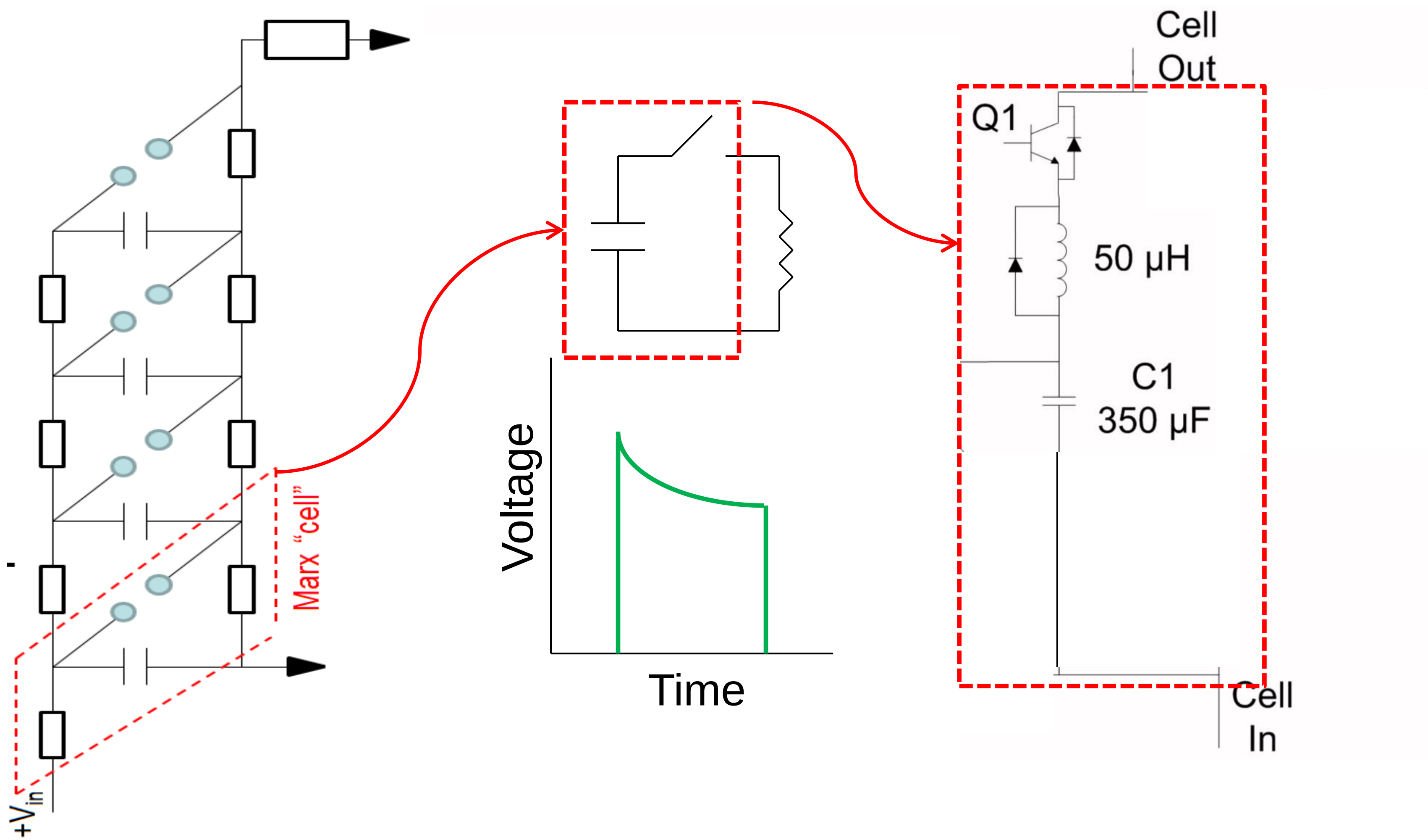
- *Another implementation, using solid-state switches in place of the charging inductors for smaller size and less diversion of capacitor current from load*



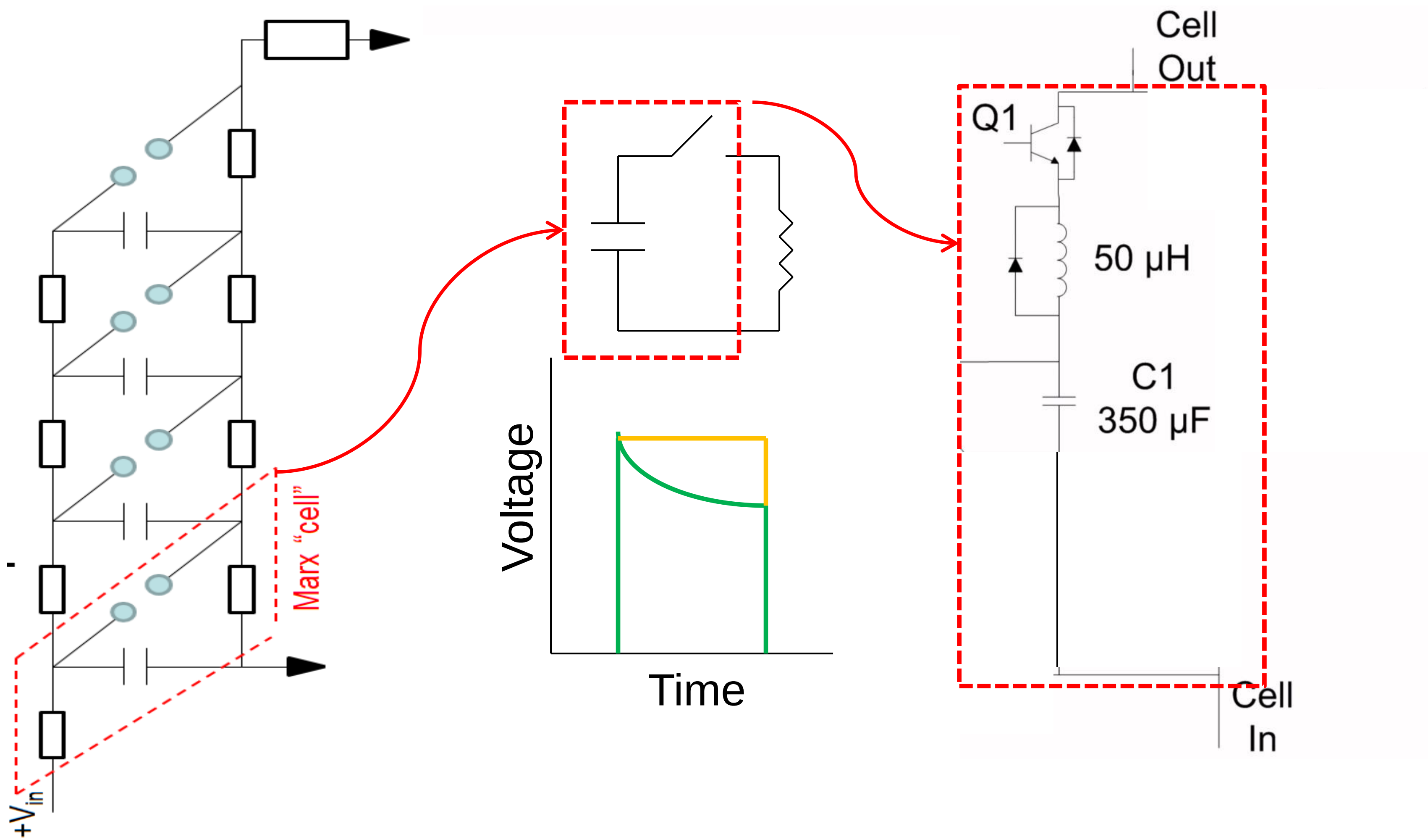


SLAC Marx P2 Generator Update

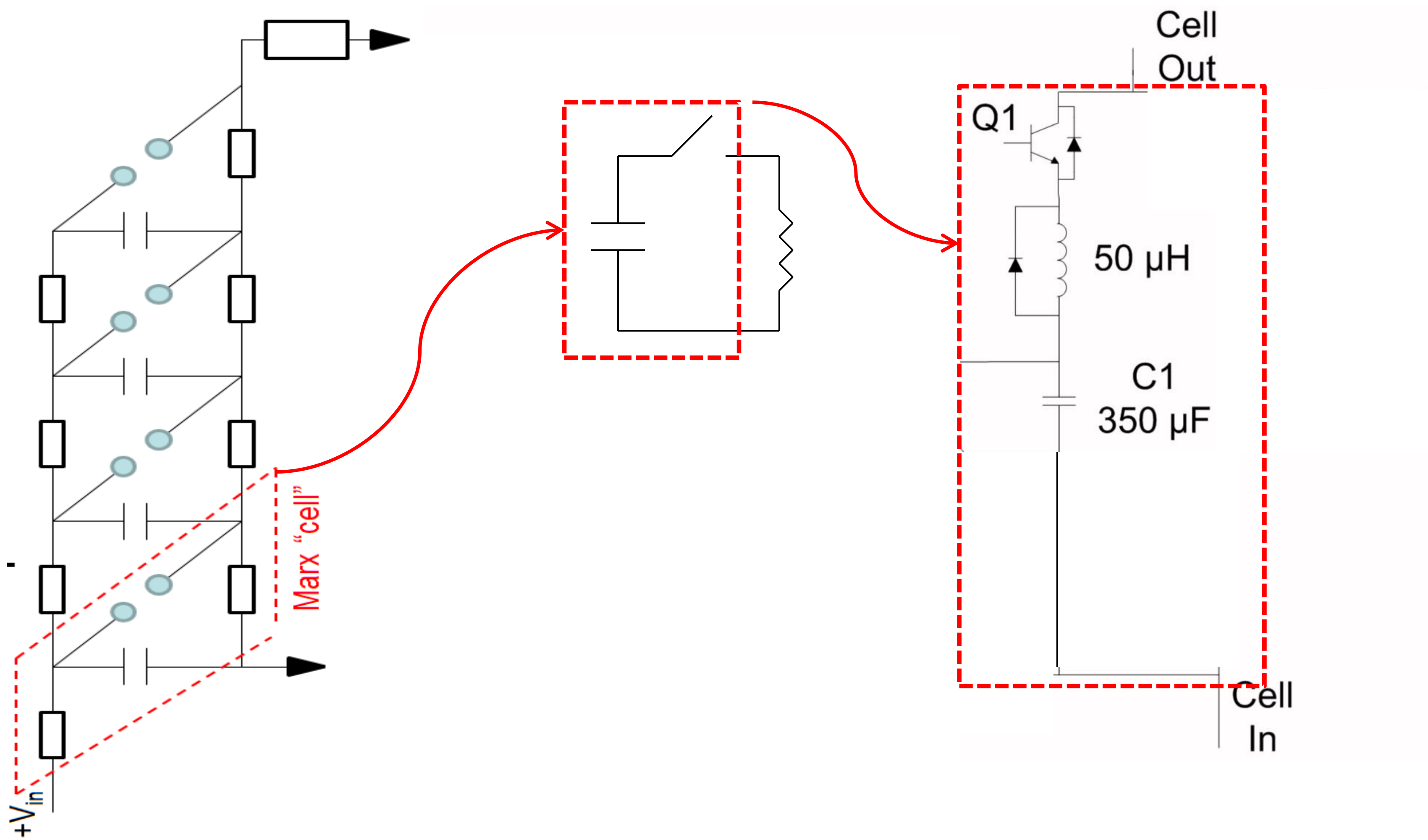
SLAC Marx P2 Cell Schematic

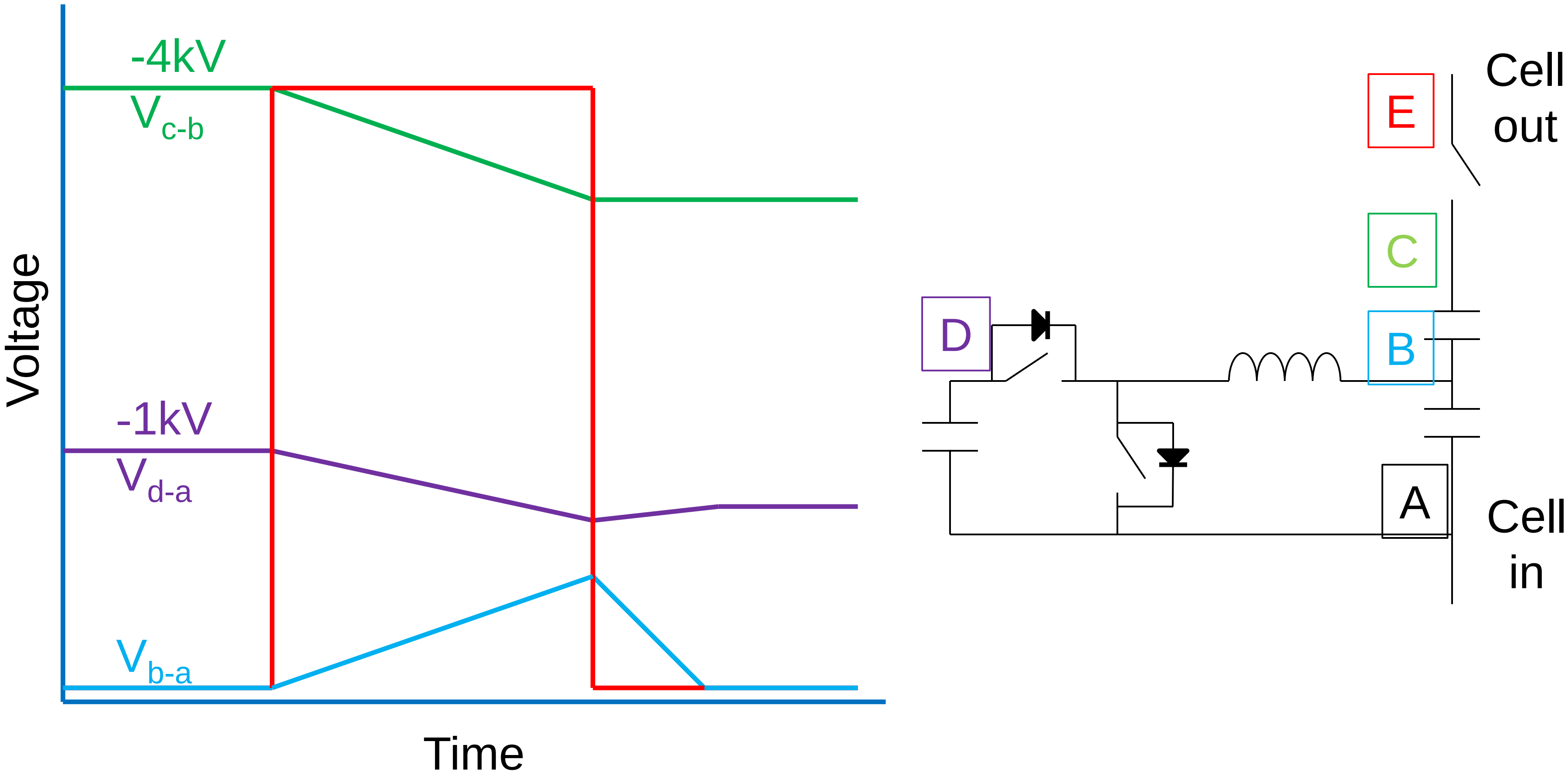


SLAC Marx P2 Cell Schematic



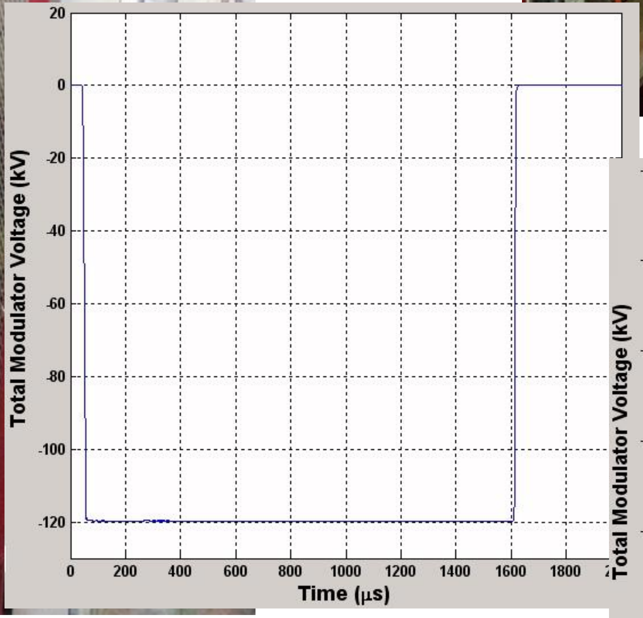
SLAC Marx P2 Cell Schematic

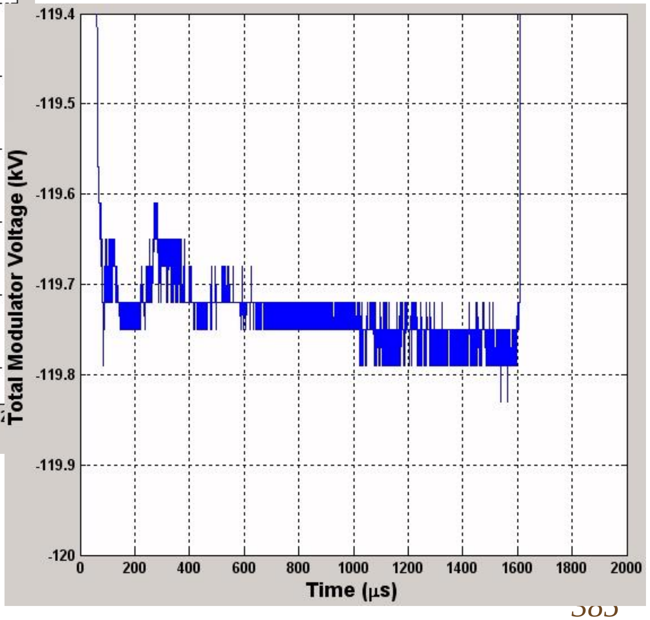




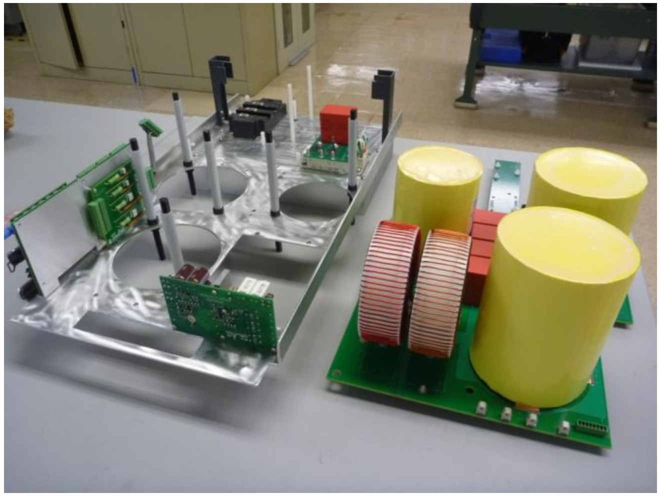
-4kV
Vc-b
-1kV
Vd-a
Vb-a
Voltage
Time
Cell
out
E
C
D
B
A
Cell
in

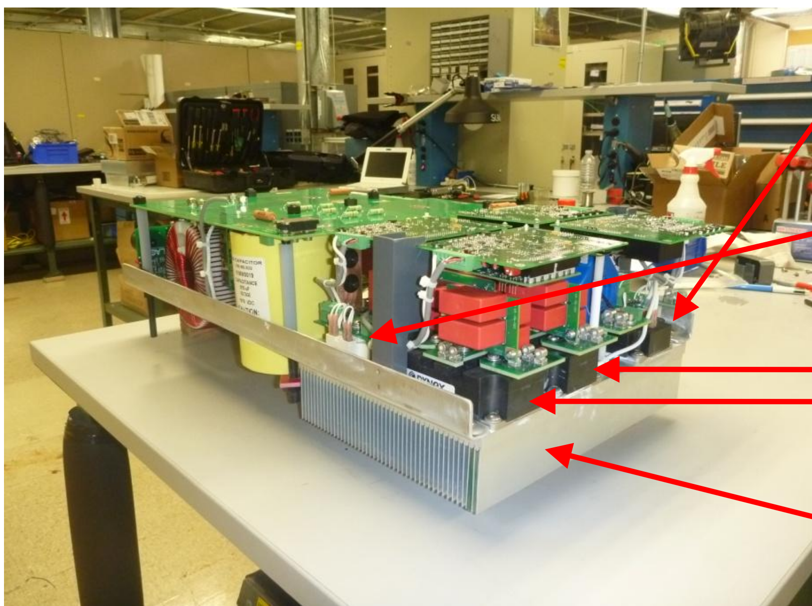
SLAC Marx P2 Assembly and Results





SLAC Marx P2 Modules



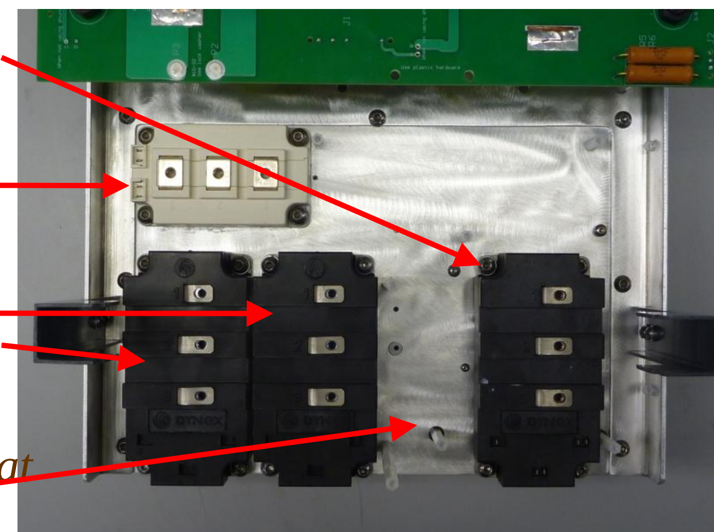


6.5kV IGBT half-bridge

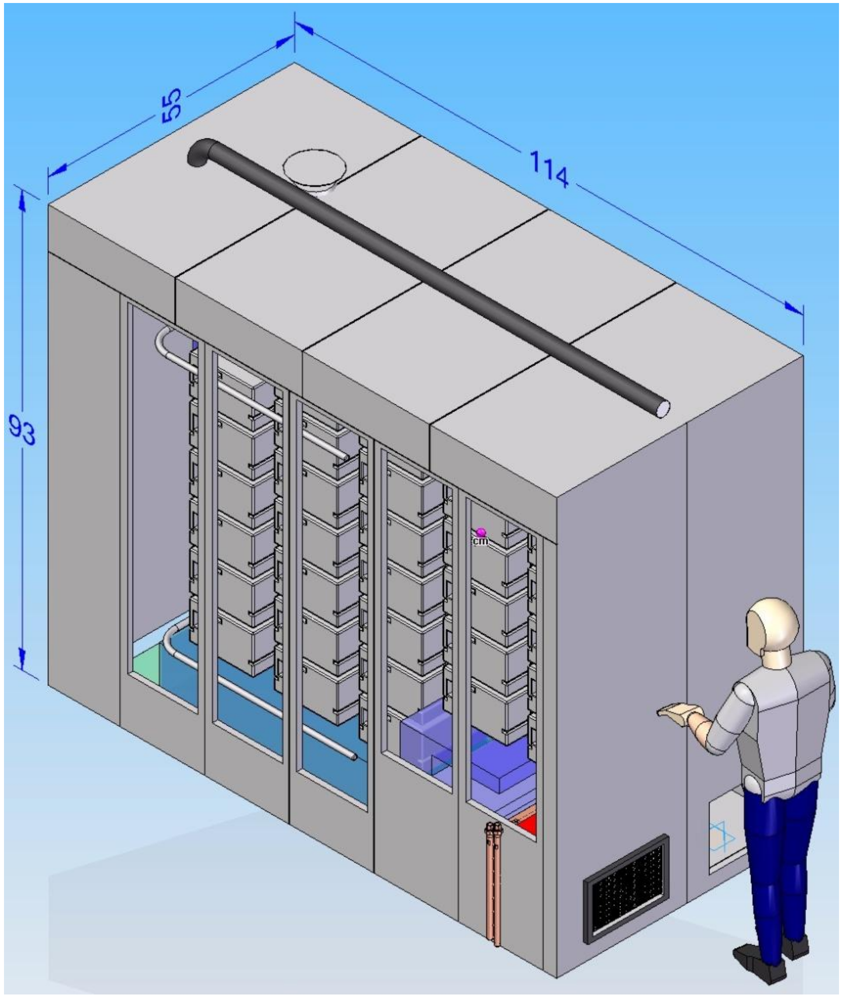
1.7kV IGBT half-bridge

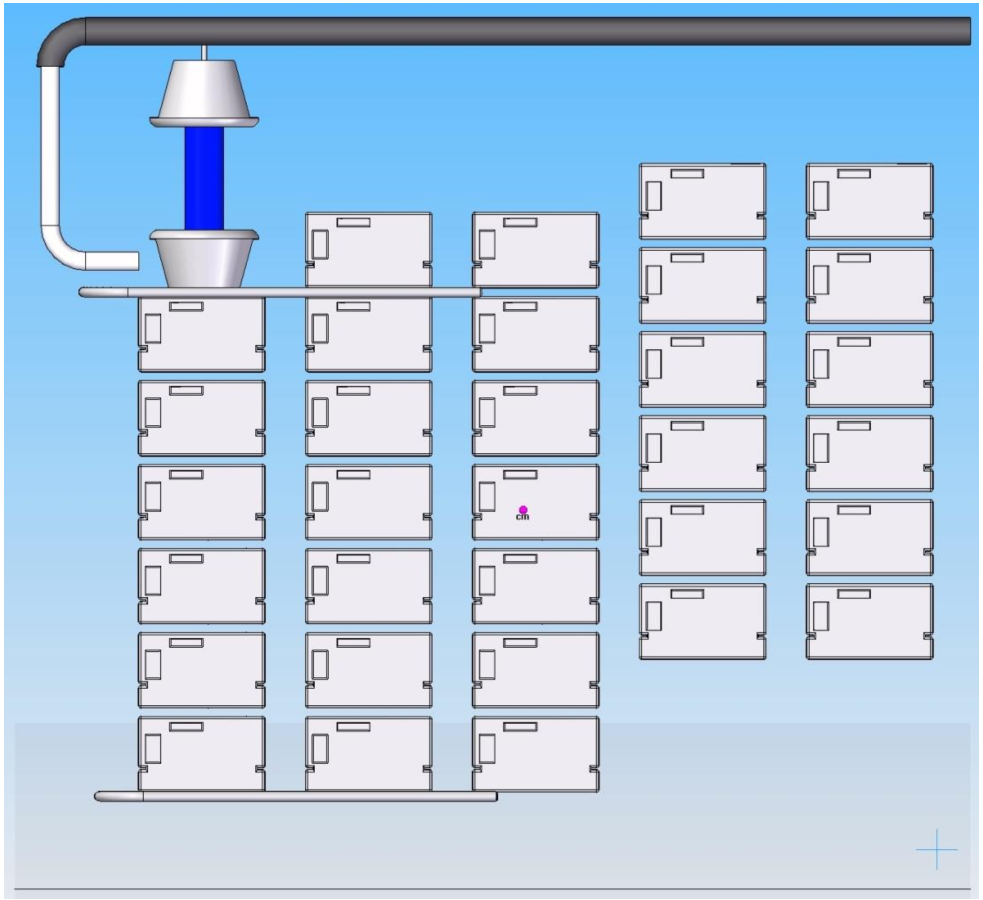
6.5kV dual diode module

Common heat sink



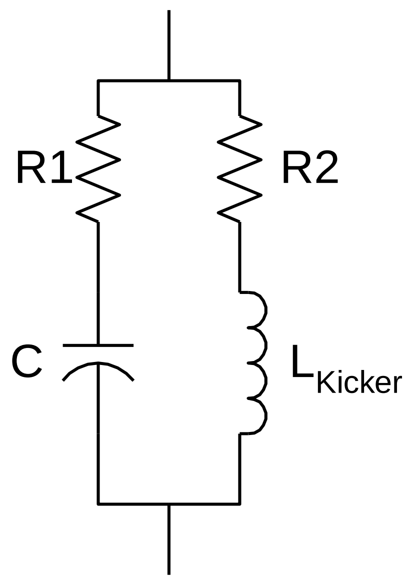
SLAC Marx P2 Packaging and Maintainability





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 7

- *Magnetics*

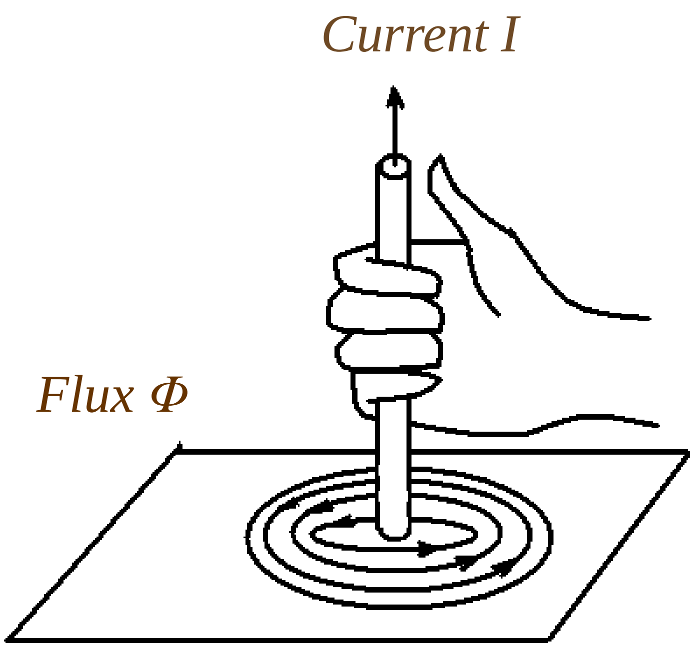
The Electric - Magnetic Equivalence

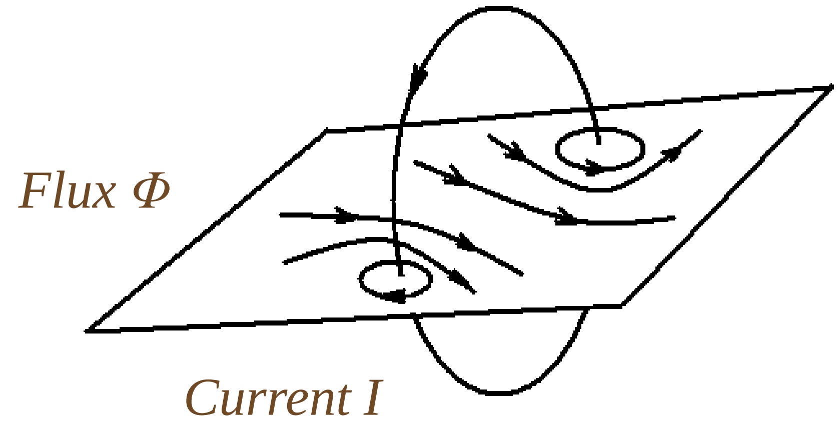
- *Magnetic circuits are analogous to electric circuits and are important for the analysis of magnetic devices. The equations for both electric and magnetic circuits show strong similarities*

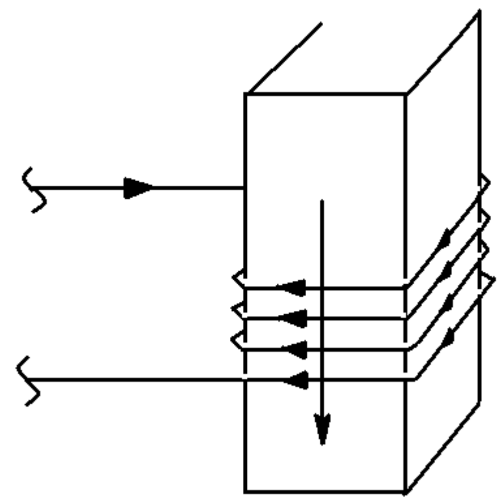
- *Various magnetic types, such as transformers and filter inductors, play a key role in many of the components used in power supplies*

- *Magnets are also extensively used in accelerators to guide, direct, steer and focus beams*

Field Due to a Current







Flux Φ Direction

Right Hand Rule:

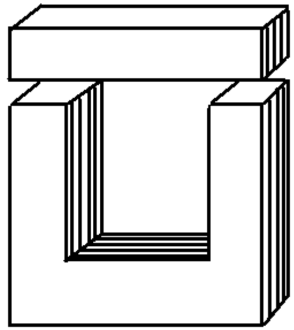
- *Thumb = Current*
- *Fingers Point in Direction of Magnetic Field*

Magnetic Units Including Turns

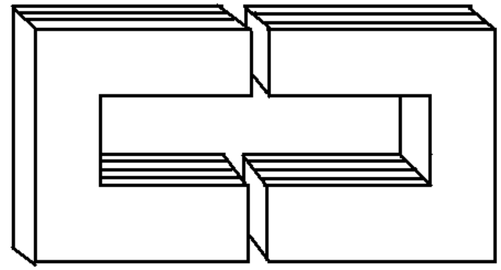
Symbol	Description	SI units	cgs units
N	*Winding turns*	*turn (t)*	*t*
H	*Field intensity*	*(A·t)/m*	*Oersted (Oe)*
B	*Flux density*	*tesla (T)*	*gauss (G)*
μ	*Permeability*	*T·m/A·*	*G/Oe*
F	*Magnetomotive force*	*A·t*	*gilbert (Gb)*
Φ	*Flux*	*weber/t (Wb/t)*	*maxwell*
R	*Reluctance*	*A·t/Wb*	
P	*Permeance*	*henry/t*	*H/t*
I	*Current*	*ampere (A)*	*A*
L	*Inductance*	*henry (H)*	*H*

Core Shapes

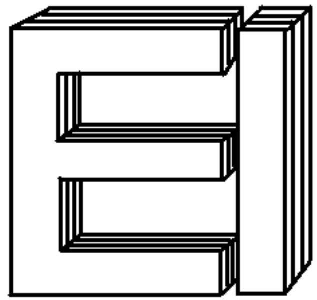
- U-U, U-I cores
- E-E, E-I, ETD cores
- POT cores
- RM cores
- PQ and PM cores
- EP, EFD and ER cores
- Toroid



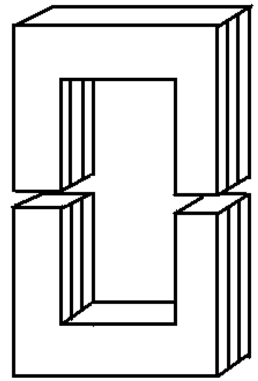
U-I



cut C core

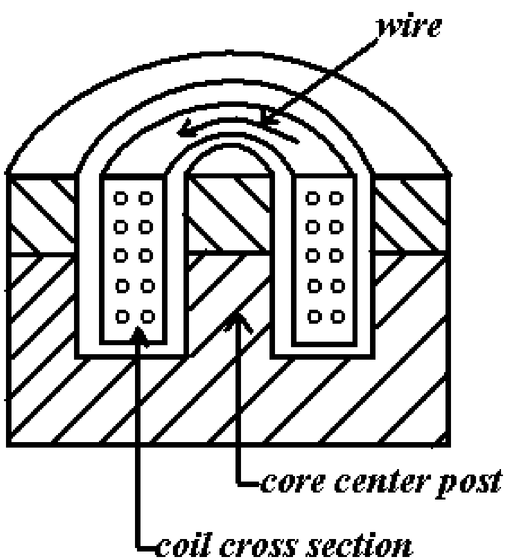


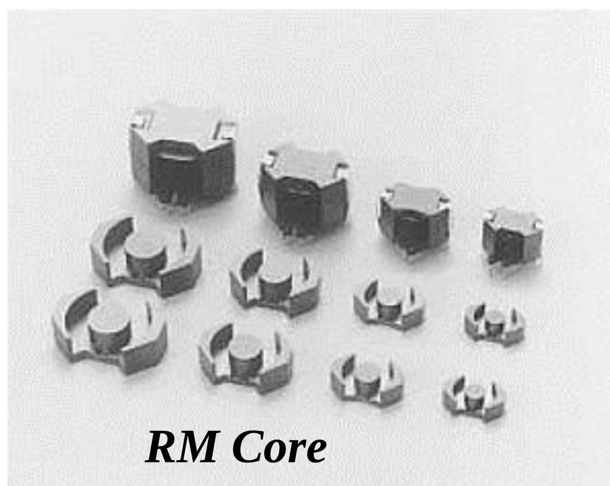
E Core

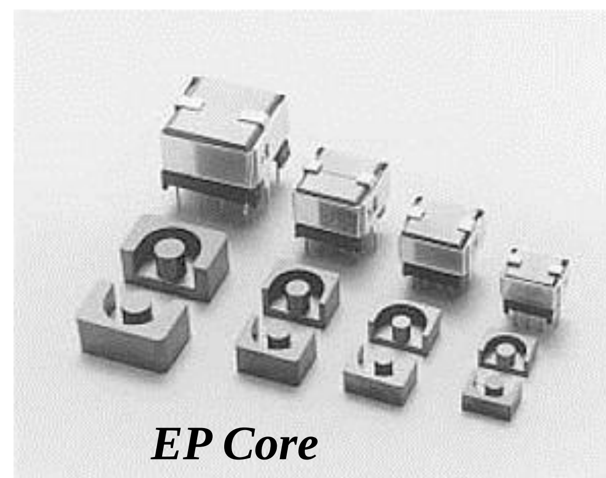


U-U

Pot cores



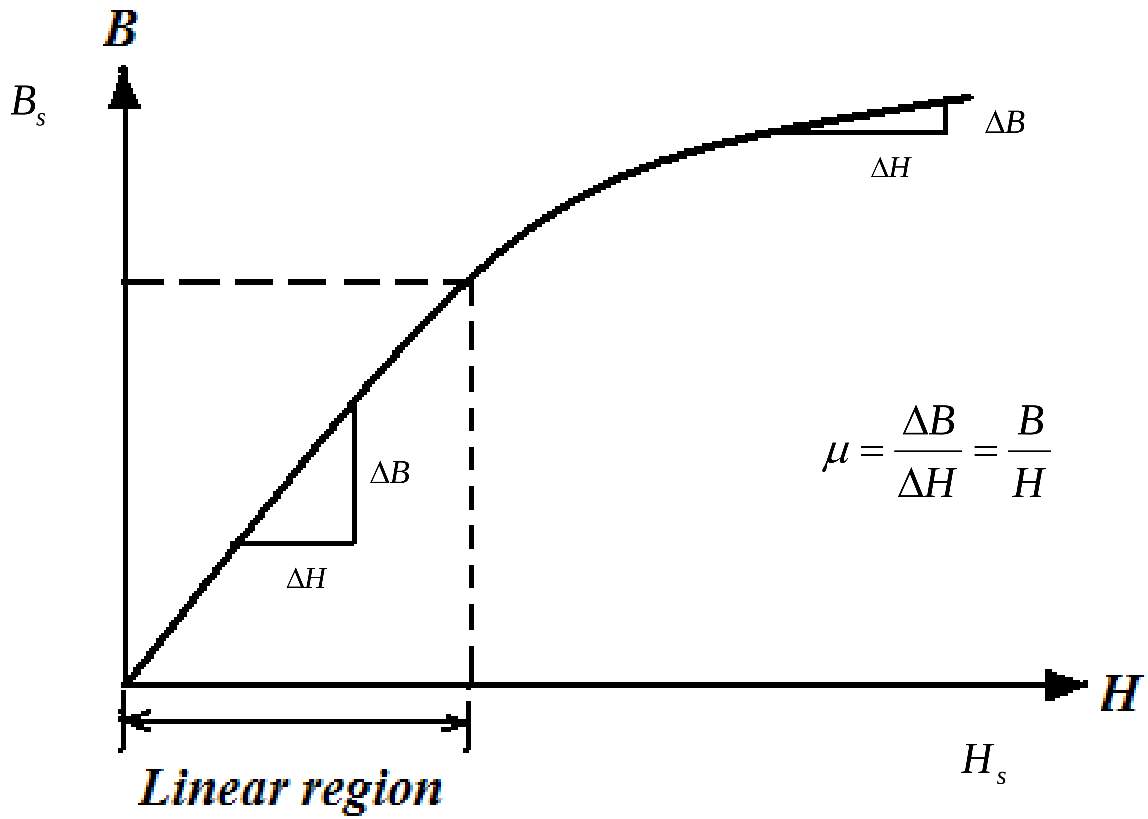




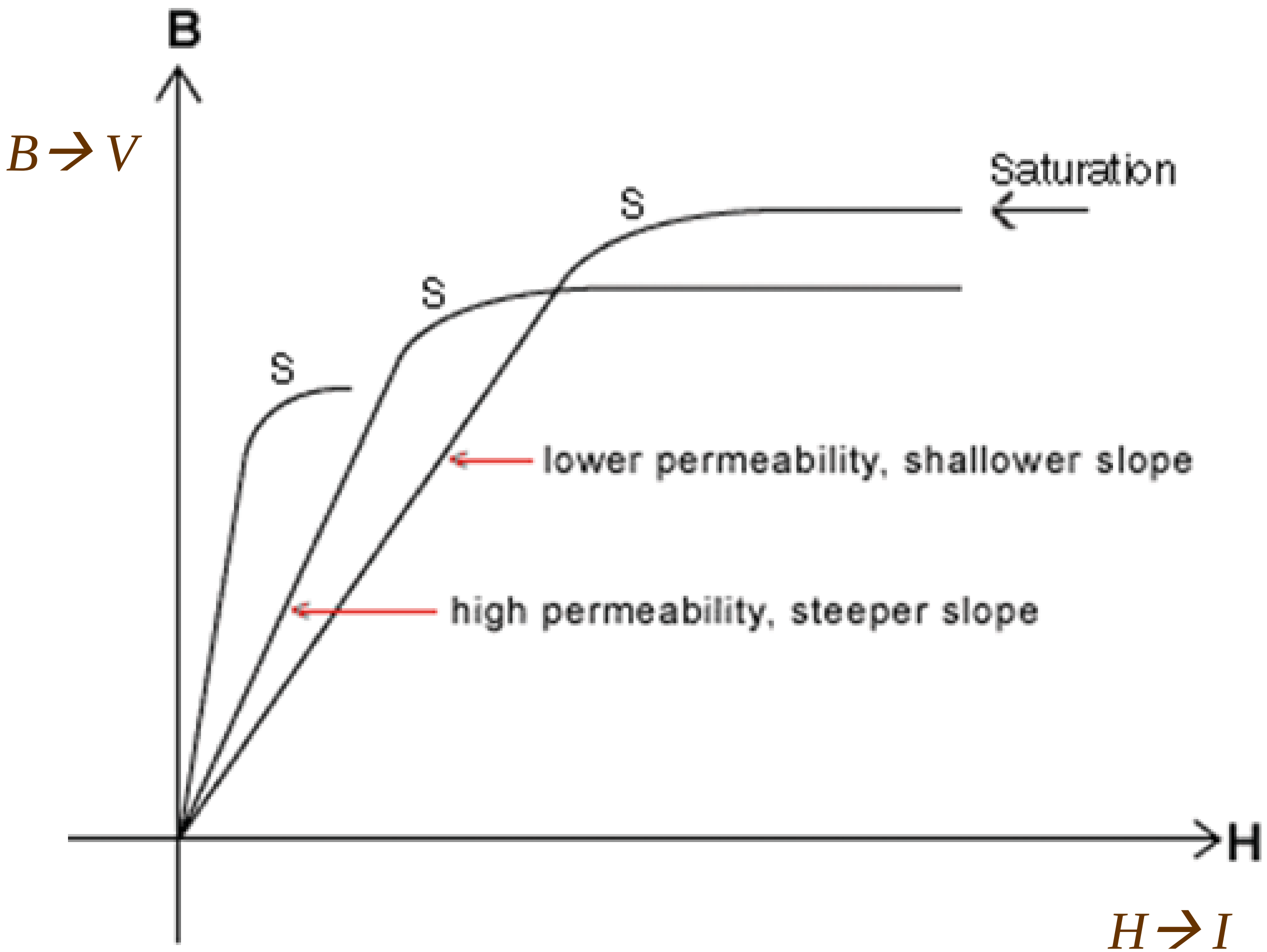
Permeability Definitions

- 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*

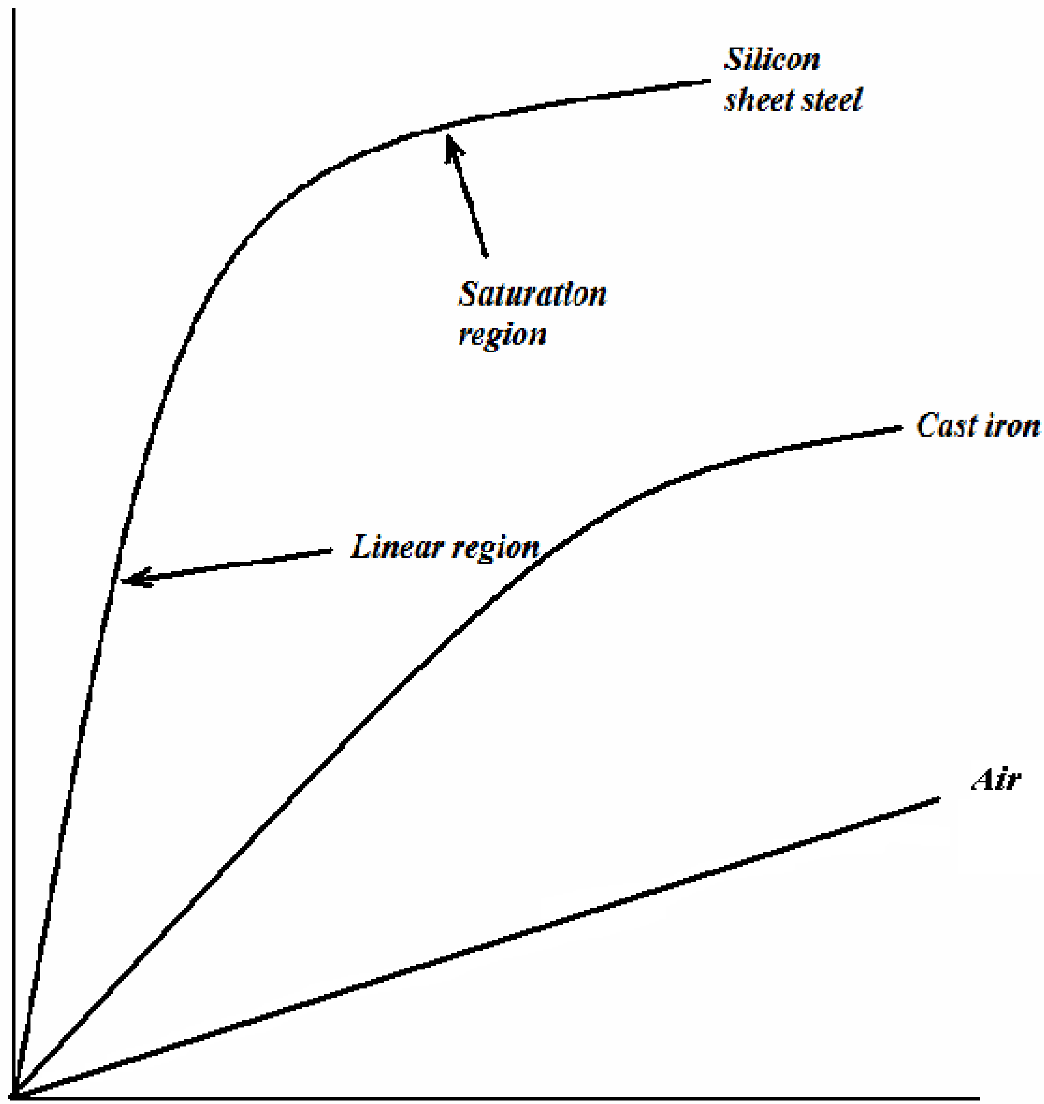
Core Materials
Air
Alloys
Amorphous
Iron Powder
Manganese-Zinc Ferrite
Molybdenum Permalloy Powder
Nickel-Zinc Ferrite
Sendust
Silicon Steel



$$\mu = \frac{\Delta B}{\Delta H} = \frac{B}{H}$$


B
$B \rightarrow V$
Saturation
S
S
S
lower permeability, shallower slope
high permeability, steeper slope
H
$H \rightarrow I$

