US Particle Accelerator School

University of California, Santa Cruz

Accelerator Power Electronics Engineering

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Topics

2. Purpose, Goals and Intended Audience

Purpose

- *Provide an overview of Accelerator Power Electronics Engineering with an emphasis on Power Conversion*

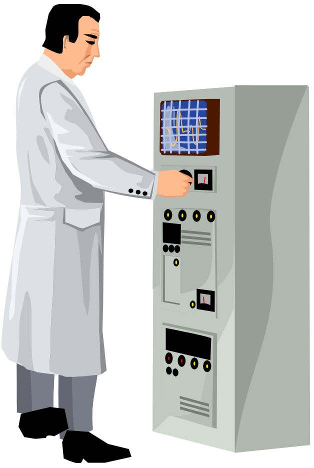
Goals

- *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 Conversion Engineering*
- *Survey the most pertinent power supply topologies from the perspectives of 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*

3. Typical Load Types

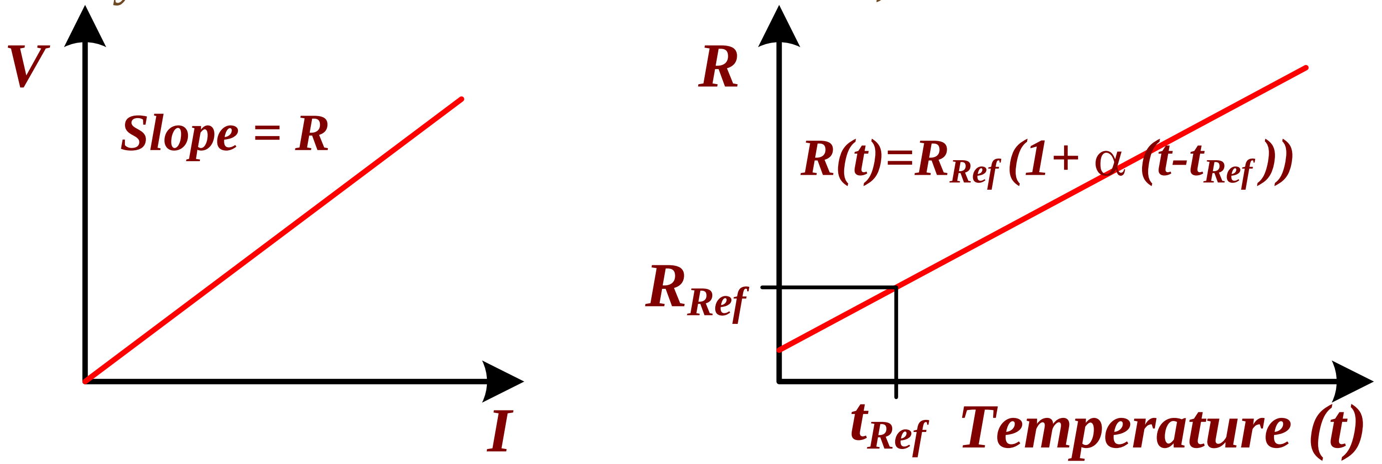
Typical Load Types

- *Resistive - Filament and Titanium Sublimation Pumps (TSPs)*
- *Capacitive Loads*
- *Direct Current (DC) Magnets*
- *Pulsed Magnets – Beam Separators, Deflectors, Electron Beam Guns, Kickers*
- *Radio Frequency (RF) loads - Klystrons, Thyratrons, Power Tubes*
- *Laser Drivers*

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

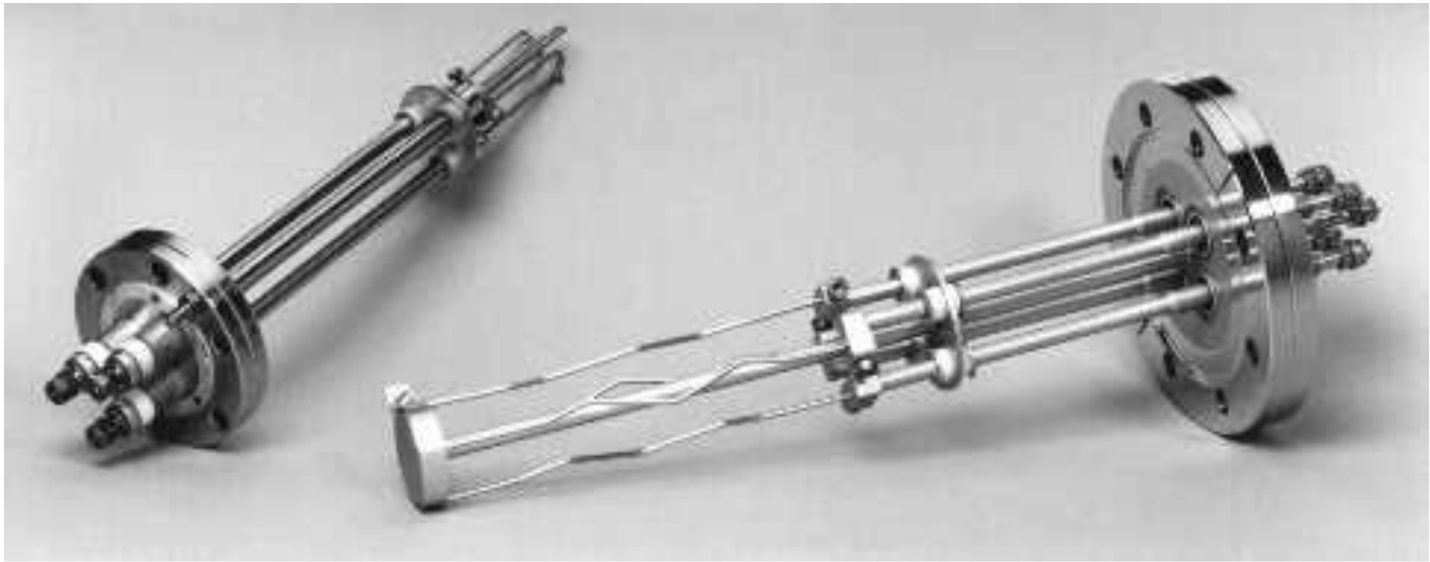
- *Low potential barrier (work function)*
- *High melting point*
- *Chemical stability at high temperatures*
- *Long life*

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*
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*

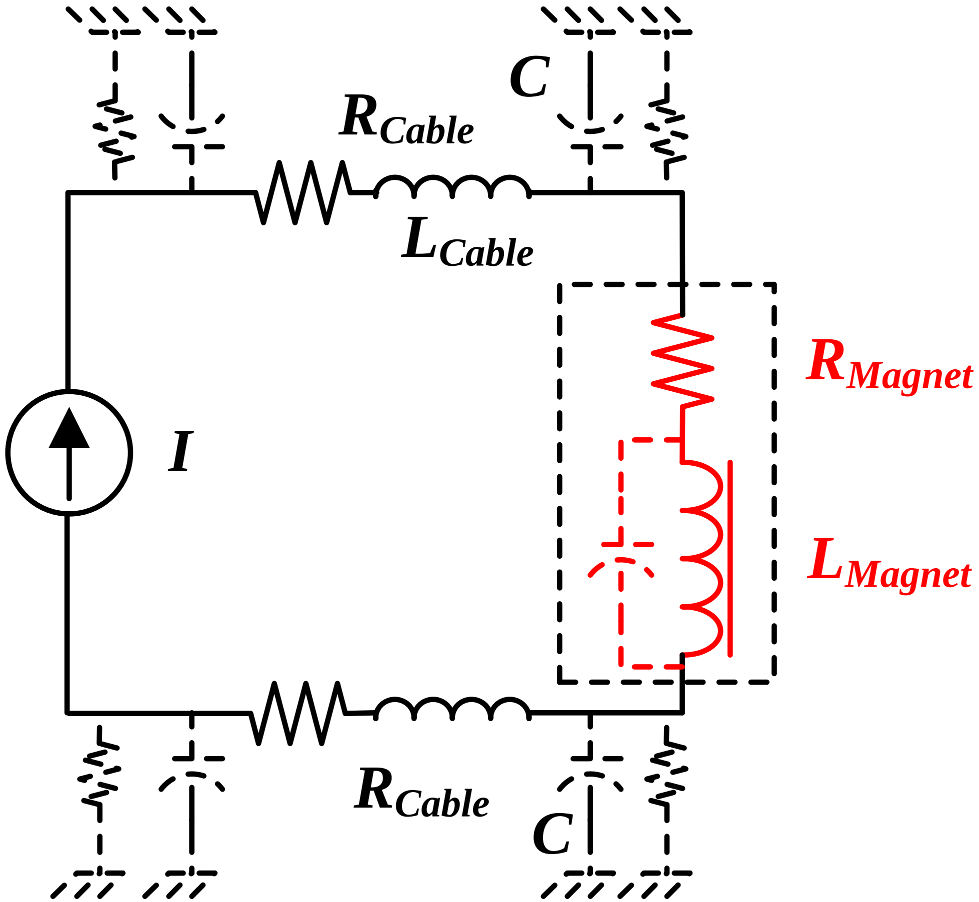


Sublimate *- To transform directly from the solid to the gaseous state or from the gaseous to the solid state without becoming a liquid.*

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

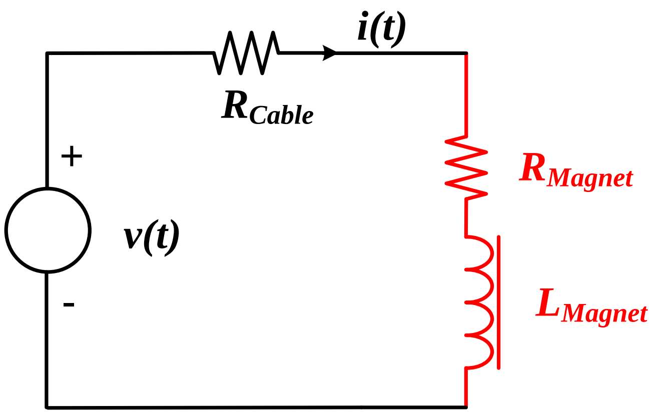
Ampere's Law

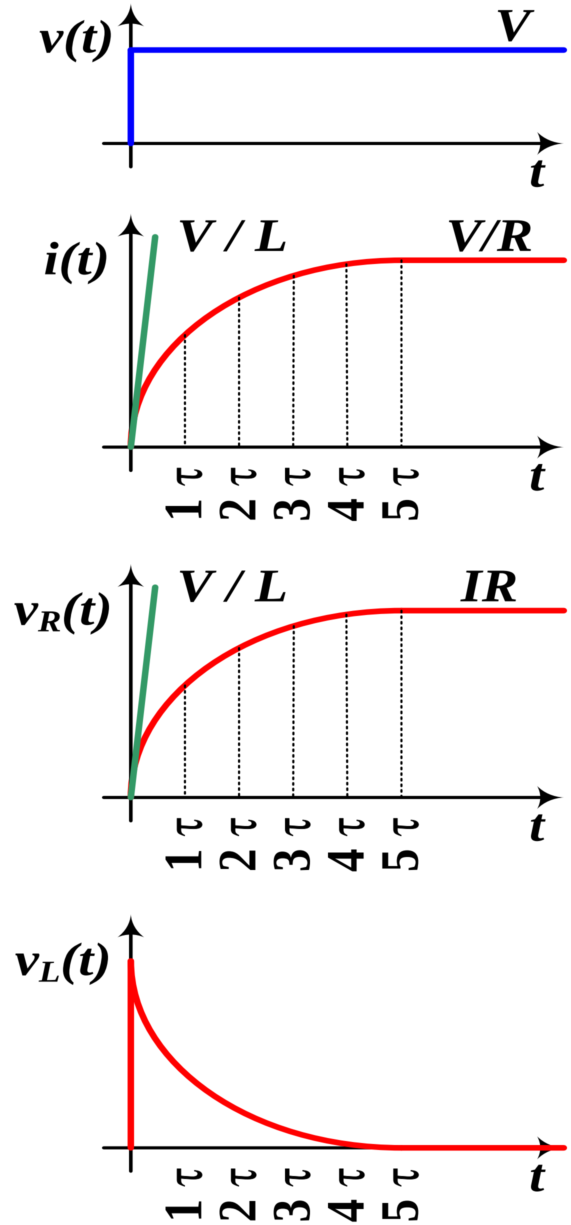
$$B = \mu H = \frac{\mu_r \mu_0 N I}{l}$$

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

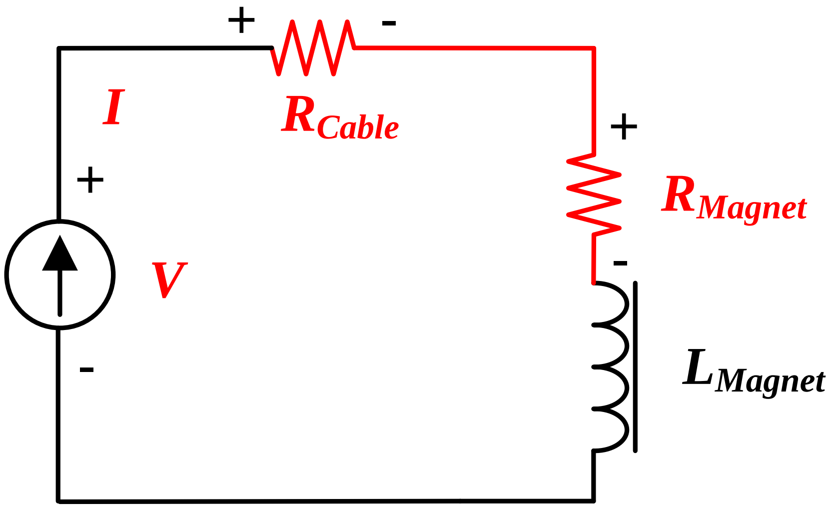
$$R\,I(s) + LsI(s) - L\,i(0) = V(s), \qquad \text{But } i(0) = 0 \text{ and } V(s) = \frac{V}{s}$$

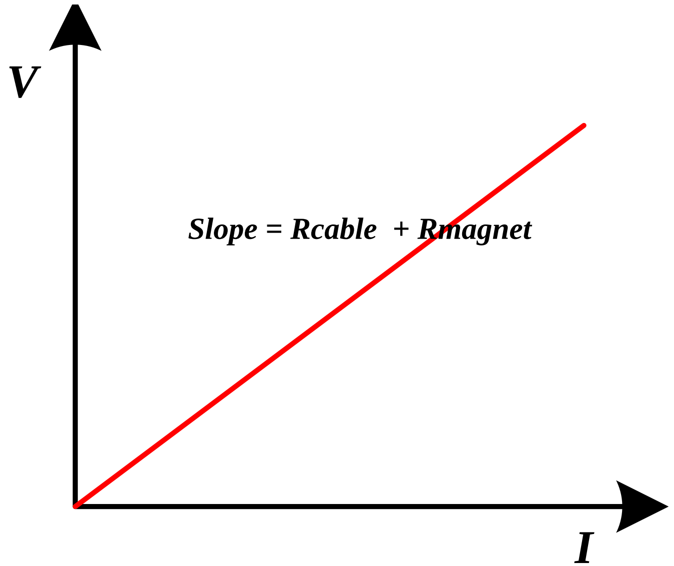
Rearranging gives

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

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

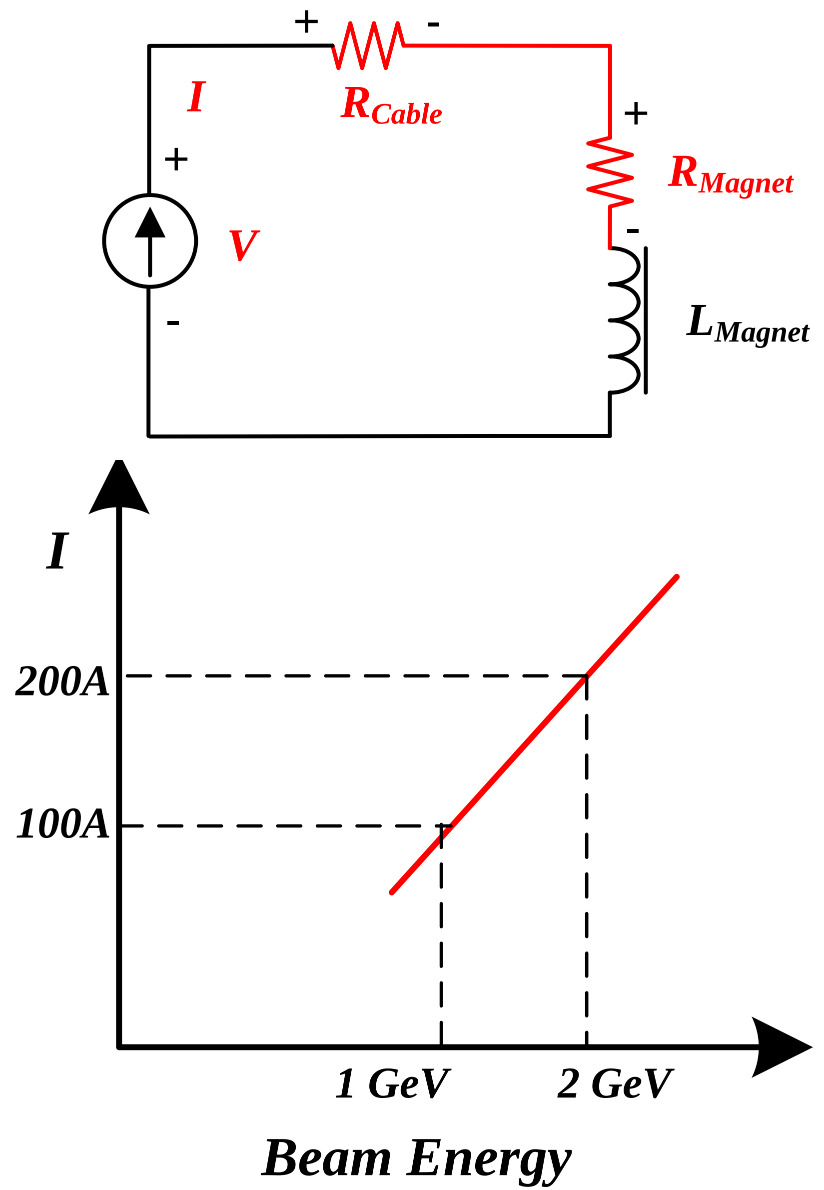
DC Magnet Loads – Characteristics

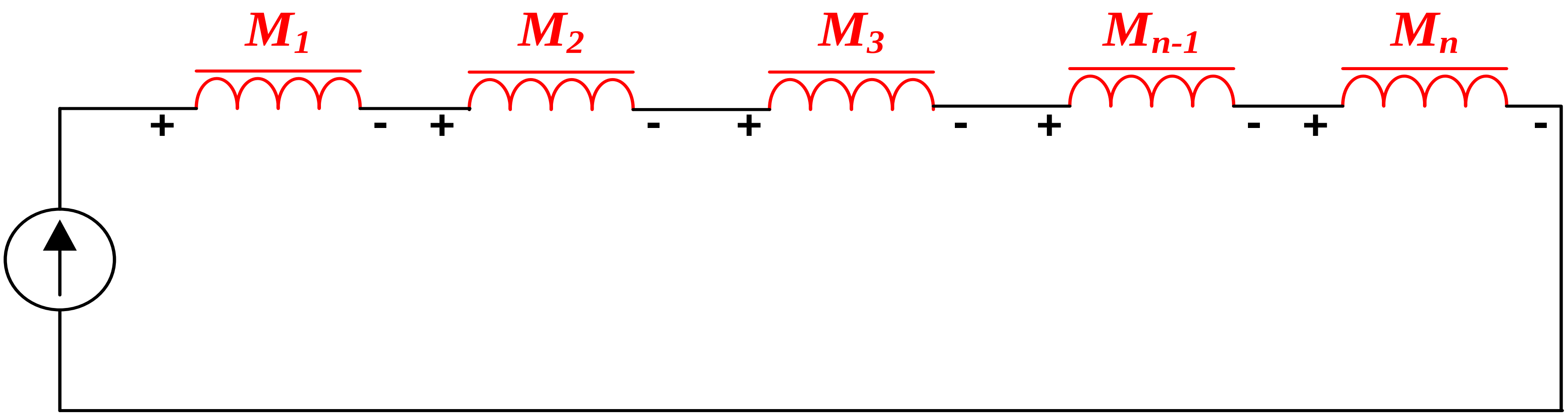




DC V-I Characteristic

DC Magnet Loads – Characteristics

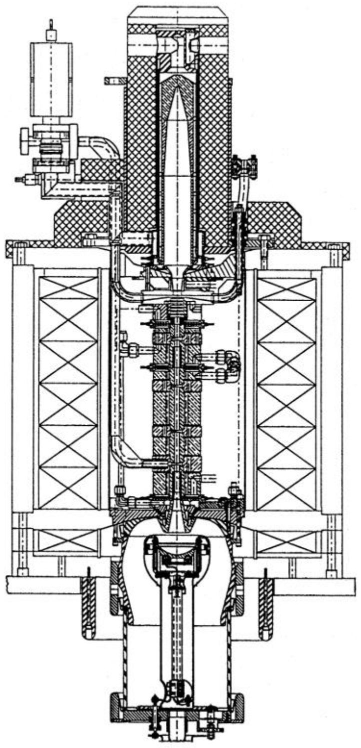


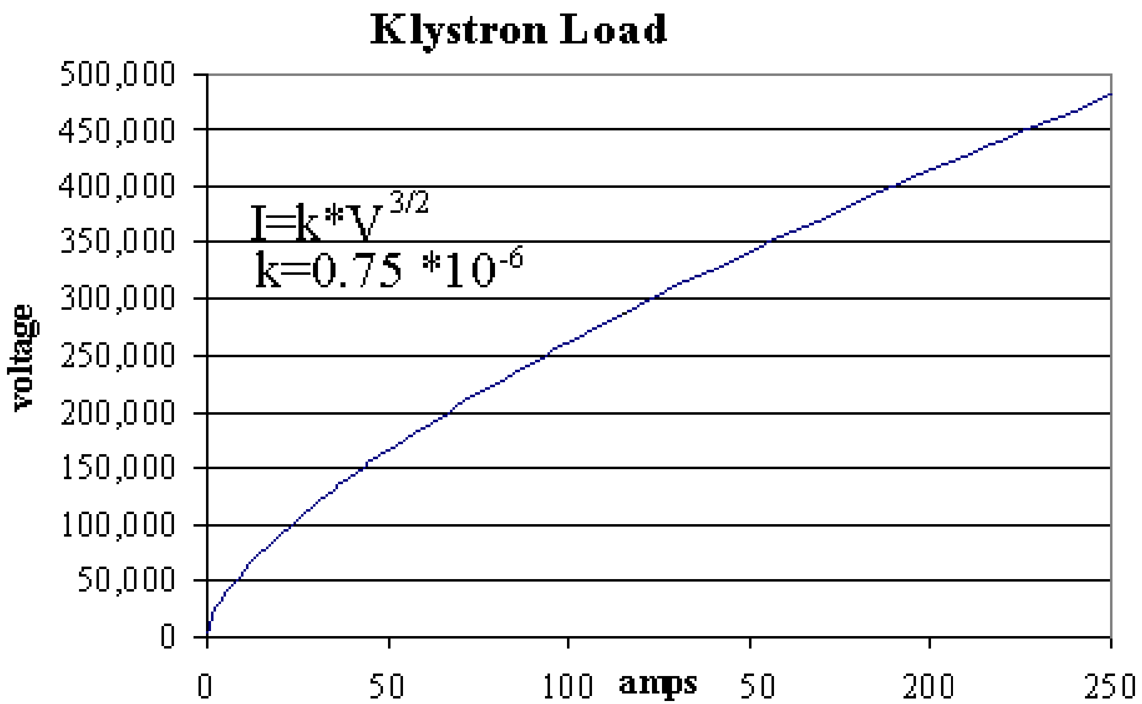


String (series-connect) magnets for economy when magnets are not adjacent to insertion devices or no local optics tuning is involved. The current in each series-connected magnet is the same.

Klystron Load

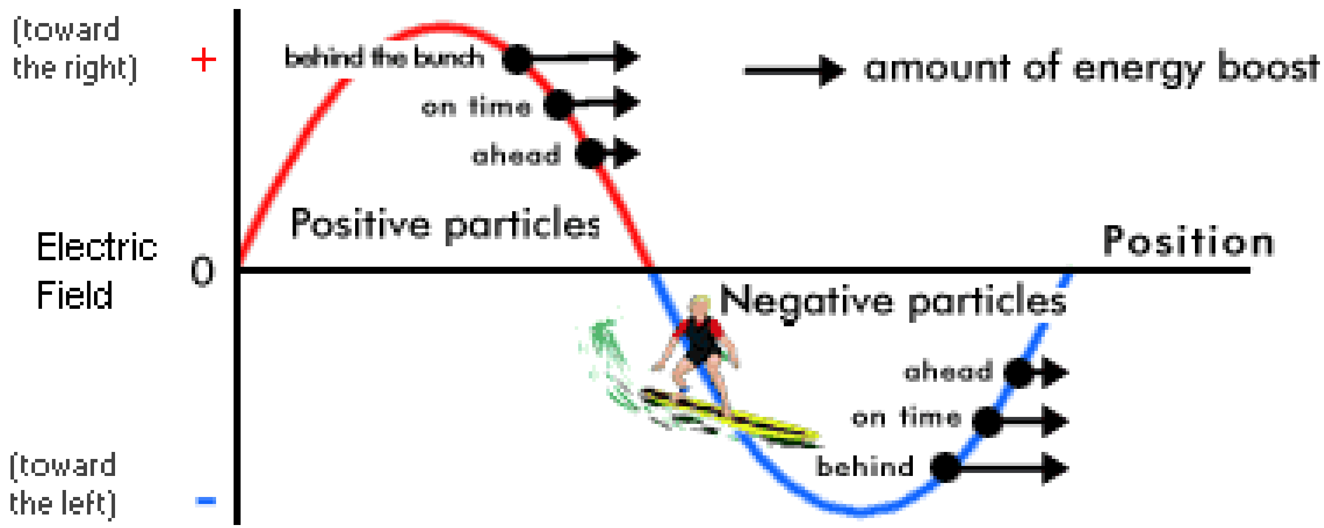
- Klystrons are used in RF and microwave systems to accelerate electron beams
- Their transfer function is called perveance (k) which is the ratio between beam current and accelerating voltage. Perveance is usually expressed in μp.
- In booster rings they are used in a pulsed mode to accelerate the electron beam
- In 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





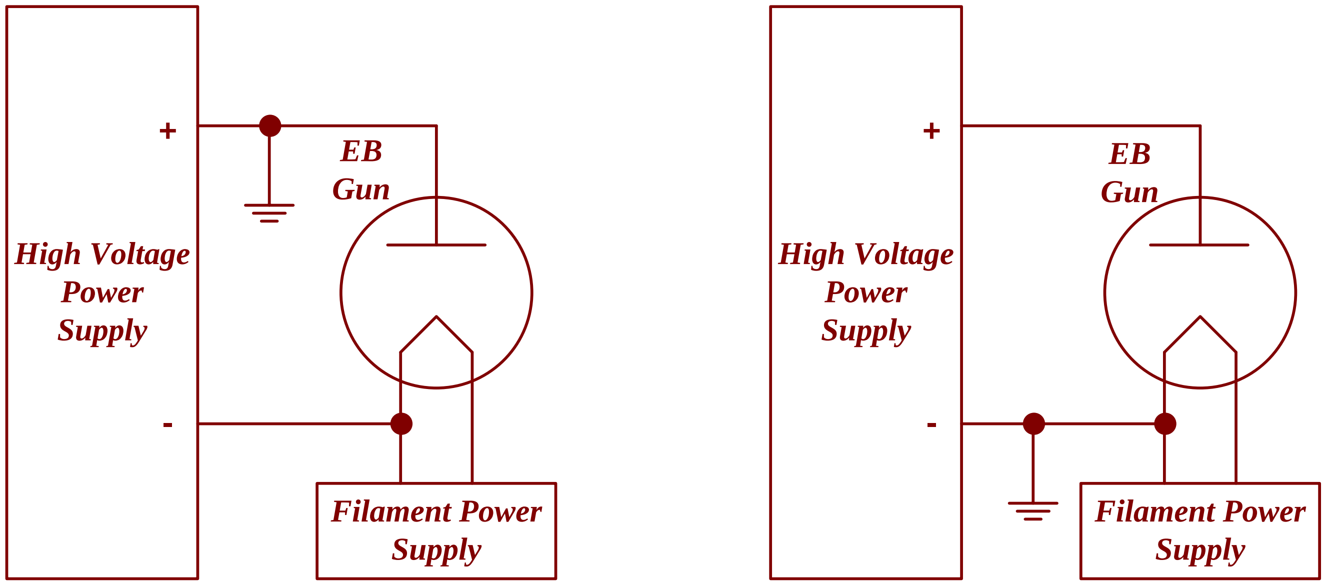
Klystrons and Linear Accelerators

- *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

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

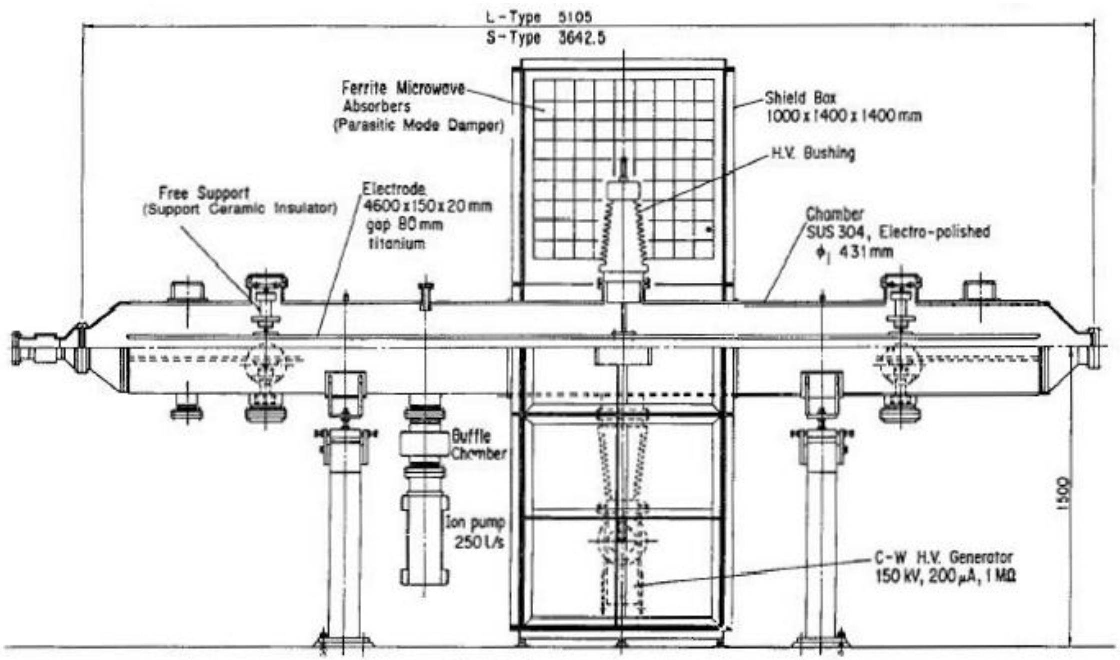


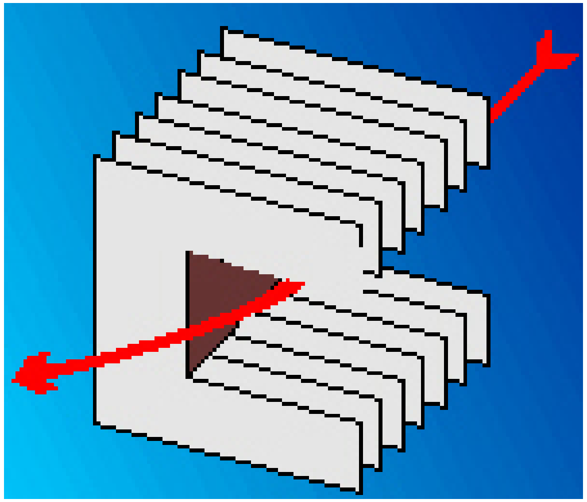
Fig.2 Separator chamber.

Pulsed Magnet Loads - Kickers, Pulsed Deflectors, Etc.

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

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

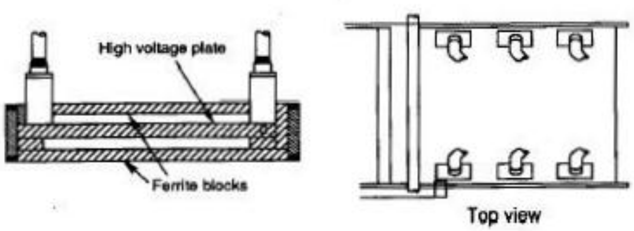
- *An ejection kicker will do the inverse, that is, kick a particle beam into a linear line section from a storage ring*



Pulsed Magnet Loads - Kickers, Pulsed Deflectors

- *Short time constants (τ = 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.



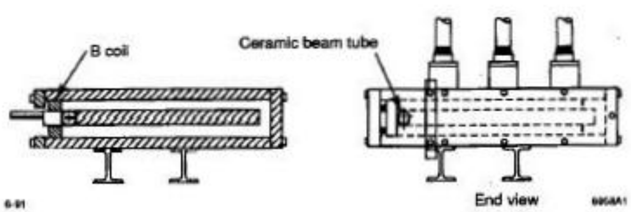
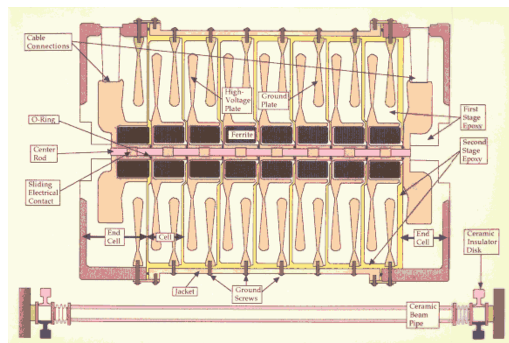
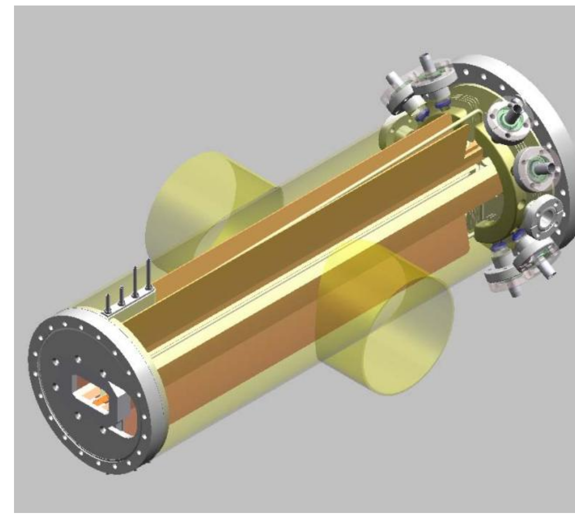
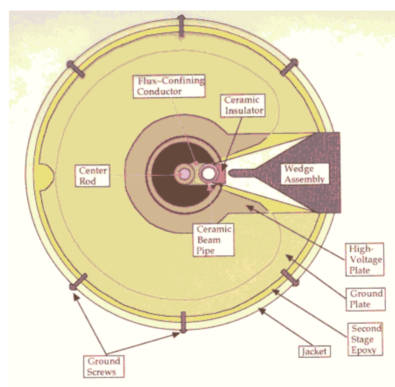
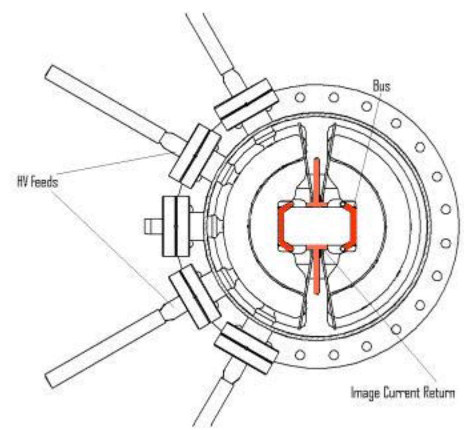


Fig. 6. SLAC-style kicker magnet.



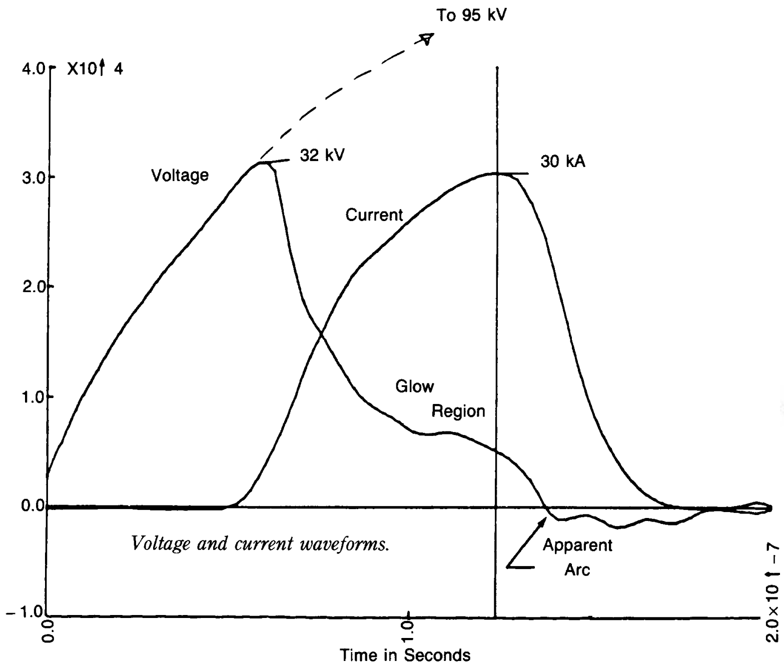






Flash Lamp Load Characteristics

- *Pulsed load - a gas-filled flash lamp*
- *High voltage, high current load*
- *Highly non-linear load, subject to break-down*
- *Subject to aging, misfiring, arcing, and jitter*
- *Limited energy capability - arc protection (crowbar) needed*



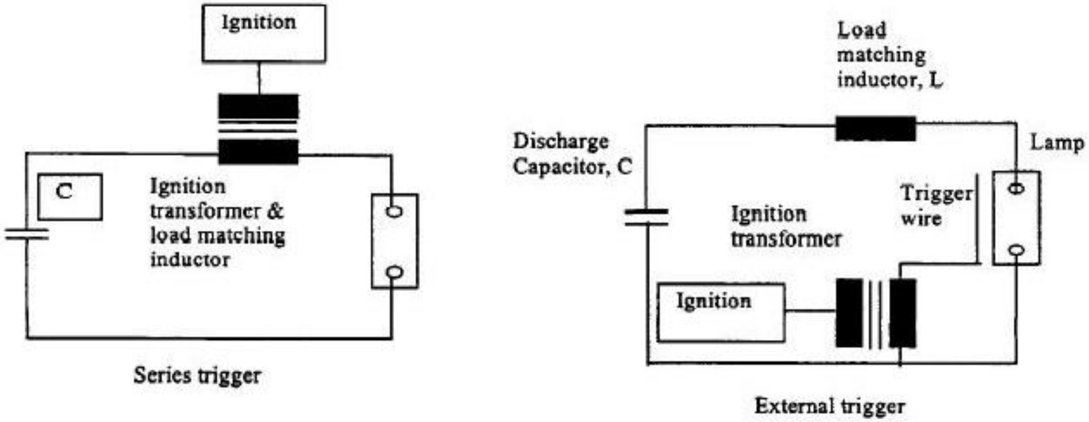


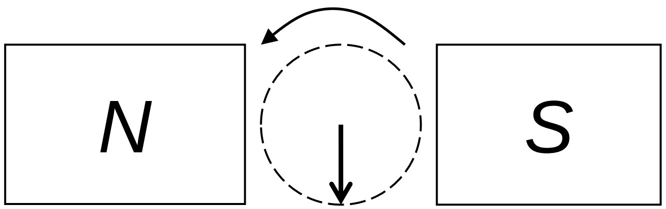
Fig.2 Series and Coil based Trigger systems

4. Power Line Considerations

Power Line Considerations

- *Fundamental Quantities*
- *The "Per Unit" Calculation System*
- *Harmonics and Fourier Series*
- *Harmonic Distortion and Causes*
- *Why Power Factor is Important*
- *Electromagnetic Interference (EMI) / Electromagnetic Compatibility (EMC)*

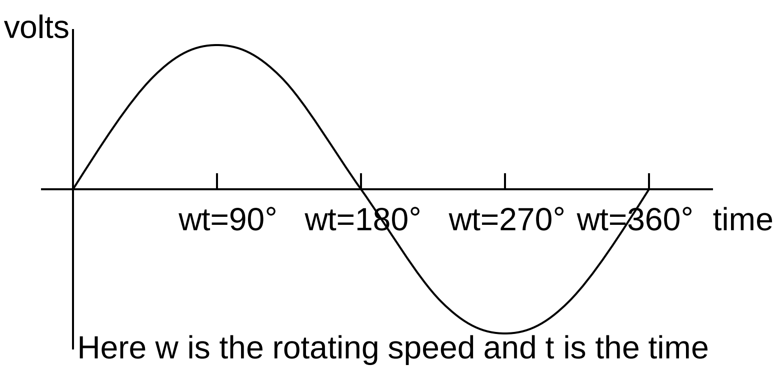
- *Generation of sine waves*



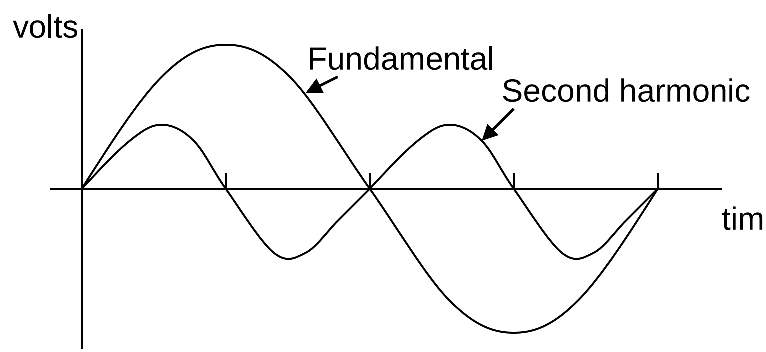
- *Expression of sine waves*

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

- *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

$$v(t) = V_m \cos(\omega t), then \quad V_{ave} = \frac{1}{T}\int_0^T V_m \cos(\omega t)dt = 0$$

- *RMS value:*

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

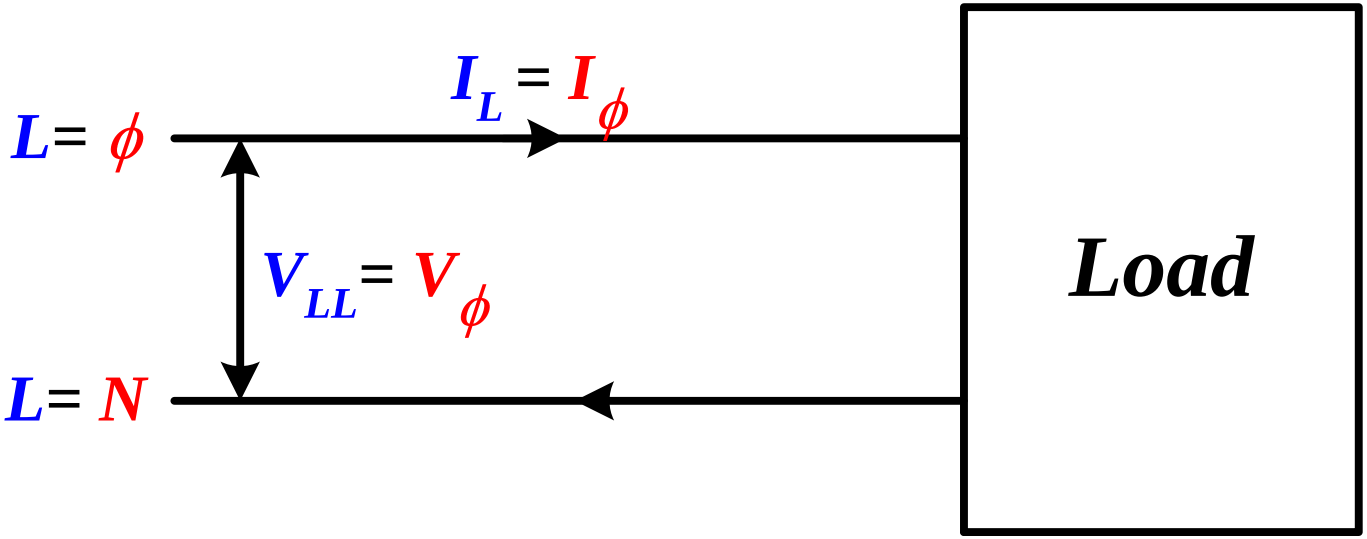
for AC sine system

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T (V_m \cos(\omega t))^2 dt} = V_m \sqrt{\frac{1}{T}\int_0^T \frac{1+\cos(2\omega t)}{2} dt} = \frac{V_m}{\sqrt{2}}$$

Some American "Standard" 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

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



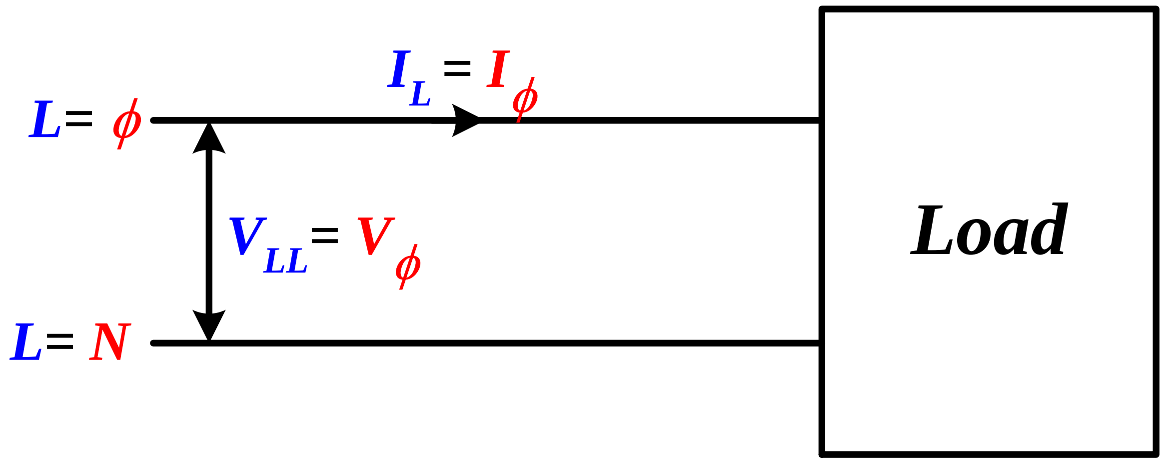
For 1ϕ AC input

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

$$I_\phi = I_L$$

where V_ϕ and I_ϕ are RMS values

Single Phase Quantities



The Apparent, Real and Reactive "powers" are:

Apparent	$S_{1\phi} = V_{LL}\ I_L = P_{1\phi} + j\ Q_{1\phi}$	*VA*	
Real	$P_{1\phi} = V_{LL}\ I_L \cos(\alpha_{I_L} - \beta_{V_{LL}})$	*Watt*	$\cos(\alpha_{I_L} - \beta_{V_{LL}}) =$ *power factor*
Reactive	$Q_{1\phi} = V_{LL}\ I_L \sin(\alpha_{I_L} - \beta_{V_{LL}})$	*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 Quantities

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

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

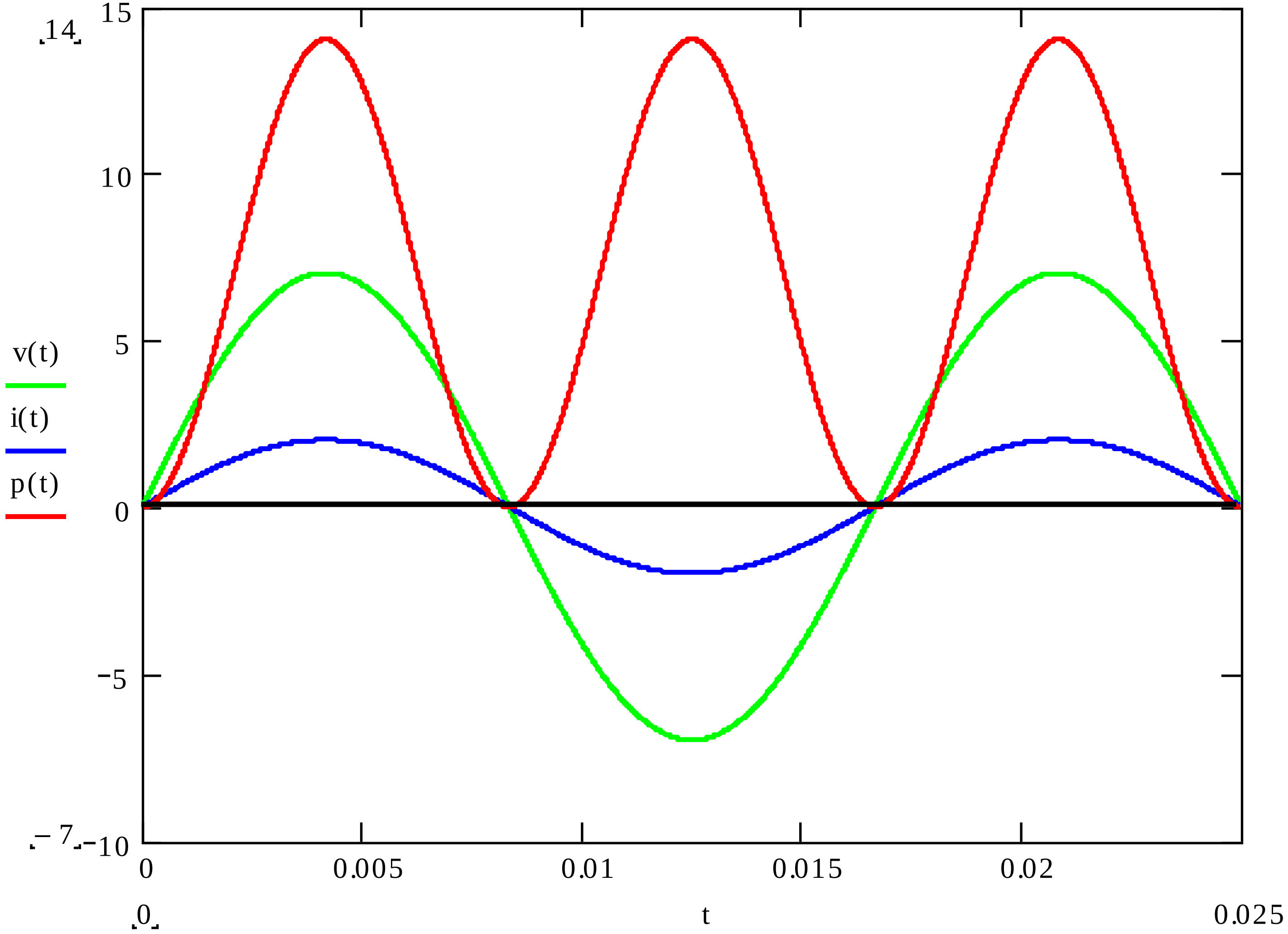
It is seen that

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

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

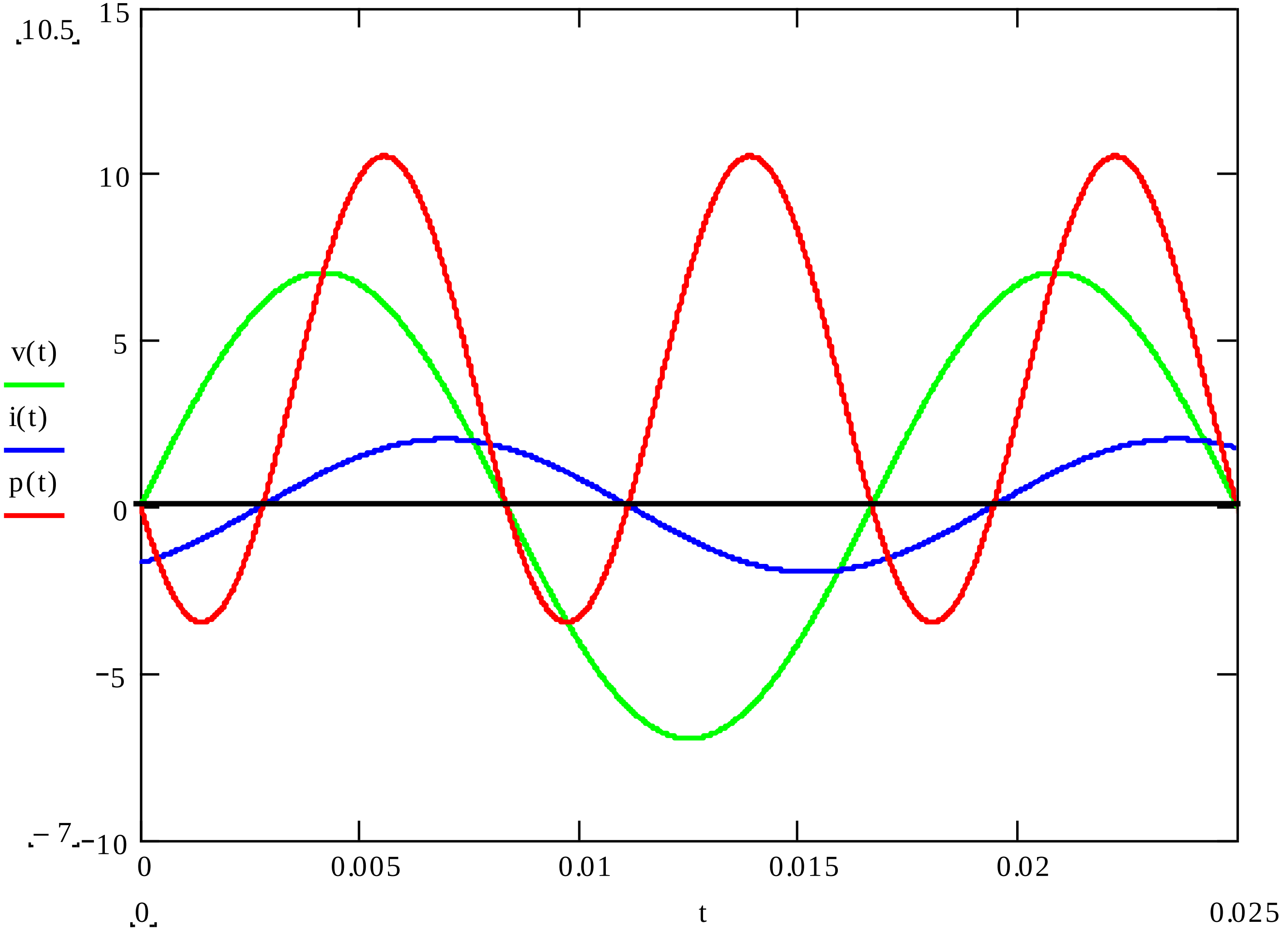
The power is the product of the RMS values of the line – line voltage and line current

Single Phase Quantities



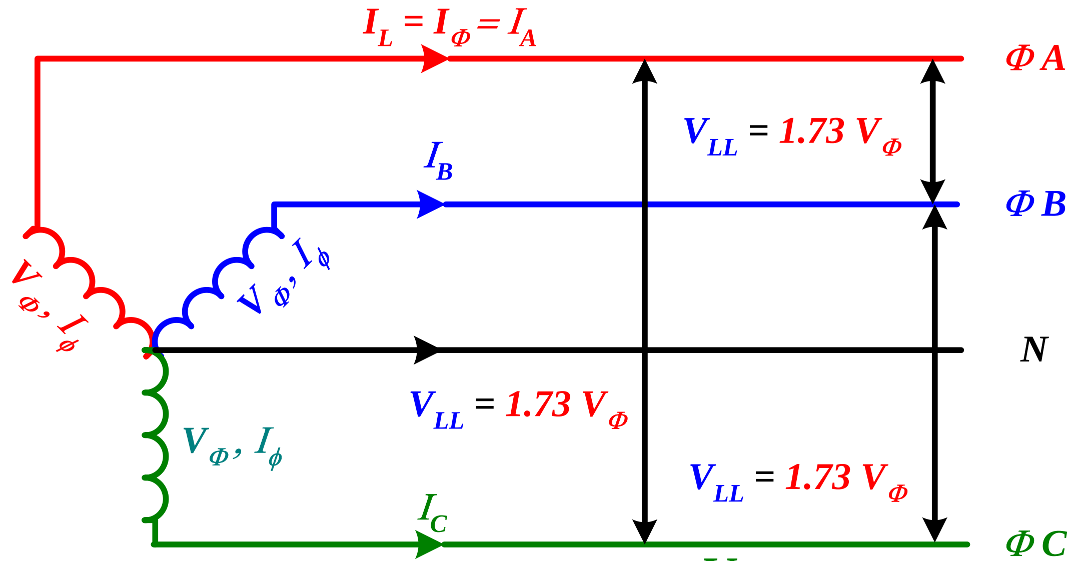
- *Voltage and current are in phase at 60 Hz*
- *Power is + (delivered to load) at 120 Hz*

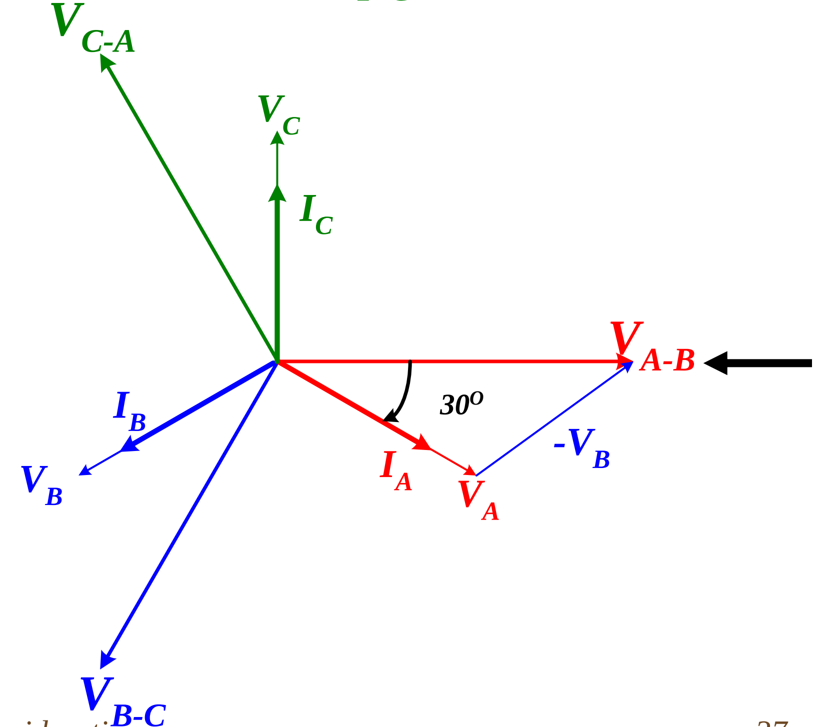
Single Phase Quantities



- Voltage leads current by 60^O at 60 Hz
- Power is + (delivered to load) and – (returned to the AC line) and 120 Hz

Three Phase Wye

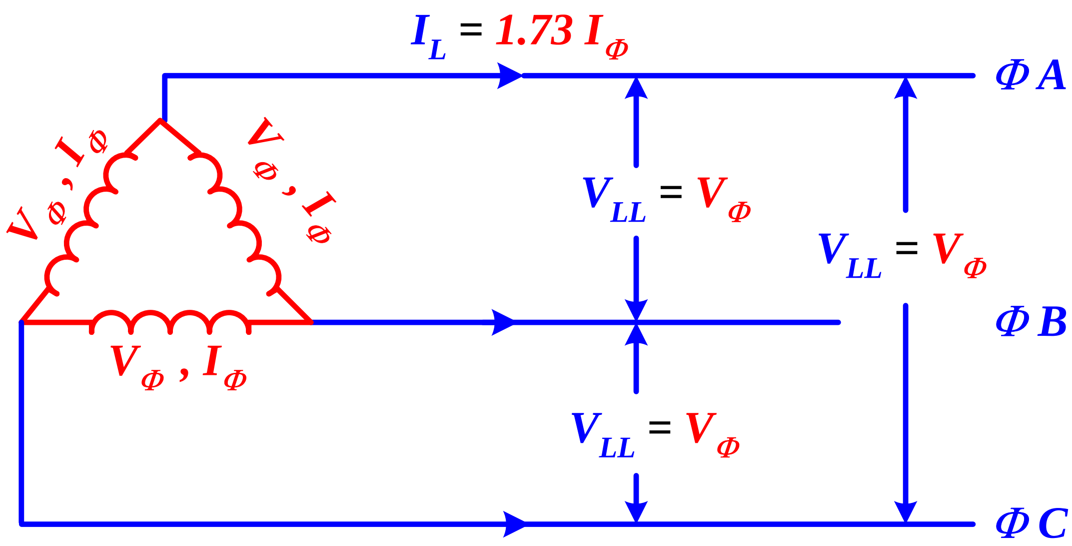




$$V_{LL} = \sqrt{3}\ V_{\phi}\ \text{and}\ I_L = I_{\phi}$$

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

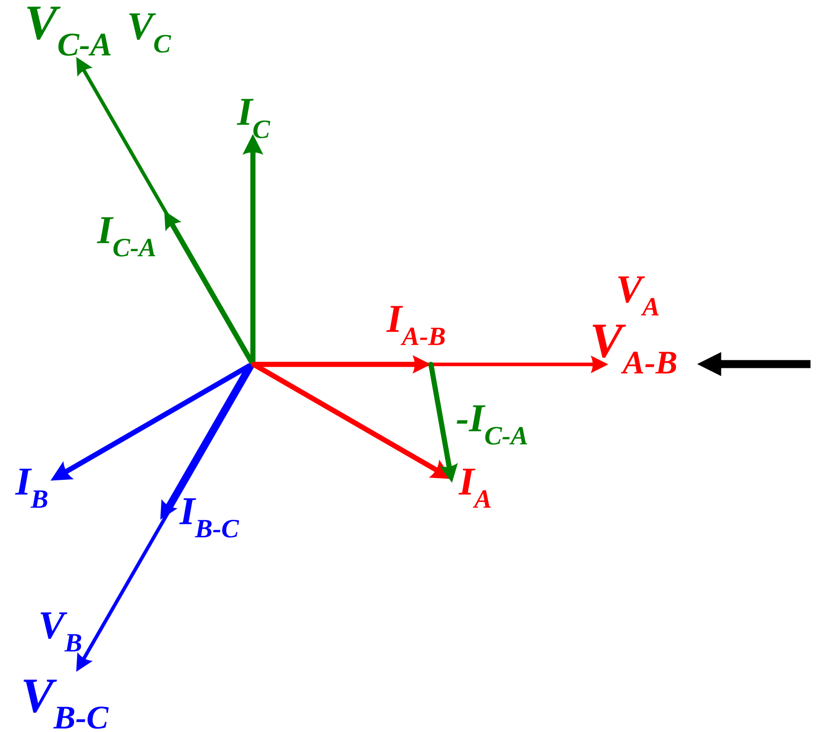
$$S_{3\phi} = \sqrt{3}\ V_{LL}\ \ I_L$$

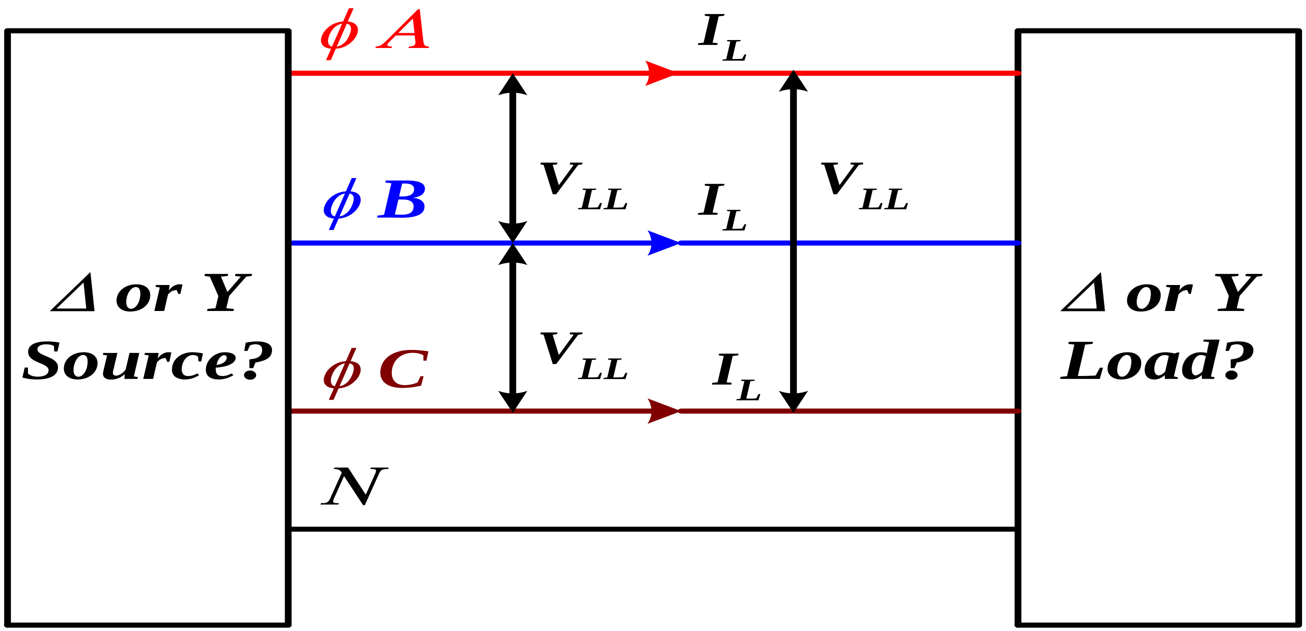


$$V_{LL} = V_{\phi} \quad and \; I_{L} = \sqrt{3}\, I_{\phi}$$

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

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





For Wye

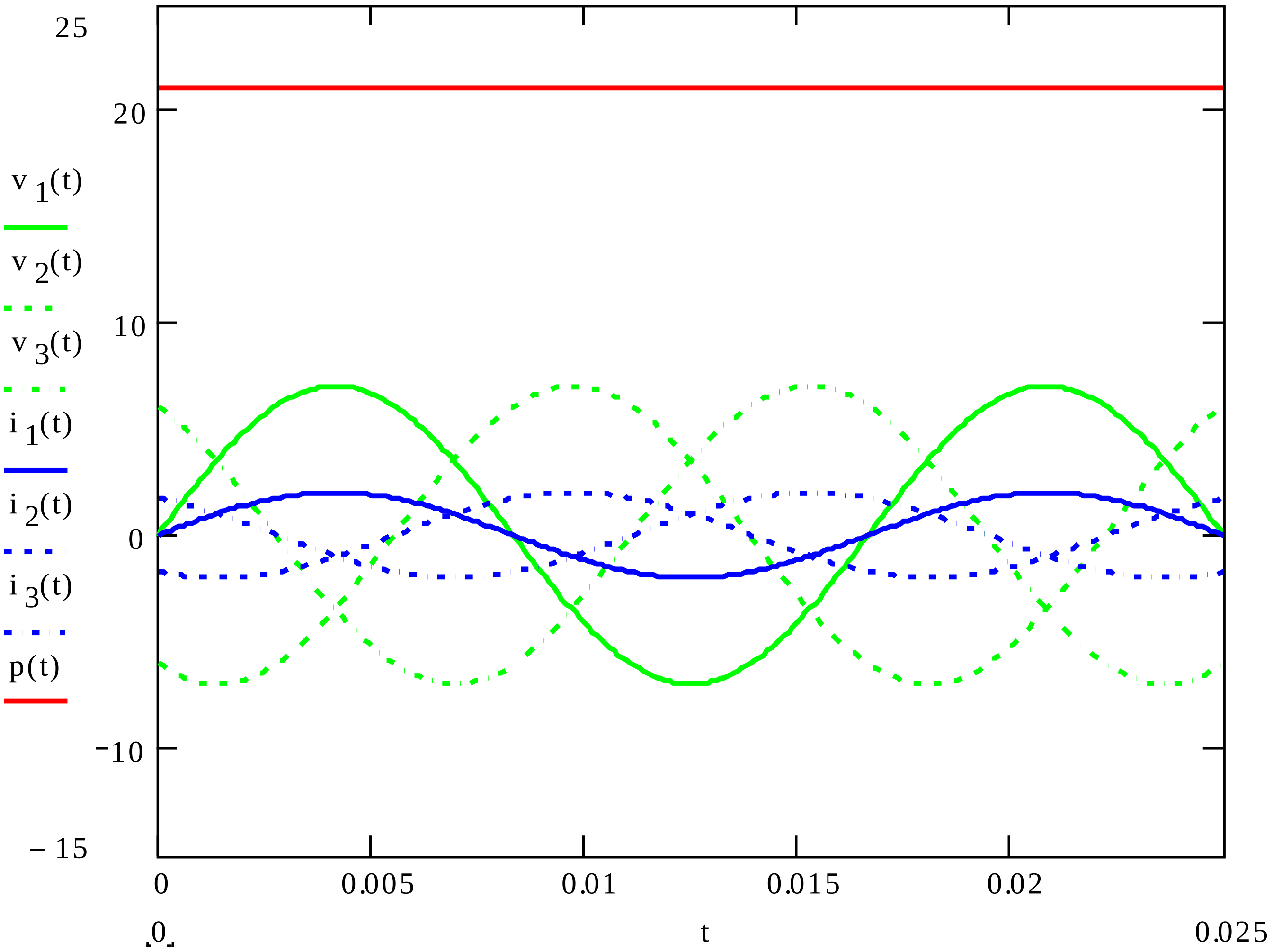
$$S_{3\phi} = \sqrt{3}\, V_{LL} \;\; I_L$$

For Delta

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

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

Three Phase Quantities



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

Three Phase Quantities

This will show that three phase power is constant

$$p(t) = v_{ab}(t) + v_{bc}(t) + v_{ca}(t)$$

$$p(t) = \frac{1}{\sqrt{3}}\Big[\sqrt{2}|V_a|\sin(\omega t)\sqrt{2}|I_a|\sin(\omega t - \phi)$$
$$+\sqrt{2}|V_b|\sin(\omega t - 120^o)\sqrt{2}|I_b|\sin(\omega t - 120^o - \phi)$$
$$+\sqrt{2}|V_c|\sin(\omega t - 240^o)\sqrt{2}|I_c|\sin(\omega t - 240^o - \phi)\Big]$$

But $\frac{|V_a|}{\sqrt{3}} = \frac{|V_b|}{\sqrt{3}} = \frac{|V_c|}{\sqrt{3}} = \frac{|V|}{\sqrt{3}}$ *and* $|I_a| = |I_b| = |I_c| = |I|$

Identity

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

Making the substitutions we have

$$p(t) = \frac{1}{\sqrt{3}}\Big[|V||I|[\cos(\omega t - \omega t + \phi) - \cos(\omega t + \omega t - \phi)$$
$$+|V||I|[\cos(\omega t - 120^o - \omega t + 120^o + \phi) - \cos(\omega t - 120^o + \omega t - 120^o - \phi)$$
$$+|V||I|[\cos(\omega t - 240^o - \omega t + 240^o + \phi) - \cos(\omega t - 240^o + \omega t - 240^o - \phi)\Big]$$

$$p(t) = \frac{|V|}{\sqrt{3}}|I|[\cos(\phi) - \cos(2\omega t - \phi) + \cos(\phi) - \cos(2\omega t - 240^o - \phi) + \cos(\phi) - \cos(2\omega t - 480^o - \phi)]$$

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

$$p(t) = \frac{|V|}{\sqrt{3}}|I|[\cos(\phi) - \cos(2\omega t - \phi) + \cos(\phi) - \cos(2\omega t - 240^o - \phi) + \cos(\phi) - \cos(2\omega t - 120^o - \phi)]$$

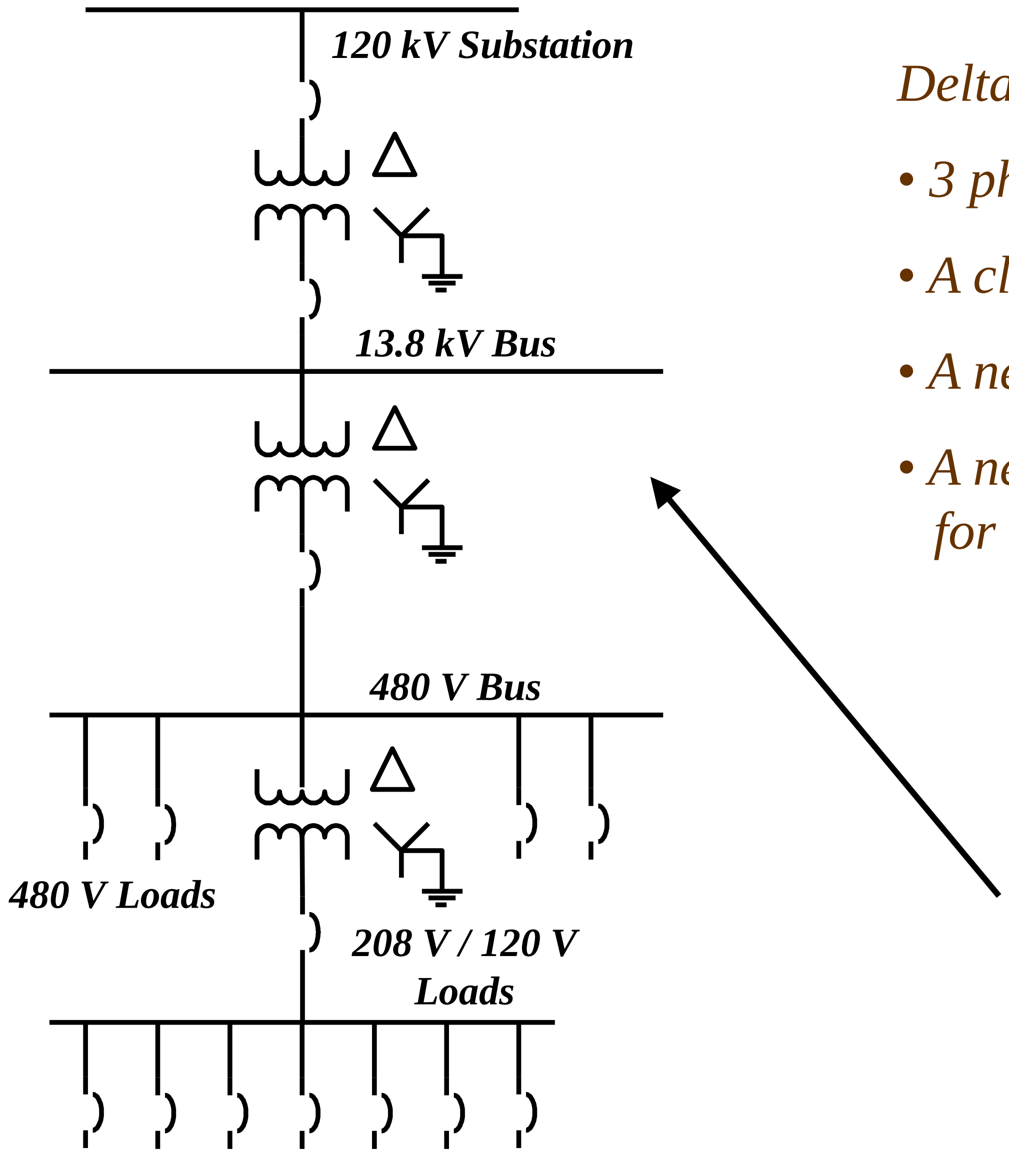
$$p(t) = \frac{|V|}{\sqrt{3}}|I|[3\cos(\phi) - (\cos(2\omega t - \phi) + \cos(2\omega t - 120^o - \phi) + \cos(2\omega t - 240^o - \phi))]$$

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

$$p(t) = 3\frac{|V|}{\sqrt{3}}|I|\cos(\phi) = \sqrt{3}|V||I|\cos(\phi)$$

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

Delta - Wye Configuration – The Preferred Choice For Power Systems

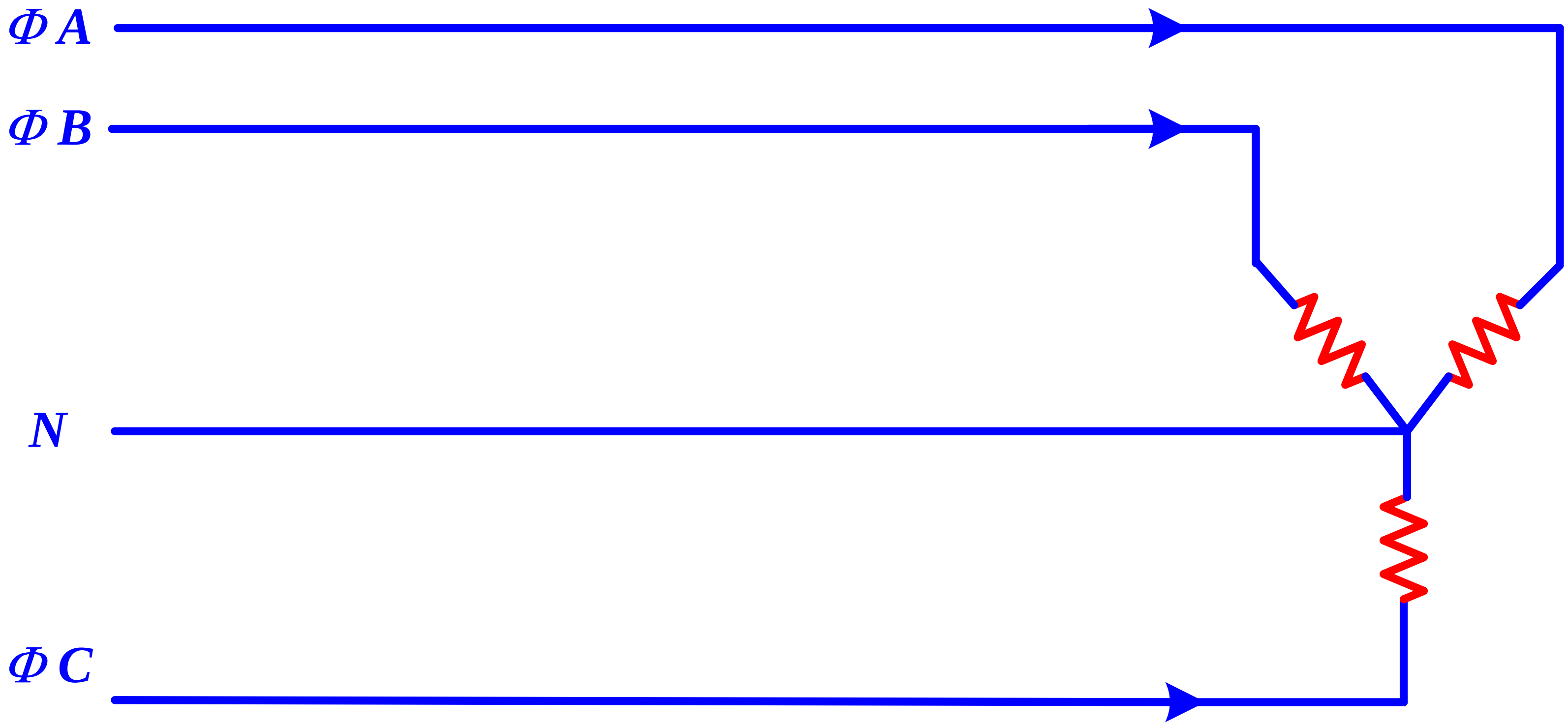


Delta - Wye Provides

- 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

Neutral Wire Size – Balanced, Linear Load



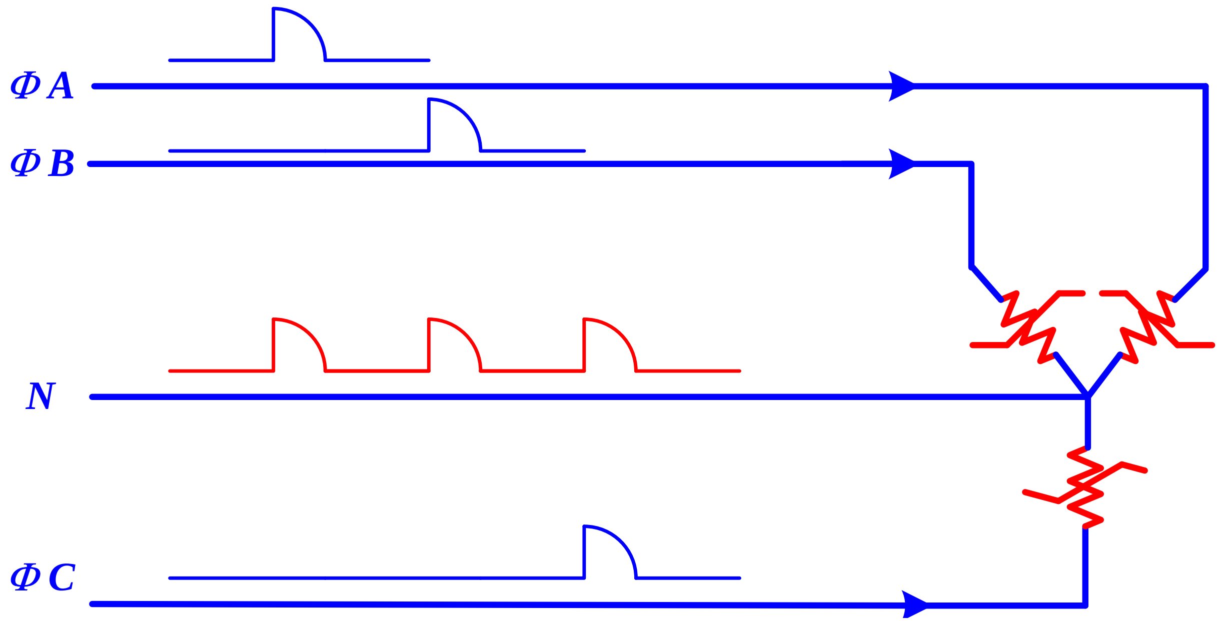
$$I_A = |I_A| e^{-j30} \qquad I_B = |I_B| e^{-j150} \qquad I_C = |I_C| e^{-j270}$$

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

$$I_N = I_A + I_B + I_C$$

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

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



For balanced linear or 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 $\sqrt{3} * MAX(I_A, I_B, I_C)$

The "Per Unit" or "Percent" Calculation System in AC Systems

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, 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!

"Per Unit" 1ϕ Example to Calculate Line Currents

Establish Bases

In Section A

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

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

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

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

Section B

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

$$V = 138\,kV$$

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

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

Section C

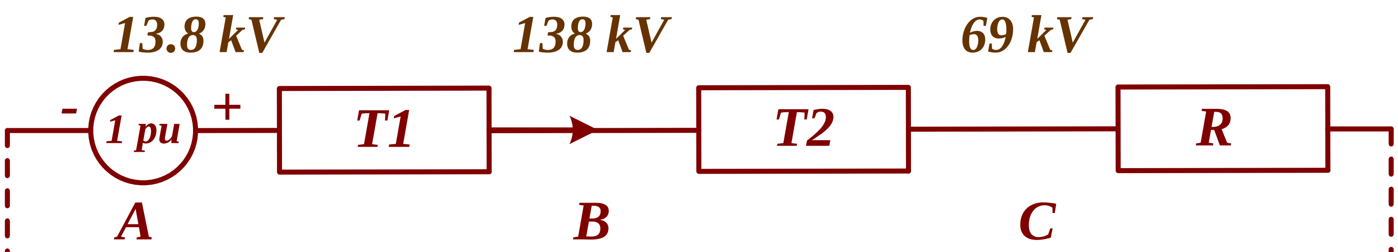
$$S = 10{,}000\,kVA$$

$$V = 69\,kV$$

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

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

Obtain pu values

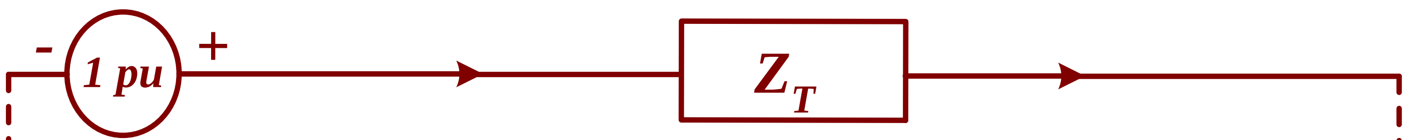


$$j0.1 * \frac{10{,}000kVA}{15{,}000kVA} = j0.067\ pu$$

$$j0.05$$

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

Combine impedances – Solve for I



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

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

$$|I| = 1.56\ pu$$

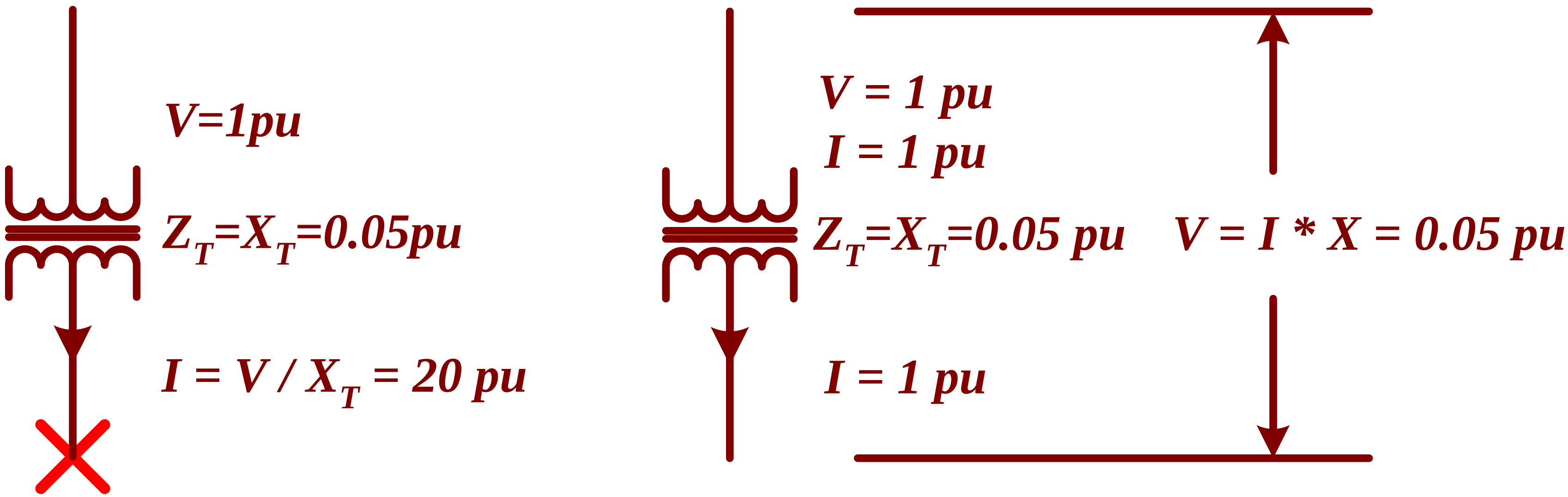
$$|I_A| = 1.56\ pu * 725\,A = 1{,}131\,A$$

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

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

A transformer impedance of 5% means:

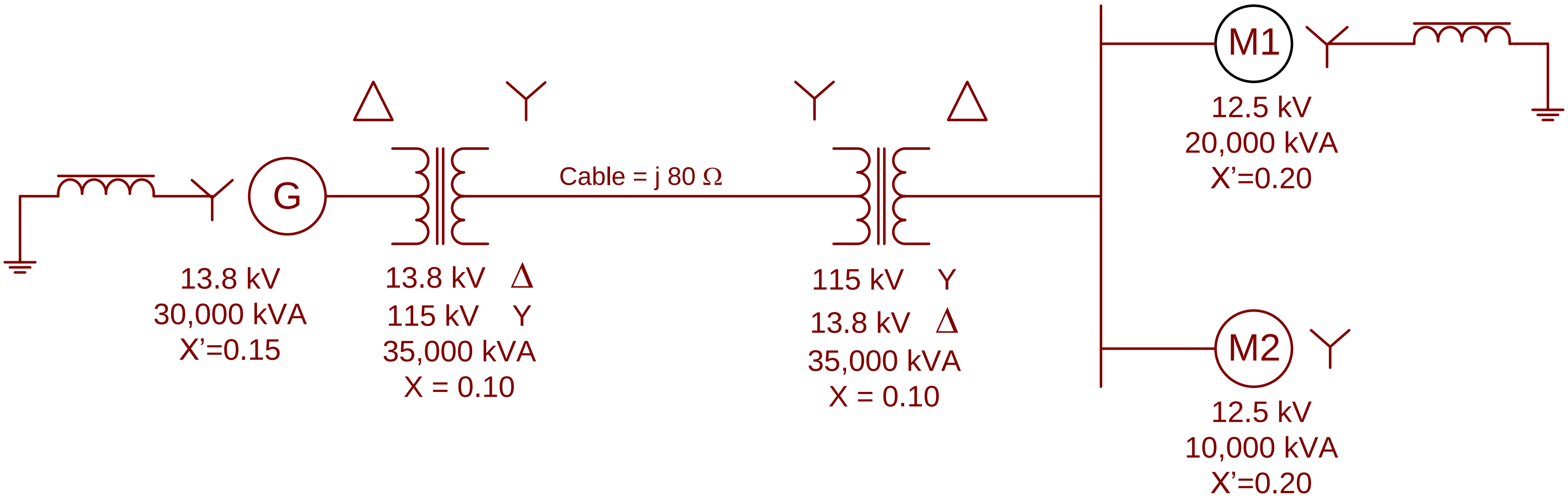
- *The short circuit current is 20X rated full load input / output*
- *The voltage drop across the transformer at full load is 5% of rated*



Homework Problem #1

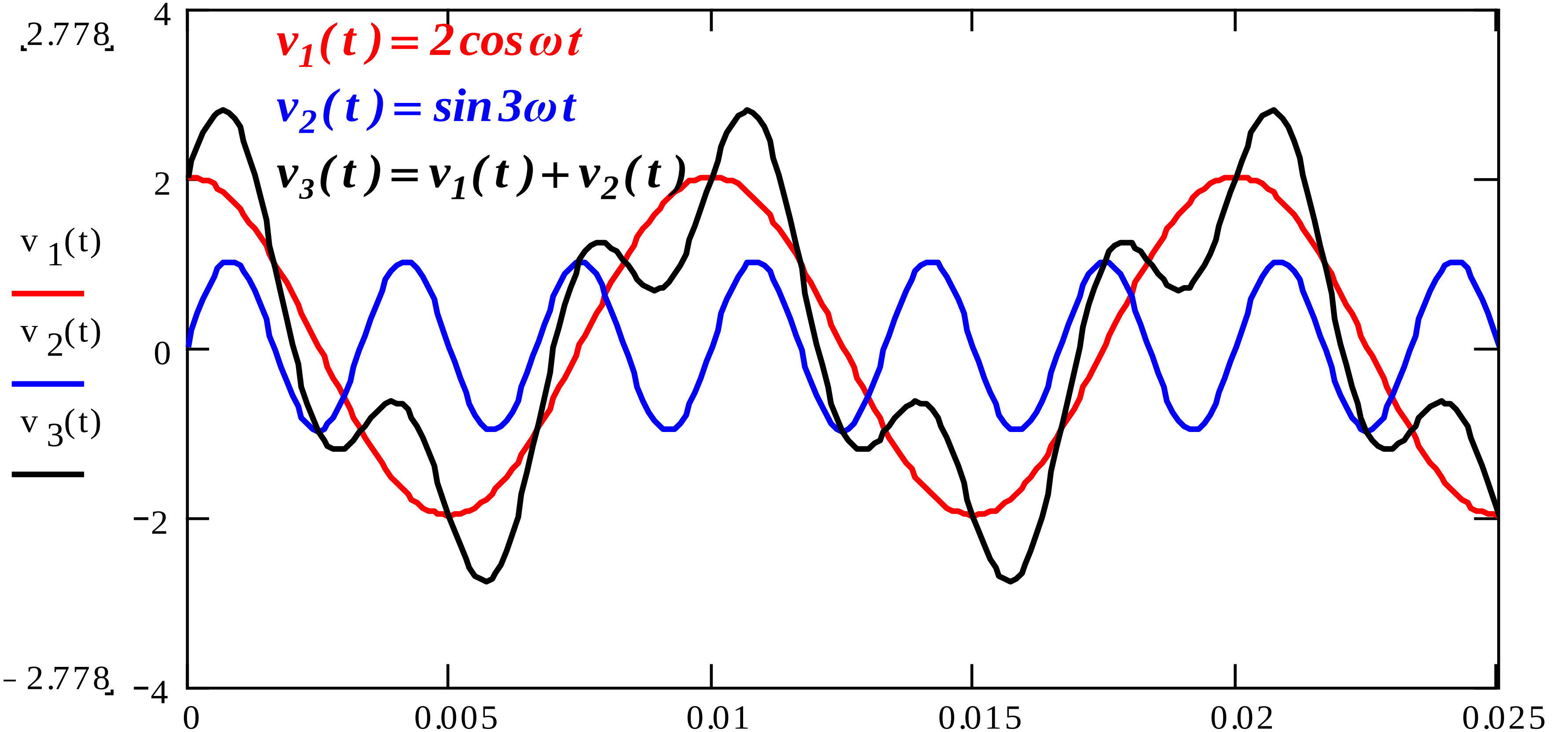
Referring to the one-line diagram below, determine the line currents in the:

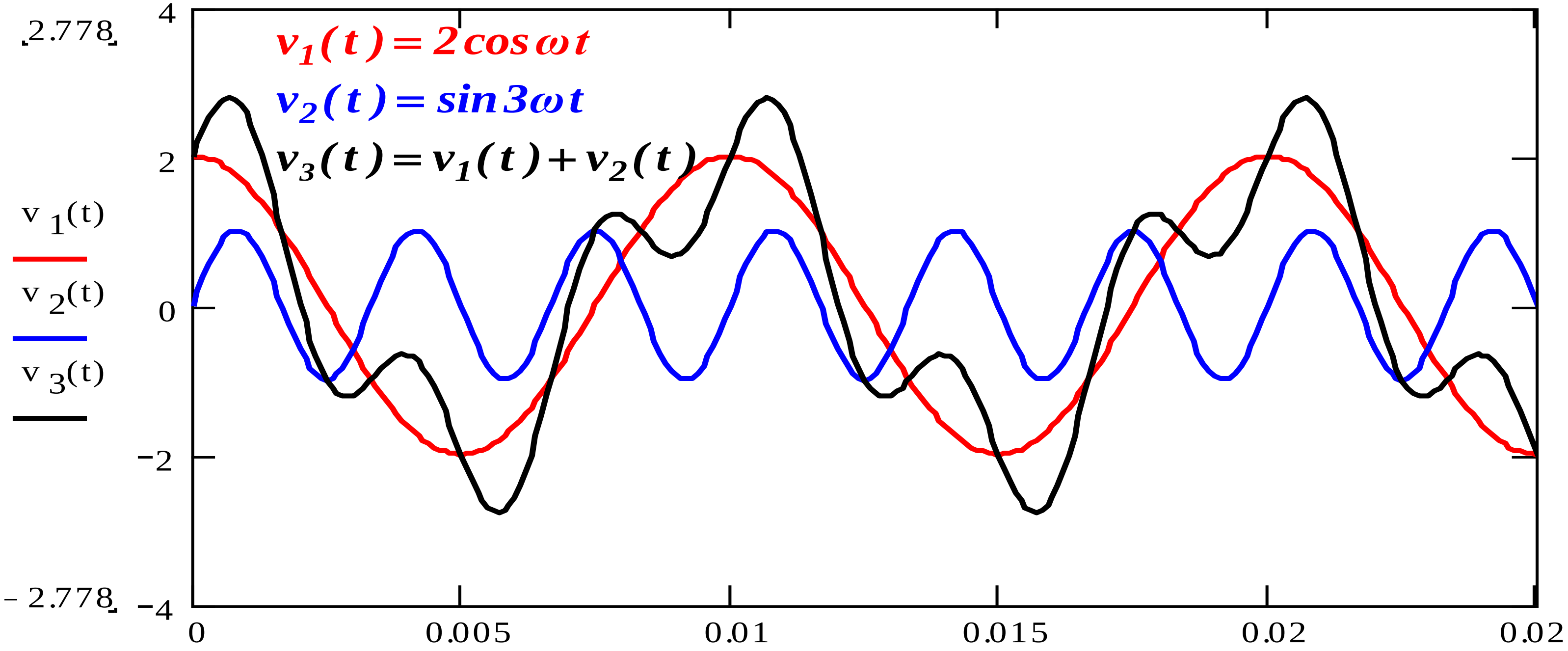
A. Generator ***B. Transmission Line*** ***C. M1*** ***D. M2***



- *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.*





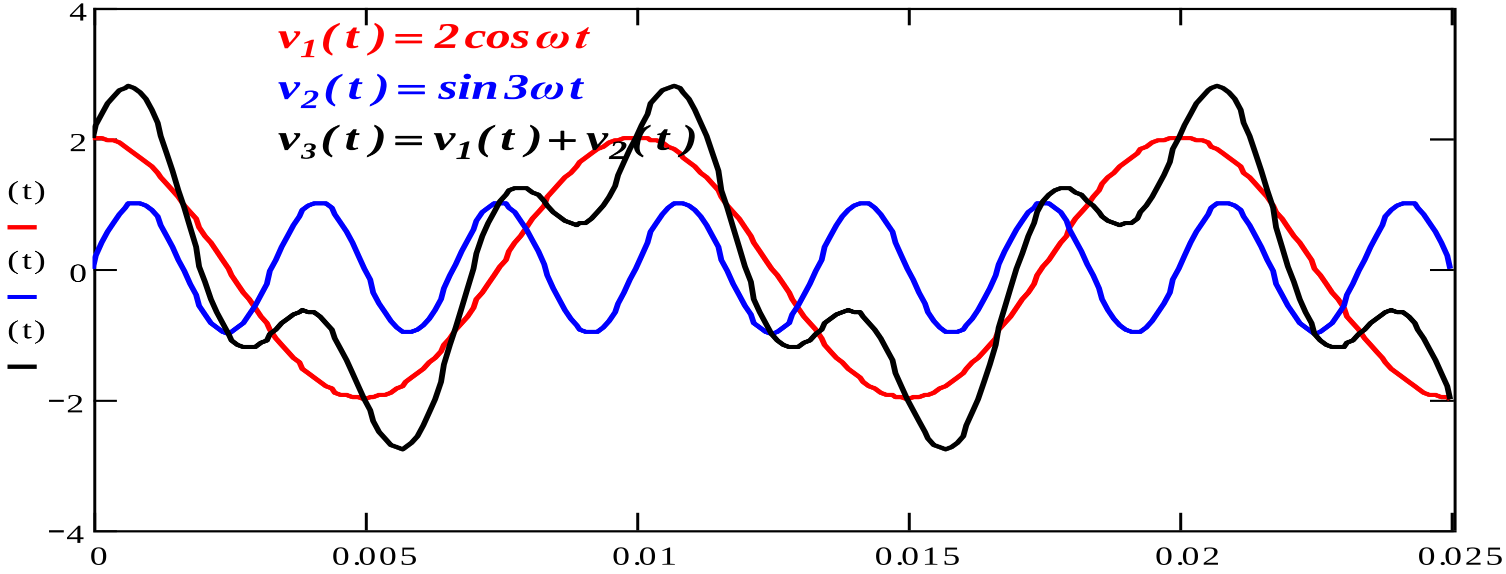
Trigonometric form of the Fourier Series

$$a_0 = \frac{1}{T}\int_0^T f(t)dt \qquad a_k = \frac{2}{T}\int_0^T f(t)\cos k\omega_0 t dt \qquad b_k = \frac{2}{T}\int_0^T f(t)\sin k\omega_0 t dt$$

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

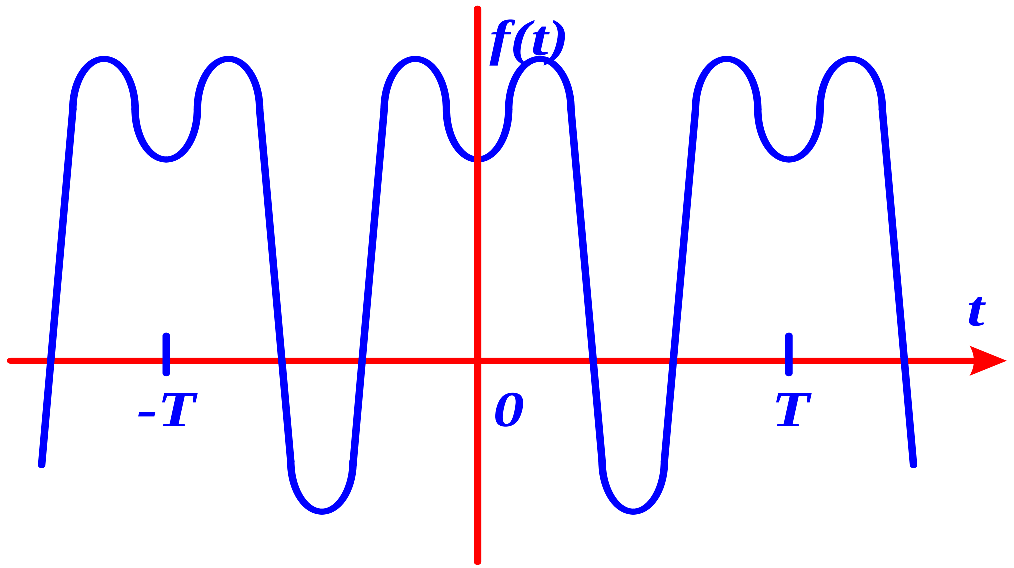
$$c_k = \frac{1}{T}\int_0^T f(t)e^{-jk\omega_0 t}\, dt$$

Fourier Coefficient Facilitators

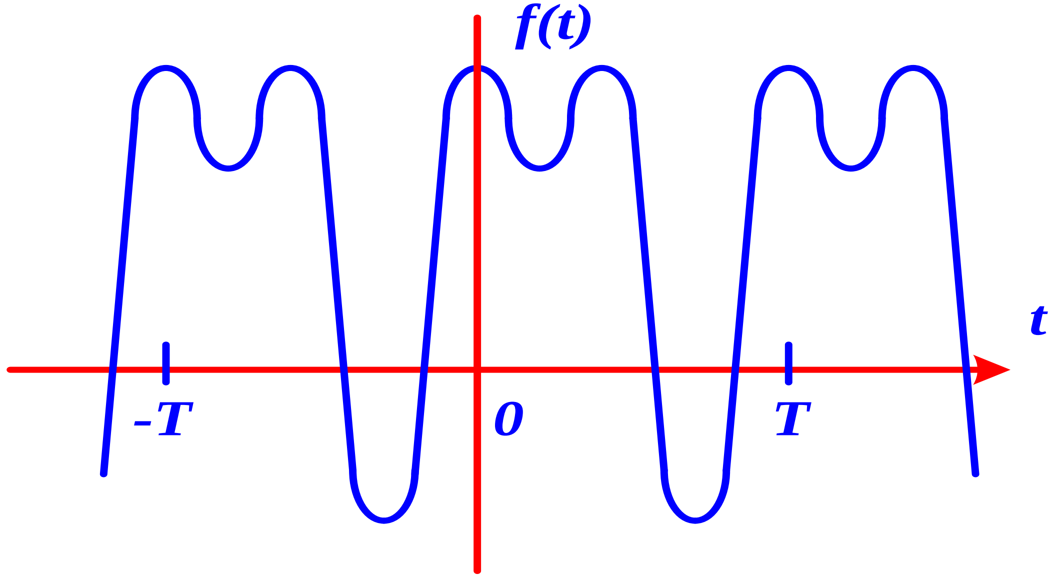


Even function symmetry	*f (t) = f (-t)*	*No sine terms*	*Has DC component if no half-wave symmetry*
Odd function symmetry	*f (t) = - f (-t)*	*No cosine terms*	*No DC component*
Half-wave symmetry	*f (t) = - f (t -1/2T)*	*Have sines and cosines but only odd harmonics*	*No DC component*

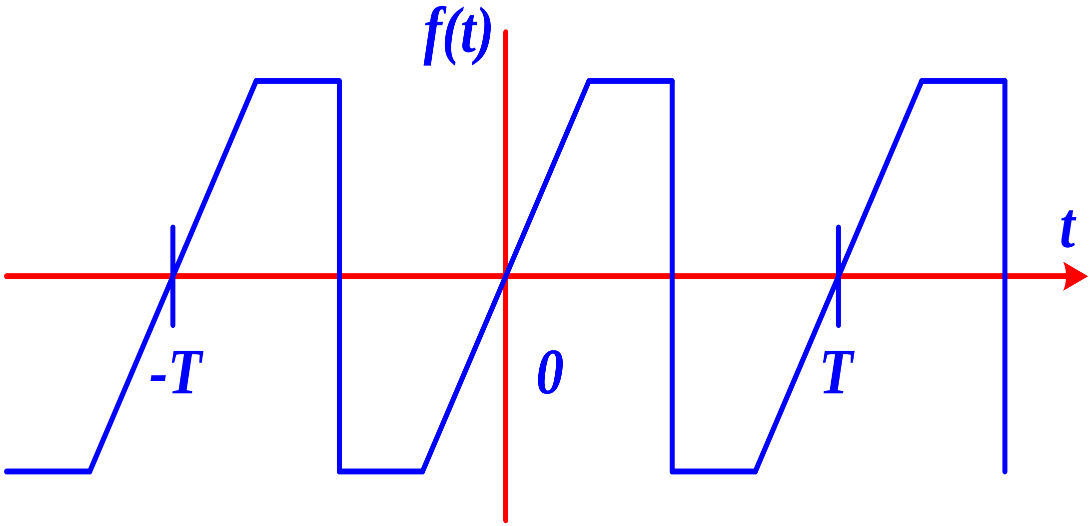
Example of Even Function Symmetry



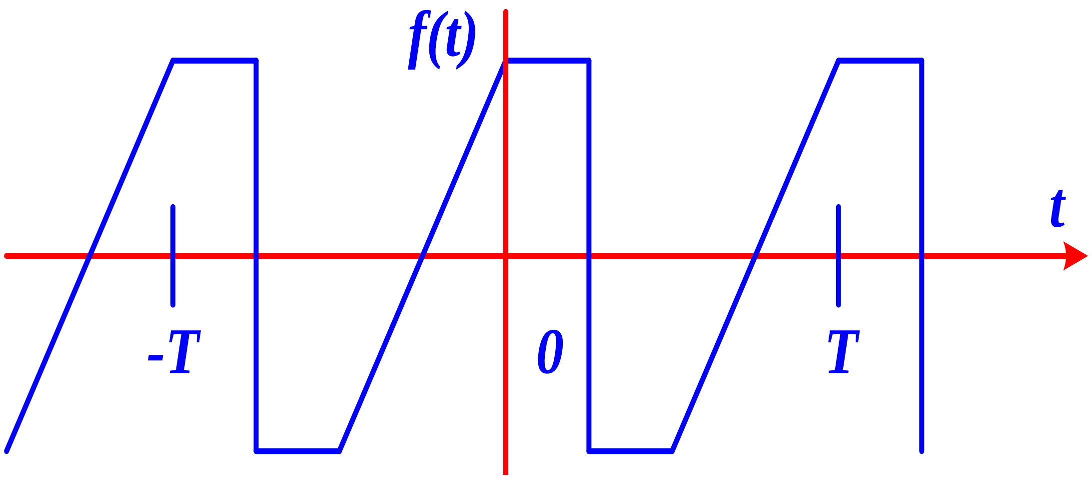
- $f(t) = f(-t)$ even function
- No sine terms
- No half-wave symmetry
- DC component, a_o
- $a_k = \frac{2}{T}\int_0^T f(t)\cos k\omega_o t\, dt$



- 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

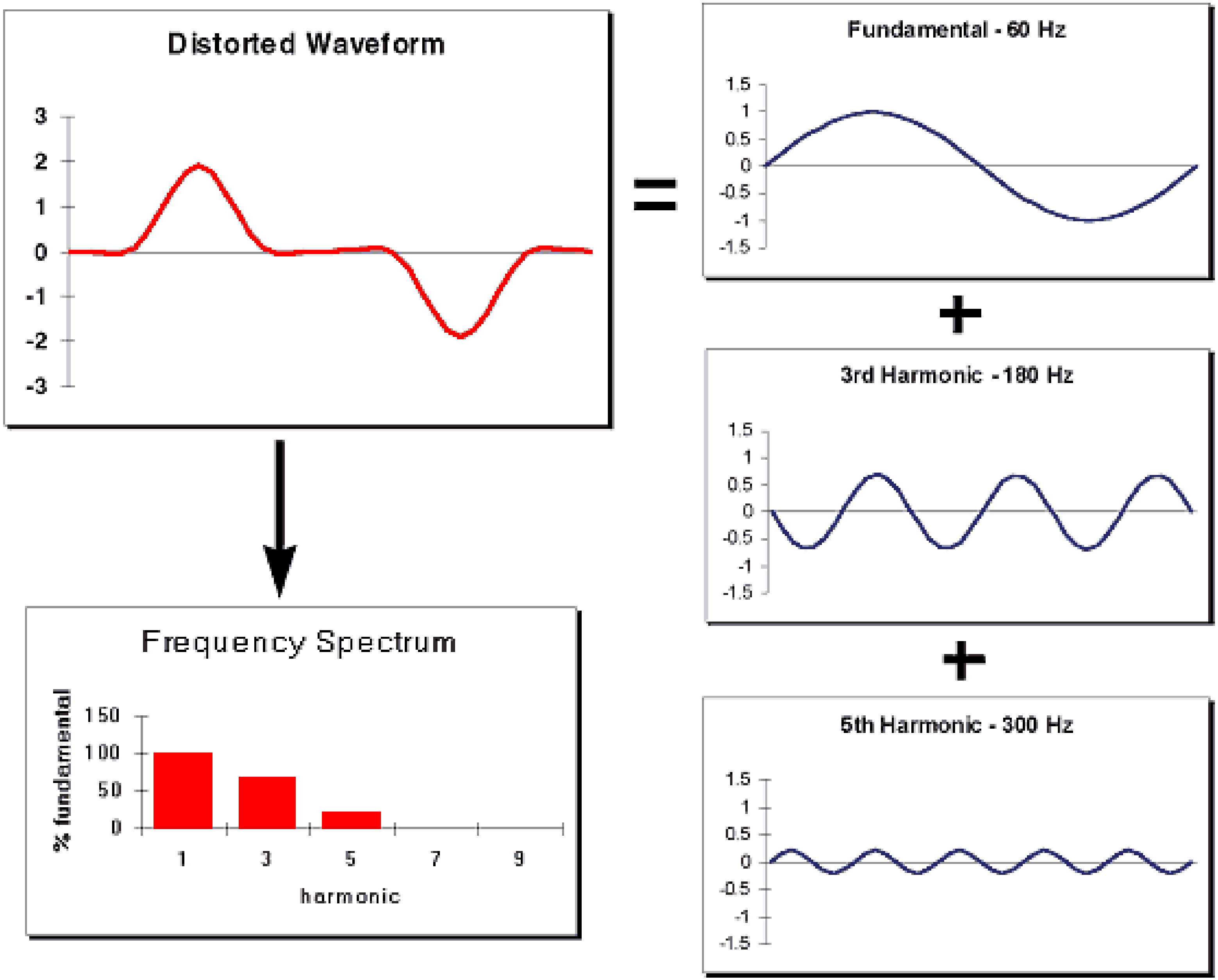


- f(t)=-f(-t) odd function
- No cosine terms
- Half-wave symmetry
- No DC component
- $b_k = \frac{2}{T}\int_0^T f(t)\sin k\omega_o t\,dt$



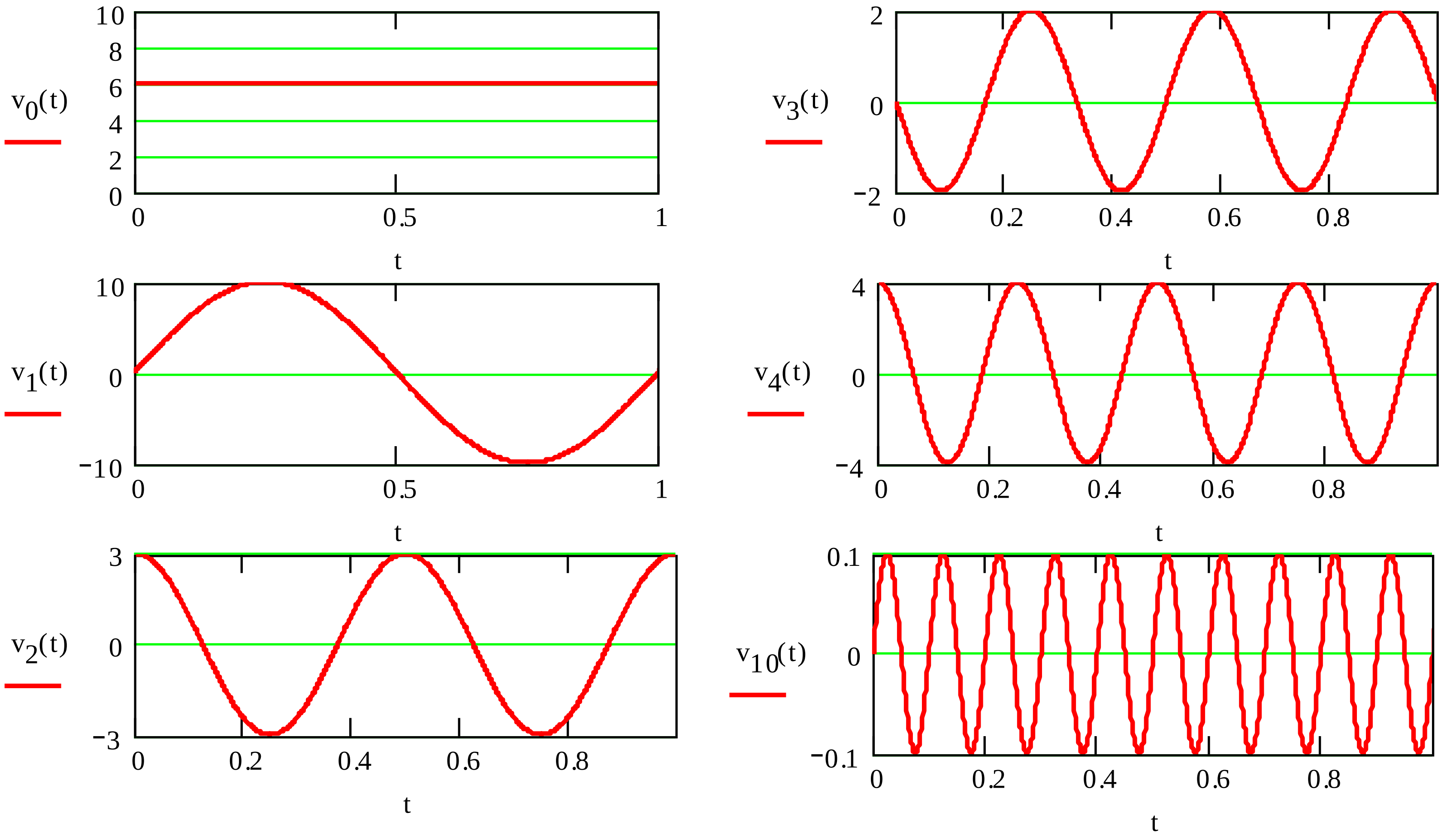
- No even or odd function symmetry
- Have sine and cosine terms
- No half-wave symmetry
- DC component exists
- a_o , a_k , b_k

Distorted (Complex) Waveforms



Homework Problem #2

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



Homework Problem #2 (Continued)

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

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

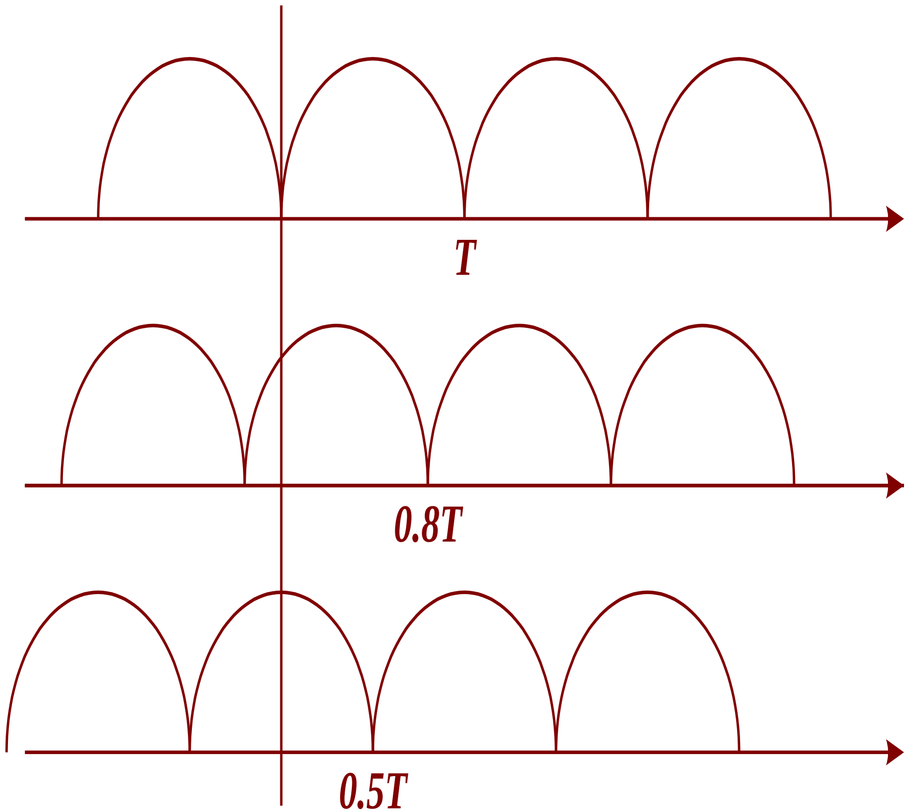
c. Give the numerical result of

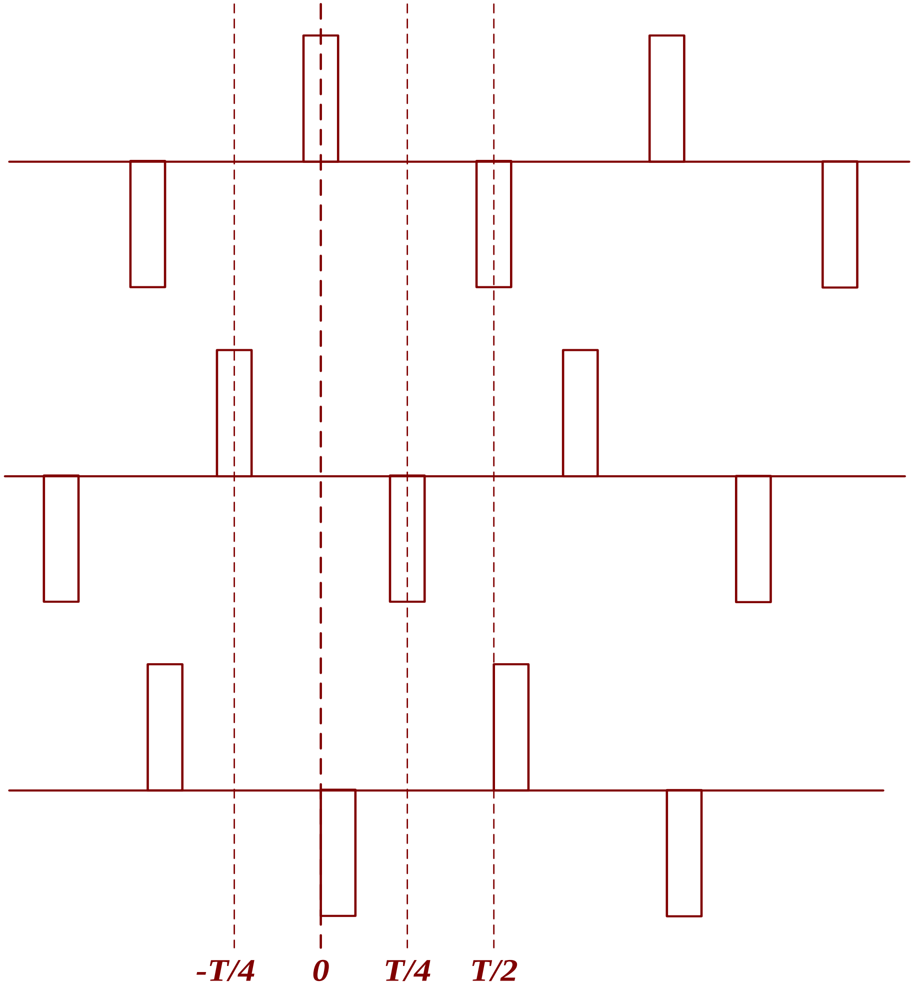
$$b_3 = \frac{2}{T}\int_0^T v(t)\sin 3\omega t\, dt \qquad \text{Help}: \int \sin^2(3\omega t)\, dt = \frac{1}{3} * \frac{\frac{1}{2}\cos(3\omega t)\sin(3\omega t) + \frac{3}{2}\omega t}{\omega}$$

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

Homework Problem #3

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*

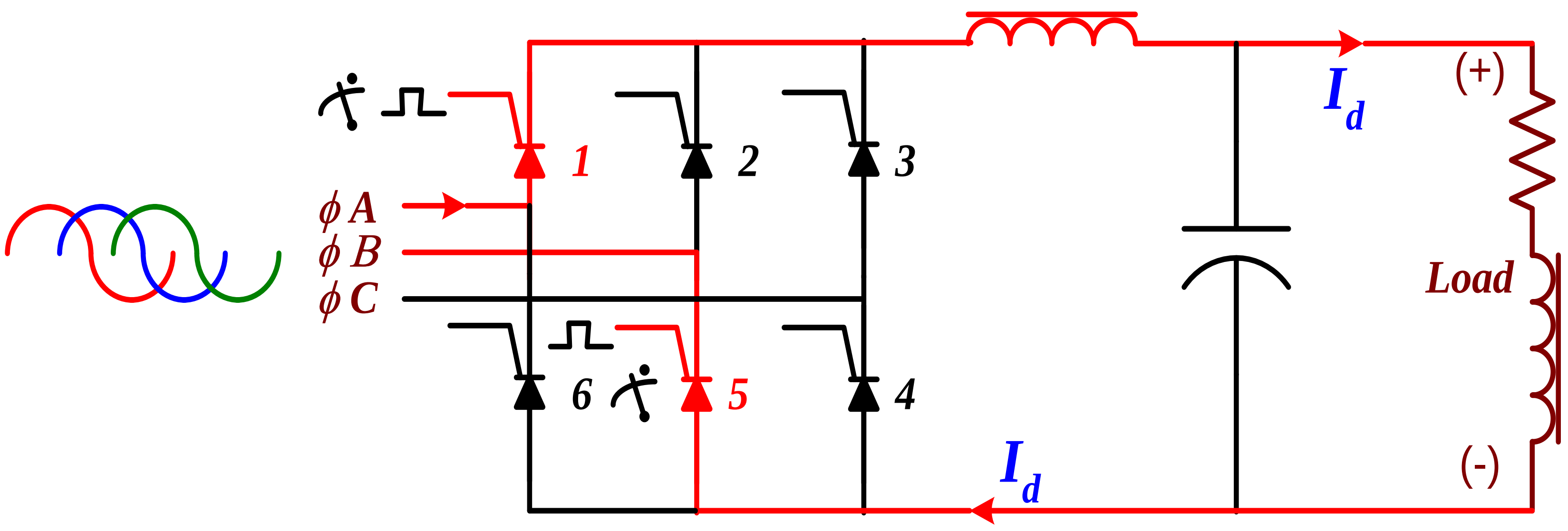
$$THD_V = \frac{\left[\sum_{i=2}^{N} V_i^2\right]^{1/2}}{V_1} * 100\%$$

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

Causes of Harmonic Distortion

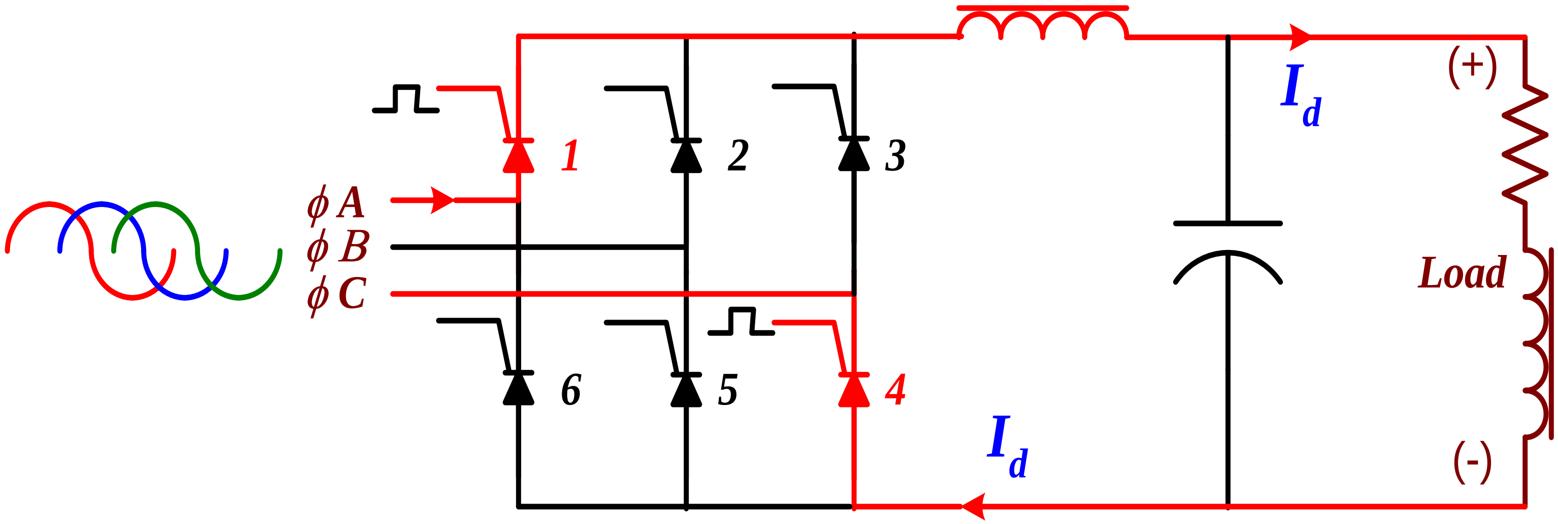
- *Unbalanced 3-phase, non-linear loads*
- *SCR or diode commutation*