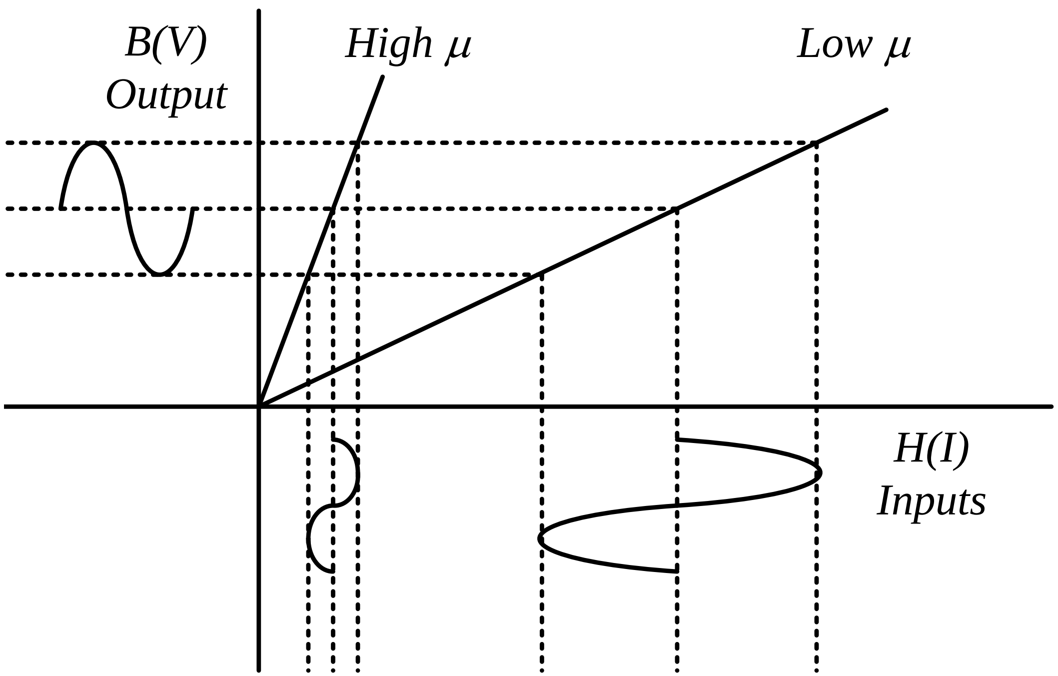
Material Comparison



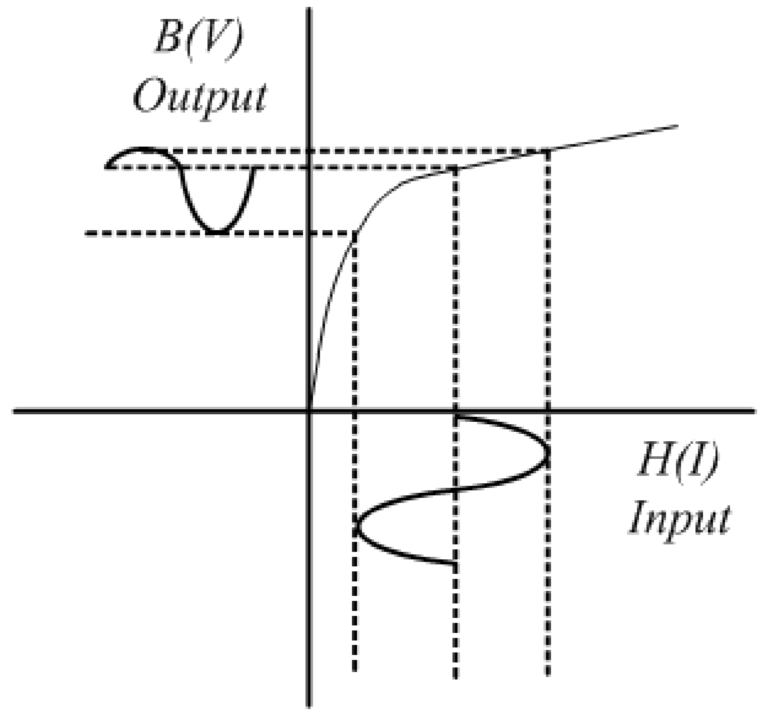
Core Material Guidelines

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

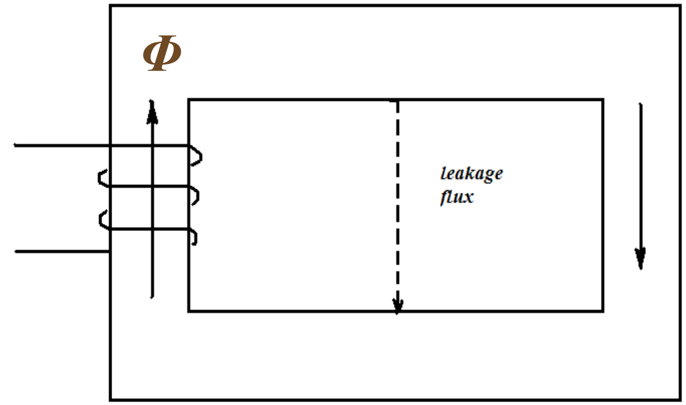
Effect of permeability magnitude on transformer current



Effect of permeability nonlinearity on transformer current



Relationship Between v(t) and B(t)



$$v(t) = -\frac{d\Phi(t)}{dt} = V_{max}\cos 2\pi f t$$

$$v_t(t) = \frac{v(t)}{N_p} = \frac{V_{max}\ \cos 2\pi f t}{N_p}$$

$v_t(t)$ = volts per primary winding turn

$$\Phi(t) = -\int v_t(t)dt = \int_s B(t)\bullet da_c$$

$$\int_s B(t)\bullet da_c = -\int v_t(t)dt = -\int \frac{V_{max}\cos 2\pi f t}{N_p}\,dt$$

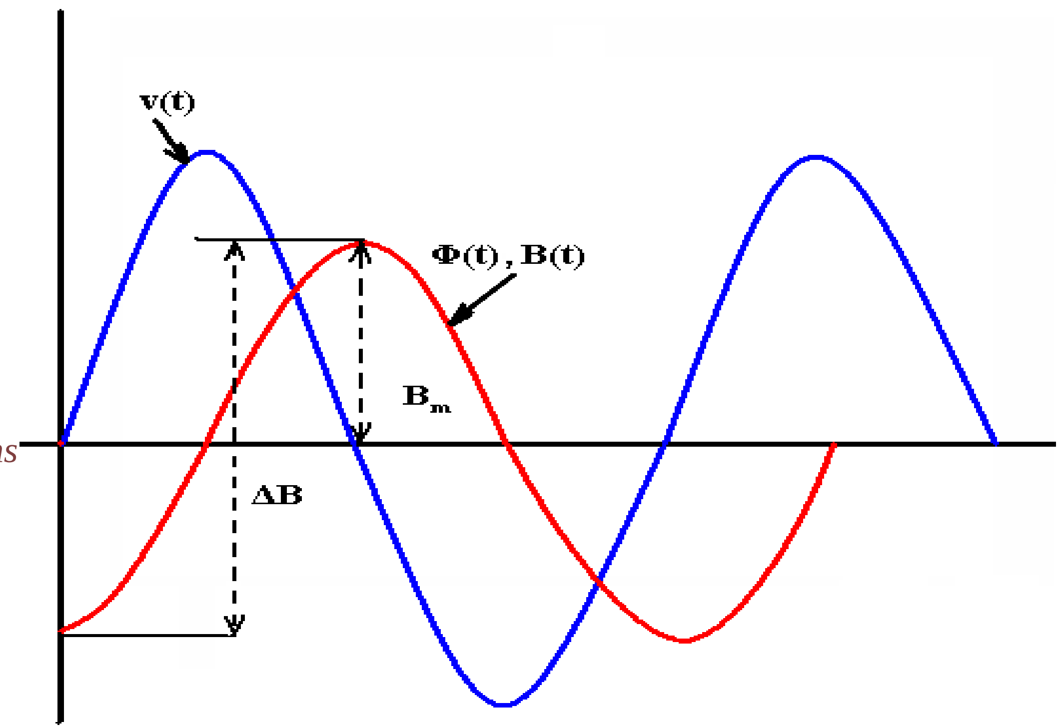
a_c = core crossectional area

$$B(t)a_c = \frac{V_{max}\sin 2\pi f t}{2\pi f N_p}$$

$$B(t) = \frac{V_{max}\sin 2\pi f t}{2\pi f N_p a_c}$$

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

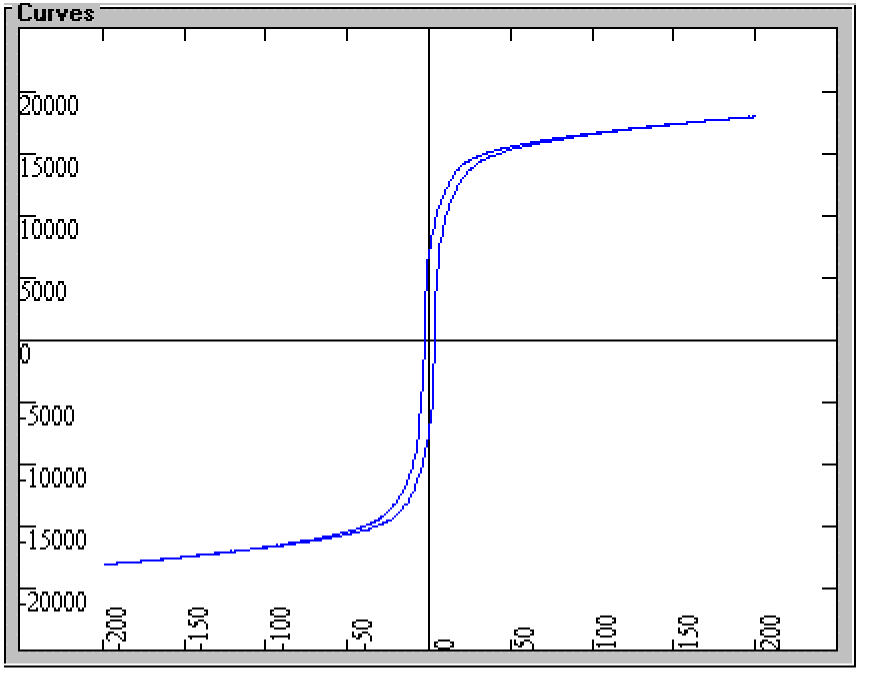
$4.44 = \frac{\sqrt{2}}{2\pi}$ converts peak AC to rms and ω to f

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

$$B_{max} = \frac{480V * 1.05(\text{voltage safety factor})}{4.44 * 60\,Hz * 300\,cm^2 * 60\,turns * 10^{-8}} = 10{,}510 \text{ gauss}$$

For square wave or rectangular wave excitation

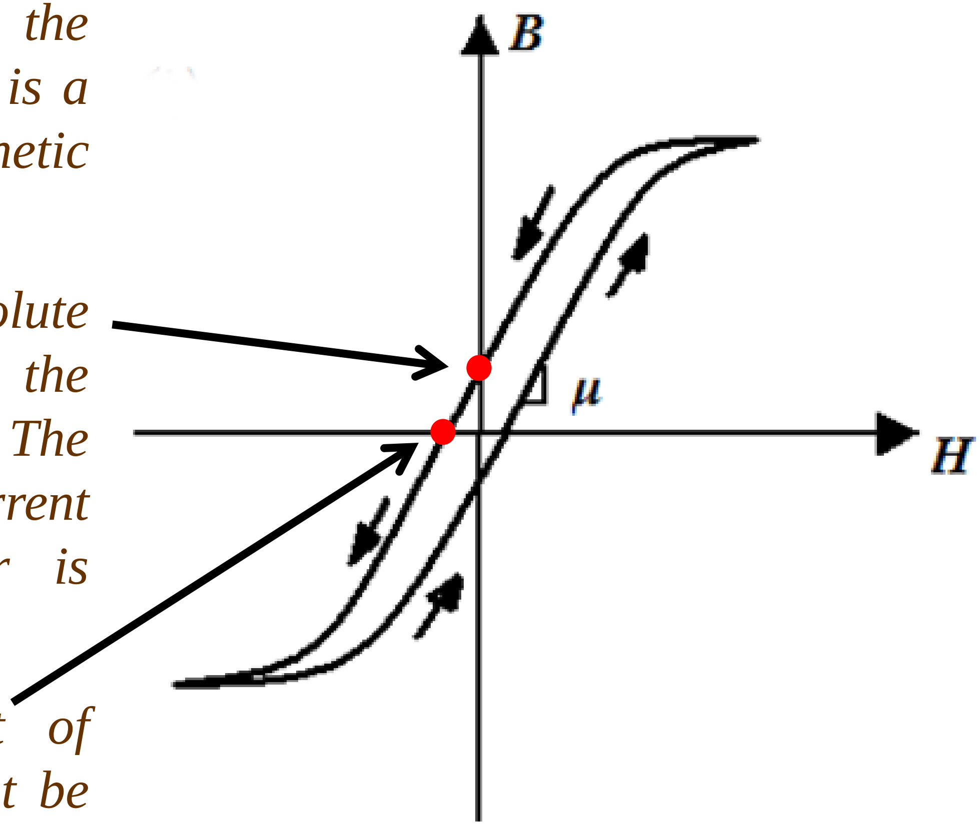
$$B_{max} = \frac{D * V_{peak}}{4 * f * A_c * N_p * 10^{-8}}$$

where

D = duty cycle the wave

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.*



Transformer Design Issues – Inrush Current

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

A_c = the crossectional area of the core in sq inches

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

A_s = effective square inches of the air-core magnetic field

Example $I_{fl} = \frac{600kVA}{\sqrt{3} * 480V} = 722A$, the inrush current is

$$i_{inrush} = \frac{10^3 * 40 * 46.5 * ((43 + 2 * 71) - 130)}{3.2 * 60 * 69.4} = 6.56kA$$

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.*

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"*

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

This is the depth where the fields or current in

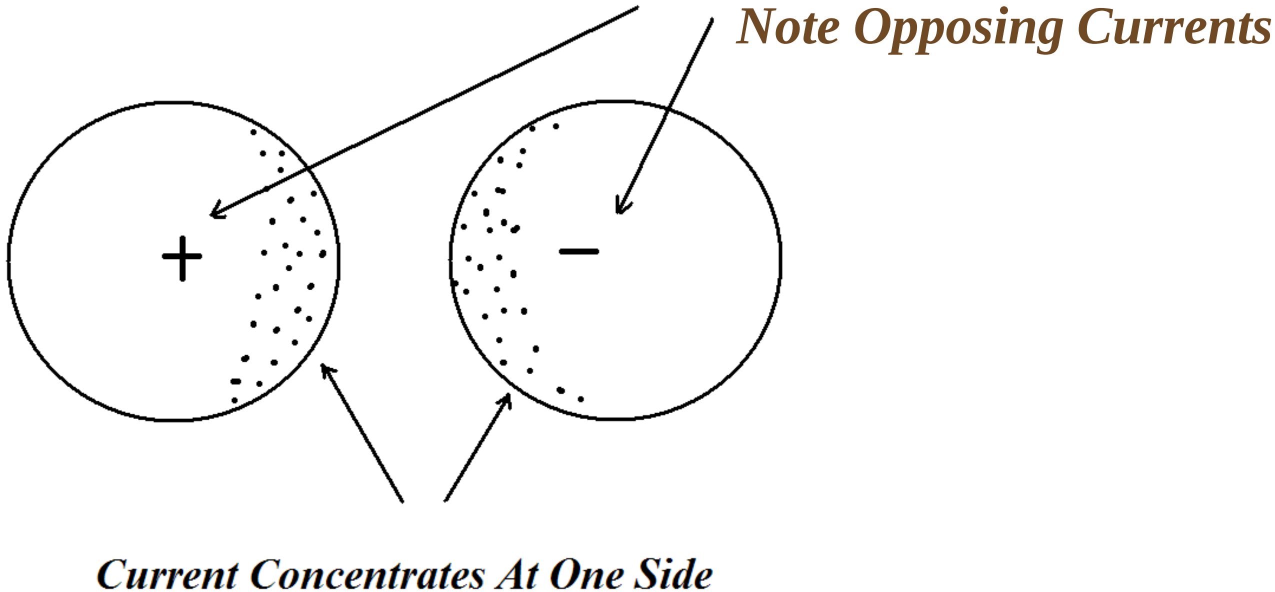
a conductor have decreased to 37% of their nominal value.

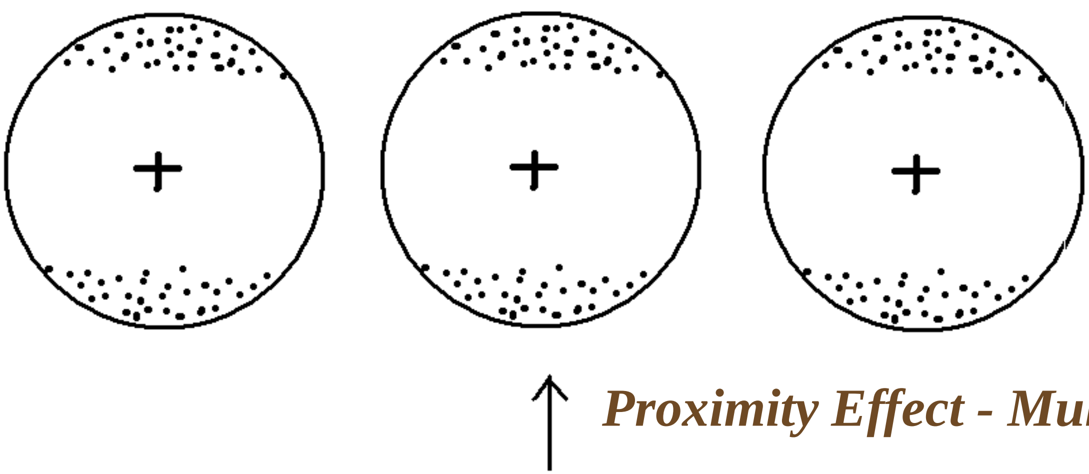
In other words 63% of the current is carried in this depth.

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.*

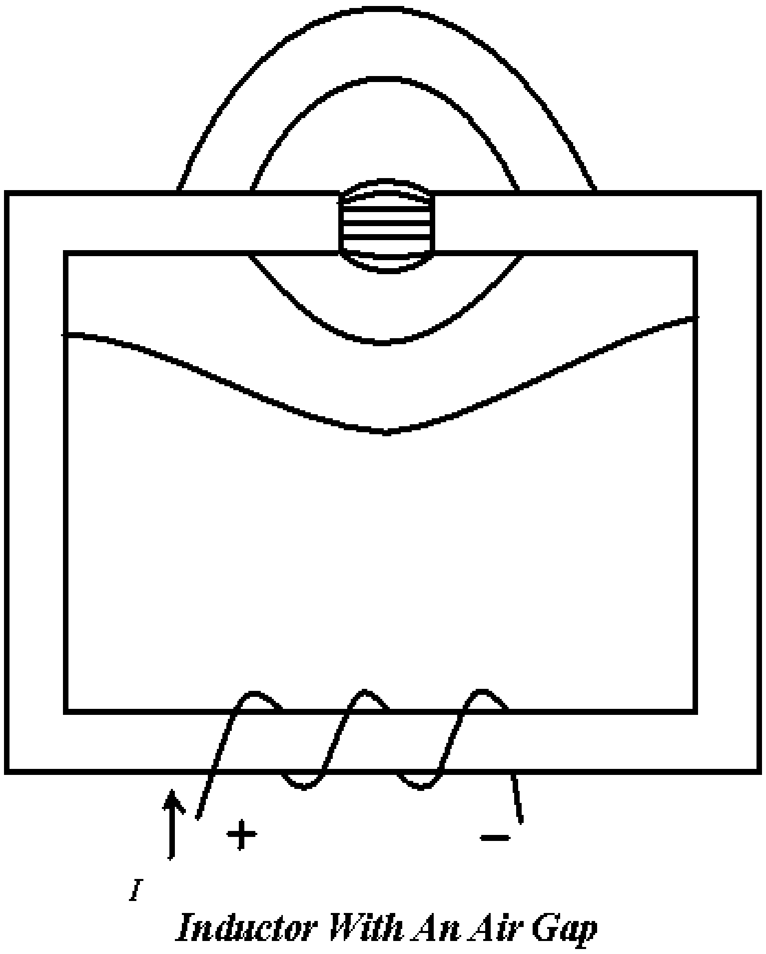
Proximity Effect

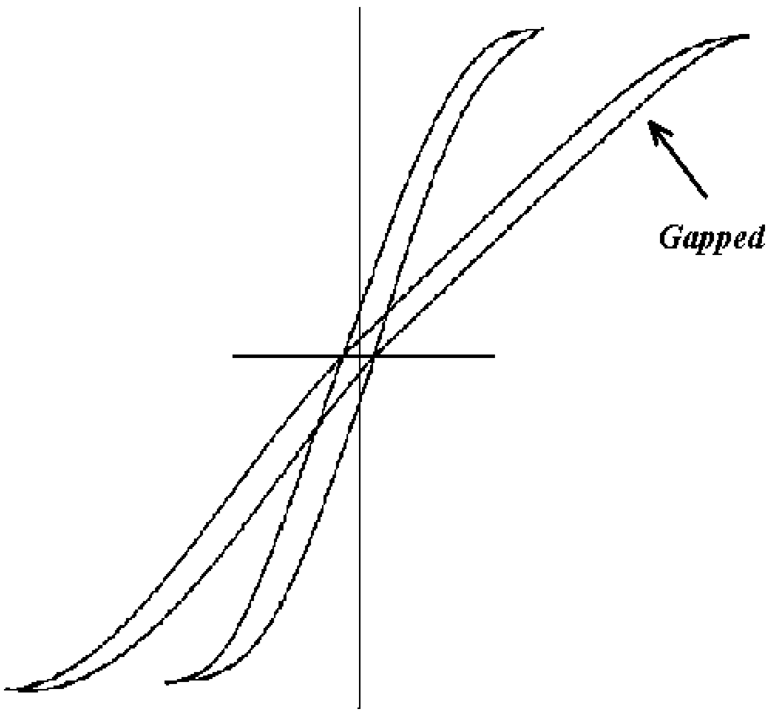




Proximity Effect - Multiple Parallel Wires

Effect of Air Gap





B-H Loop

Why Do 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*

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*

μ_r *is dimensionless*

$$\mu_0 = \frac{4\pi * 10^{-7} H}{m}$$

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.*

Section 8 - Controls

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

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

A linear system, $h[x]$*, is defined such that for functions* x_1 *and* x_2 *if*

$$y_1 = h[x_1] \text{ and } y_2 = h[x_2]$$

then $ay_1 + by_2 = h[ax_1 + bx_2]$ *This is the principle of superposition*

Examples of Linear Systems

Constant gain system $h_1[x] = A_1 x$

Sum of two constant gain systems $h_2[x] = A_2 x + A_3 x$

Integrals $h_3[x] = \int_{t_0}^{t} x(\tau)\, d\tau$

Derivatives $h_4[x] = \frac{dx}{dt}$

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:

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

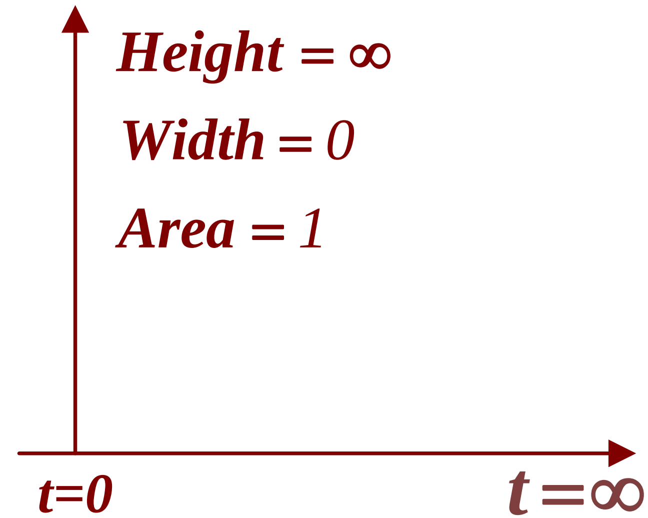
We note that non-linear systems can often be approximated by linear systems

- *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

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

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



Functional representation

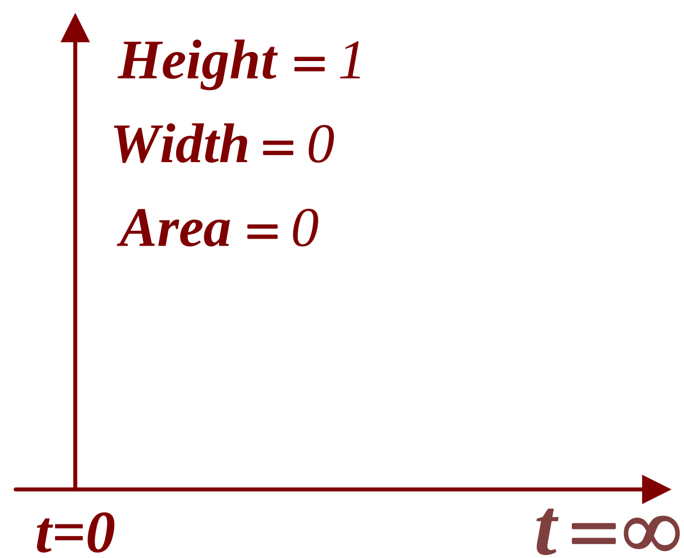
$$y(t_0) \;\; = \int_{-\infty}^{\infty} f(t)\,\delta(t - t_0)\, dt$$

Discrete impulse function properties

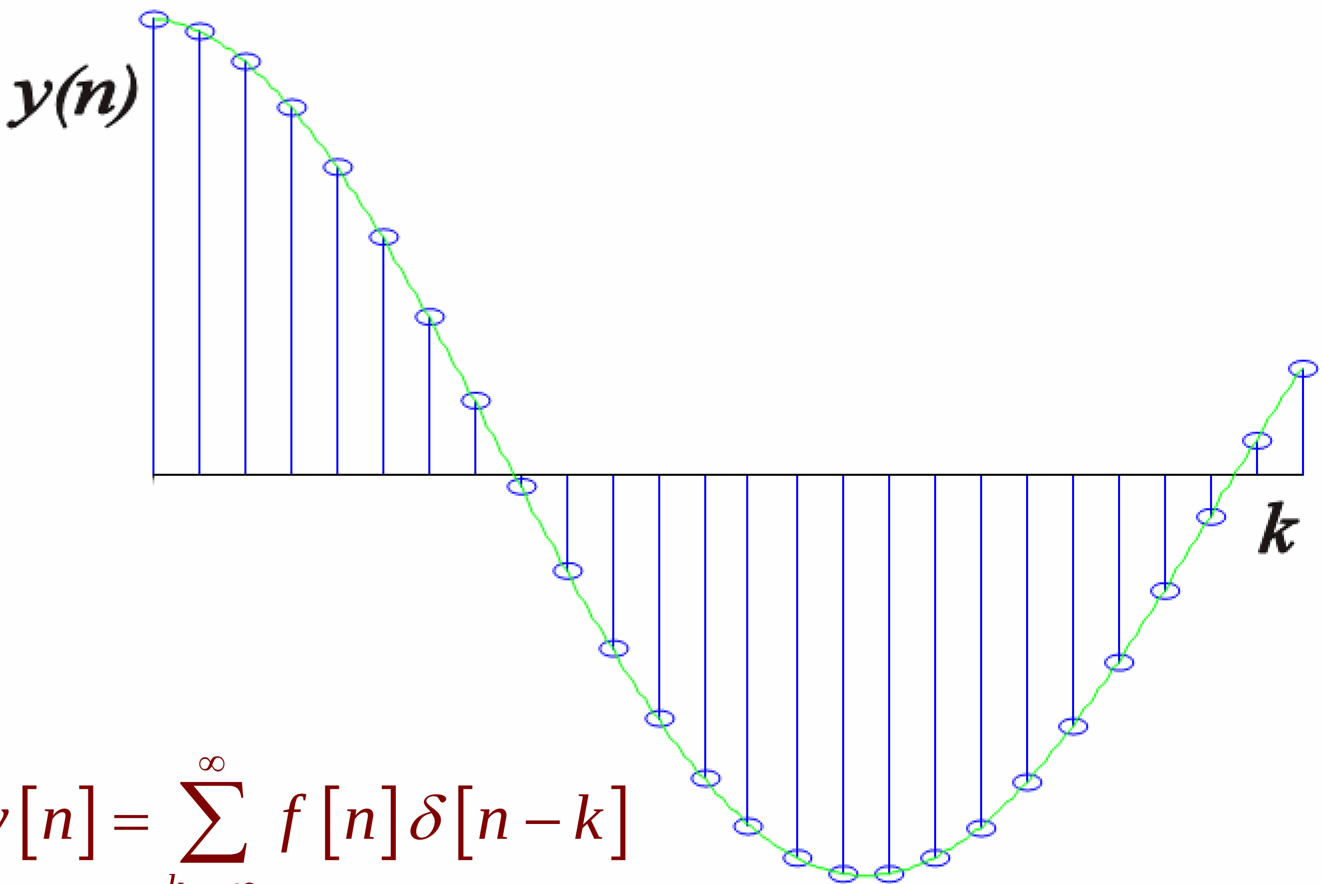
$$\delta[n] = 0, \quad n \neq 0 \qquad\qquad \delta[n] = 1, \quad n = 0$$

Functional representation

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



Mathematical Preliminaries - Function as Sum of Delta Functions



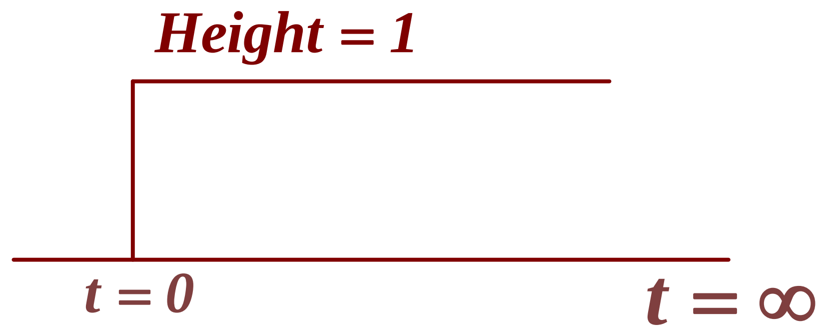
$$y[n] = \sum_{k=-\infty}^{\infty} f[n]\,\delta[n-k]$$

Mathematical Preliminaries - Continuous Step Function

Properties

$$U(t) = 0, \quad t < 0$$

$$U(t) = 1, \quad t \geq 0$$



Relation to impulse

$$\delta(t) = \frac{dU(t)}{dt}$$

Functional representation

$$y(t_0) = -\int_{-\infty}^{\infty} f(t)\frac{dU(t_0 - t)}{dt}dt$$

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

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

Heaviside step function

Properties

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

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

Relation to impulse

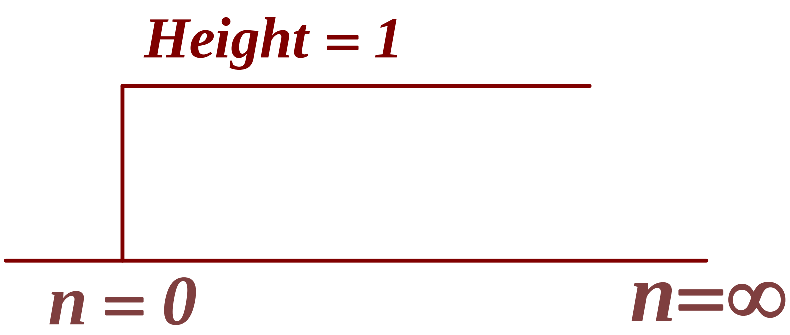
$$\delta[n] = U[n] - U[n-1]$$

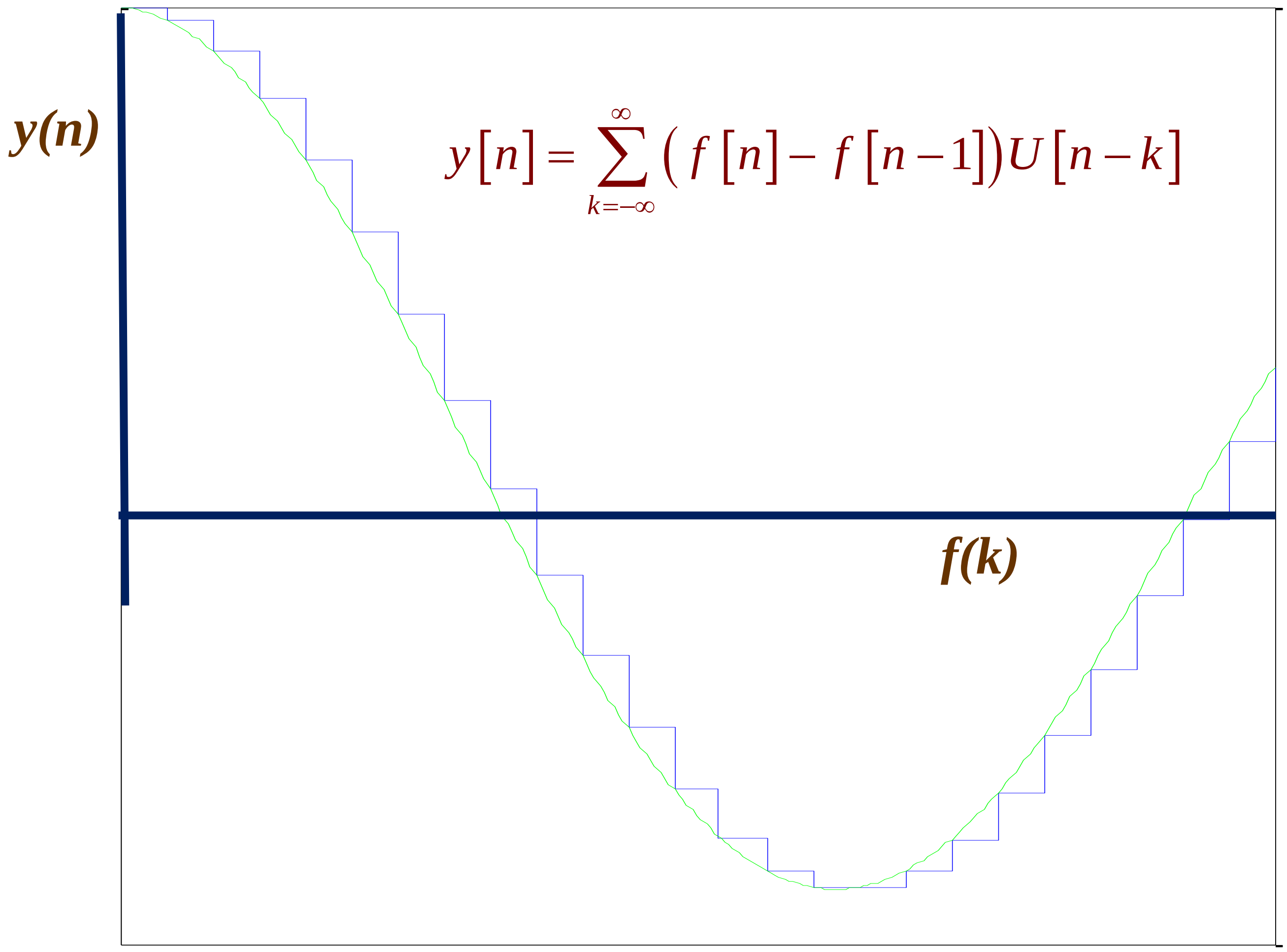
Functional representation

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

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

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





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

- *Introducing the complex exponential according to the Euler formula*

$$P = A * \angle\theta$$

$$A * e^{j\omega t} = A * (\cos \omega t + j \sin \omega t)$$

$$\omega = 2 * \pi * f$$

$$j = \sqrt{-1}$$

- *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*
- *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.*
- *The phasor amplitude is the eigenvalue of that frequency*

Eigenvalue = proper value or characteristic roots

For example the roots of the quadratic formula y=(-b+/-SQRT bsquared-4ac)/2a=eigenvalues or the roots of the equation

- *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

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

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

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

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

- *When working with linear, time-invariant systems, there are several advantages to moving from the time domain to the frequency domain.*

$$\text{If } \; x_1 \rightarrow y_1, \quad x_2 \rightarrow y_2 \; \text{ and if } \; ax_1 \rightarrow ay_1, \; bx_2 \rightarrow by_2$$
$$\text{and if } \; ax_1 + bx_2 \rightarrow ay_1 + by_2, \text{ then system is linear}$$

$$\text{If } \; x(t) \rightarrow y(t) \text{ and if } \; x(t - t_0) \rightarrow y(t - t_0), \text{ then system is time-invariant}$$

- *Each frequency corresponds to a unique eigenfunction of the system and the system response for each frequency can be calculated independently.*

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

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

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

- *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 definition of the Laplace transform is $F(s) = \int_0^\infty f(t) e^{-st}\,dt$

Some simple transforms

$f(t) \quad = \delta(t - t_0) \;\; t_0 > 0 \qquad\qquad F(s) = 1$

$f(t) \quad = U(t) \qquad\qquad F(s) = \frac{1}{s}$

Unit step with delay

$f(t) = U(t - t_0) \quad t \ge 0 \qquad\qquad F(s) = \frac{e^{-st_0}}{s}$

Exponentially decreasing function, starting at t=0

$f(t) = e^{-at} U(t) \;\; a \ge 0 \qquad\qquad F(s) \; = \frac{1}{s+a}$

Laplace transform of a derivative

let $\quad f(t) = \frac{dg(t)}{dt} \qquad\qquad F(s) = sG(s) - g(0)$

Mathematical Preliminaries - Inverting Laplace Transforms

- *Laplace Transforms simplify the calculations of system behavior, but these calculations are performed in the* 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://mathworld.wolfram.com/FourierTransform.html

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*

$$Ve^{j\omega t} = R\,I\,e^{j\omega t} + L\,j\omega I\,e^{j\omega t} - i(0) = (R + j\omega L)\,I\,e^{j\omega t}$$

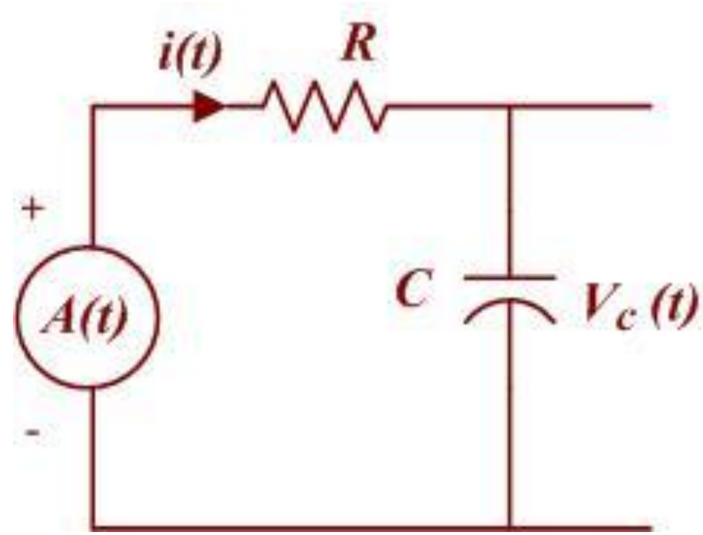
$I\,e^{j\omega t}$ *is the eigenfunction*

$(R + j\omega L)$ *is the eigenvalue, which, is the impedance,* $Z(\omega)$

$$KVL \quad -A(t)+Ri(t)+v_c(t)=0 \qquad But\ i(t)=C\frac{dv_c(t)}{dt}$$

System equation

$$RC\frac{dv_c(t)}{dt}+v_c(t)=A(t) \qquad Let\ RC=\tau$$



Solution

$$v_c(t)=v_c(0)e^{-\frac{t}{\tau}}+\tau^{-1}e^{-\frac{t}{\tau}}\int_0^t A(t)e^{\frac{t}{\tau}}\,dt$$

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

$$C\left[sV_c(s)-v_c(0)\right] = -\frac{1}{R}V_c(s)+\frac{1}{R}A(s)$$

$$\left(sC+\frac{1}{R}\right)V_c(s) = Cv_c(0)+\frac{1}{R}A(s)$$

$$V_c(s) = \frac{1}{s+\tau^{-1}}v_c(0)+\frac{\tau^{-1}}{s+\tau^{-1}}A(s) \qquad \text{let } \tau^{-1}=\alpha$$

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

$$V_c(s) = \frac{1}{s + \tau^{-1}} v_c(0) + \frac{\tau^{-1}}{s + \tau^{-1}} A(s)$$

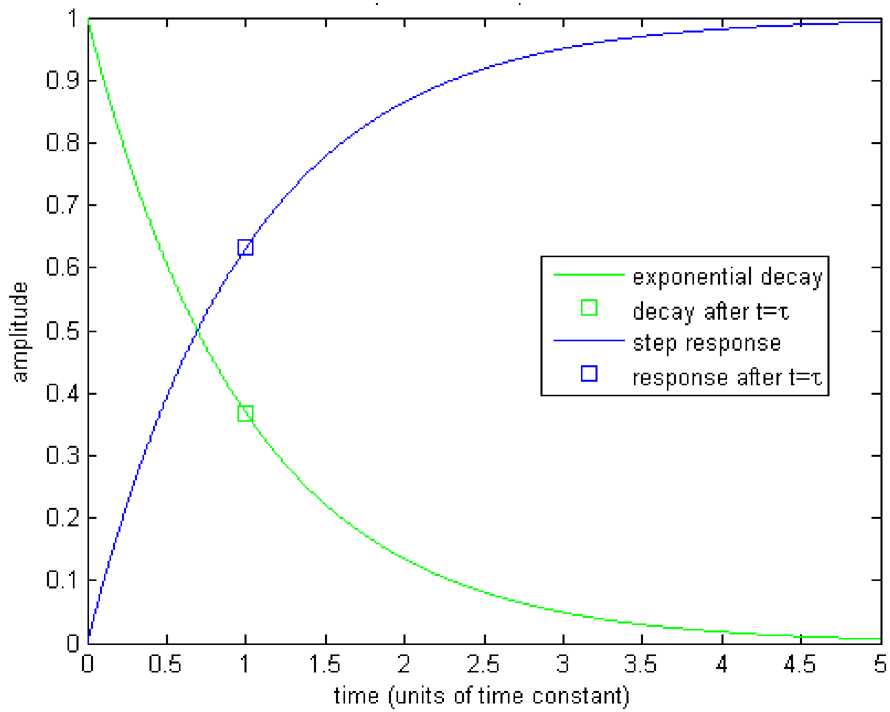
we can immediately read off the system transfer function

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"*
- *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*

$$H(j\omega) = \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}}$$

$$= \frac{\tau^{-1}}{j\omega + \tau^{-1}}$$

$$= \frac{1}{1 + j\omega\tau}$$

$$\text{Magnitude} \qquad |H(j\omega)| = \frac{1}{\sqrt{1+(\omega\tau)^2}}$$

$$|H(j\omega)|_{dB} = 20\,log_{10}|H(j\omega)|$$

$$= -10\,log_{10}\left[1+(\omega\tau)^2\right]$$

$$\cong 0 \quad for\ \omega\tau \ll 1$$

$$\text{3 dB (half-power) point} = -10\,log_{10}2 \quad for\ \omega\tau=1$$

$$\text{20 dB per decade attenuation} \cong -20\,log_{10}\omega - 20\,log_{10}\tau \quad for\ \omega\tau \gg 1$$

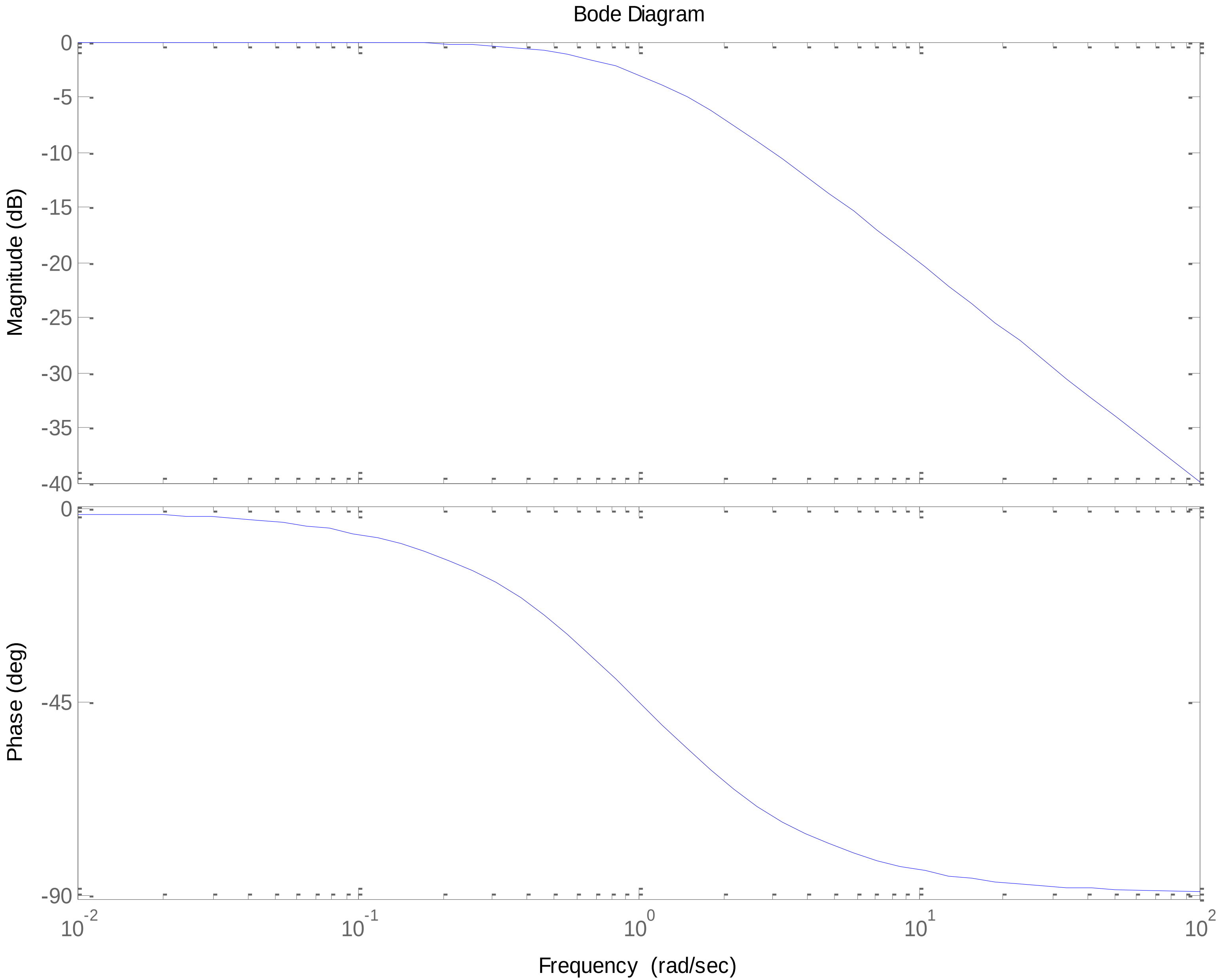
$$\text{Phase} \qquad \angle H(j\omega) = -arctan(\omega\tau)$$

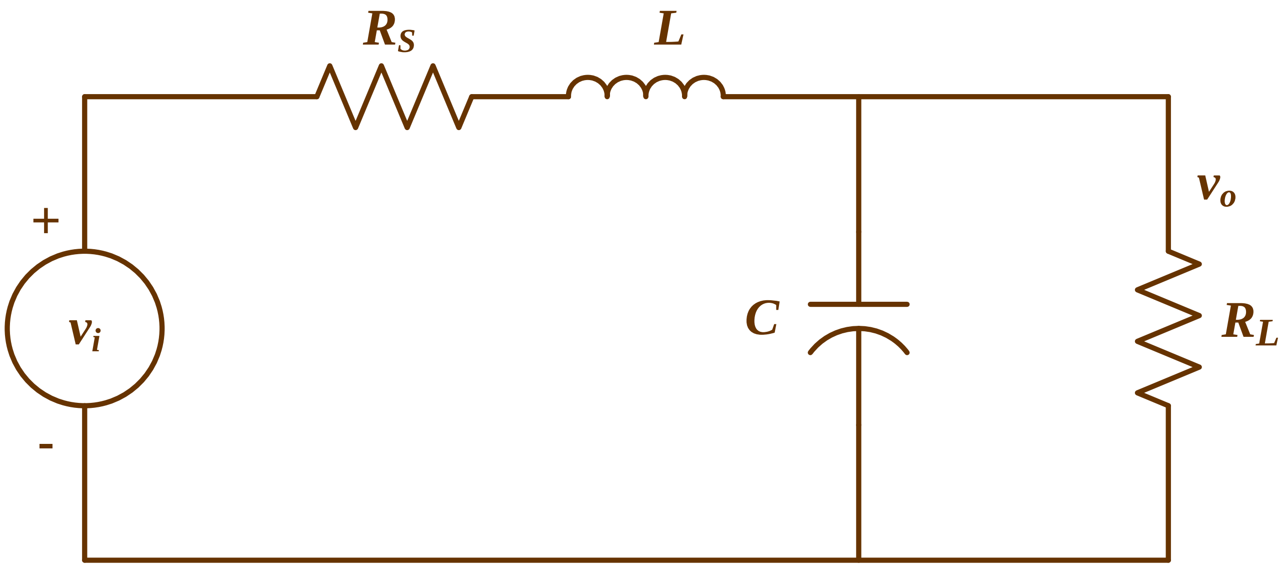
$$\cong 0 \qquad \omega\tau \ll 1$$

$$= -45^0 \qquad \omega\tau = 1$$

$$\cong -90^0 \qquad \omega\tau \gg 1$$

Electrical Circuit Theory - One Pole LP Frequency Response





R_S
L
v_o
+
v_i
-
C
R_L

Find transfer function of voltage divider

$$H(j\omega) = \frac{\dfrac{R_L/j\omega C}{R_L + 1/j\omega C}}{R_S + j\omega L + \dfrac{R_L/j\omega C}{R_L + 1/j\omega C}} = \frac{R_L}{-R_L LC\omega^2 + j(R_L R_S C + L)\omega + (R_S + R_L)}$$

$$= \frac{1}{LC}\frac{1}{-\omega^2 + j(R_S/L + 1/R_L C)\omega + (1 + R_S/R_L)(1/LC)} \qquad let\ \omega_0^2 = 1/LC$$

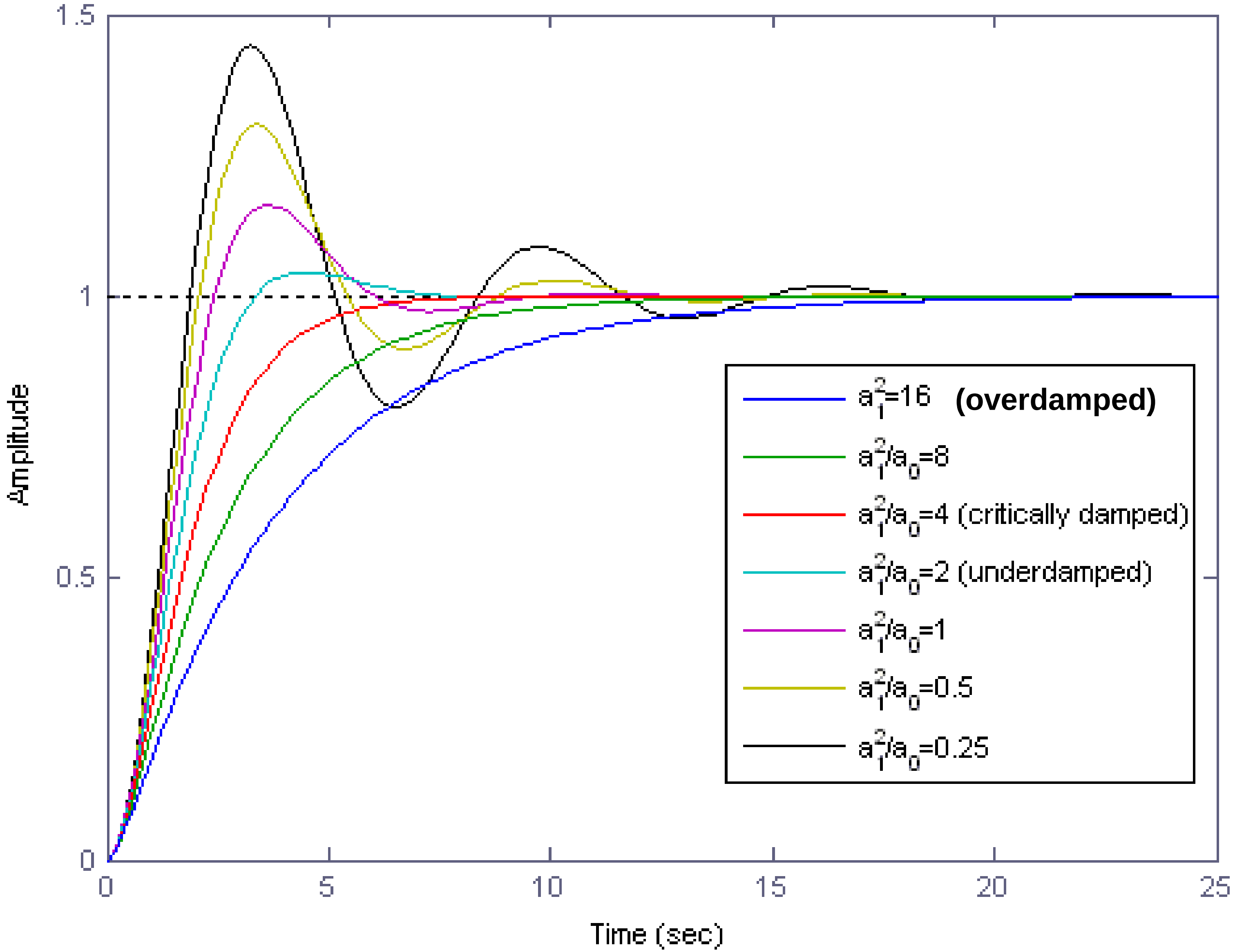
$$= \frac{\omega_0^2}{-\omega^2 + j(R_S/L + 1/R_L C)\omega + (1 + R_S/R_L)\omega_0^2}$$

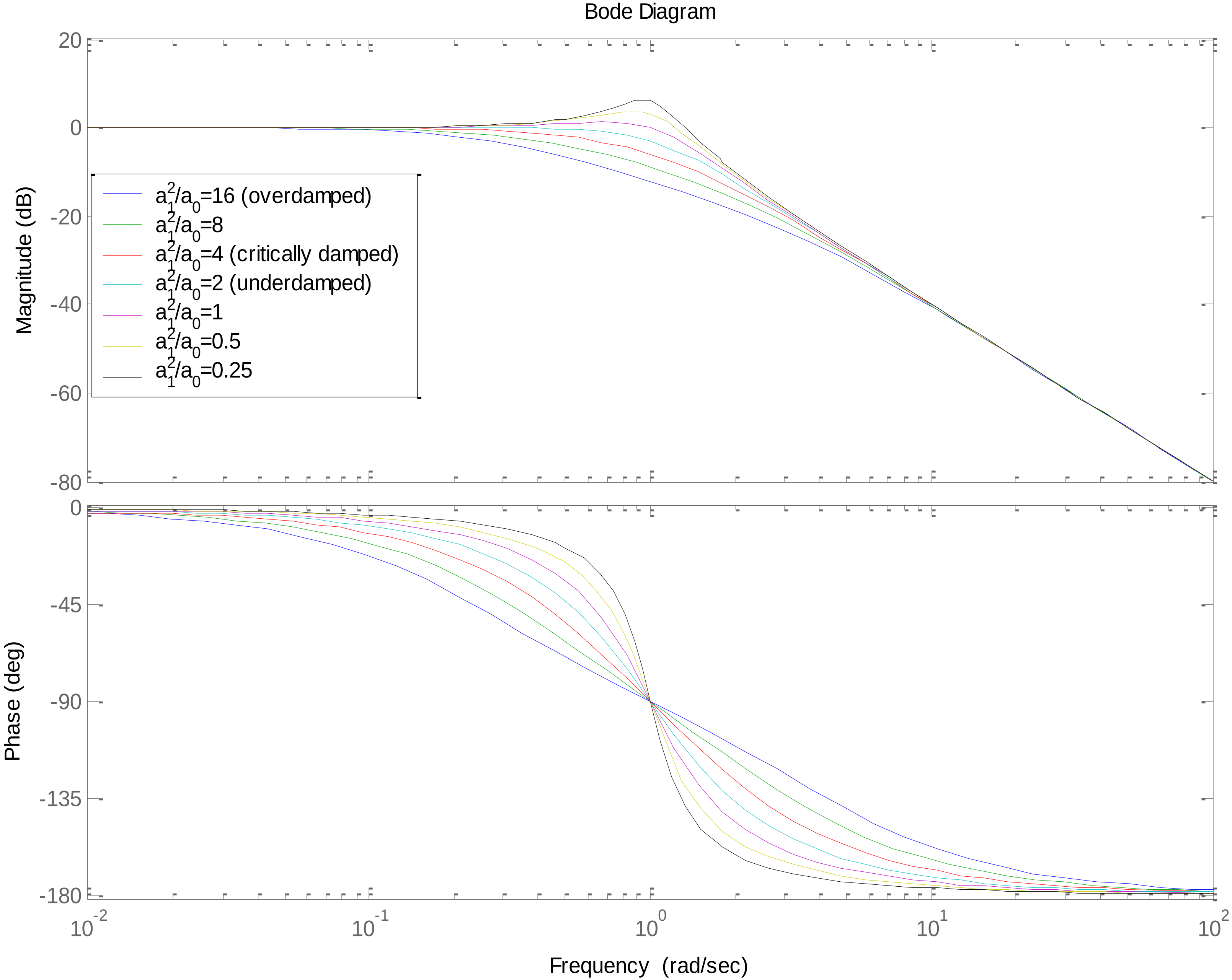
This has the form

$$H(s) = \frac{a_0}{s^2 + a_1 s + a_0} \qquad = \frac{a_0}{(s - s_1)(s - s_2)}$$

$$s_1 = -\frac{a_1}{2} + \sqrt{\left(\frac{a_1}{2}\right)^2 - a_0} \qquad s_2 = -\frac{a_1}{2} - \sqrt{\left(\frac{a_1}{2}\right)^2 - a_0}$$

- *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* $a_1^2 / a_0 > 4$
  - *Both poles are real*
  - *No oscillation in step response*
- *Critically damped system* $a_1^2 / a_0 = 4$
  - *Both poles are real and identical*
  - *Fastest step response with no oscillation*
- *Under-damped system* $a_1^2 / a_0 < 4$
  - *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)
$a_1^2=16$ (overdamped)
$a_1^2/a_0=8$
$a_1^2/a_0=4$ (critically damped)
$a_1^2/a_0=2$ (underdamped)
$a_1^2/a_0=1$
$a_1^2/a_0=0.5$
$a_1^2/a_0=0.25$


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*

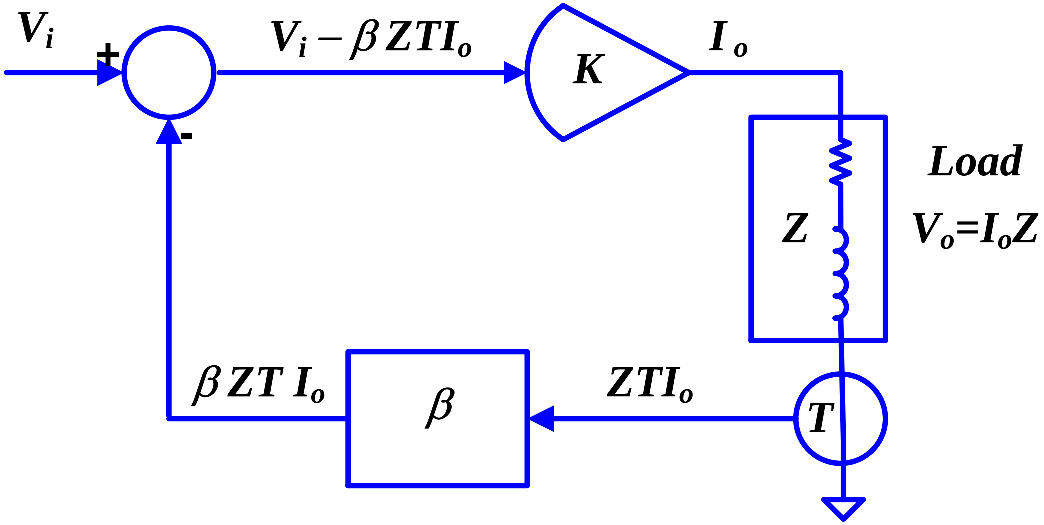
  Near the pole frequency, their behavior depends on the damping factor of the complex pole pair

- *Similar rules exist for zeros*

  6 dB/octave increase in gain above zero

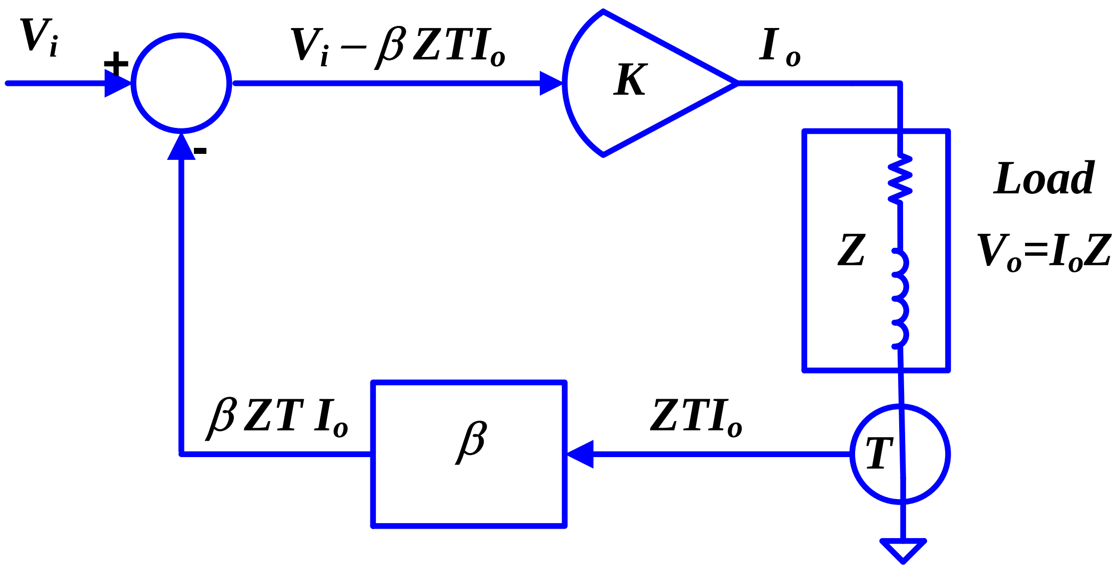
  +45 degree phase shift at the zero

- *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*



$$I_o = K(V_i - \beta\ T\ Z\ I_o) \quad \textit{rearranging gives} \quad \frac{I_o}{V_i} = A_{CL} = \frac{K}{1 + \beta\ T\ Z\ K}$$

- A_{CL} *is called the closed loop gain*
- *For* $\beta\ TZ\ K >> 1$ $$A_{CL} = \frac{1}{\beta\ T\ Z}$$
- *Power supply characteristics (K) relatively unimportant, gain dependent upon* $\beta\ T\ Z$



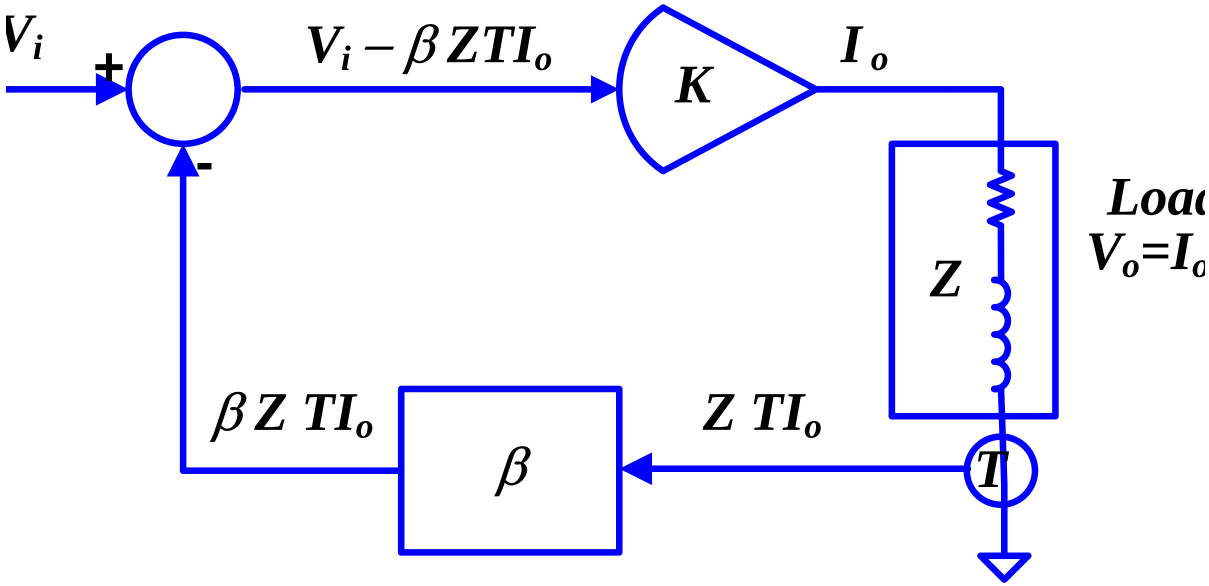
The feedback loop acts as an active null detector so that the output always follows the input

	$I_o = K(V_i - \beta Z T I_o)$	
V_i	$V_i - \beta Z T I_o \rightarrow 0$	I_o
$V_i \downarrow$	$V_i - \beta Z T I_o \rightarrow 0$	$I_o \downarrow$
I_o	$V_i - \beta Z T I_o \rightarrow 0$	$I_o \downarrow$
$I_o \downarrow$	$V_i - \beta Z T I_o \rightarrow 0$	I_o

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

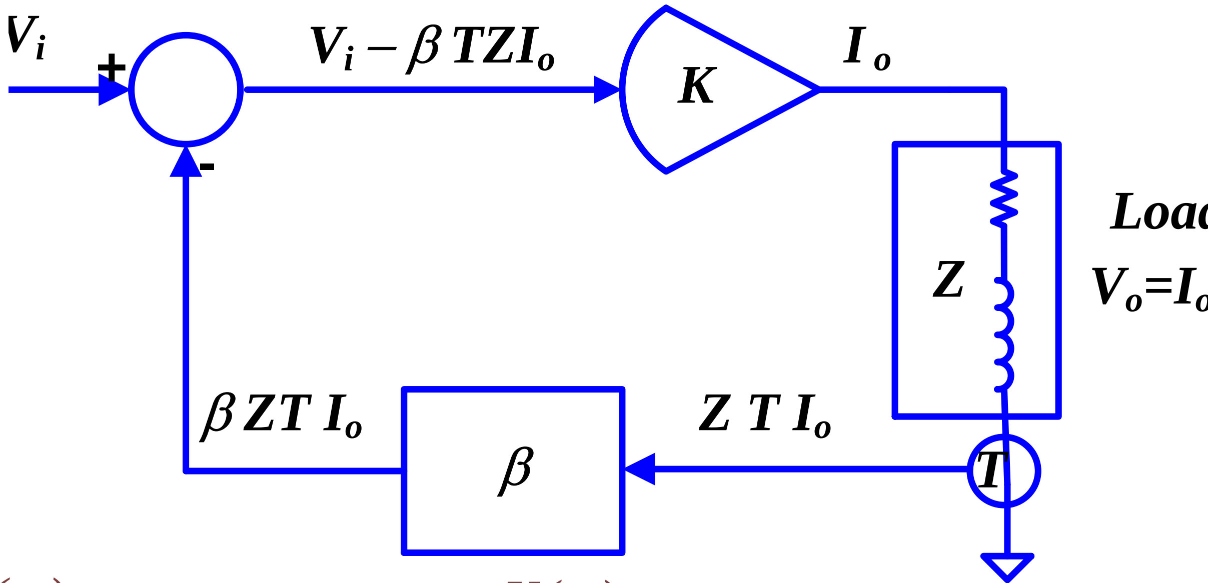


$$\frac{I_o}{V_i} = A = \frac{K}{1 + \beta TZ K}$$

$$\frac{I_o(s)}{V_i(s)} = A(s) = \frac{K(s)}{1 + \beta(s)T(s)Z(s)K(s)}$$

All the elements of the transfer function, gain, or in this case, the transconductance, are all functions of frequency $s = j\omega = j2\pi f$

Stability Against Oscillation



$$\frac{I_o(s)}{V_i(s)} = A(s) = \frac{K(s)}{1+\beta(s)T(s)Z(s)K(s)}$$

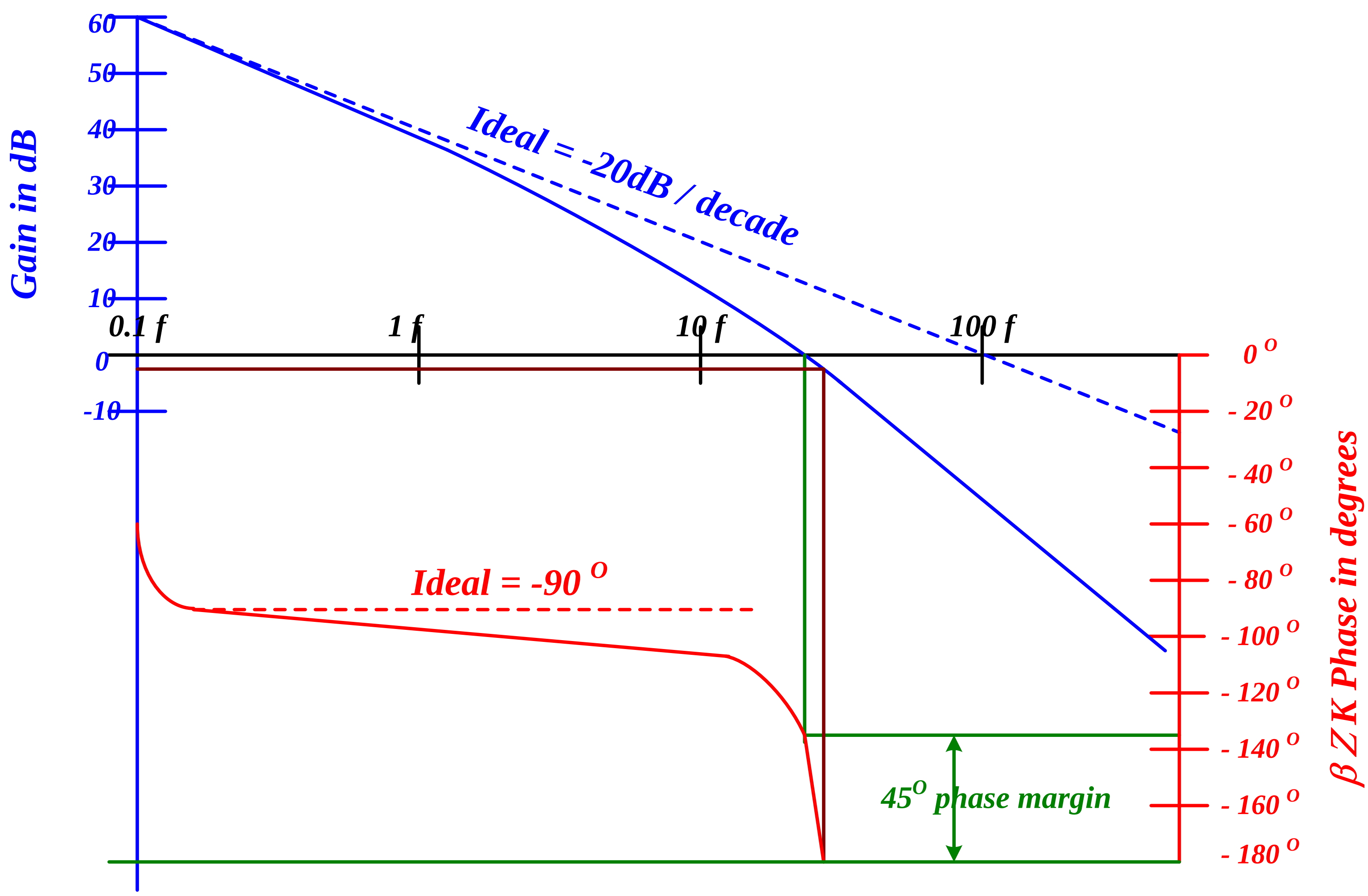
Very simply : 1+β(s) T(s)Z(s)K(s) must not = 0 or approach 0

β(s) T(s) Z(s) K(s) must not = -1 in order to avoid oscillations

$$|\beta|e^{j\alpha}\,|T|\,e^{j\beta}\,|Z|e^{j\chi}\,|K|e^{j\varphi} = |\beta|\,T\,||Z||K|e^{j(\alpha+\beta+\chi+\varphi)}$$

$$|\beta||\,T\,||Z||K| \neq 1 \quad when \quad \alpha+\beta+\chi+\varphi = \pm 180^{o}$$

Stability Against Oscillation



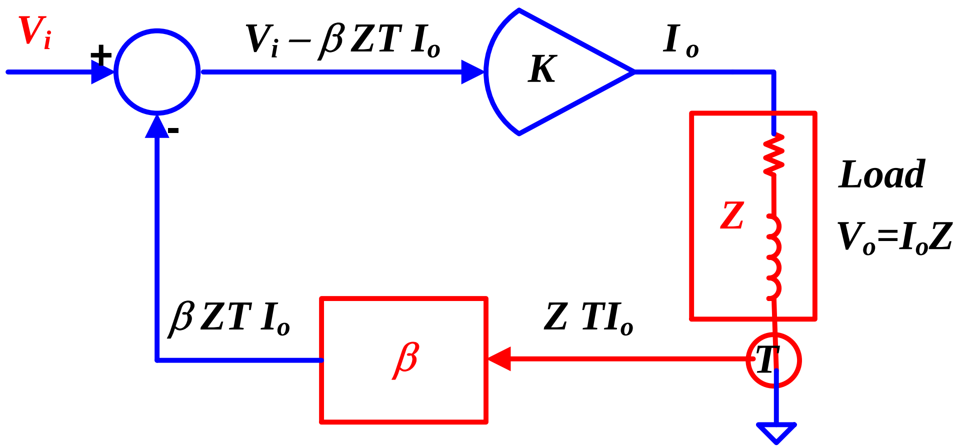
- For stability, the phase shift must be < 180 ^{O} when the |gain| =1
- For stability, the |gain| must be < 1 when the phase shift is 180 ^{O}

Short-Term (24 hour) Stability - *essentially stability against cyclic or diurnal temperature changes.*

$$\frac{I_o}{V_i} = A_{CL} = \frac{K}{1 + \beta TZ K}$$

Since $\beta TZK >> 1$, $\frac{I_o}{V_i} = A_{CL} = \frac{1}{\beta TZ}$ *K is unimportant,*

behavior dependent on load Z, transductor T, feedback factor β, *and upon* V_i *stability*



The part that has the greatest influence short-term stability is the feed-back signal β *because the feedback acts as an active null detector.*

V_i *is sometimes 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 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) $\cong$ 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 Model 866
0 - ±600 A
±400 mA out
0.3 ppm / ^{O} C
DC – 100 kHz
10 kA / mS
Separate burden resistor

LEM 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/ OC Shunt Resistor

http://www.isotekcorp.com

Factors That Affect Long-Term Stability

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"

- 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"

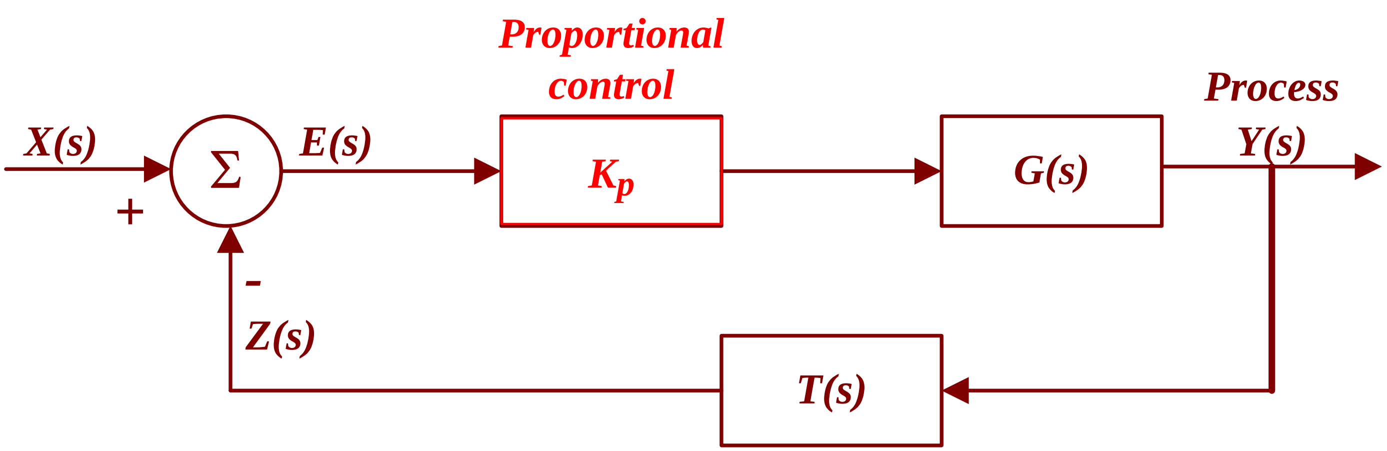
Factors that Affect Stability (Regulation) Against Transient Effects

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.*

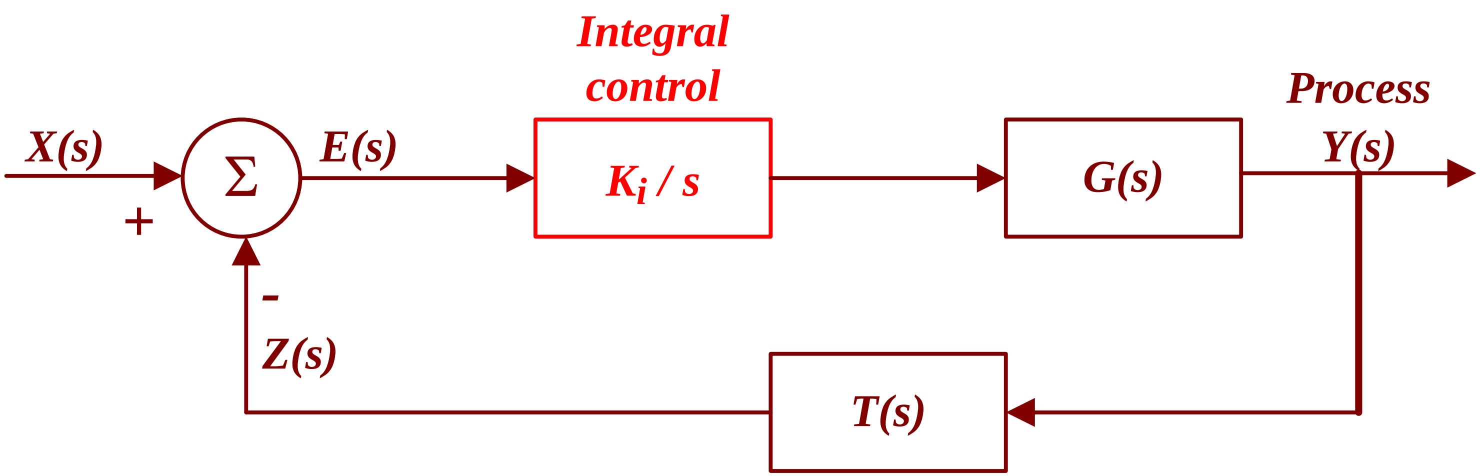
PID Loops - Proportional Control

- *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*

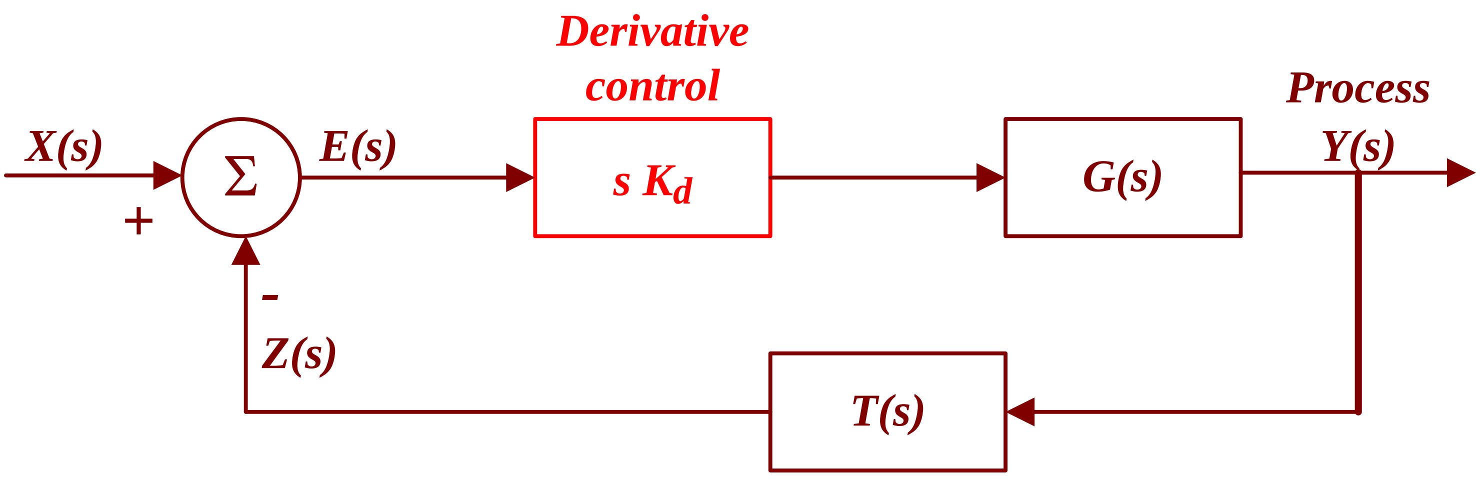


PID Loops - Integral Control

- *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*

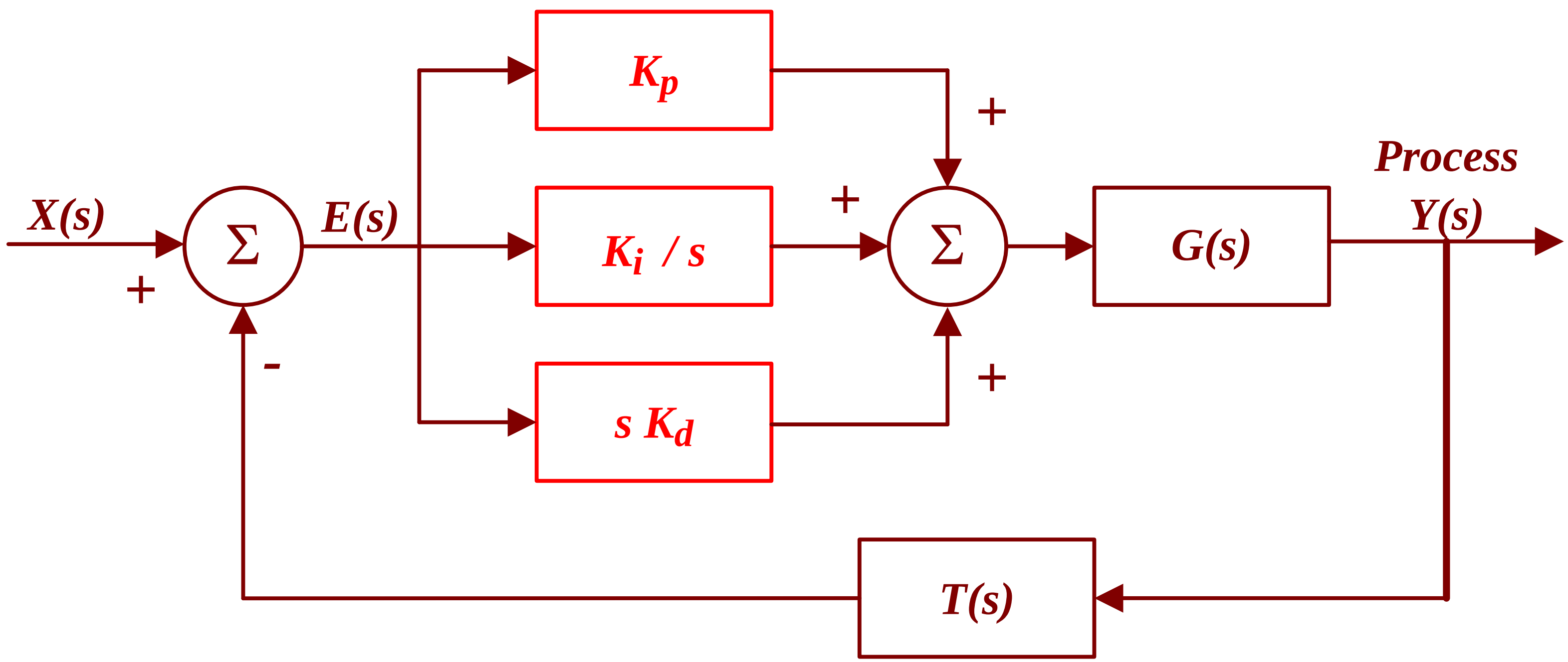


- Responds to the change of the error signal
- Control effort increases with frequency of error signal $s\,K_d$
- Useful either to cancel a pole or to predict periodic behavior
- Can emphasize high frequency noise



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 compensates for changes in the error signal or process

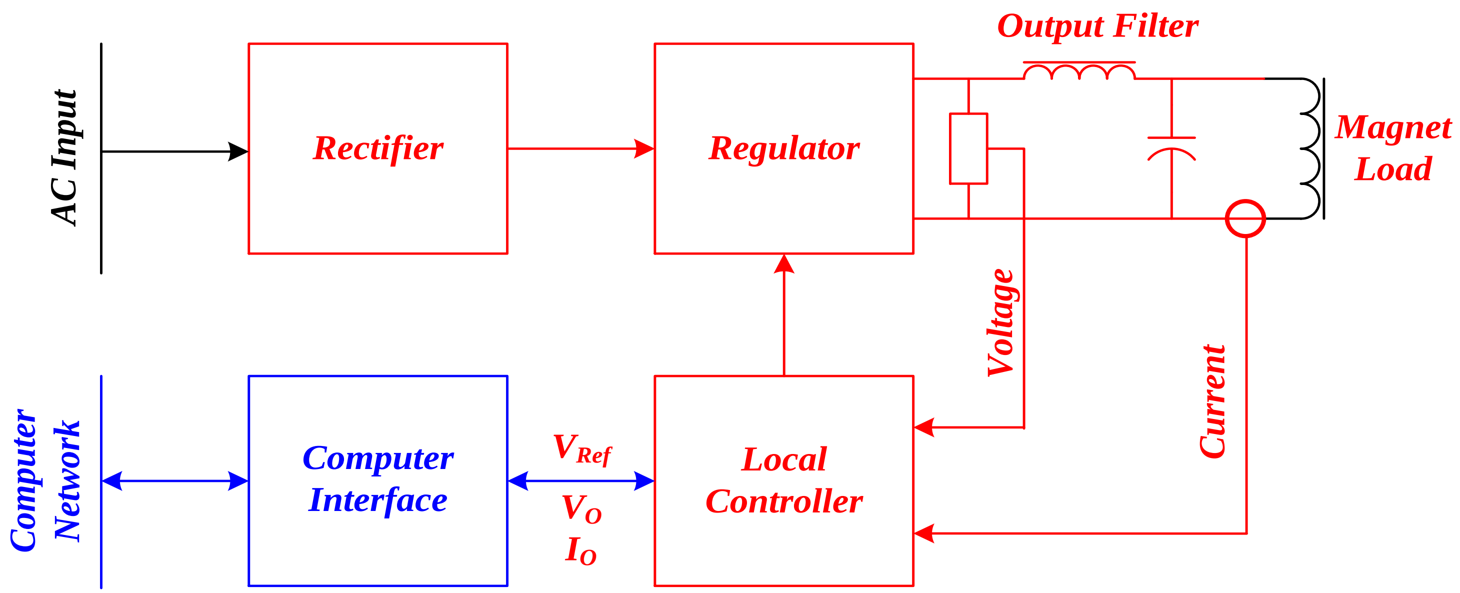


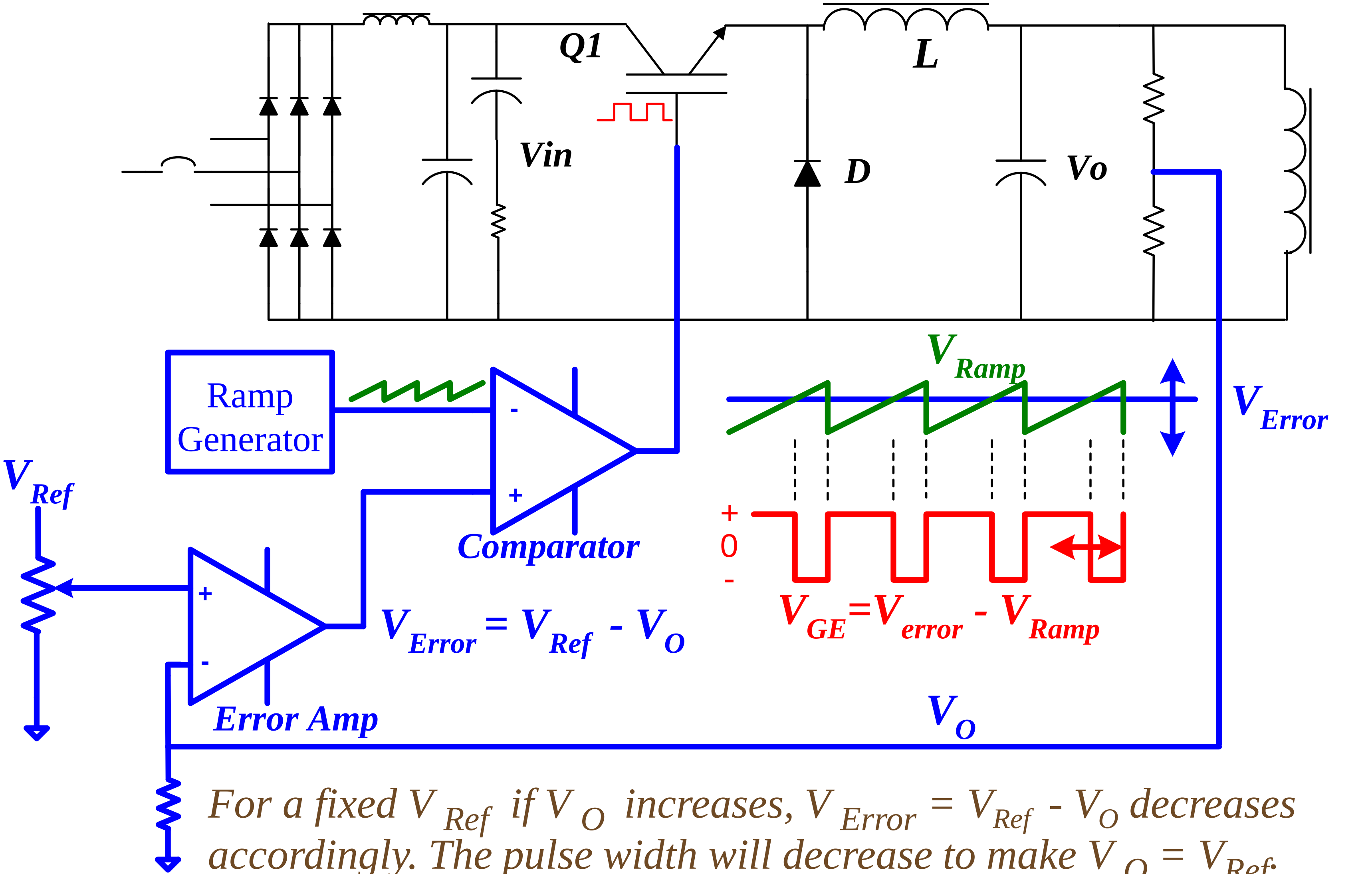
Stability and Feedback Summary

- *The transfer function is the relation between the input, x, and the output, y*
- *y more closely approaches the desired output by increasing feedback gain*
- *The efficiency of feedback for a dynamic (time-varying) system involves not only the gains, but also the speed of the system response*
  - *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