SCR Commutation as Distortion Cause



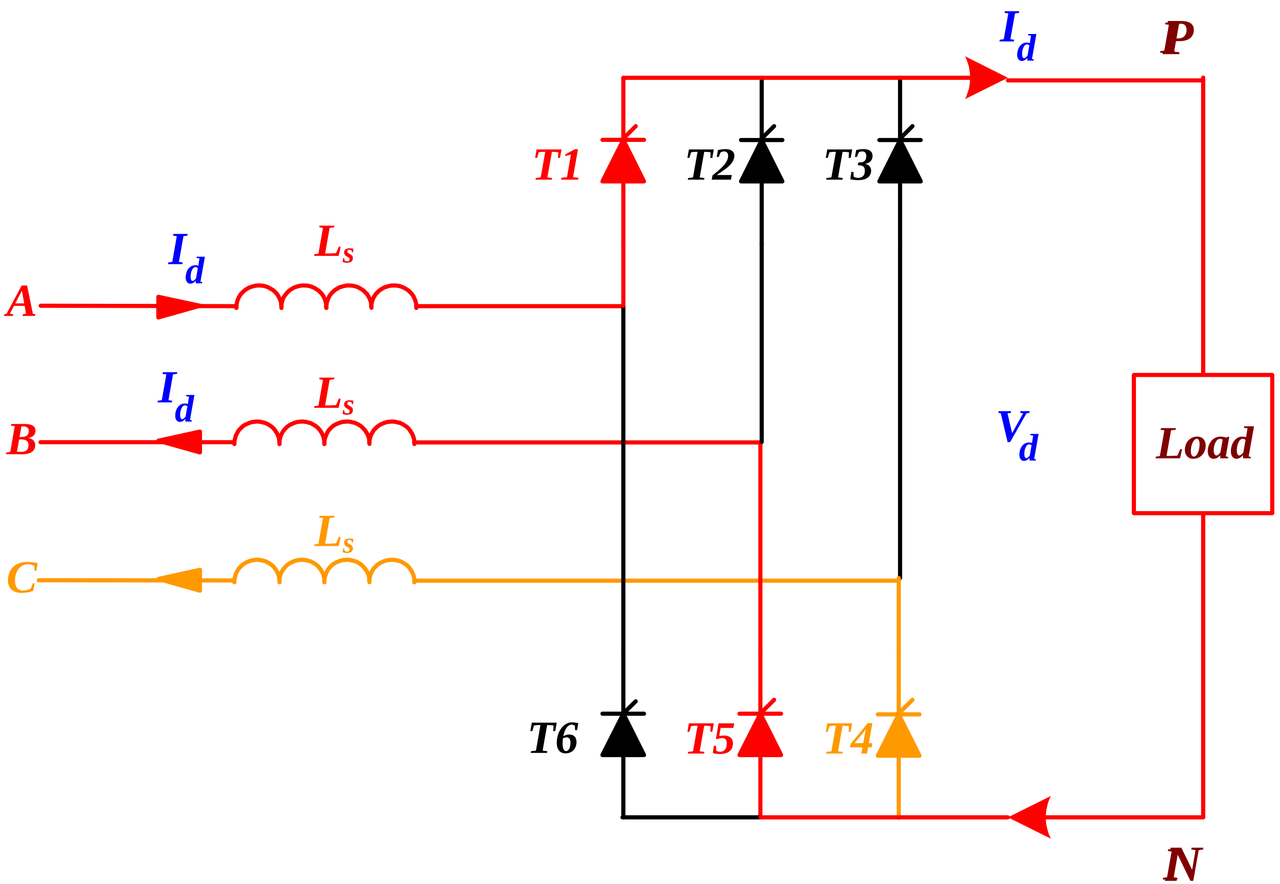
State 1: A-B (+) SCR s 1 – 5 On

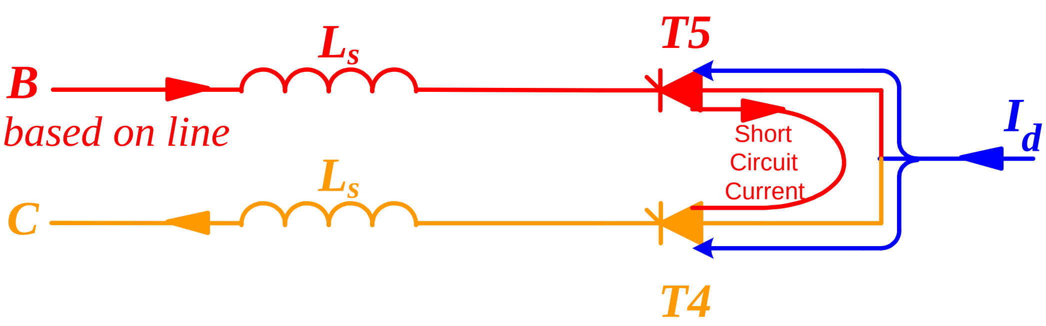
SCR Commutation



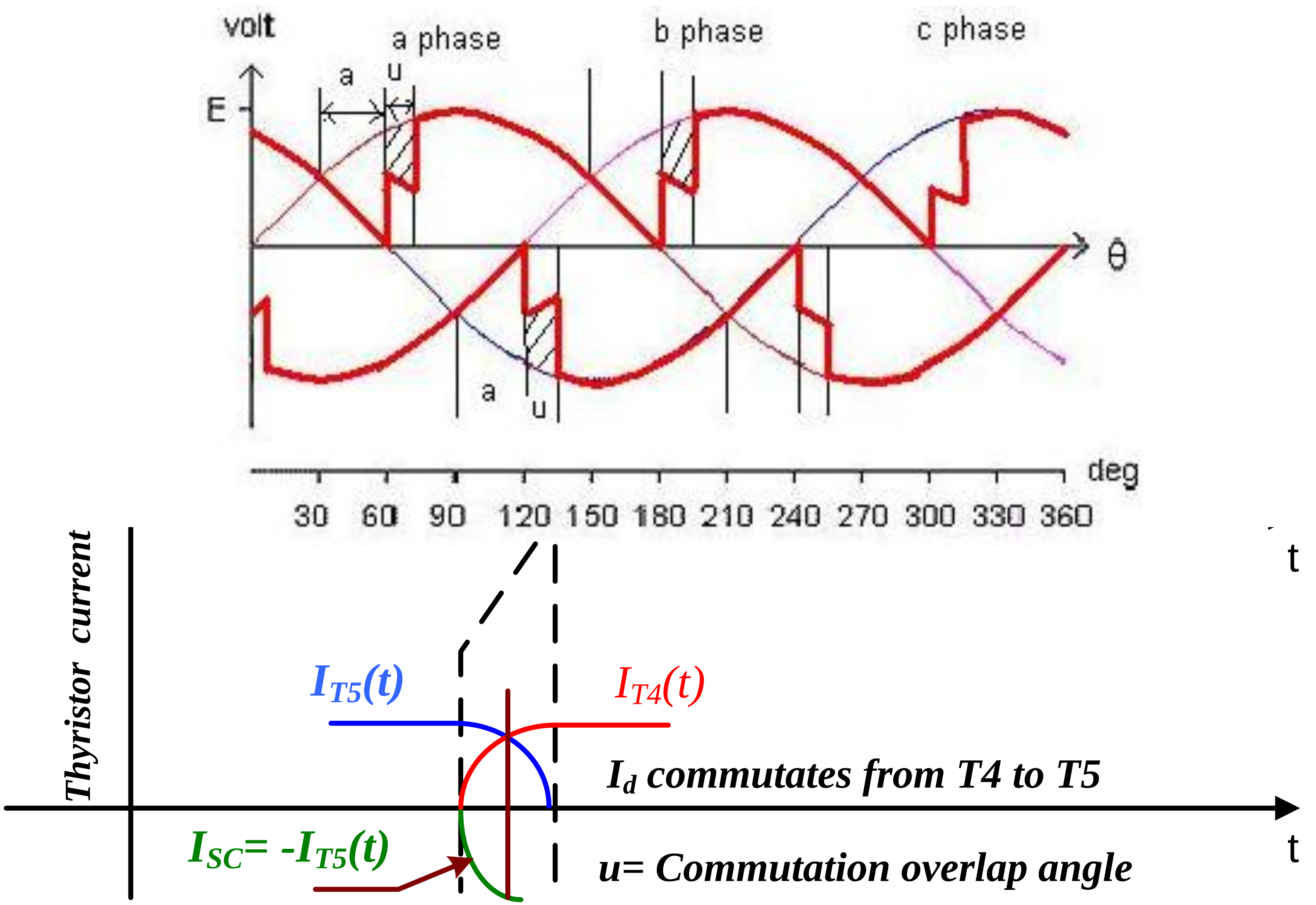
State 2 : C-A (-), 5 off, 4 on, SCR s 1 – 4 On

Causes of Distortion – SCR Commutation





Line current is based on line voltage B to C


volt
a phase
b phase
c phase
a
u
E
θ
a
u
deg
30 60 90 120 150 180 210 240 270 300 330 360
Thyristor current
t
I_T5(t)
I_T4(t)
I_d commutates from T4 to T5
I_SC= -I_T5(t)
t
u= Commutation overlap angle

SCR Commutation

$$V_{PN} = V_{AN} - V_{Ls} \qquad V_{Ls} = L_s \frac{di_A}{dt}$$

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

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

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

Commutation voltage drop

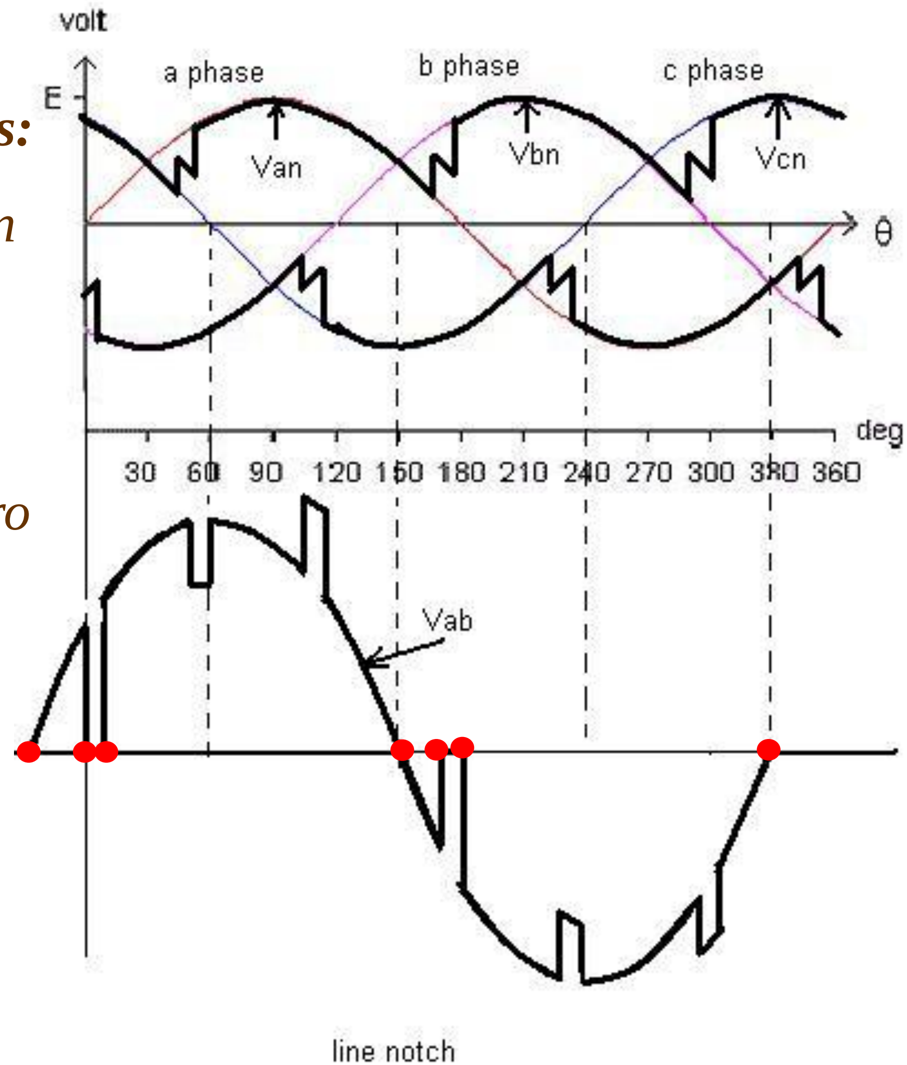
α = gate trigger retard angle and q= number of possible rectifier states

Conclusions

- The current commutation takes a finite commutation interval u.
- During the commutation interval, three SCRs conduct.
- Commutation voltage drop and hence the 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

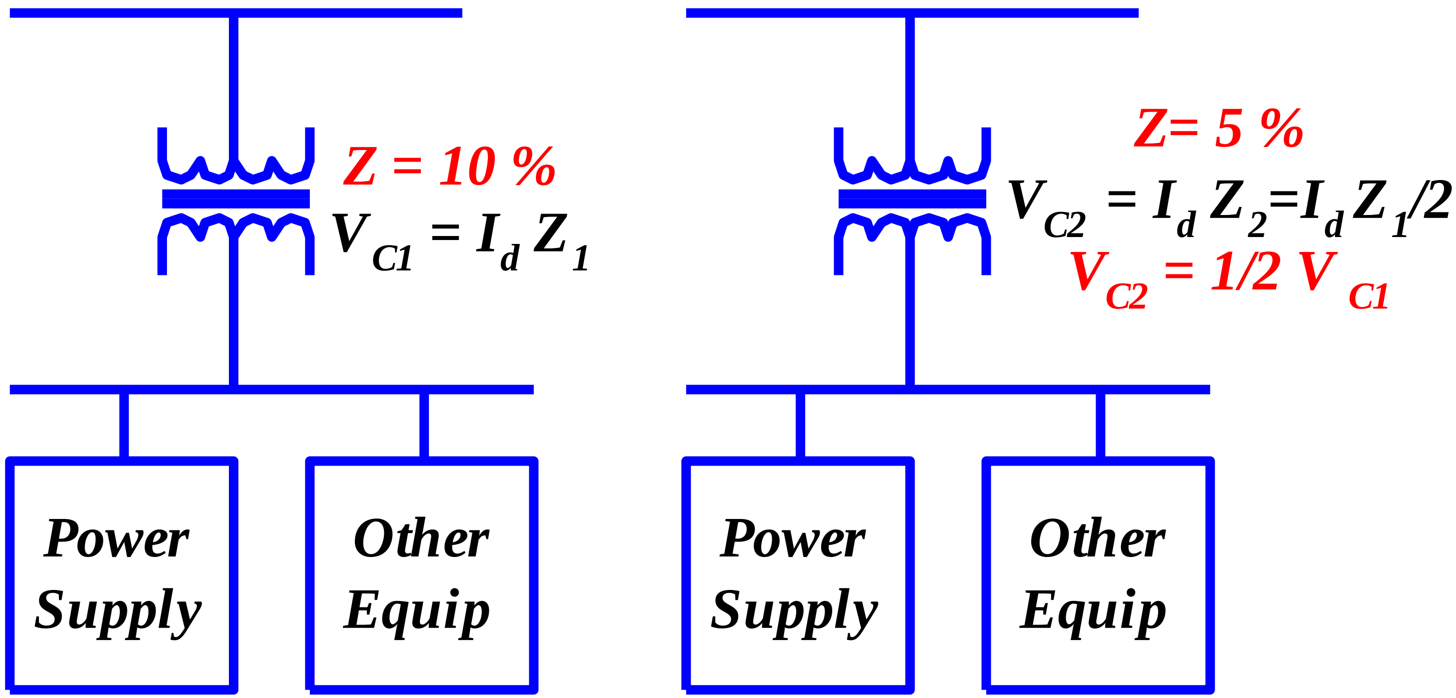
SCR / diode commutation line notches:

- *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 additional 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.*



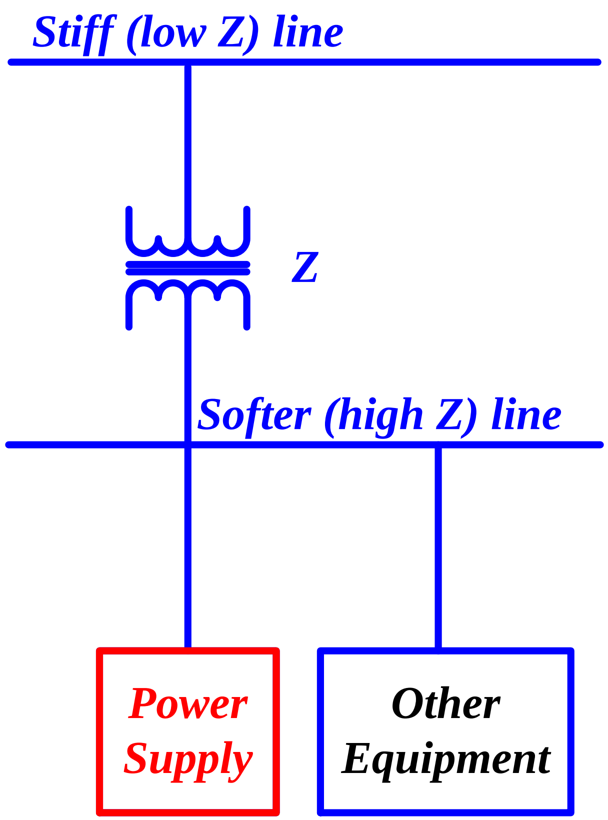
Reducing SCR commutation effects

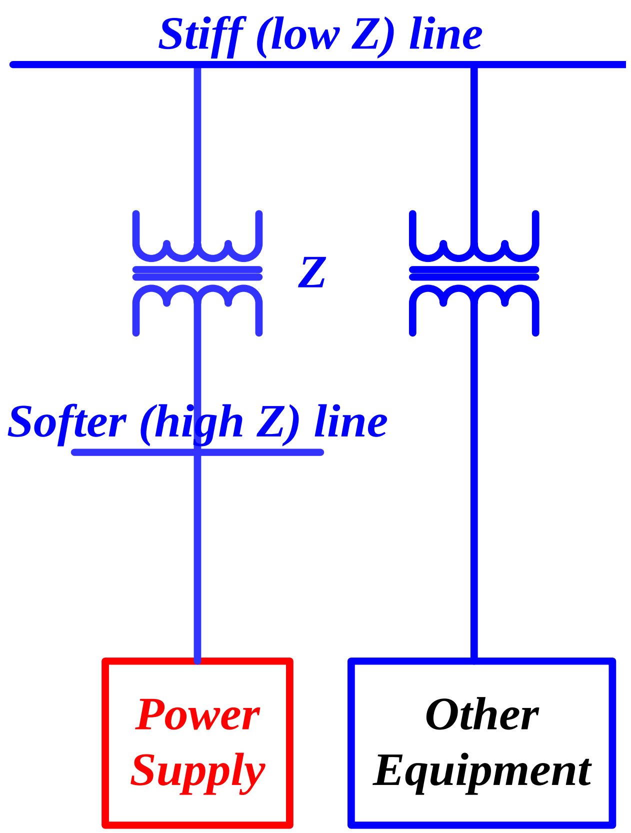
• *Commutation notches (voltage drops) are directly proportional to system Z and DC load current. To reduce commutation notch depth, use a stiff (large, low Z) line.*



Reducing SCR commutation effects on other equipment

- *Isolate other equipment by placing them on another line*





International Harmonic Distortion Standards

Australia	AS 2279 - "Disturbances in Mains Supply Networks"
Britain	G5/3 - "Standard for Harmonic Control in Power Systems"
Europe	Verband Deutscher Elektrotechniker (VDE) IEC 555 Series for harmonic current distortion limits for small devices
United States	IEEE 519 – 1992 "Standard Practices and Requirements for Harmonic Control in Electrical Power Systems" . Used as the standard around the world

IEEE 519- 1992 Voltage Distortion Limits

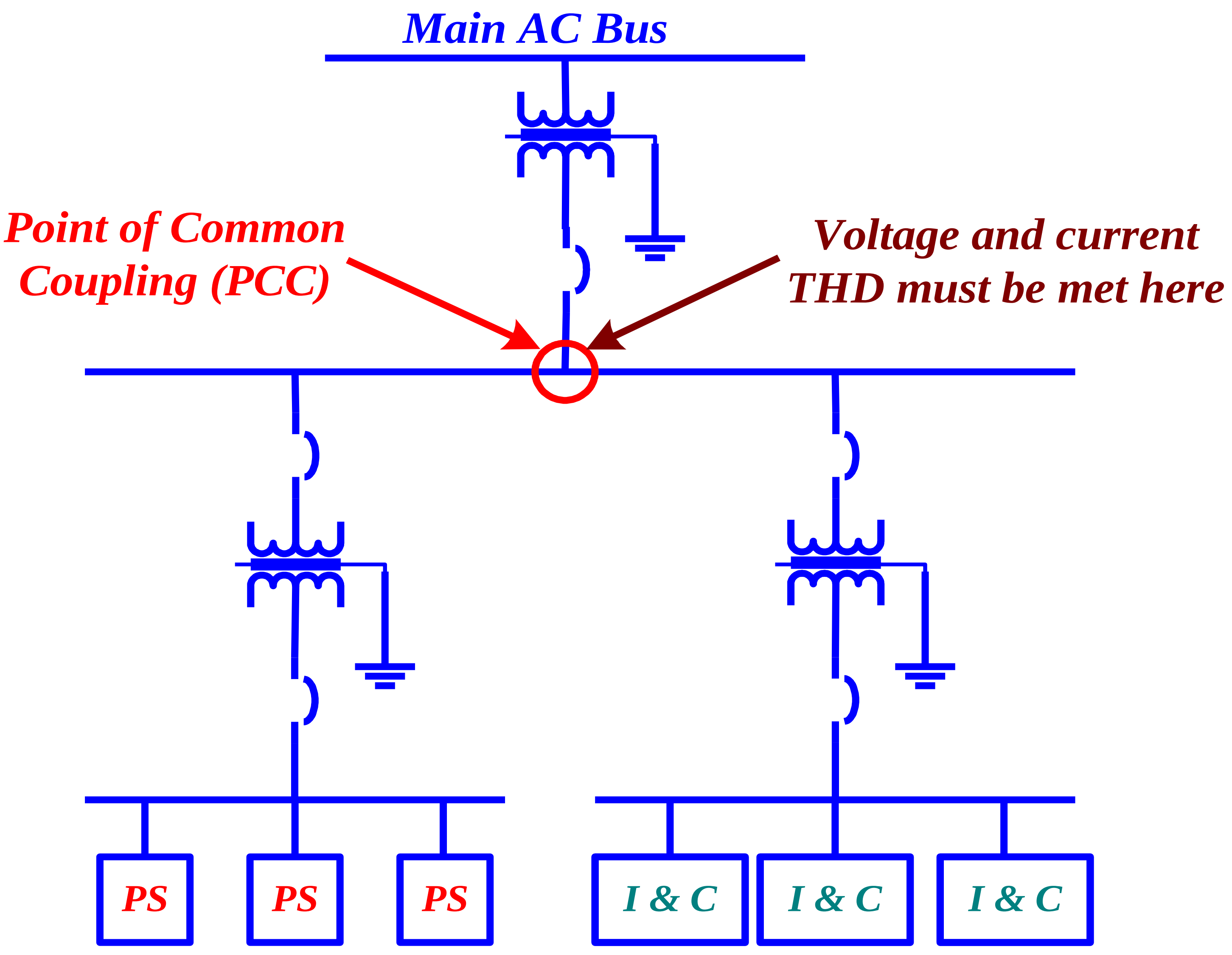
Table 10.2 Low Voltage System Classification And Distortion Limits			
	Special Applications [1]	General System	Dedicated System [2]
THD (Voltage)	3%	5%	10%
Notch Depth	10%	20%	50%
Notch Area [3]	16,400 V - μ S	22,800 V - μ S	36,500 V - μ S

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

IEEE 519- 1992 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


Main AC Bus
Point of Common Coupling (PCC)
Voltage and current THD must be met here
PS
PS
PS
I & C
I & C
I & C

Calculation and Importance of Power Factor

Single Phase

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

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

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

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

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

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

Calculation and Importance of Power Factor

Balanced three Phase

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

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

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

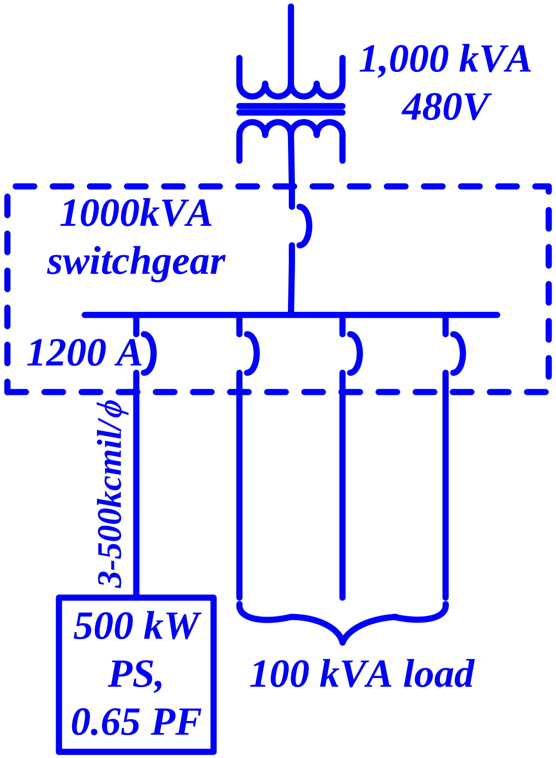
Unbalanced three phase power

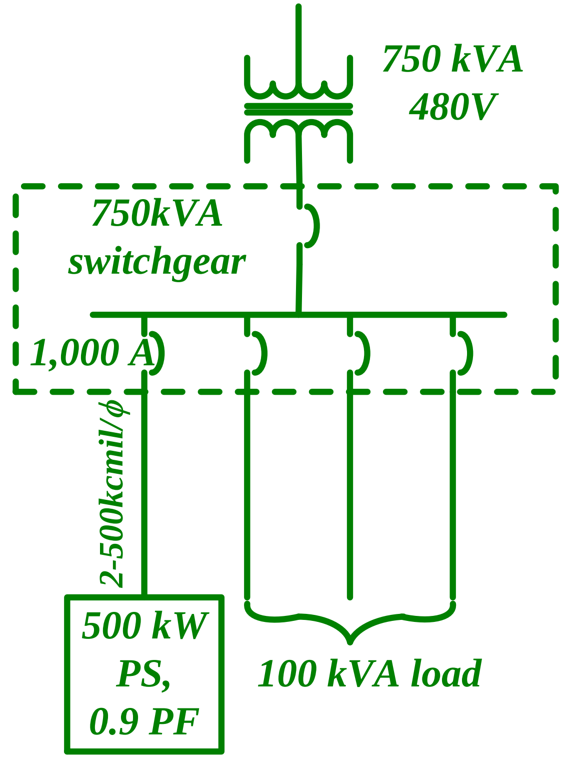
$$S_{3\phi} = V_{\phi A} I_{\phi A} + V_{\phi B} I_{\phi B} + V_{\phi C} I_{\phi C}$$

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

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

Power Factor is Important - Capital Equipment Cost





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

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

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

Buy 1000kVA switchgear/transformer

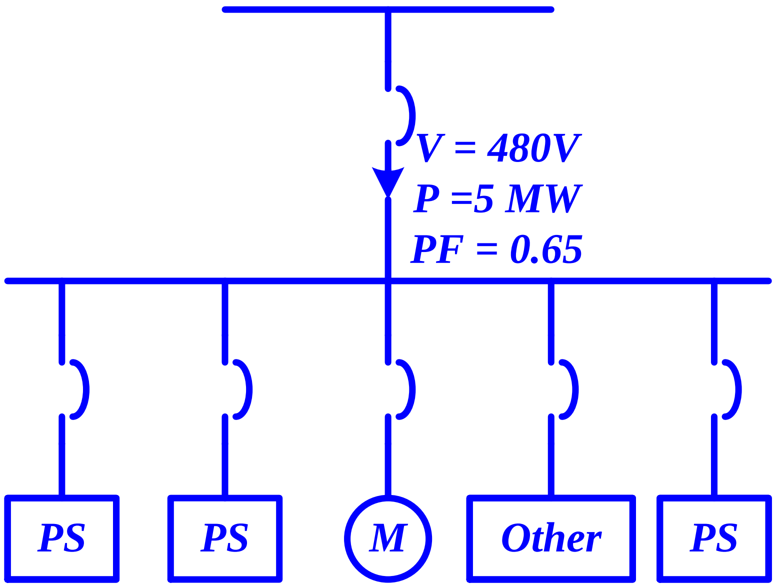
$$S = \frac{P}{PF} = \frac{500kW}{0.9} = 555kVA$$

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

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

Buy 750kVA switchgear/transformer

Power Factor is Important – Energy Cost



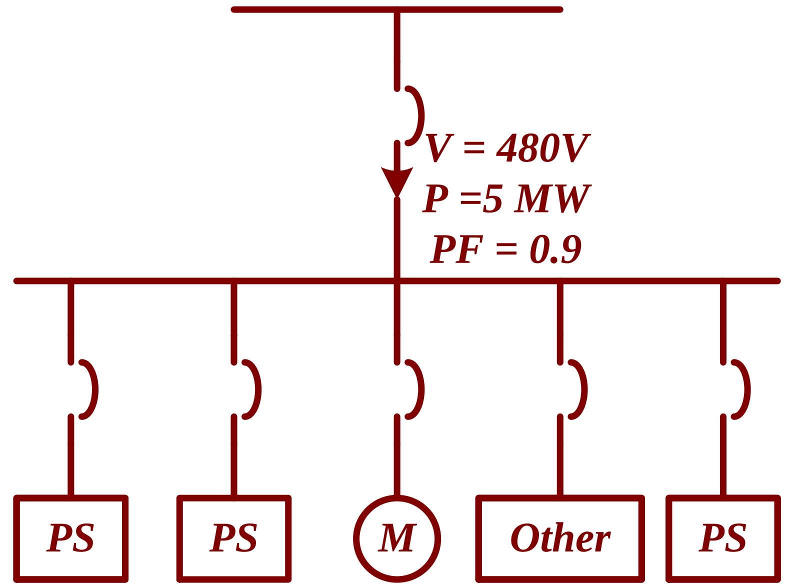
$$S = \frac{P}{PF} = \frac{5MW}{0.65} = 7.7MVA$$

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

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

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

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



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

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

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

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

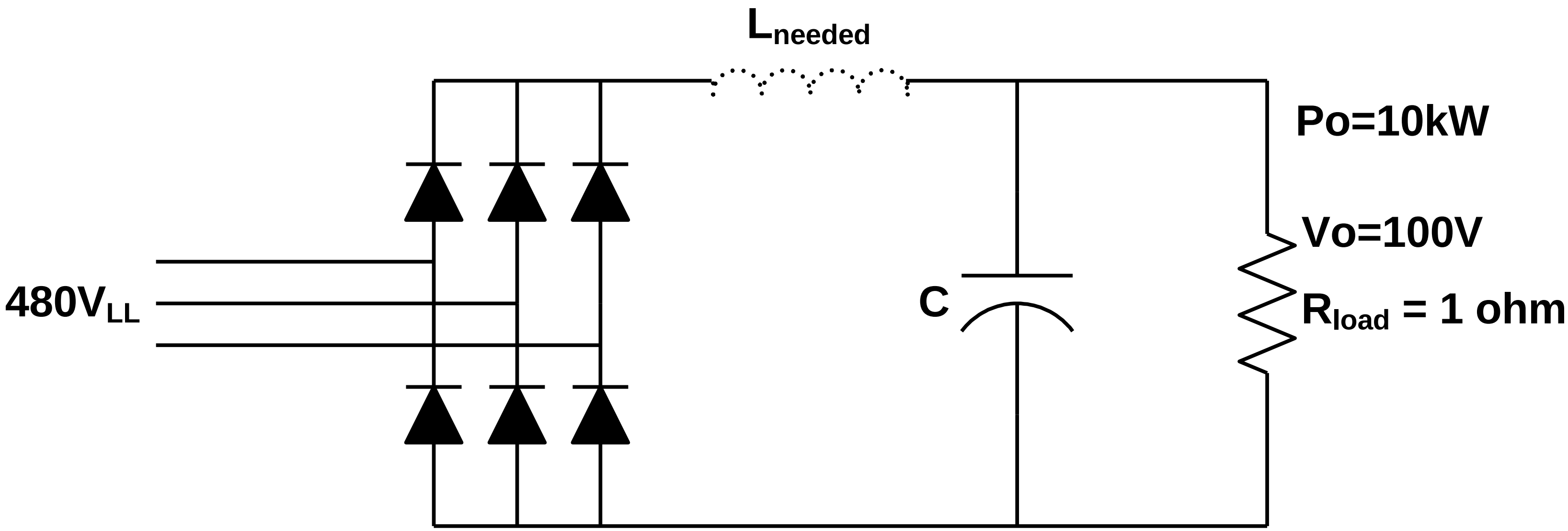
$$\frac{\$2.2M}{yr} * 20yr = \$44M$$

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*

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 the inductor needed to improve the power factor to leading 0.95.



Electromagnetic Interference (EMI)
Electromagnetic Compatibility (EMC)

Glossary of EMI Terms

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* $dB\,\mu A$.

Glossary of Terms

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

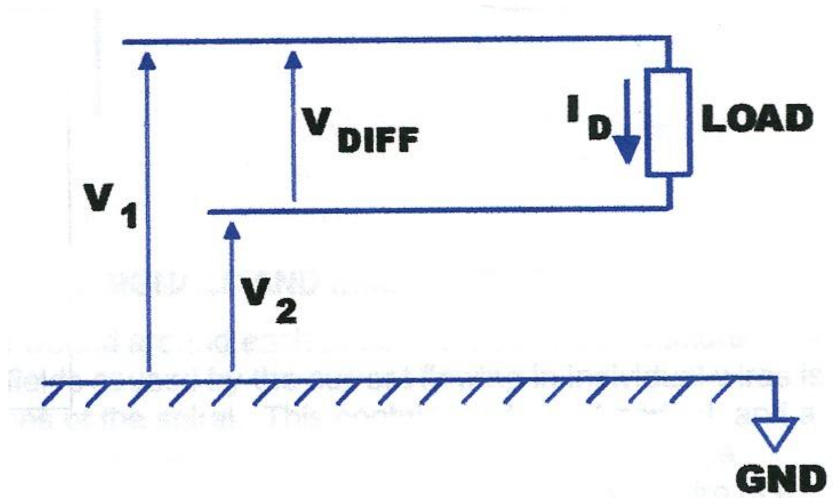
Verband Deutscher Elektrotechniker (VDE) has developed VDE 0871 for Level A and Level B.

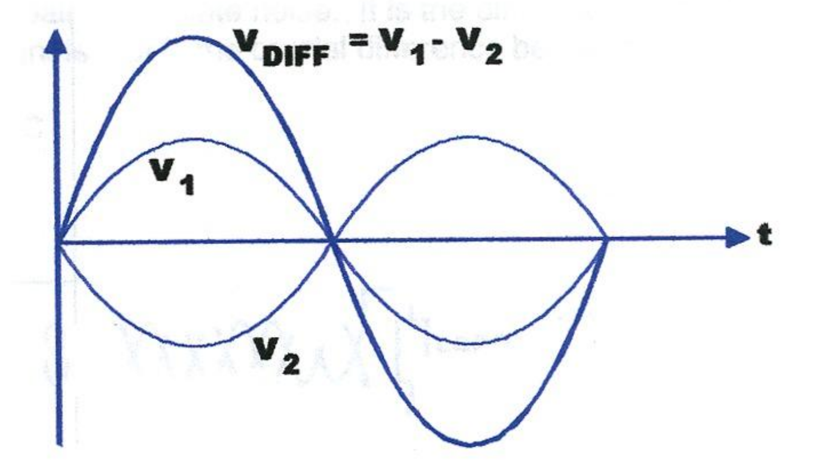
European Community

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.

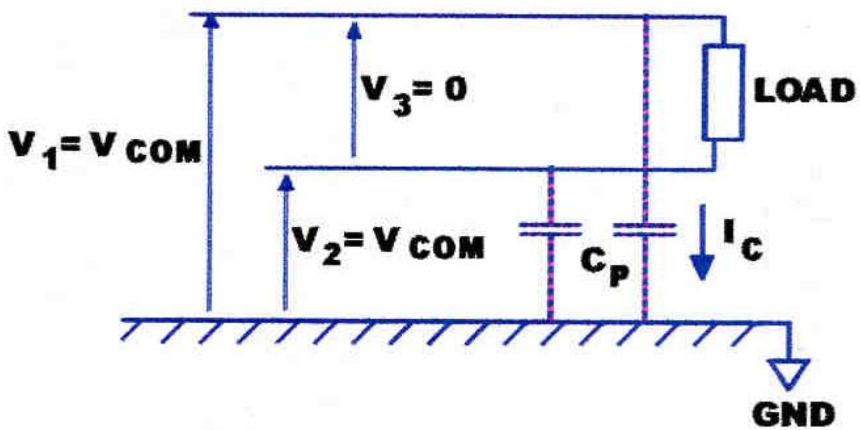
Differential Mode Noise

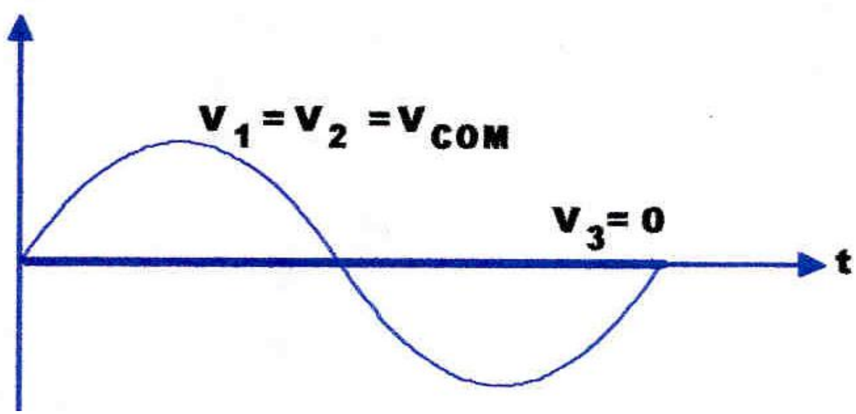




- *Produced as a natural result of complex, high frequency switching of V and I*
- $V_1 = - V_2$
- *Magnitudes are equal*
- *Phase difference is* 180^O
- $V_{SUM} = V_1 + V_2 = 0$
- $V_{DIFF} = V_1 - V_2$
- $I_{DIFF} = (V_1 - V_2) / R_{Load}$
- *Filter from line-to-line*

Common Mode Noise



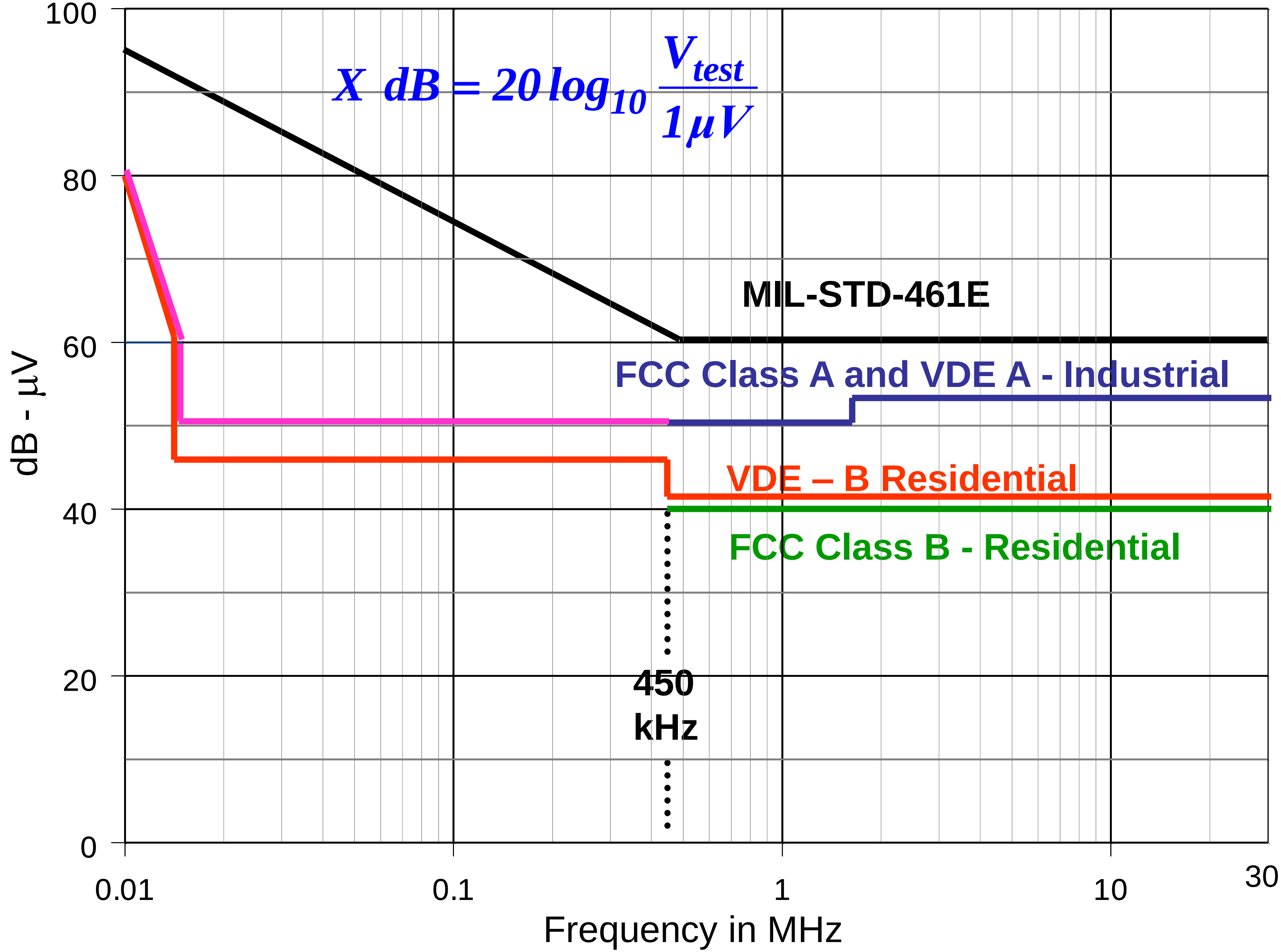


- *Produced as a result of circuit imbalances, currents produced by simultaneous high frequency voltages on (+) and (-) lines*
- *Capacitive coupled to ground*
- $V_1 = V_2 = V_{COM}$
- *Magnitudes are equal*
- *Phase difference is* 0^O
- $I_{COM} = V_{COM} / 2 \pi f C_P$
- *Common mode current flows to ground*
- *Filter from lines to ground*

Conducted emissions

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

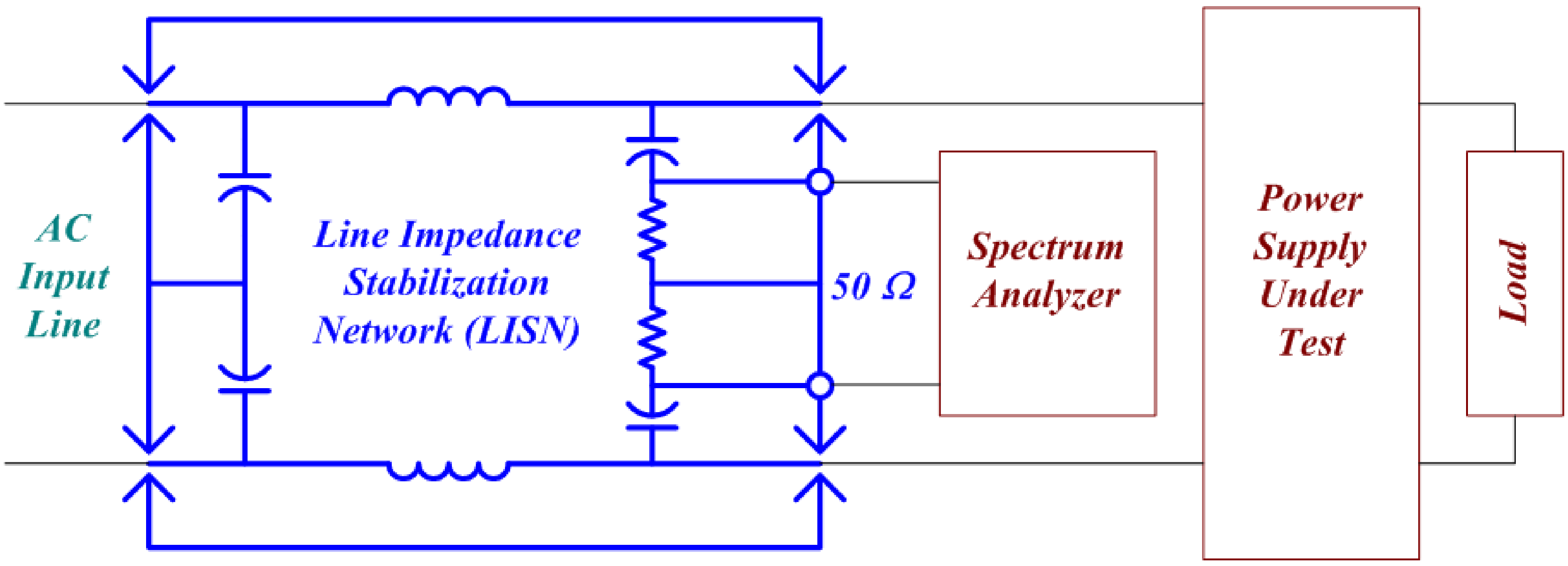
$$dB = 20 * \log_{10} \frac{\text{measured } \mu V}{1 \mu V}$$



$X\ dB = 20\log_{10}\frac{V_{test}}{1\mu V}$
MIL-STD-461E
FCC Class A and VDE A - Industrial
VDE – B Residential
FCC Class B - Residential
450
kHz
100
80
60
40
20
0
dB - µV
0.01
0.1
1
10
30
Frequency in MHz

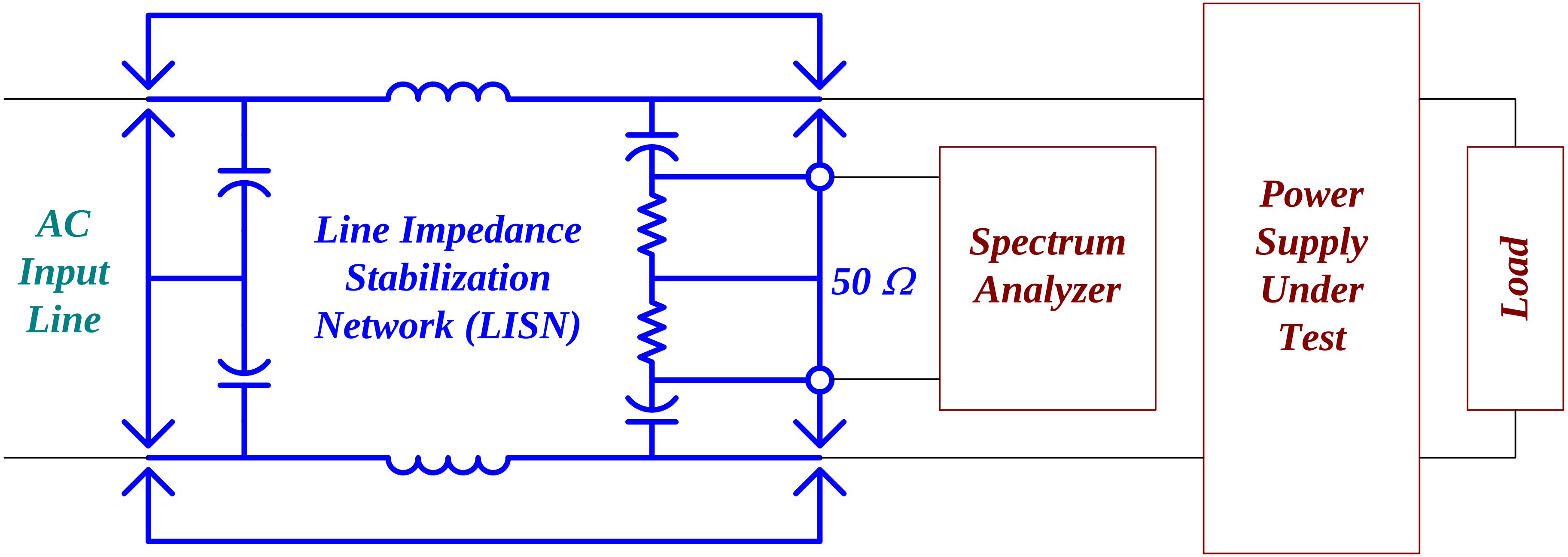
Test equipment used – *Spectrum analyzers with Line Impedance Stabilization Networks (LISNs) that*

- *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*

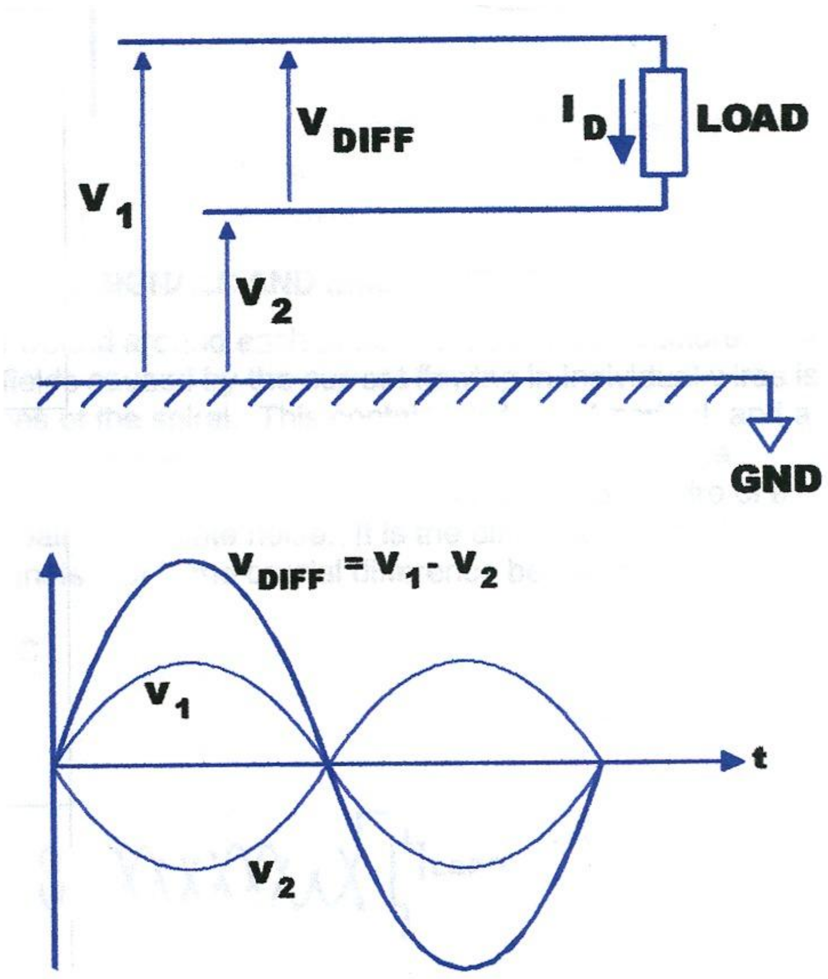


LISN considerations:

- *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)*
- *Load current*

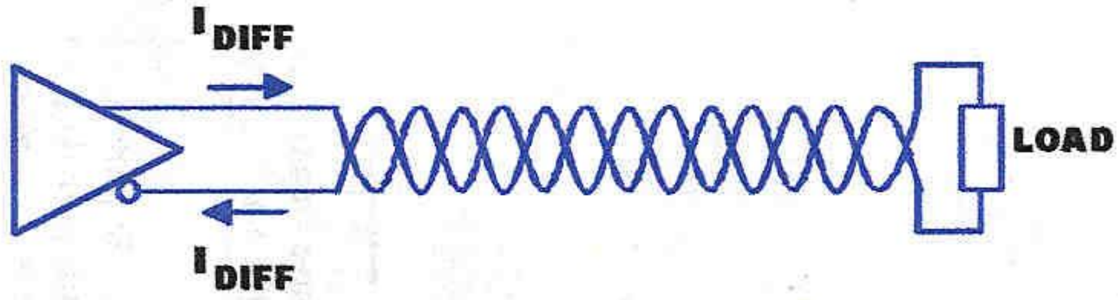


Noise Filters

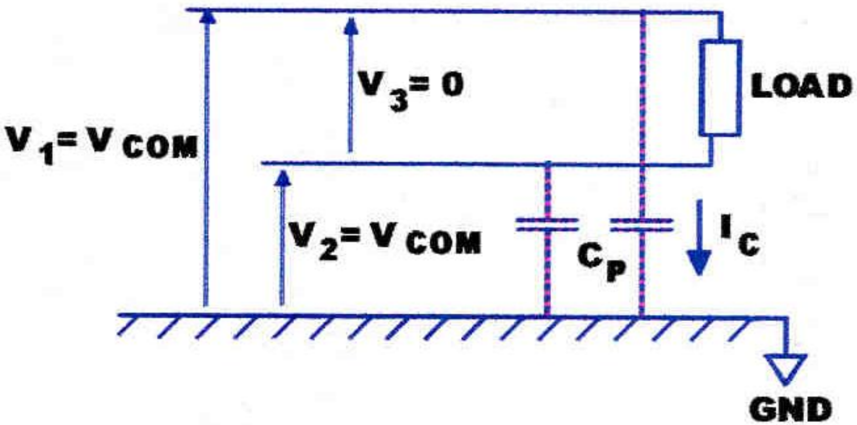


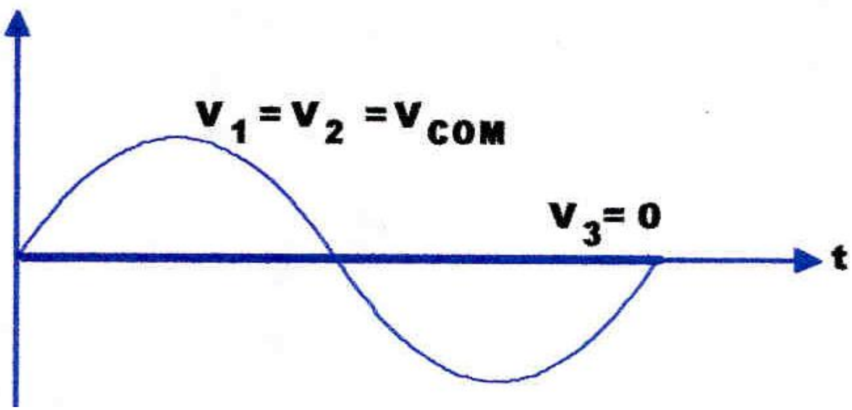
- *Produced as a natural result of complex, high frequency switching V and I*
- $V_1 = - V_2$
- *Magnitudes are equal*
- *Phase difference is 180*^{O}
- $V_{DIFF} = V_1 – V_2$ *= unwanted signal*
- $I_D = (V_1 – V_2) / R_{Load}$

Differential Mode Electromagnetic Compatibility

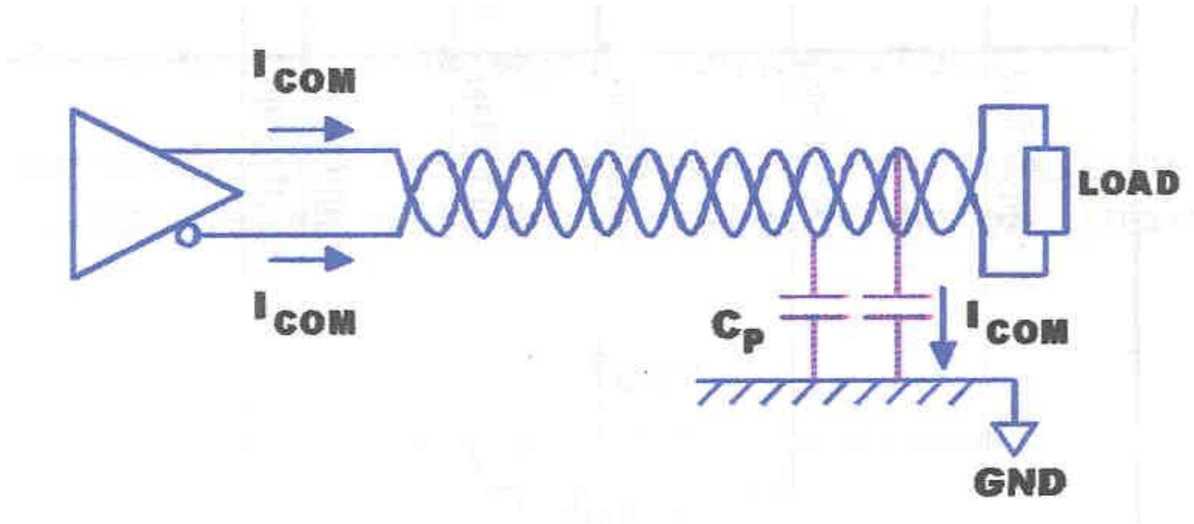


- *Current flow in opposite directions so that the magnetic field is contained within the spirals*
- *The tighter the cable twist the greater the containment and noise attenuation*
- *Shielding the pair (and tying the shield to ground in one or more places) will also increase noise attenuation*





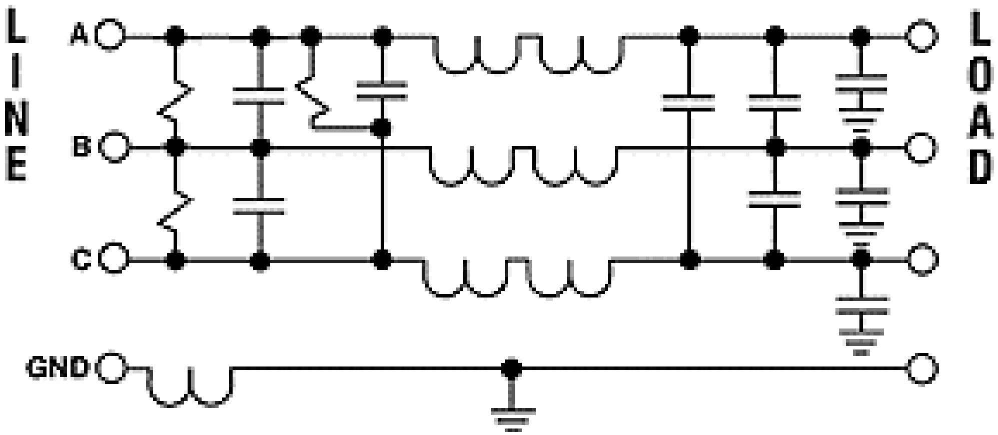
- *Produced as a result of circuit imbalances, currents produced by simultaneous high frequency voltages on (+) and (-) capacitively coupled to ground*
- $V_1 = V_2 = V_{COM}$
- *Magnitudes are equal*
- *Phase difference is* 0^O
- $V_{DIFF} = V_1 - V_2 =$ *wanted signal*
- $I_D = (V_1 - V_2) / R_{Load}$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

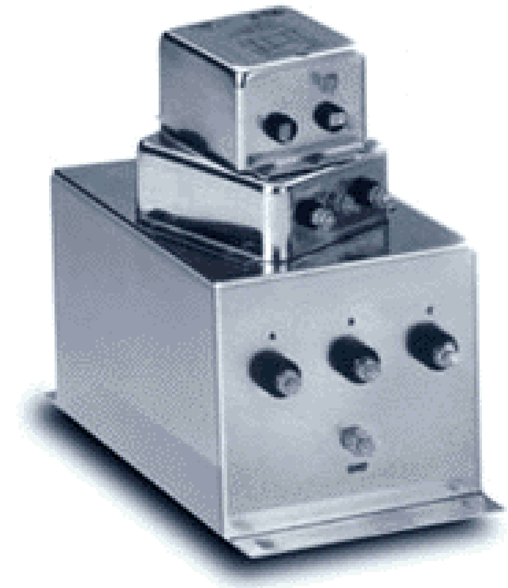


- *Common mode current generated by common mode voltages impressed across parasitic capacitances to ground*
- *Current flows are the same magnitude and in the same direction so that the spirals have no effect on containing the magnetic fields*
- *The pair must be shielded and the shield tied to ground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

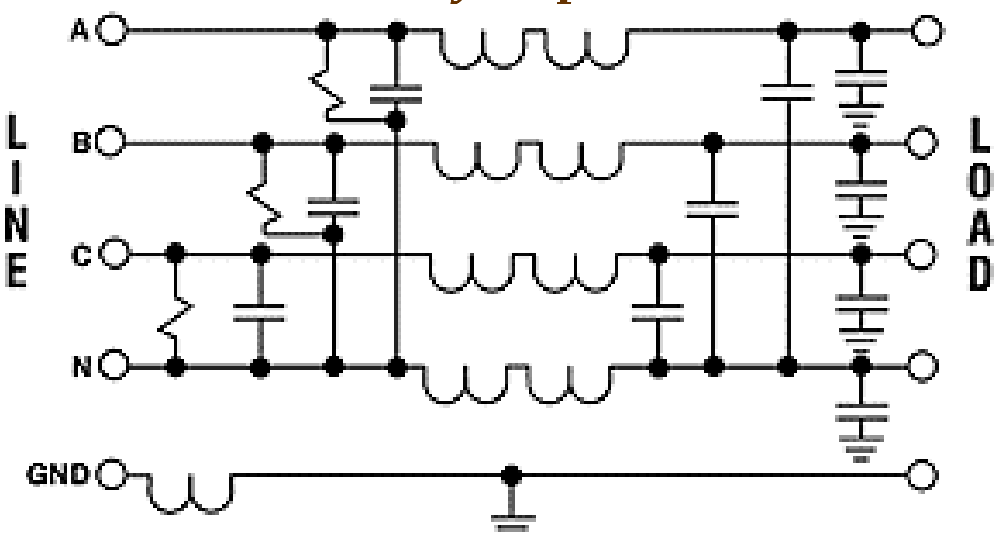
Input Conducted Line Noise Filters

Delta input





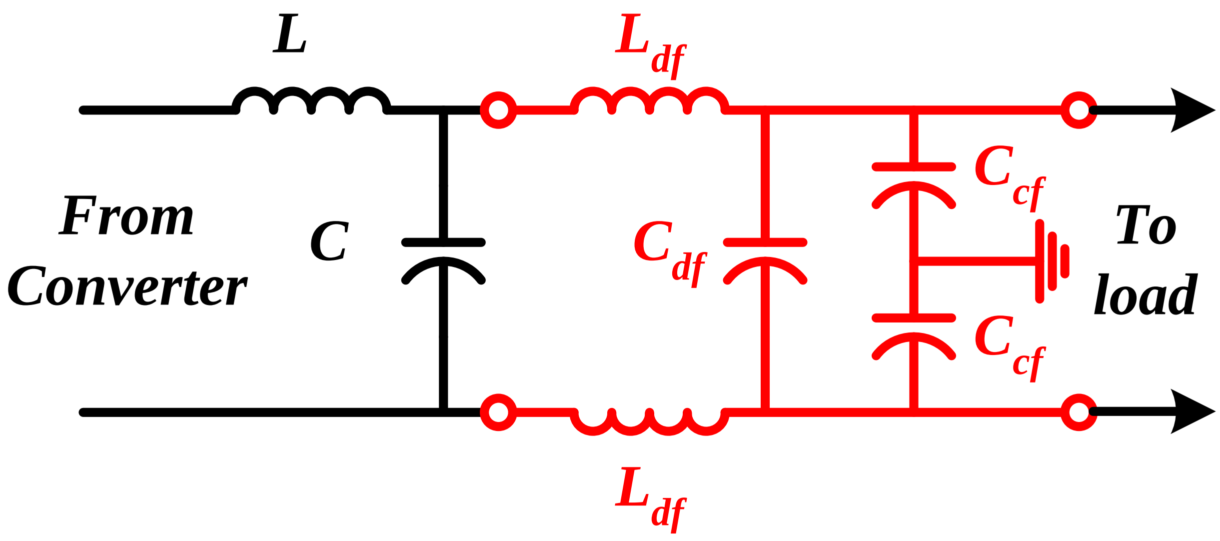
Wye input



- *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

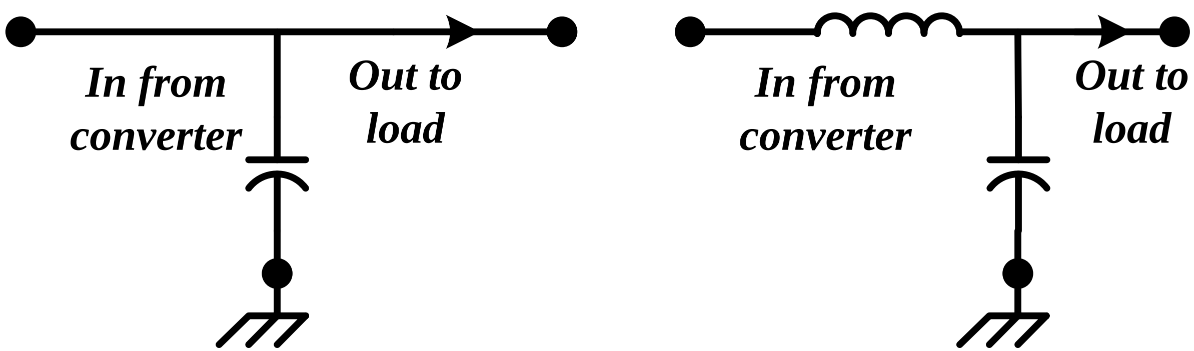
Input / Output Line Noise Filters



- 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

Output Line Feed-through Noise Filters

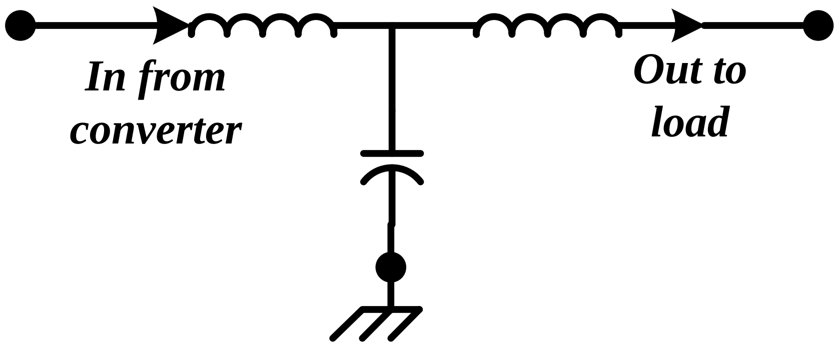
- **C filters** are the most common EMI filter, consisting of a 3 terminal feed-thru capacitor, used to attenuate high frequency signals