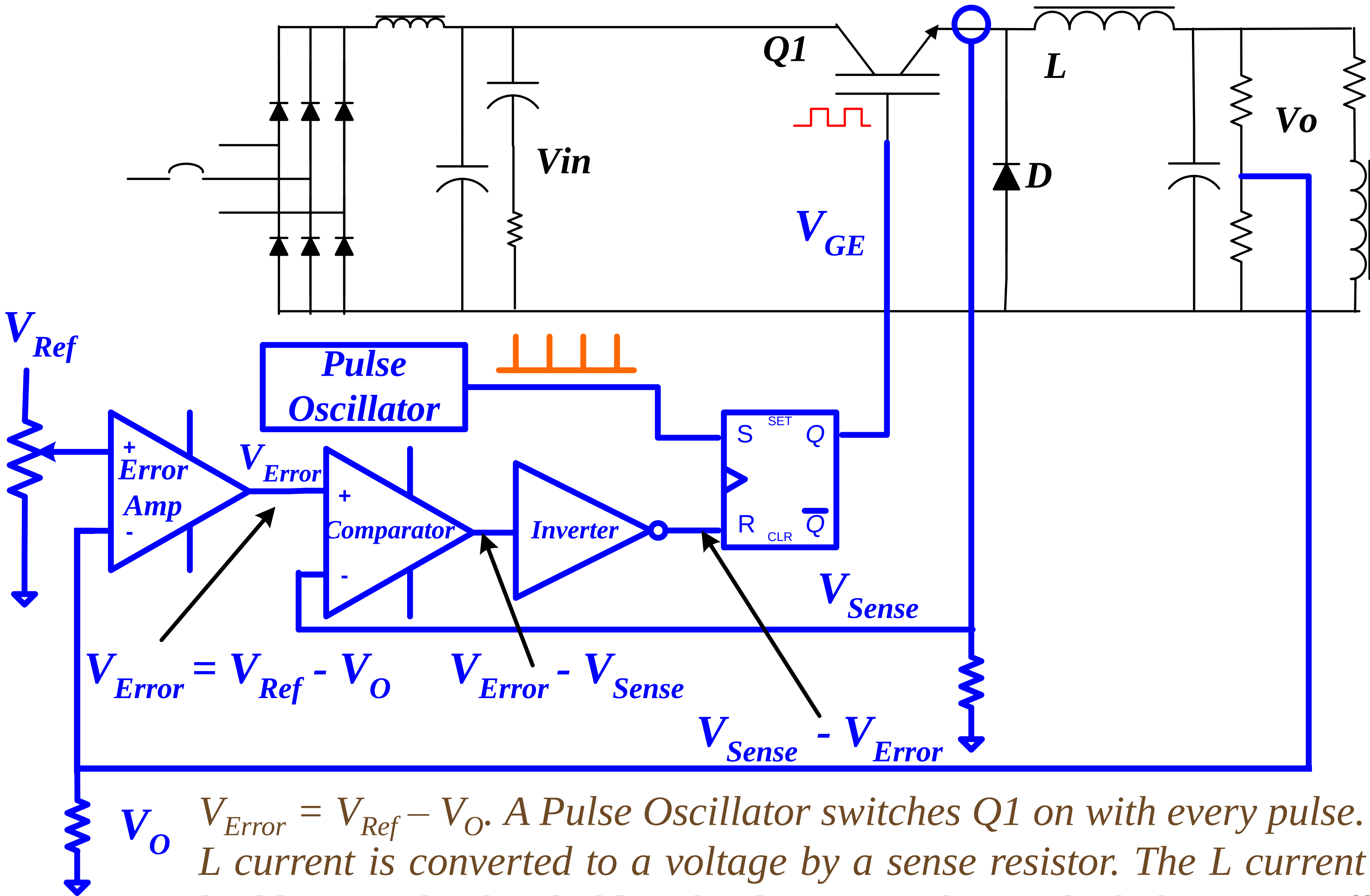
- *Set the output voltage or current to a desired value*
- *Regulate the output voltage or current to the desired value in the presence of line, load and temperature changes*
- *Monitor load and power supply actual versus desired performance*



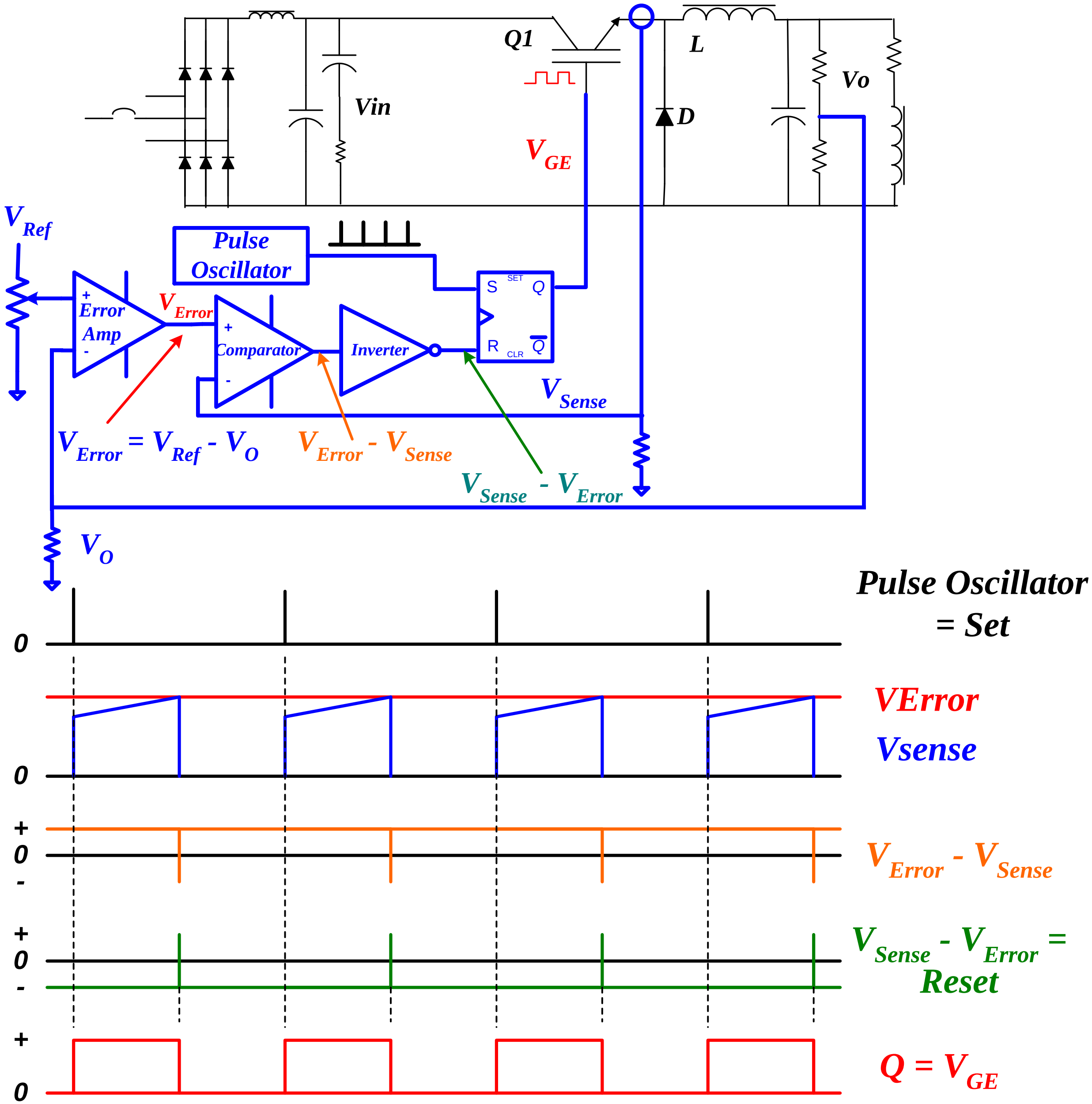


For a fixed V_{Ref} if V_O increases, $V_{Error} = V_{Ref} - V_O$ decreases accordingly. The pulse width will decrease to make $V_O = V_{Ref}$.

If V_O decreases, V_{Error} increases accordingly. The pulse width will increase to keep $V_O = V_{Ref}$.



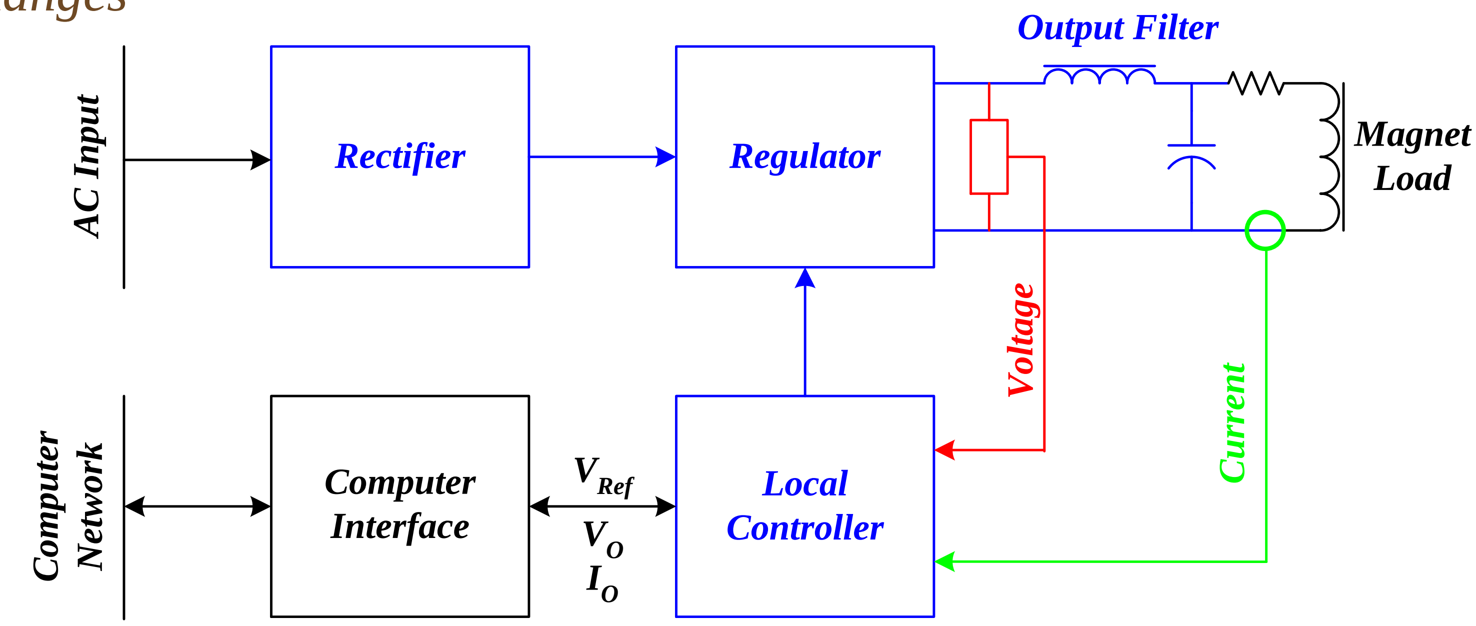
$V_{Error} = V_{Ref} – V_O$. A Pulse Oscillator switches Q1 on with every pulse. L current is converted to a voltage by a sense resistor. The L current builds up to the threshold set by the error voltage which then turns off Q1 in order to keep the output voltage or current constant.

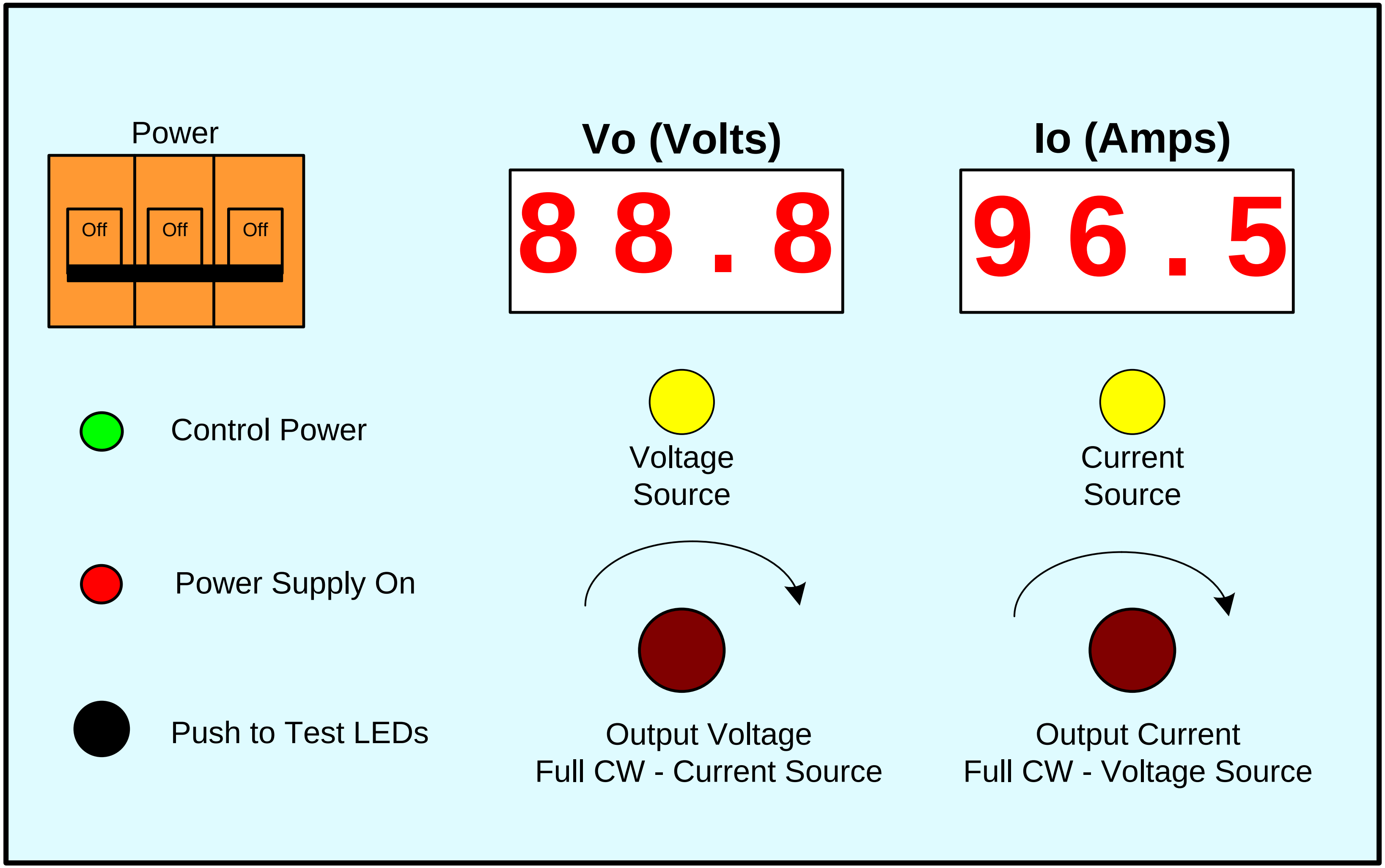


Q1
L
Vin
Vo
D
V_{GE}
V_{Ref}
Pulse Oscillator
Error Amp
V_{Error}
Comparator
Inverter
S SET Q
R CLR $\bar{Q}$
V_{Sense}
$V_{Error} = V_{Ref} - V_O$
$V_{Error} - V_{Sense}$
$V_{Sense} - V_{Error}$
V_O
0
Pulse Oscillator = Set
VError
Vsense
+
0
-
$V_{Error} - V_{Sense}$
$V_{Sense} - V_{Error}$ = Reset
$Q = V_{GE}$

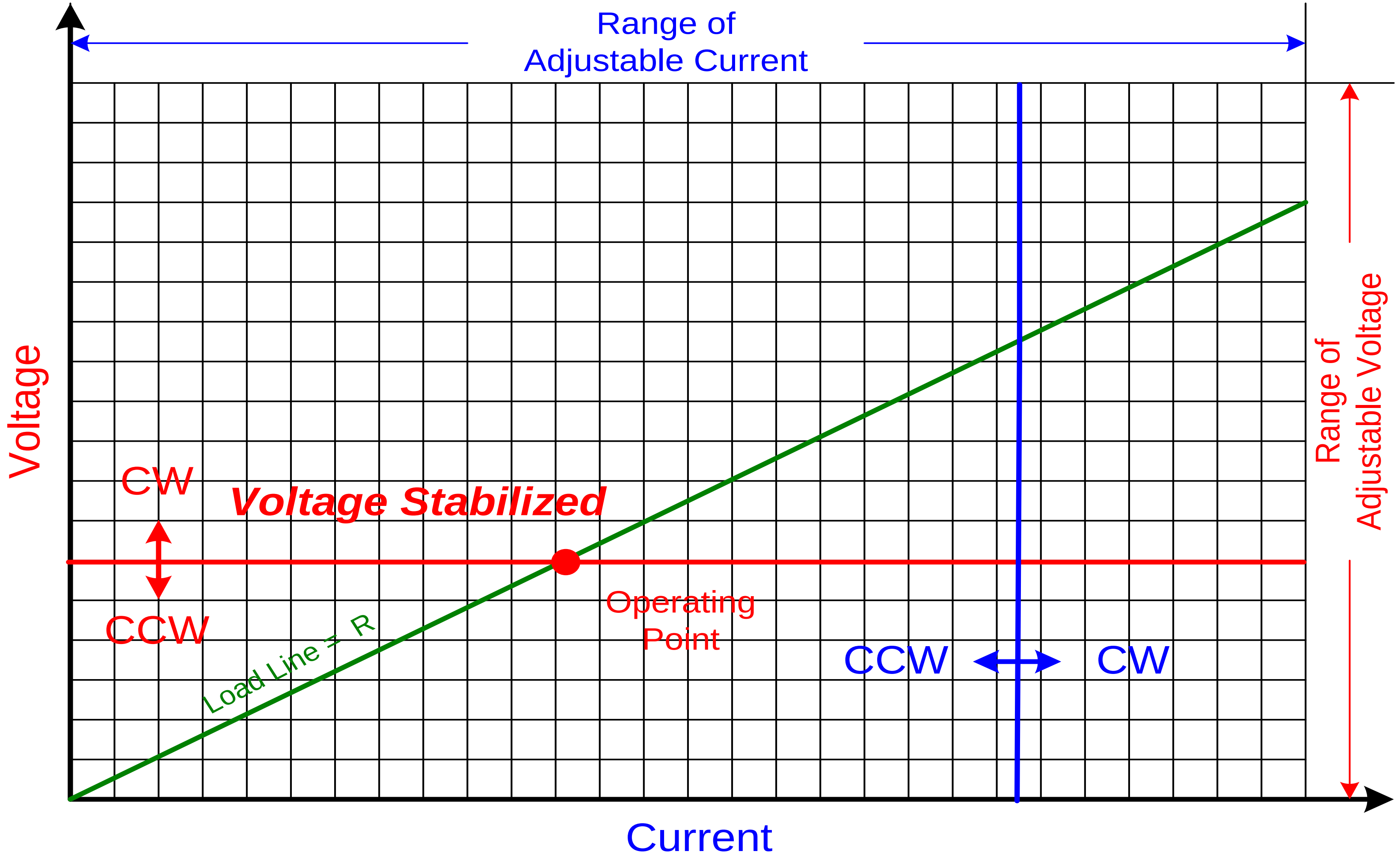
Summary

- 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



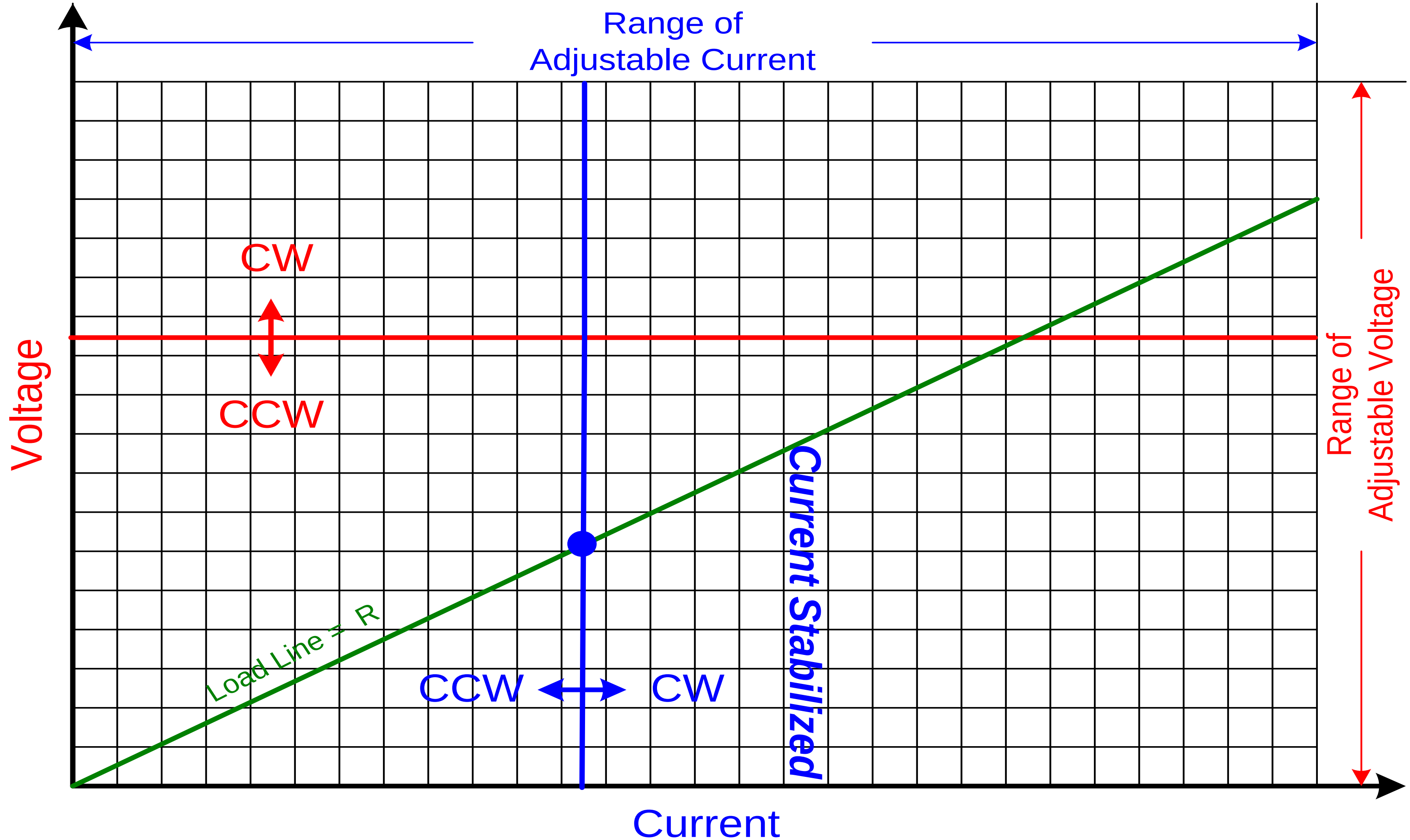


Power Supply Front Panel



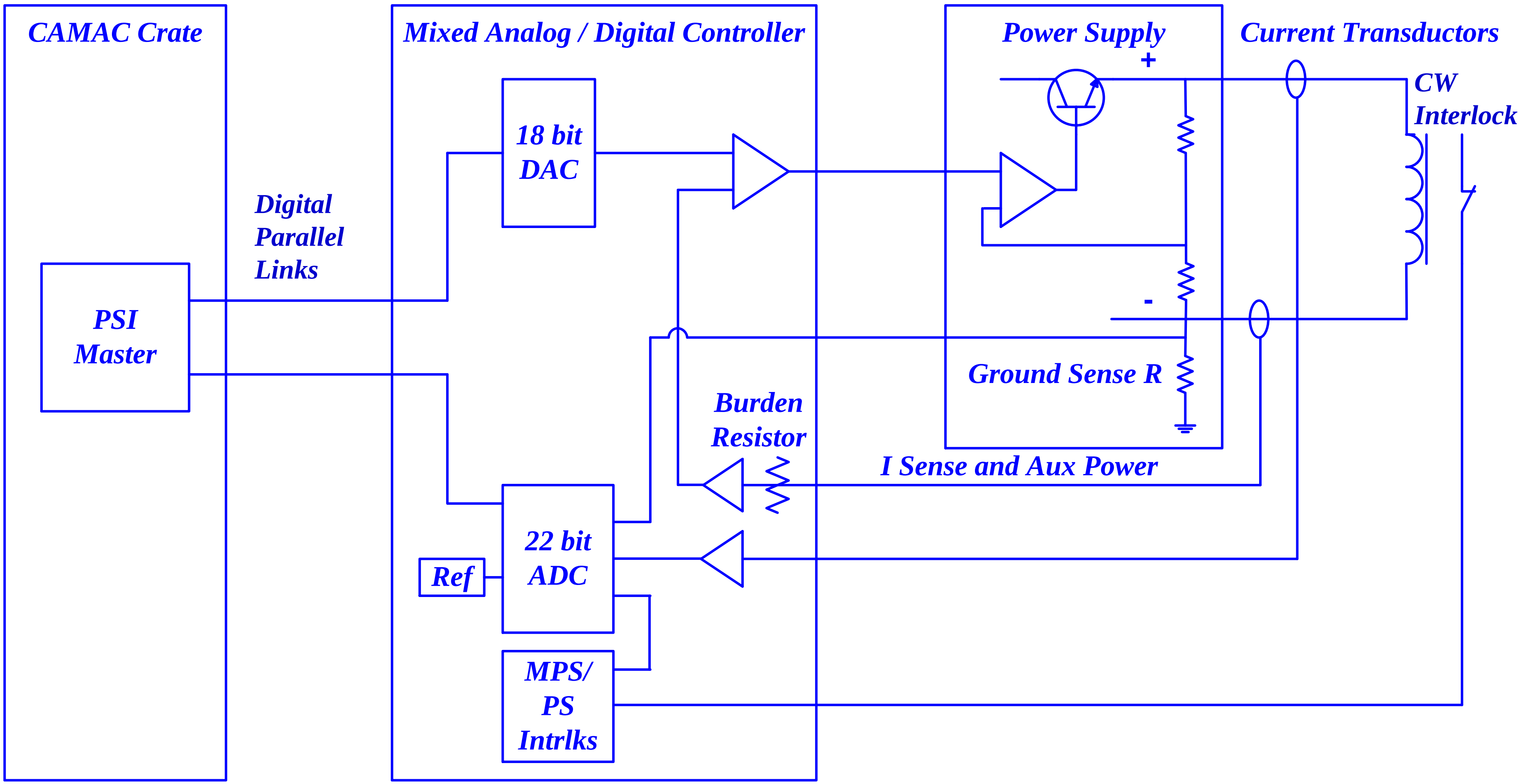
Constant Voltage Mode. *The power supply will operate in this mode whenever the current demanded by the load is less than that defined by the front panel current control. The output voltage is set by the front panel voltage control. The output current is set by the load resistance and the Vset.*

Power Supply Controllers - Automatic Voltage/Current Crossover – Example 2

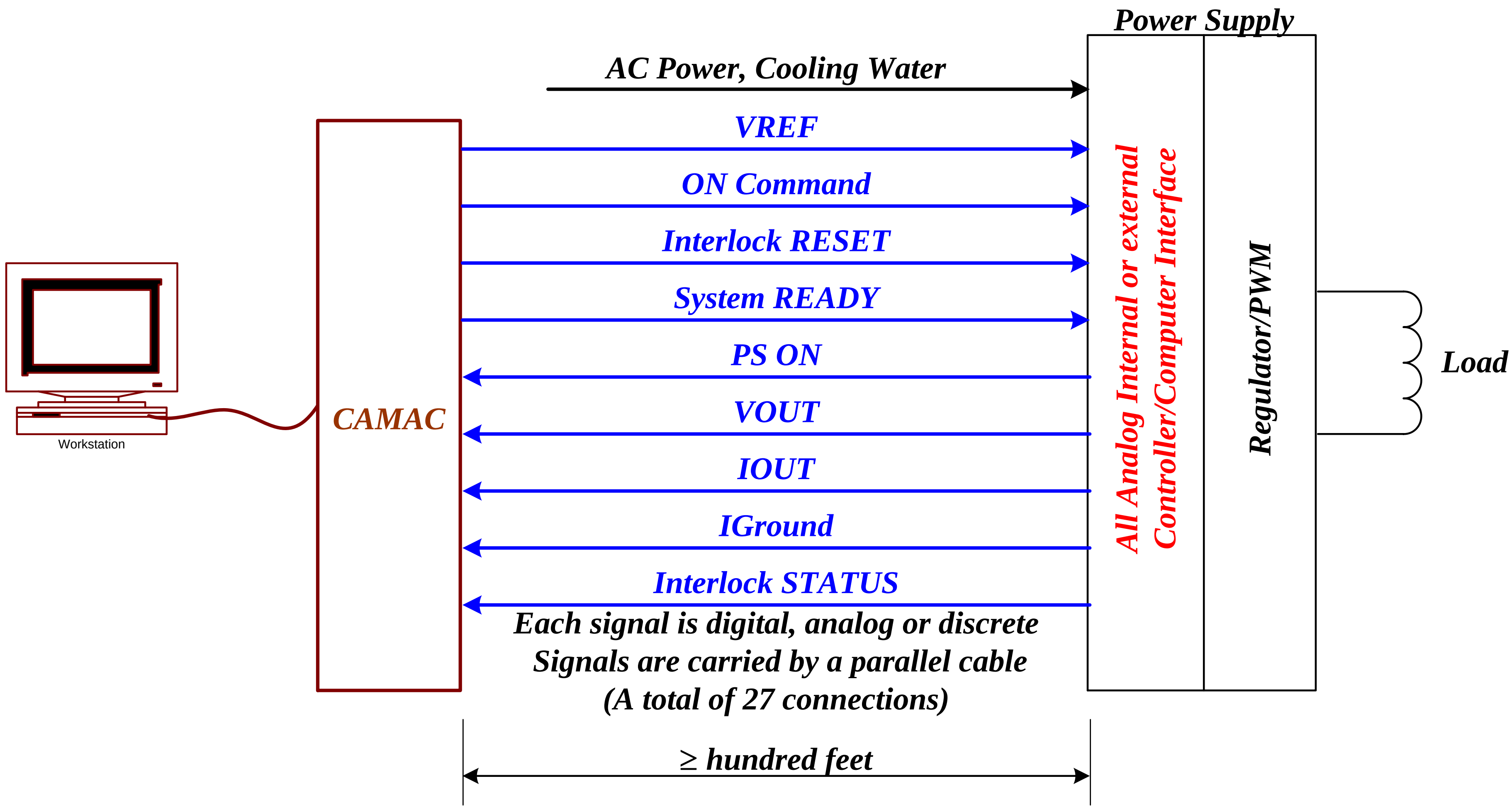


Constant Current Mode. *The power supply will operate in this mode whenever the voltage demanded by the load is less than that defined by the front panel voltage control. The output current is set by the front panel current control. The output voltage is set by the load resistance and the I set.*

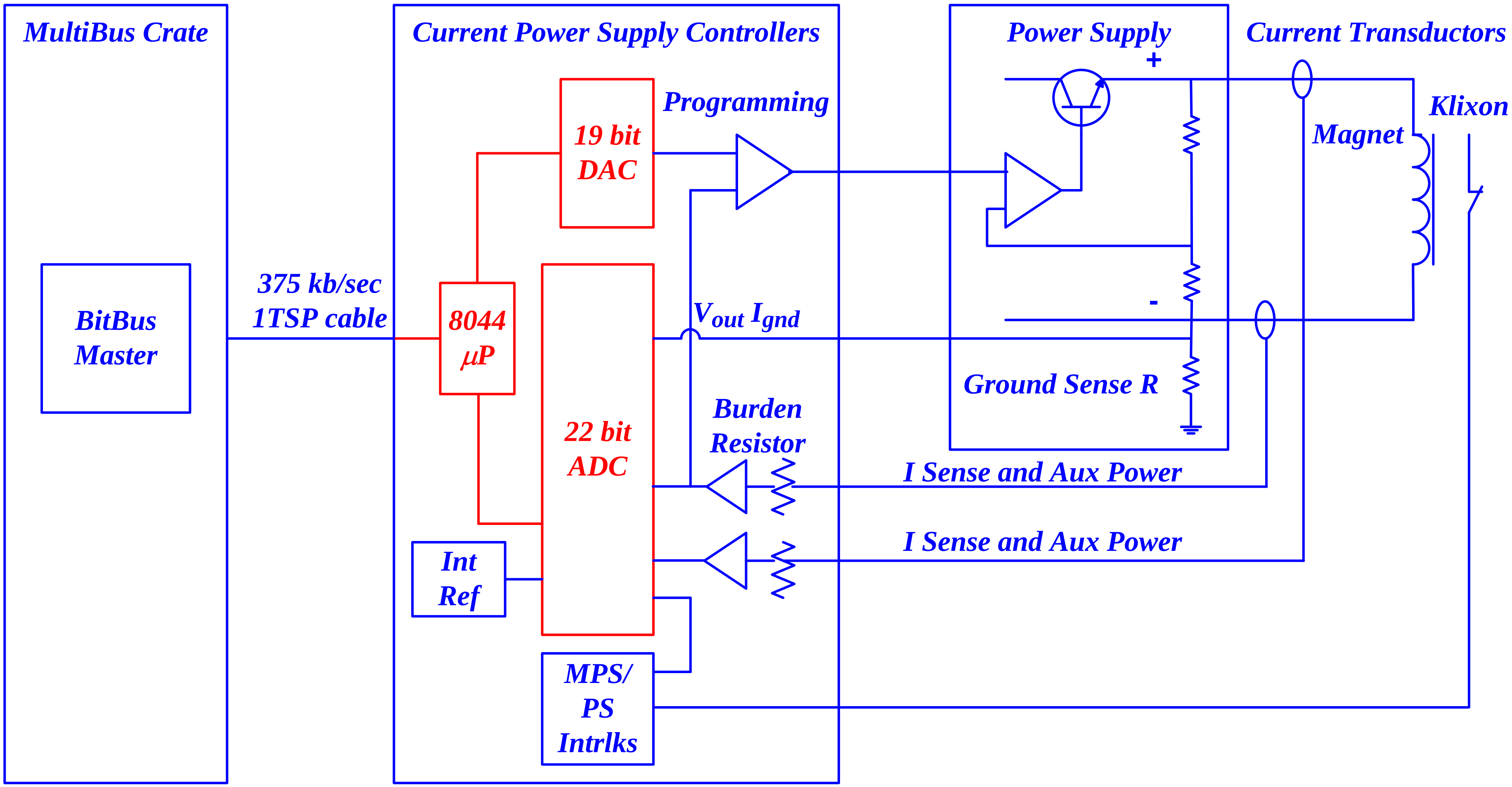
All-Analog Power Supply Controllers – Circa 1970s to 1980s



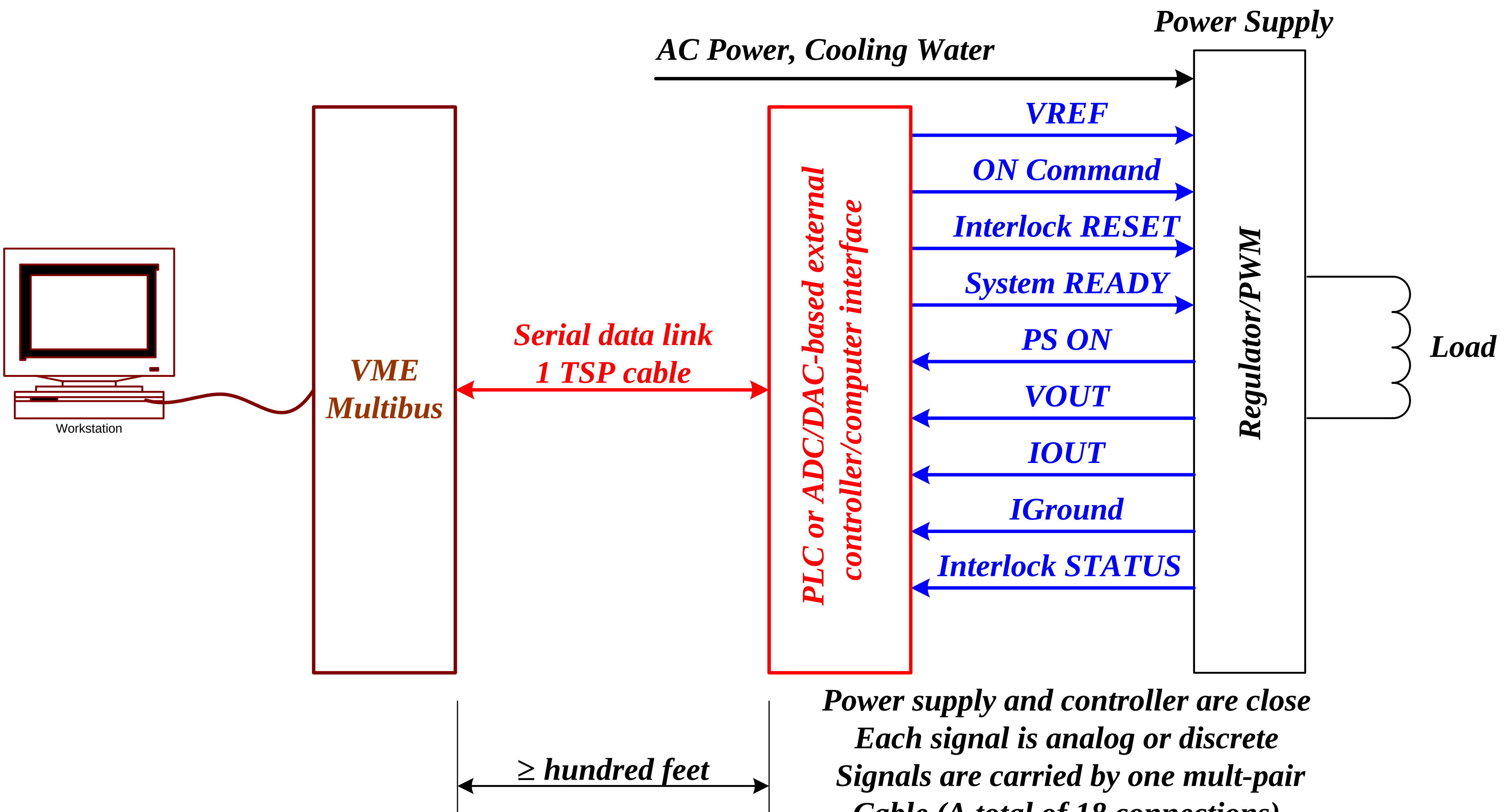
All-Analog Power Supply Controllers – Circa 1970s to 1980s



Hybrid Analog/Digital Power Supply Controllers – Circa 1980s to Present

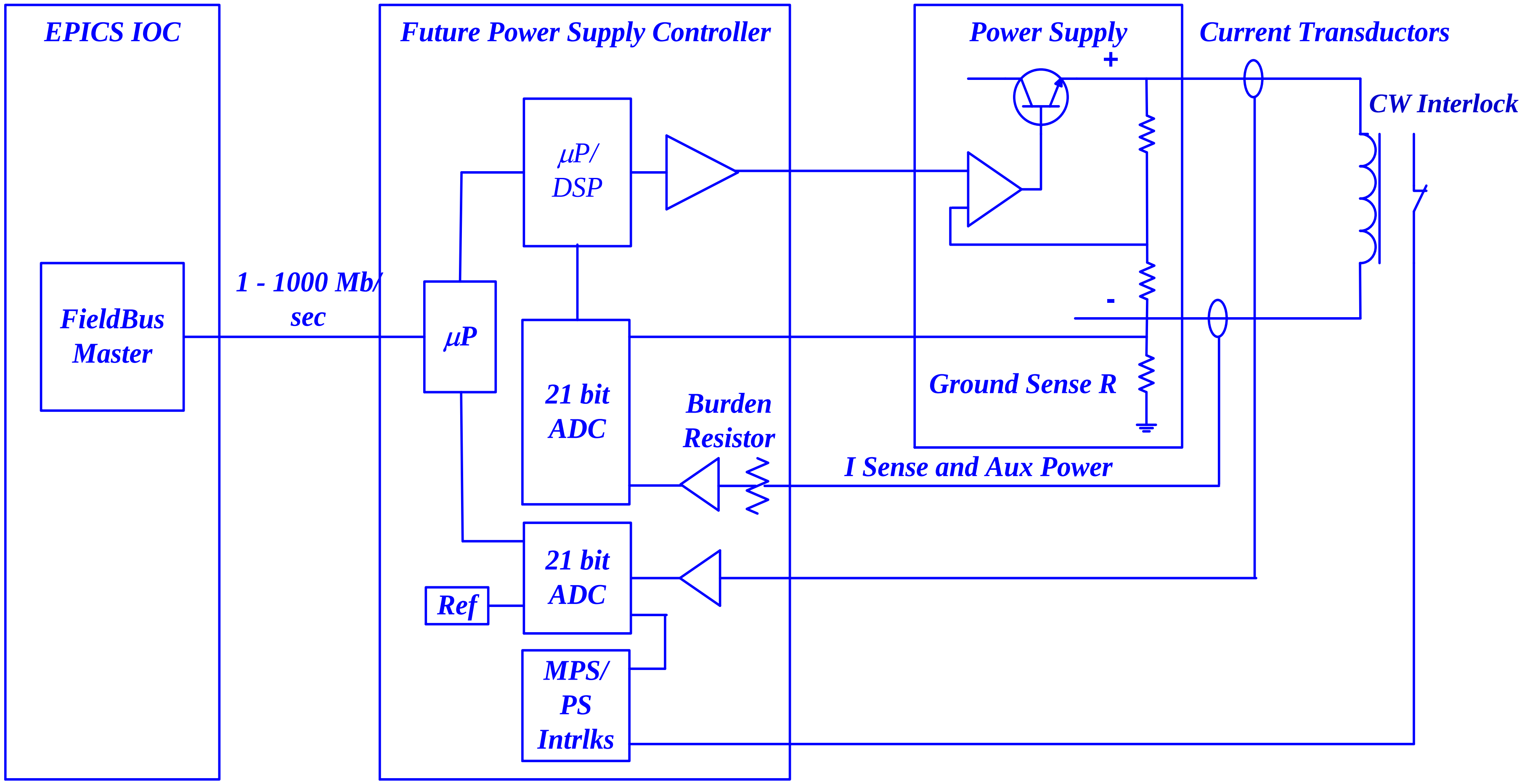


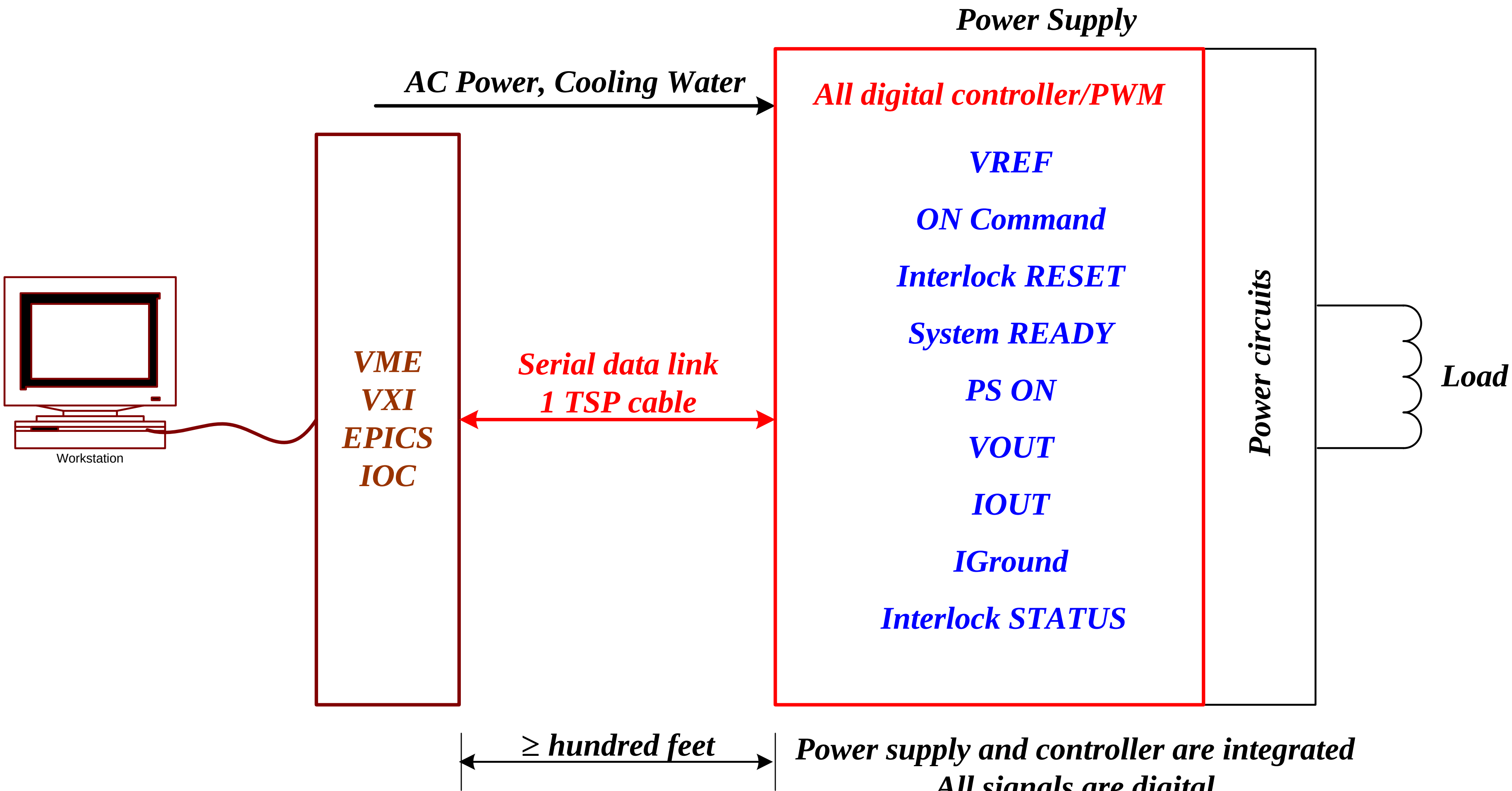
Hybrid Analog/Digital Power Supply Controllers – Circa 1980s to Present