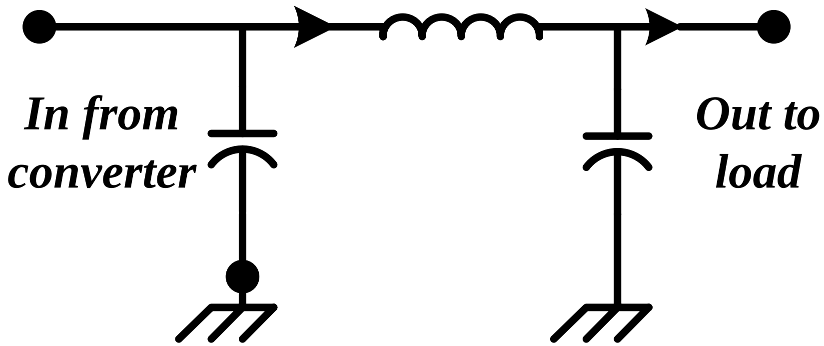
- **L filters** consist of one inductive element and one capacitor. One disadvantage is that the inductor element in smaller filters consists of a ferrite bead that will saturate and lose effectiveness at larger load currents

Output Line Feed-through Noise Filters

- ***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*

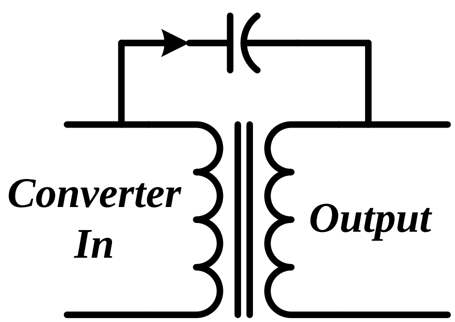


- ***Pi*** *filters consist of two capacitors and one inductor. They present a low impedance to both source and load. The additional capacitor element, provides better high frequency attenuation than the C or L filters*

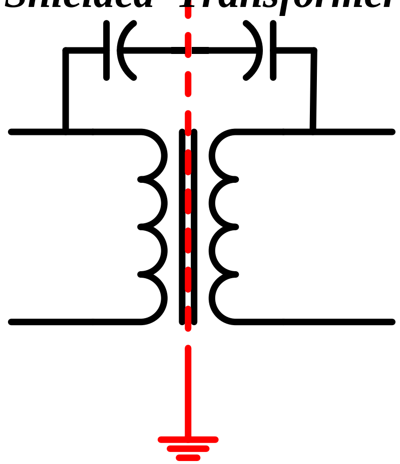


Other Conducted Noise Filters

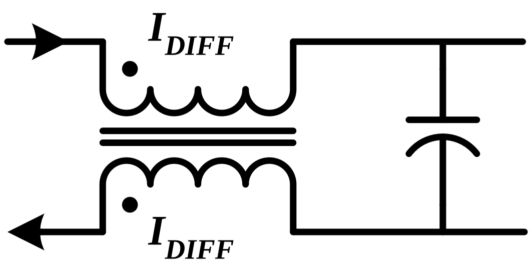
Plain Transformer

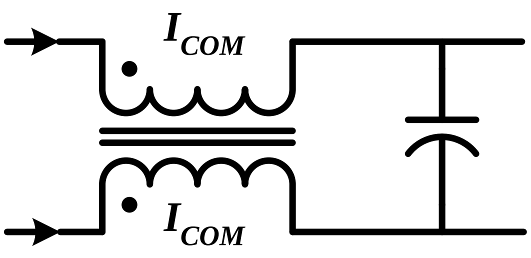


Electrostatic (Faraday) Shielded Transformer



Common Mode Choke

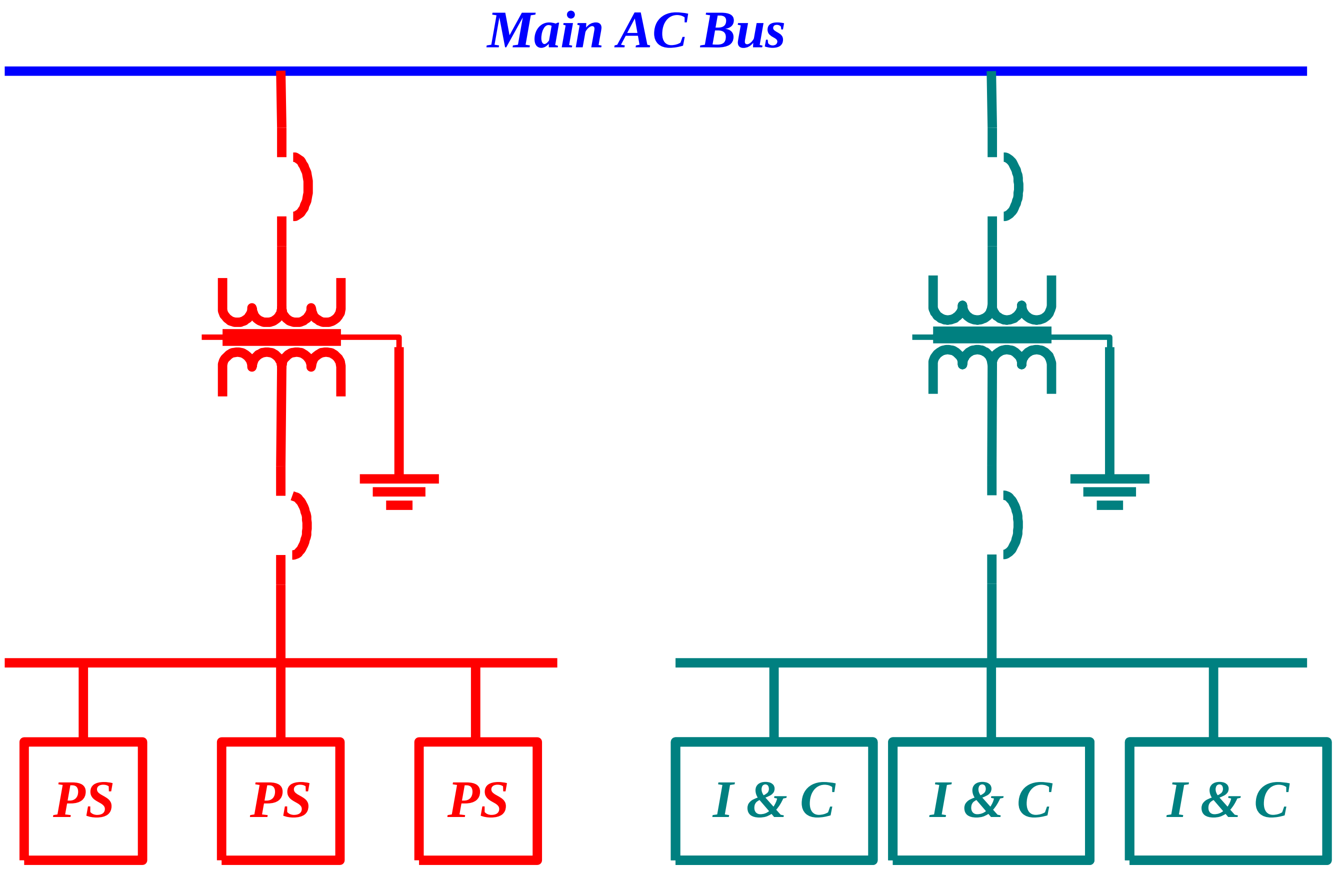




Differential mode currents flow in opposite directions. Magnetic fields cancel, choke presents low impedance, low attenuation to noise

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

Reducing Conducted Noise on Other Systems / Equipment



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

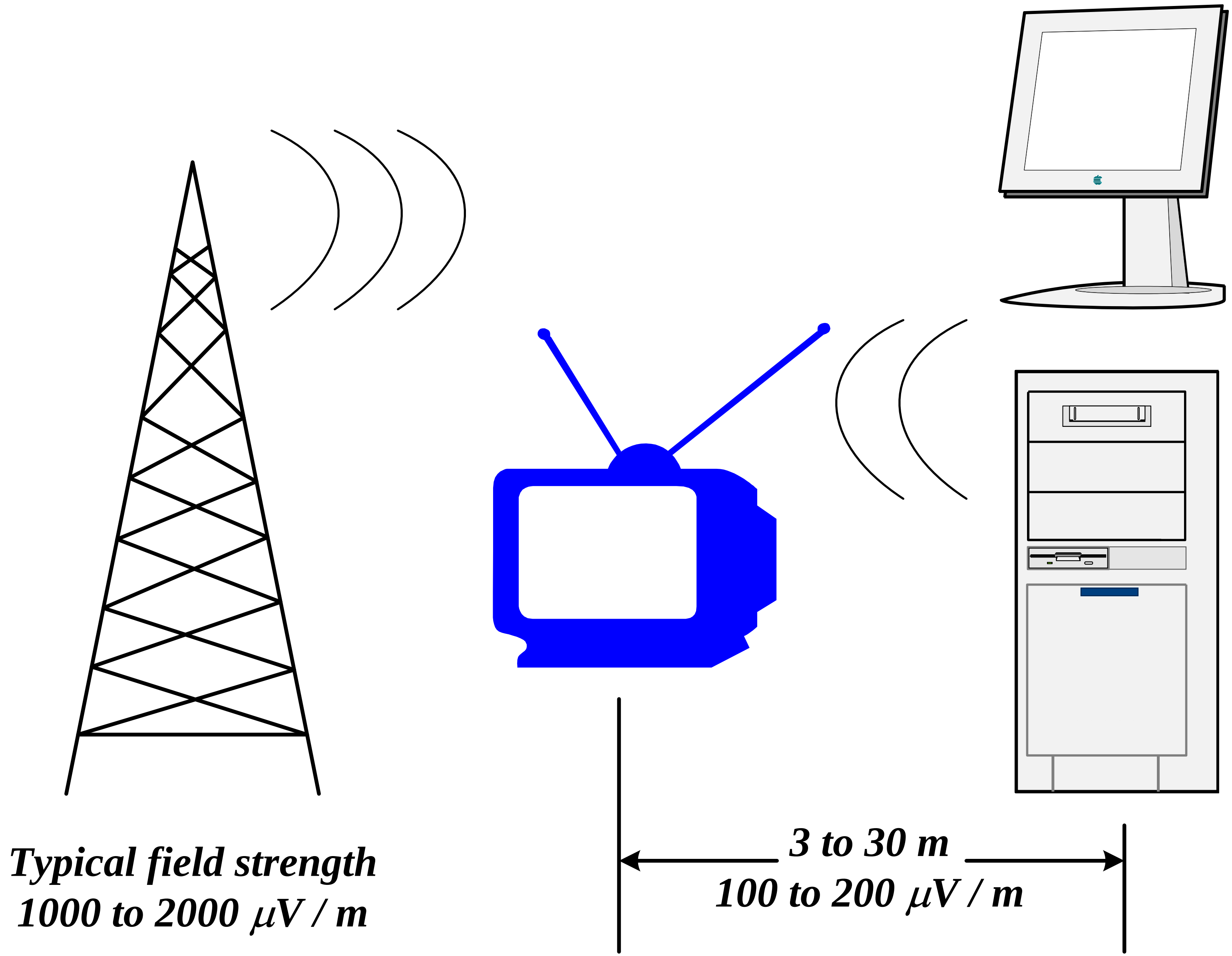
Radiated emissions

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

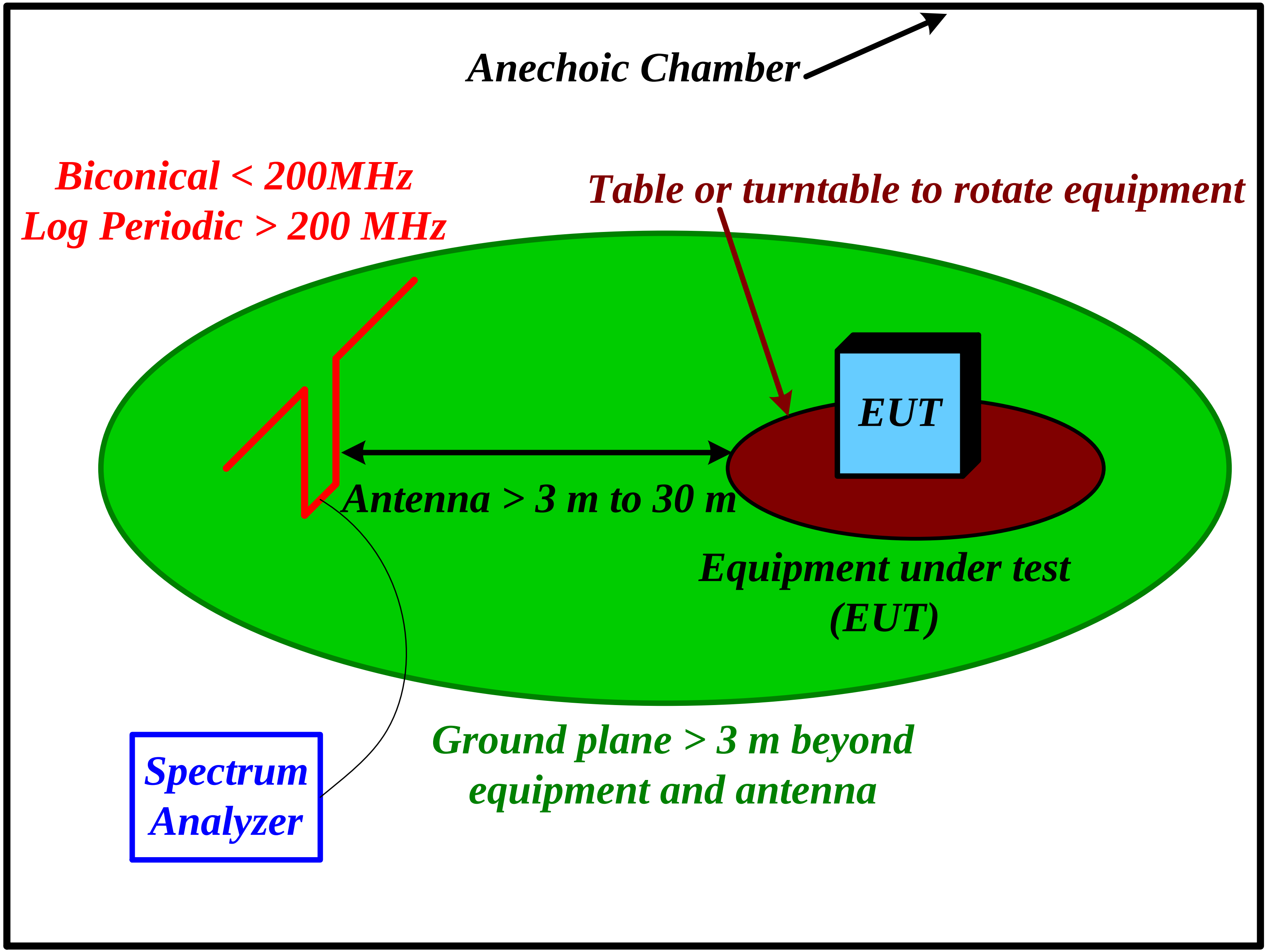
Test equipment used

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

Basis For Commercial – Residential Emission Limits

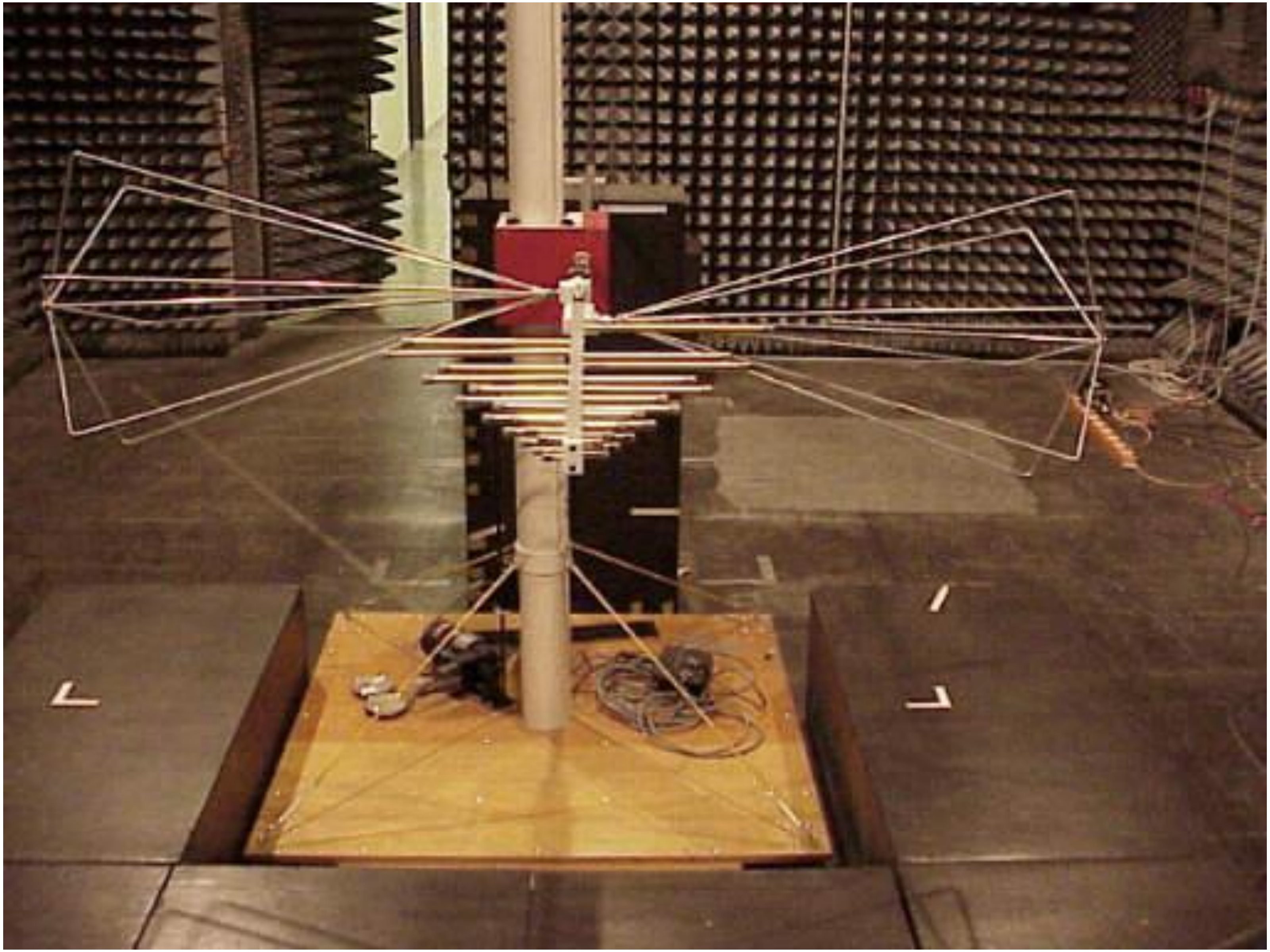


Radiated Emissions Test Setup



Log-Periodic Antenna

Bi-Conical Antenna



Any component or cable > 1/20 wavelength (λ) will be an efficient radiating or receiving antenna

Cable Lengths Vs Wavelength			
Frequency	**λ**	**1/4 λ**	**1/20 λ**
10 kHz	30 km	7500 m	1500 m = 59,000 in
100 kHz	3 km	750 m	150 m = 5,900 in
1 MHz	300 m	75 m	15 m = 590 in
10 MHz	30 m	7.5 m	1.5 m = 59 in
30 MHz	10 m	2.5 m	50 cm = 20 in
100 MHz	3 m	75 cm	15 cm = 6 in
1 GHz	30 cm	7.5 cm	1.5 cm = 0.6 in

Radiated Noise Reduction – Small Loops

- $B = T = 10{,}000$ 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*

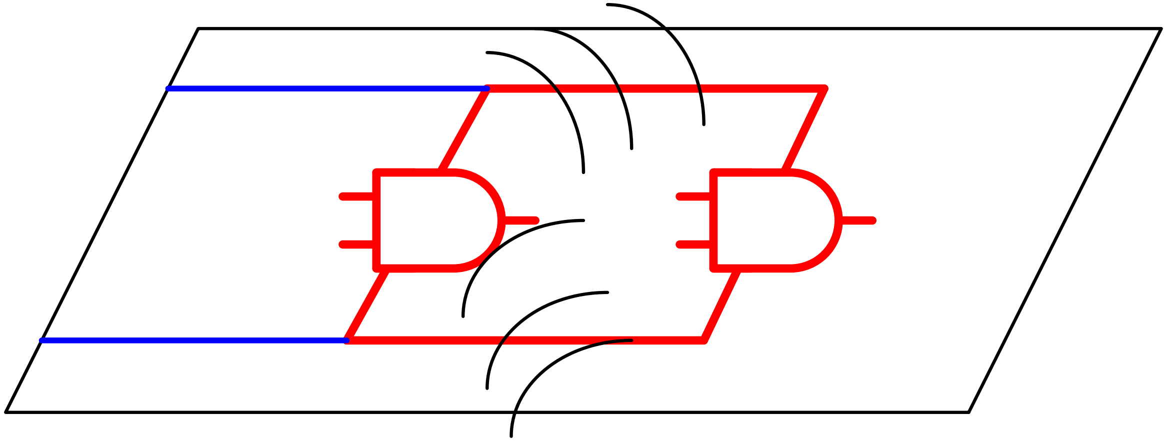
$$V \propto A$$ *the area of the loop cut by flux*

Moral - minimize loop areas by:

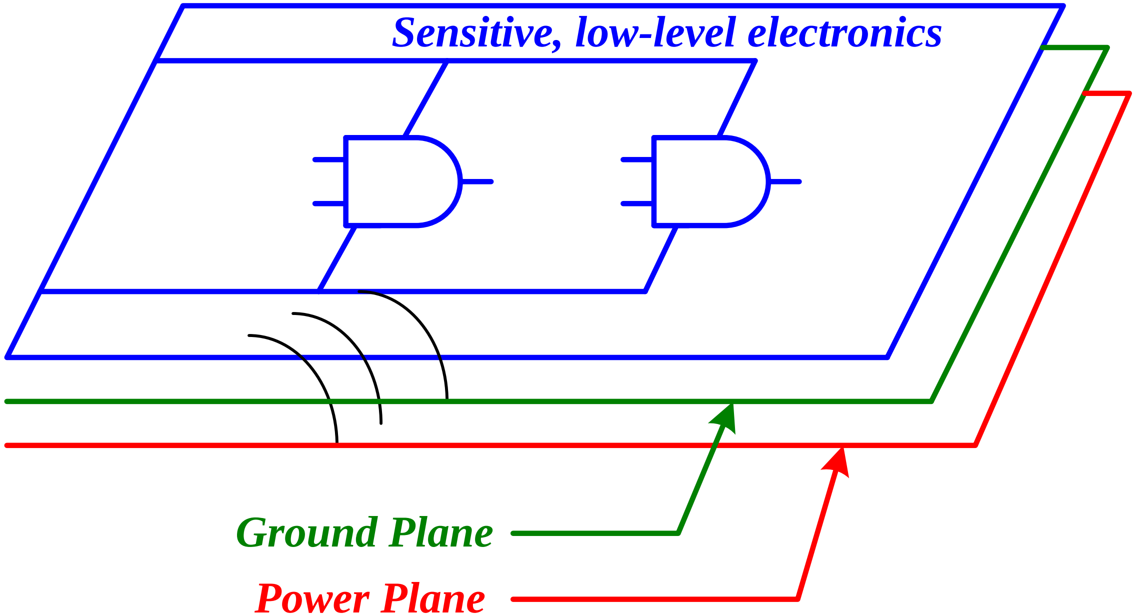
running supply and return bus or cable conductors together

twisting cables whenever possible

Radiated Noise Reduction By PCB Small Loops

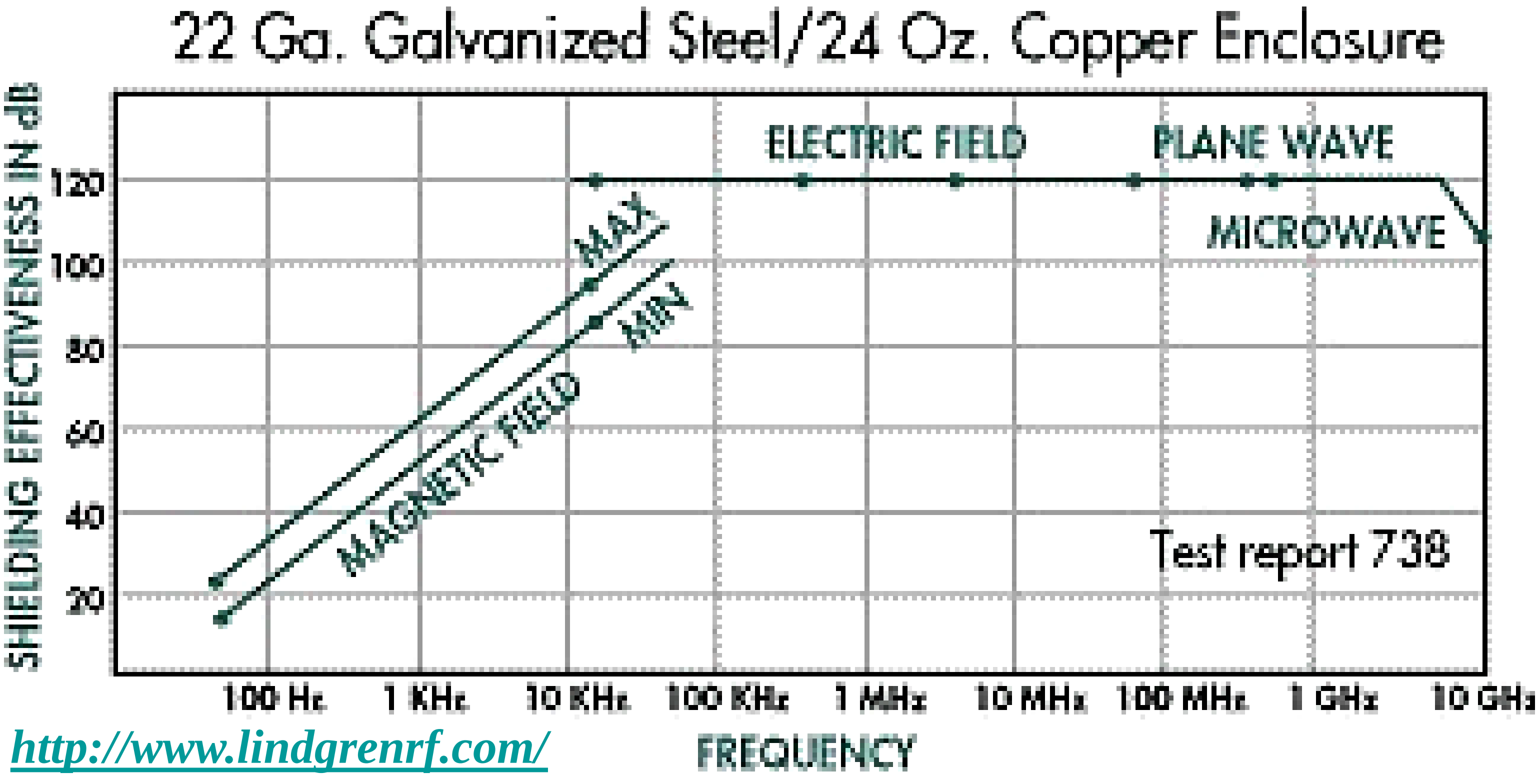


Radiated Noise Reduction By PCB Ground Planes



Use shielded cables

Use shielded enclosures (if necessary for interior controls)



http://www.lindgrenrf.com/

Radiated Noise Reduction – Other Considerations

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 # 5

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 $\mu\,\Omega * cm$.

Section 5. DC Power Supplies

Power Supplies

- *Definition, Purpose and Scope*
- *The Recent Past*
- *The Present*
- *DC Power Supplies in Particle Accelerators*

Power Supply Definition and Purpose

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*

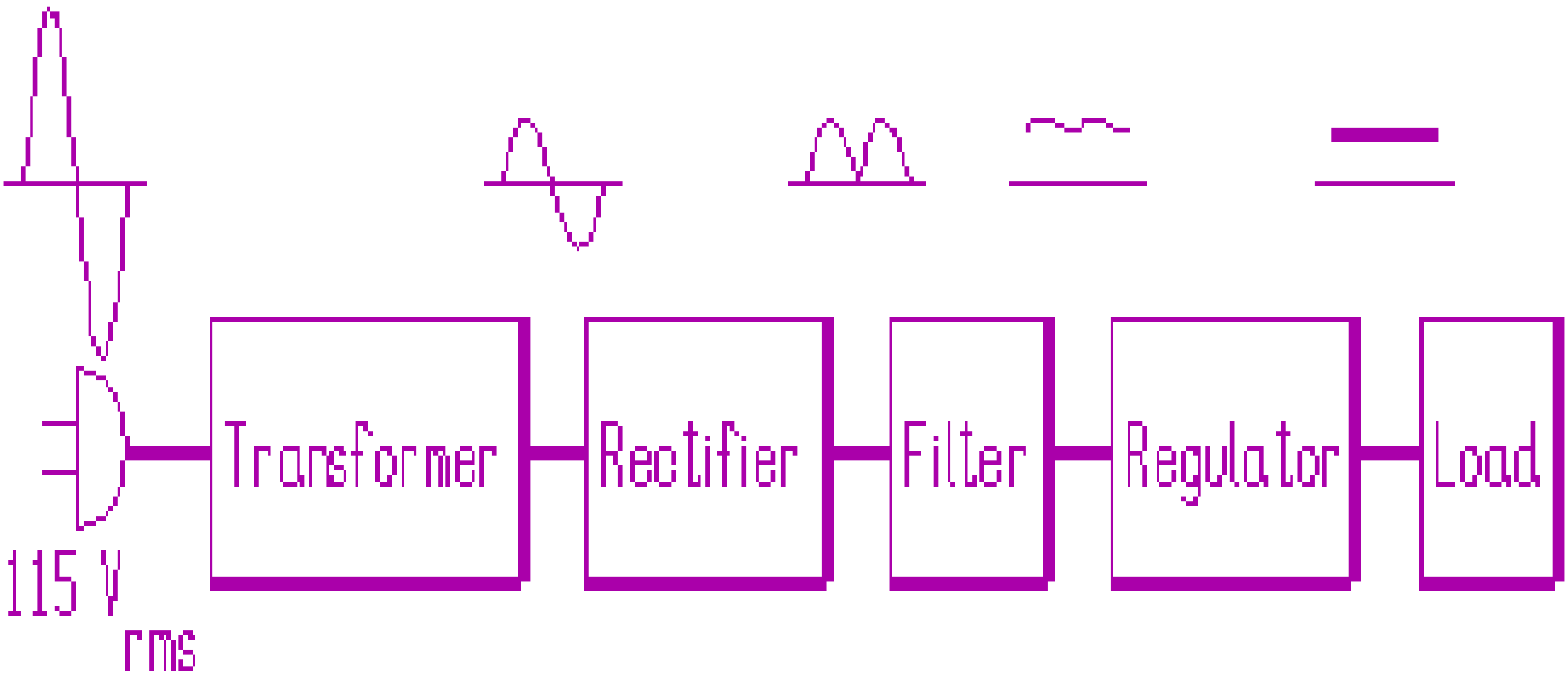
Purpose

- *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

- *208 VAC is available. The load is a logic circuit in a personal computer that requires regulated 5V DC power. The power supply makes the 208 V AC power source and 5V DC load compatible*

Power Supply Block Diagram



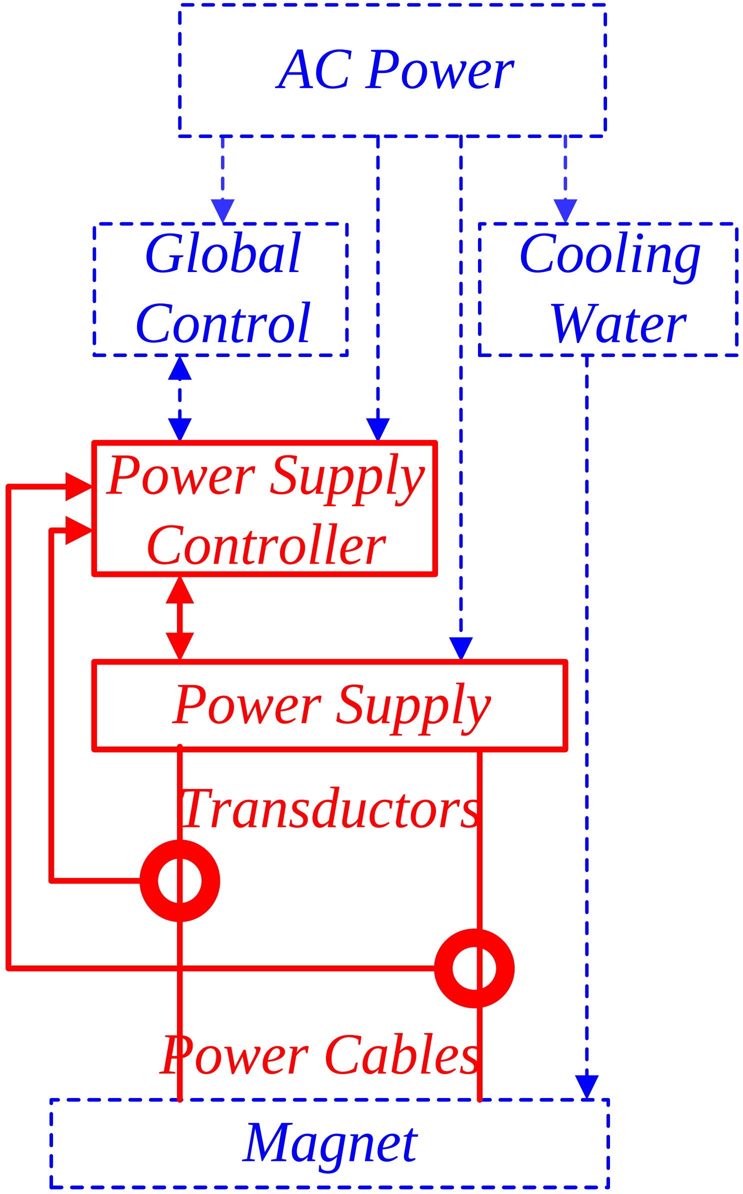
Power Line EMI/EMC

Controls

Interlocks

Reliability

Power System Types - The DC Magnet Power System



Scope

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*

The Recent Past
Circa 1960 - 1990

60 Hz Low Frequency Transformers

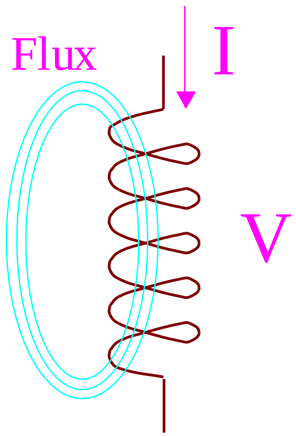
60 Hz Low Frequency Transformers

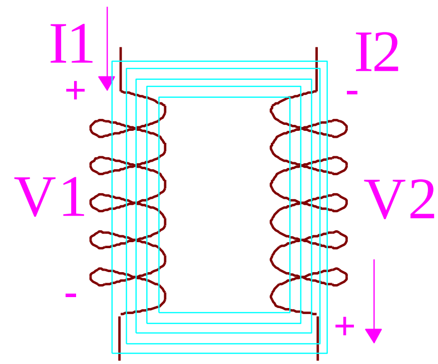
- *Transformers are inductors with linked flux φ:*

*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)* **$V = L_m * di / dt$**





- *L_m is derived from the number of turns, the area of turn path, length of flux and μ of the iron. It is normally referred to as the magnetizing inductance*
- *Iron core transformers are used at frequencies below 1 kHz*
- *Magnetizing inductance for a low frequency transformer is large, typically requiring > 1% of the total current to produce the desired voltage*

Equivalent Transformer Circuit

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

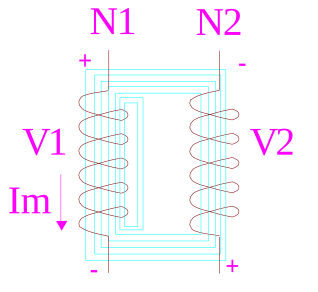
  1. *The magnetizing inductance in which the current is out of phase with the voltage.*

  2. *The magnetizing losses which are in phase with the current are due to eddy current losses and magnetizing current losses or hysteresis losses.*

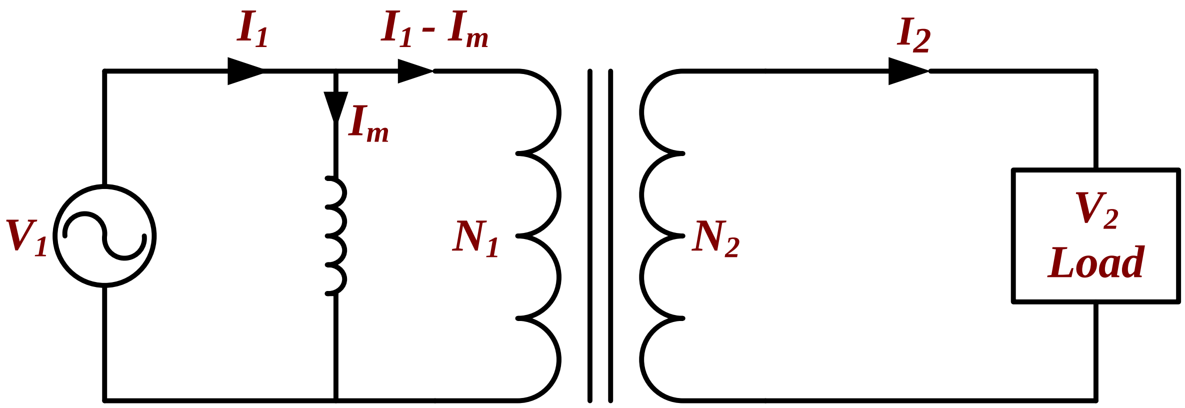
- *The inductance is obtained by driving the transformer with the secondary open circuited $I_2=0$ and measuring the Primary voltage and current.*

$$L_m = (V_1 / I_1) / (2 * \pi * f) \text{ out of phase}$$

$$R_m = V_1 / I_1 \text{ in phase}$$



60 Hz Low Frequency Transformers



Turns cut by the same flux produce a voltage with the same volts per turn as the driving turns

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

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

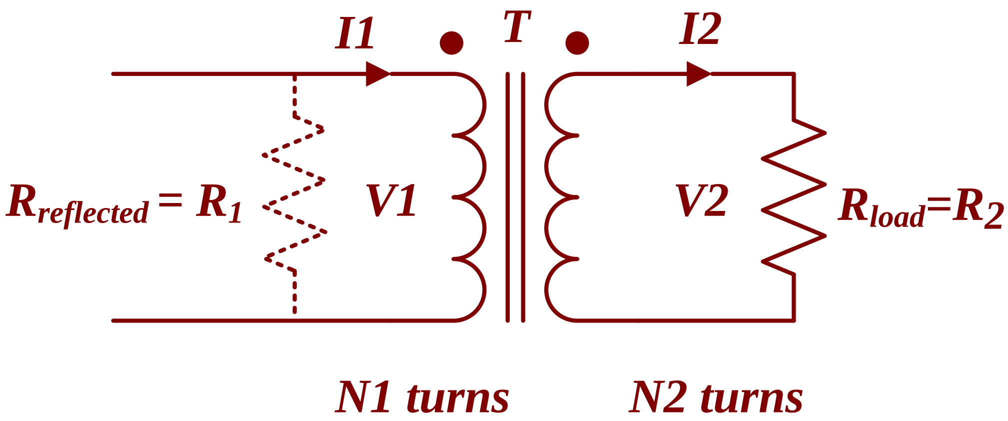
With a source and a load, the primary current equals the source current minus the magnetizing current. Ampere-turns in the primary and secondary must equate

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

If $I_m << I_1$ then

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

Impedance Ratios and Reflected Impedances

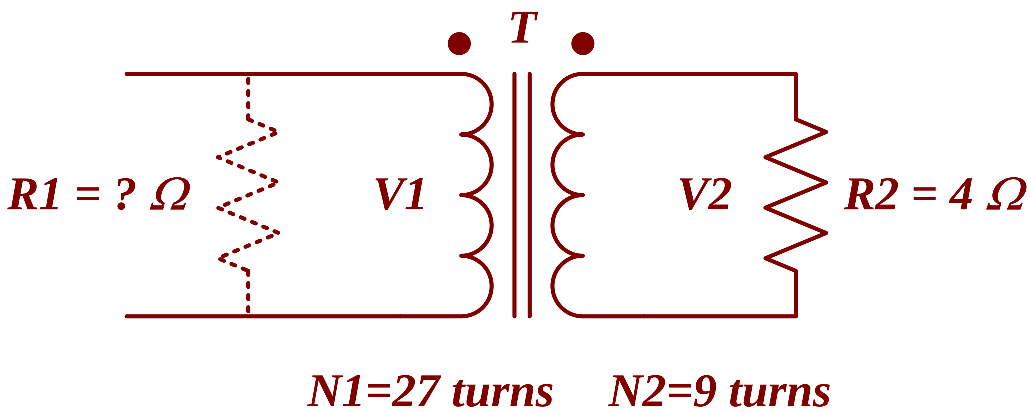


$$R_1 = \frac{V_1}{I_1} = \frac{\frac{N_1}{N_2} V_2}{\frac{N_2}{N_1} I_2} = \frac{N_1 V_2}{N_2} * \frac{N_1}{N_2 I_2}$$

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

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

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

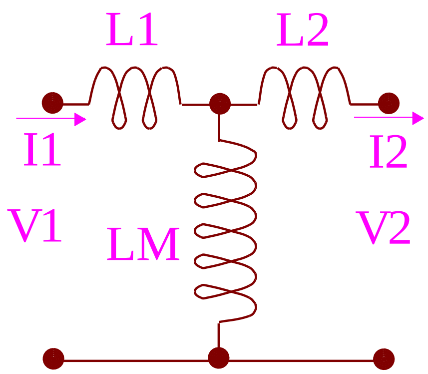


$$R_1 = \frac{N_1^2}{N_2^2} * R_2 = \frac{27^2}{9^2} * 4\Omega$$

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

Leakage Inductance - Equivalent Transformer Circuit

- *Flux which does not couple both windings is called the leakage flux and acts like series inductors 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*

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

Homework Problem #6

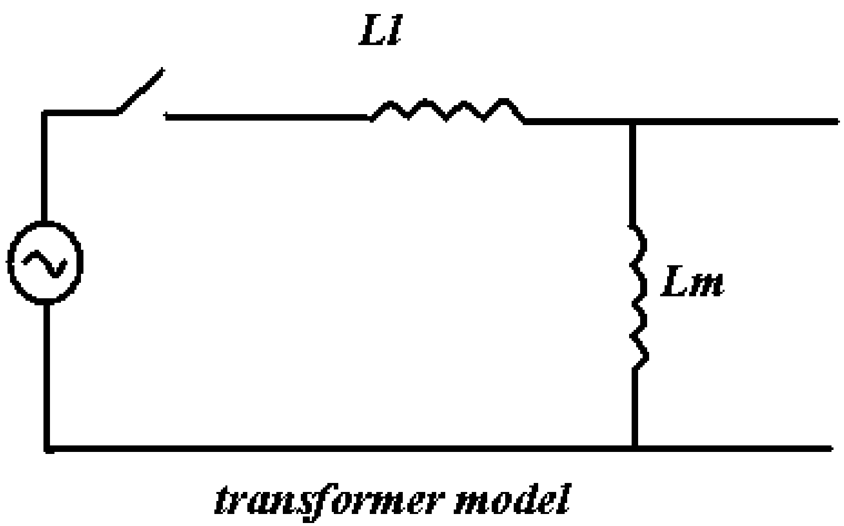
A 1000kVA, 12.47kV to 480V, 60Hz three-phase transformer has an impedance of 5%. Calculate:

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

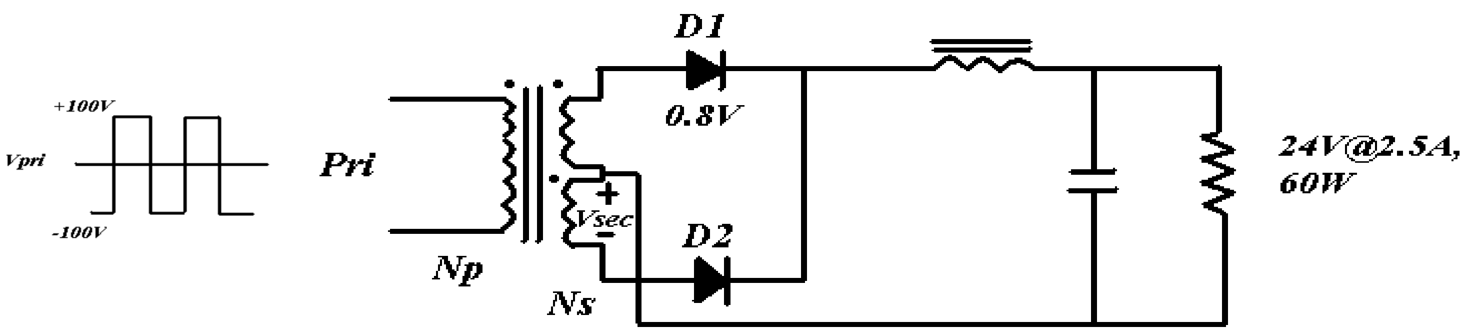
Transformer Model



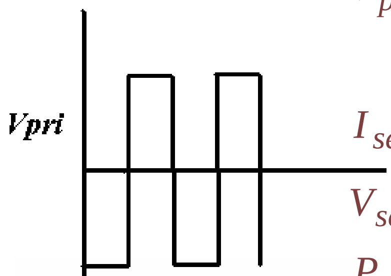
An air gap is undesirable in a transformer because:

- *a large L_m is desired to reduce the magnetizing and inrush current*
- *a small L_l is desired to lower energy and switching losses*

Transformer Example



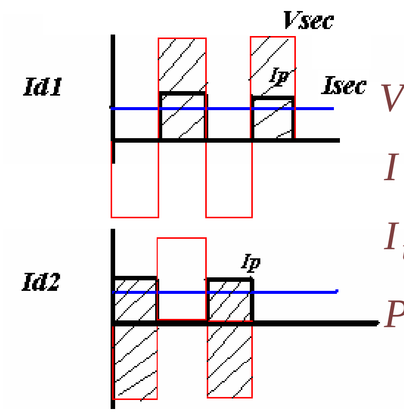
$V_{pripeak} = 100V \quad V_o = 24V \quad V_d = 0.8V \quad V_{secpeak} = 24.8V \quad I_o = 2.5A \qquad D = 0.5$



$I_{secrms} = I_{secavg} * \sqrt{D} = I_o * \sqrt{D} = 2.5 * \sqrt{0.5} = 1.77A$ 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

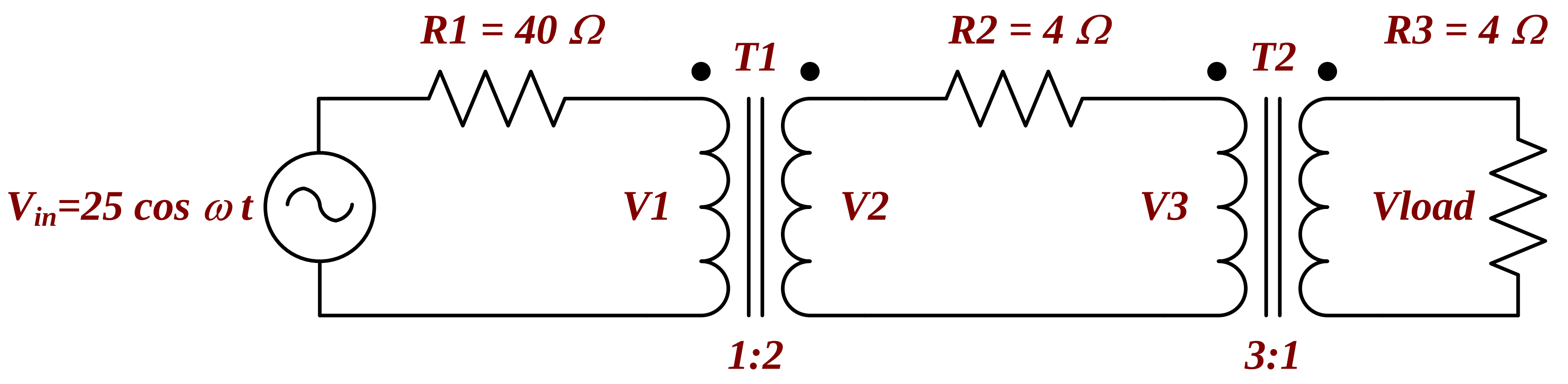
$I_{totalprirms} = 0.439A * 2 = 0.878A$

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

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

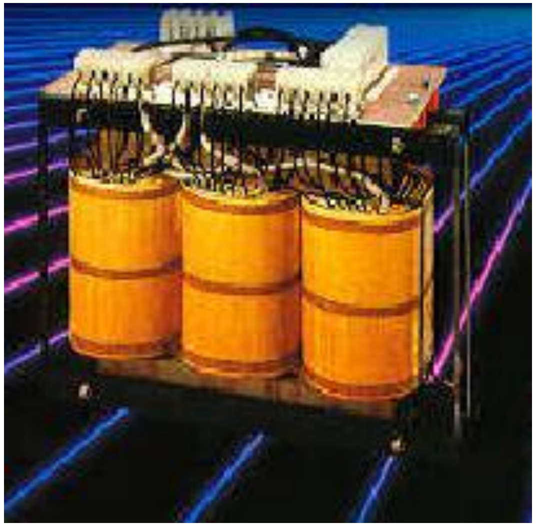
Homework Problem # 7

Calculate the output voltage in the circuit shown below.



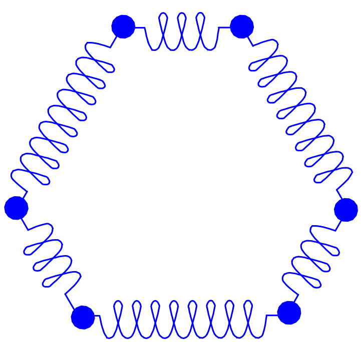
Transformer Configuration

- Low frequency, 60 Hz, transformers almost always use 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 transformer 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

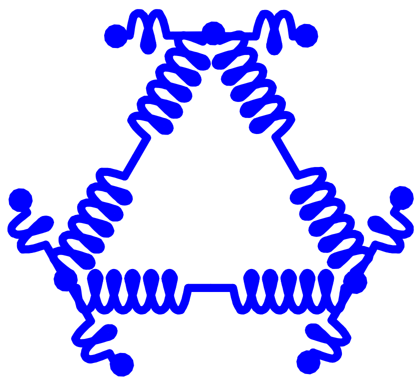


Common Transformer Types

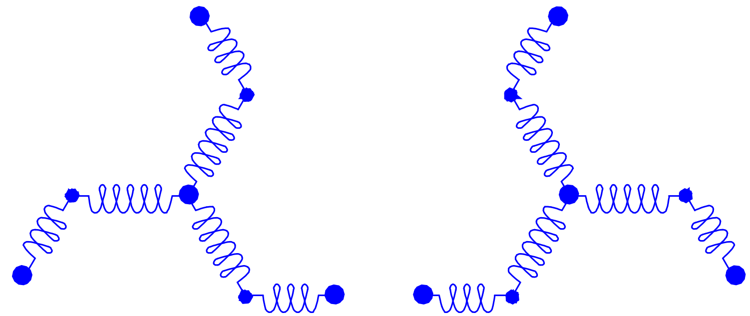
Delta -wye, extended delta, polygon and zig-zag produce 6 phase outputs



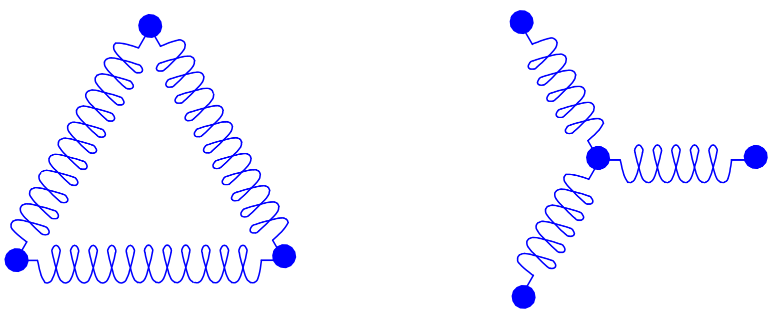
Polygon



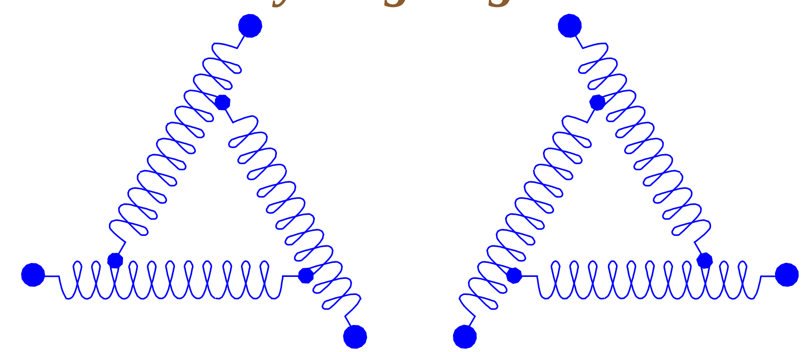
Delta Zig-Zag



Wye Zig-Zag



Delta-Wye

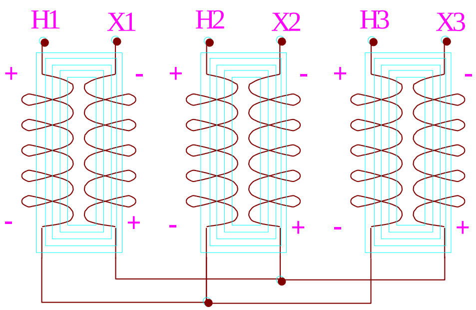


Extended delta

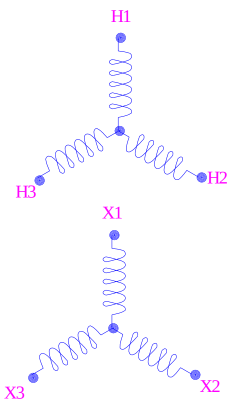
Three phase Transformer most common type

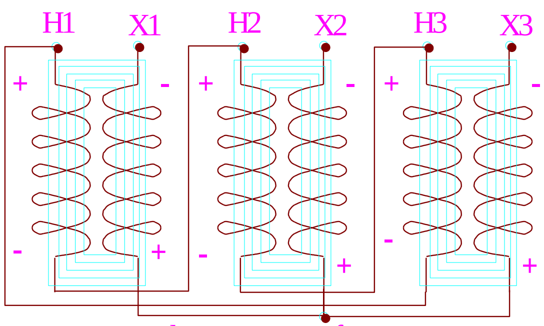
Three phase Transformers

- *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*

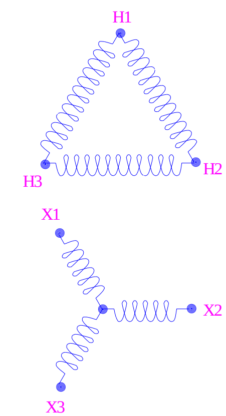


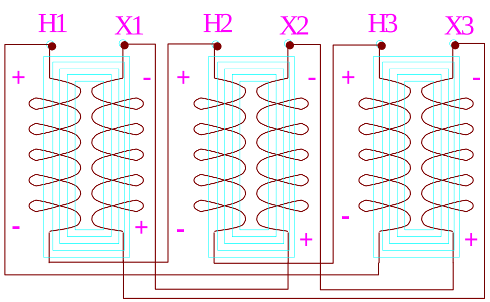
Wye-Wye Transformer



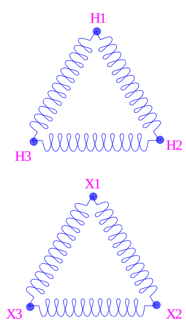


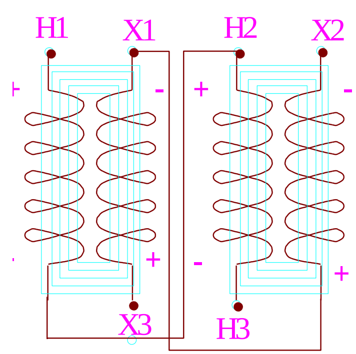
Delta -Wye Transformer



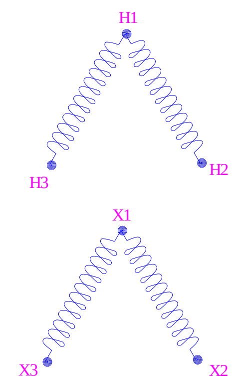


Delta - Delta Transformer





Core Delta -Delta Transformer



open Wye

Balanced Bridge Harmonics - Trigonometric Identities

Addition formulae

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

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

Therefore

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

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

and

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

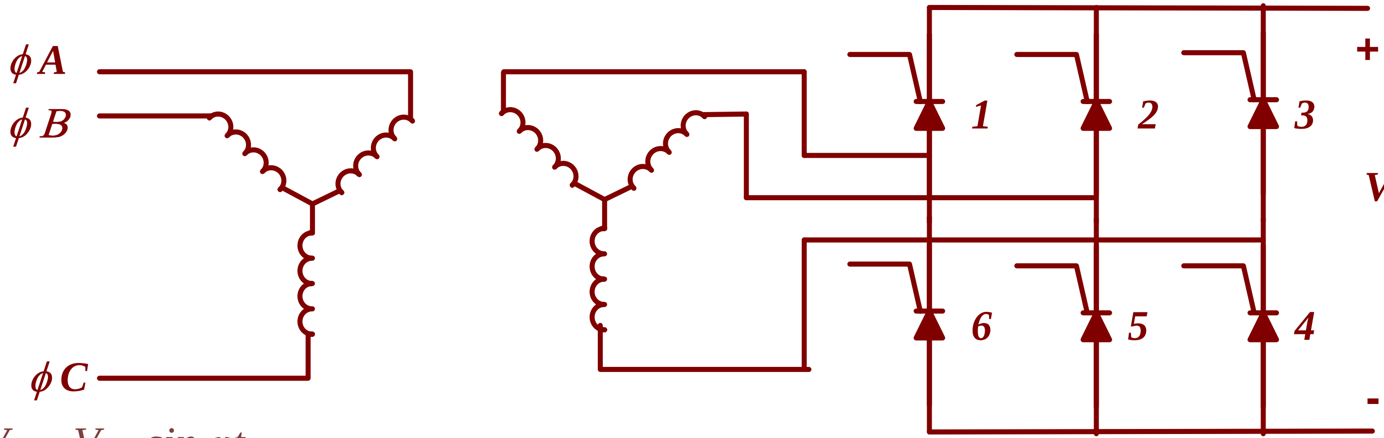
$$\sin a - \sin b = 2\sin\frac{a-b}{2}\cos\frac{a+b}{2}$$

Similarly, since

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

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

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



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

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

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

$$V_{AB} = V_A - V_B$$

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

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

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

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

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

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

For a transformer ratio, N_{YY}

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

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

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

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

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

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

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

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

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

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,

$$a_0 = a_n = 0$$

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

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

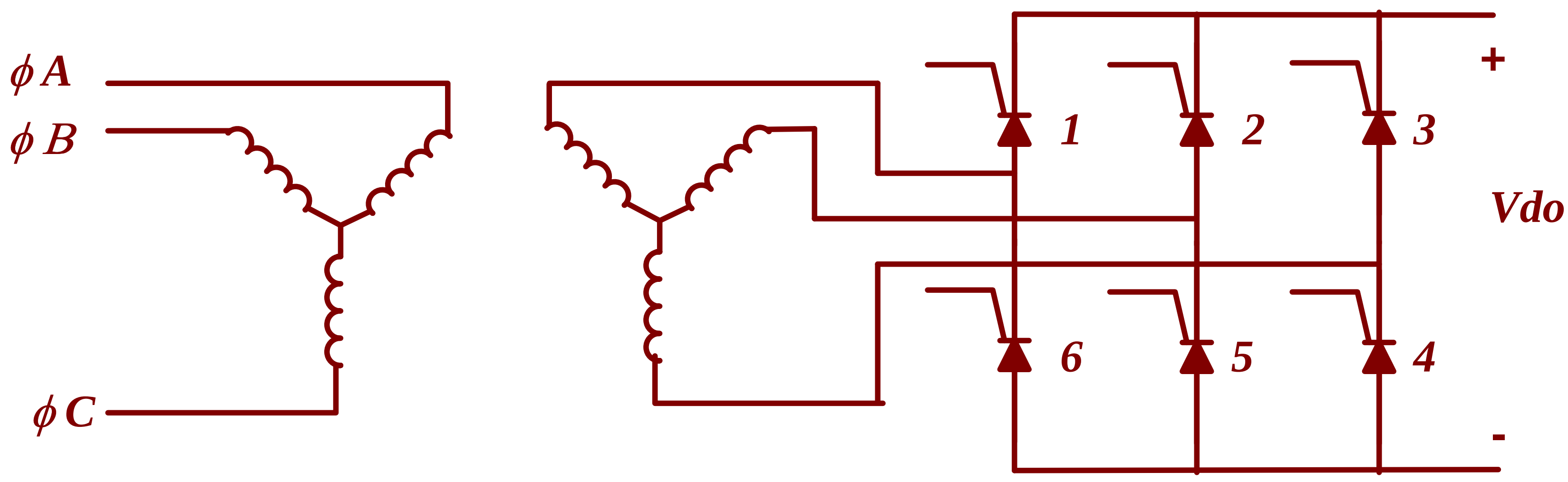
$$= \frac{4I_L}{T}\int_{T/12}^{5T/12} \sin\frac{2\pi nt}{T}\,dt$$

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

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

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

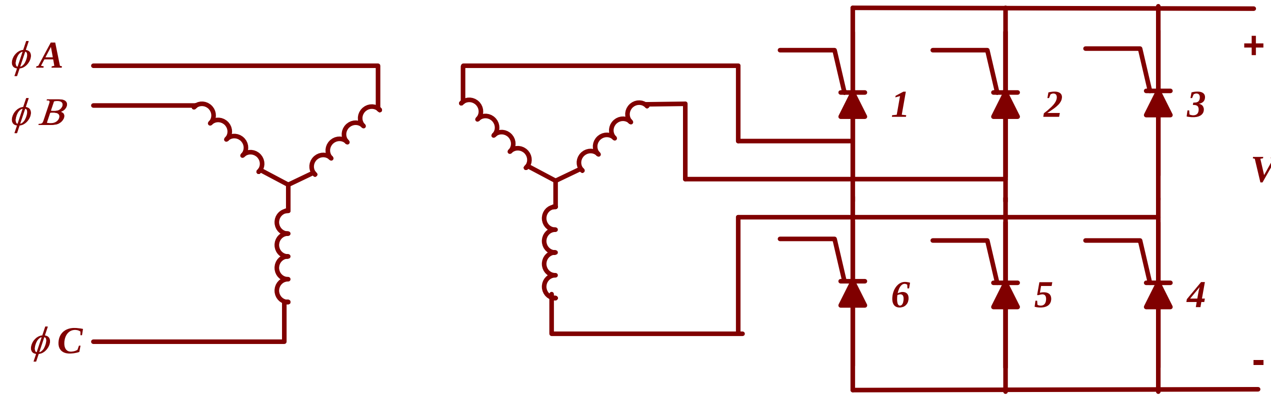
Wye-Wye Primary Current

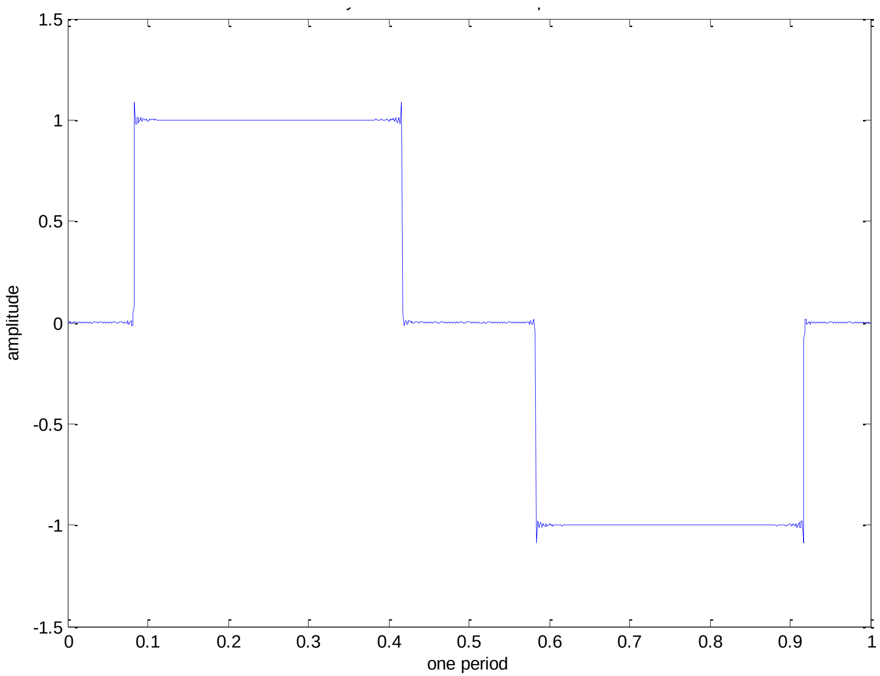


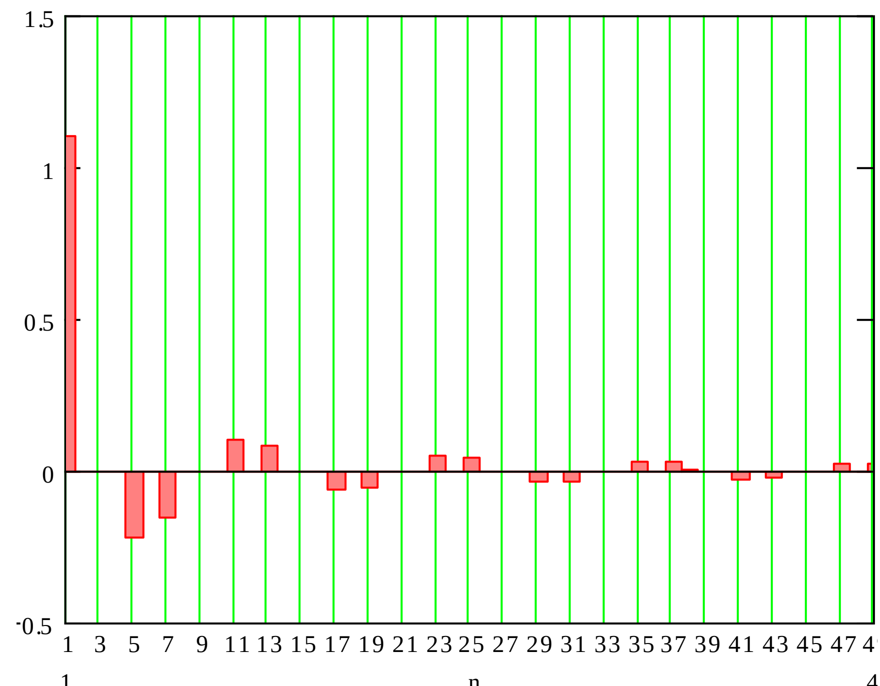
Note that the first term eliminated all of the even harmonics and the second eliminated all multiples of the third harmonic. The current on the primary leg of the transformer, due to the YY winding is

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

Wye-Wye Primary Current

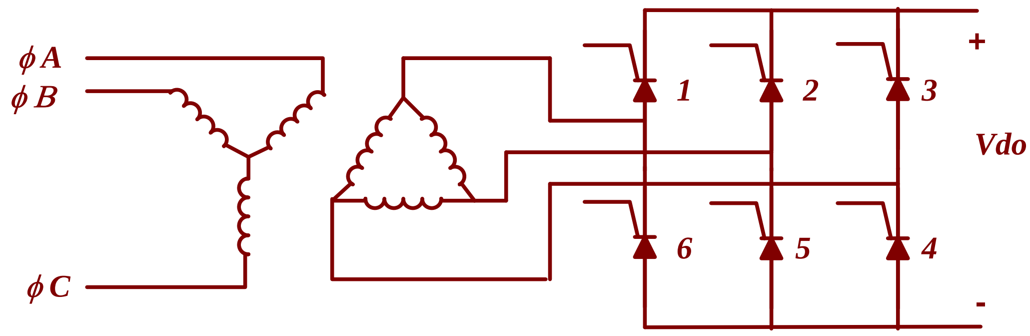






Harmonic	1	3	5	7	9	11	13	15	17	19
Frequency	60	180	300	420	540	660	780	900	1020	1140
Amplitude	1.103	0	-0.221	-0.158	0	0.100	0.085	0	-0.065	-0.058

Three Phase Wye-Delta



In order to have balanced current on the primary

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

When two delta leg A switches conduct

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

so that

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

The current through the switch is then

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

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

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

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

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

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

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

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

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

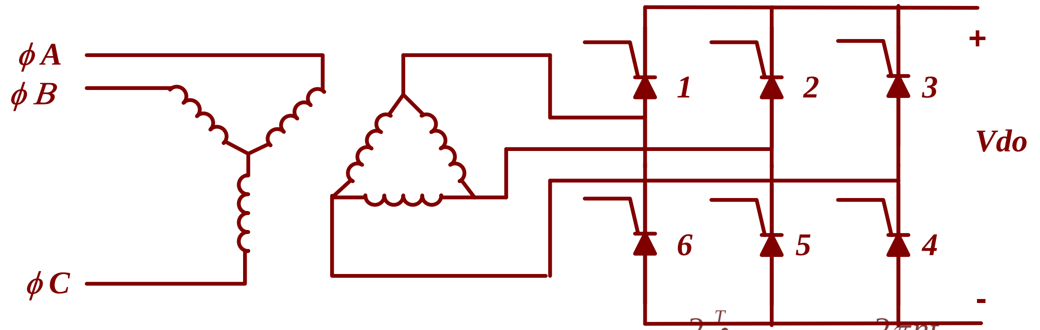
$$I_{BC\Delta s} = \left(V_{LNp} / N_{Y\Delta}\right) \sin(\omega t - 2\pi/3 + \phi_Z)$$

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

For equal secondary voltages

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

Wye-Delta Spectrum



The current through the A winding is

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

$$a_0 = a_n = 0$$

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

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

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

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

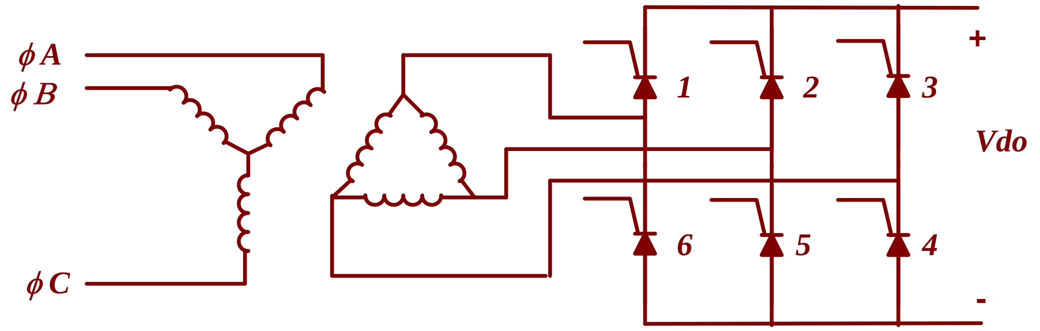
$$= \frac{2I_L}{3n\pi}\left[\left(cos\,0 + cos\frac{\pi n}{3}\right) - \left(cos\frac{2\pi n}{3} + cos\,\pi n\right)\right]$$

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

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

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

Primary Current in the Wye-Delta



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

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

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

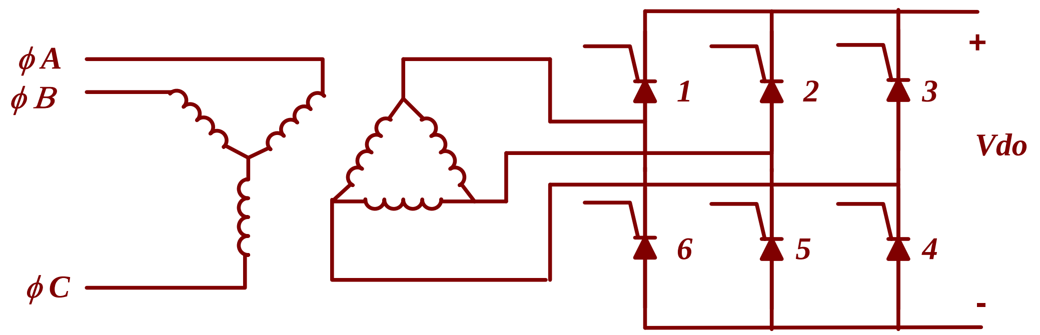
The non-vanishing terms are $n=1,5,7,11,\cdots$, *for which the magnitude is* $\sqrt{3}/2$.

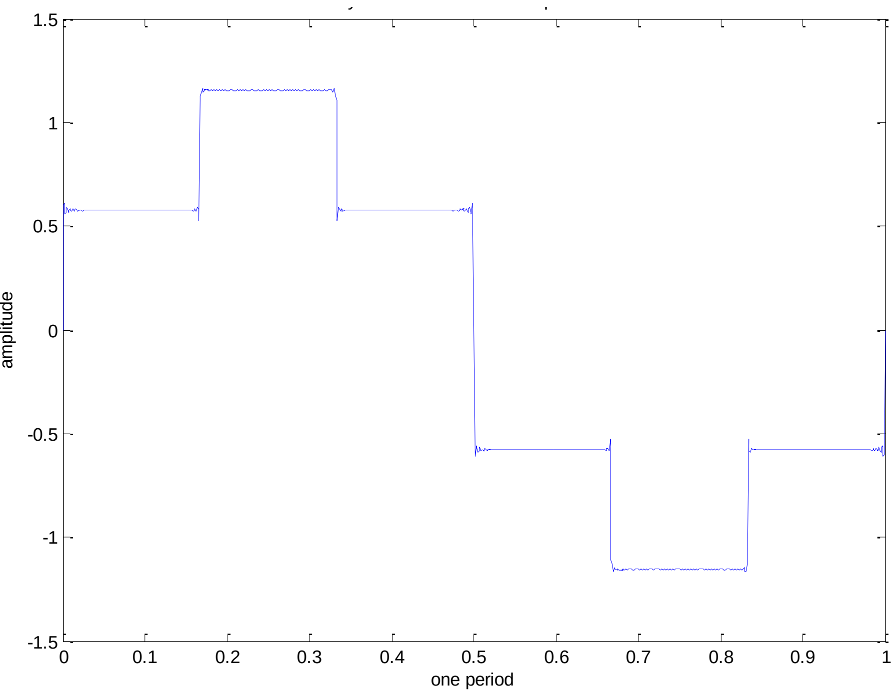
Referred back to the primary, the current is

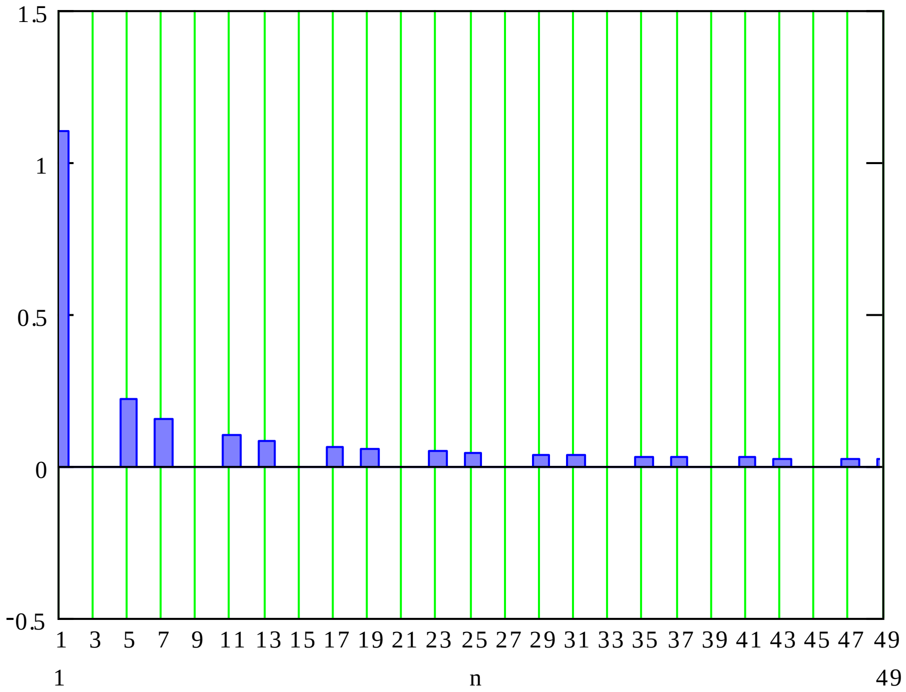
$$I_{A\Delta p}(t)=N_{Y\Delta}\frac{8I_L}{3n\pi}\sum_{n=1}^{\infty}\cos\frac{n\pi}{6}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\frac{2\pi nt}{T}$$

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

Primary Current in the Wye-Delta

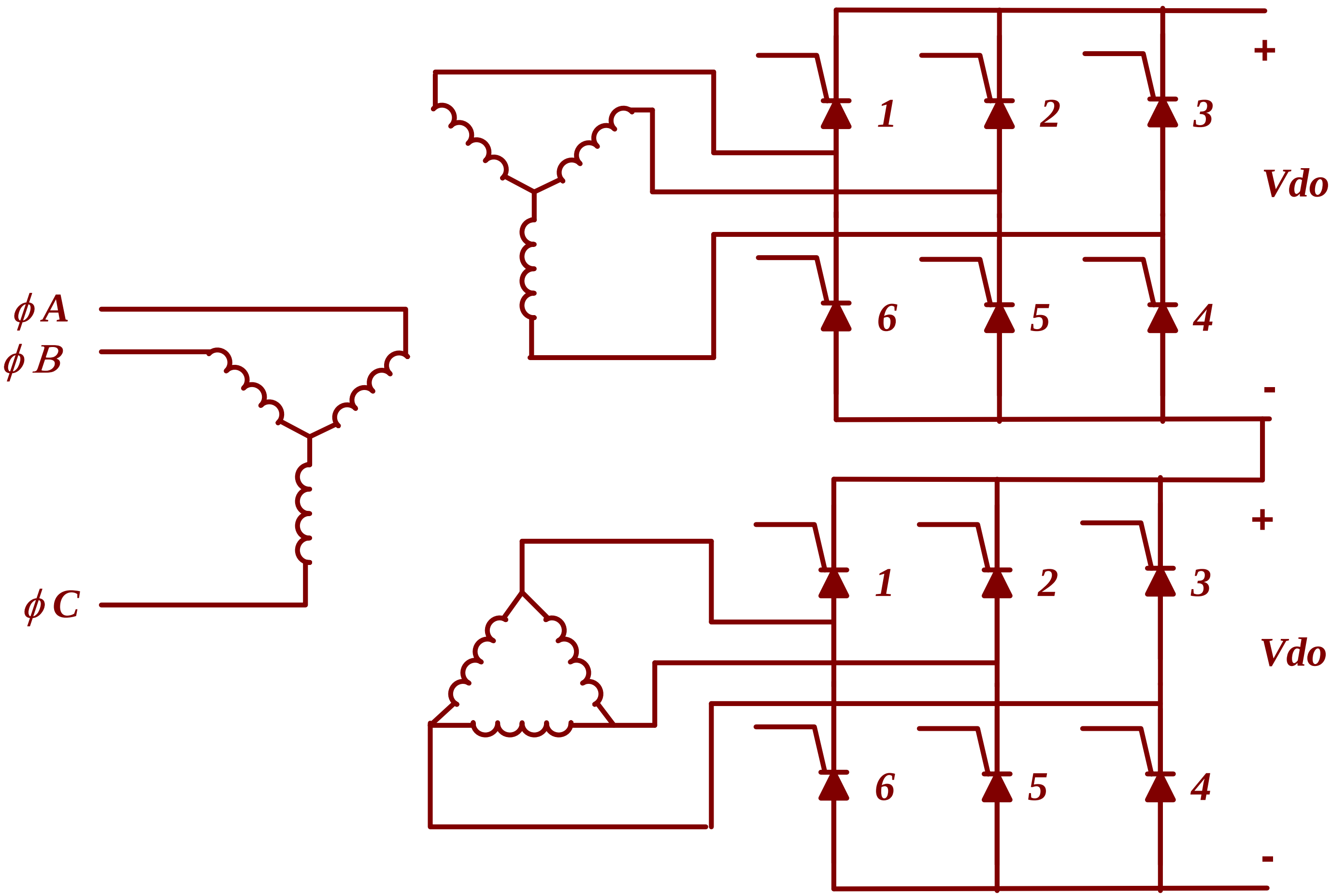






Harmonic	1	3	5	7	9	11	13	15	17	19
Frequency	60	180	300	420	540	660	780	900	1020	1140
Amplitude	1.103	0	0.221	0.158	0	0.100	0.085	0	0.065	0.058

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



Total Primary Current in Wye-Wye-Delta

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

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

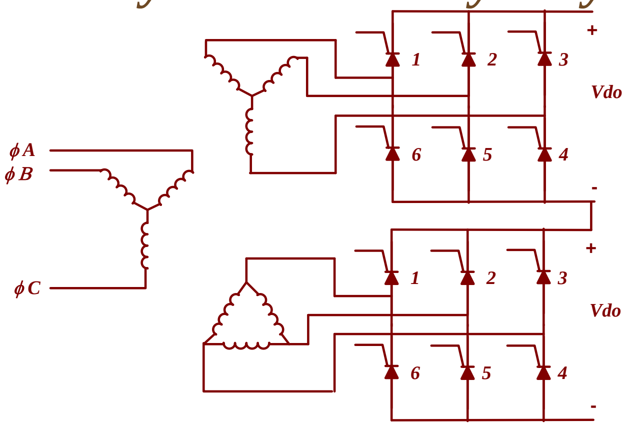
The only non-vanishing terms in both of these series are $n = 1,5,7,11$

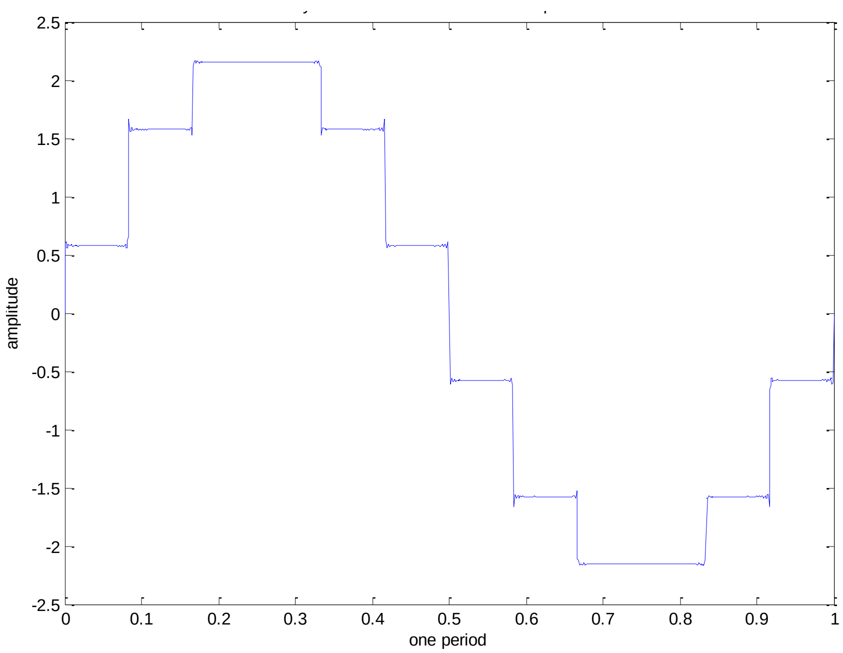
and all other values of n which have the same phase

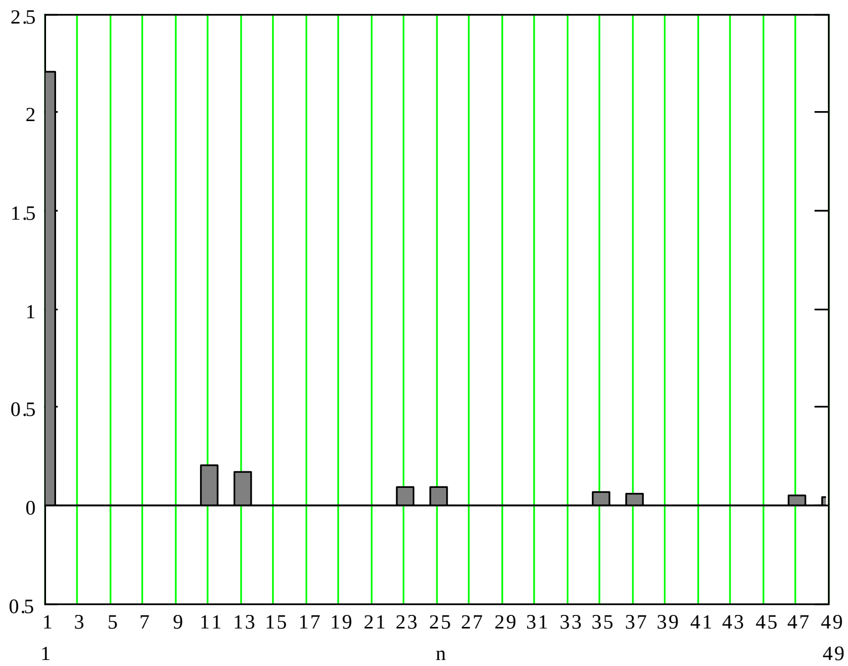
The values of $\cos\frac{n\pi}{6}$ for these n are $\frac{\sqrt{3}}{2},-\frac{\sqrt{3}}{2},-\frac{\sqrt{3}}{2},\frac{\sqrt{3}}{2}$

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

Total Primary Current in Wye-Wye-Delta

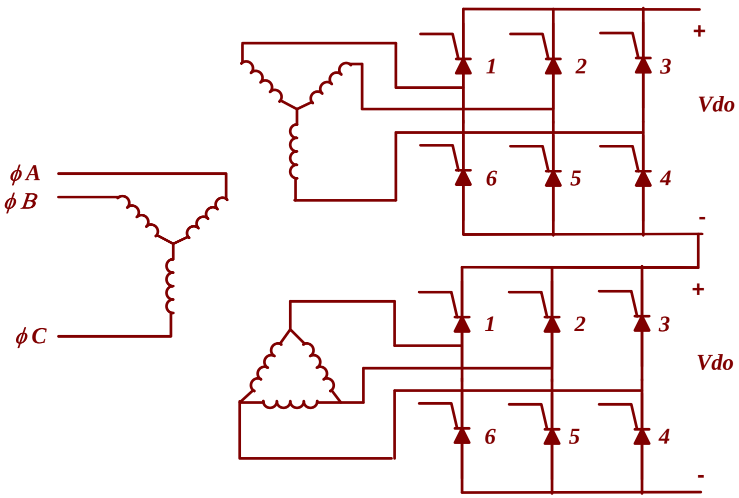


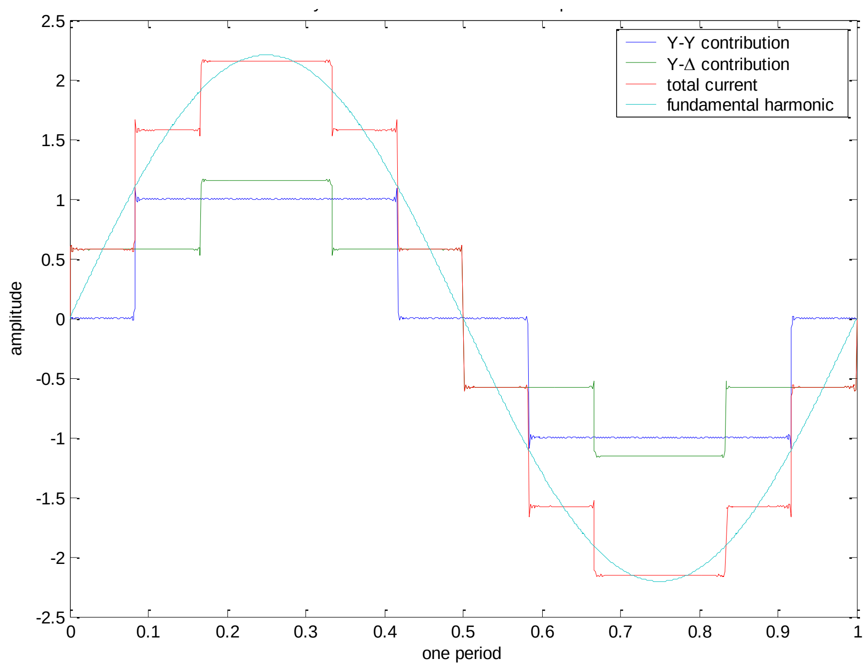




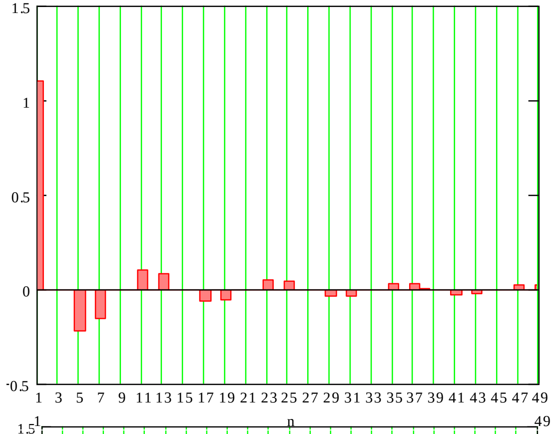
Harmonic	1	3	5	7	9	11	13	15	17	19
Frequency	60	180	300	420	540	660	780	900	1020	1140
Amplitude	2.205	0	0	0	0	0.200	0.085	0.170	0	0

Total Primary Current in Wye-Wye-Delta

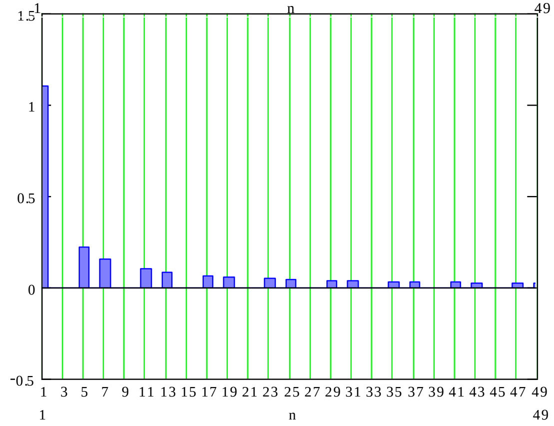




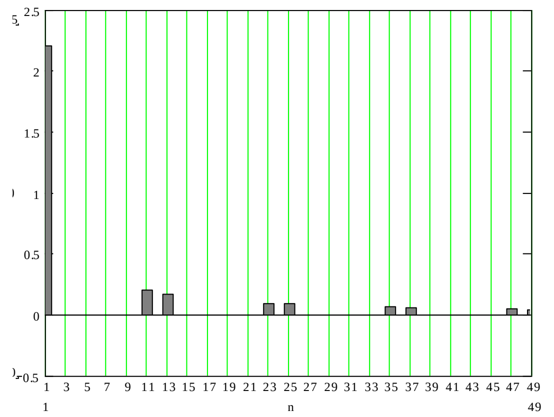
Wye-Wye



Wye-Delta

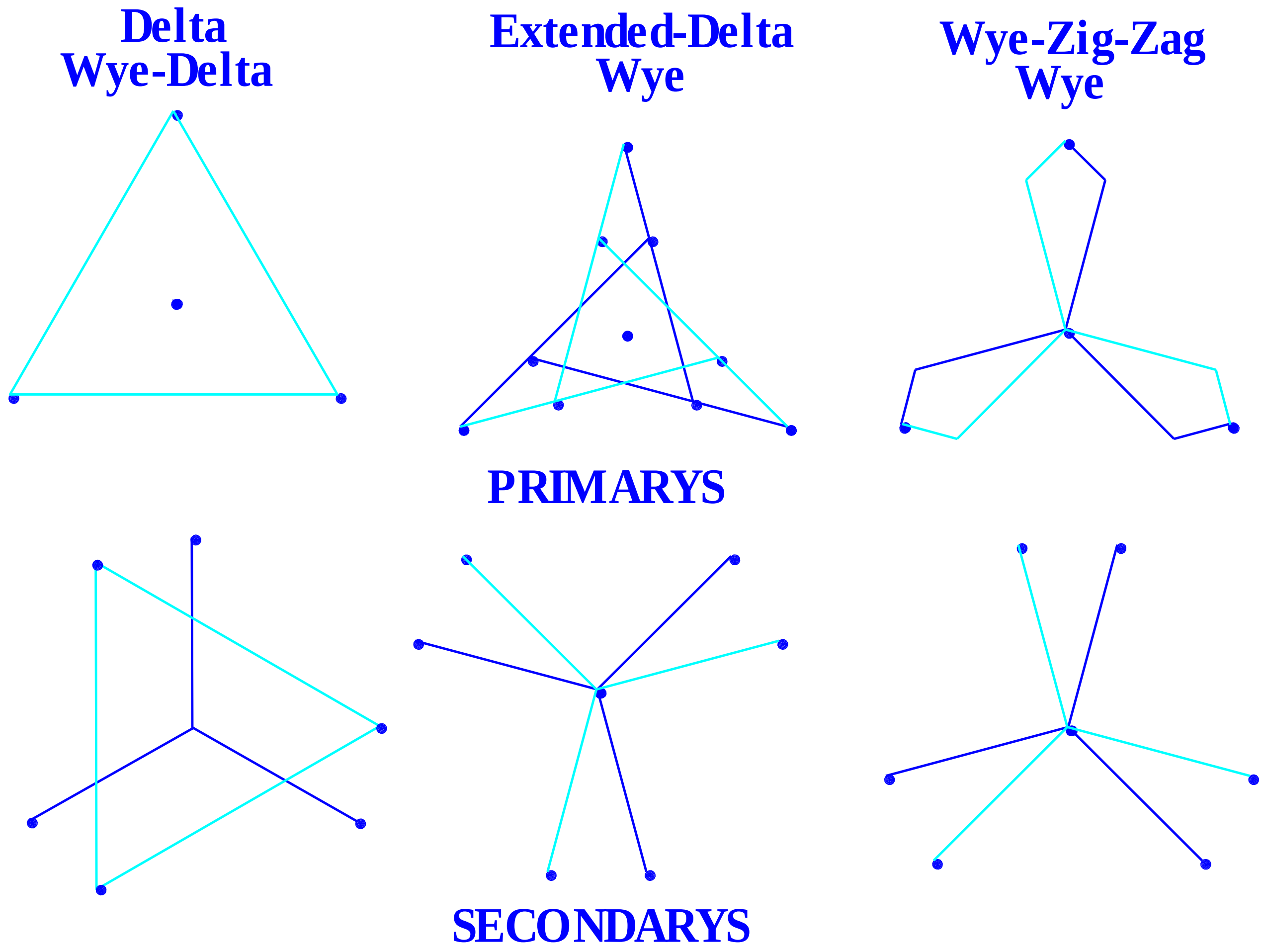


Wye-Wye-Delta



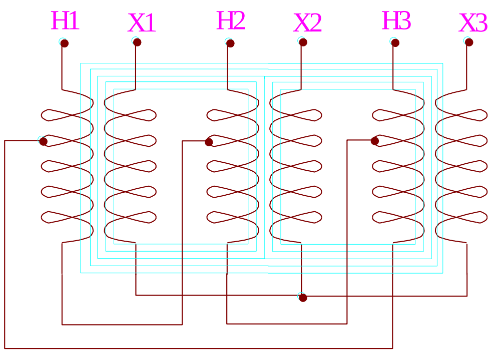
Three Phase Phase Shifting Transformer

Phase shifting transformer for 12 Pulse operation



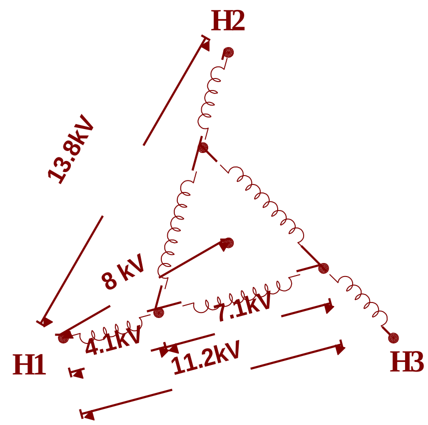
Three Phase Phase Shifting Transformer

Extended Delta Phase shifting transformer

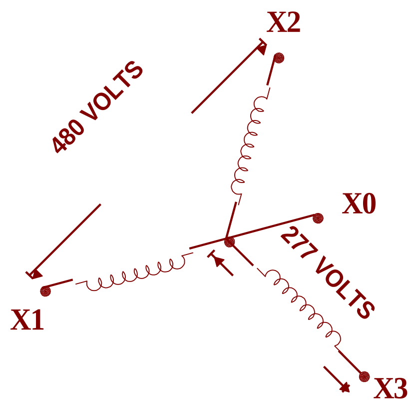


Extended Delta-Wye Transformer 3 core

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

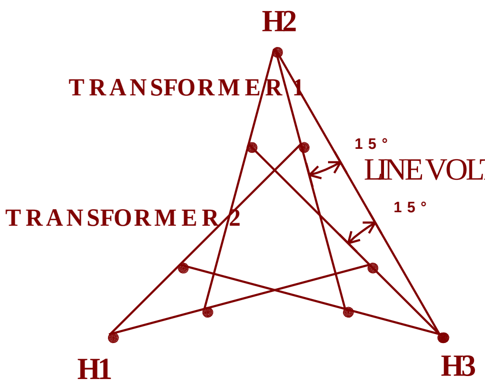


PRIMARY VOLTAGE RELATIONSHIP

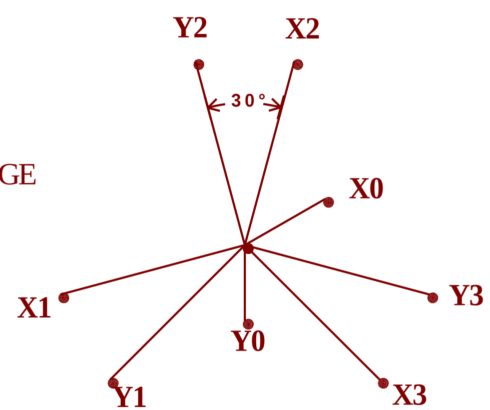


SECONDARY VOLTAGE RELATIONSHIP

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

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 & Inductors for Electronic power conversion Equipment ANSI/IEEE std 388-1992

Insulation Class Recommended for Rectifier Transformer.

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

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

3) 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

60 Hz Low Frequency Transformers 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.*

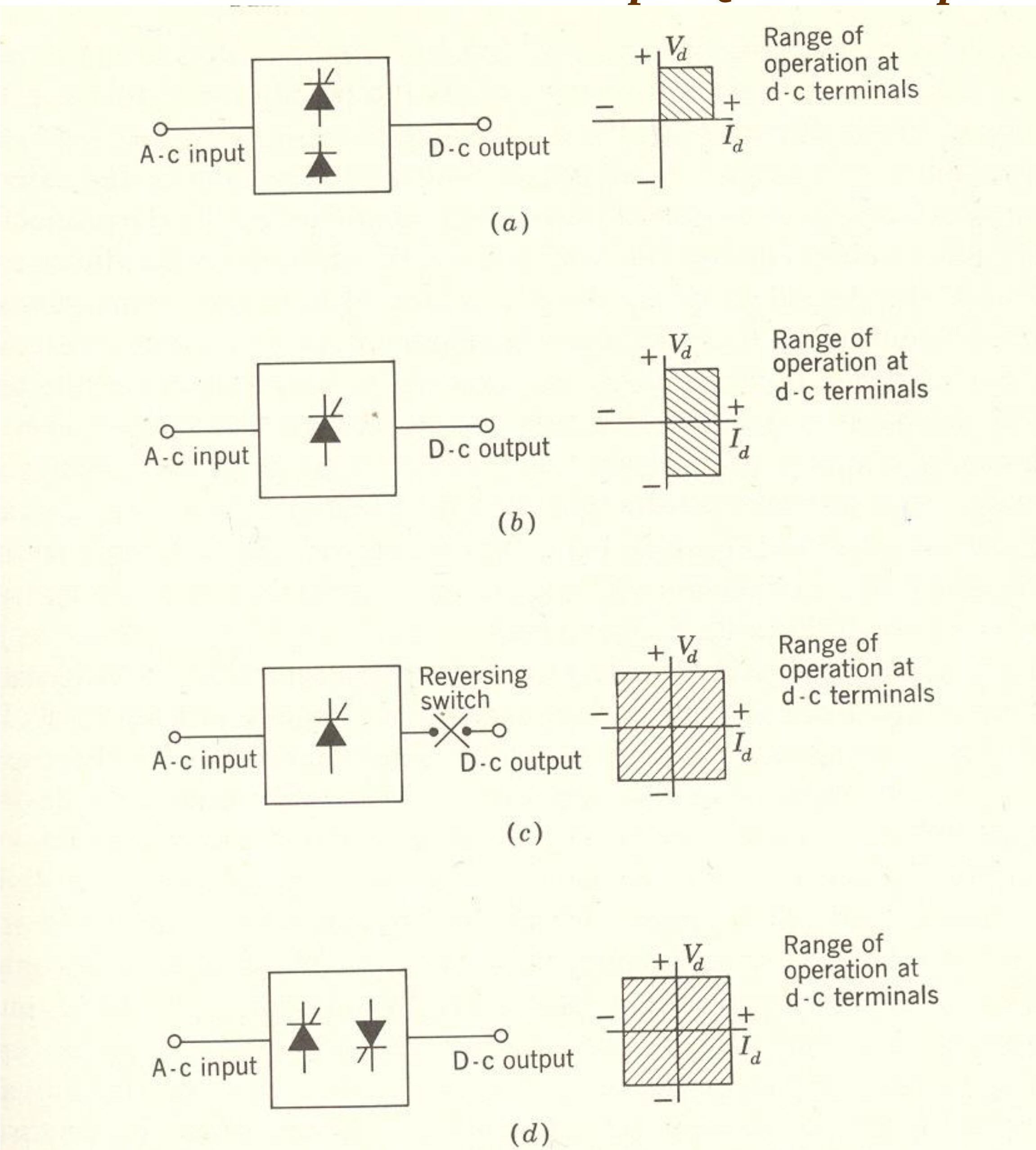
Rectifiers

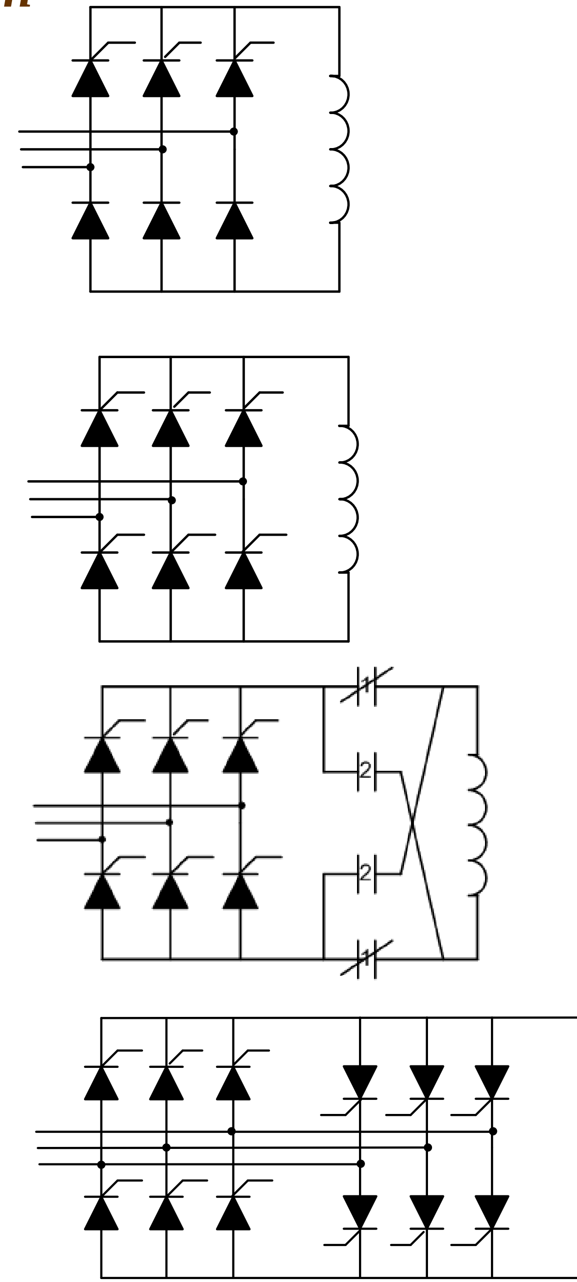
Introduction to power supplies, diodes, SCRs and rectifiers

Four Types of Converters

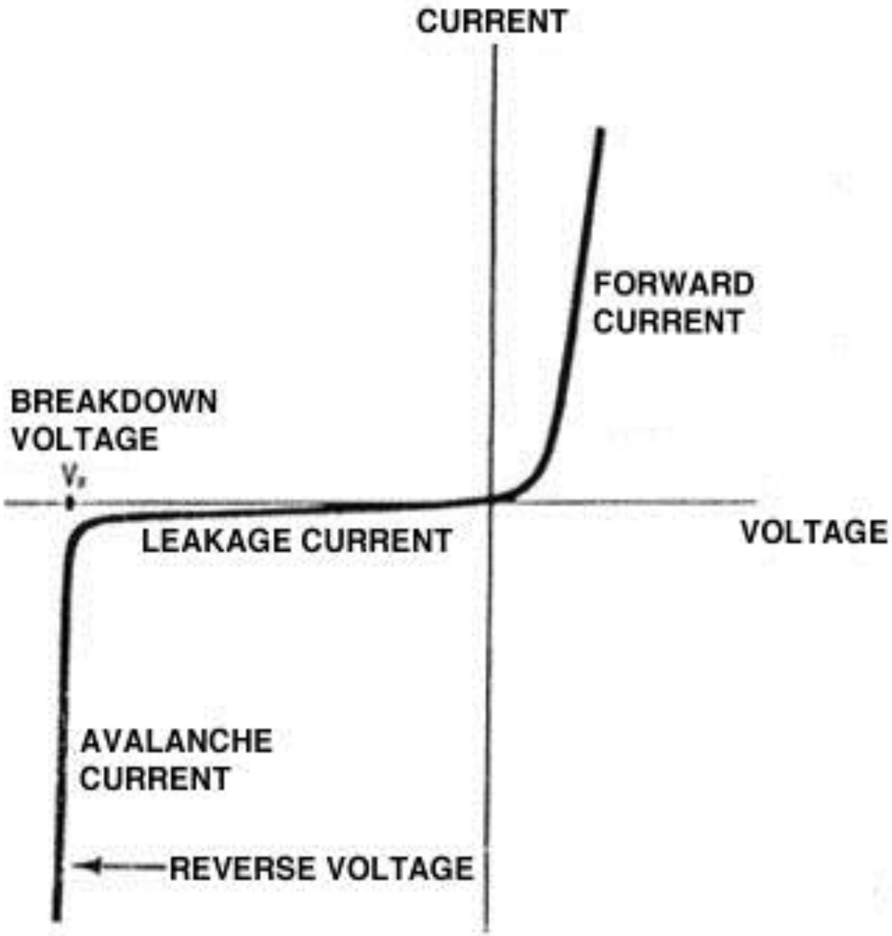
- *Rectifier converting an ac voltage to a dc voltage*
- *Inverter converting a dc voltage to an ac voltage*
- *Chopper or a switch-mode power supply that converts a dc voltage to another dc voltage*
- *Cycloconverter and cycloinverter converting an ac voltage to another ac voltage*

Multiple Quadrant Operation





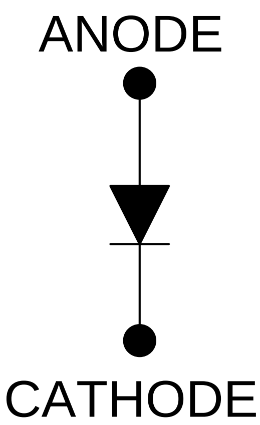
Diode Characteristics



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

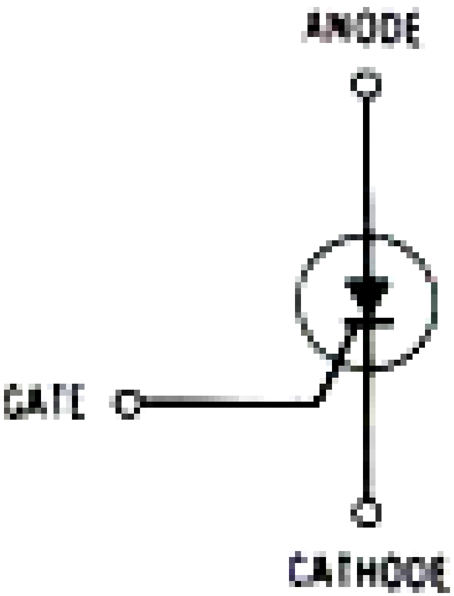
Diode Considerations



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*

Thyristors - Silicon Controlled Rectifier (SCR)

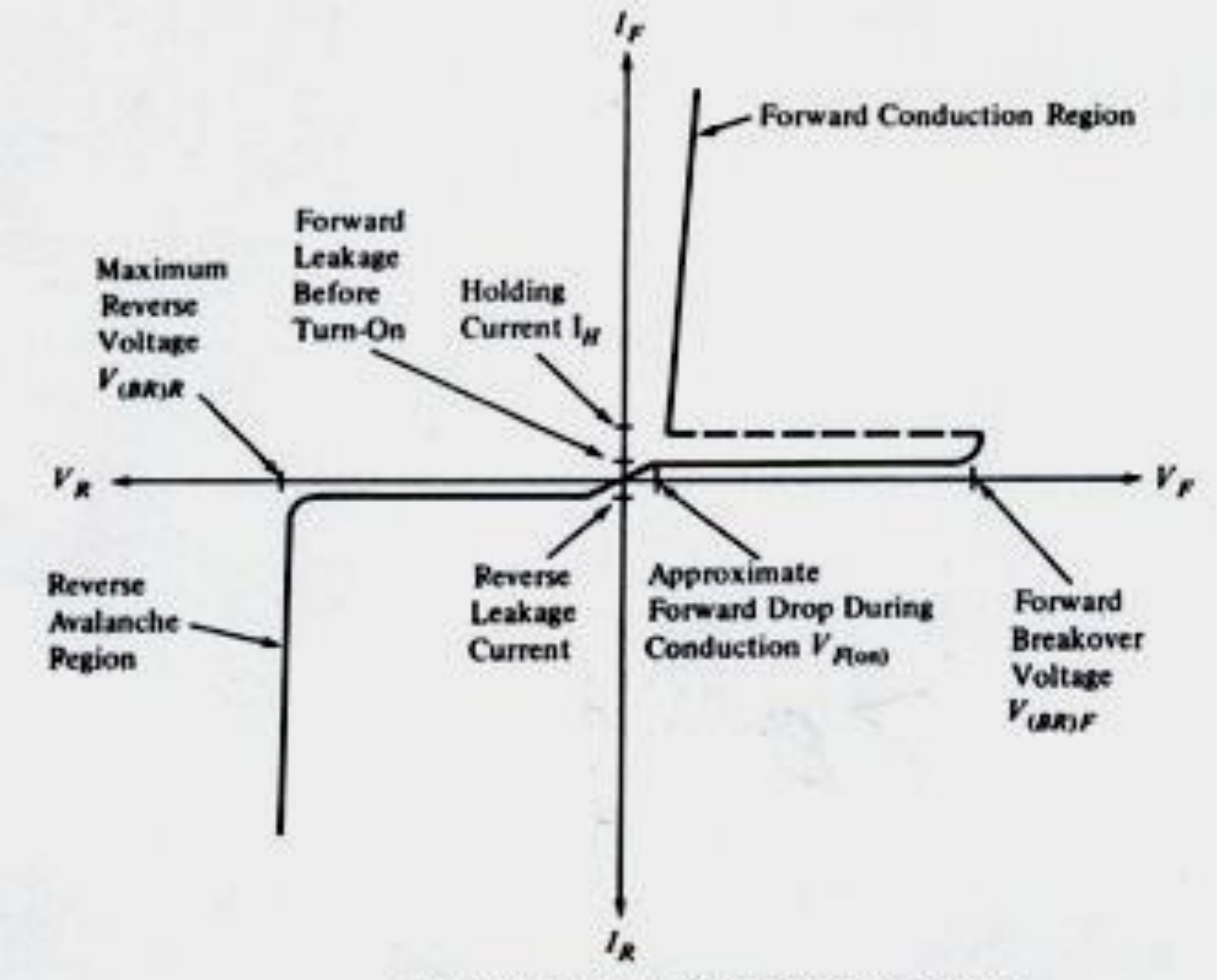


Schematic representation

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*

SCR Characteristics



V–I characteristics of the SCR with gate open.

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*

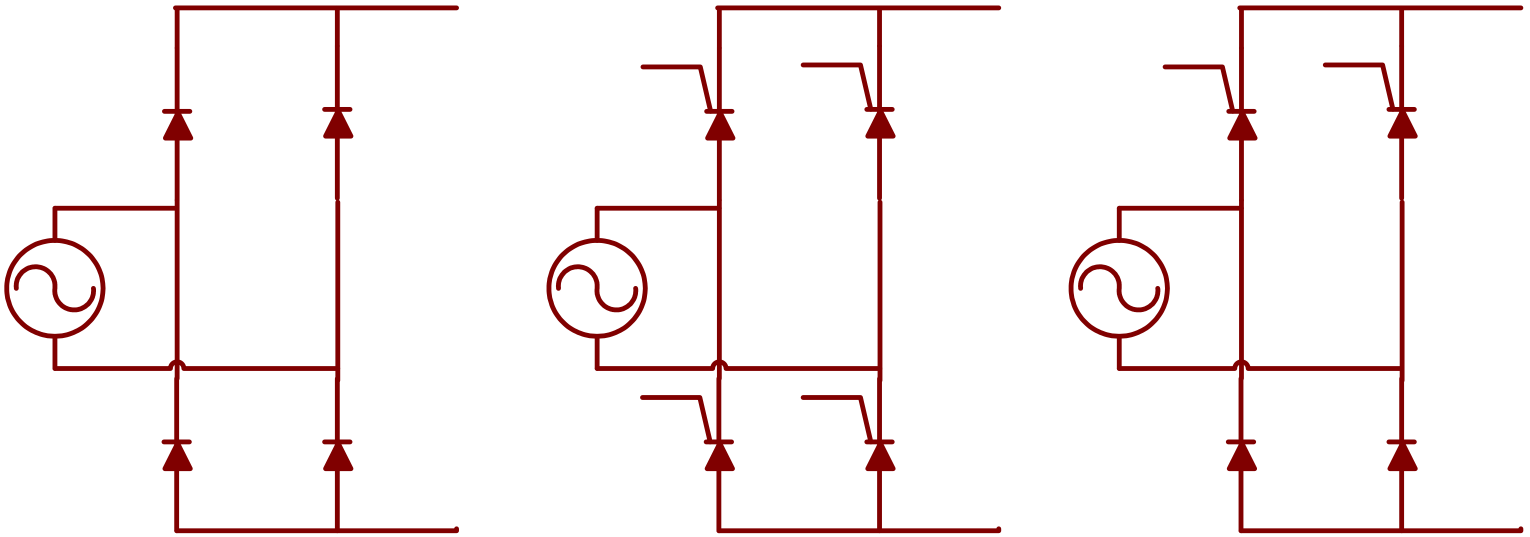
Rectifiers

- A rectifier converts ac voltage to dc voltage
  - Classifications

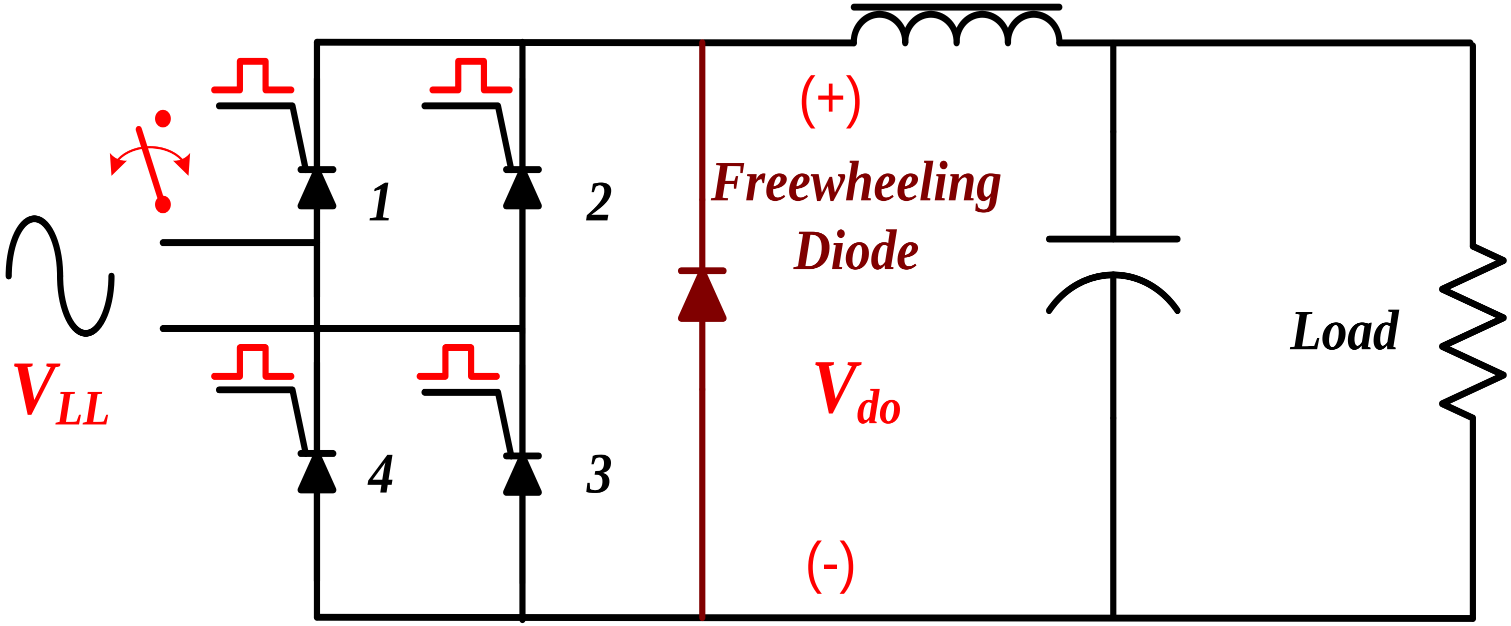
    Uncontrolled rectifiers (diodes)

    Fully Controlled rectifiers (all SCRs)

    Semi-controlled rectifiers (SCRs and diodes)

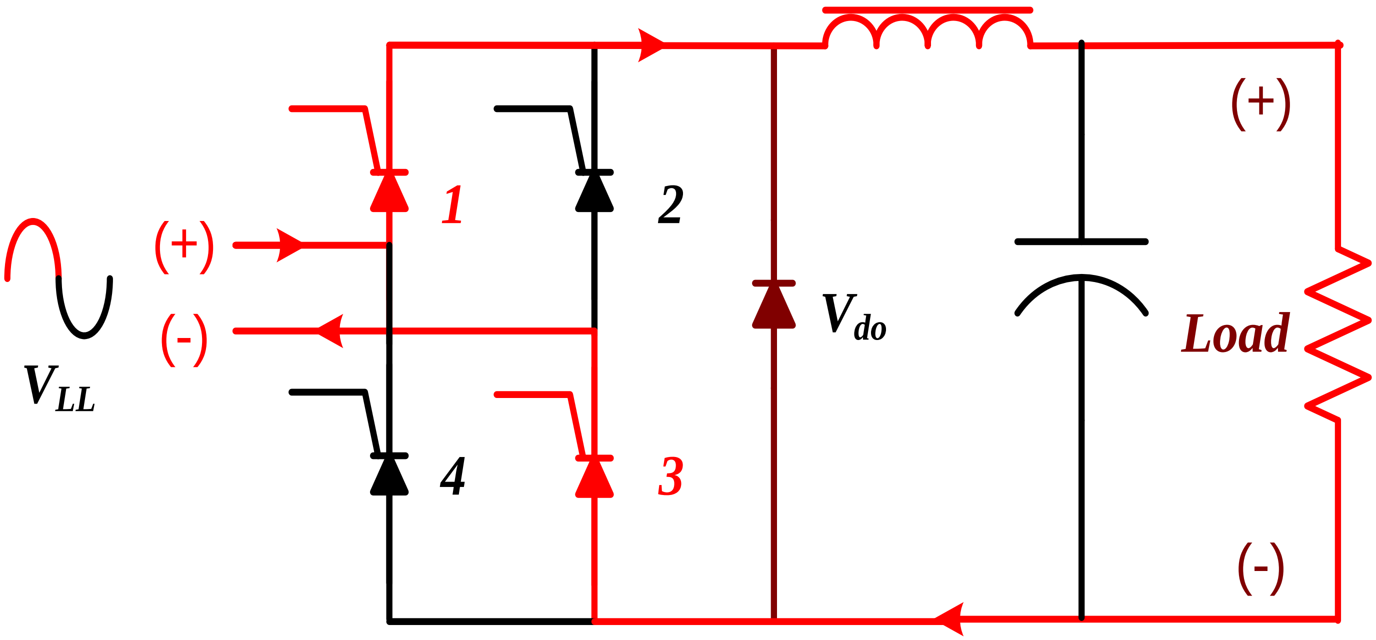


1 ϕ Full Wave (q = 2 Pulse) Rectifier



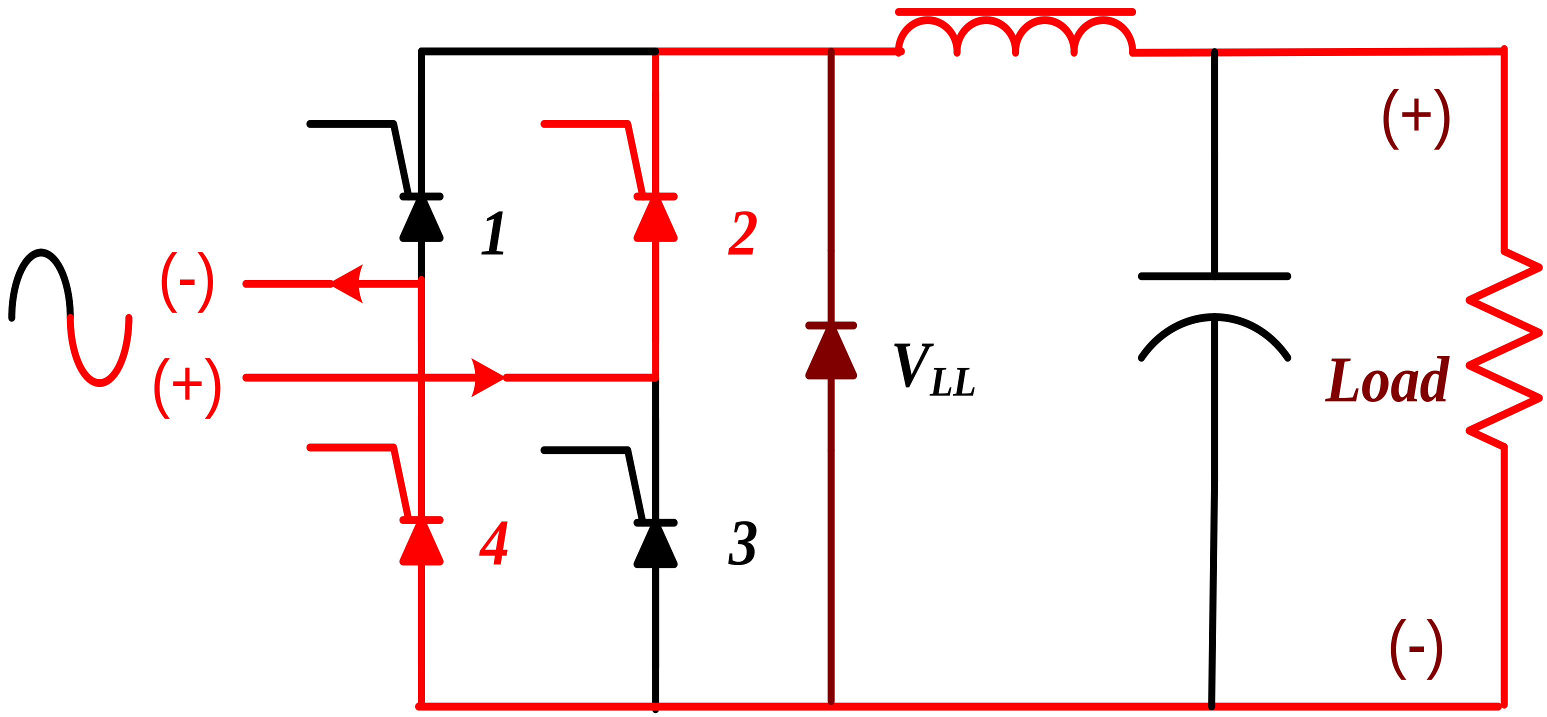
- $q \equiv$ the number of possible rectifier states
- SCR s are electronic switches
- Freewheeling diode normally does nothing, but dissipates energy stored in an inductive load if power supply is suddenly turned off
- For inductive load freewheeling diode conducts if SCR retard is large and if load VI phase angle is large