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)

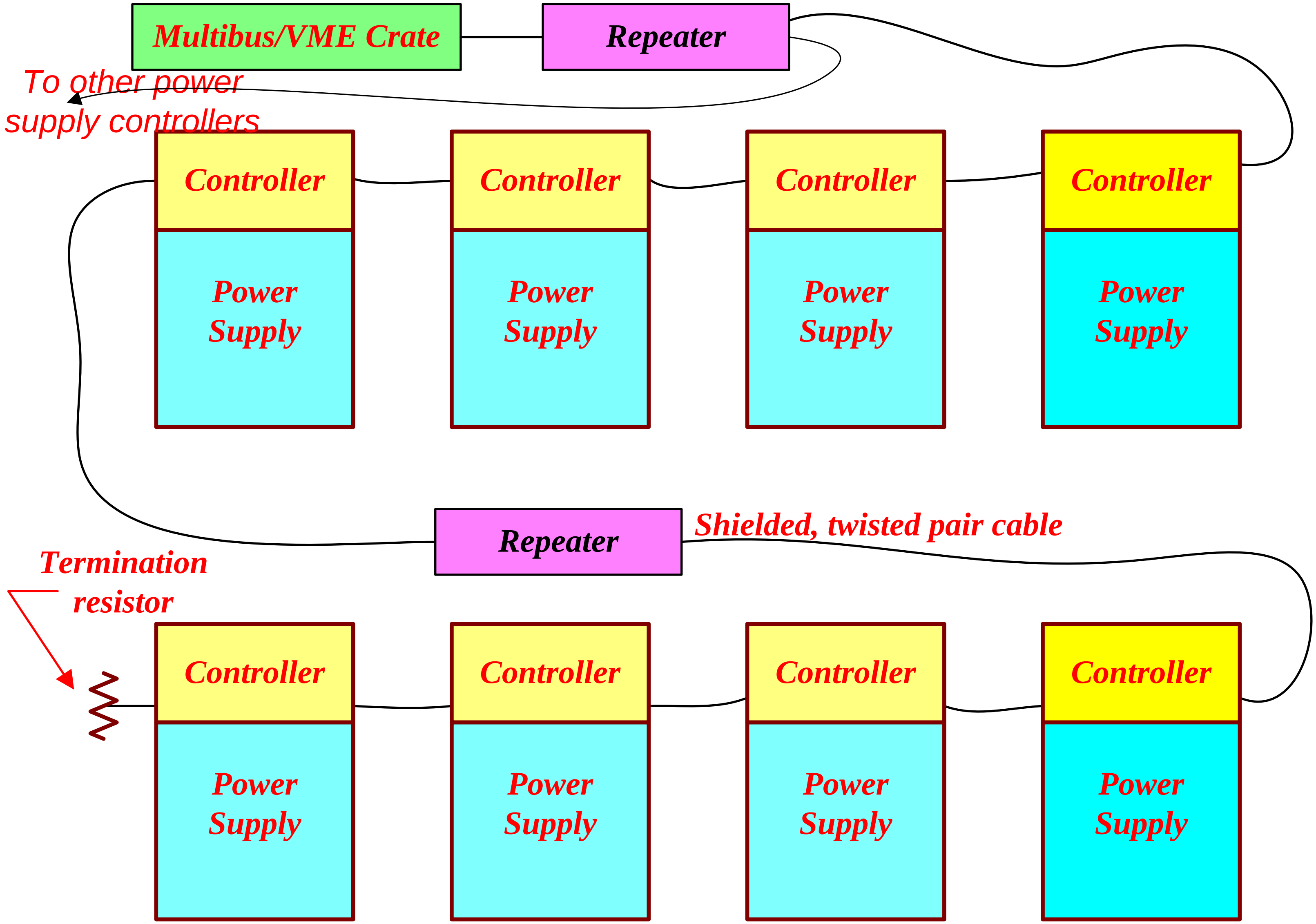
All Digital Power Supply Controllers – Circa the Future





Power supply and controller are integrated
All signals are digital

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 →+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 9 – Personnel and Equipment Safety

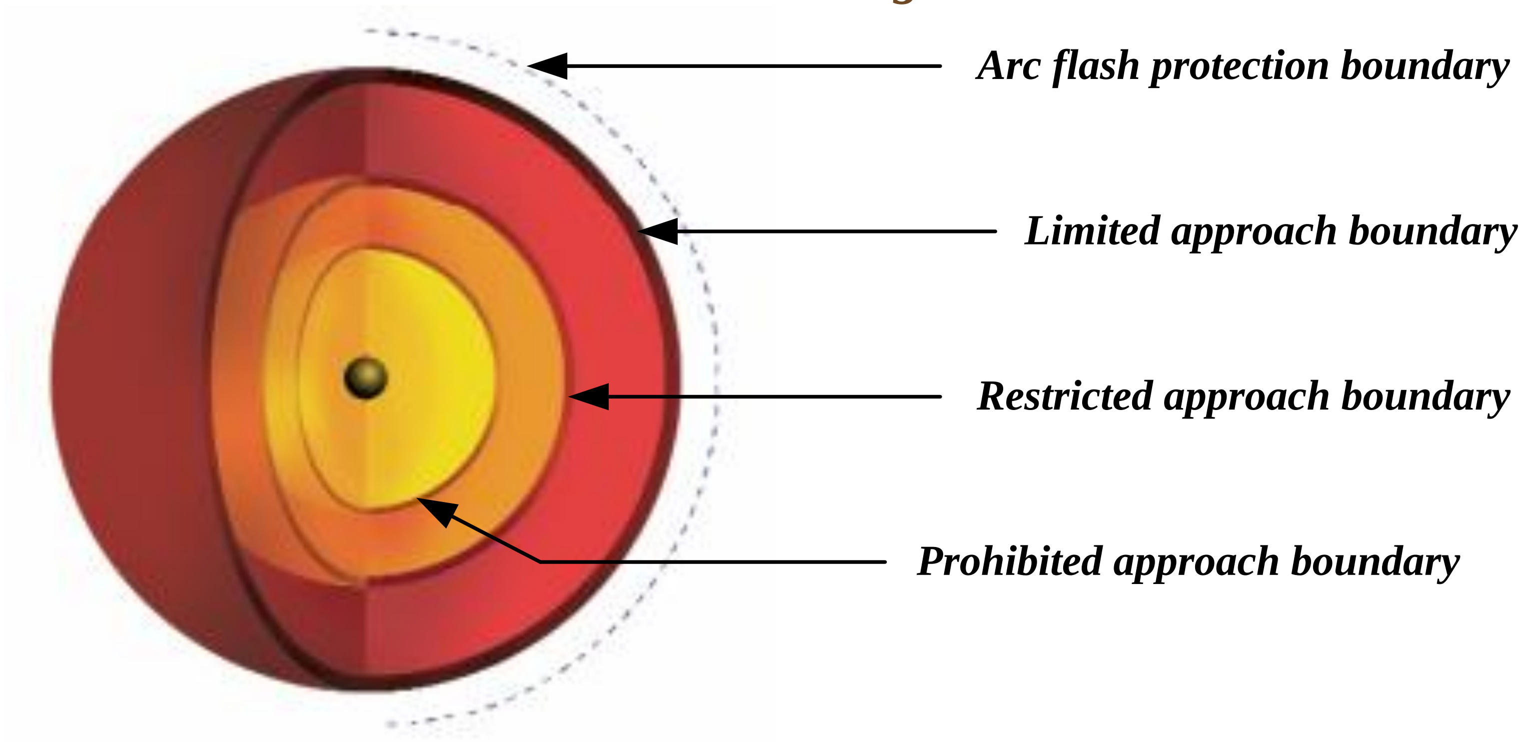
- *NFPA 70E - Safety in the Workplace*
  - *The Voltage Hazard*
  - *Arc Flash*
- *NFPA 70 – National Electrical Code*
- *Interlocks*
  - *Personnel Protection Systems (PPS)*
  - *Load Protection Systems-Machine Protection Systems (MPS)*
  - *Power Supply Protection*
  - *Programmable Logic Controllers (PLCs)*
- *Lockout/Tagout (LOTO)*

NFPA 70E

NFPA 70E - 2004 - Standard for Electrical Safety in the Workplace

- *Addresses employer and employee 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*

NFPA 70E - The Voltage Hazard



- 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

- Prohibited approach boundary is the distance from an exposed live part within which work is considered the same as making contact with the live part

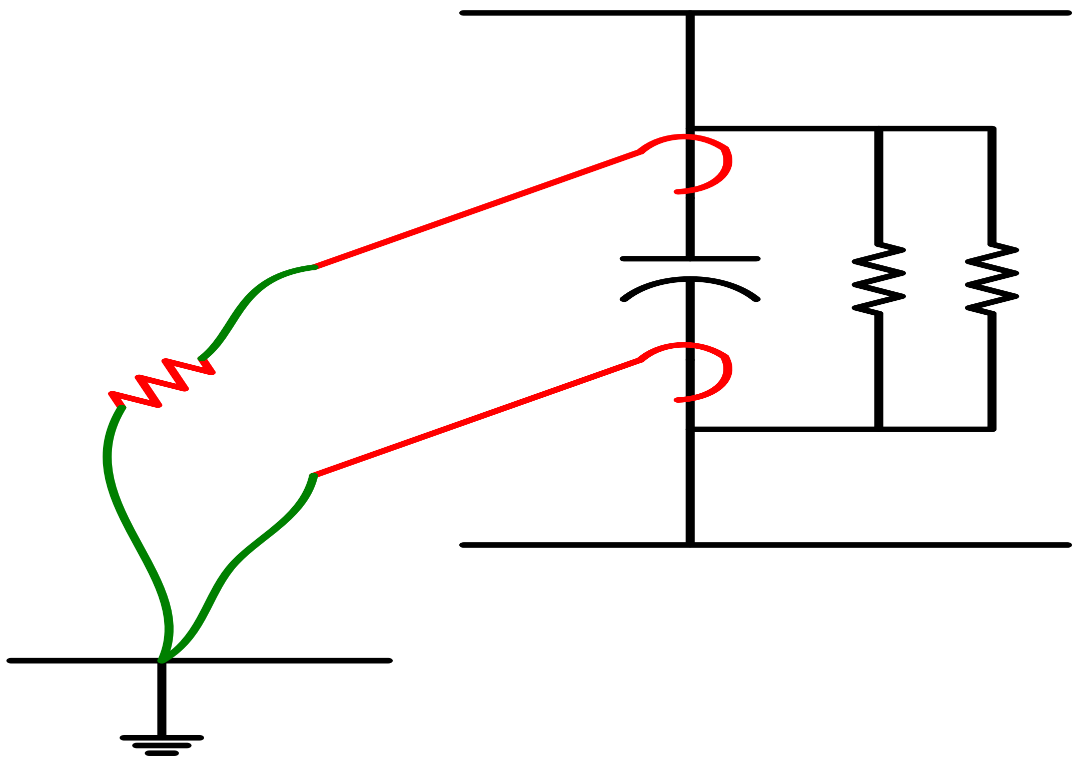
NFPA 70E - 2009 - Approach boundaries - deal with the voltage hazard

NFPA 70E, Table 130.2(C)			
AC and DC Voltage Range Line - Line	**Limited Approach Boundary Distance - No PPE**	**Restricted Approach Boundary Distance No PPE**	**Prohibited Approach Boundary Distance PPE Needed**
< 50V	None, if conditions permit	None, if conditions permit	None, if conditions permit
50 - 300V	3.5 ft	Avoid contact	Avoid contact
> 300 - 750V	3.5 ft	1 ft	1 inch
> 750 - 15kV	5.0 ft	2 ft 2 inches	7 inches
> 15kV - 36kV	6.0 ft	2 ft 7 inches	10 inches
> 36kV	See NFPA 70E	See NFPA 70E	See NFPA 70E

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 sustain 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)



NFPA 70E - What is Arc Flash?

- *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.*

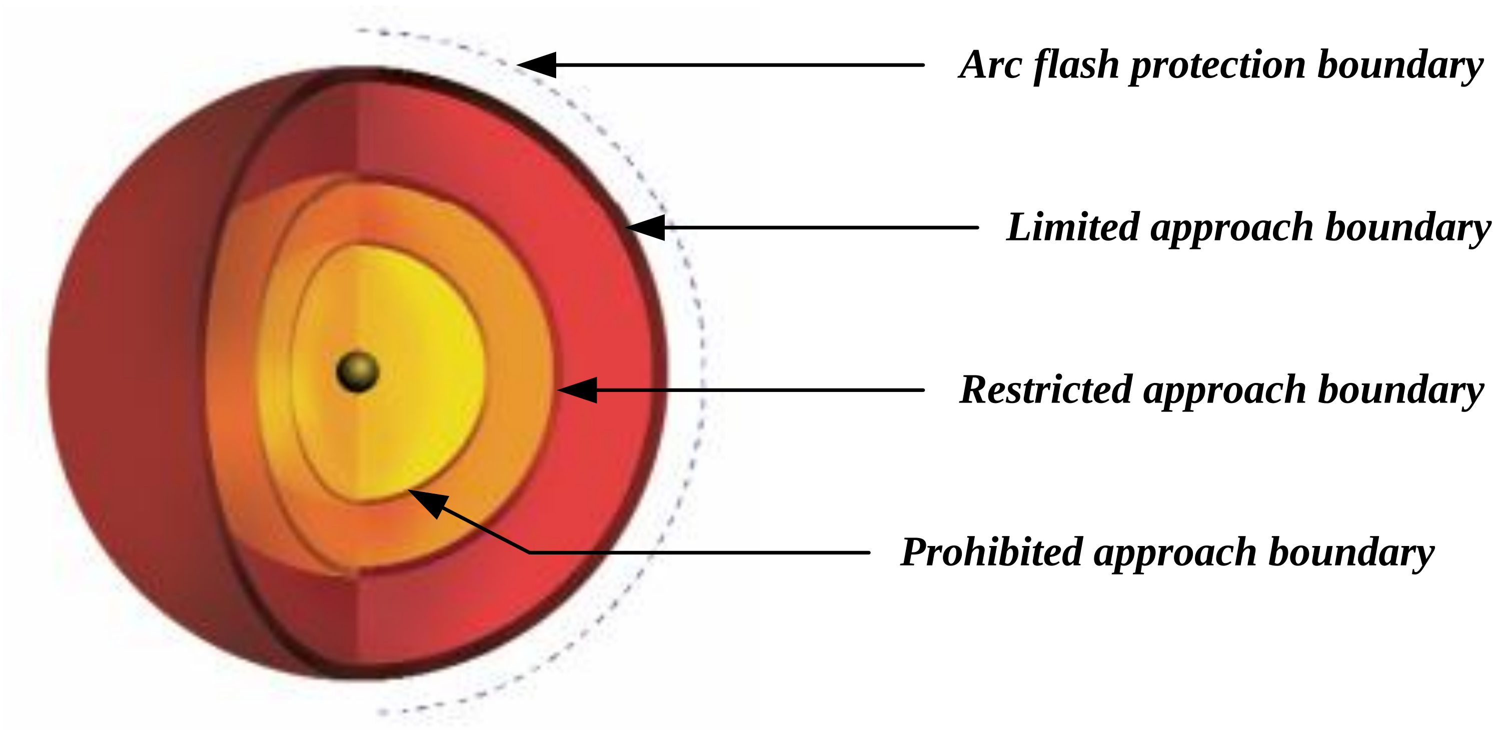
NFPA 70E - Possible Causes of Arc Flash

- *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*

NFPA 70E - The Arc Flash Hazard



- *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
0	1.2	0
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 2009 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. Some relevant Articles are*
2. *Sizing of power cables for ampacity. Some relevant Articles are*
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.

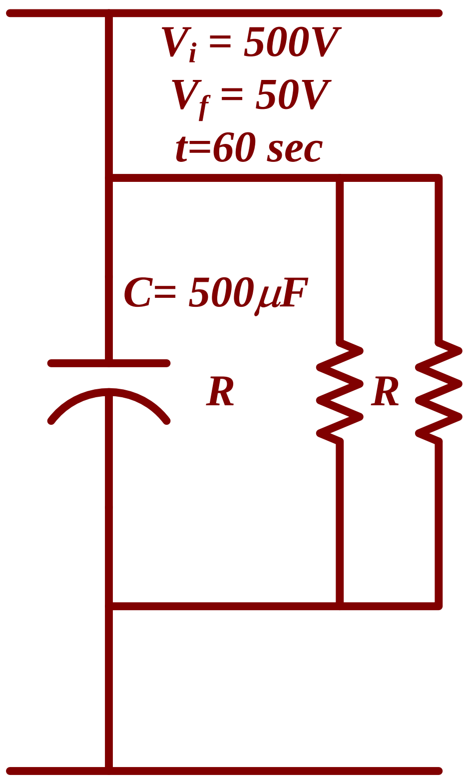
Use NEC Table 310-17 for single conductor cables in free air at 30C. The derating for the 45C ambient is 0.87. The derating for the single conductor in a cable tray is 0.65 if placed touching other cables in the cable tray. The required amapcity is

$$\text{Ampacity} = \frac{I_{PS}}{\text{deratings}} = \frac{375\,A}{0.87 * 0.65} = 663\,A$$

From Table 310-17 the basic amapcity of 500kcmil cable is 700A > 663A.

Use 2-1/C500kcmil cables

- *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*



$$V_f = V_i \, e^{\frac{-t}{RC}}$$

$$R = \frac{-t}{C \ln(V_f / V_i)} = \frac{-60 * sec}{500\,\mu F \ln(50V \,/\, 500V)}$$

$$R = 50\,kohm$$

$$P_R = \frac{V_i^2}{R} = \frac{(500V)^2}{50k\Omega} = 5W$$

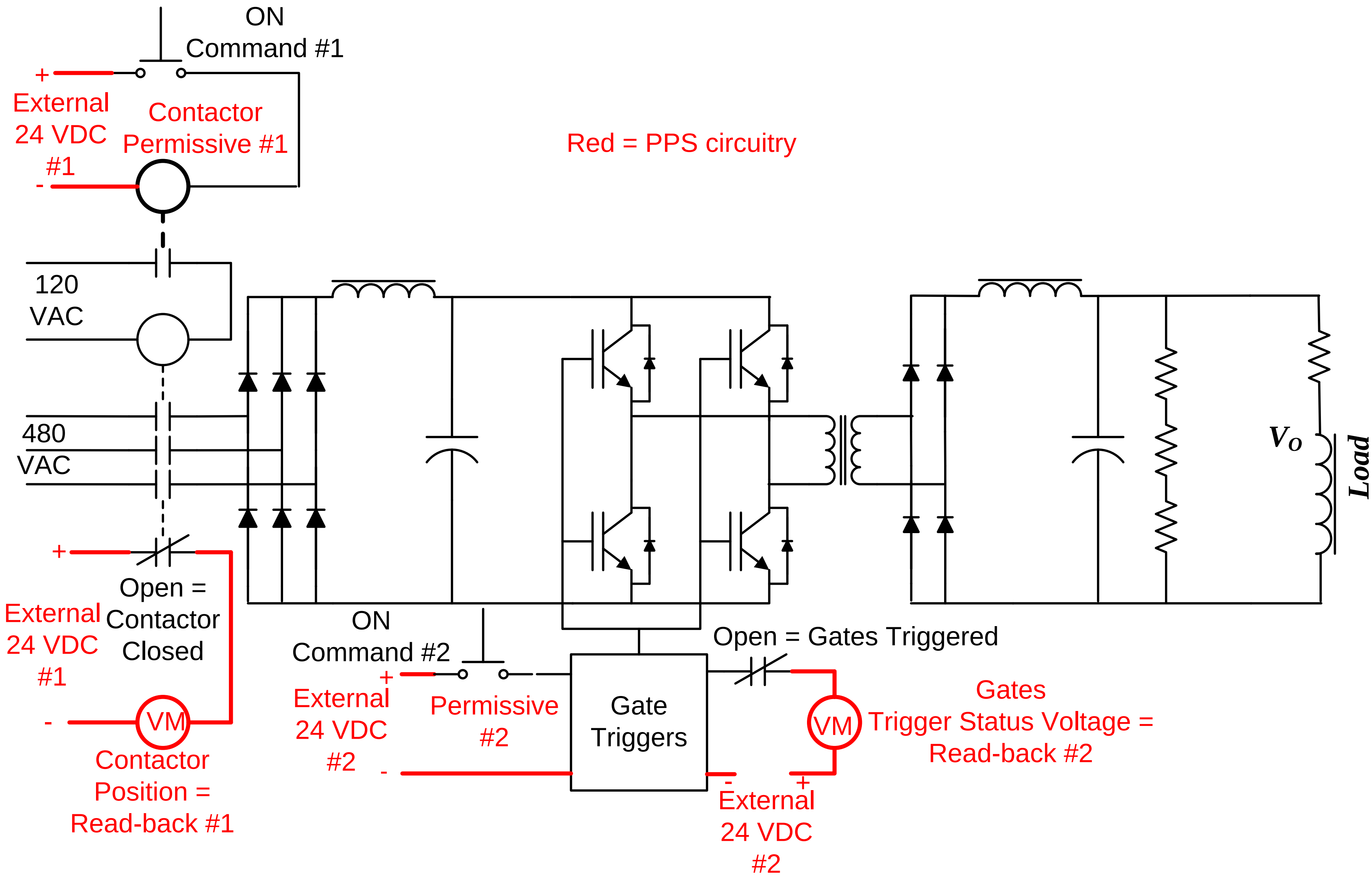
Use two 5W, 100kΩ resistors in parallel

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*

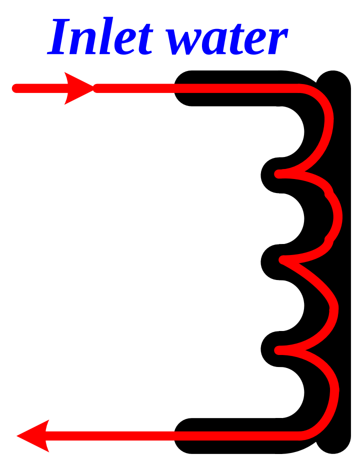
Orbit Interlock System

- *Sensors consist of Beam Position Monitors and switches. Function is essentially the same in the magnet cooling water system*

- *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*

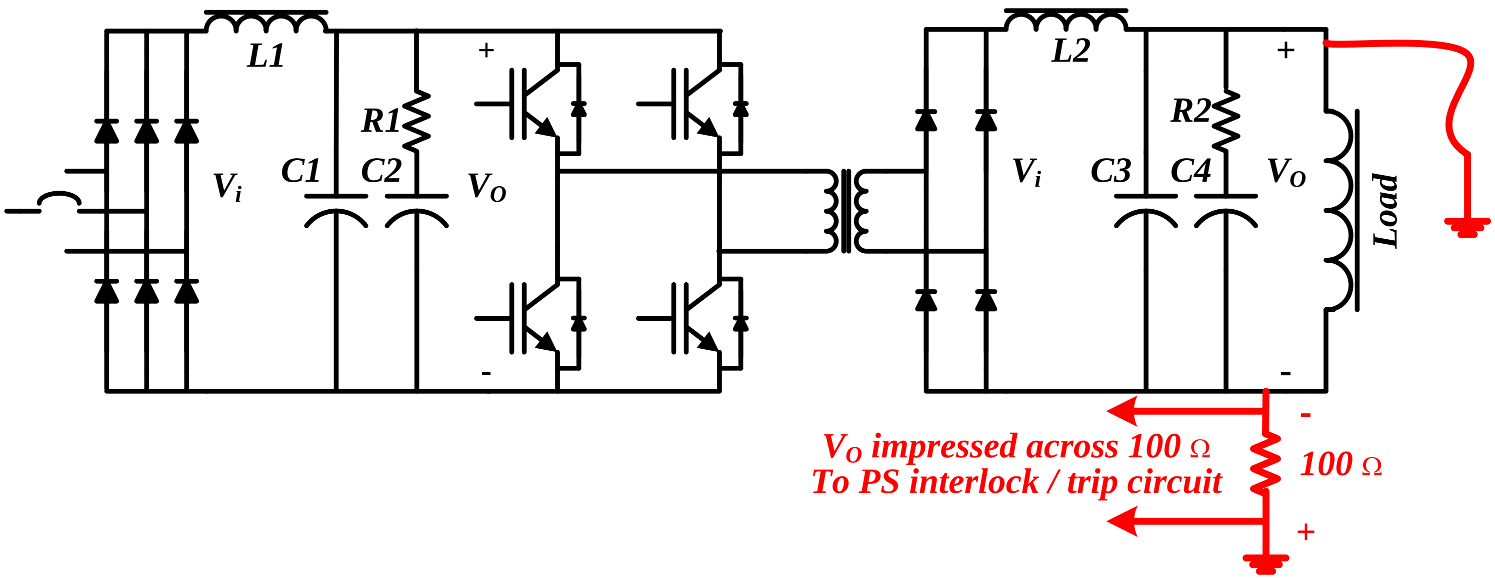


Outlet water temperature monitored via Klixon switch

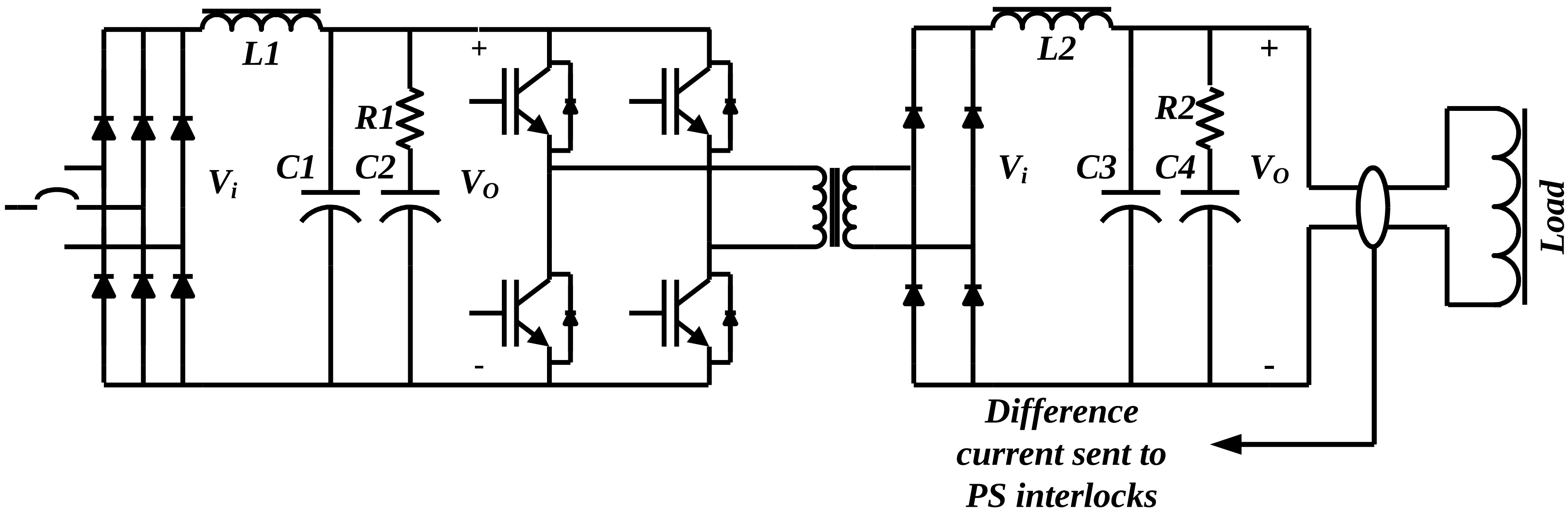
Klixon switches

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

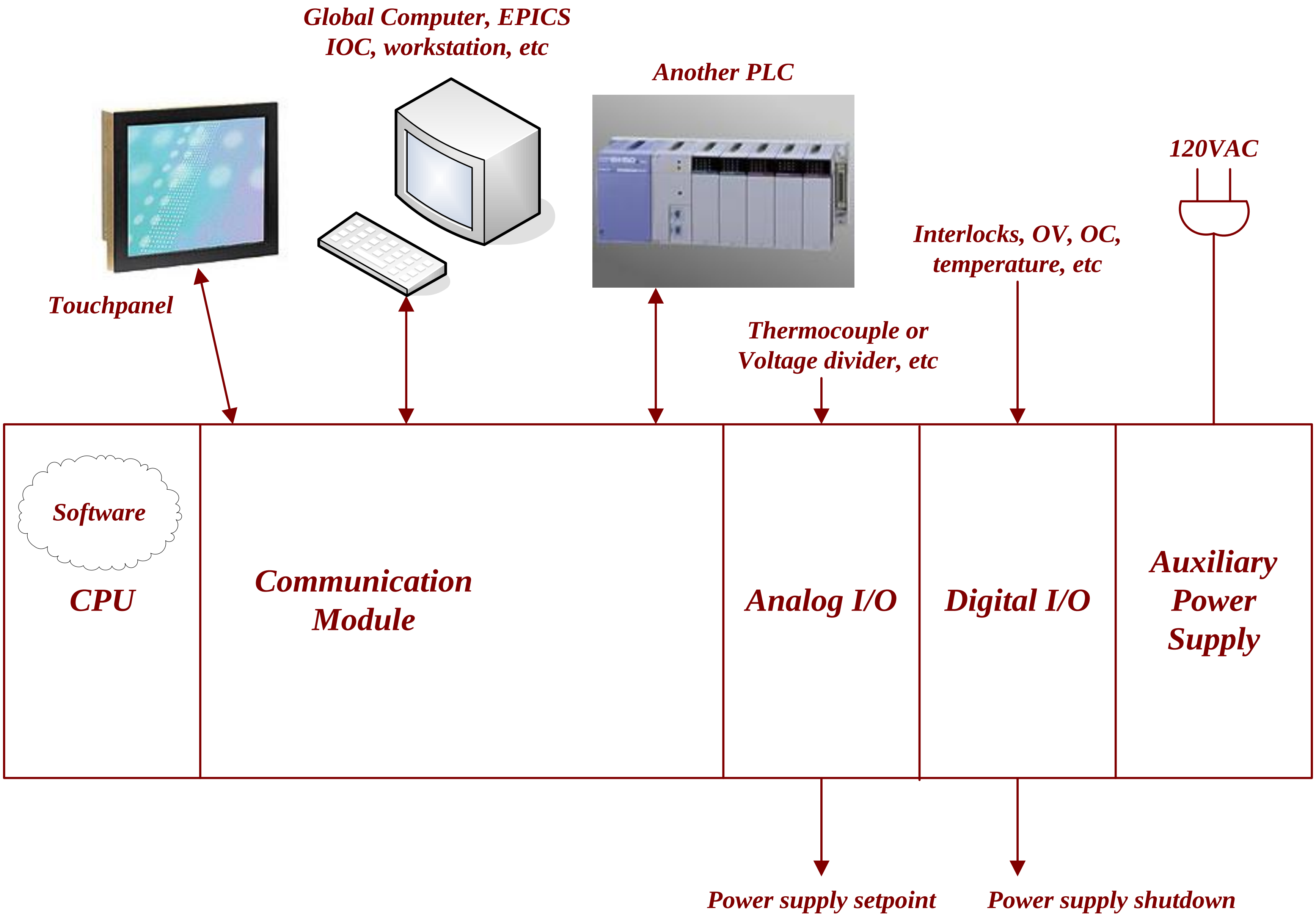
Manufacturers are many

- *Allen-Bradley*
- *Rockwell International (AB)*
- *Siemens*
- *General Electric*
- *IDEC*

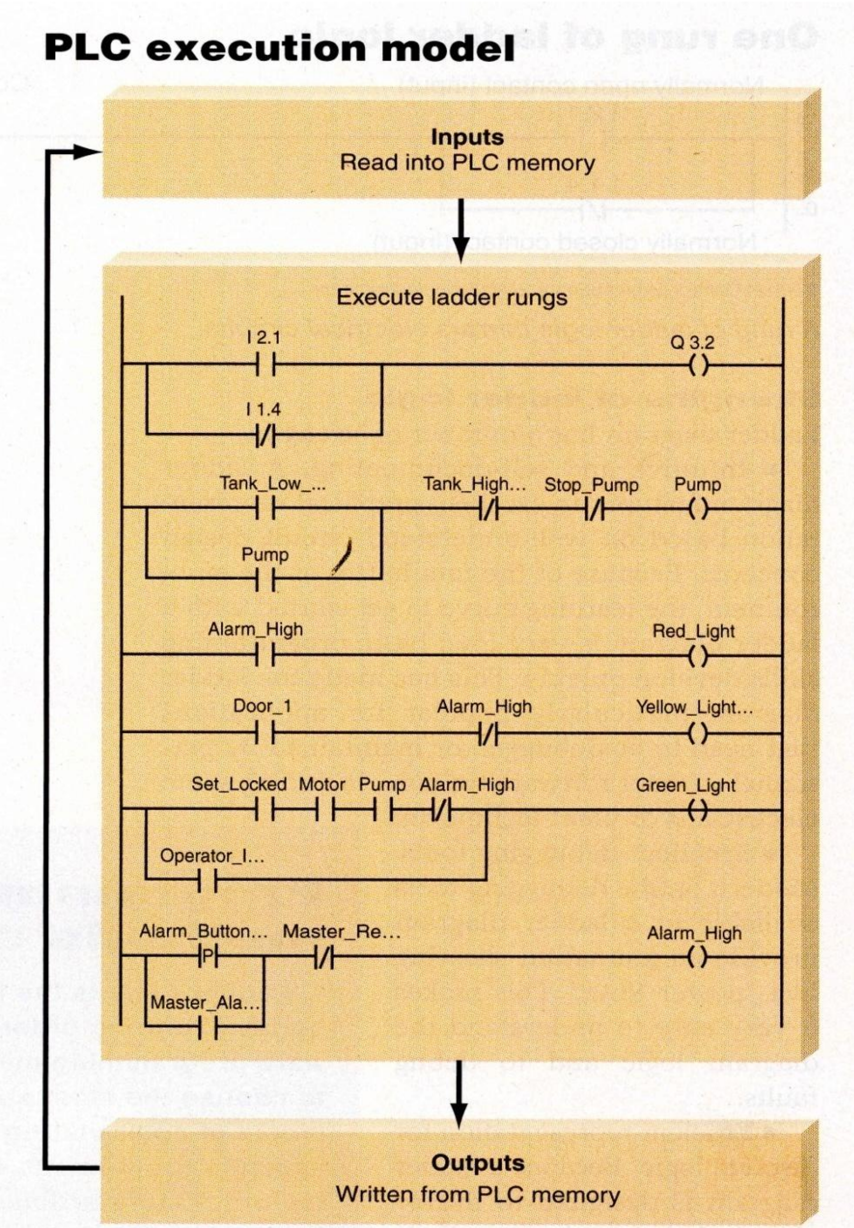
Programming logic

- *Ladder logic*
- *C language*
- *LabView*
- *Functional block diagrams*
- *Structured text*

PLC Uses and Networks



Ladder Logic



Source: Control Engineering *and* National Instruments

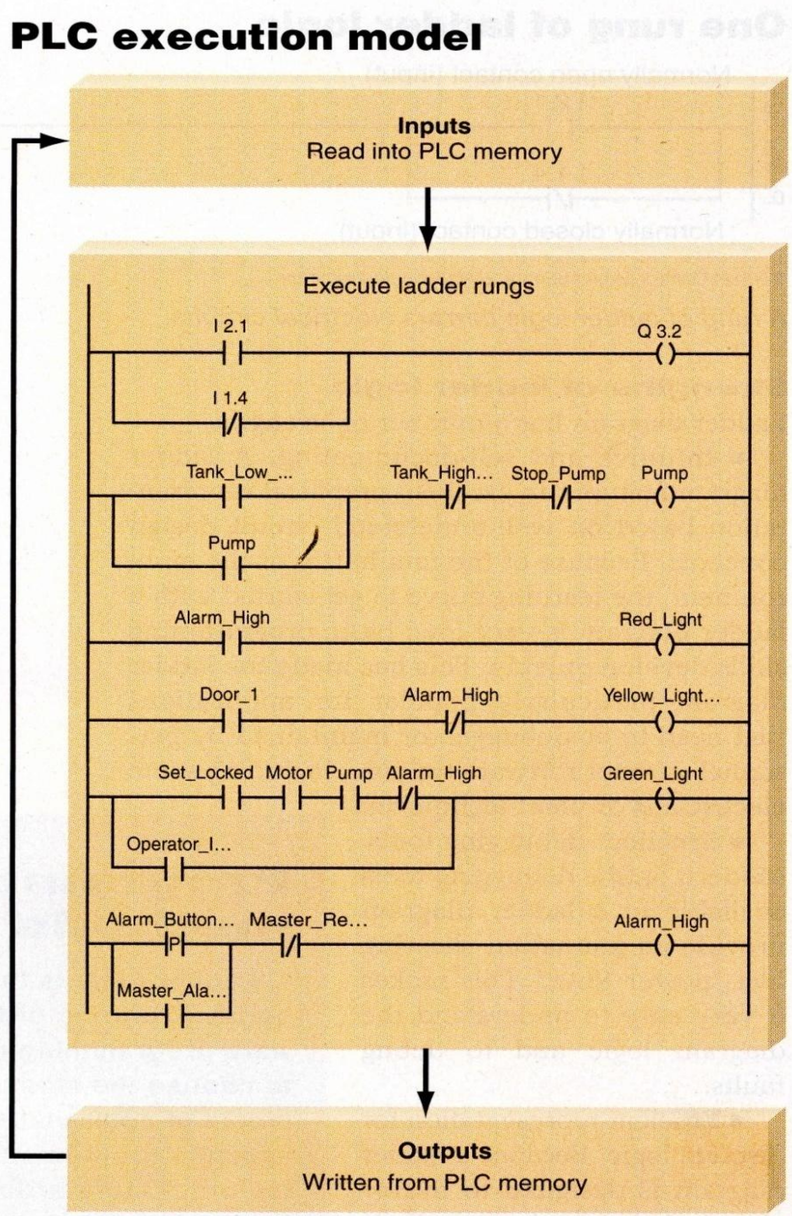
Ladder diagrams evolved in the 1960s when the automobile industry needed a more flexible and self-documenting alternative to relay and timing cabinets. A microprocessor was added and software designed to mimic the relay panels.

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



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*

Lockout – Tagout (LOTO)

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 10 - 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.