1 ϕ Full Wave (q = 2 Pulse) Rectifier



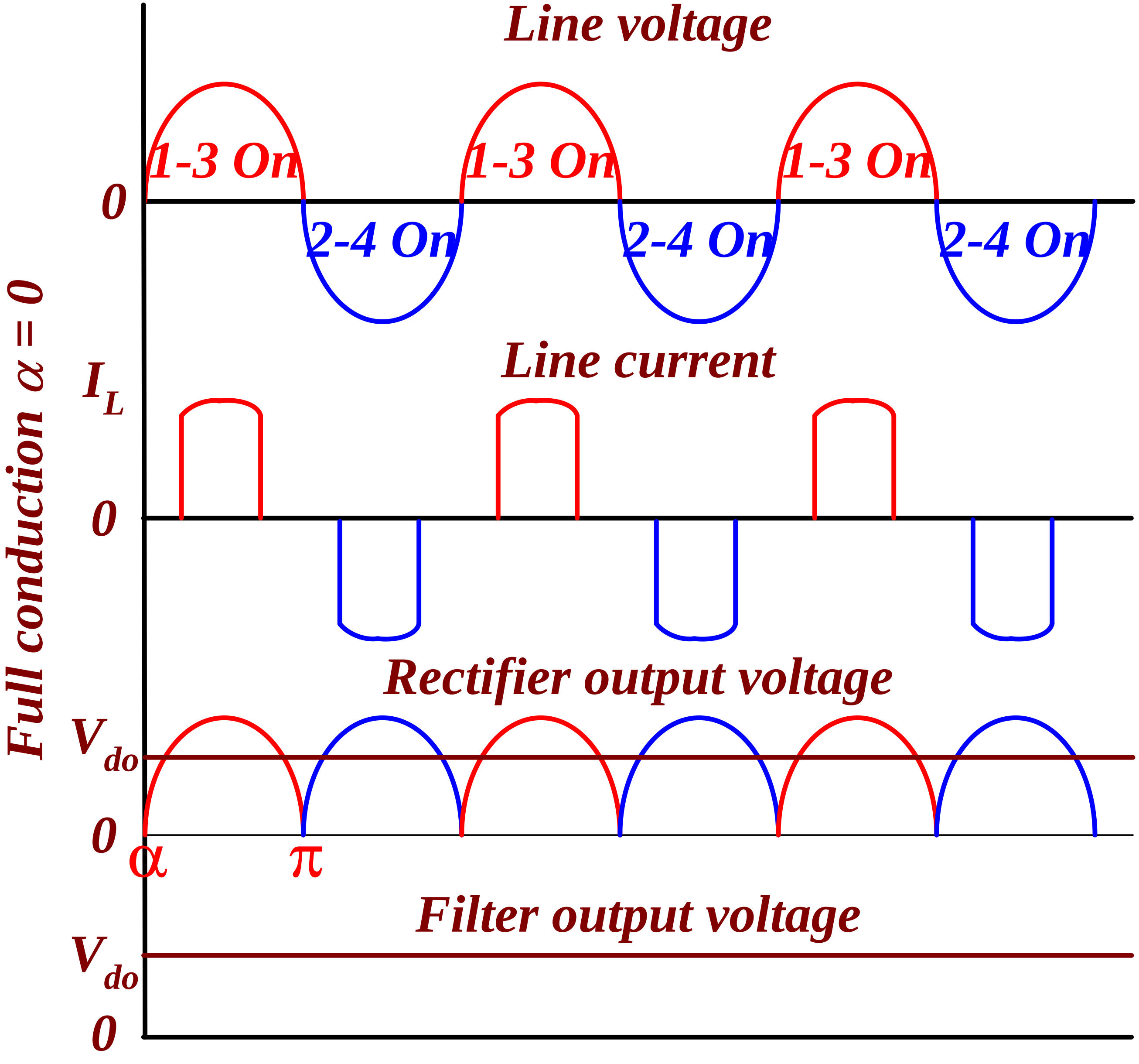
State 1 : SCR s 1 – 3 On

1 ϕ Full Wave (q = 2 Pulse) Rectifier

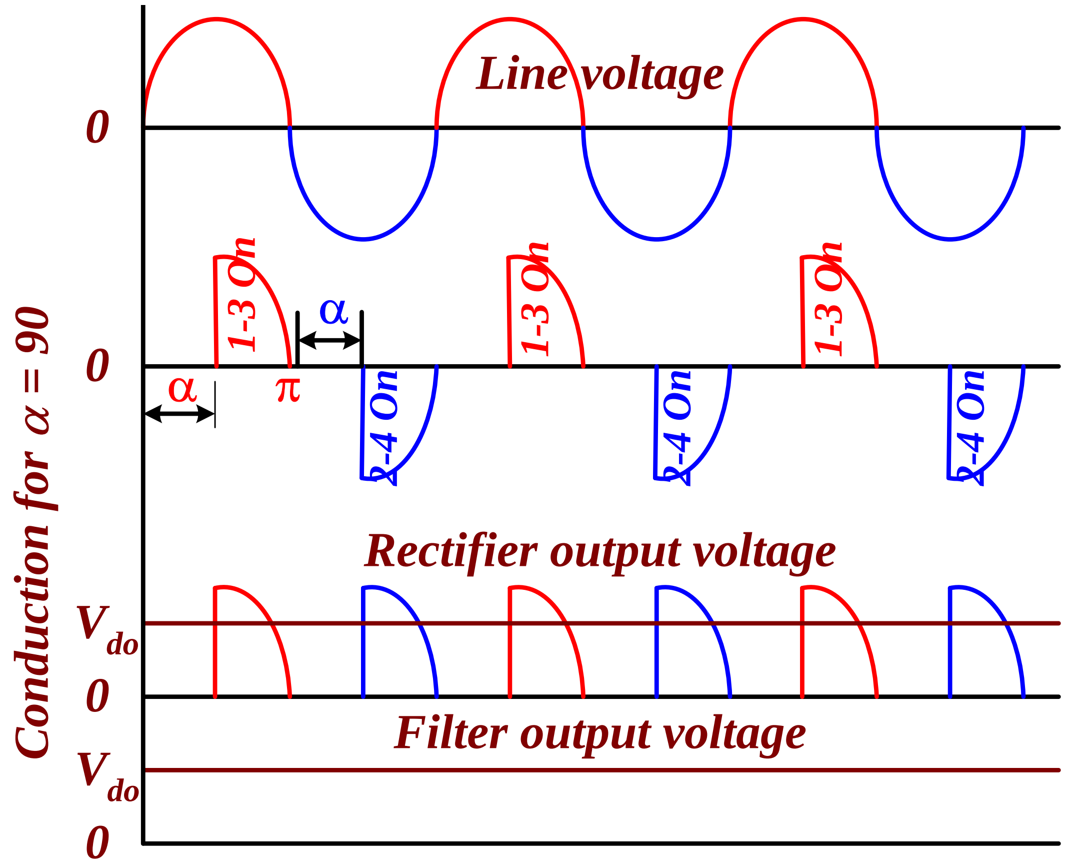


State 2 : SCR s 2 – 4 On

1 ϕ Full Wave (q = 2 Pulse) Rectifier



1 ϕ Full Wave (q = 2 Pulse) Rectifier



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

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

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

$1\ \phi$, Full Wave (q = 2 Pulse) Rectifier Summary

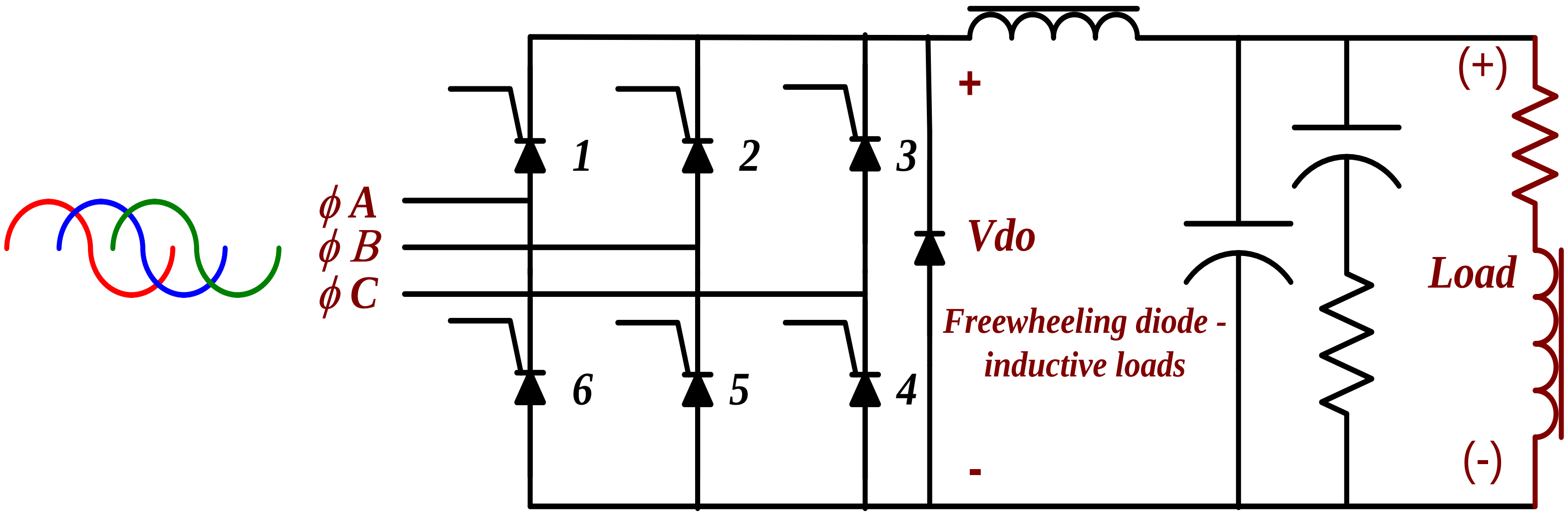
- *2 pulse rectifier – low input power factor, high output ripple*
- *Freewheeling diode needed whenever filter or load V-I angle is large*
- *Ripple frequency is 120 Hz (if input is 60 Hz)*
- *Large filter needed*
- *Limited in use to power supplies < 2.5 kW*

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

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

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

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

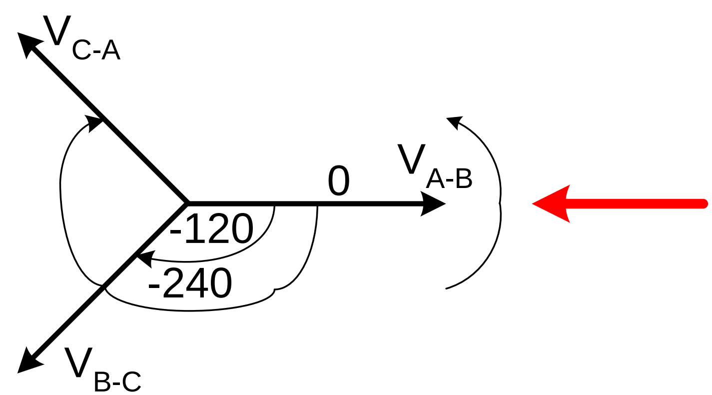


Assuming the American standard phase rotation of

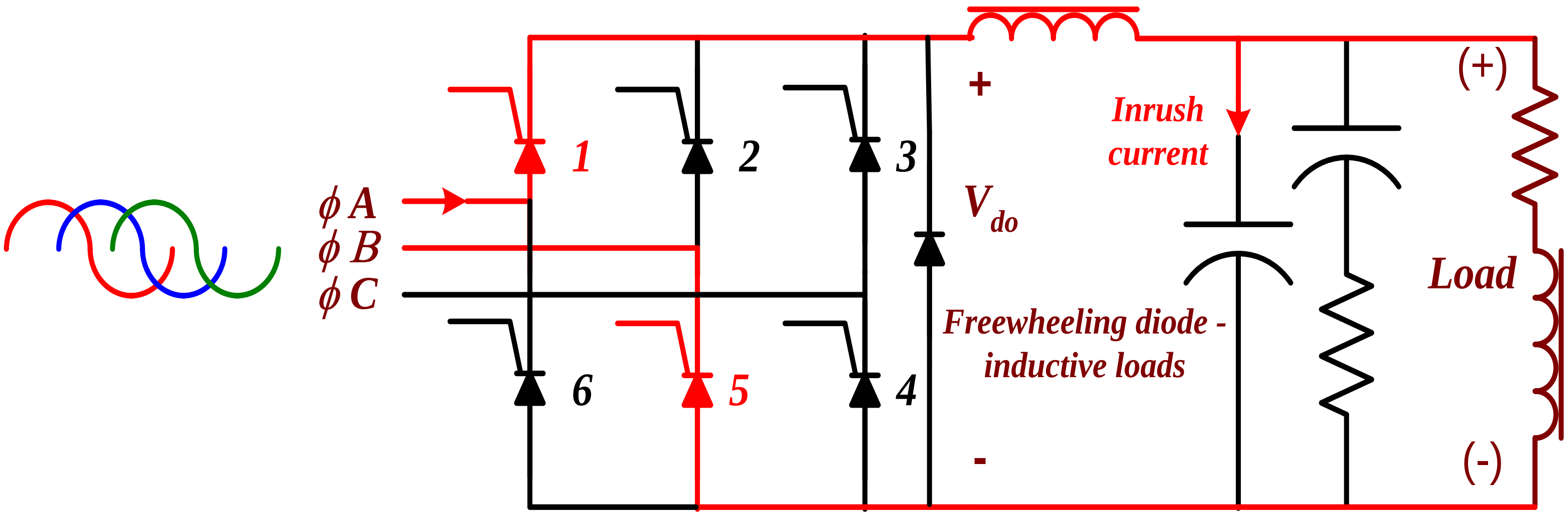
$$V_{A-B} = |V|\, e^{j0} \qquad V_{B-C} = |V|\, e^{-j120} \qquad V_{C-A} = |V|\, e^{-j240}$$

The thyristor firing sequence is:

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



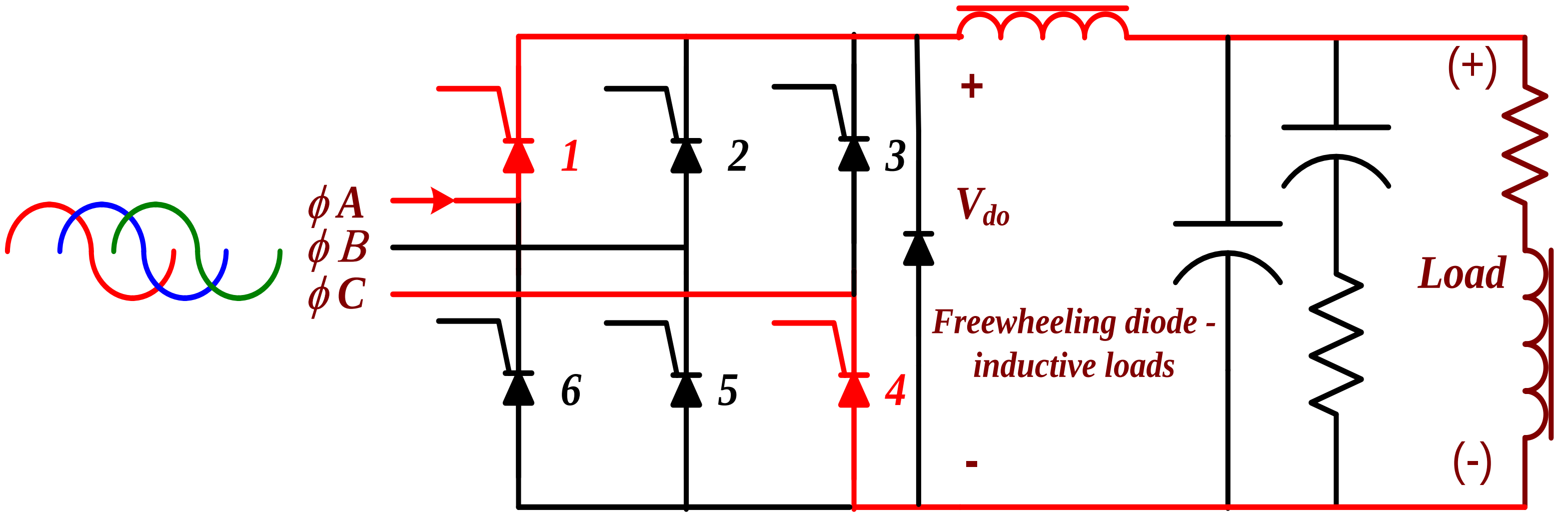
3 ϕ, q = 6 Pulse Rectifier



State 1: A-B (+) SCR s 1 – 5 On

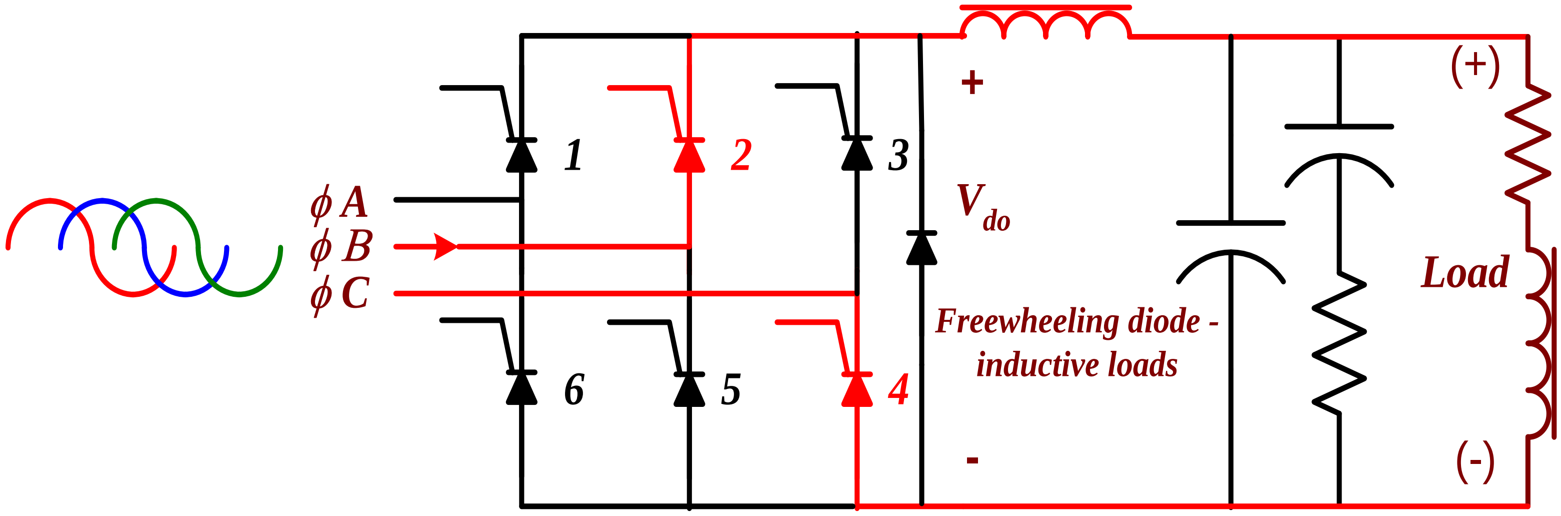
Note: Phase SCRs from full retard to full forward slowly to bring the rectifier output voltage up slowly and reduce the capacitor inrush current

3 ϕ, q = 6 Pulse Rectifier



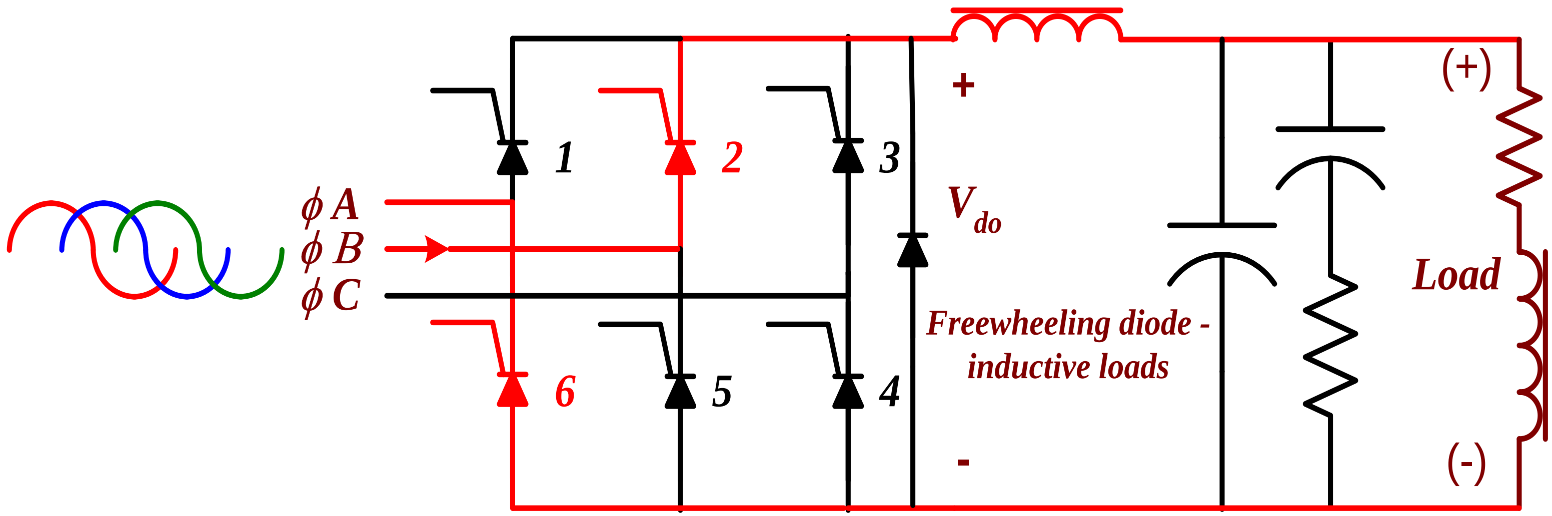
State 2 : C-A (-), 5 off, SCR s 1 – 4 On

3 ϕ, q = 6 Pulse Rectifier



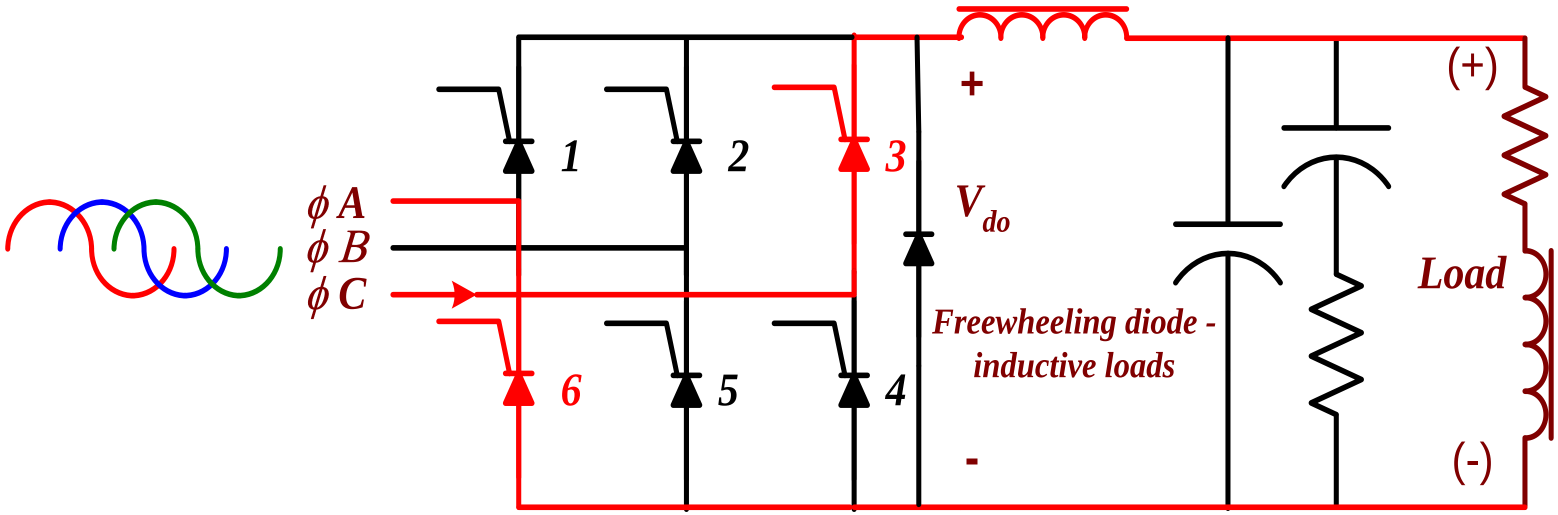
State 3 : B-C (+), 1 off, SCR s 2 – 4 On

3 ϕ, q = 6 Pulse Rectifier



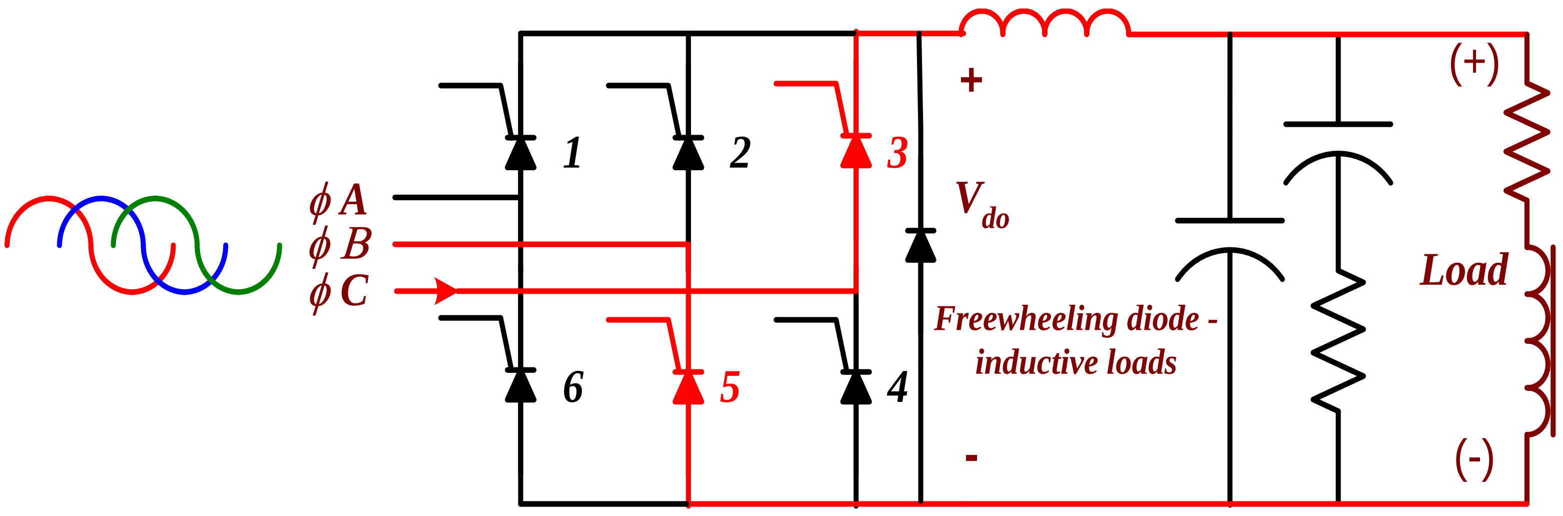
State 4 : A-B (-), 4 off, SCR s 2 – 6 On

3 ϕ, q = 6 Pulse Rectifier



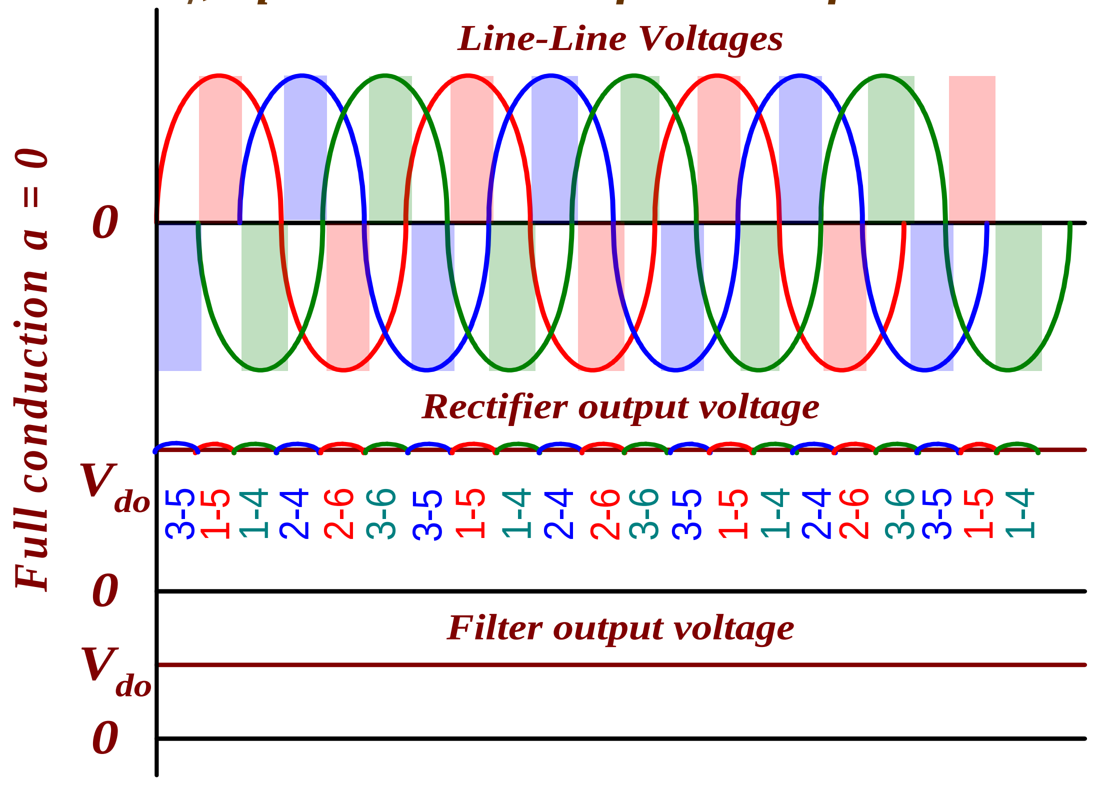
State 5 : C-A (+), 2 off, SCR s 3 – 6 On

3 ϕ, q = 6 Pulse Rectifier



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

3 ϕ, q = 6 Pulse Rectifier Waveforms



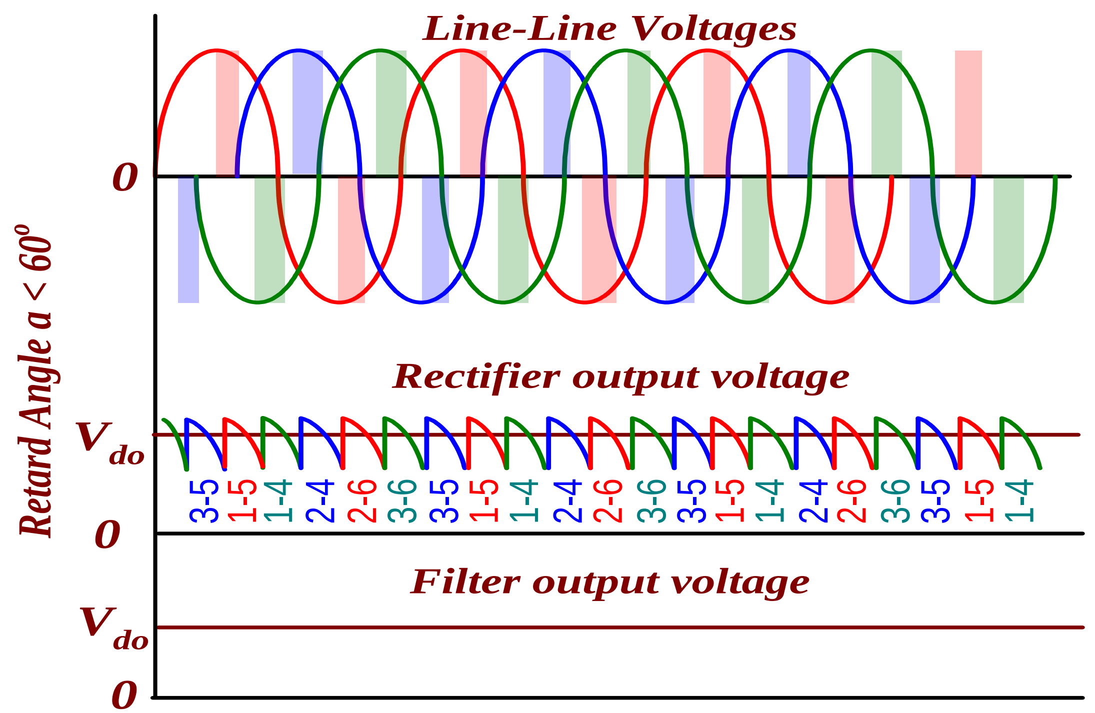
For $0 \le \alpha \le \frac{\pi}{3}$ where α is the gate trigger retard angle and conduction is continuous

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

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

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

$3\ \phi,\ q = 6$ 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*

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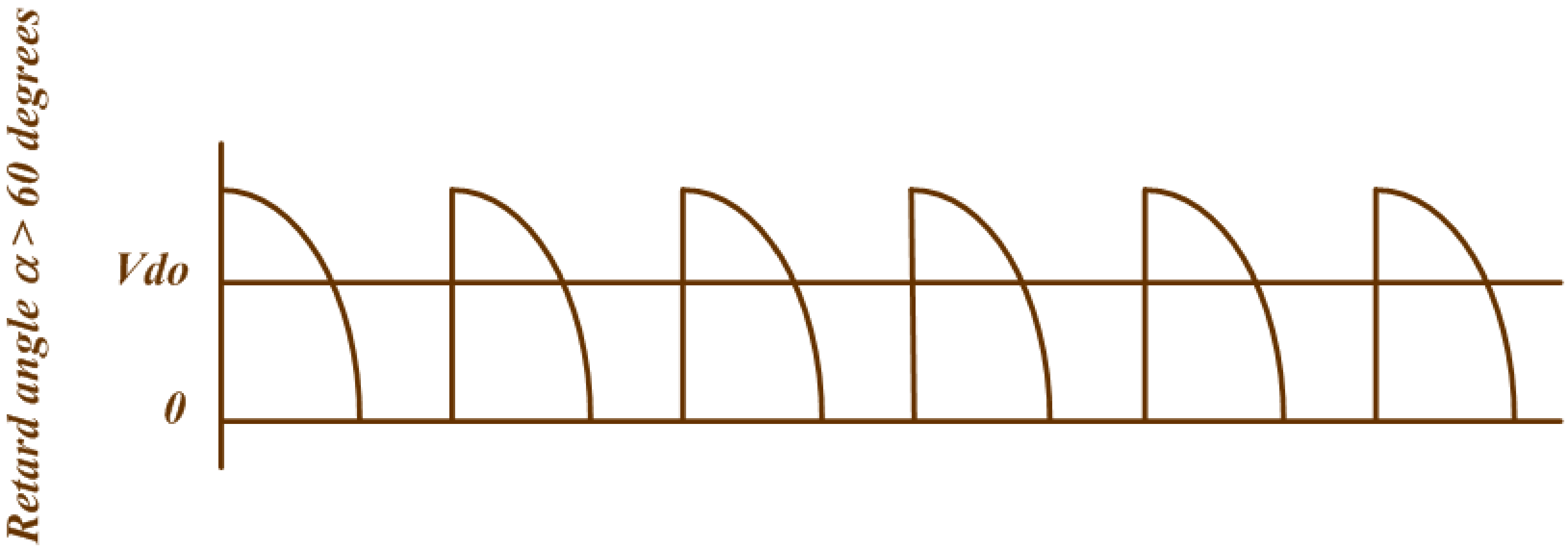
$3\ \phi,\ q = 6$ Pulse Rectifier Waveforms



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

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

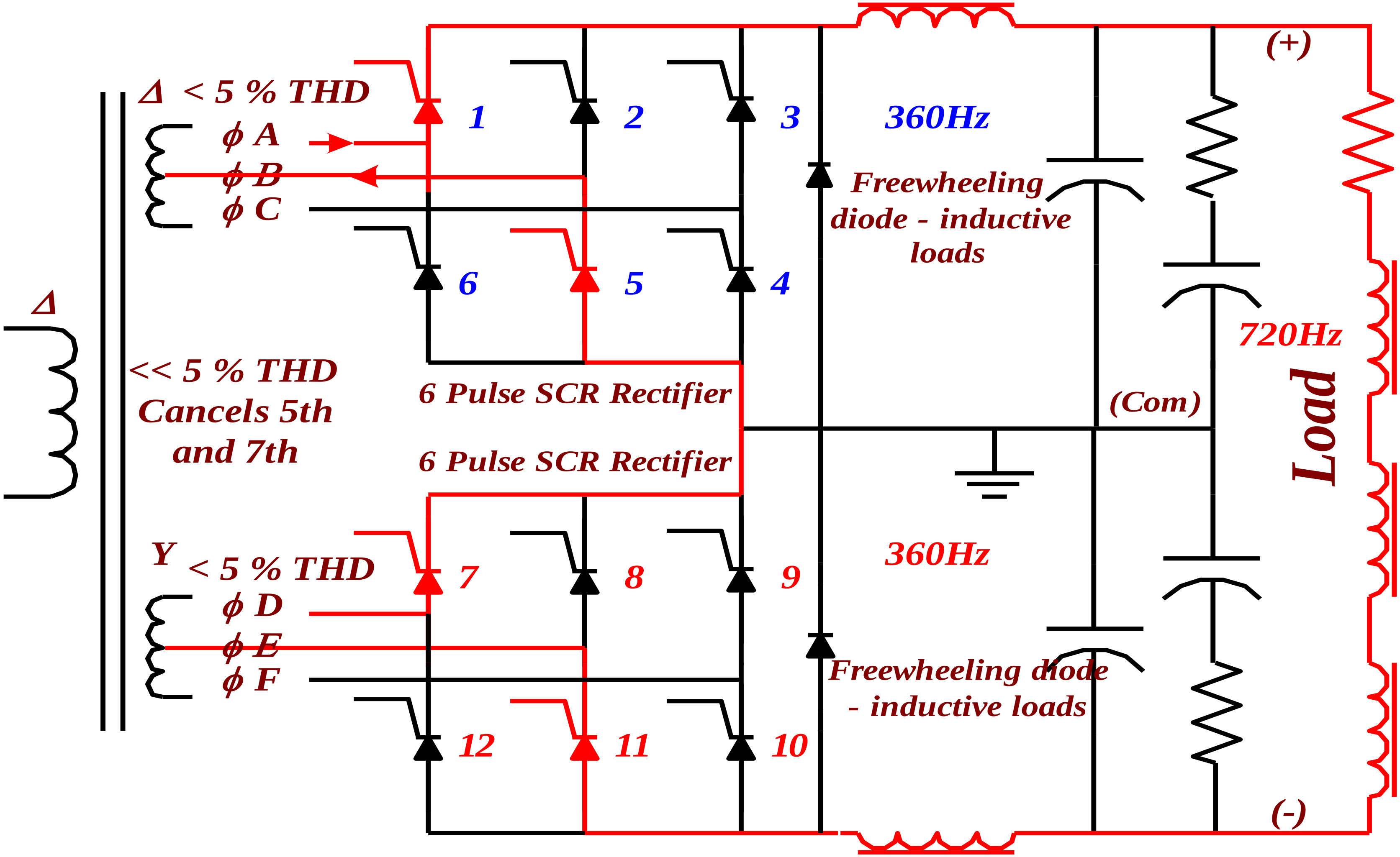
$For\ \frac{\pi}{3} \le \alpha \le \frac{2\pi}{3}$ *where conduction can be discontinuous*

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

3 ϕ, q = 6 Pulse Rectifier Summary

- 6 pulse – high input PF $\rightarrow$ 0.95
- Use soft-start to limit filter capacitor inrush current.
- Freewheeling diode for inductive loads where VI angle is large
- 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

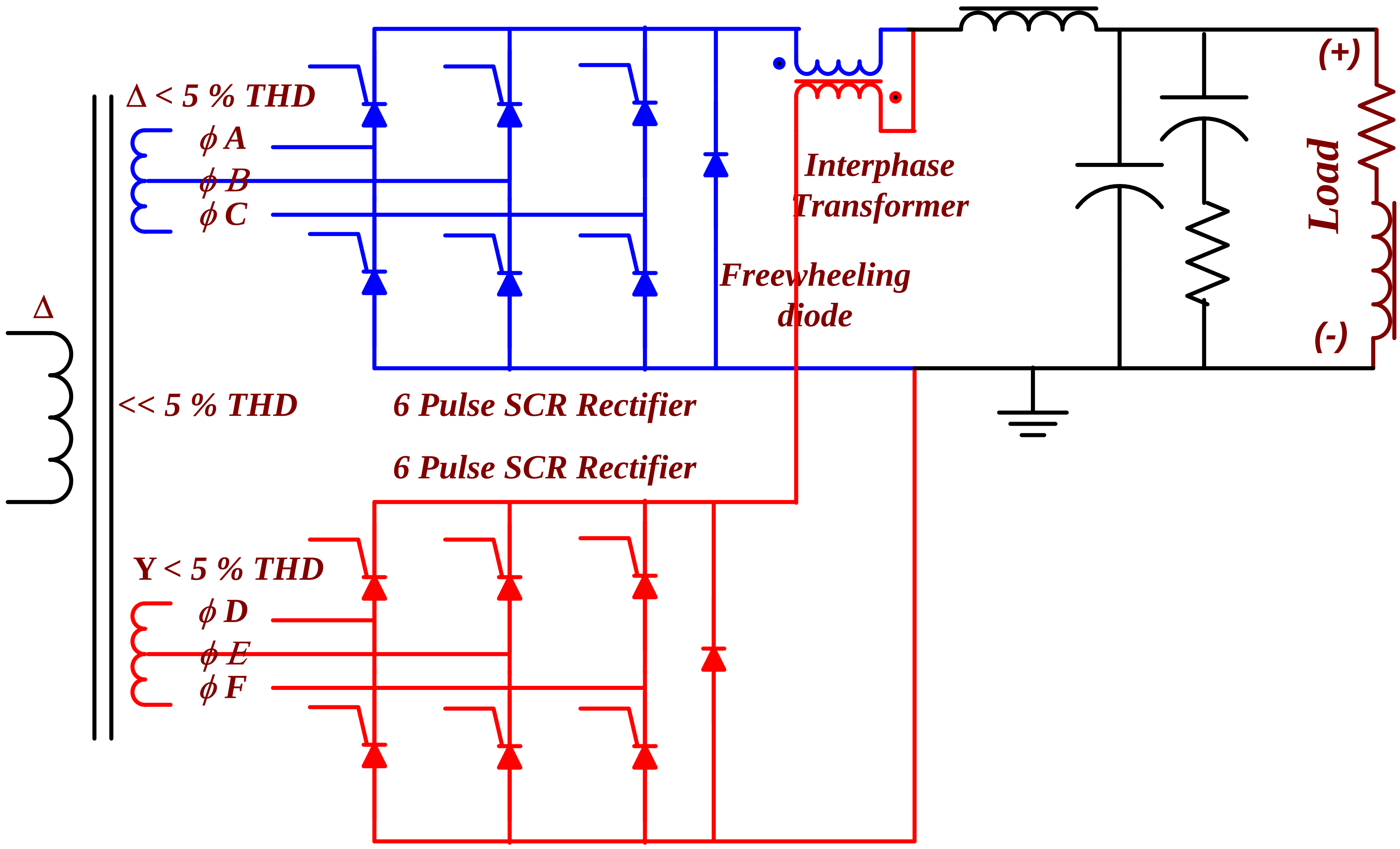
6 ϕ, q = 12 Pulse By Series Bridges



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

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 inductive loads where VI angle is large
- For loads $\geq$ 350 kW

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

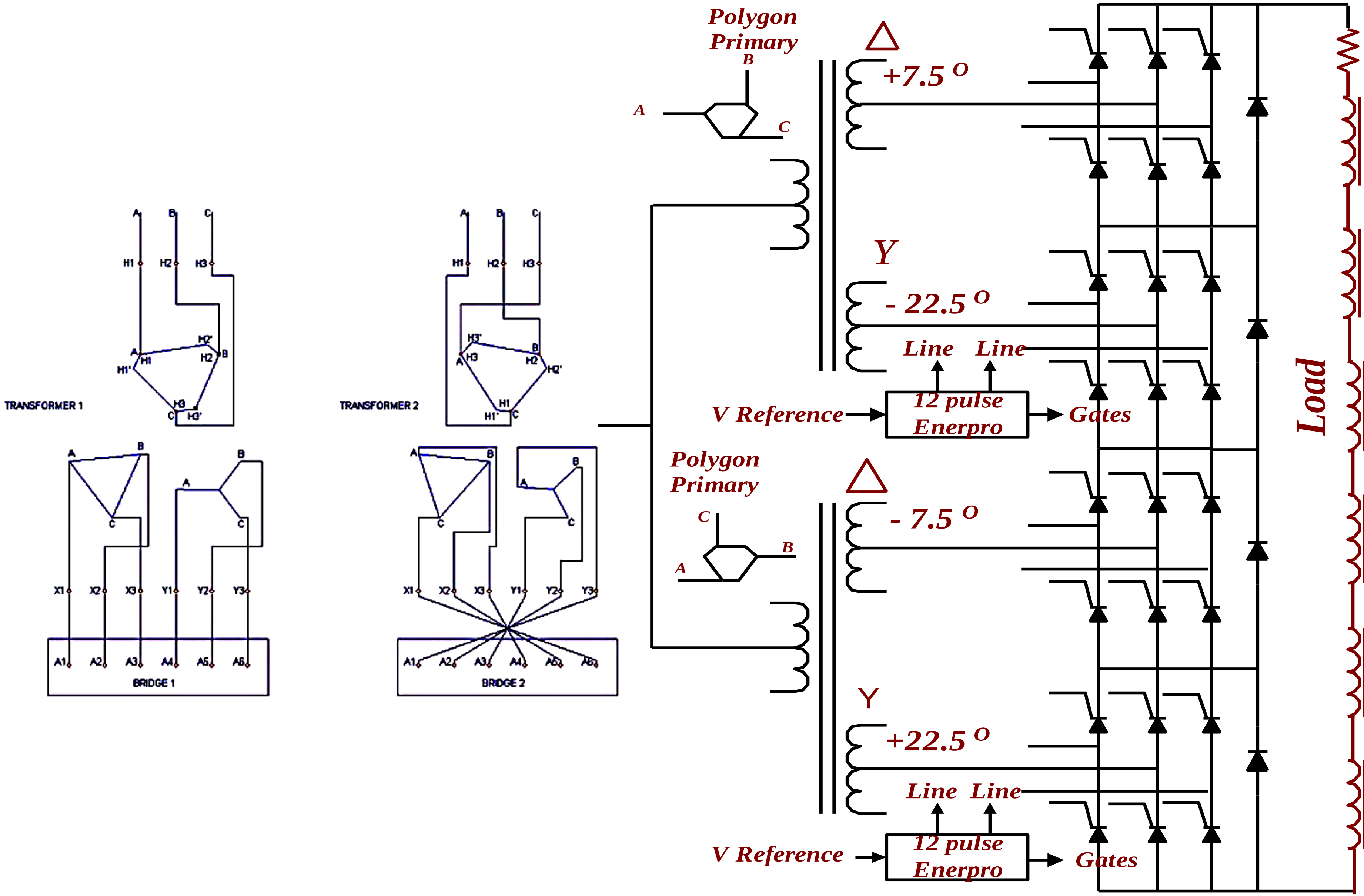
Series-connected bridges

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

Parallel-connected bridges

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

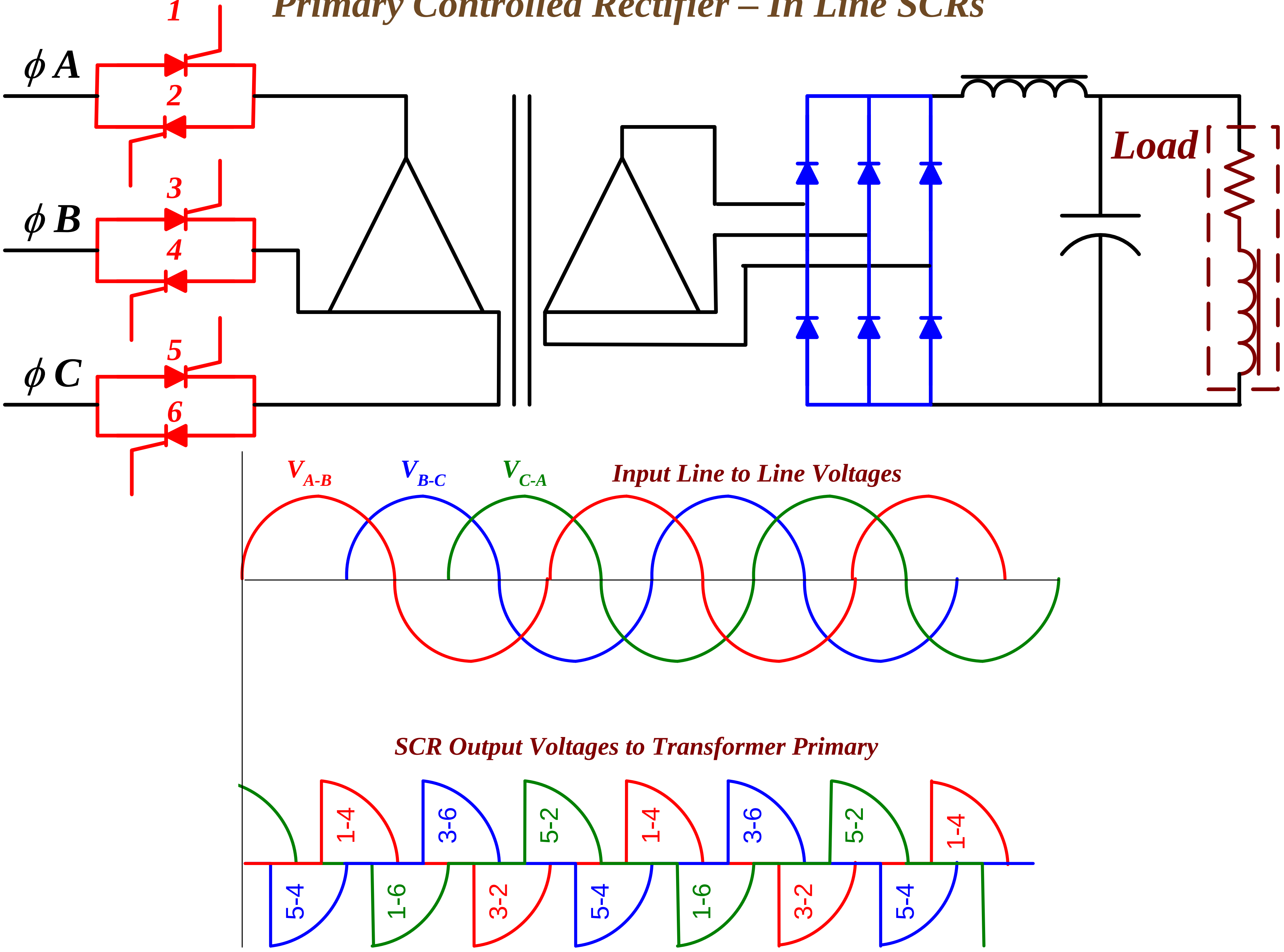
12 ϕ, q = 24 Pulse Rectifier



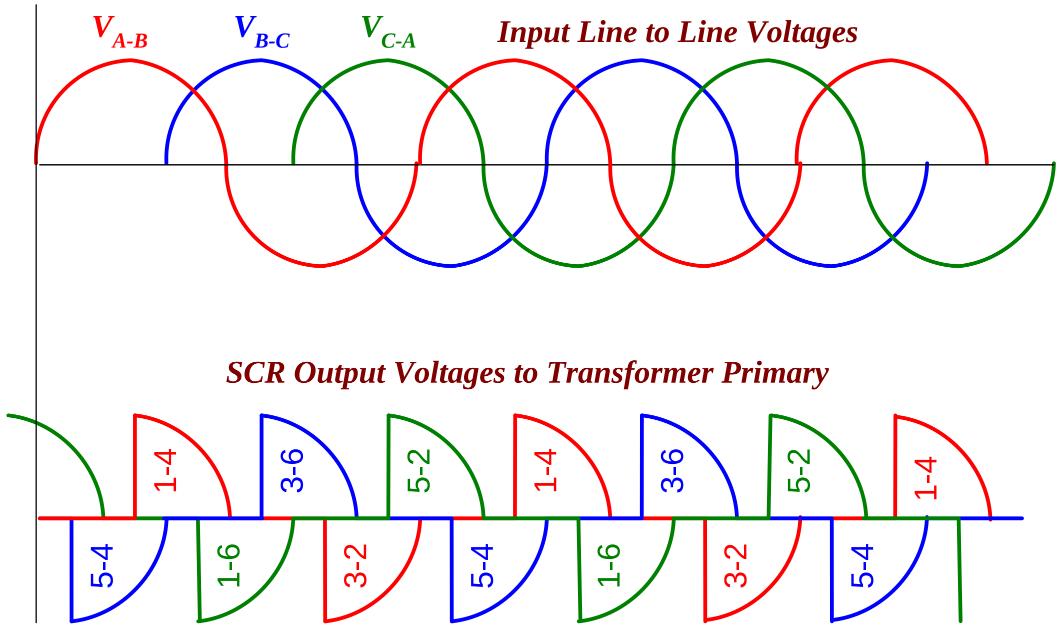
12 ϕ, q = 24 Pulse Rectifier Summary

- *Input transformer polygon primary to + 7.5^{O} $\Delta - Y$ secondaries for -30^{O} shift*
- *Input transformer polygon primary to - 7.5^{O} $\Delta - Y$ 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



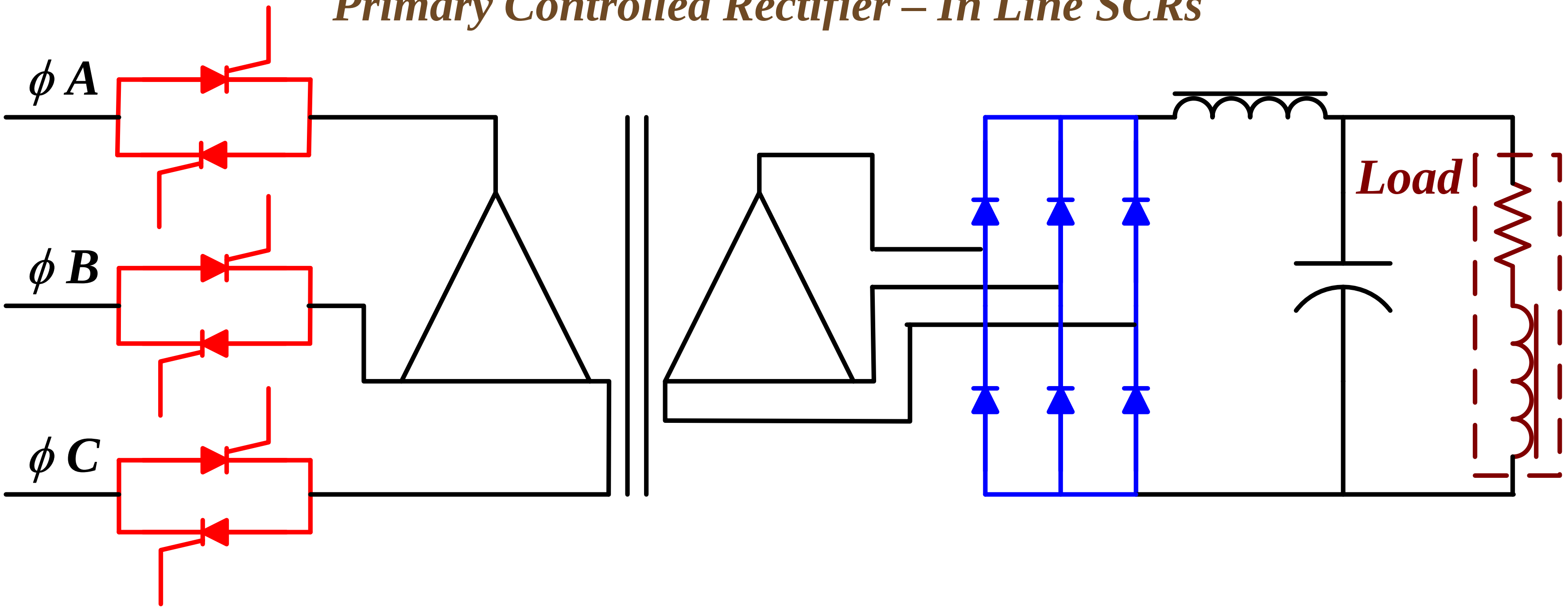
Primary Controlled Rectifier – In Line SCRs



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

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

Primary Controlled Rectifier – In Line SCRs



Advantage Compared To Secondary Control

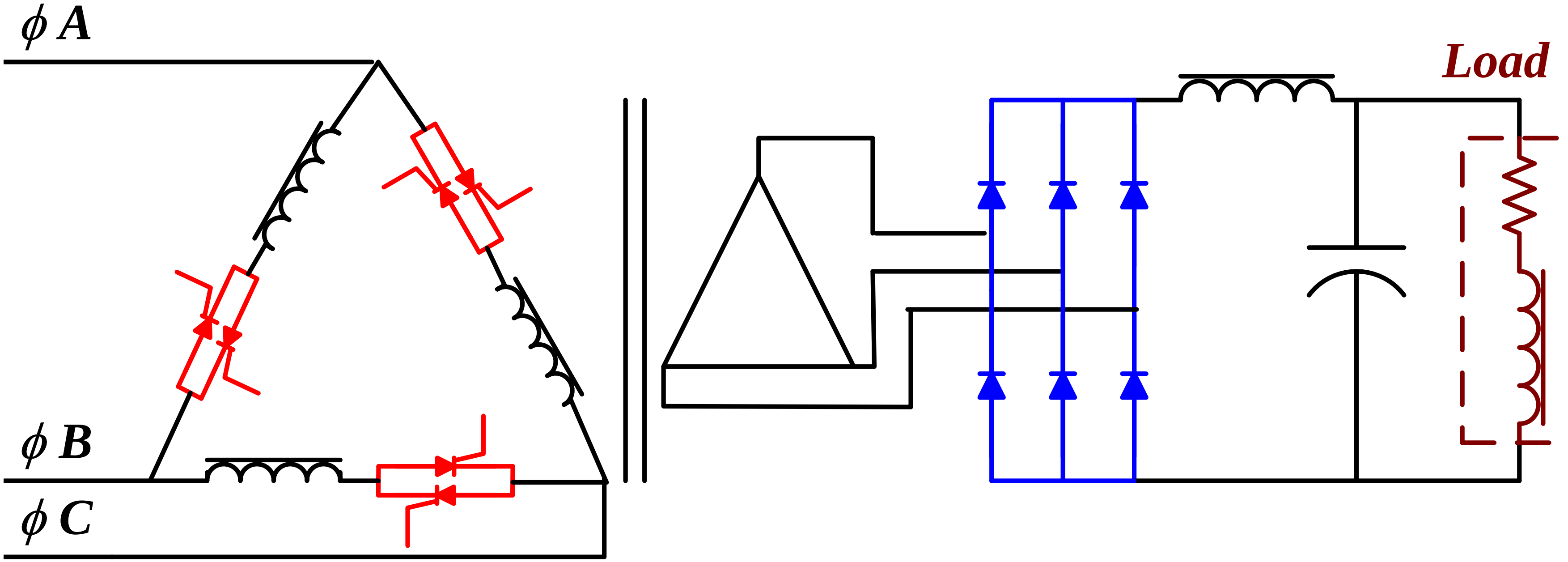
- Keep SCR controls out of the HV and HV oil

Disadvantage Compared To secondary Control

- Twice the semiconductors mean higher losses and lower efficiency

Similarities

- PF
- Input / output harmonics
- Output ripple frequency



Advantage Compared To In Line SCRs

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

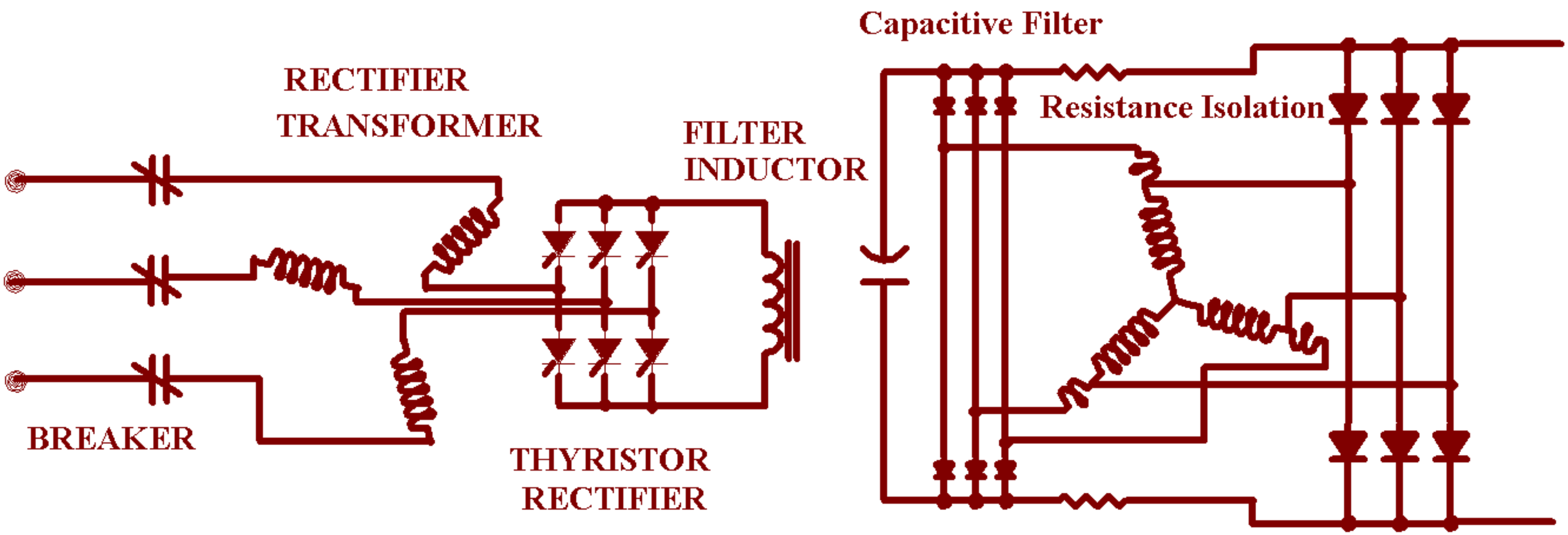
Disadvantage

- Transformer wiring more complex

Similarities

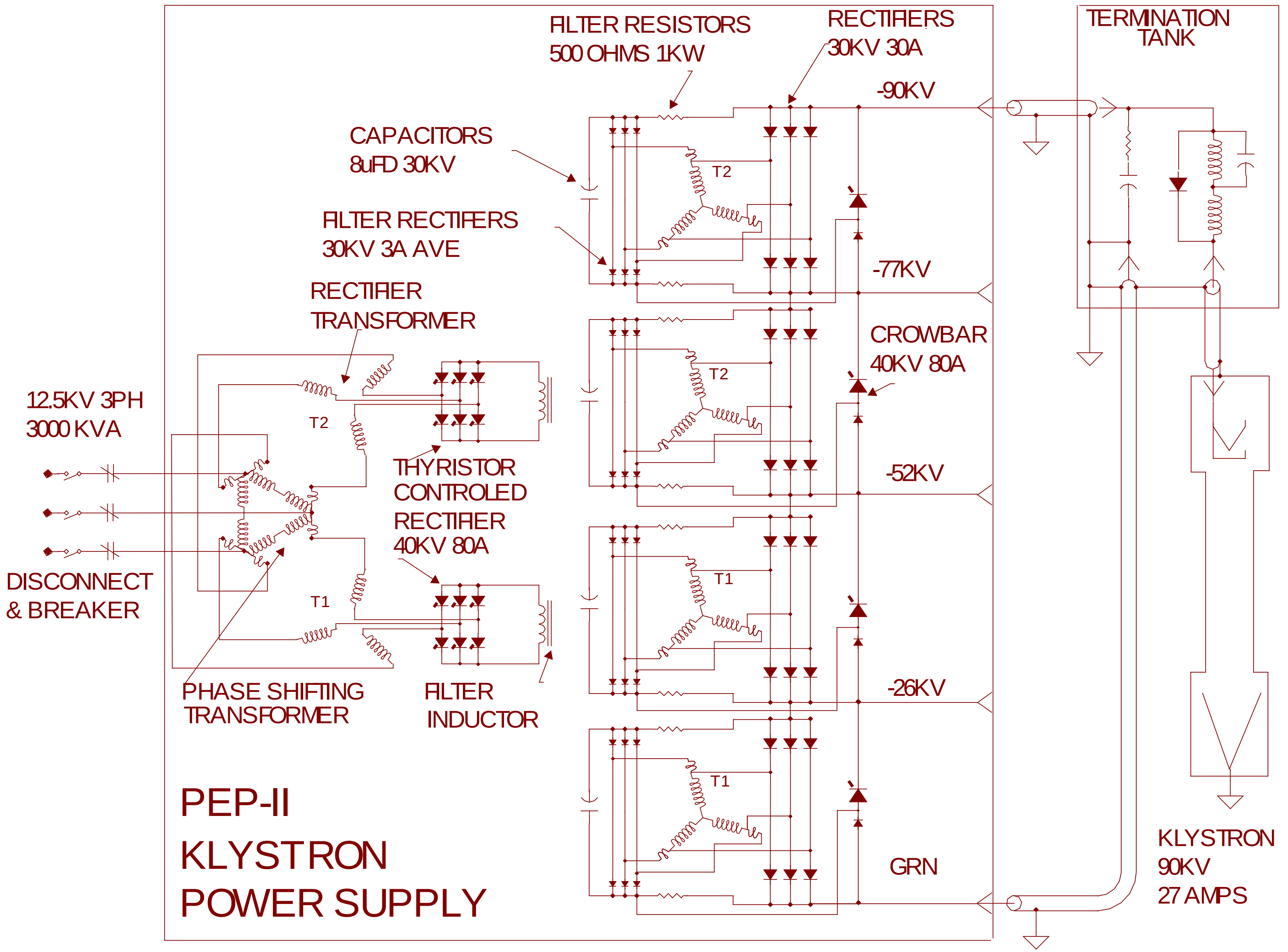
- Other characteristics similar to In Line SCR controller

6 Pulse SCR Star Point Rectifier



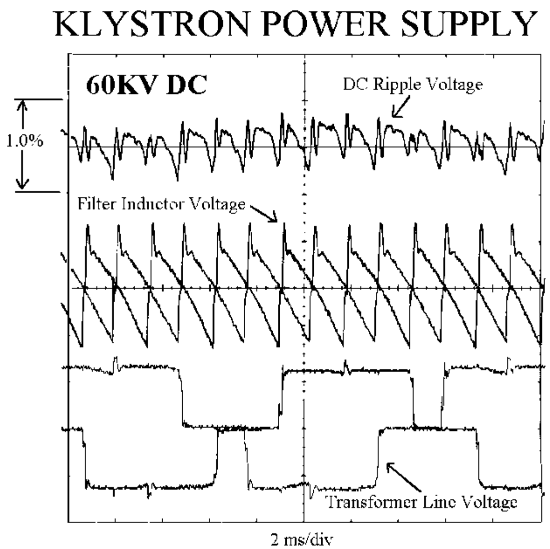
- *Primary SCR in open wye with filter inductor in lower voltage primary*
- *High voltage secondary with diodes and filter capacitor isolated from main load*
- *Protected against secondary faults. High output impedance, capacitor bank isolated from load*
- *Secondary uses diodes only.*

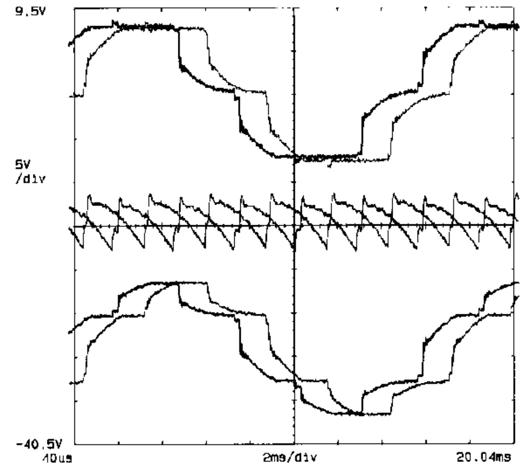
6 Phase SCR Star Point Rectifier with Isolated filter



6 Phase SCR Star Point Rectifier

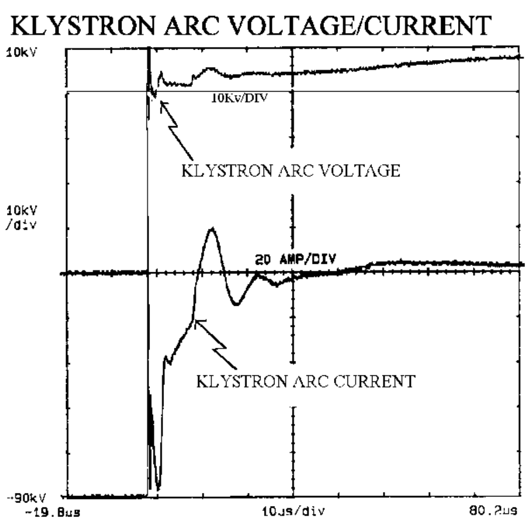
- *Large Joules under Load with Fault from filter Capacitor and Inductor*

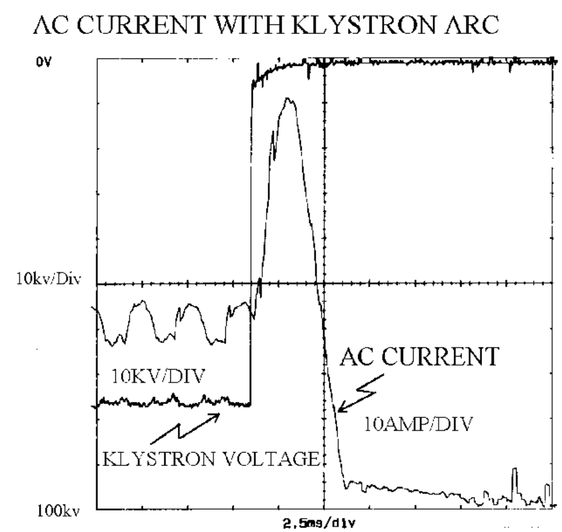




- *Large Joules under Load Fault from filter Capacitor*

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





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

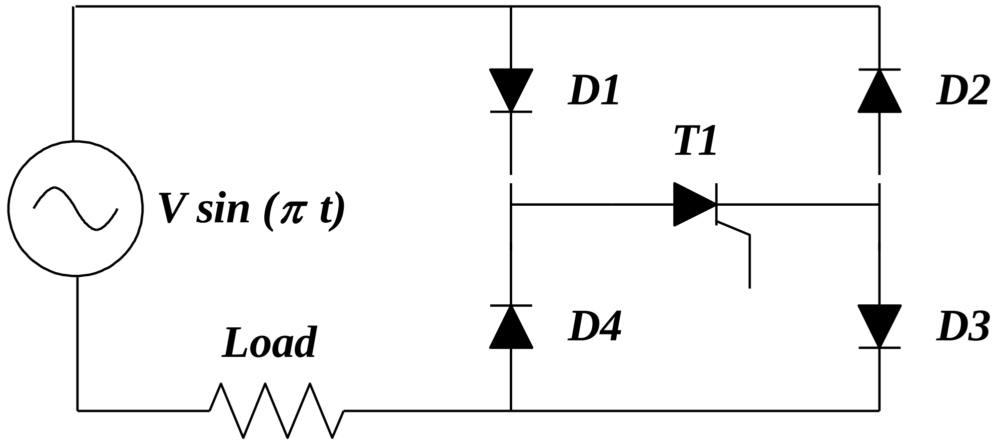
SCR Gate Firing Boards

Enerpro FCOP-1200

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

http://www.enerpro-inc.com

Homework Problem # 8



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

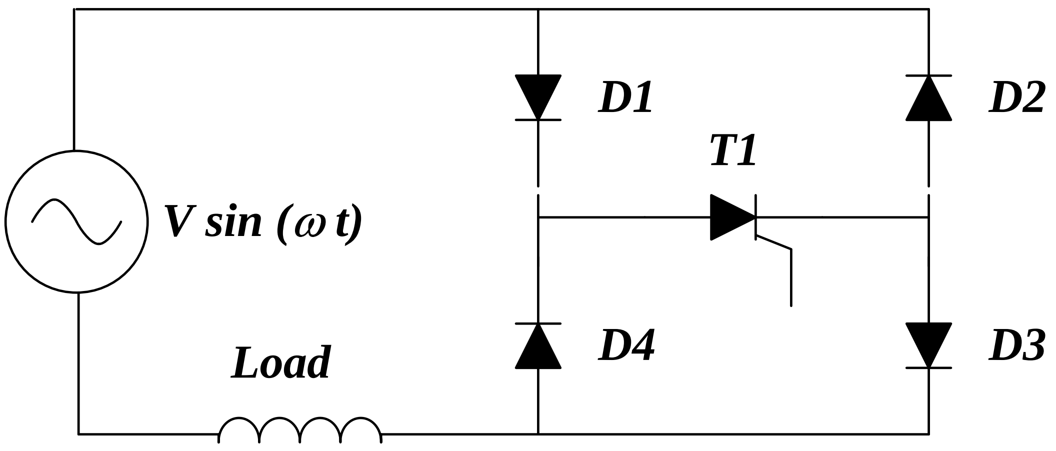
A. Explain how the circuit operates

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:

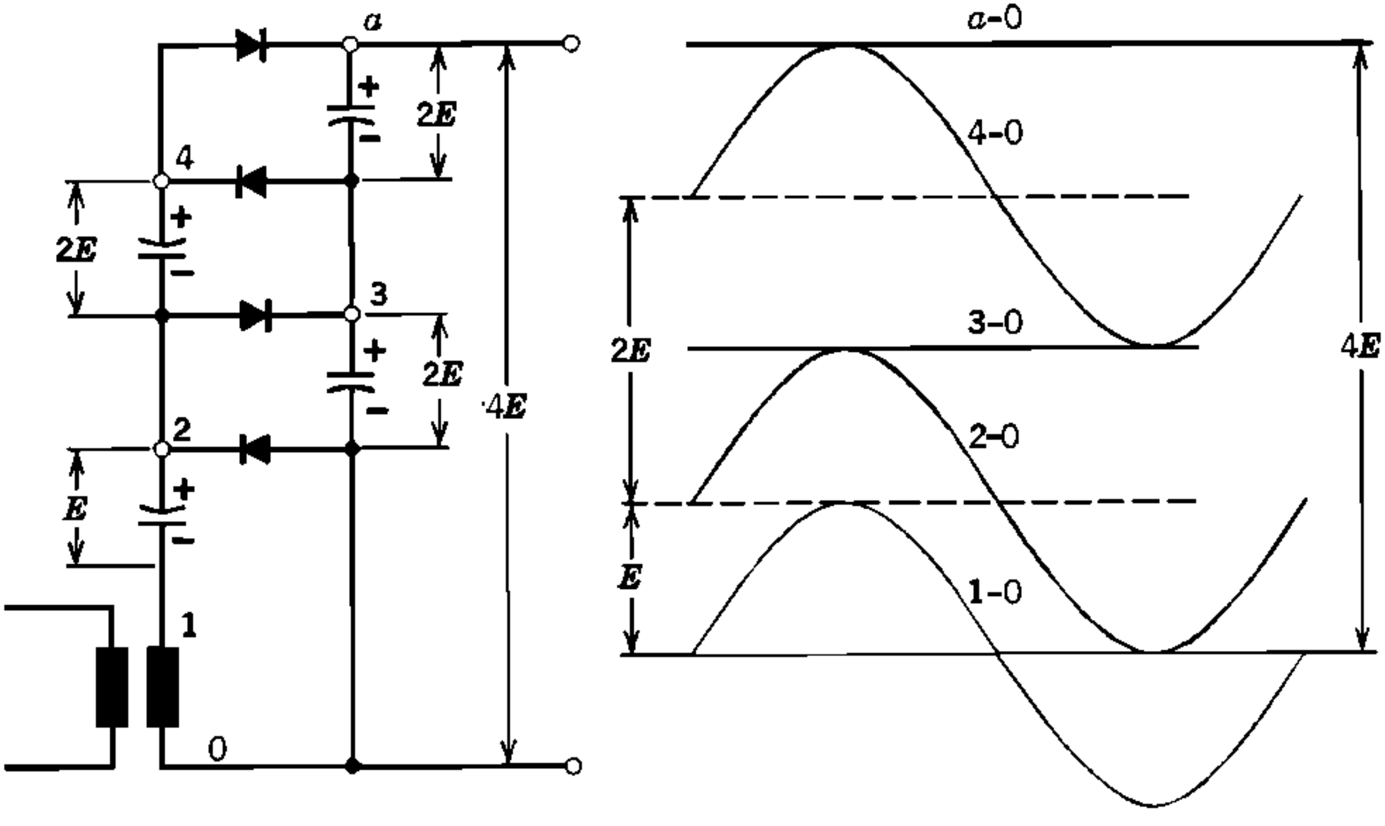
A. Explain how the circuit operates.

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

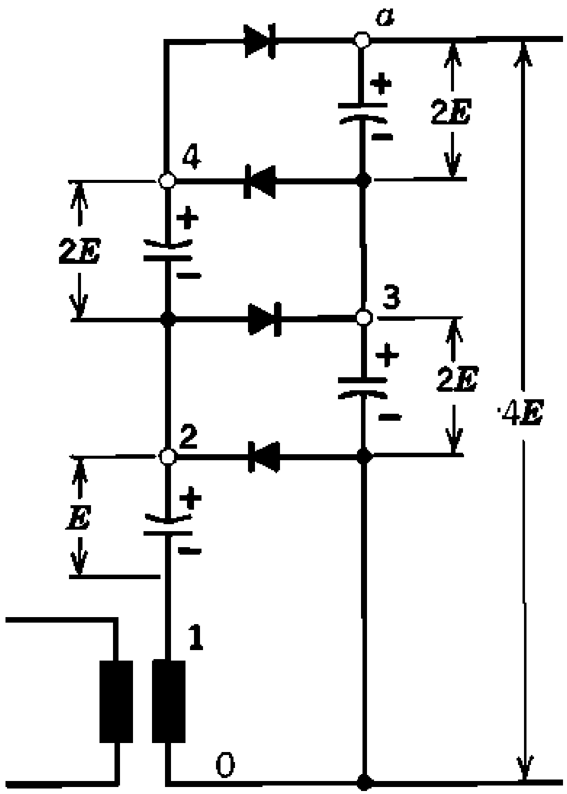
C. Calculate the average load voltage and average load current as a function of α

D. Find the RMS value of the load current.

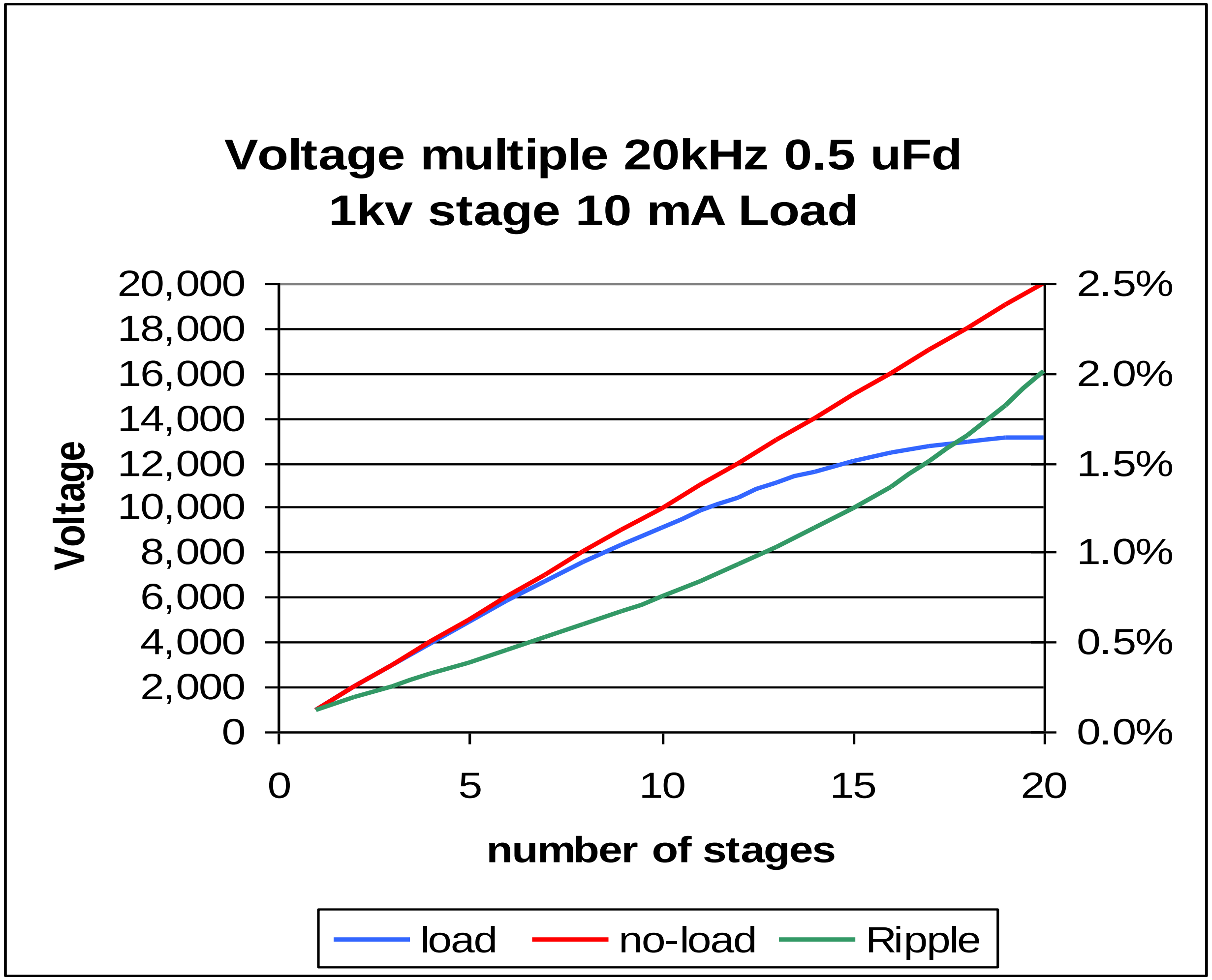
Voltage Multipliers, Cockroft Walton or Cascade Supplies



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

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 ≠ 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)*

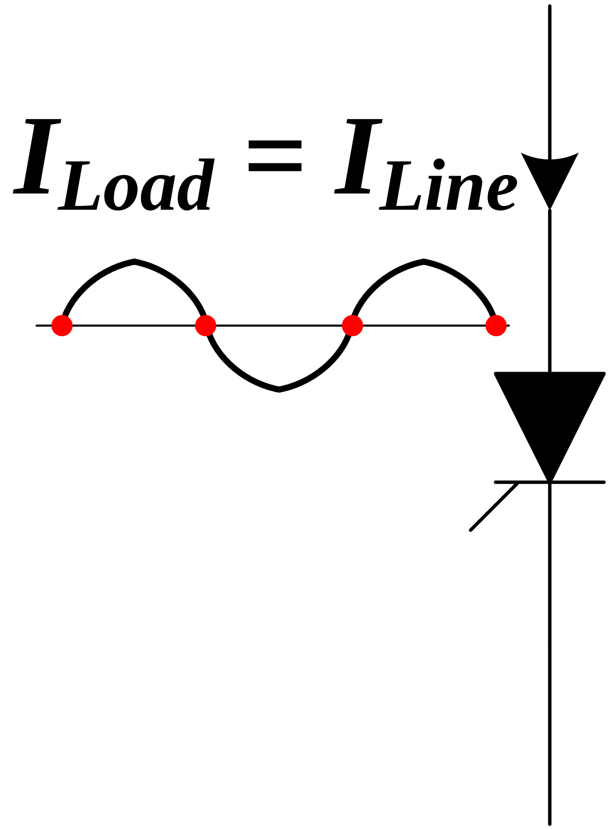
SCR Regulation Vs Switchmode Regulation

	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*

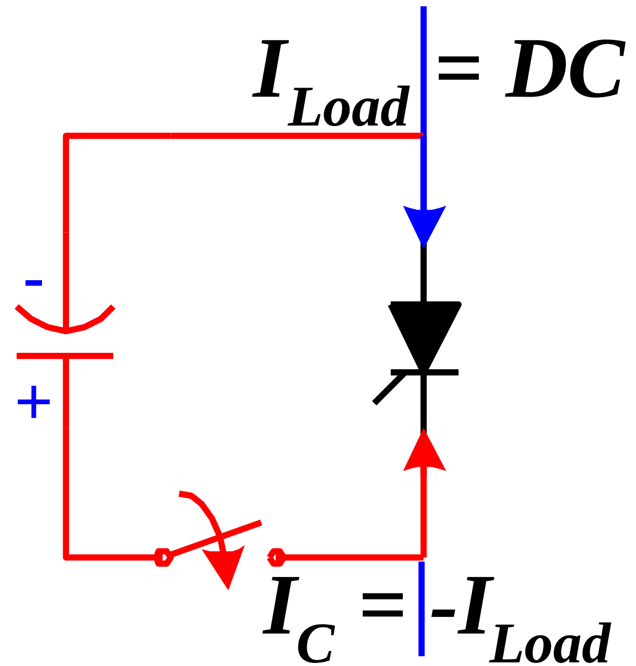
Line Commutated Switches



- 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

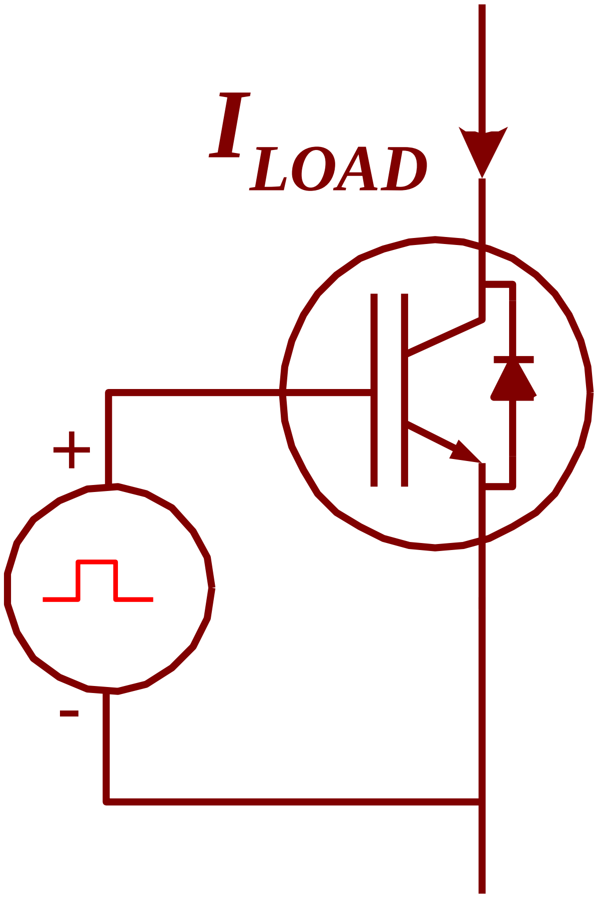
Force Commutated

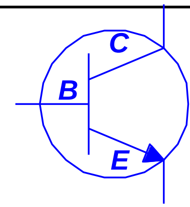
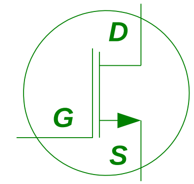
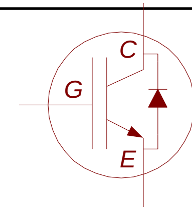
- *Typically SCRs, Triacs*
- *Artificial current zero is manufactured by pre-charged capacitor* $I_c = -I_{Load}$
- *Complex and power-consuming charging and discharging circuits for capacitor*
- *Not suitable approach for fast switches*



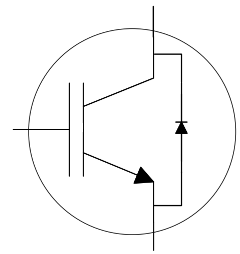
Self Commutated

- *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*

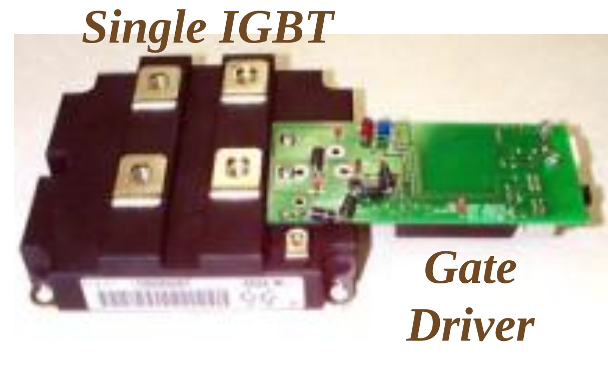


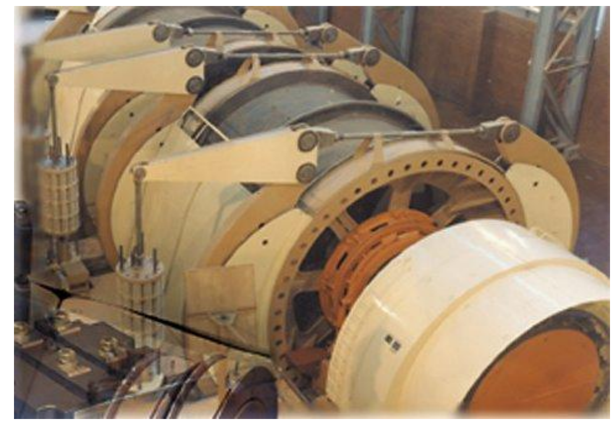
Self-Commutated Device	Bipolar Junction Transistor (BJT)	Metal Oxide Field Effect Transistor (MOSFET)	Insulated Gate Bipolar Transistor (IGBT)
Symbol			
Available Ratings	600 V, 10 $\rightarrow$ 100 A 1000V, 10 $\rightarrow$ 100A	150 V, 10 $\rightarrow$ 600 A 600 V, 10 $\rightarrow$ 100 A 1200V, 10 $\rightarrow$ 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	$DC \le fs \le 2$ kHz	$DC \le fs \le 1{,}000$ kHz	$DC \le fs \le 20$ kHz
Vce or Vds f(Vge/Vgs, Ic/Id)	0.5 V $\rightarrow$ 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

- *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/*

- *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

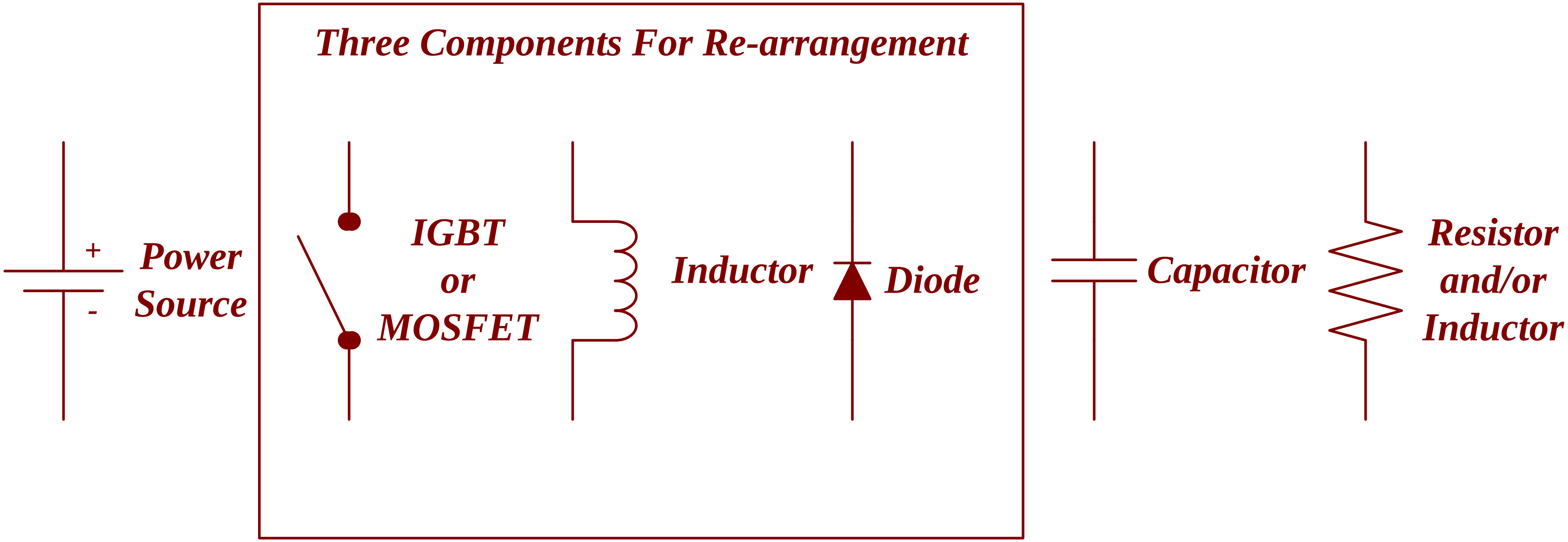
Typical Forward Converters Listed In Order Of Increasing Use

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

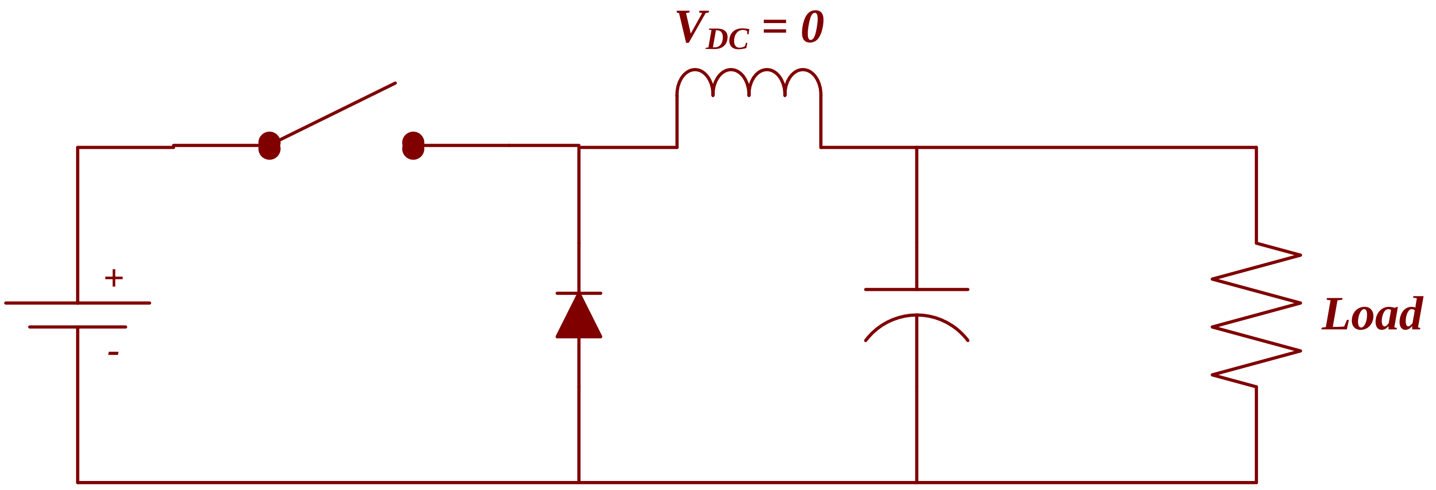
Typical Forward Converters Listed in Order of Increasing Complexity

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

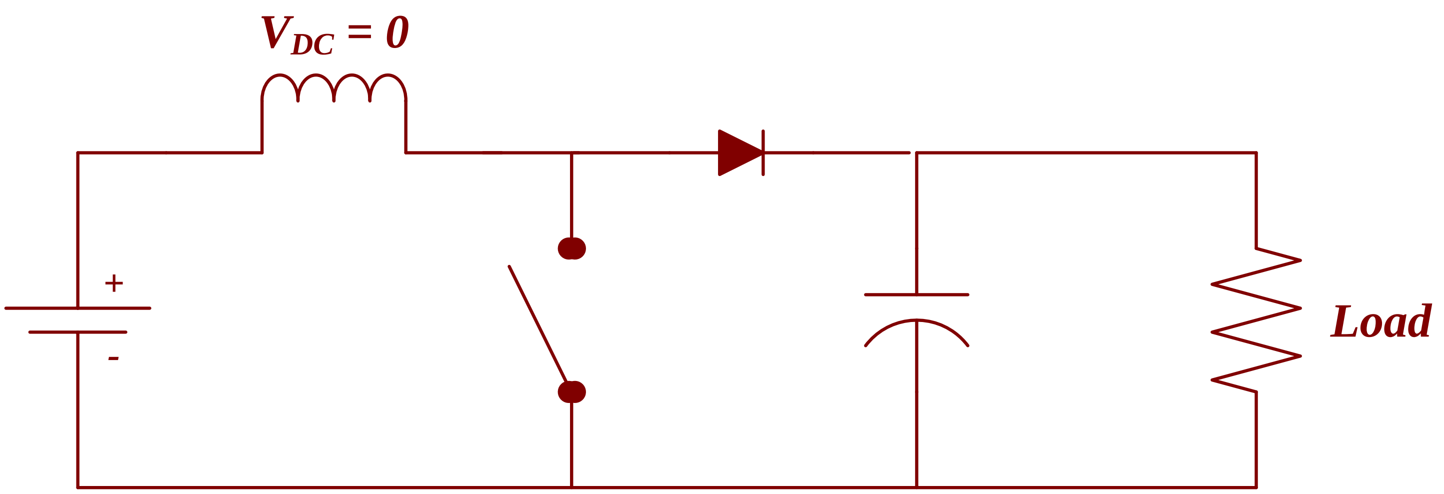
Basic switchmode tool kit



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

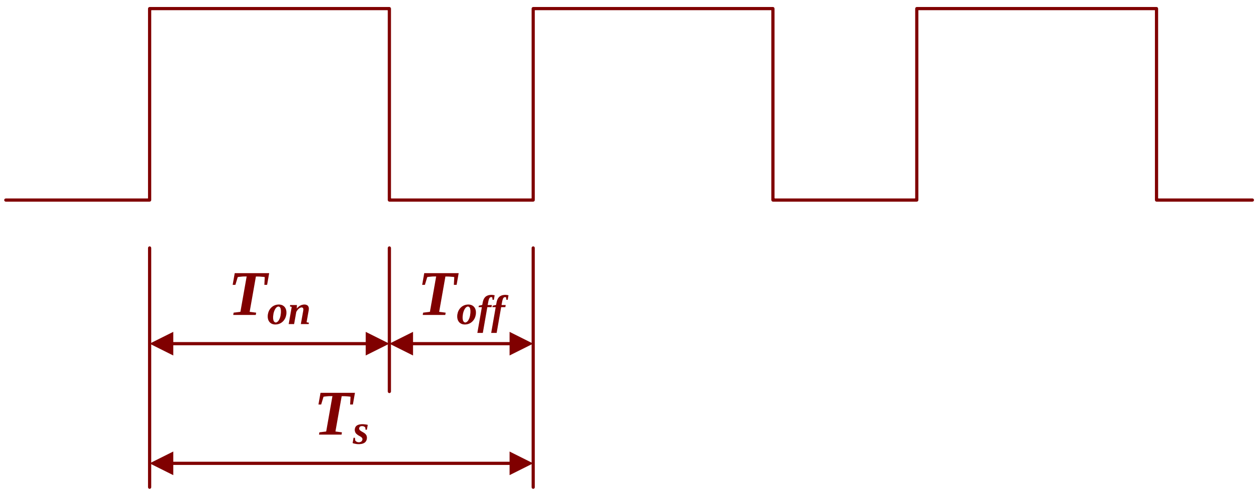


Buck



Boost

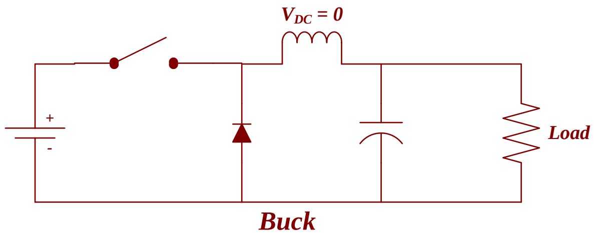
Definition of the Pulse Width Modulated (PWM) Waveform

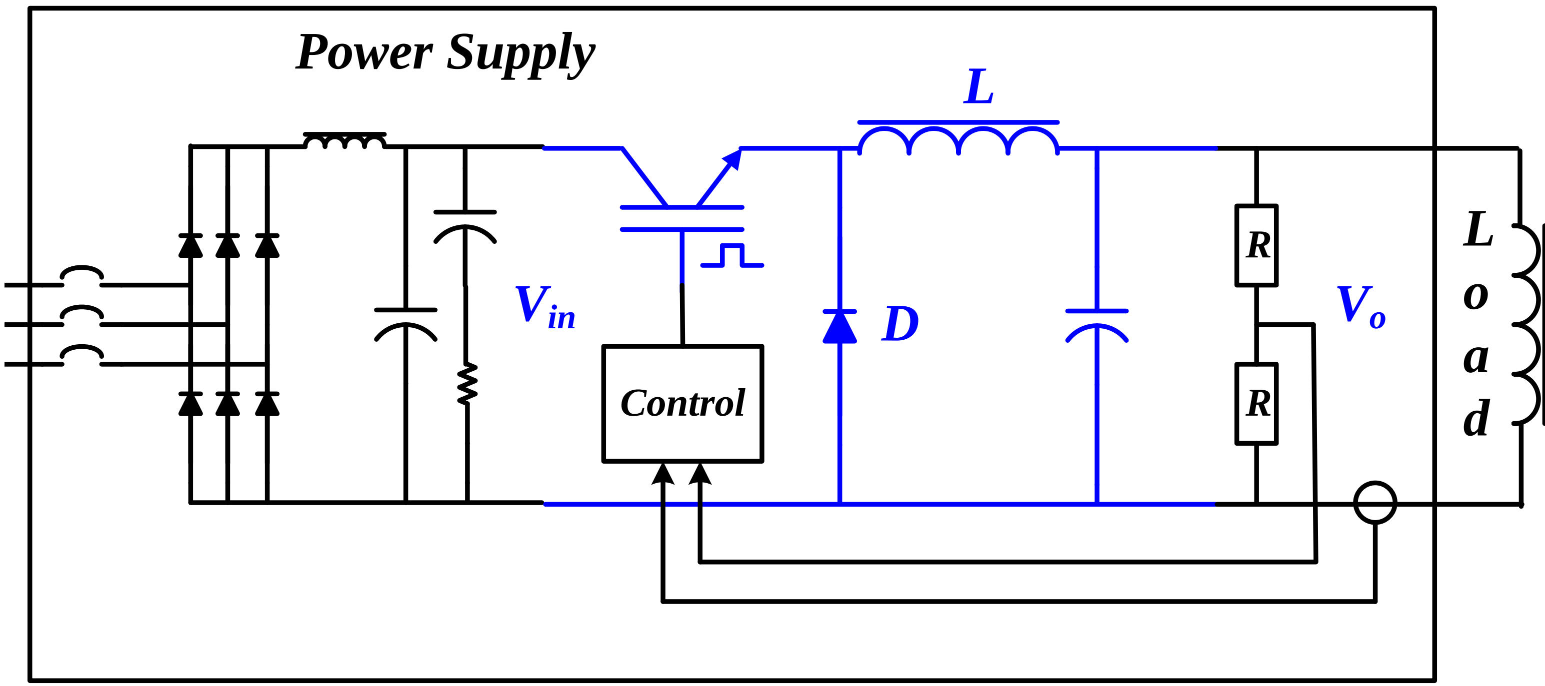


$$\text{Duty Cycle} = \text{Duty Ratio} = D = \frac{T_{on}}{T_{on} + T_{off}} = \frac{T_{on}}{T_s}$$

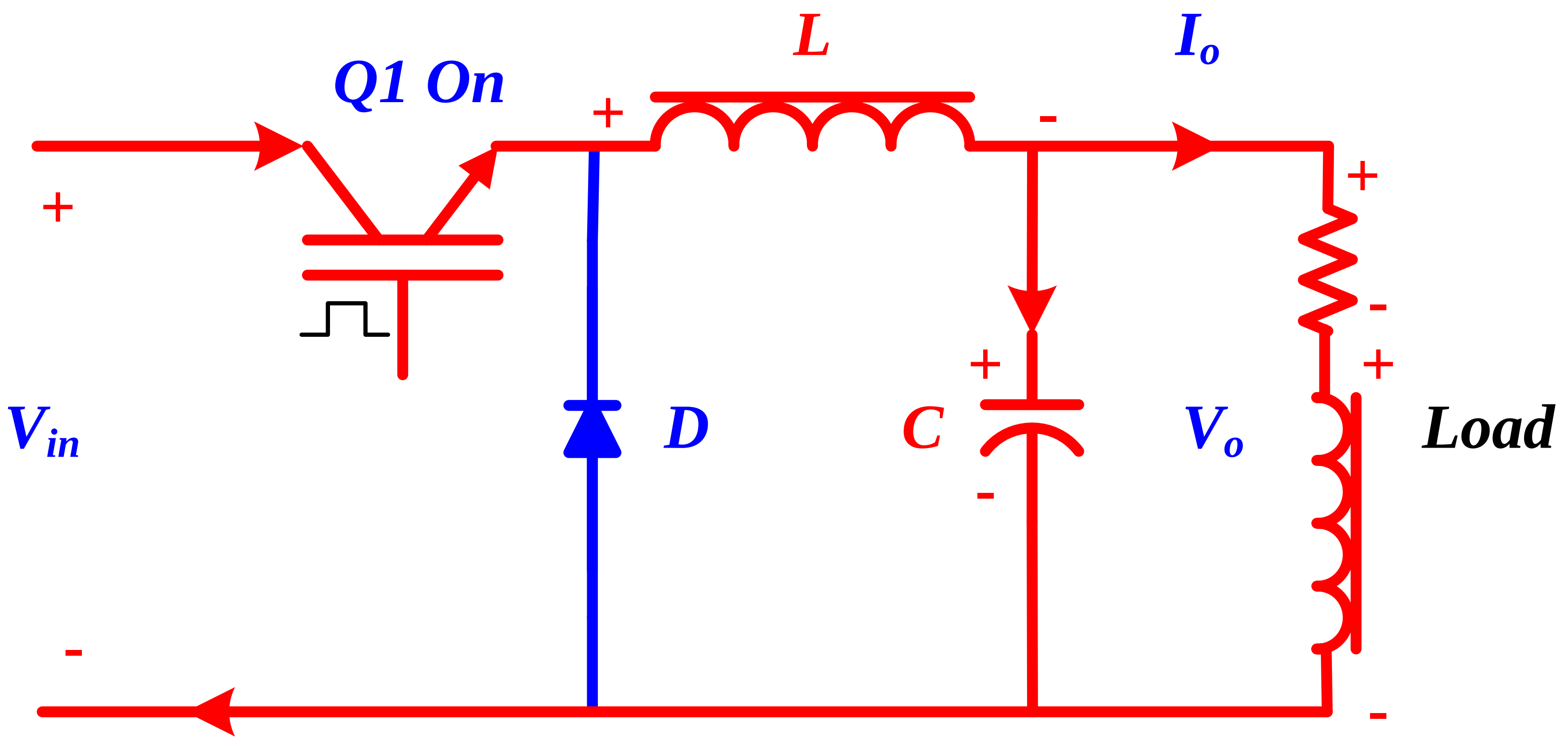
$$D' = 1 - D = \frac{T_{off}}{T_{on} + T_{off}} = \frac{T_{off}}{T_s}$$

Buck Converter (Regulator)





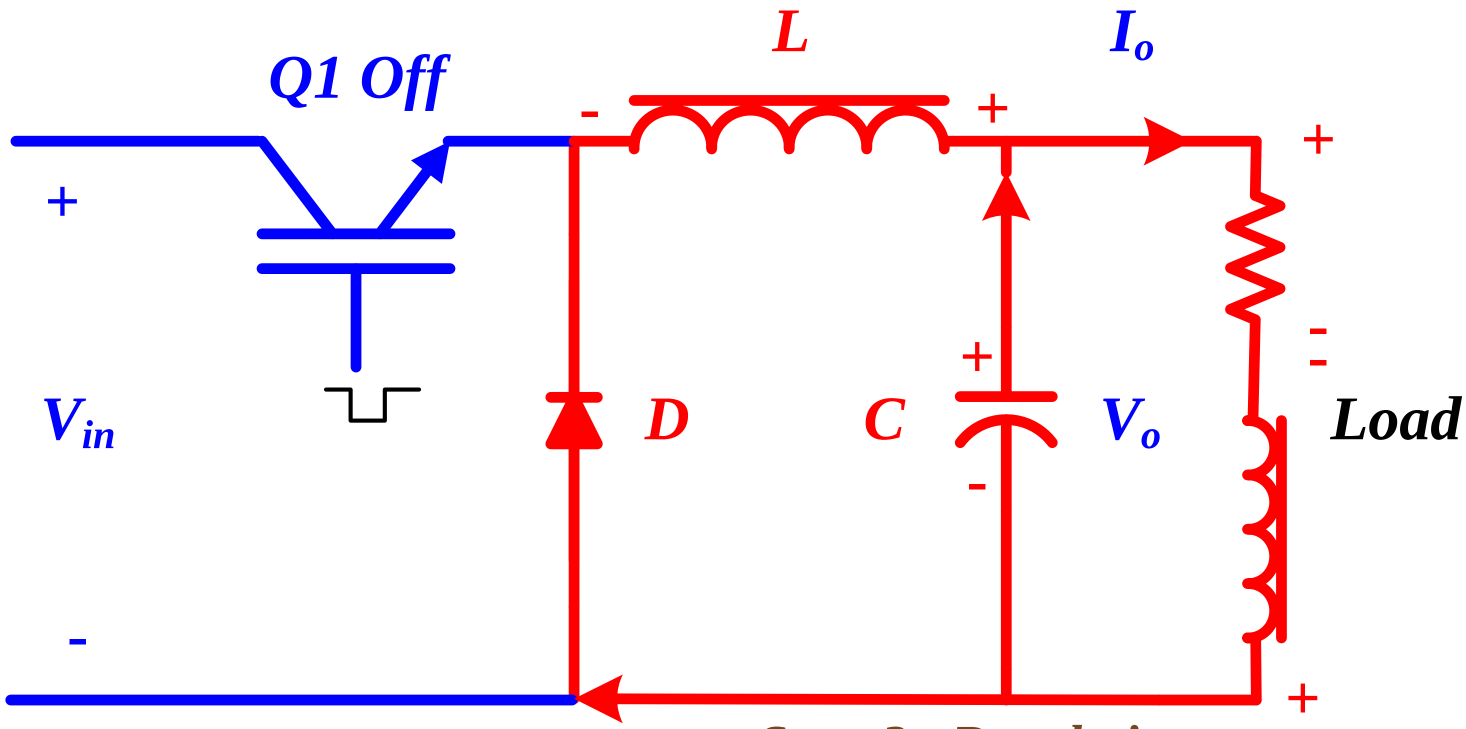
- Used in the majority of switchmode power supplies
- Bucks the input voltage down to a lower voltage
- Perhaps the simplest of all
- Input current discontinuous (chopped) – output current smooth



State 1 – Power Transfer

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

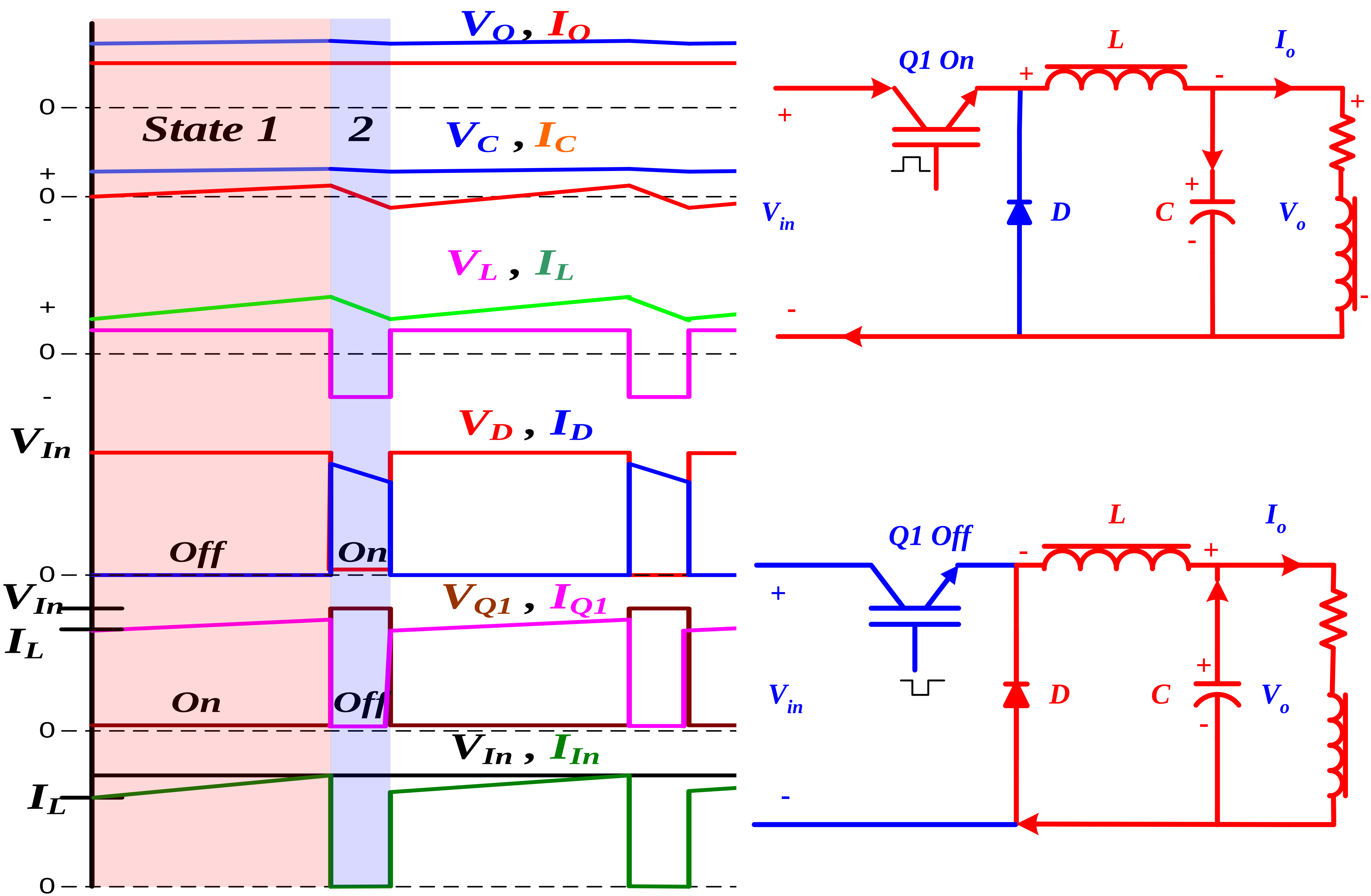
Buck Converter



State 2 - Regulation

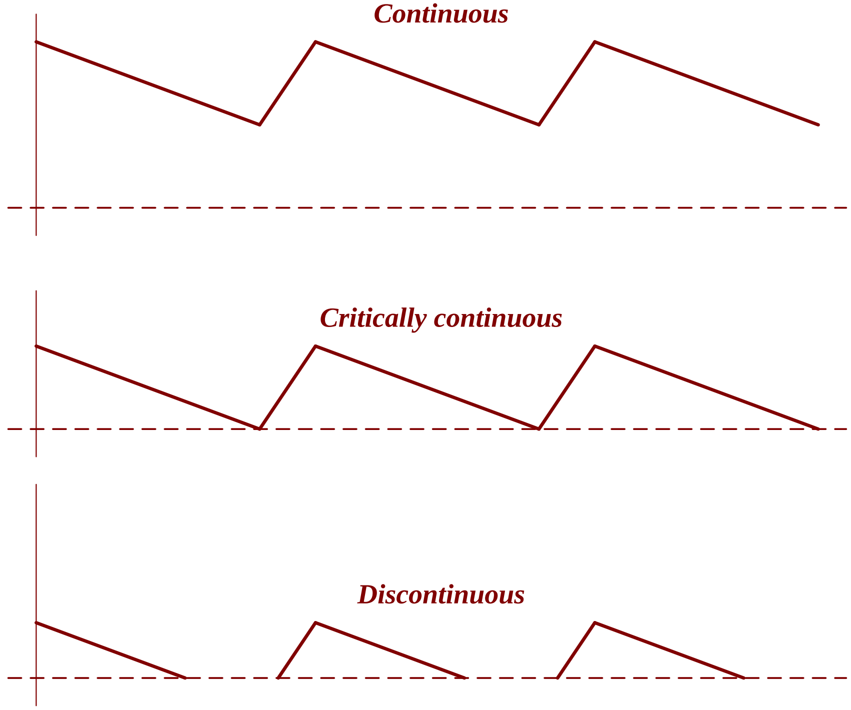
- Switching device Q1 turns off
- Voltage across L reverses: – Vo impressed across L
- Diode D turns on
- Current in L decreases linearly
- C discharges into the Load

Buck Converter Waveforms



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 ≠ D* Vin*

Summary

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

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

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

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

Buck Converter Vs Other Topologies

An Advantage

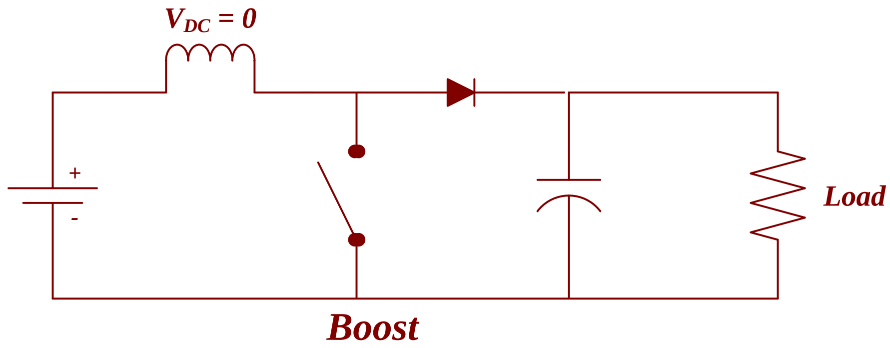
- *Few components, 1 switch – simple circuit, high reliability if not overstressed*

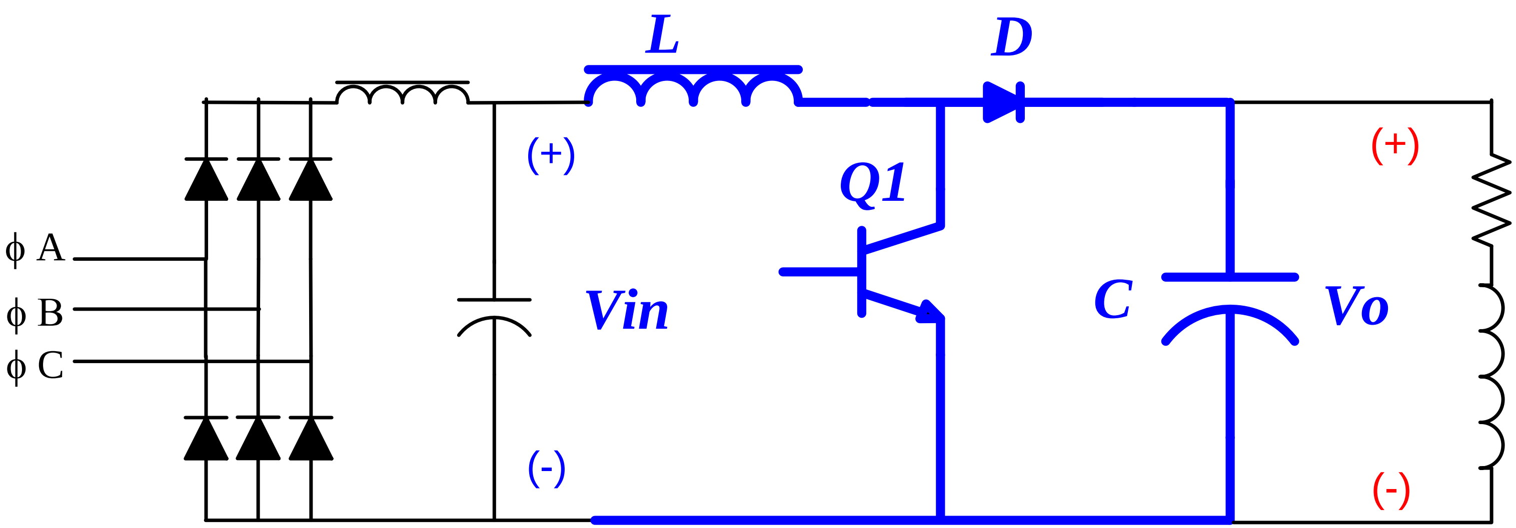
Disadvantages

- *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

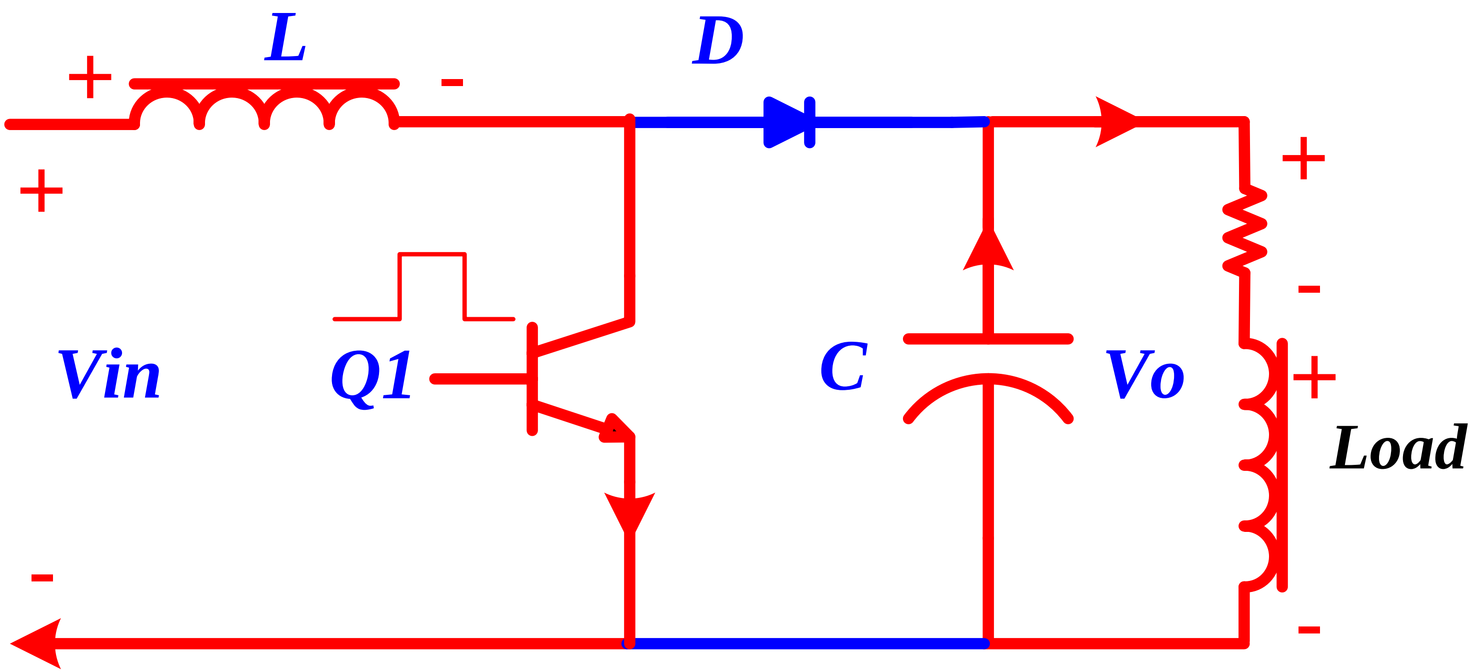
- *Used very widely in accelerator power systems, typically for large power supplies (perhaps ≥ 350 kW and used in conjunction with a 12-pulse rectifier with 6-phase transformer)*





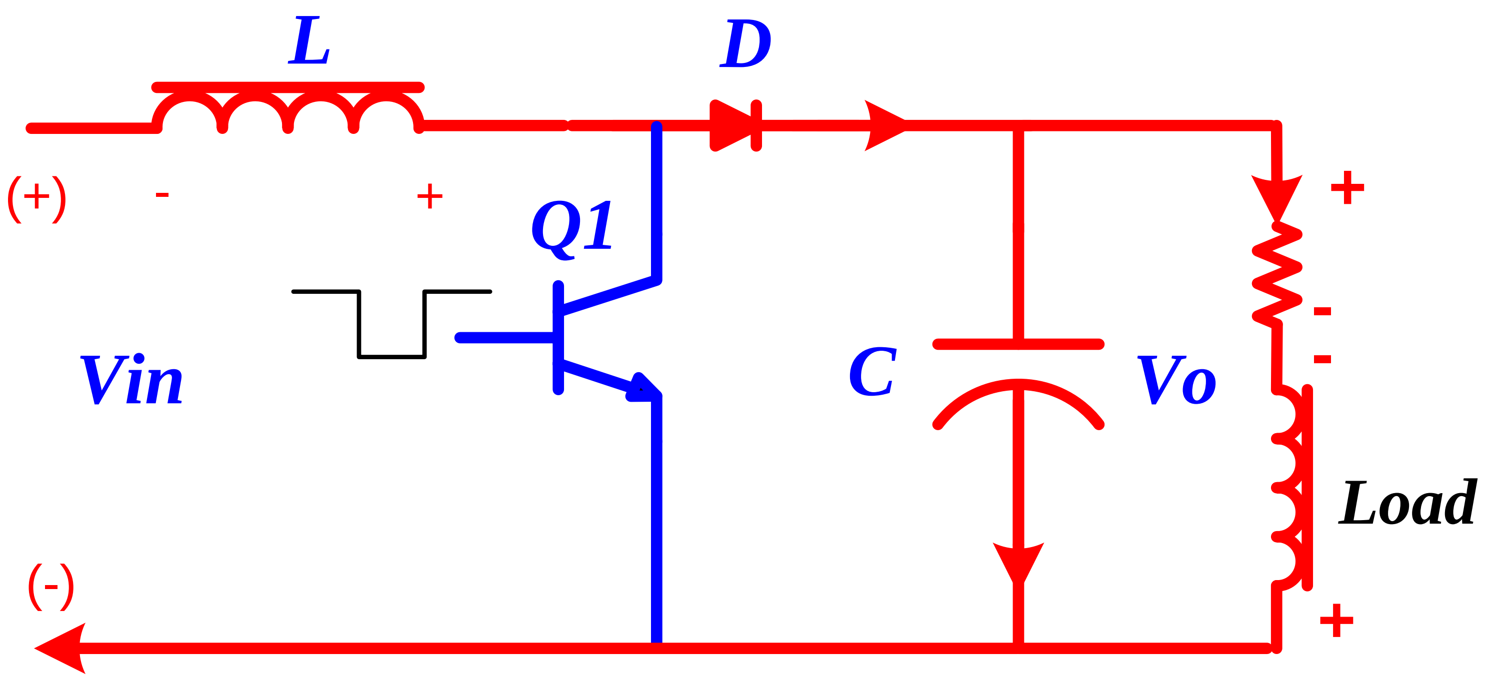
- *Boosts the input voltage to a higher output voltage*
- *Input current is smooth – output current is discontinuous (chopped)*

Boost Converter



State 1 – Power Transfer

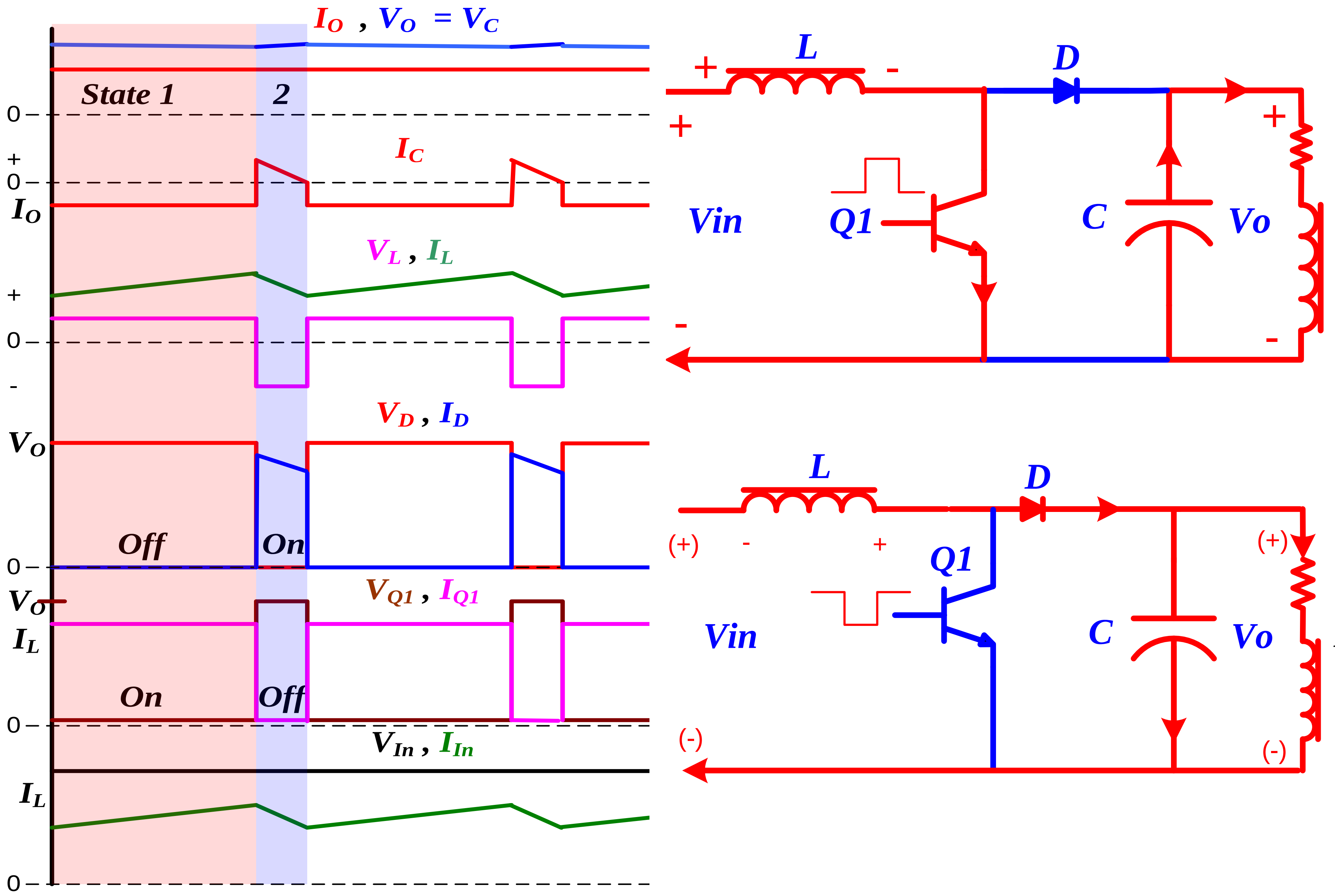
- *Switching device Q1 turned on by square wave drive circuit with controlled on-to-off ratio (duty factor, D)*
- *V_{in} impressed across L*
- *Current in L increases linearly in forward direction*
- *Diode D is reversed biased (open)*
- *Capacitor C discharges into the load*



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

Boost Converter Waveforms



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 choke and diode
- Output voltage is not related to load current so output impedance is very low (approximates a true voltage source).