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
$MTBF_R$	The rated MTBF 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)
$\lambda, \lambda_O, \lambda_R$	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

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	$R_S(t)$	$= \prod_{i=1}^{N} e^{-\lambda_i t} = \prod_{i=1}^{N} R_i(t)$	$(dimensionless)$
Failure N series components	$Q_S(t)$	$= \prod_{i=1}^{N} Q_i(t) = 1 - \prod_{i=1}^{N} R_i(t)$	$(dimensionless)$
Reliability of N parallel components	$R_P(t)$	$= \prod_{i=1}^{N} e^{-\lambda_i t}$	$(dimensionless)$
Probability of failure of parallel	$Q_P(t)$	$= 1 - R_P(t) = 1 - \prod_{i=1}^{N} e^{-\lambda_i t}$	$(dimensionless)$

Homework Problem # 16

Homework Problem:

A. At least 2 of 4 parallel 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.

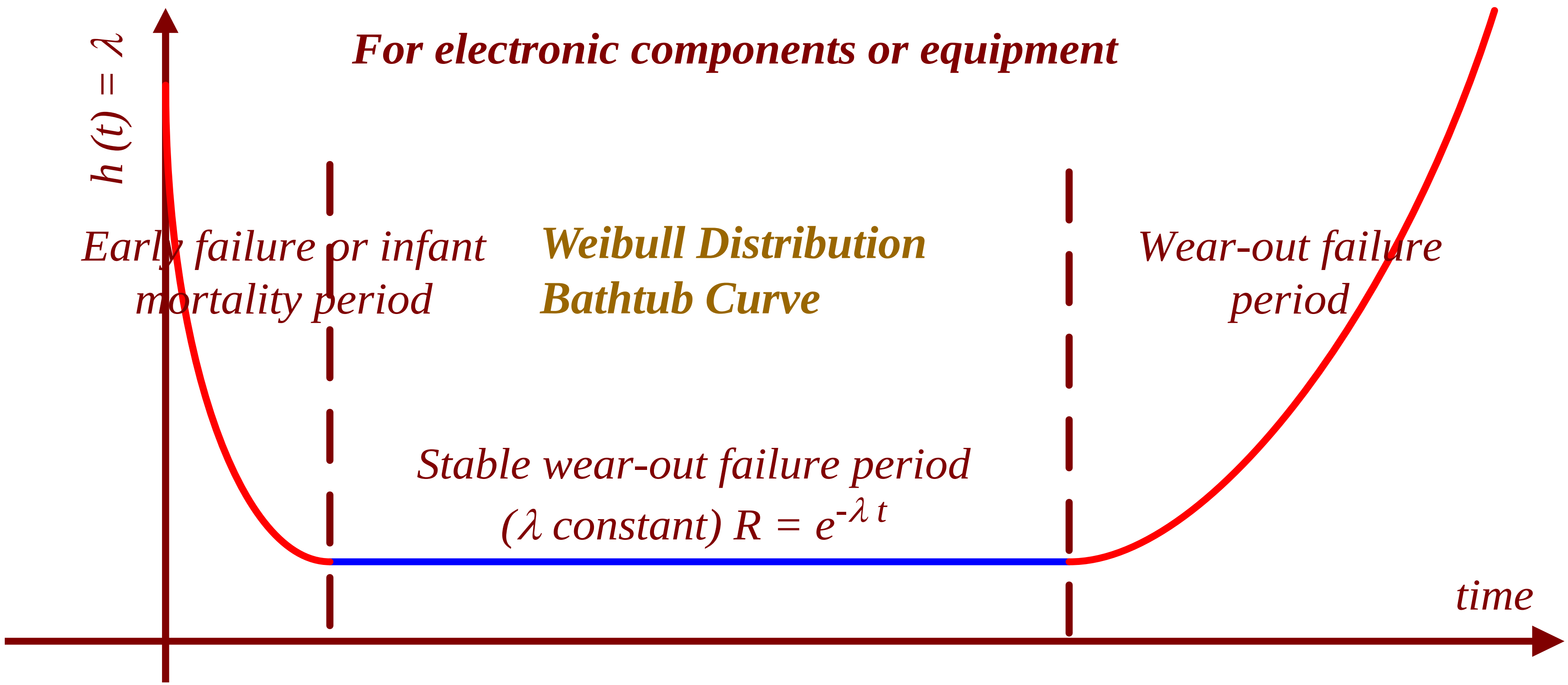
B. Solve for three out of four for success

C. Solve for four out of four for success

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 - 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_{GF}) 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* $\quad 0 < \Pi_{GB} < \infty$

Π_{T} = *ambient temperature* $\quad 0 < \Pi_{T} < \infty$

Π_{MQ} = *manufacturing quality* $\quad 0 < \Pi_{MQ} < \infty$

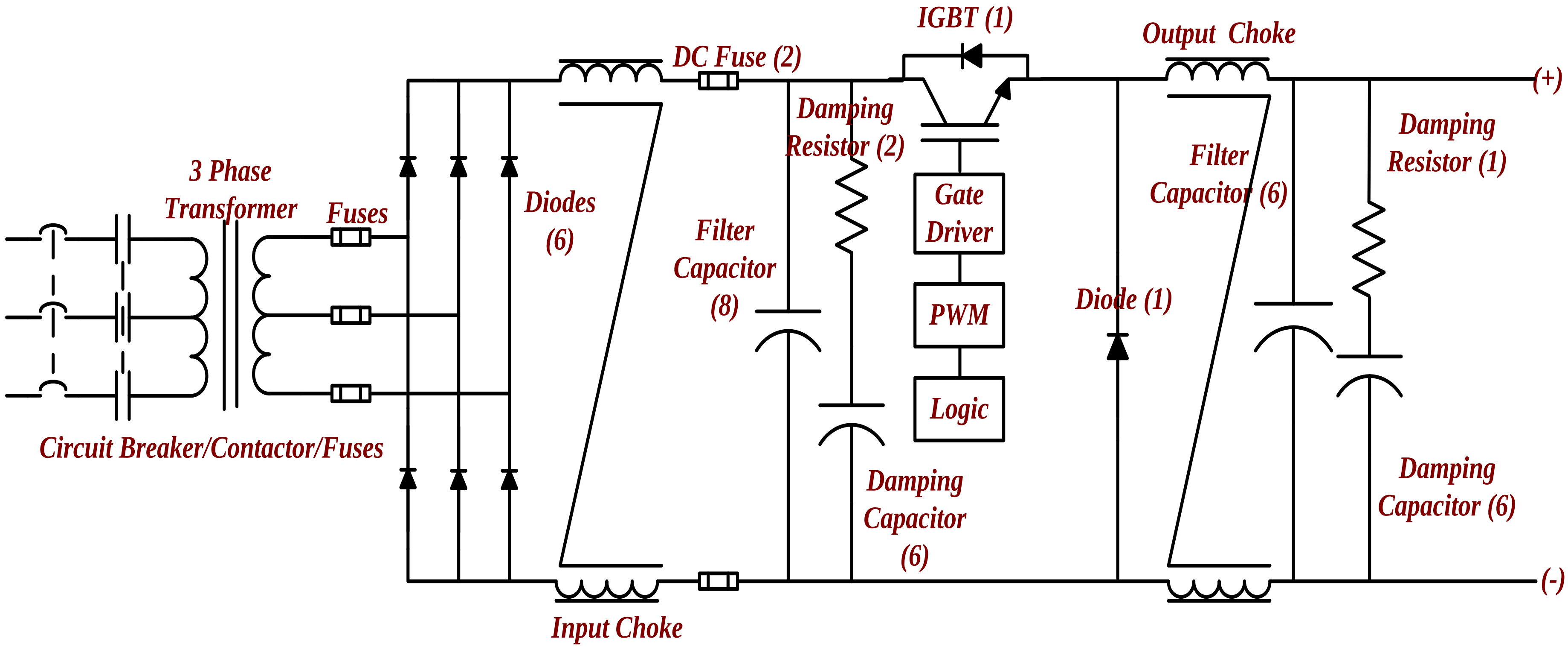
Π_{VS} = *voltage stress factor* $\quad 0 < \Pi_{VS} < \infty$

Π_{IS} = *current stress factor* $\quad 0 < \Pi_{IS} < \infty$

Π_{PS} = *power stress factor* $\quad 0 < \Pi_{PS} < \infty$

$$\lambda_{resultant} = \lambda_{initial} * \Pi_{GB} * \Pi_{T} * \Pi_{MQ} * \Pi_{VS} * \Pi_{IS} * \Pi_{PS}$$

Example of Reliability Calculation – Power Supply



Example of Reliability Calculation – Power Supply

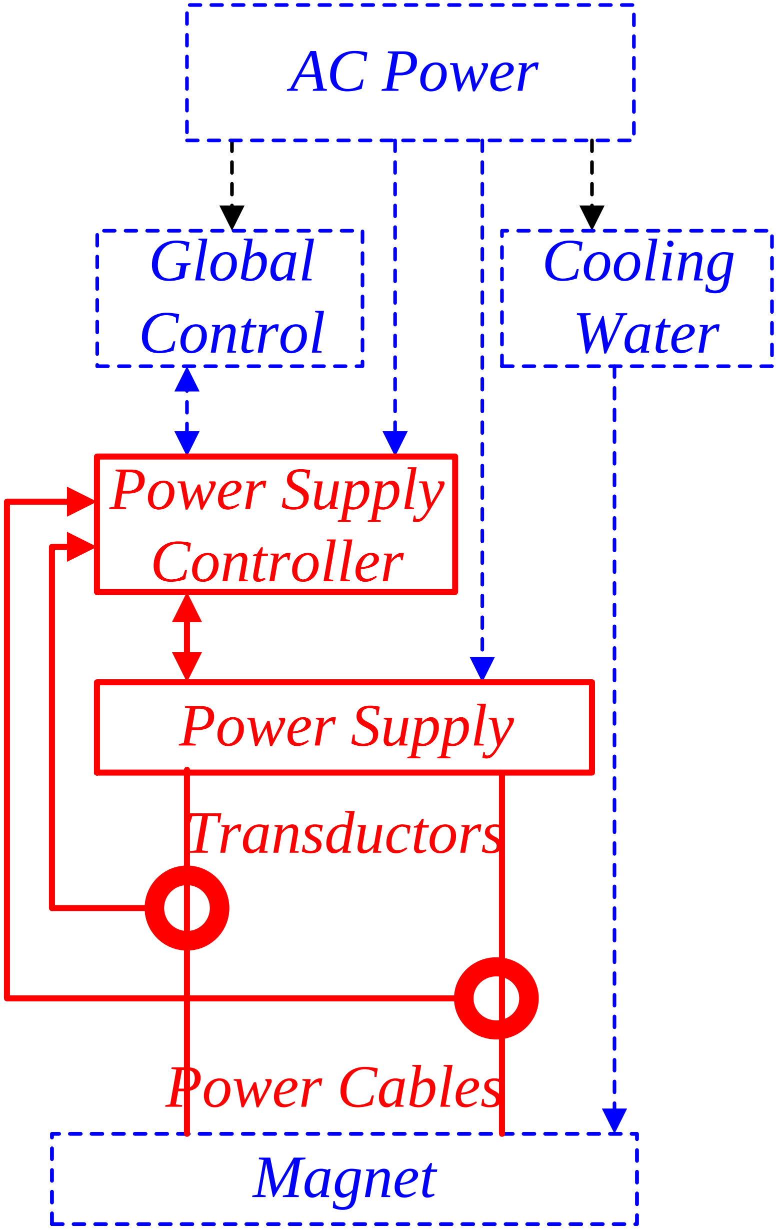
Component Description	Qty	λ	π_{GB}	π_{T}	π_{MQ}	π_{VS}	π_{IS}	π_{PS}	Mission Loss	Total Rate $\lambda_T\ 10^{-6}$
Circuit Breaker/Contactor/Fuse	5	0.42	1.00	1.10	1.00	1.01	1.05	1.10	Yes	2.695
3 Phase Transformer	1	0.05	1.00	1.10	1.00	1.50	1.50	1.50	Yes	0.186
Input/Output Filter Choke	2	0.02	1.00	1.10	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 # 17

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

Reliability Software

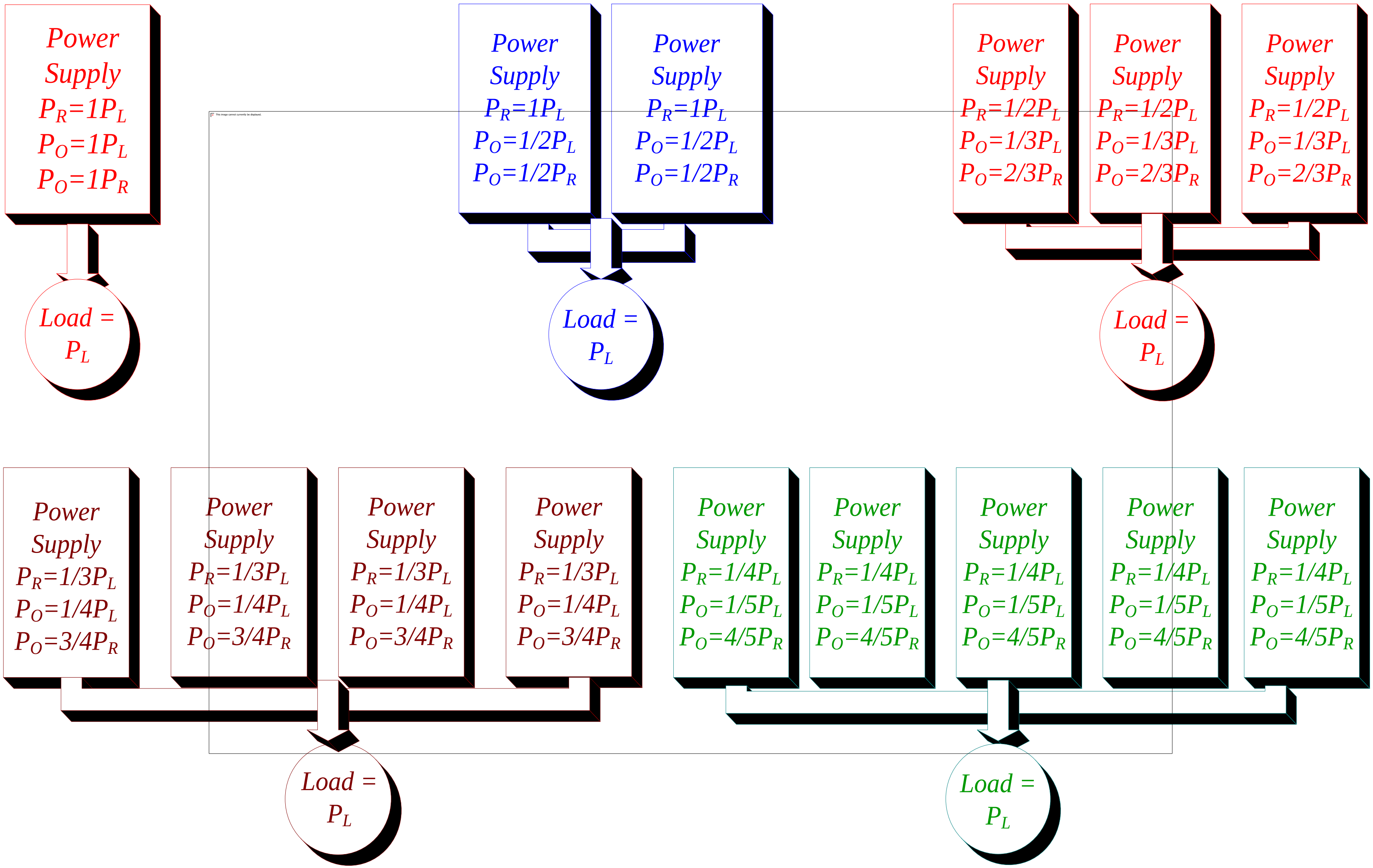
Relex by Relex Software

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



- *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

$R(t) = e^{-n\lambda t}$ $\qquad$ $R(t) = e^{-\lambda t}$

Availability Improvement By Oversizing and Redundancy

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	**3 Cases**
F	S	S	

$k=3$

$$\frac{3!}{0!3!} e^{-3\lambda t}(1-e^{-\lambda t})^{0} = 1 \; e^{-3\lambda t}$$

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

$$P_O = \frac{m}{n} P_R$$

$$MTBF_O = \frac{P_R}{P_O} MTBF_R = \frac{n}{m} MTBF_R \qquad \lambda_O = \frac{m}{n}\lambda_R \quad \text{linear relationship is conservative}$$

$$R_{Om/n}(t) = \sum_{k=m}^{n} \left(\frac{n!}{(n-k)!k!} \right) \left(e^{-\lambda_O t} \right)^k \left(1 - e^{-\lambda_O t} \right)^{n-k} = ne^{-m\lambda_O t} - me^{-n\lambda_O t}$$

$$MTBF_{Om/n}(t) = \frac{ne^{-m\lambda_O t} - me^{-n\lambda_O t}}{mn\lambda_O e^{-m\lambda_O t} - mn\lambda_O e^{-n\lambda_O t}}$$

$$A_{Om/n}(t) = \frac{MTBF_{Om/n}(t)}{MTBF_{Om/n}(t) + MTTR}$$

Active Redundancy - One Full Rated Power Supply

For the case of 1 power supply with a power rating equal to the required operational power

$$P_R = P_O$$

$$MTBF_R = MTBF_O$$

$$\lambda_R = \lambda_O$$

$$R_O = e^{-\lambda_O t} = e^{-\lambda_R t}$$

$$A_O = \frac{MTBF_O}{MTBF_O + MTTR} = \frac{MTBF_R}{MTBF_R + MTTR}$$

Active Redundancy - One Out of Two Case

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

$$MTBF_O = \frac{P_R}{P_O} MTBF_R = \frac{5}{4} MTBF_R \qquad \lambda_O = \frac{4}{5}\lambda_R$$

$$R_{O4/5}(t) = 5e^{-4\lambda_O t} - 4e^{-5\lambda_O t}$$

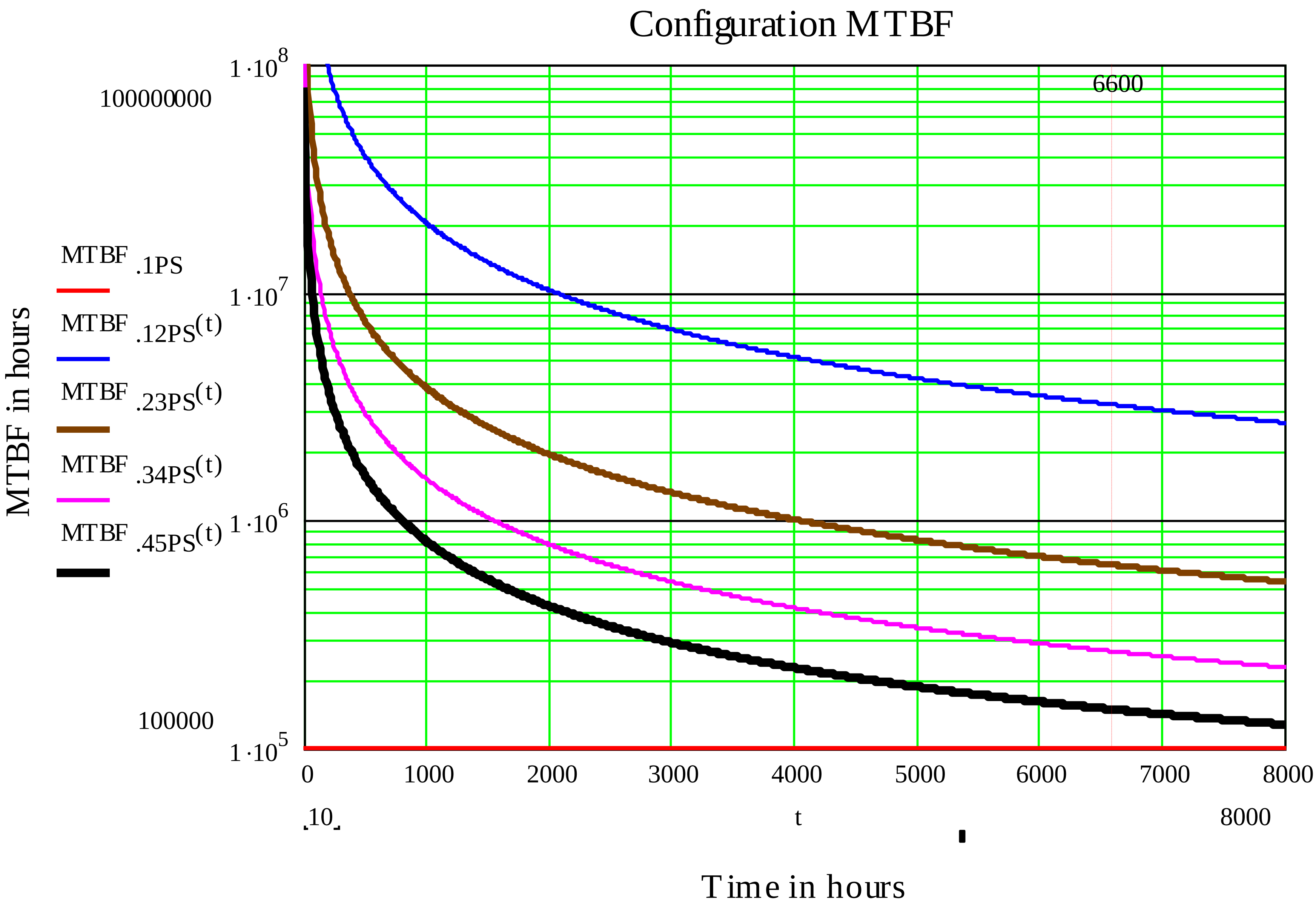
$$MTBF_{O4/5}(t) = \frac{5e^{-4\lambda_O t} - 4e^{-5\lambda_O t}}{20\lambda_O e^{-4\lambda_O t} - 20\lambda_O e^{-5\lambda_O t}}$$

$$A_{O4/5}(t) = \frac{MTBF_{O4/5}(t)}{MTBF_{O4/5}(t) + MTTR}$$

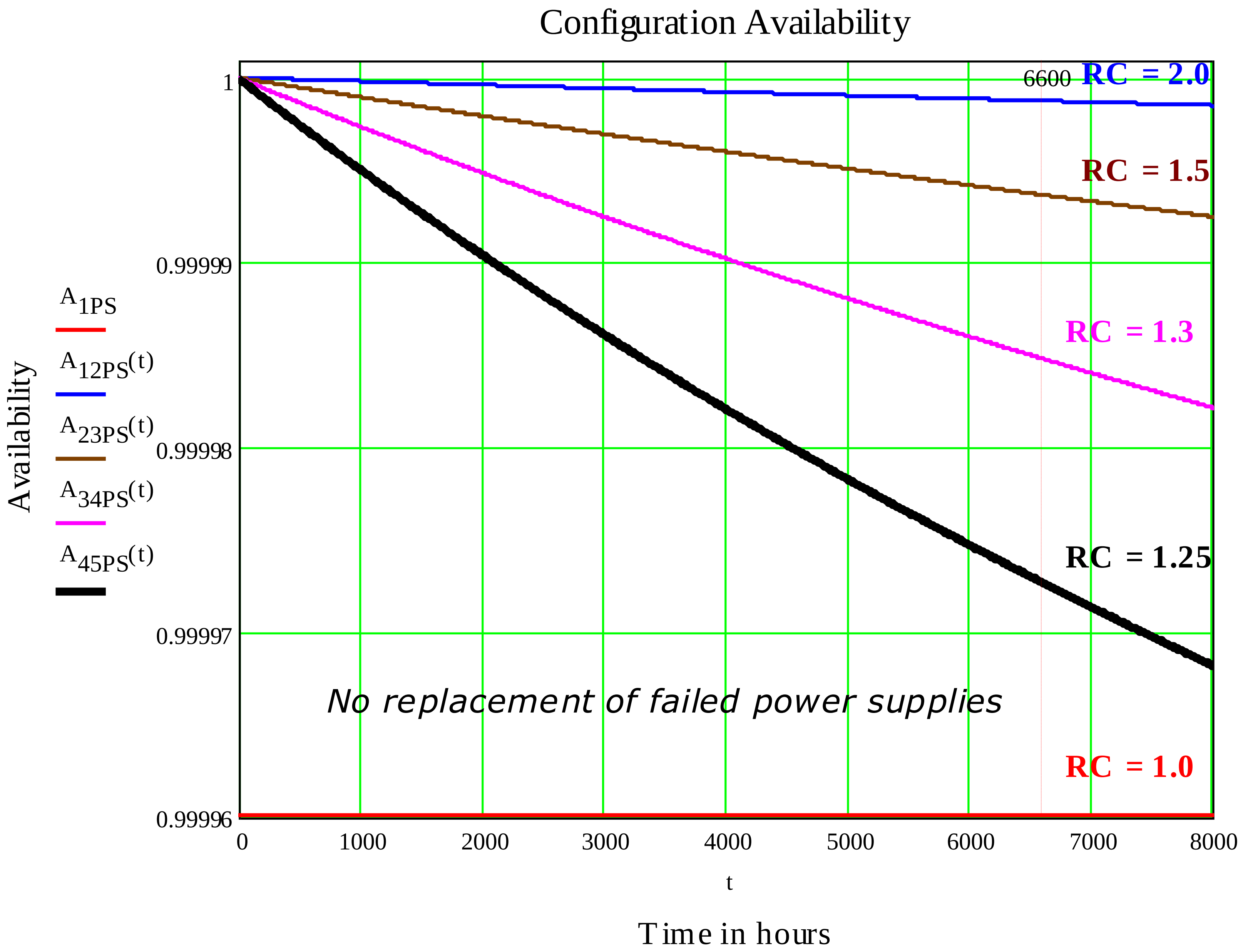
Active Redundancy Power Supply Reliability Summary

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	$\lambda_O = \dfrac{1}{2}\lambda_R$	$R_{O1/2} = 2e^{-\lambda_O t} - e^{-2\lambda_O t}$	$MTBF_{O1/2}(t) = \dfrac{2e^{-\lambda_O t} - e^{-2\lambda_O t}}{2\lambda_O e^{-\lambda_O t} - 2\lambda_O e^{-2\lambda_O t}}$	$A_{O1/2}(t) = \dfrac{MTBF_{O1/2}(t)}{MTBF_{O1/2}(t) + MTTR}$
2/3	$\lambda_O = \dfrac{2}{3}\lambda_R$	$R_{O2/3} = 3e^{-2\lambda_O t} - 2e^{-3\lambda_O t}$	$MTBF_{O2/3}(t) = \dfrac{3e^{-2\lambda_O t} - 2e^{-3\lambda_O t}}{6\lambda_O e^{-2\lambda_O t} - 6\lambda_O e^{-3\lambda_O t}}$	$A_{O2/3}(t) = \dfrac{MTBF_{O2/3}(t)}{MTBF_{O2/3}(t) + MTTR}$
3/4	$\lambda_O = \dfrac{3}{4}\lambda_R$	$R_{O3/4} = 4e^{-3\lambda_O t} - 3e^{-4\lambda_O t}$	$MTBF_{O3/4}(t) = \dfrac{4e^{-3\lambda_O t} - 3e^{-4\lambda_O t}}{12\lambda_O e^{-3\lambda_O t} - 12\lambda_O e^{-4\lambda_O t}}$	$A_{O3/4}(t) = \dfrac{MTBF_{O3/4}(t)}{MTBF_{O3/4}(t) + MTTR}$
4/5	$\lambda_O = \dfrac{4}{5}\lambda_R$	$R_{O4/5} = 5e^{-4\lambda_O t} - 4e^{-5\lambda_O t}$	$MTBF_{O4/5}(t) = \dfrac{5e^{-4\lambda_O t} - 4e^{-5\lambda_O t}}{20\lambda_O e^{-4\lambda_O t} - 20\lambda_O e^{-5\lambda_O t}}$	$A_{O4/5}(t) = \dfrac{MTBF_{O4/5}(t)}{MTBF_{O4/5}(t) + MTTR}$

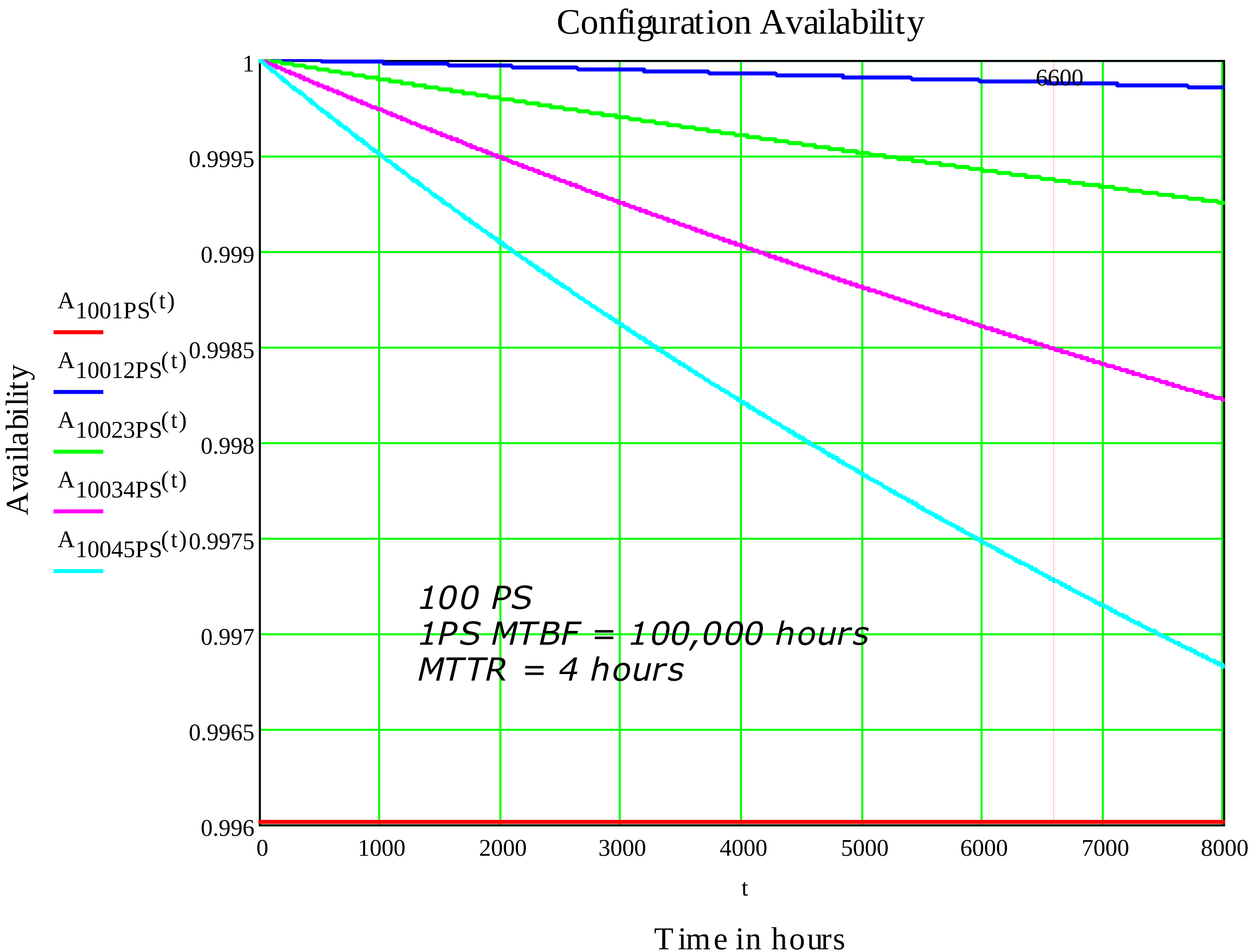
Active Redundancy MTBF Plot



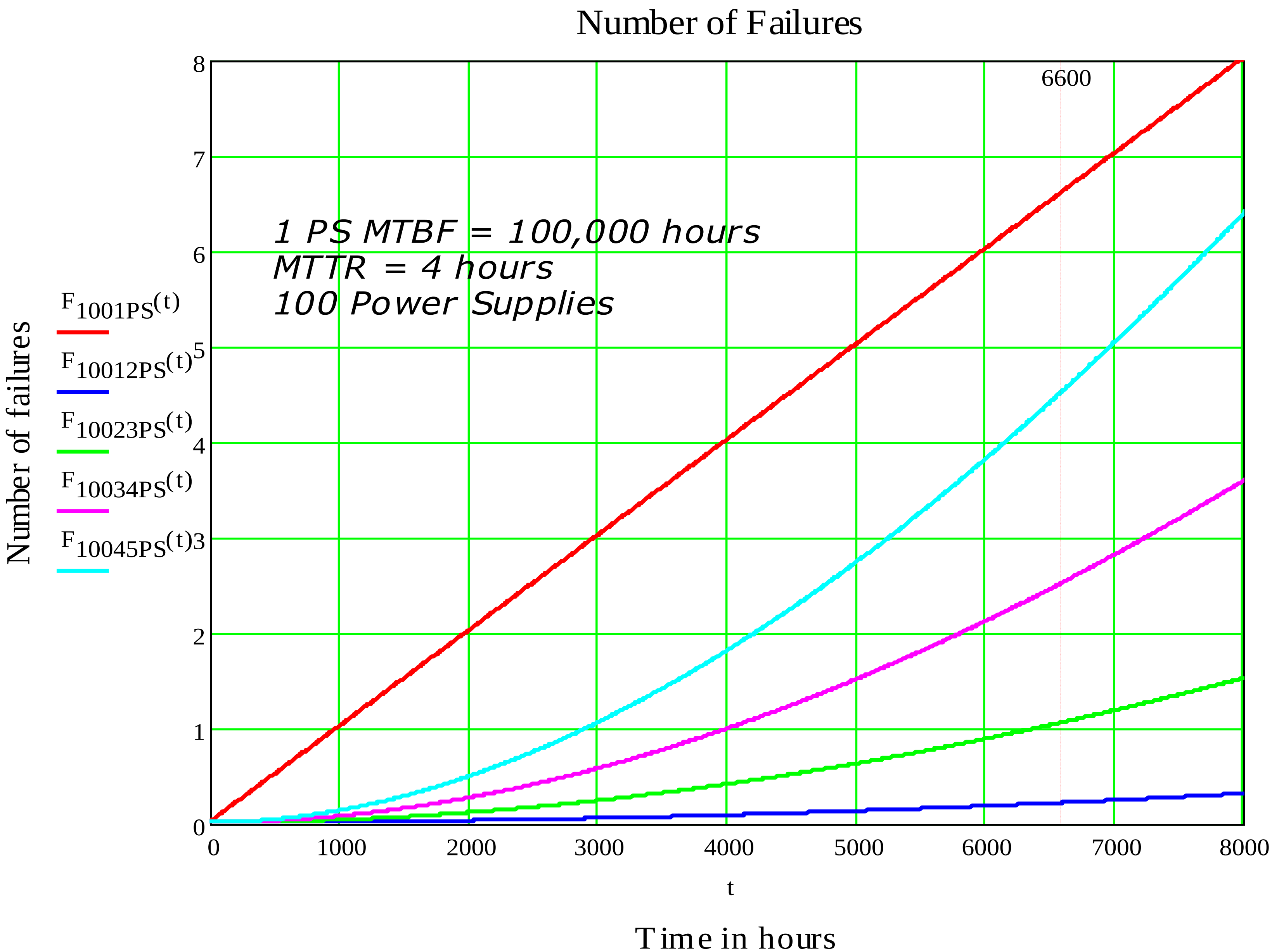
Active Redundancy - Availability



Active Redundancy - Availability of 100 Power Supplies



Active Redundancy - Number of PS Failures



Homework Problem # 18

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 λ = 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 # 19

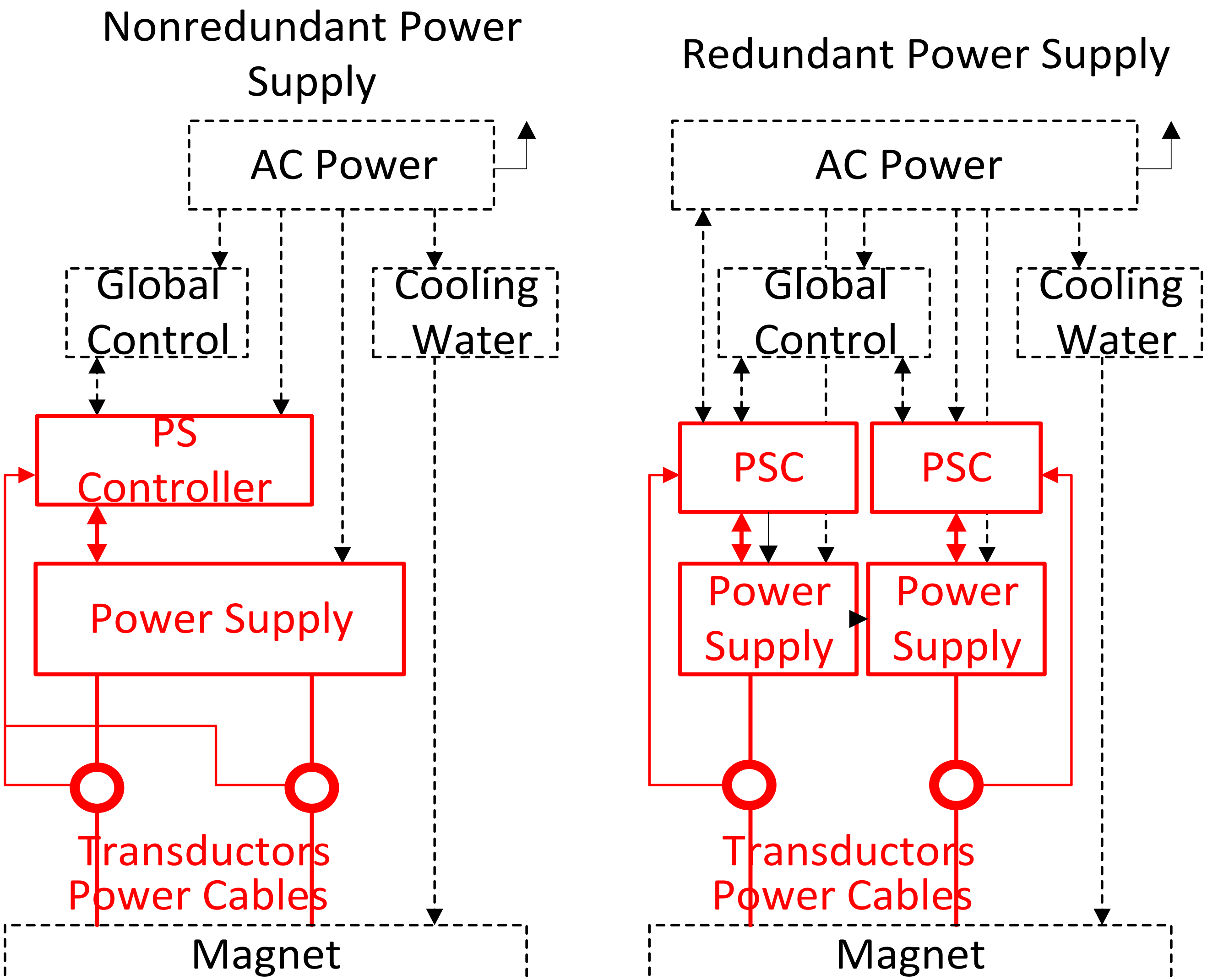
For a critical mission, 3 power supplies, each capable of supplying the total required output, are to be paralleled. The power supplies are also decoupled such that a failure of any power supply will not affect the output. The calculated failure rate of each power supply is 4 per million hours.

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.

SLAC Next-Generation High Availability Power Supply

Dave MacNair
SLAC National Accelerator Laboratory
Power Conversion Department (PCD)

Why High Availability is Essential

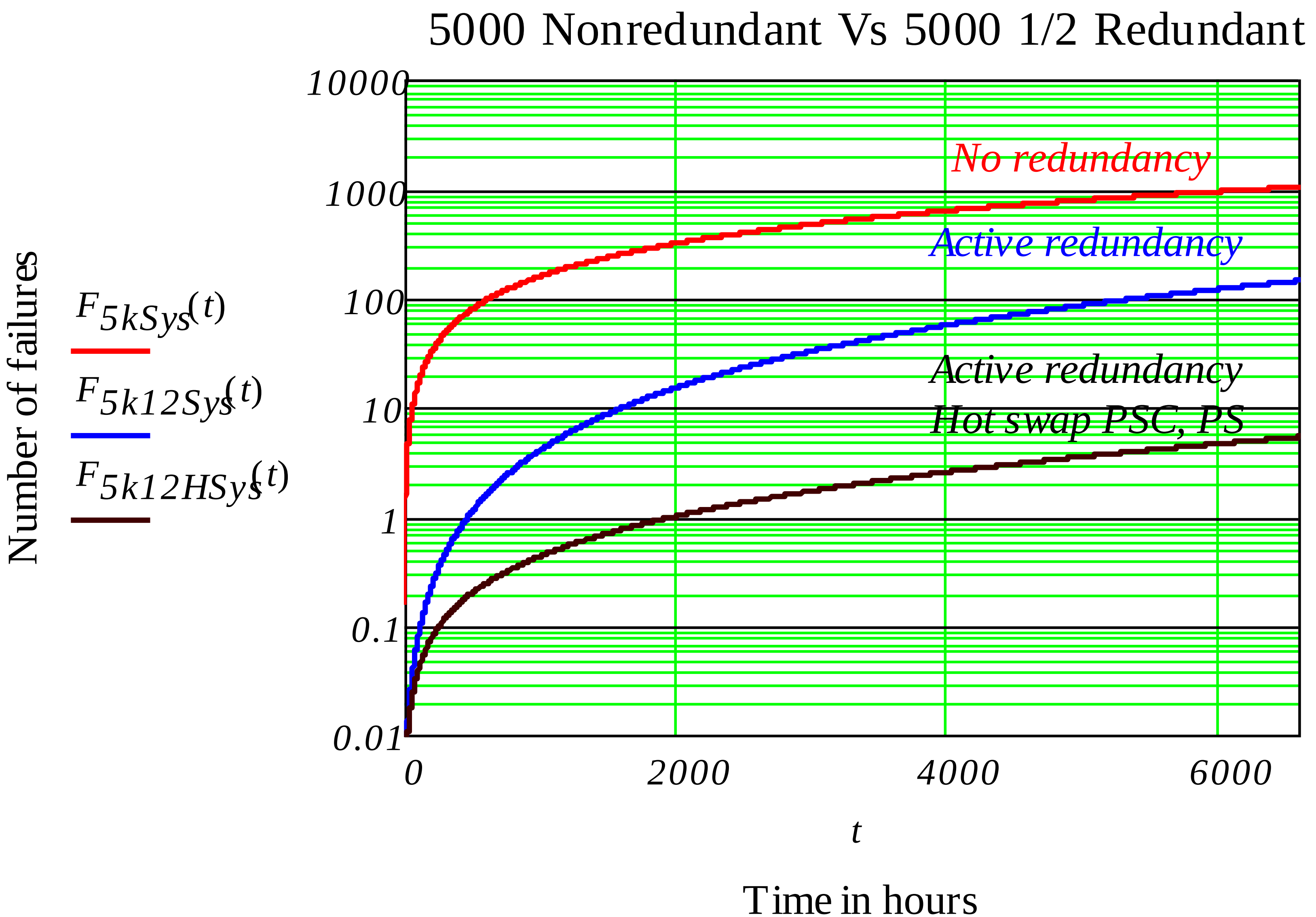


Item	***MTBF kHrs***
PSC	*110*
PS	*60*
Transductor	*381.5*
Cables/ Connectors	*14000*

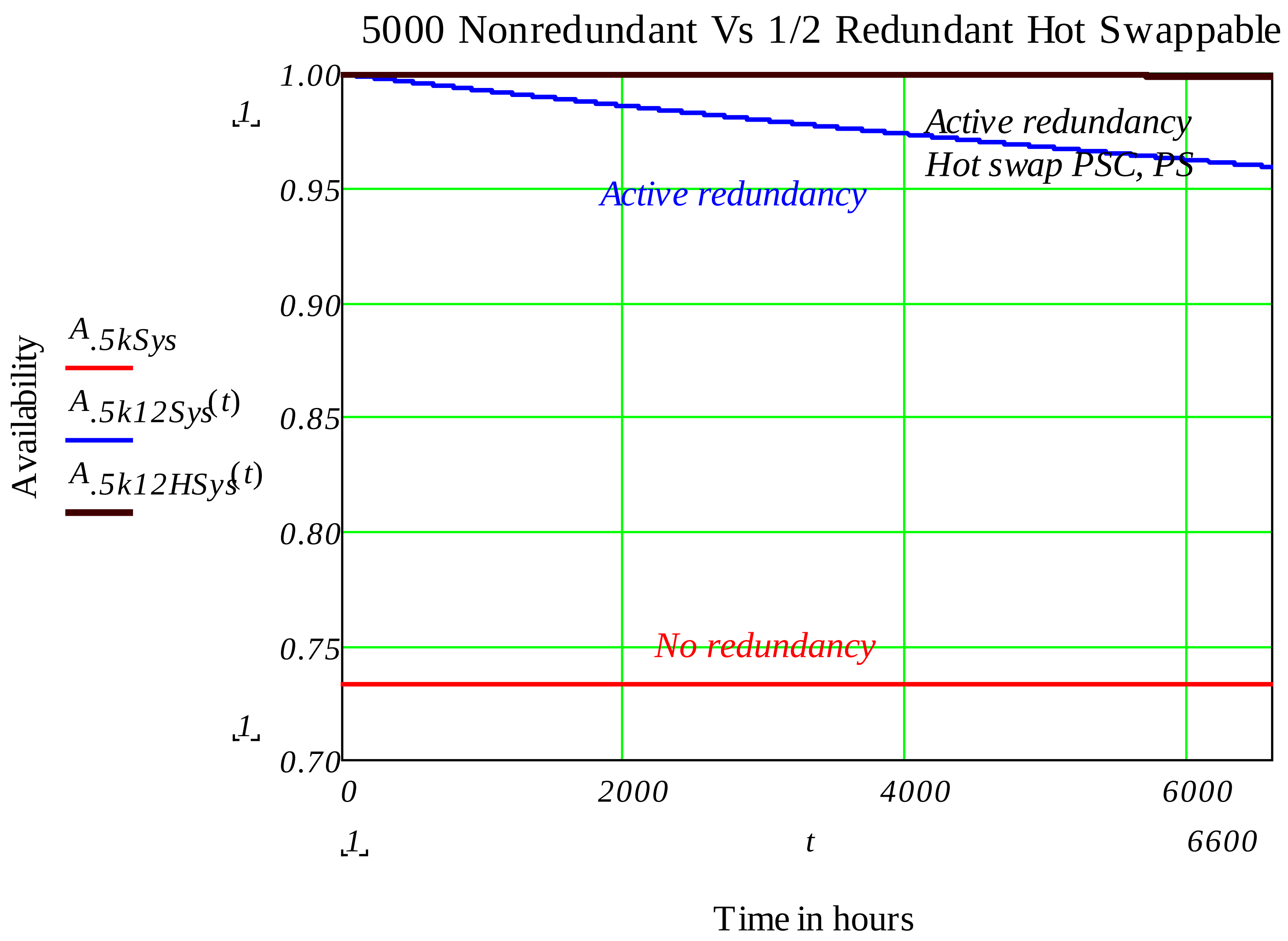
MTTR = 2 Hours

PAC 2001 Chicago, Illinois

Bellomo, Donaldson, MacNair


5000 Nonredundant Vs 5000 1/2 Redundant
Number of failures
$F_{5kSys}(t)$
$F_{5k12Sys}(t)$
$F_{5k12HSys}(t)$
10000
1000
100
10
1
0.1
0.01
No redundancy
Active redundancy
Active redundancy
Hot swap PSC, PS
0
2000
4000
6000
t
Time in hours

Hot Swap is Essential



It is clear that redundancy and hot swap are needed

SLAC Projects with Non-redundant or Redundant Power Supplies

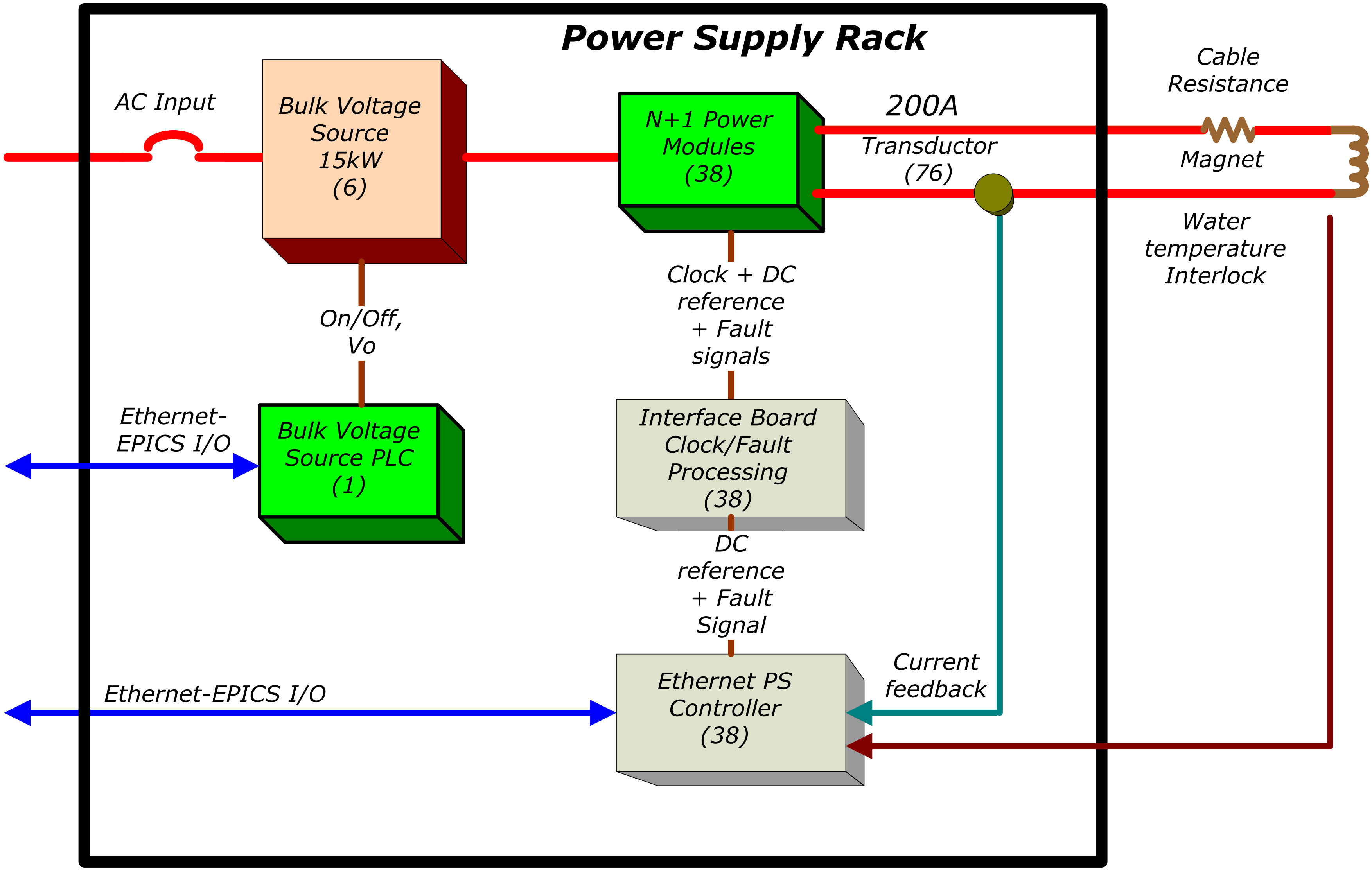
Non-redundant - PEP II, SPEAR 3, LCLS (1994 – 2006)

- *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*

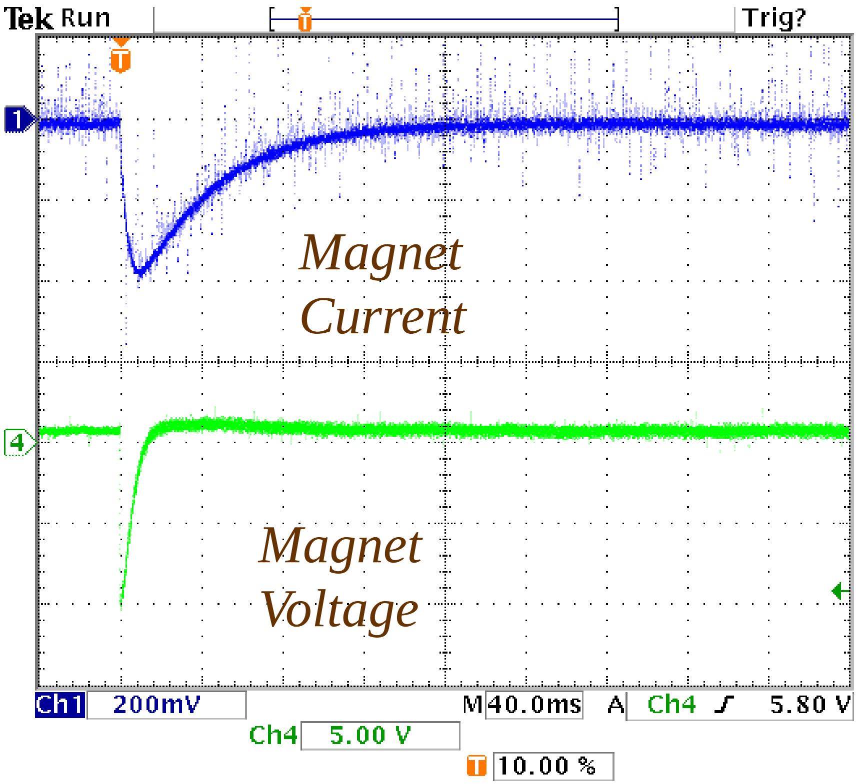
Redundant - KEK ATF 2 (2006 – 2008)

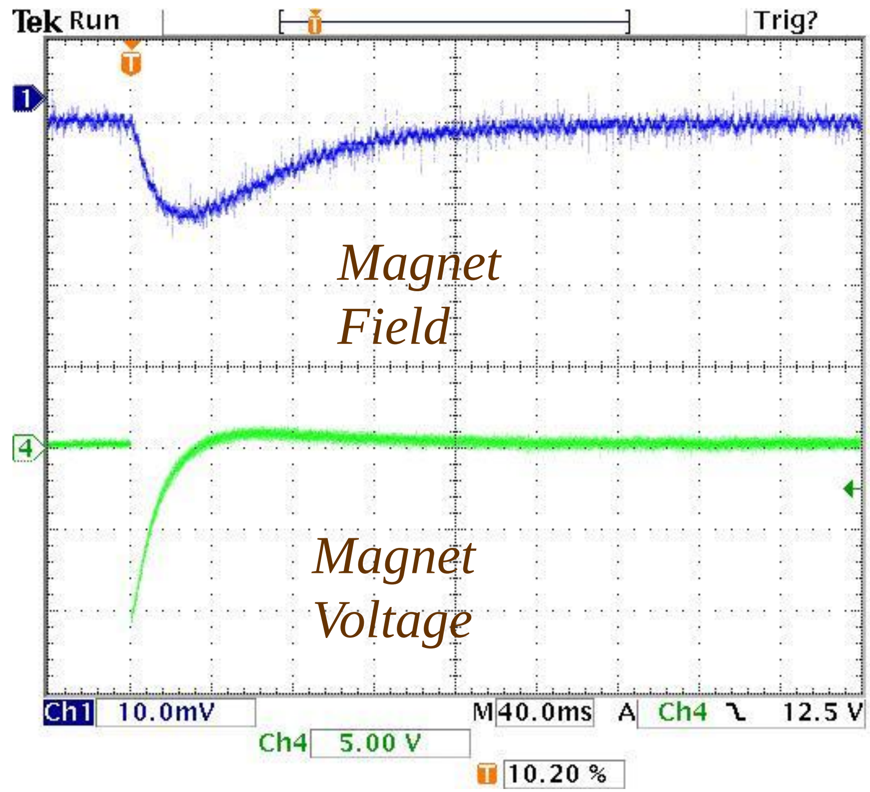
- *Mock-up of ILC Final Focus accelerator*
- *Magnet power supplies ILC-like*

ATF2 Block Diagram



ATF2 – at KEK





- *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)

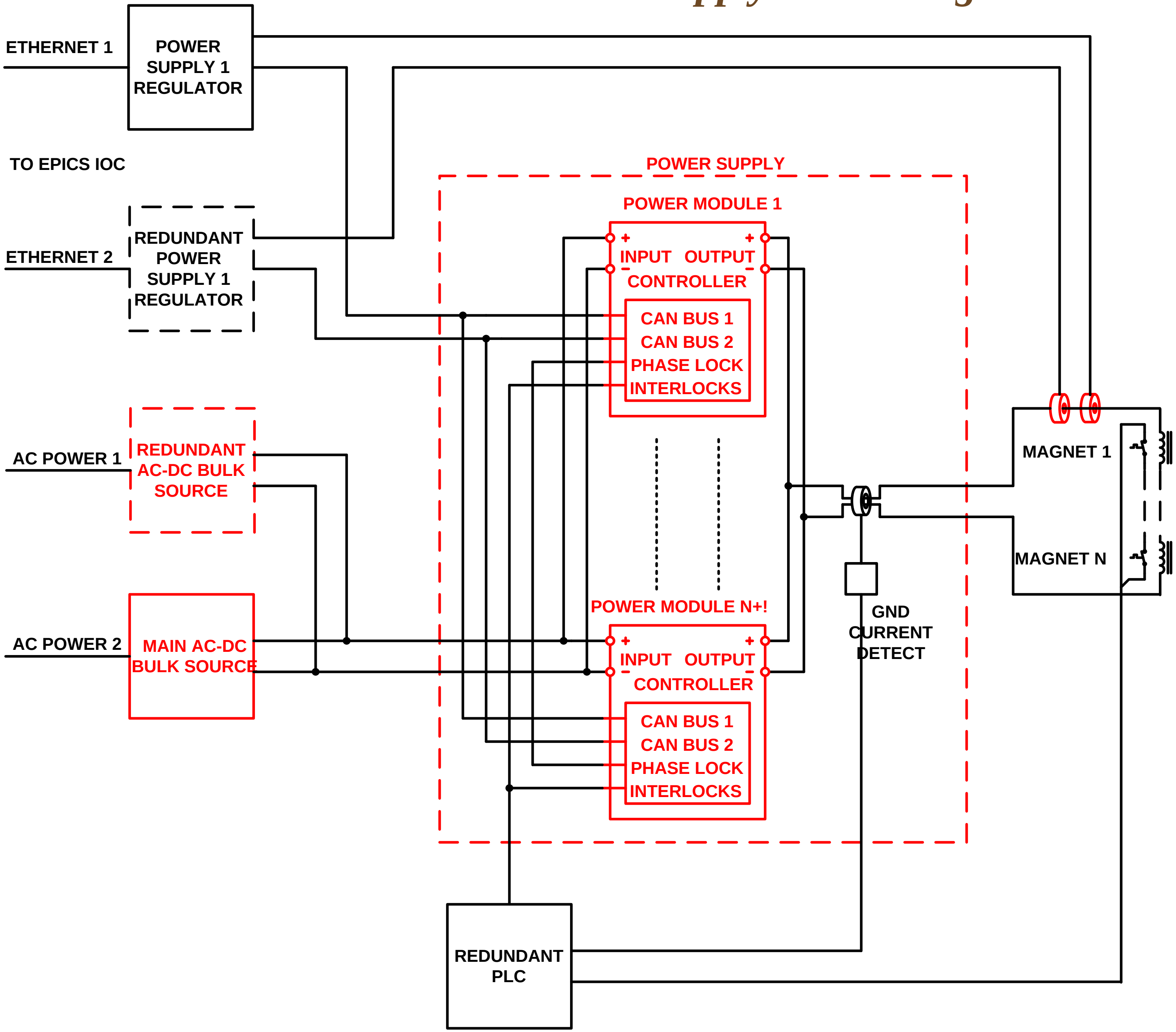
Goals

- *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*

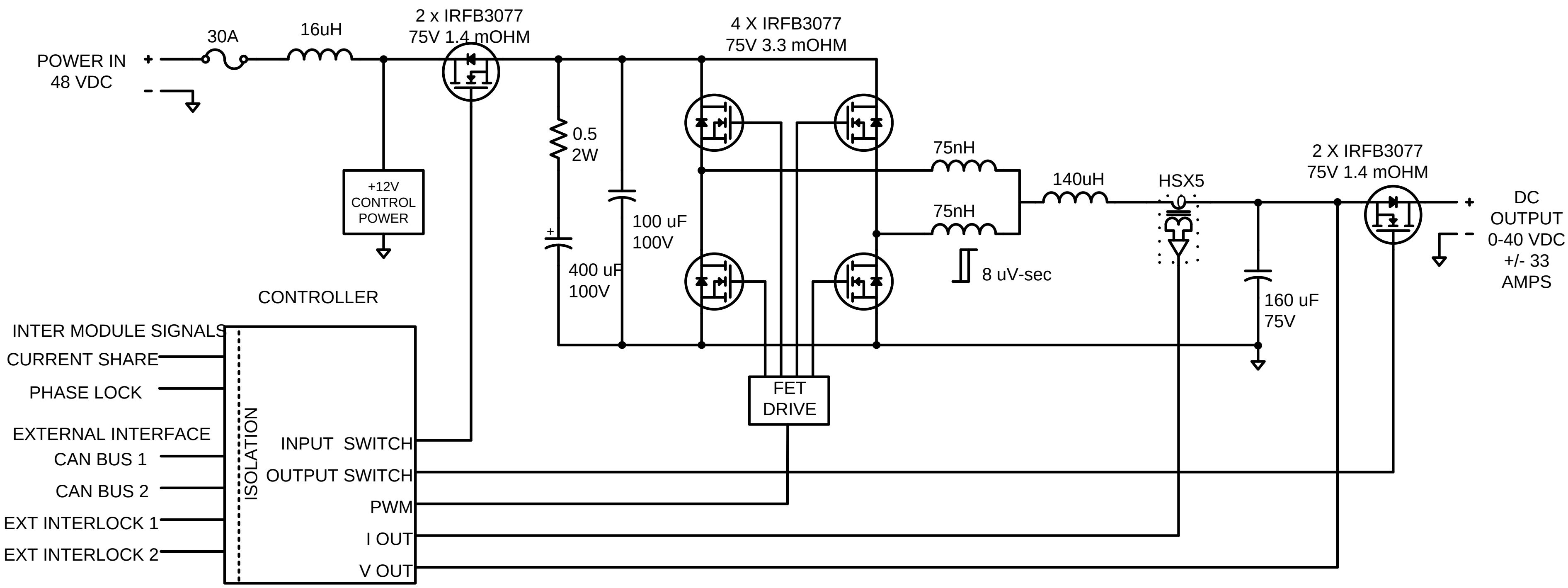
Applications

- *ILC and other future accelerators*

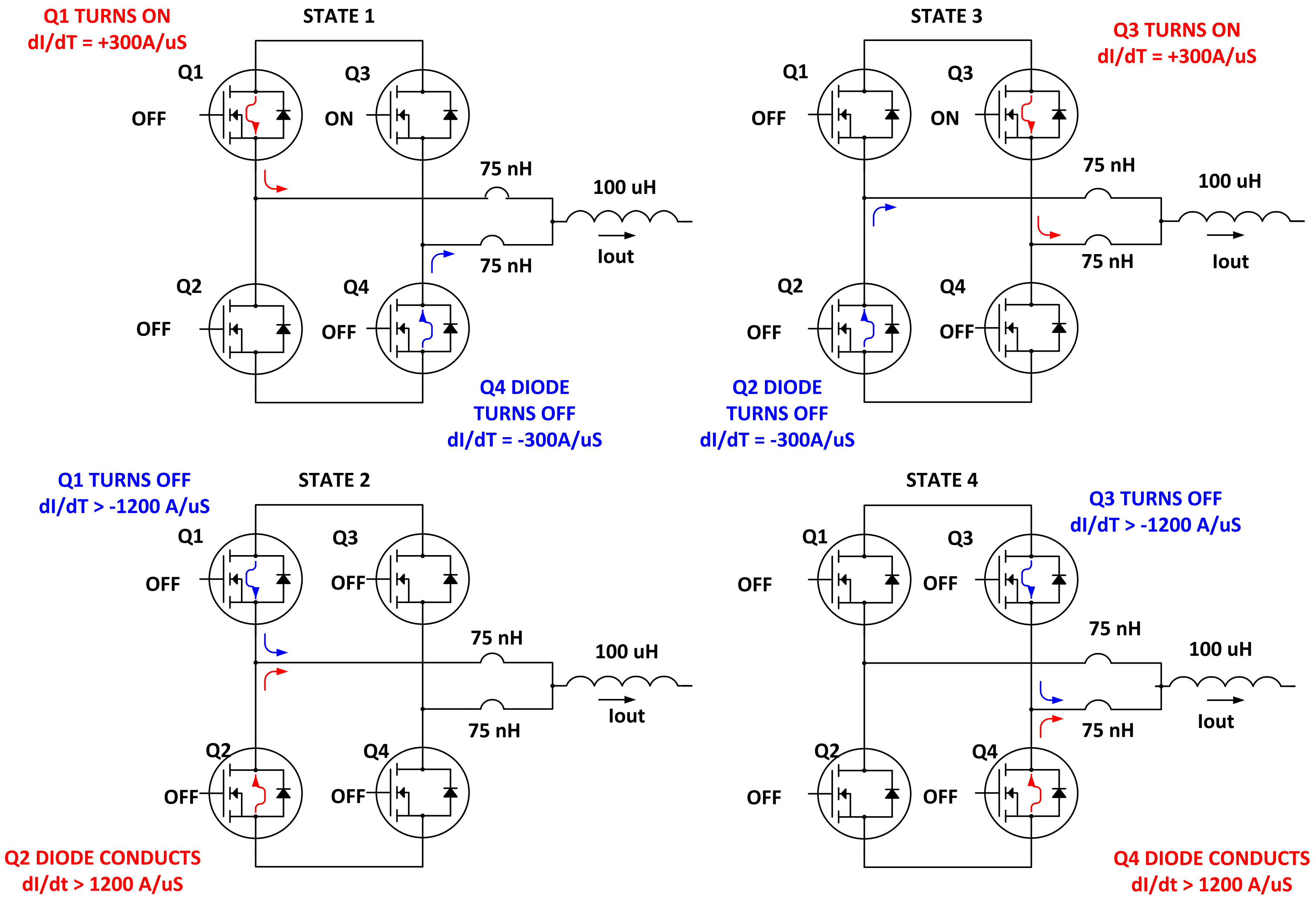
Next Generation Power Supply Block Diagram



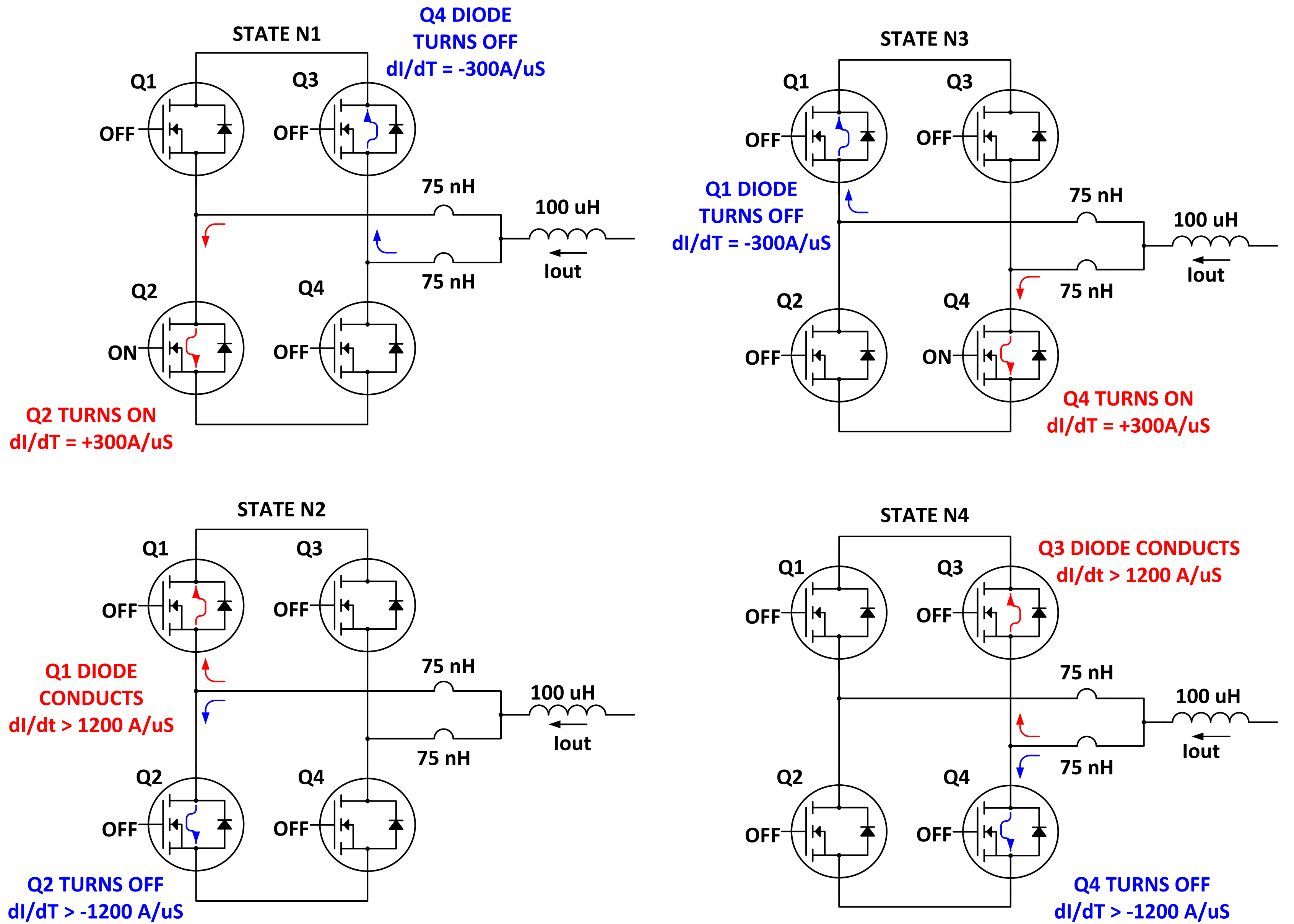
Next Generation Power Module Schematic



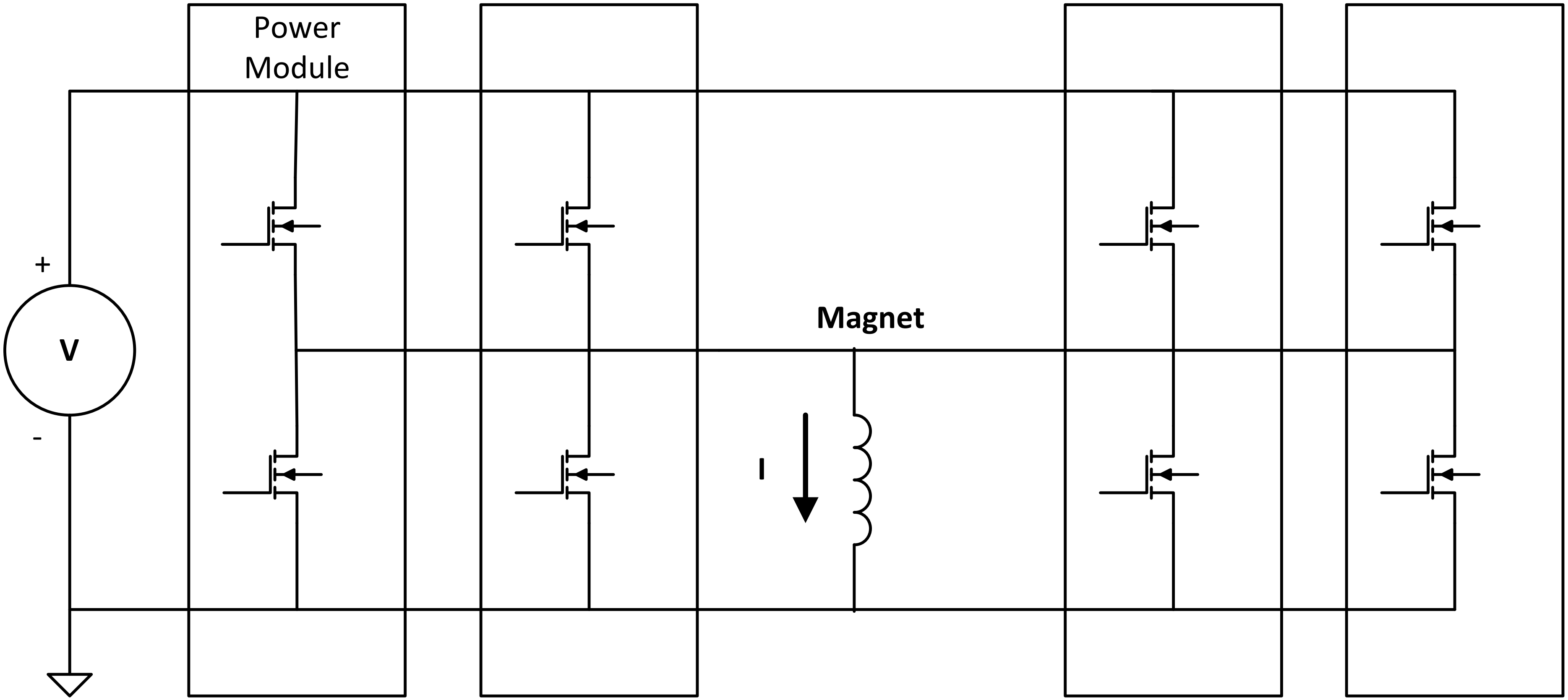
Next Generation Positive Output Current (Q1 – Q2 – Q3 – Q4)



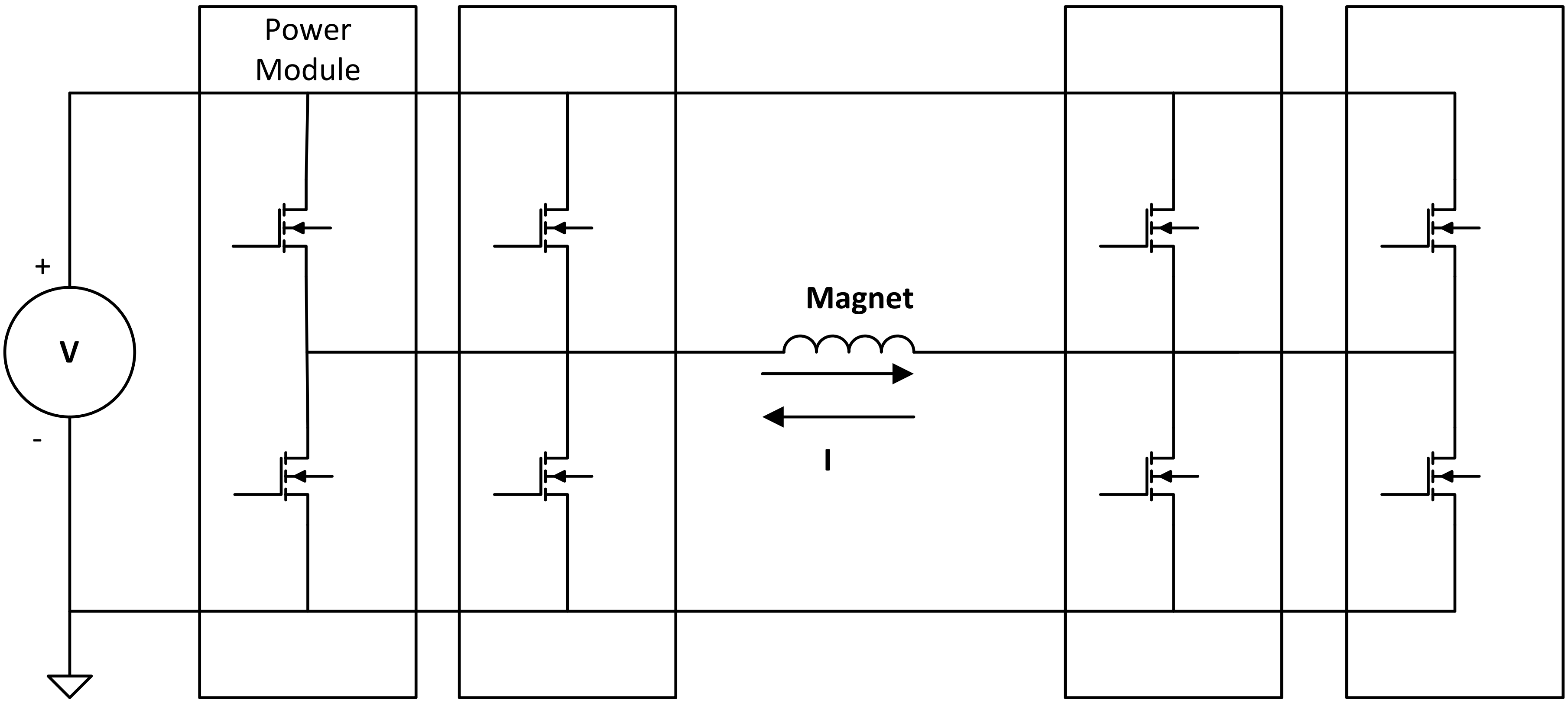
Next Generation Negative Output Current (Q2 – Q1 – Q4 – Q3)



Power Modules Connected for Unipolar Output



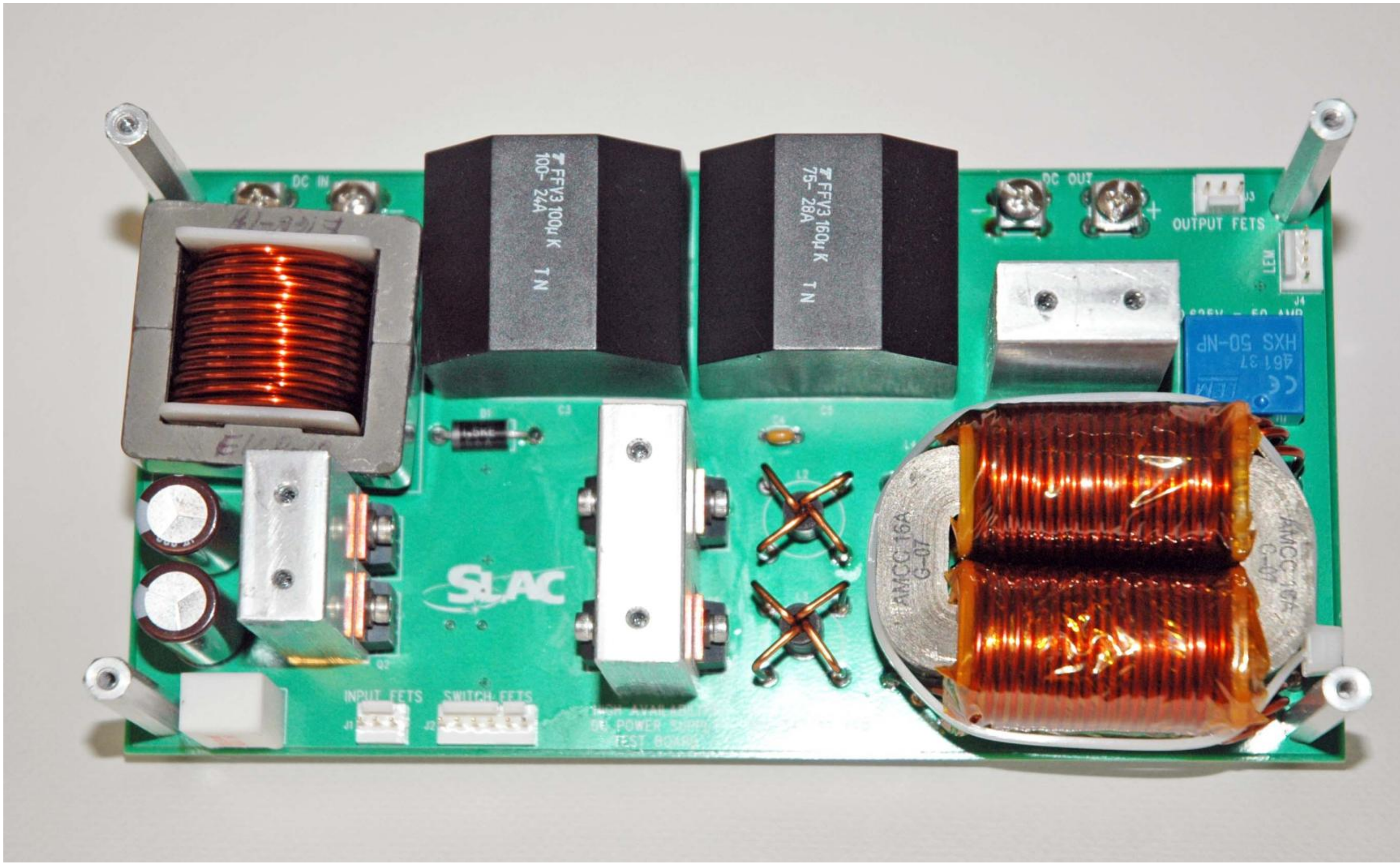
Power Modules Connected for Bipolar Output



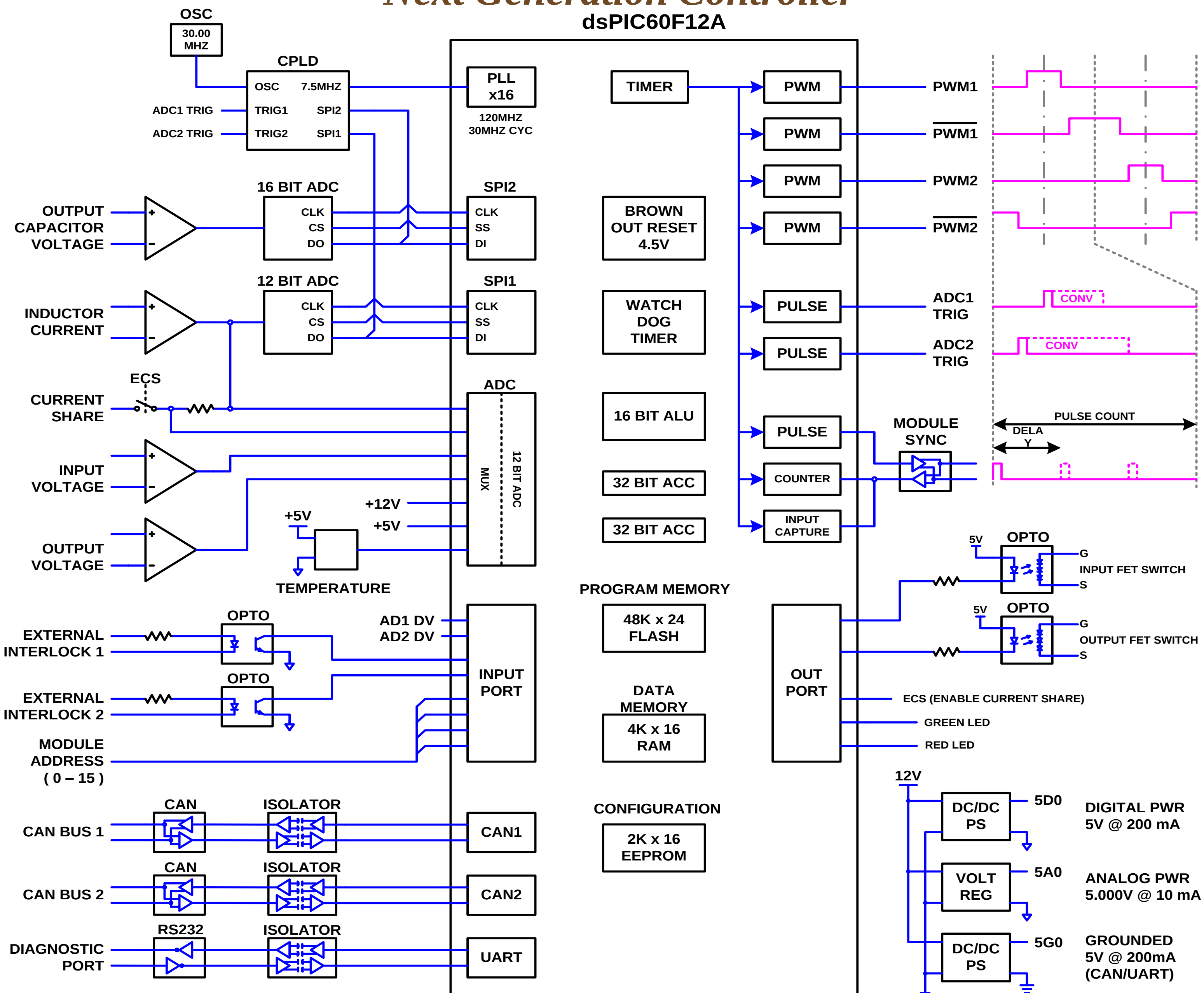
Next Generation Power Modules are "Bricks"

- *Input: 48V*
- *Output V: 0 to 40V*
- *Output I: 0 to 33A*
- *Output P: 0 to 1,320W*
- *2" X 4" X 8"*

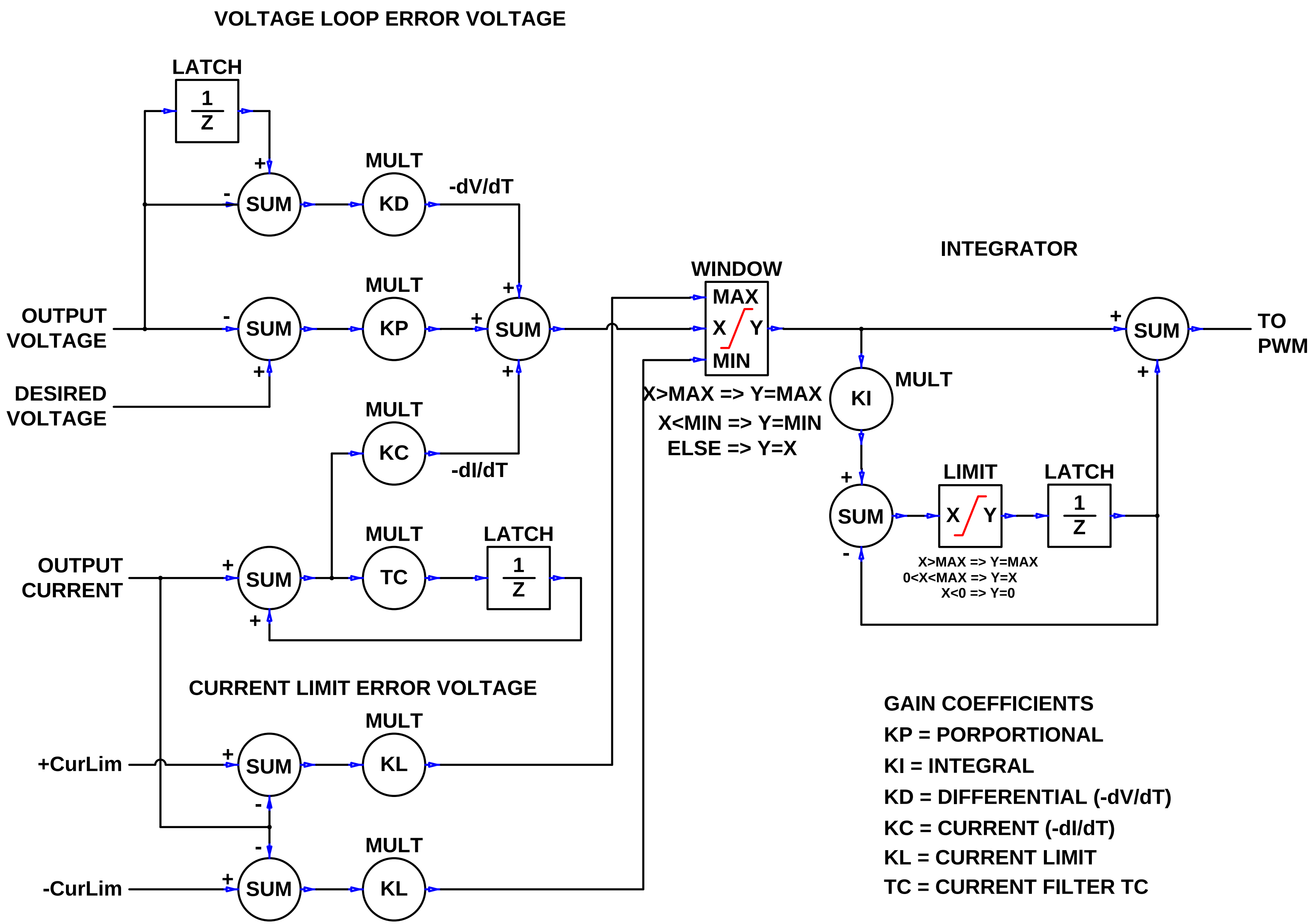
Next Generation Power Module Layout



Next Generation Controller



Next Generation PID Loops



GAIN COEFFICIENTS

KP = PORPORTIONAL

KI = INTEGRAL

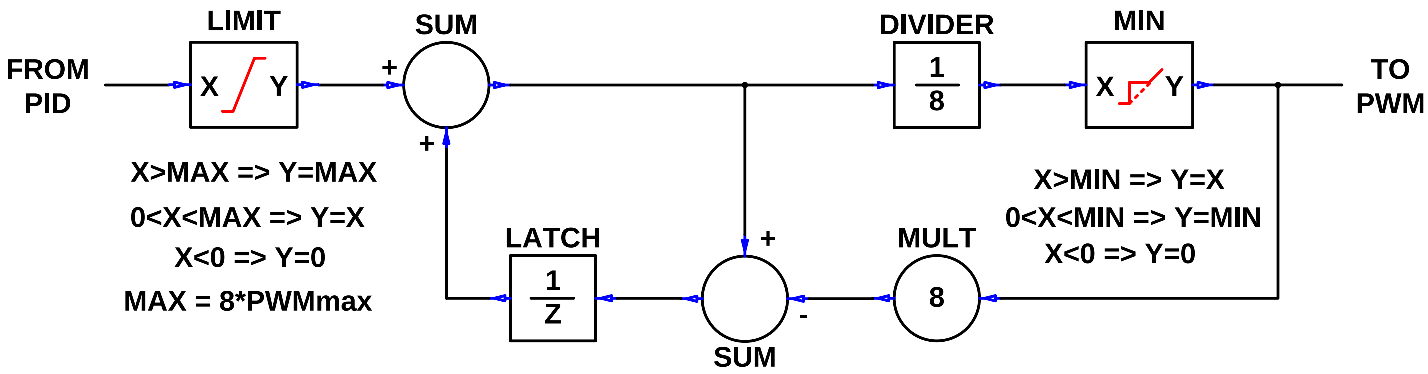
KD = DIFFERENTIAL (-dV/dT)

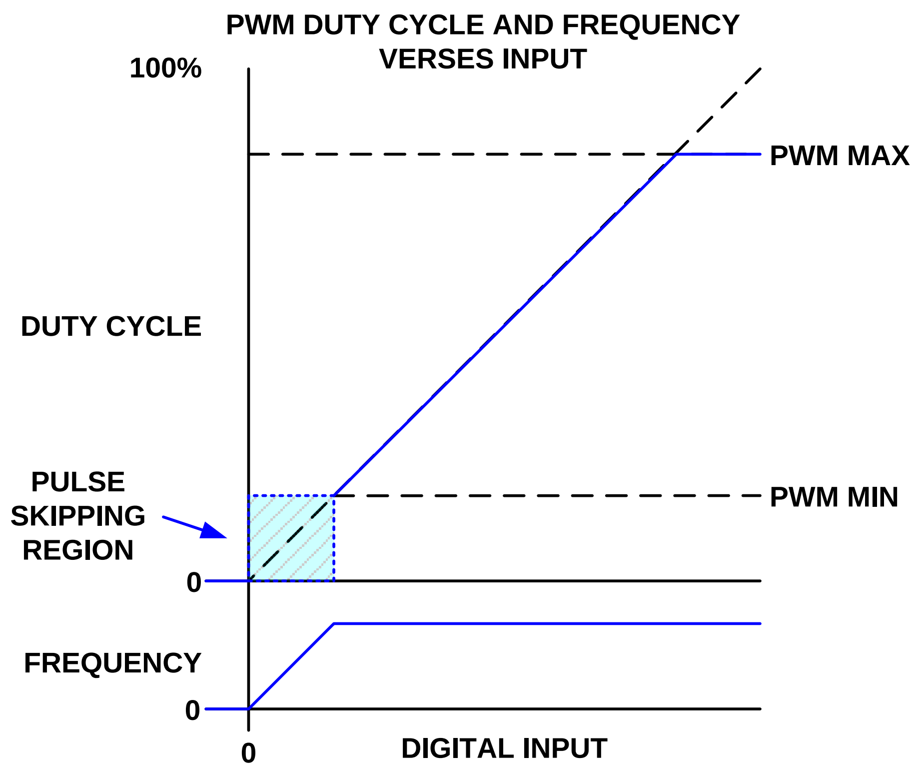
KC = CURRENT (-dI/dT)

KL = CURRENT LIMIT

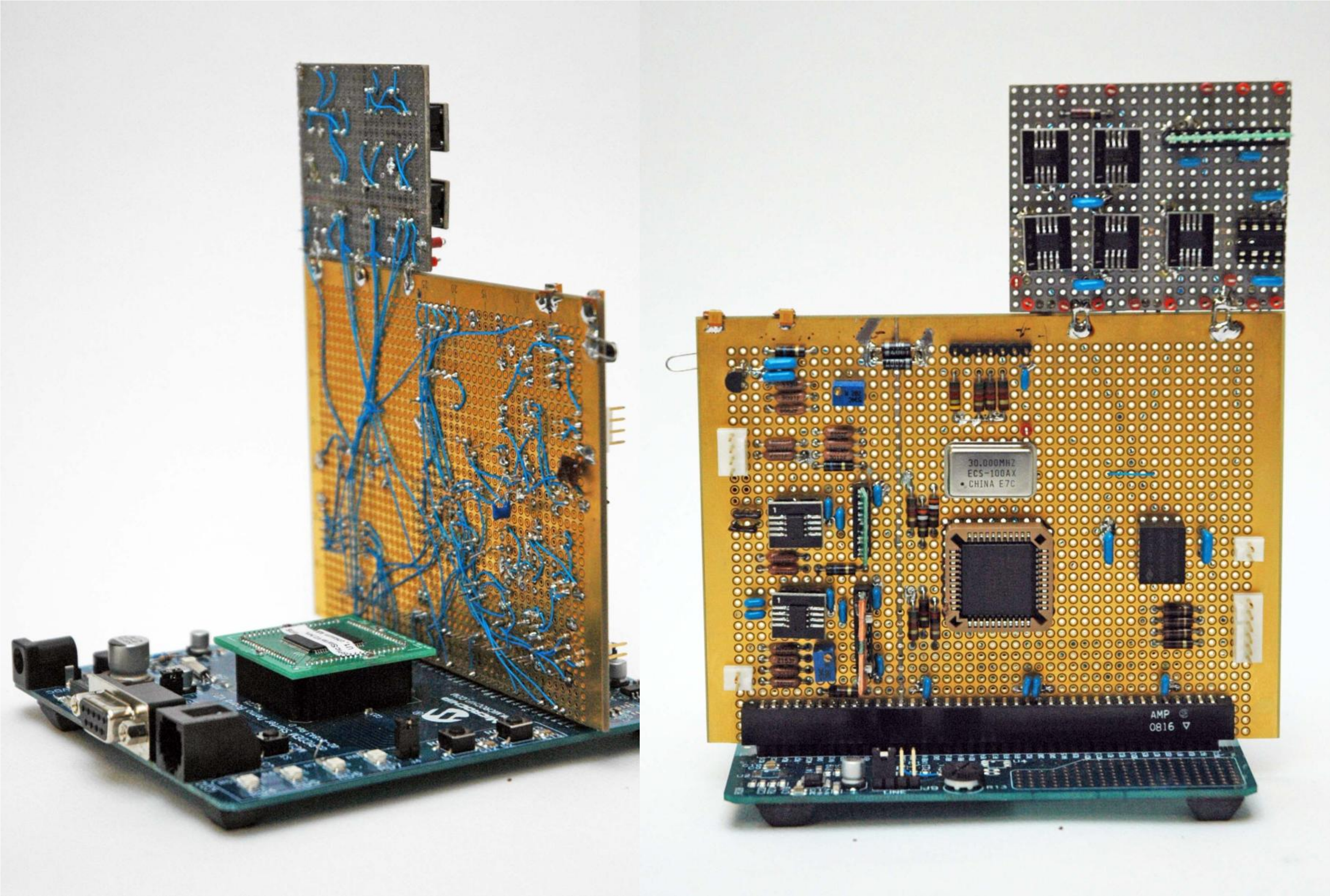
TC = CURRENT FILTER TC

Next Generation PWM Control

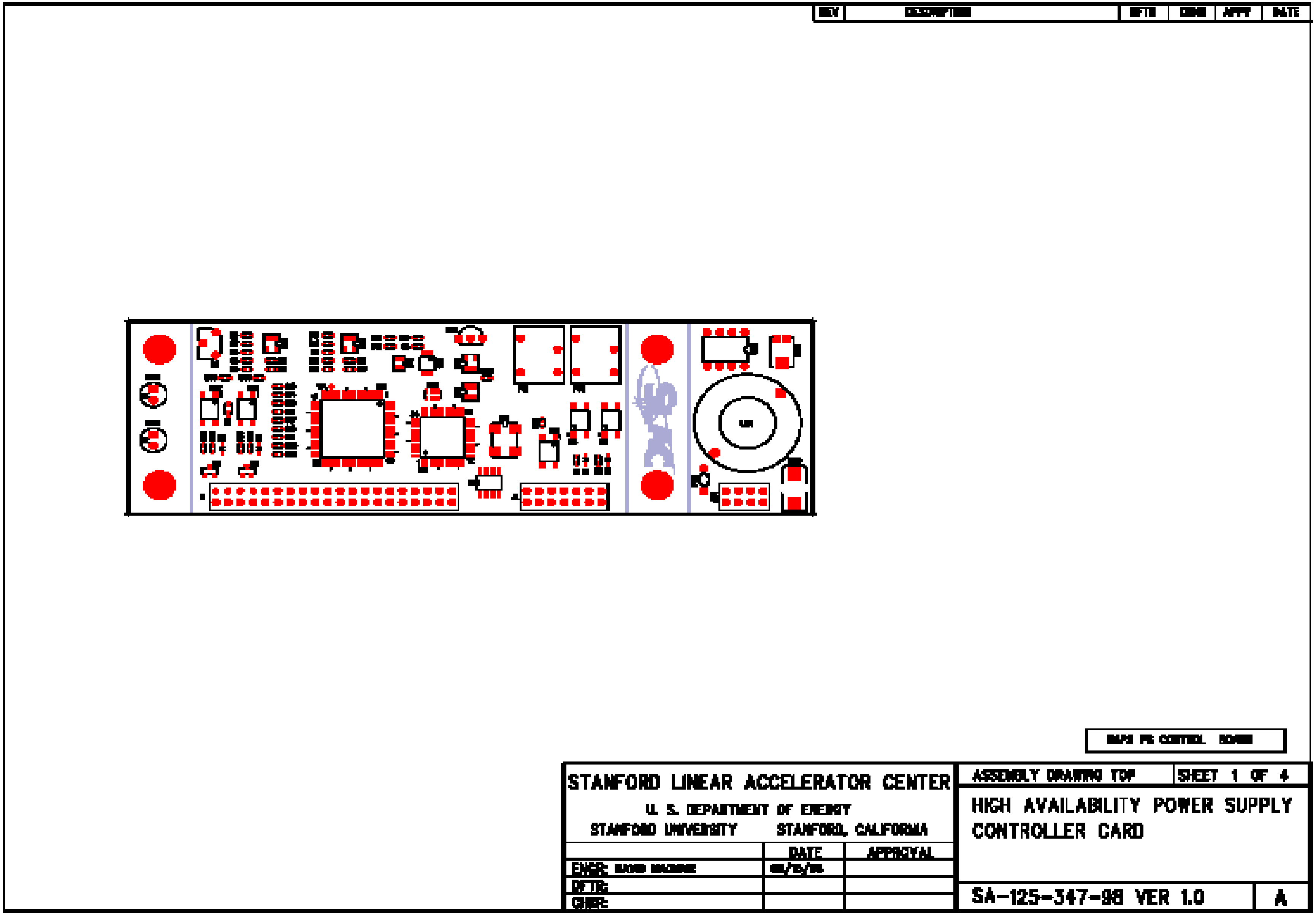




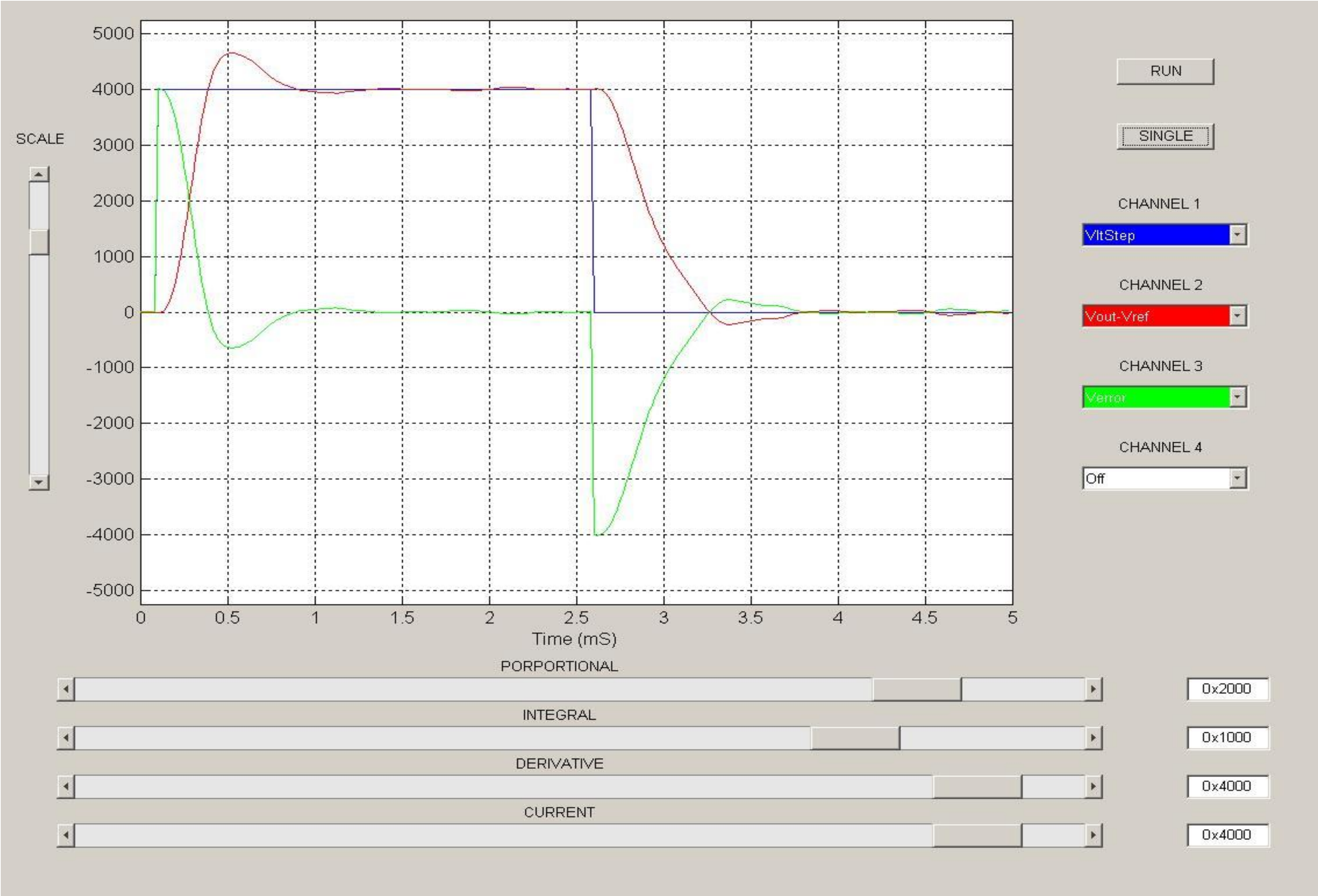
Next Generation Prototype Controller with Development Board



Next Generation – Controller Card



Next Generation – MATLAB Tuning Program



Program Status – As of January 2010

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:

$3\ years = 26280\ hours = MTBF_{Test}$

From the confidence limit table $K_L = 0.434$ *for* 80% *and* $f = 1$

Therefore, $MTBF_{80\%} = MTBF_{Predicted} * 0.434 \geq 11{,}406\ hours$

For $MTBF_{90\%} = MTBF_{Predicted} * 0.333 \geq 8{,}751\ hours$

Homework Problem # 20

It is desired to claim with 90% confidence that the actual MTBF of a power supply is 2500 hours. What must be the predicted MTBF if the test is terminated at the first test failure?

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.*

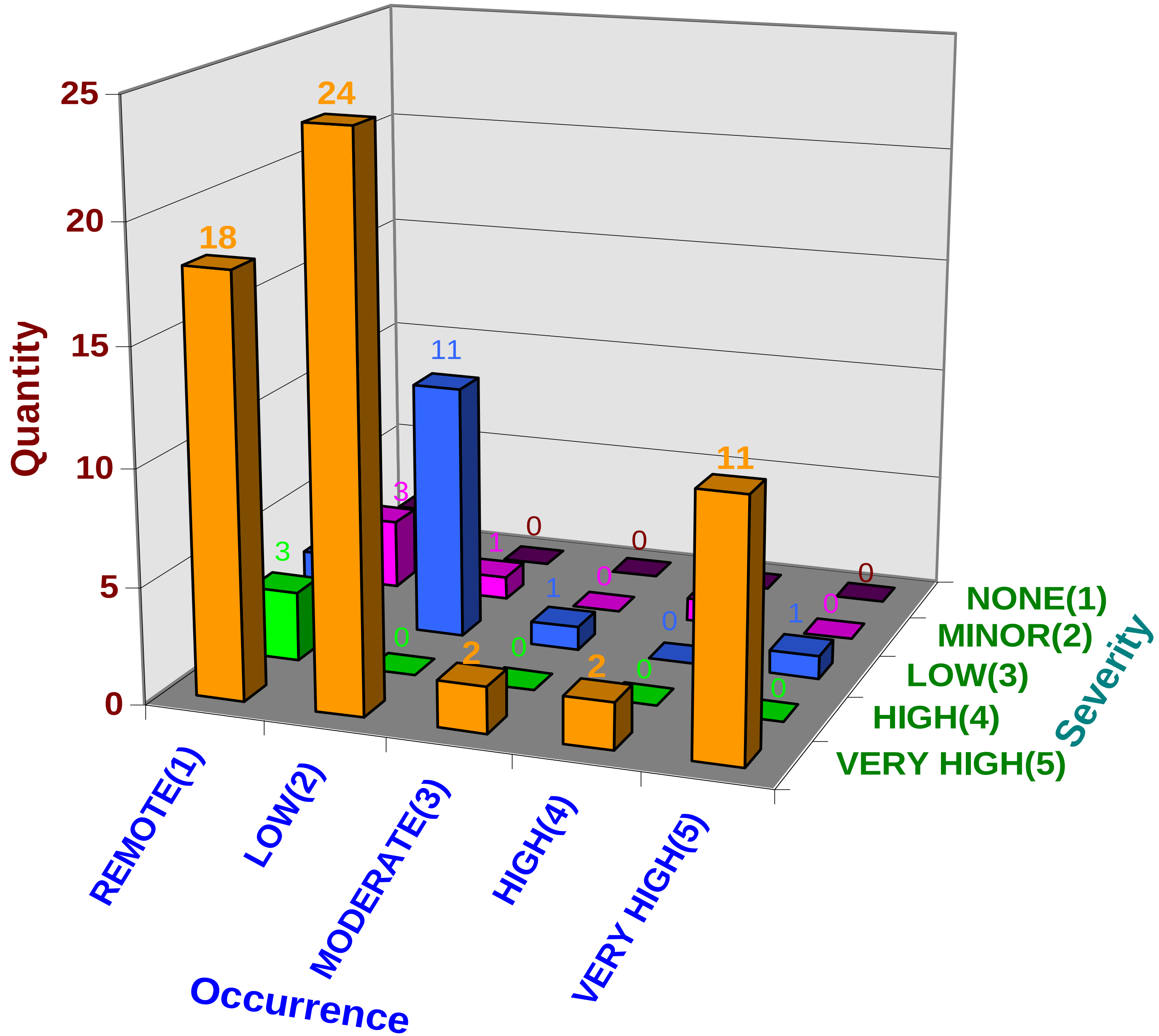
3 Major Iterations

- *Used in the Design, Fabrication and Operation Stages*

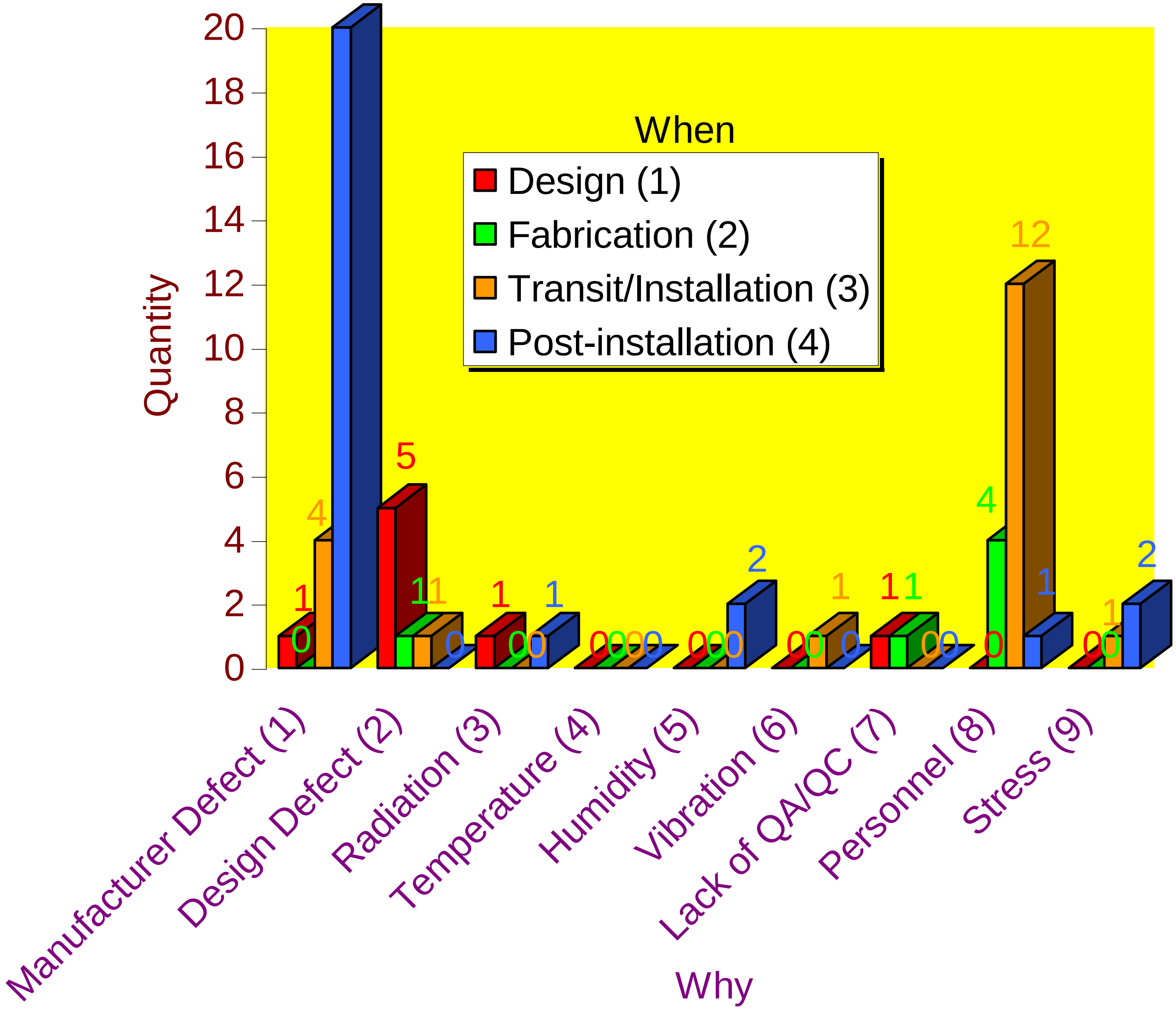
Fault Modes And Effects Criticality Analysis (FMECA)

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

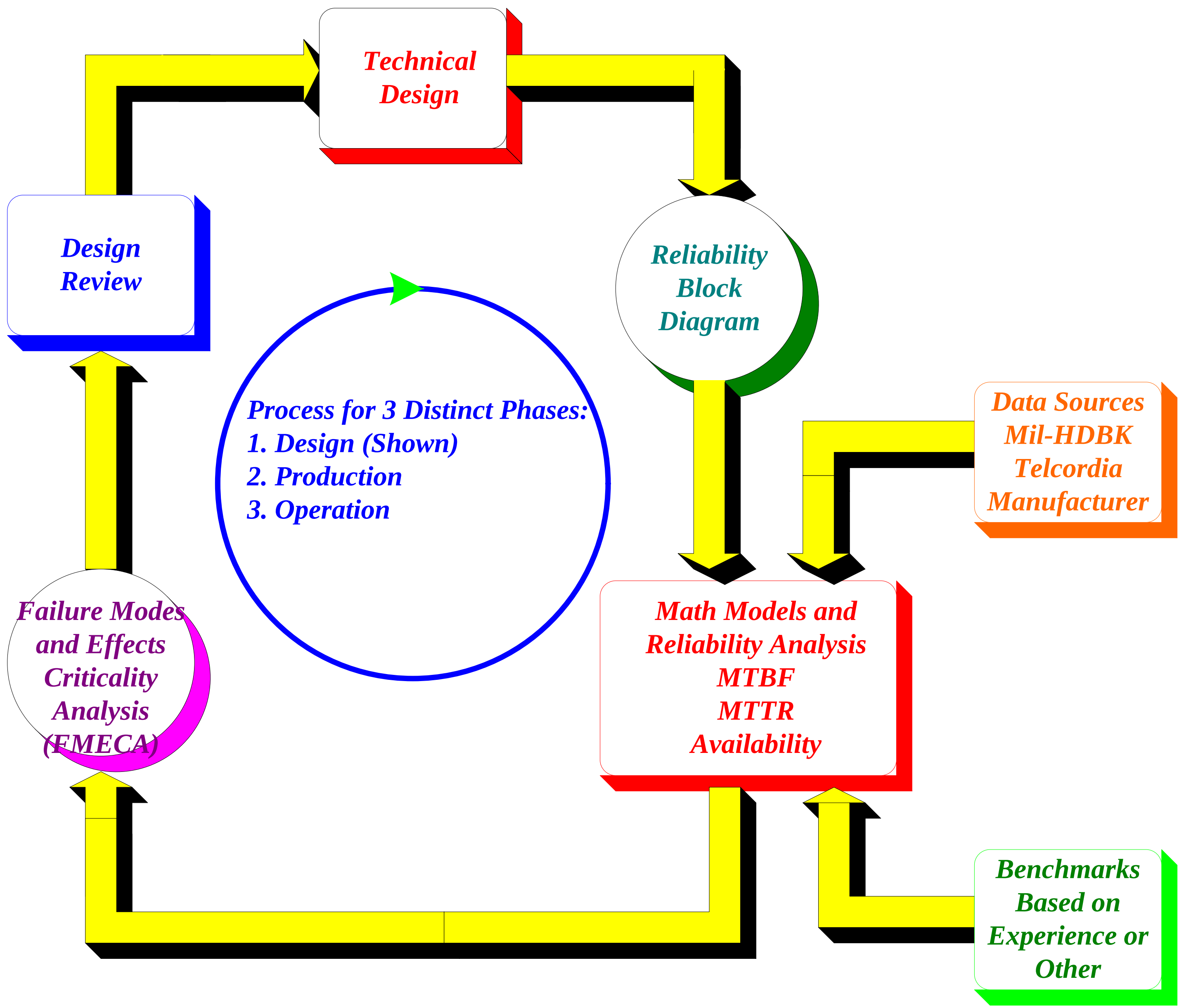
Fault Modes And Effects Criticality Analysis (FMECA)



FMECA When and Why Plot



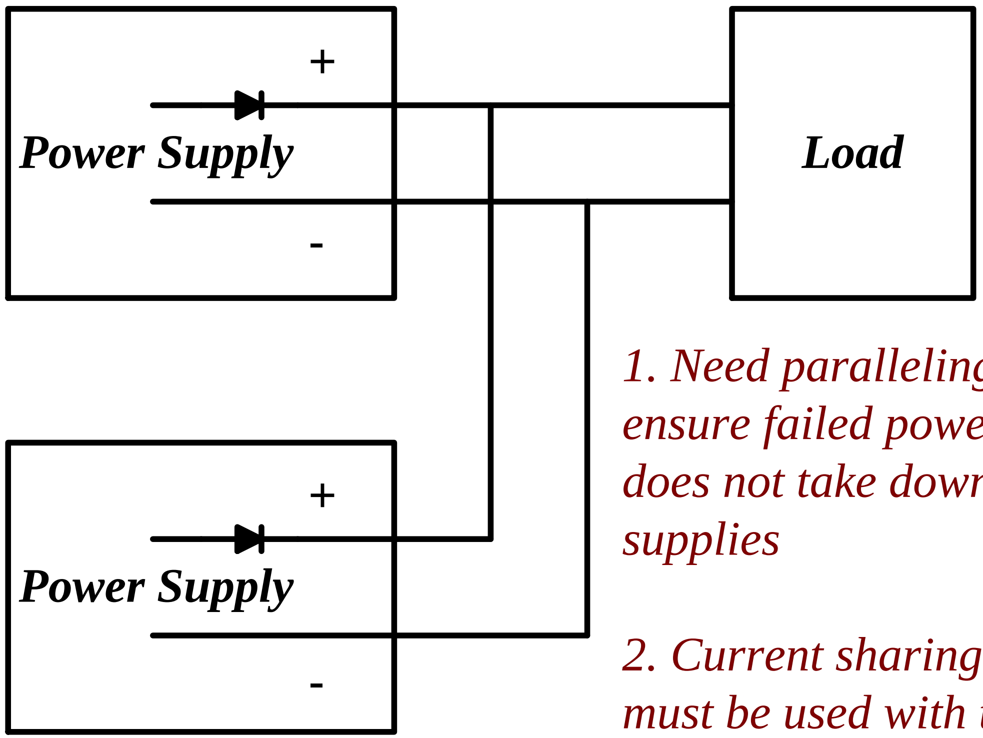
Reliability Process Diagram



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 11 - Power Supply Specifications

Power Supply Specifications

List of Specifications for 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 for 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 500μS
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

Power Supply Specifications

List of Specifications for 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 500μS
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 for 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

List of Specifications for 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 for 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 12 - 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*

Useful Textbooks And References

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*

Useful Textbooks And References

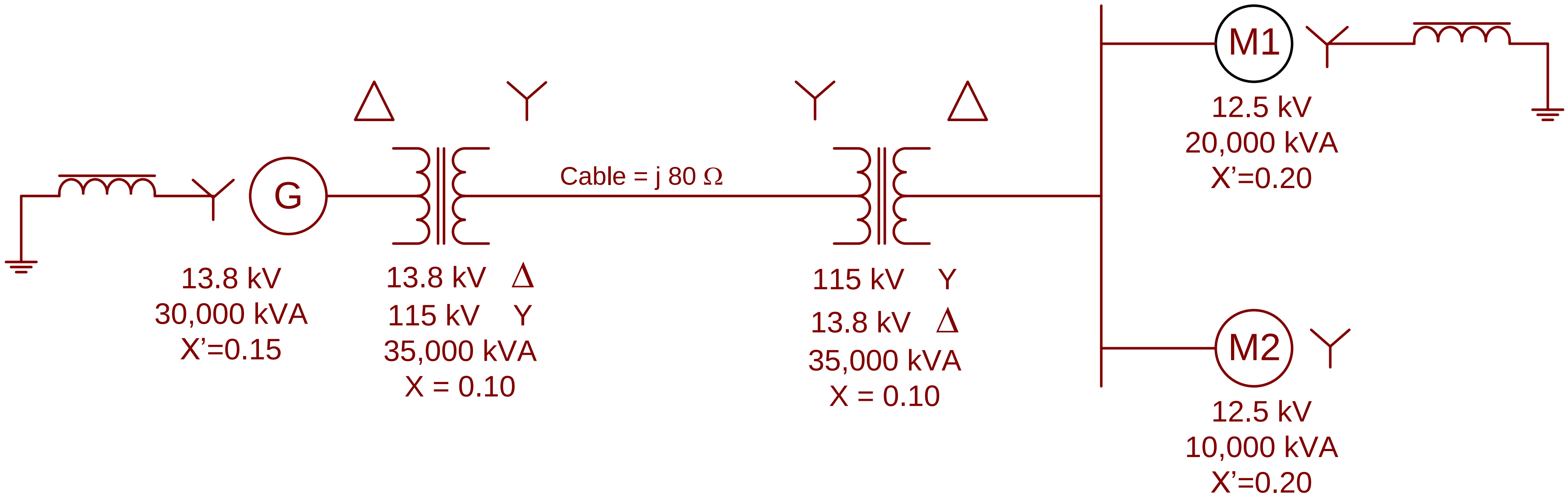
References	Used in
Table of Laplace Transforms *http://www.vibrationdata.com/Laplace.htm*	*Section 6*
Table of Fourier Transforms *http://mathworld.wolfram.com/FourierTransform.html*	*Section 6*

Section 13 - Homework Problems

Homework Problem # 1

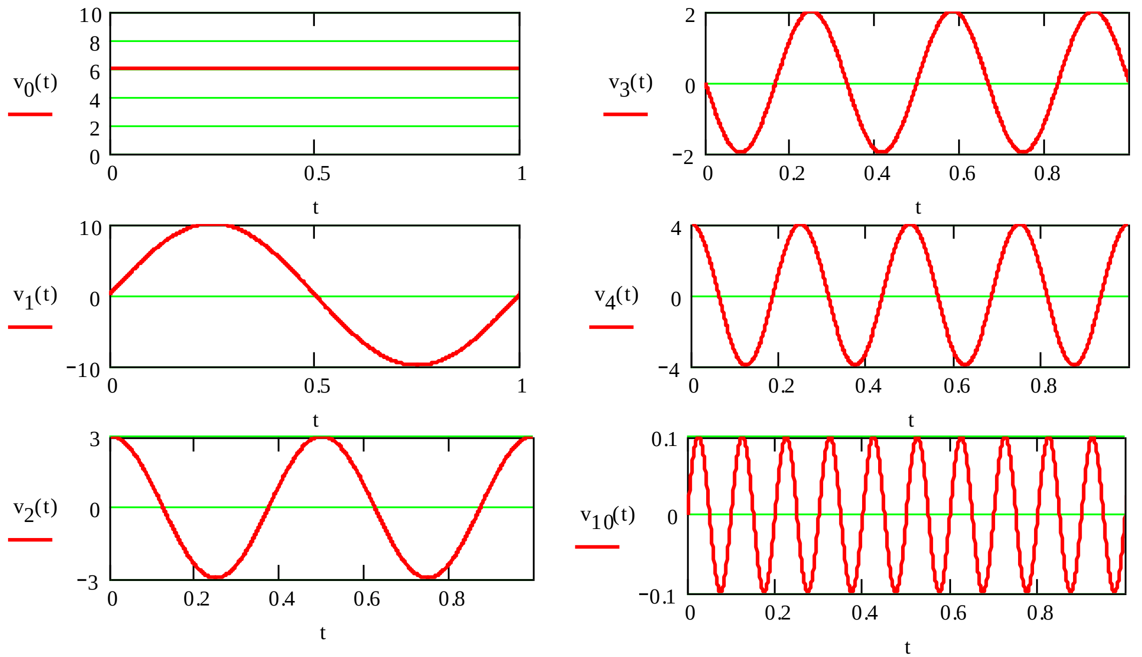
Referring to the one-line diagram below, determine the line currents in the:

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



Homework Problem # 2

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



a. Write the Fourier series for v(t) in terms of $\omega=(2*\pi)/T$

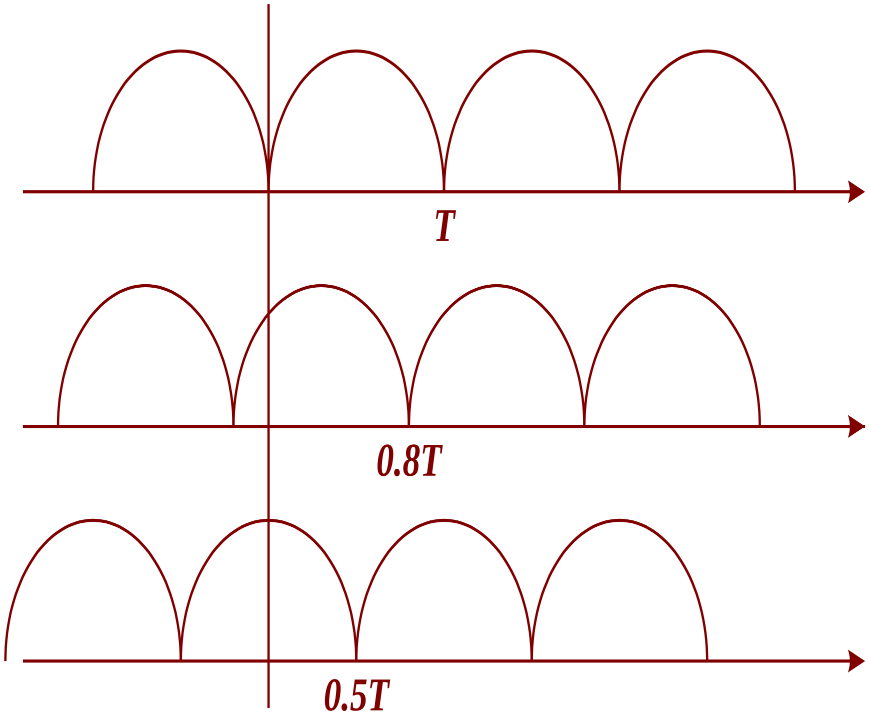
b. Show the harmonic content graphically by plotting the frequency spectrum

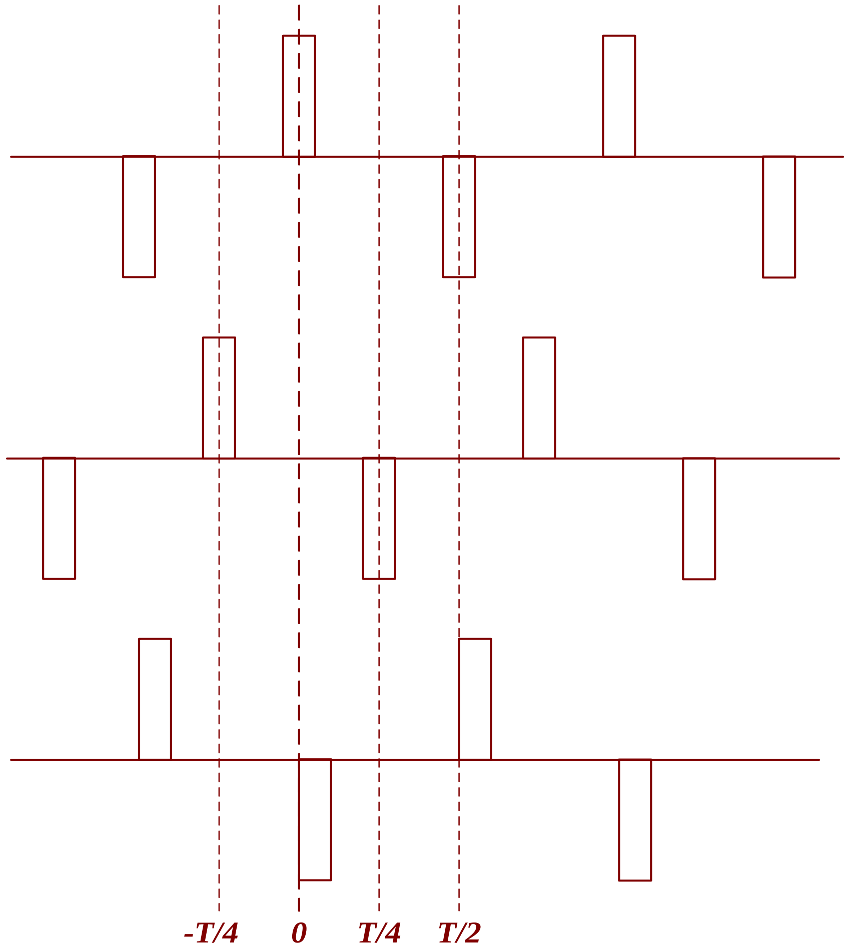
c. Give the numerical result of

$$b_3 = \frac{2}{T}\int_0^T v(t)\sin 3\omega t\,dt \qquad \textbf{Help:}\ \int \sin^2(3\omega t)\,dt = \frac{1}{3} * \frac{\frac{1}{2}\cos(3\omega t)\sin(3\omega t) + \frac{3}{2}\omega t}{\omega}$$

$$b_4 = \frac{2}{T}\int_0^T v(t)\sin 4\omega t\,dt \qquad \textbf{Help:}\ \int \cos(4\omega t)\sin(4\omega t)\,dt = \frac{-1}{8}\,\frac{\cos^2(4\omega t)}{\omega}$$

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.

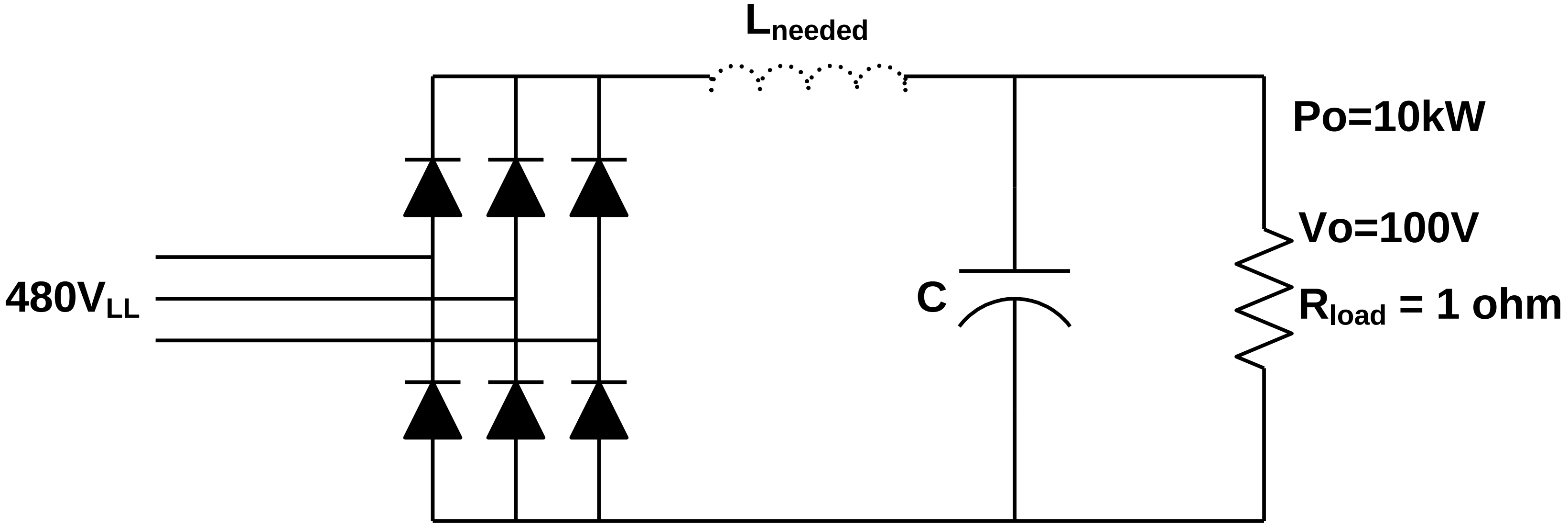




Homework Problem # 4

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 10 kW, 3 ϕ power supply has an efficiency of 90% and operates with a leading power factor of 0.8. Determine the size of a added inductor needed to improve the power factor to 0.95.



Homework Problem # 6

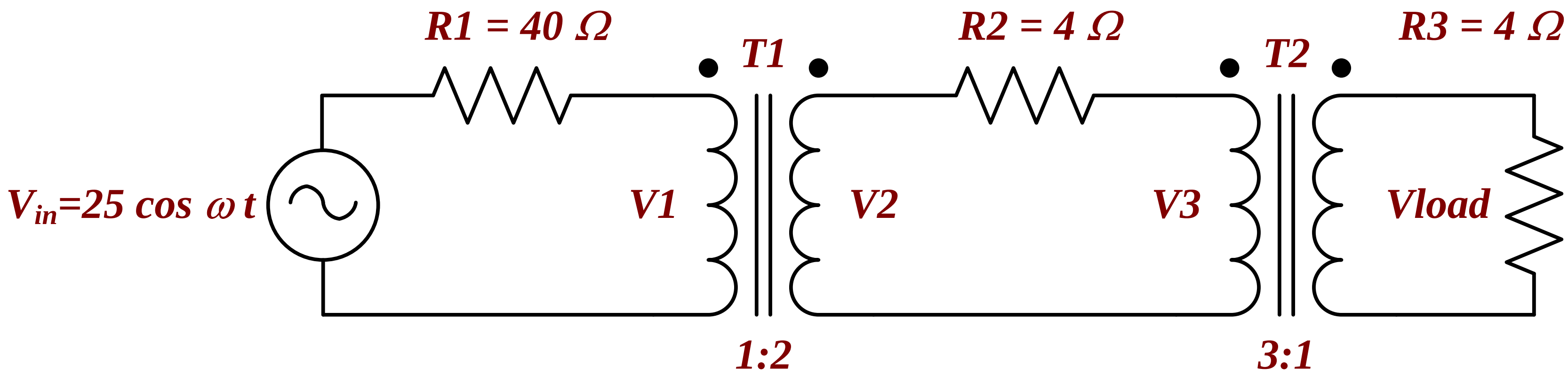
A 1000kVA, 12.47kV to 480V, 60Hz three phase transformer has an impedance of 5%. Calculate:

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

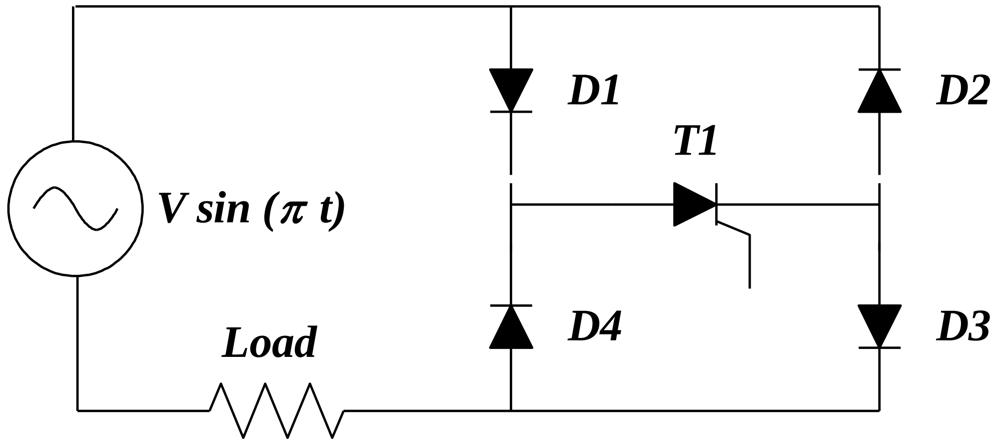
b. The actual impedance and leakage inductance referred to the secondary winding

c. The magnetizing inductance referred to the primary winding

Calculate the output voltage in the circuit shown below.



Homework Problem # 8



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

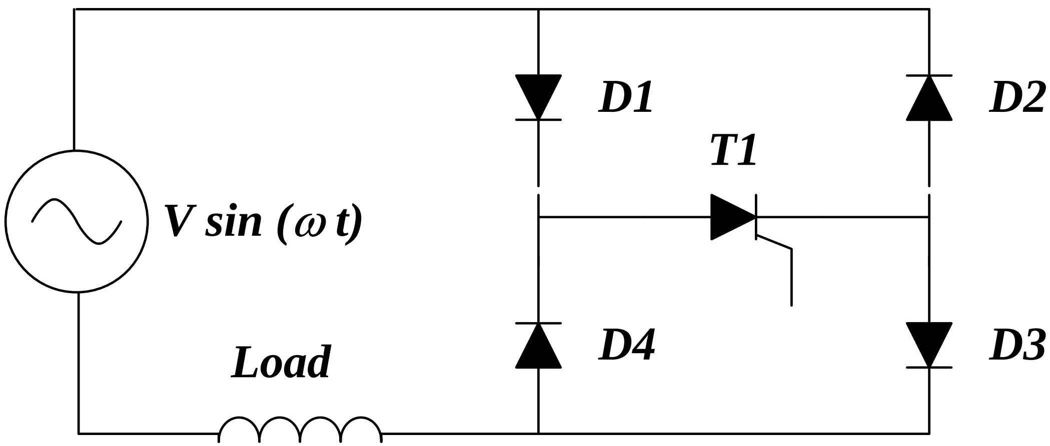
A. Explain how the circuit operates

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.

Homework Problem # 9



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

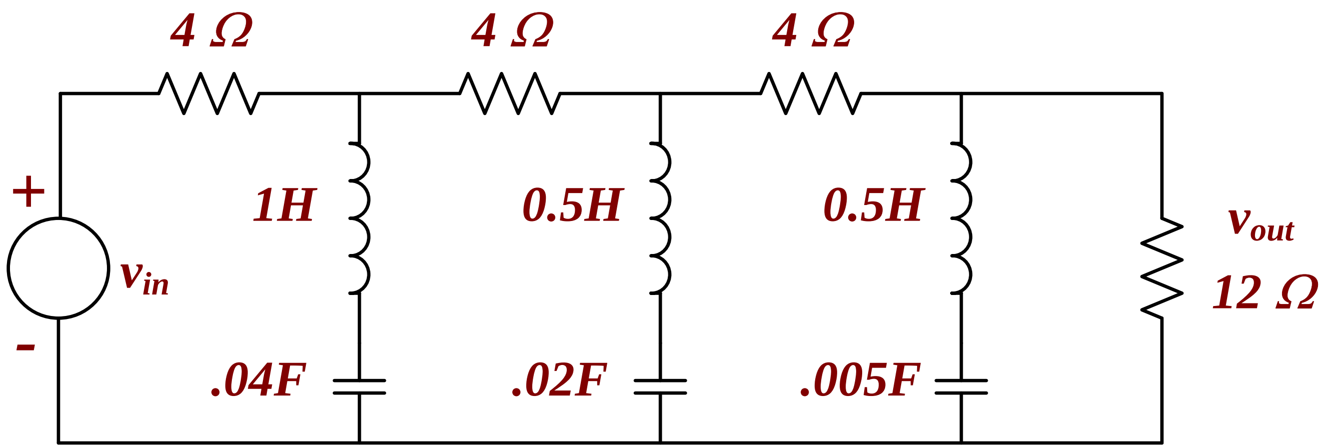
A. Explain how the circuit operates.

B. Draw the load voltage and load current waveforms 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.

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.*

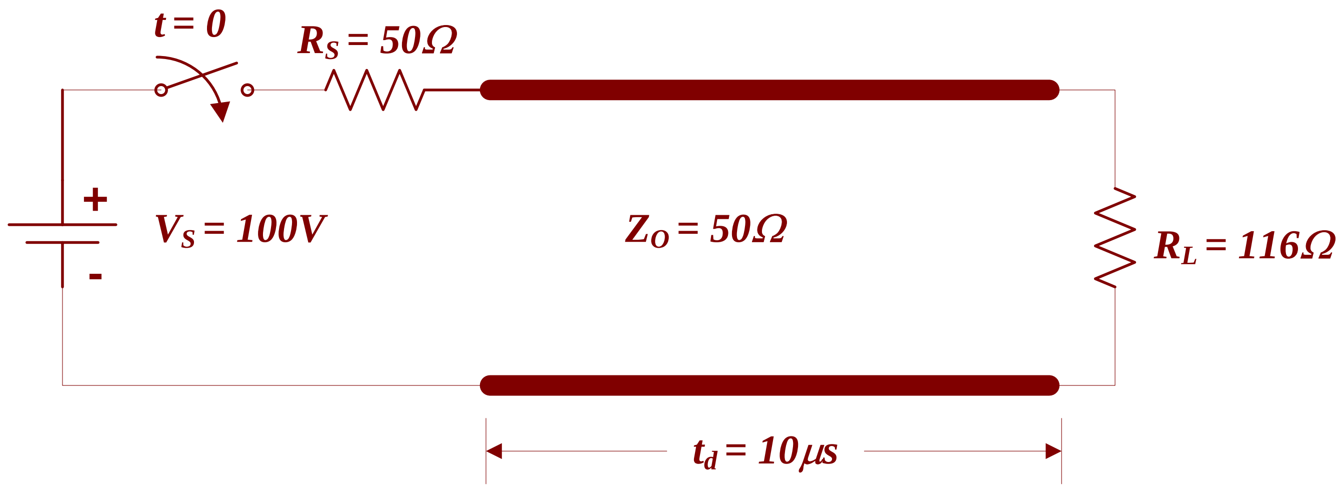
Homework Problem #12

A. *An artificial transmission line can be formed using lumped Ls and Cs. Calculate the delay of an artificial 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?*

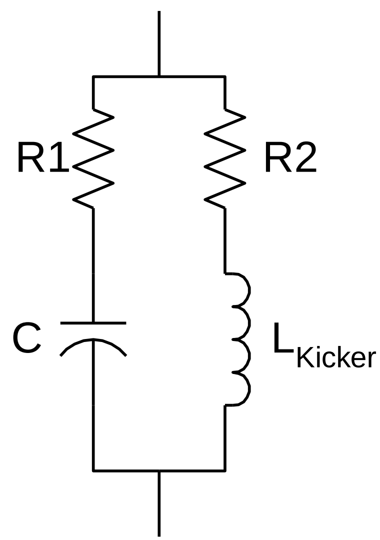
For the transmission line shown below, calculate the Reflection Coefficients Γ, the reflected voltages and the voltage and current along the line versus time.



Homework Problem # 14

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 #15

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 # 16

Homework Problem:

A. At least 2 of 4 parallel 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. Solve for three out four for success

C. Solve for four out of four for success

Homework Problem # 17

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*
- *1 each opto-isolator, λ = 1.32*
- *2 each hermetic sealed power switch transistors, λ = 0.033*
- *2 each plastic power transistors, λ = 0.026*
- *4 each plastic signal transistors, λ = 0.0052*
- *2 each hermetic sealed power diodes, λ = 0.064*
- *8 each plastic power diodes, λ = 0.019*
- *6 each hermetic sealed switch diodes, λ = 0.0024*
- *32 each composition resistors, λ = 0.0032*
- *3 each potentiometers, commercial, λ = 0.3*
- *8 each pulse type magnets, 130C rated, λ = 0.044*
- *12 each ceramic capacitors, commercial, λ = 0.042*
- *3 each film capacitors, commercial, λ = 0.2*
- *9 each Al electrolytics, commercial, λ = 0.48*

Homework Problem # 18

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 λ = 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 # 19

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.

Homework Problem # 20

It is desired to claim with 90% confidence that the actual MTBF of a power supply is 2500 hours. What must be the predicted MTBF if the test is terminated at the first test failure?