Boost Converter Vs Other Topologies

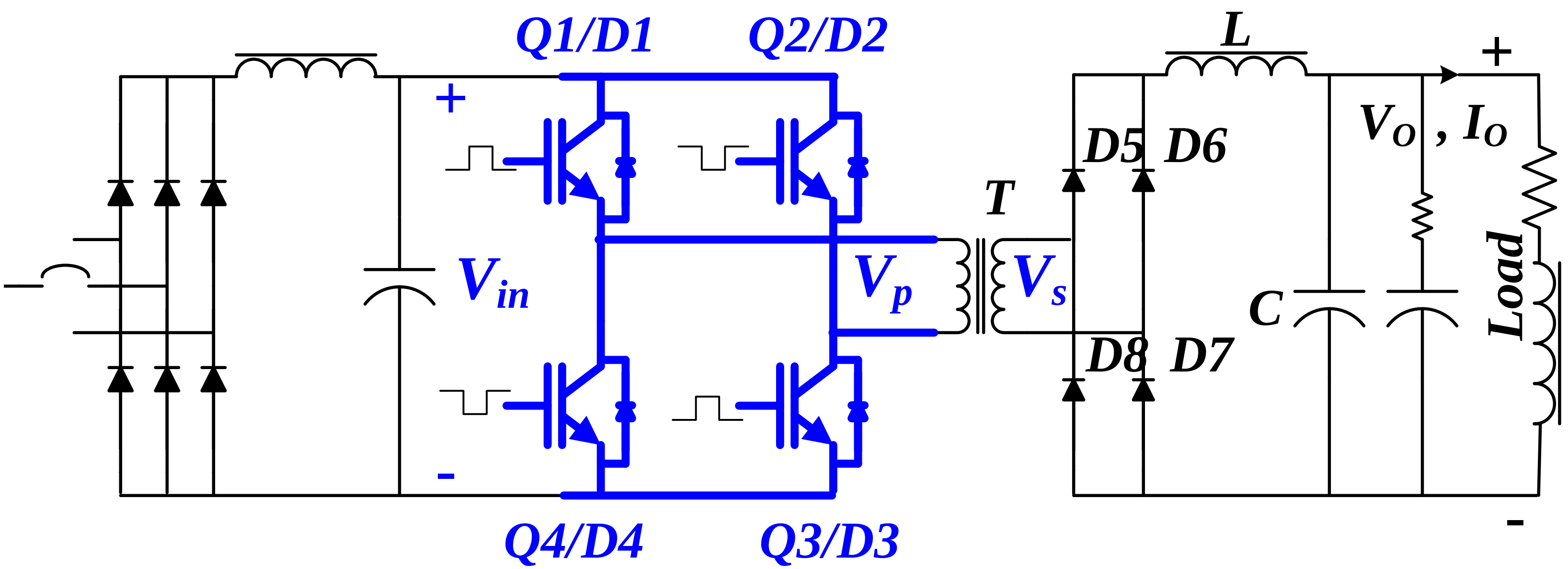
Some Advantages

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

Some Disadvantages

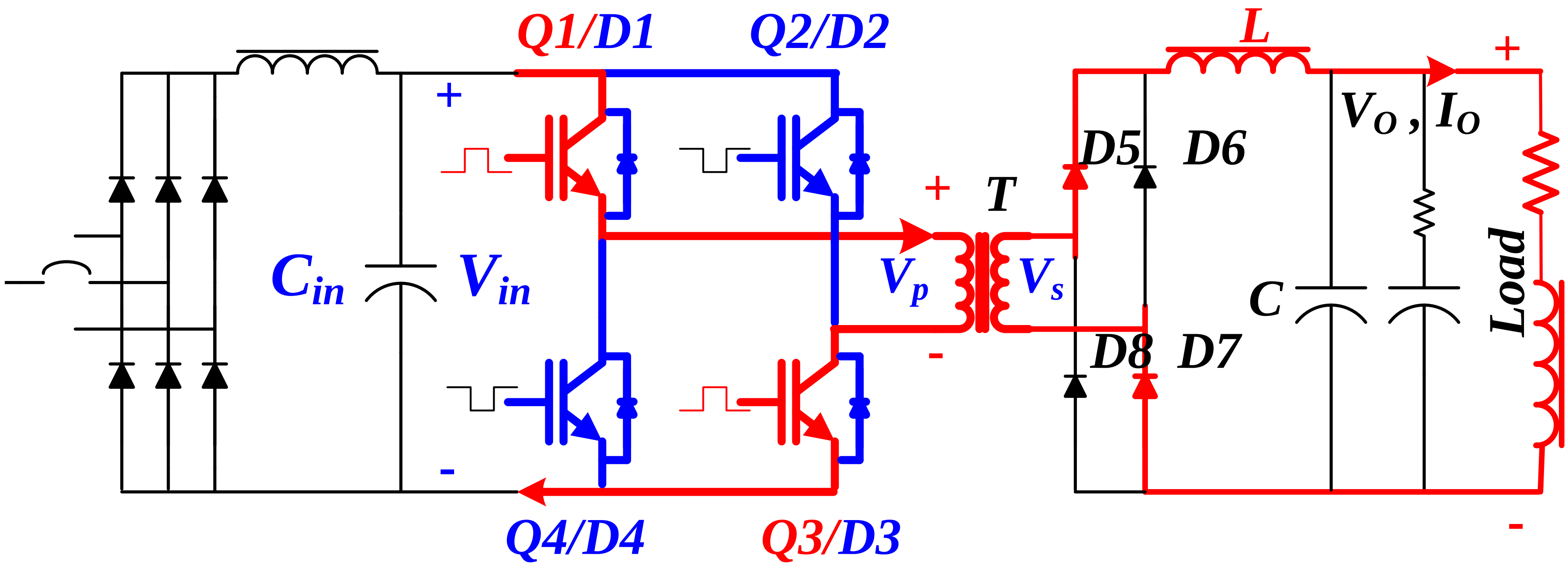
- *Capacitor C current is always discontinuous so a much larger output capacitor is needed for same output ripple voltage*
- *Output is DC and unipolar so no chance of high-frequency transformer or bipolar output*
- *Low frequency transformer must be used in front of the Boost for isolation and to match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

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

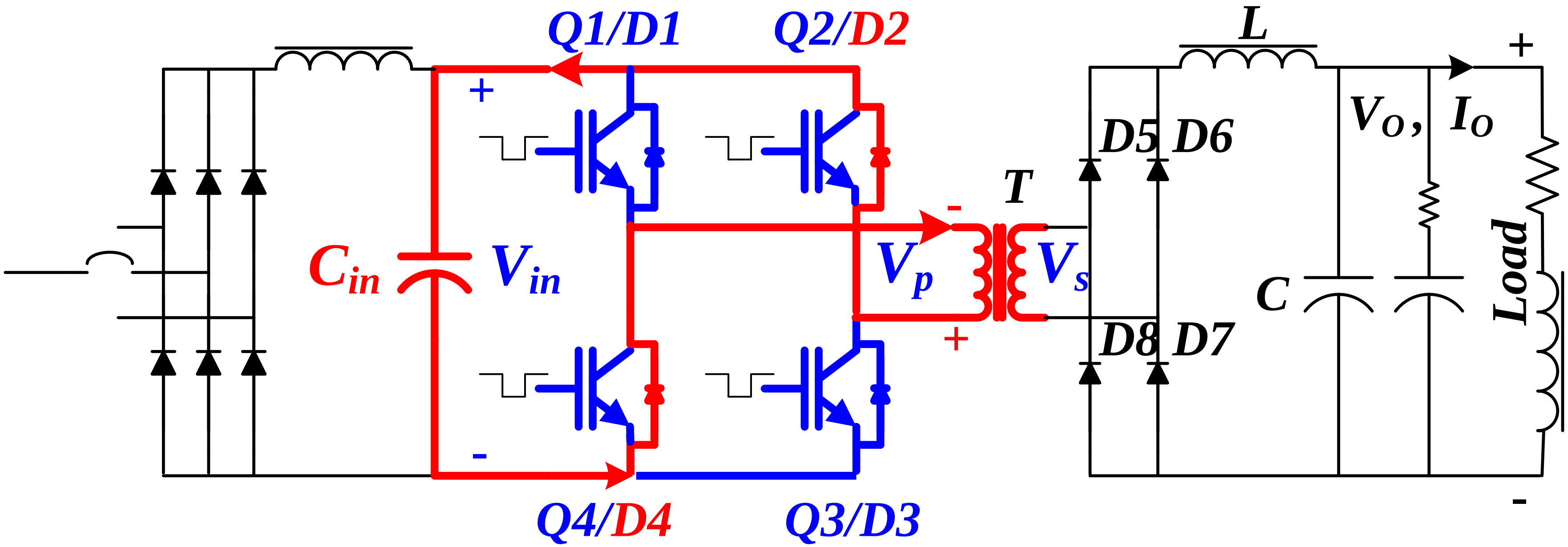
Full-Bridge Converter Switching – Q1 and Q3 On , Q2 and Q4 Off



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

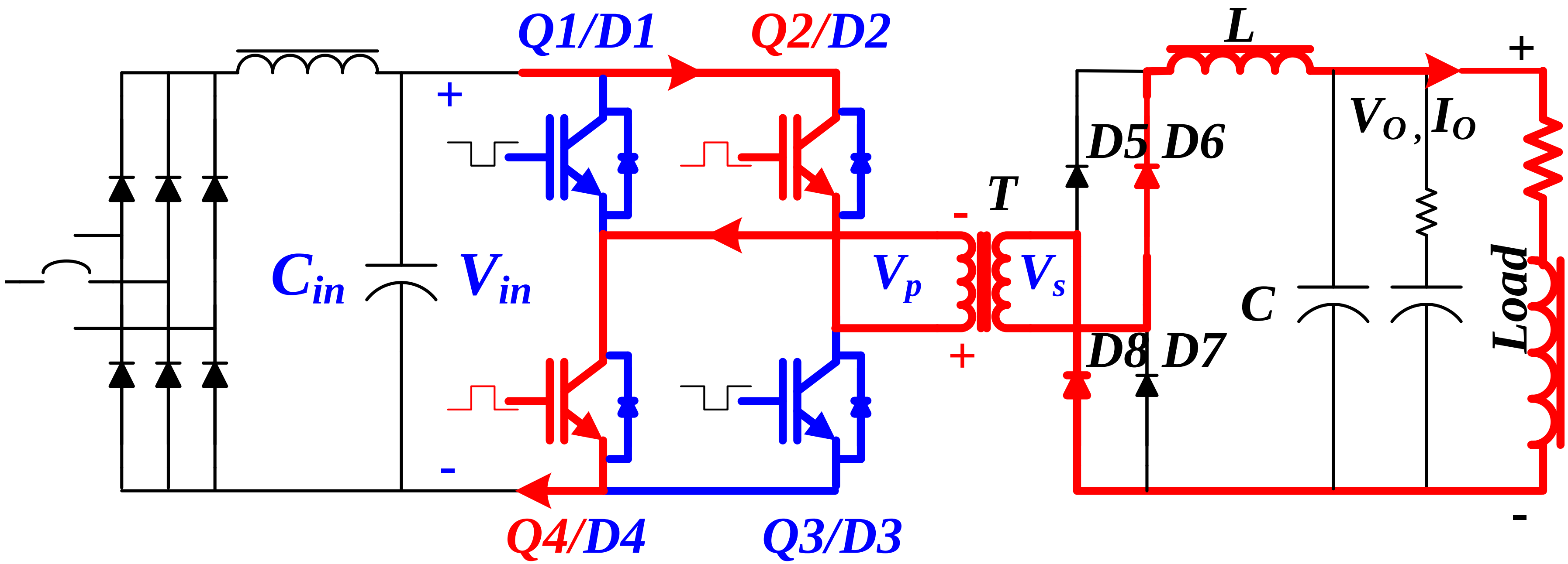
Full-Bridge Converter Switching – Q1, Q2, Q3 and Q4 Off



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

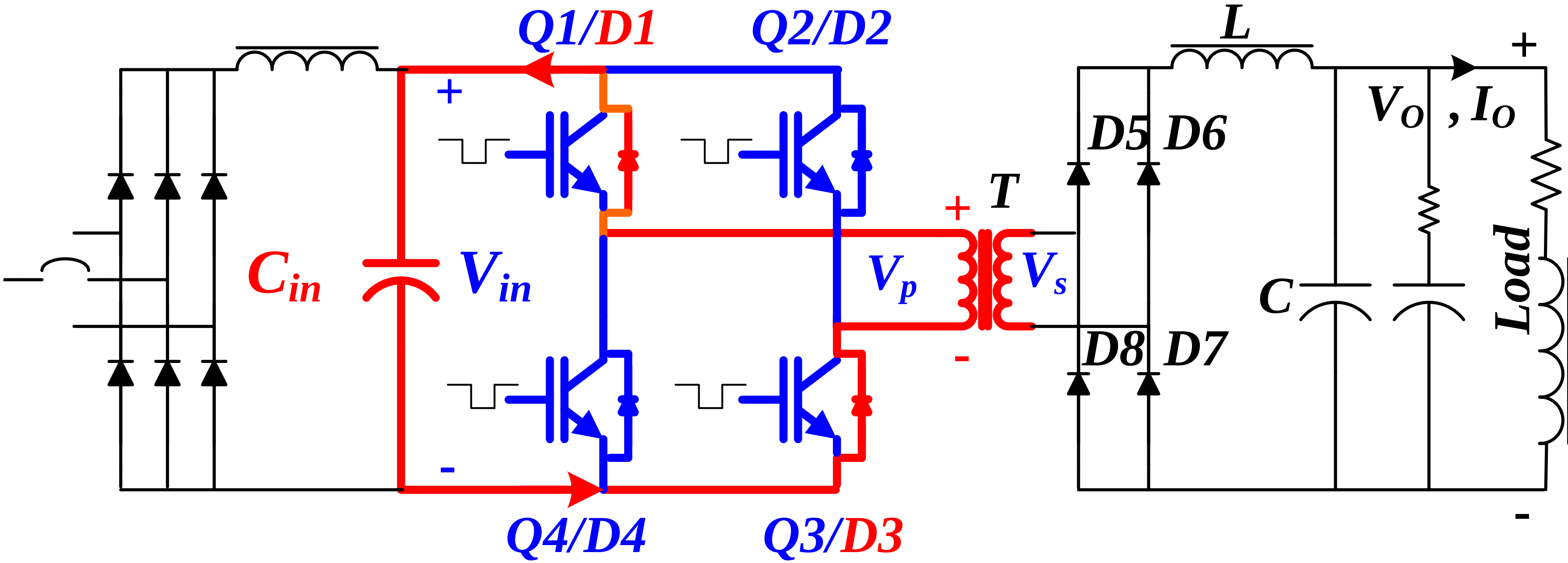
Full-Bridge Converter Switching – Q2 and Q4 On, Q1 and Q3 Off



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*

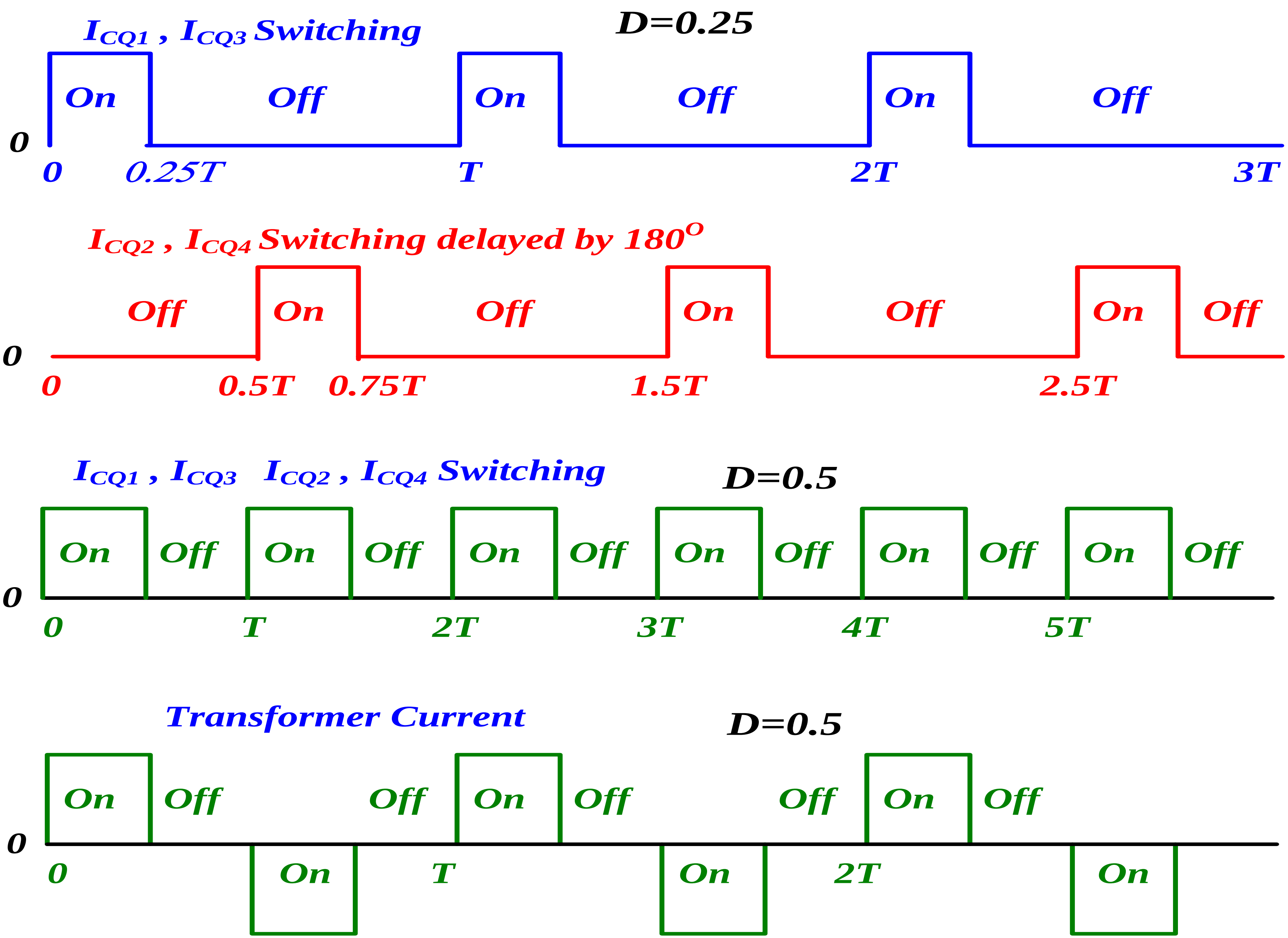
Full-Bridge Converter Switching – Q1, Q2, Q3 and Q4 Off



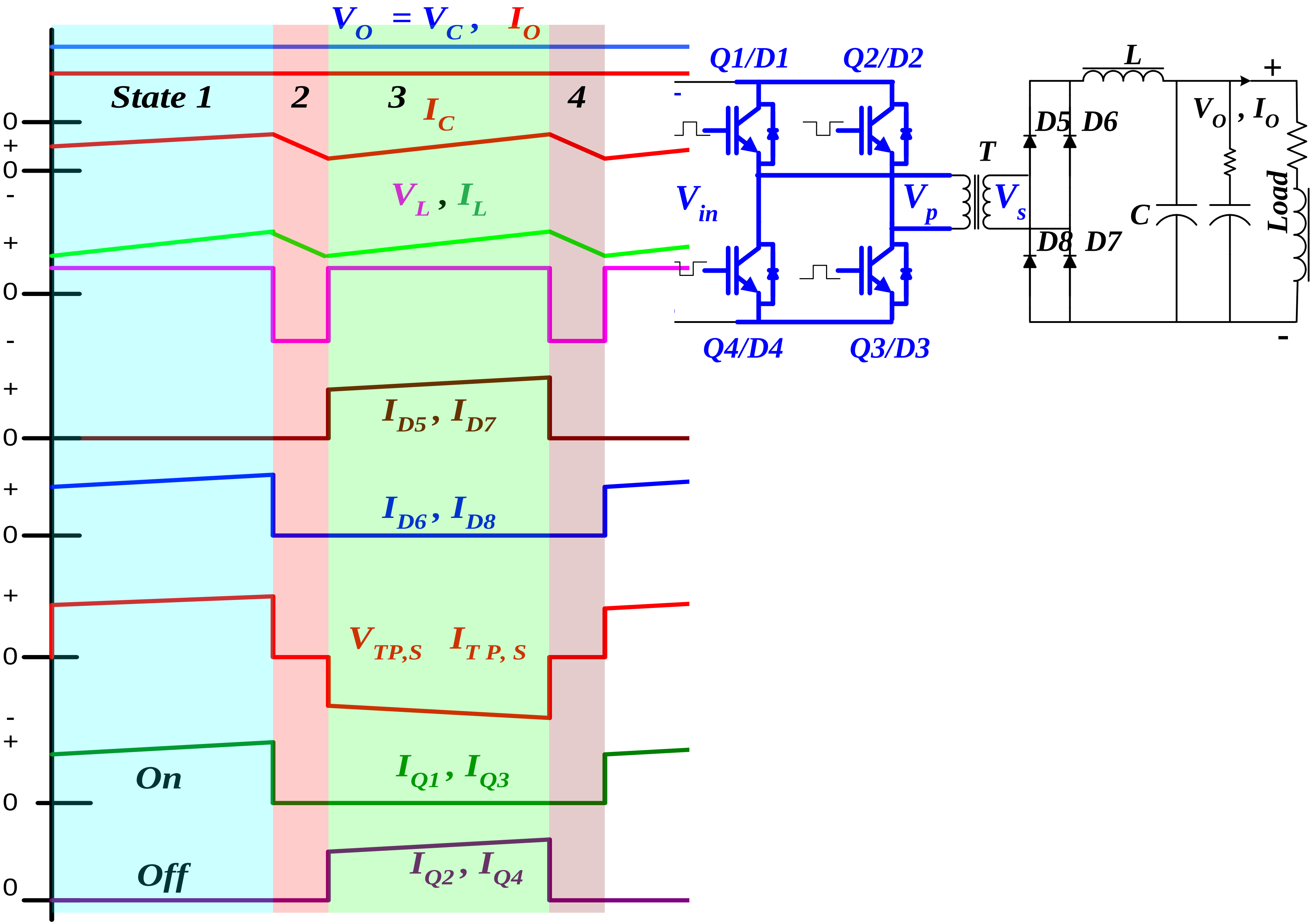
State 4 – Power Off

- *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*

Full Bridge Converter – IGBT Switching



Full Bridge Waveforms



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*

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

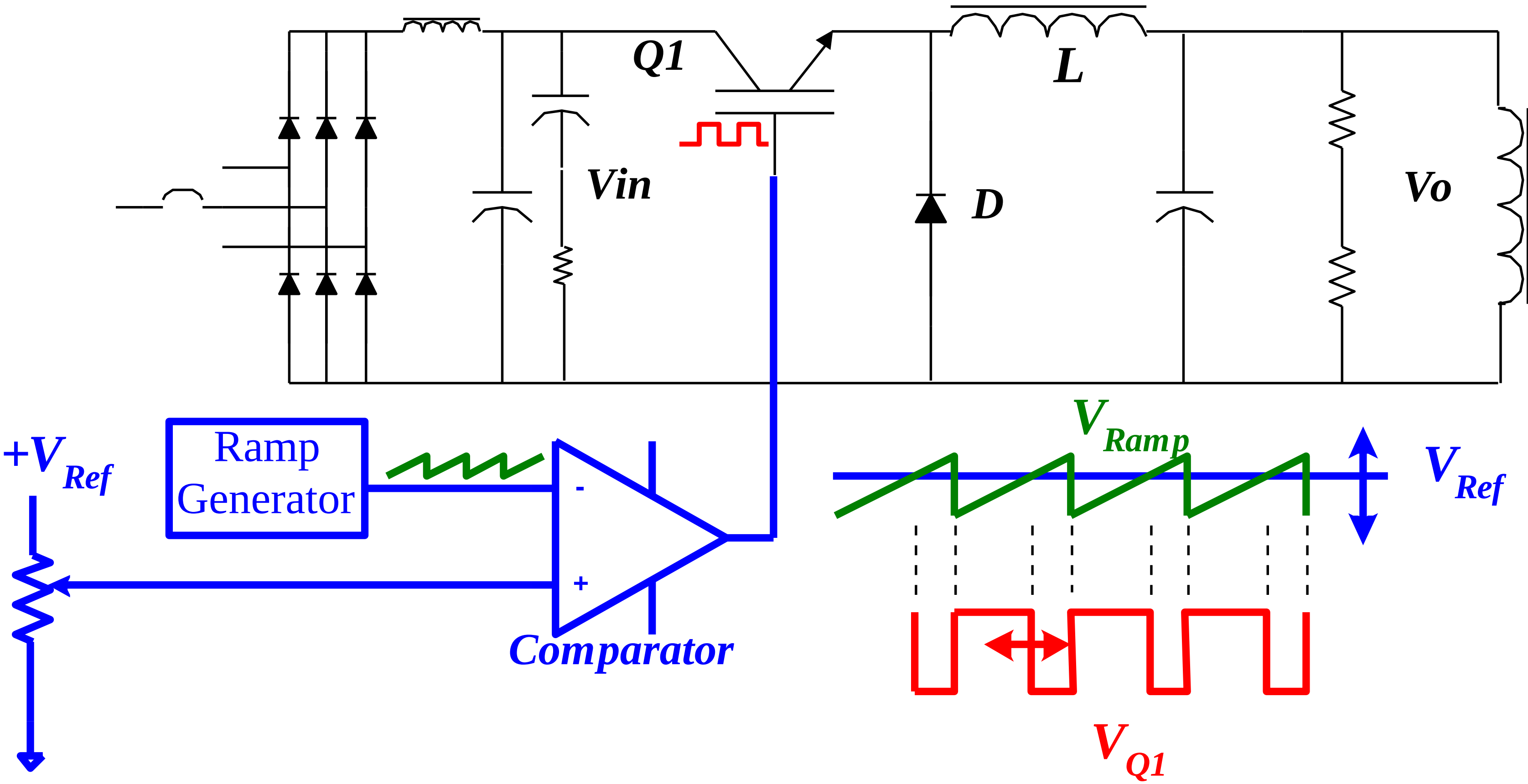
- *Four (4) switches are required, and since 2 switches operate in series, the effective saturated on-state power loss is somewhat greater than in the 2 switch, half-bridge case. In high voltage, off-line switching systems, these losses are acceptably small.*

Summary of 3 Forward Converters

Converter Type	Topology	V_o	P_o	Transformer	Output Type
Buck	1 switch	$V_o = V_{in} * D$	Any	Not possible	Unipolar
Boost	1 switch	$V_o = V_{in} / (1-D)$	I_{in} limits Po	Not possible	Unipolar
Full Bridge	4 switches Minor switch losses	$V_o = V_{in} * D * n$	Any	Possible	Unipolar/ bipolar

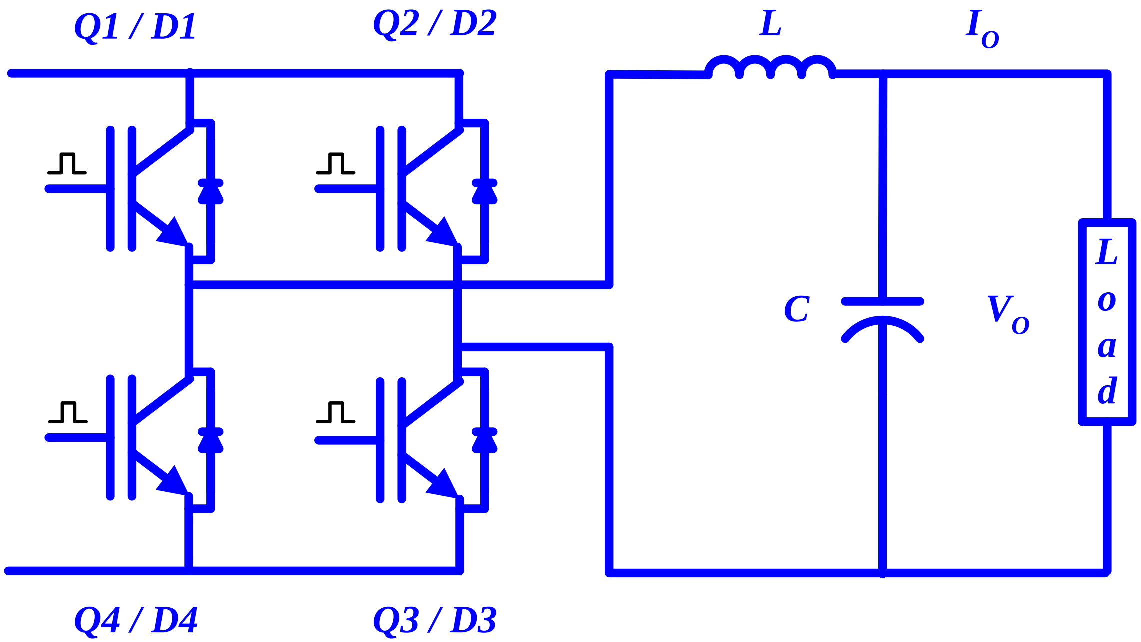
Pulse Width Modulation (PWM) Techniques

Pulse Width Modulation

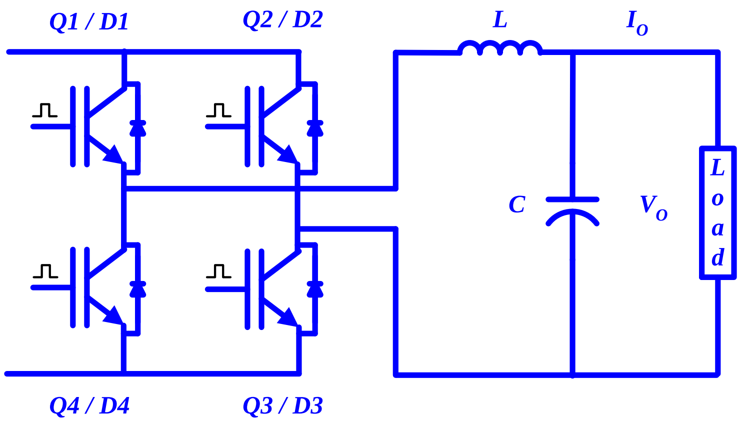


V_{Ref}	V_{Ref} - V_{Ramp} = V_{Q1} pulse width	V_O
V_{Ref} ↓	V_{Ref} - V_{Ramp} = V_{Q1} pulse width ↓	V_O ↓

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*

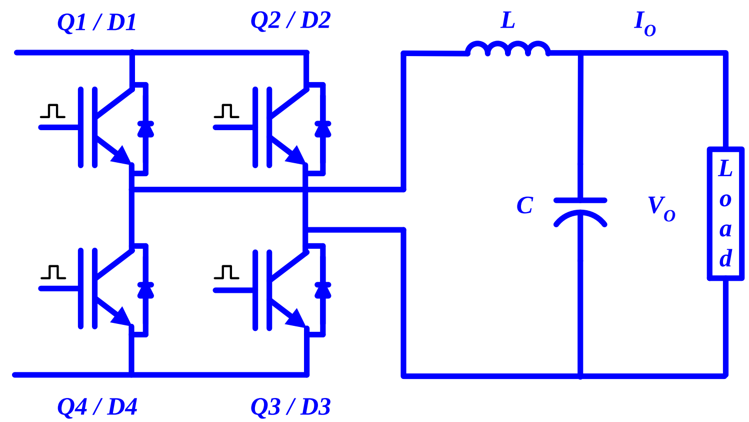
Two types of PWM

- *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*

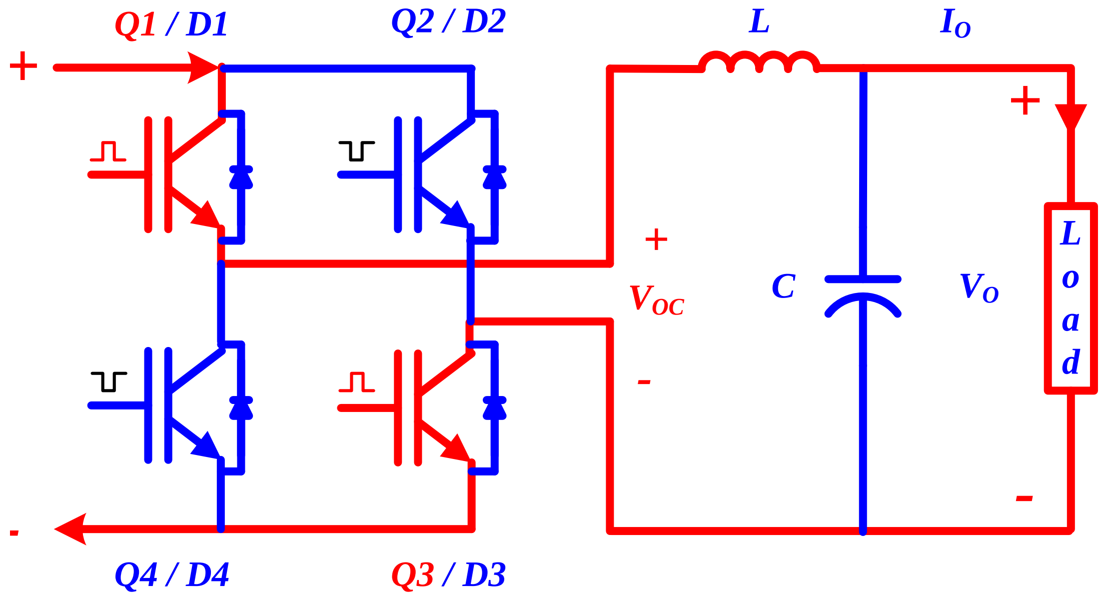
- *"50/50" scheme in which there are 2 separate, complimentary PWM signals*

Bipolar Bridge – Sign / Magnitude PWM

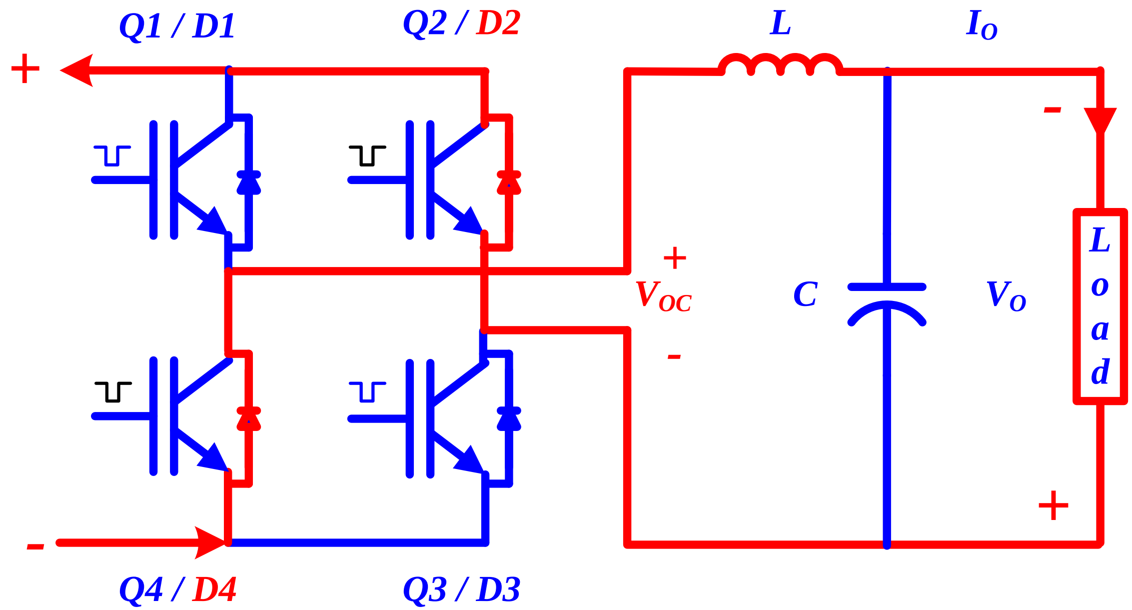
Reference Signal	*Q1/Q3 D*	*Q2/Q4 D*
0	*Off*	*Off*
+25%	*0.25*	*Off*
+50%	*0.50*	*Off*
+75%	*0.75*	*Off*
+100%	*1.00*	*Off*
-25%	*Off*	*0.25*
-50%	*Off*	*0.50*
-75%	*Off*	*0.75*
-100%	*Off*	*1.00*



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

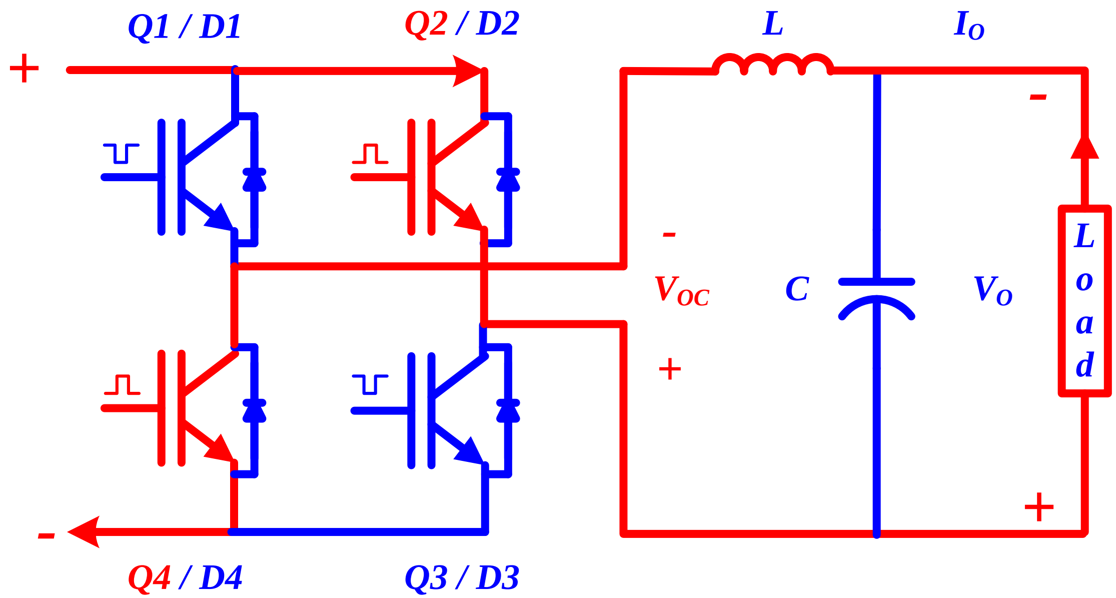


Q1/Q3 closed

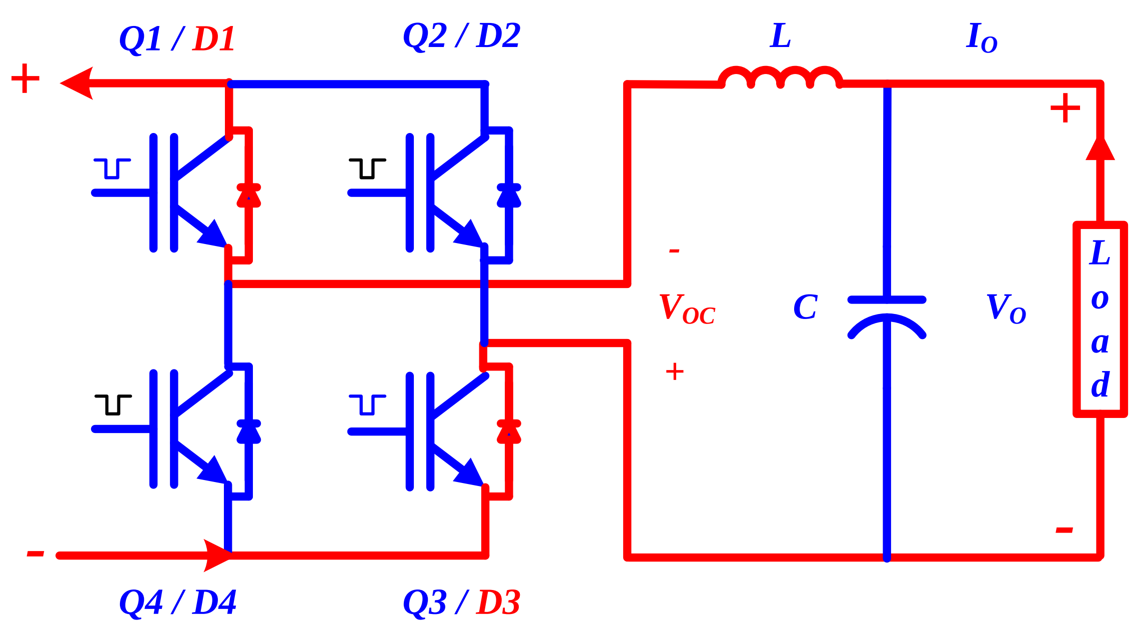


Q1/Q3 opened

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

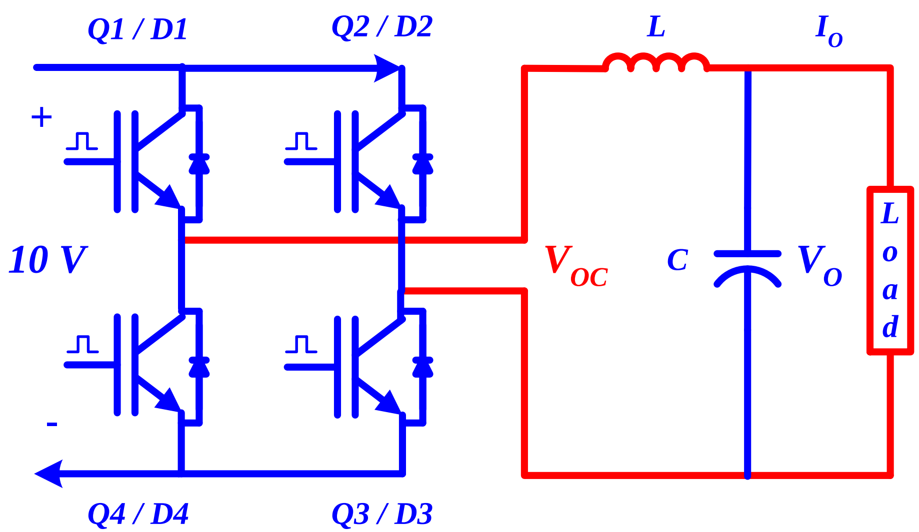


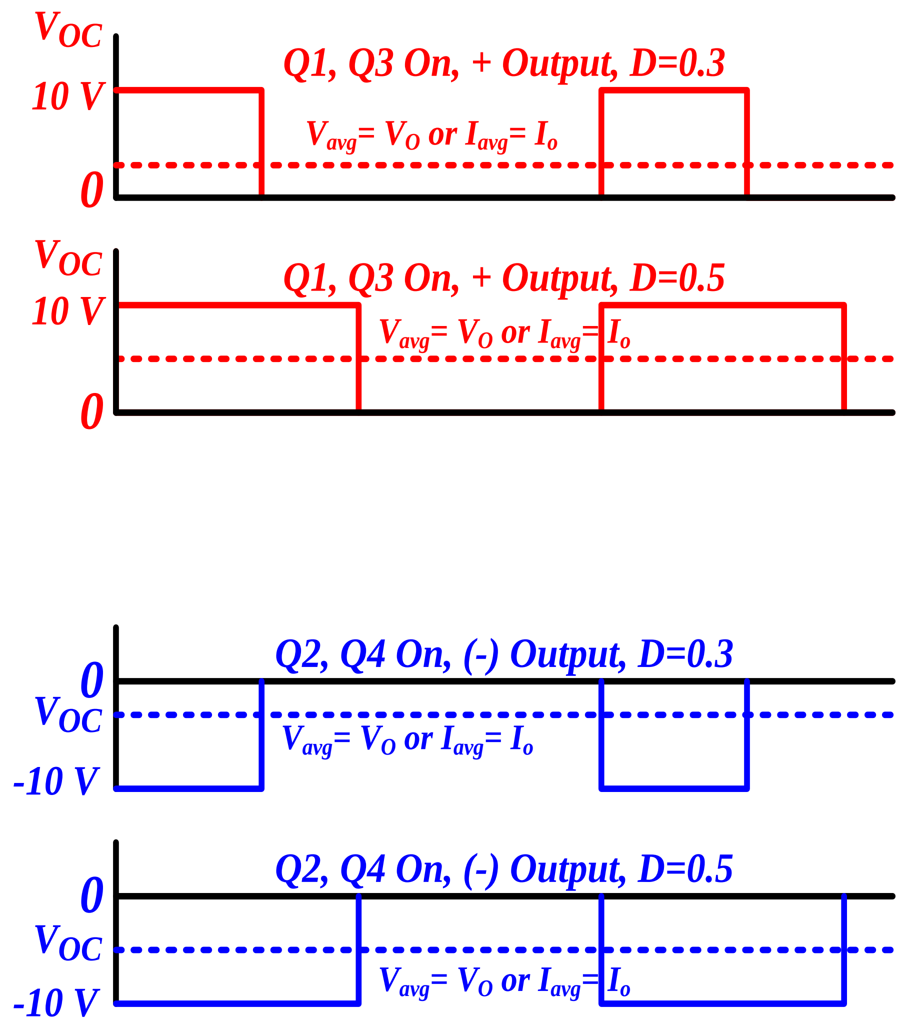
Q2/Q4 closed



Q2/Q4 opened

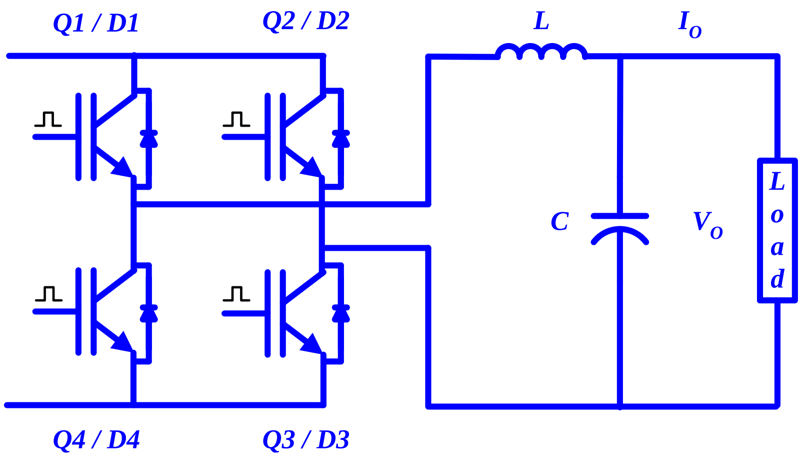
Bipolar Bridge – Sign / Magnitude PWM - Waveforms





"50/50" Bipolar PWM

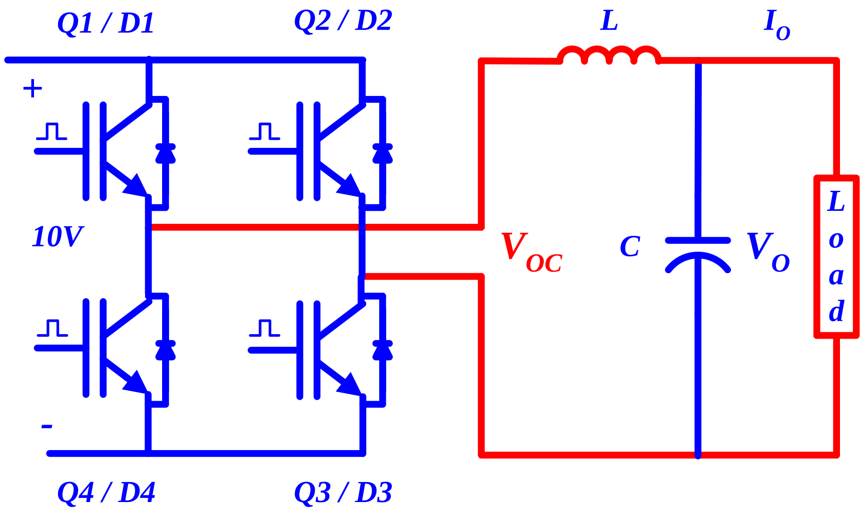
Desired Output Reference Signal	Q1/Q3D	Q2/Q4 D
-100%	0.0%	100.0%
-75%	12.5%	87.5%
-50%	25.0%	75.0%
-25%	37.5%	62.5%
0%	50.0%	50.0%
25%	62.5%	37.5%
50%	75.0%	25.0%
75%	87.5%	12.5%
100%	100.0%	0.0%

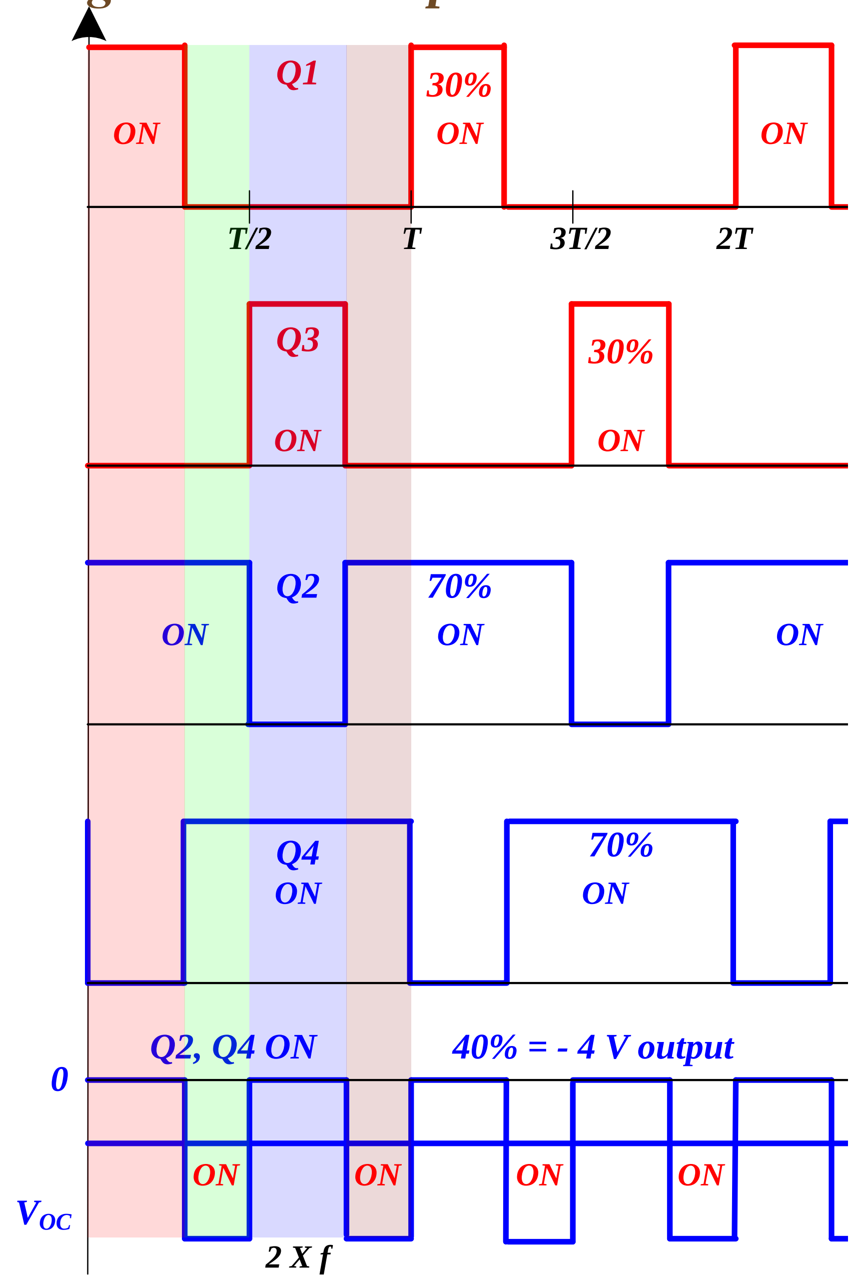


- Both bridge legs are always active
- Q1/Q3 (+) bridge
- Q2/Q4 (-) bridge
- Q1/Q3 180 ^{O} phase shifted
- Q2/Q4 180 ^{O} phase shifted
- Q1 is complement of Q4
- Q2 is complement of Q3

“50/50” Bipolar Switching For - 4 V Output

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

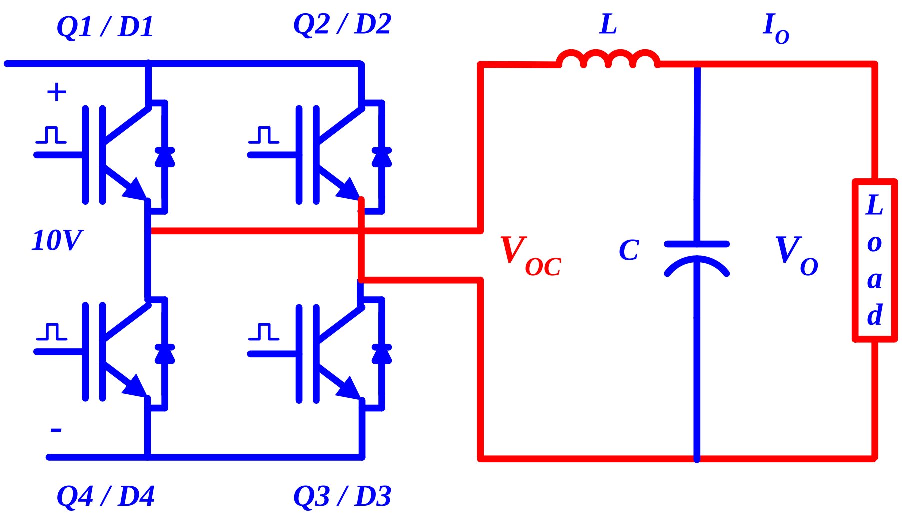




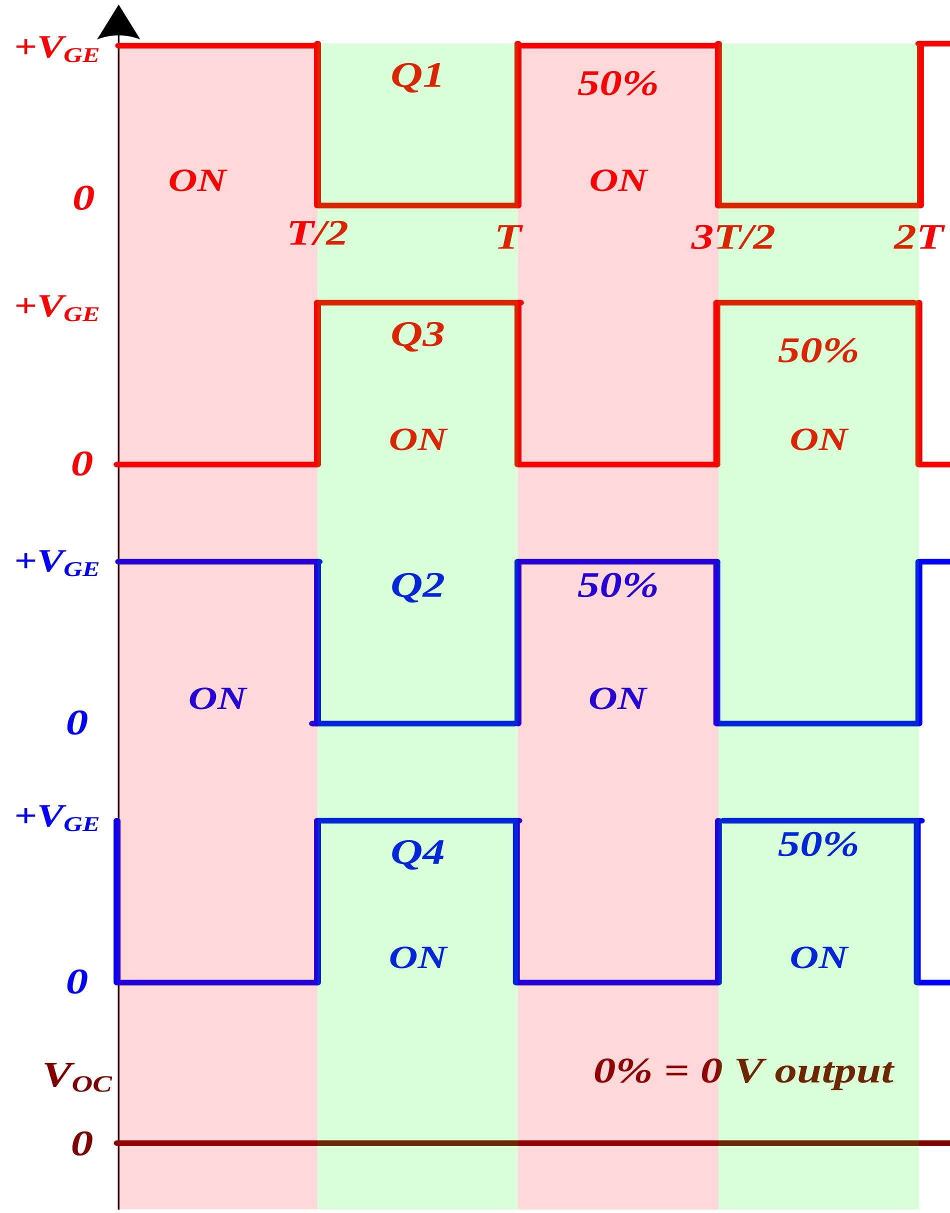
	Q1	Q3	Q2	Q4	V_{OC}
1	On	Off	On	Off	0 V
2	Off	Off	On	On	-10 V
3	Off	On	Off	On	0 V
4	Off	Off	On	On	-10 V

"50/50" Bipolar Switching For 0 V Output

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

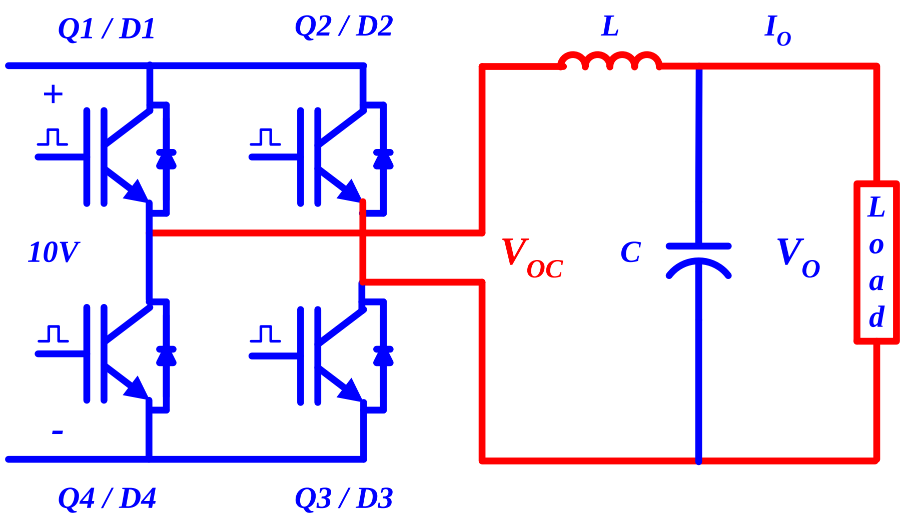


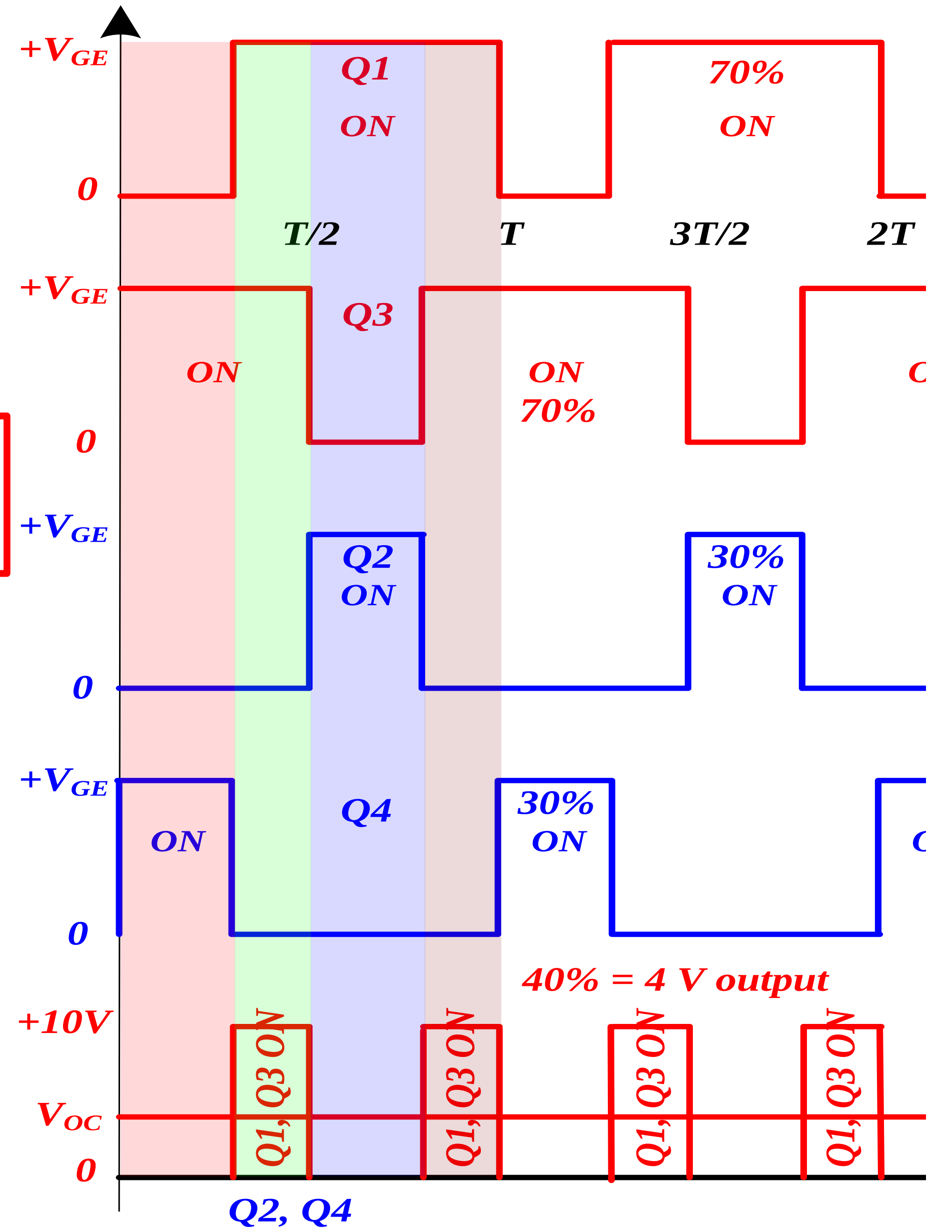
	Q1	Q3	Q2	Q4	VOC
1	On	Off	On	Off	0 V
2	Off	On	Off	On	0 V
3	On	Off	On	Off	0 V
4	Off	On	Off	On	0 V



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

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





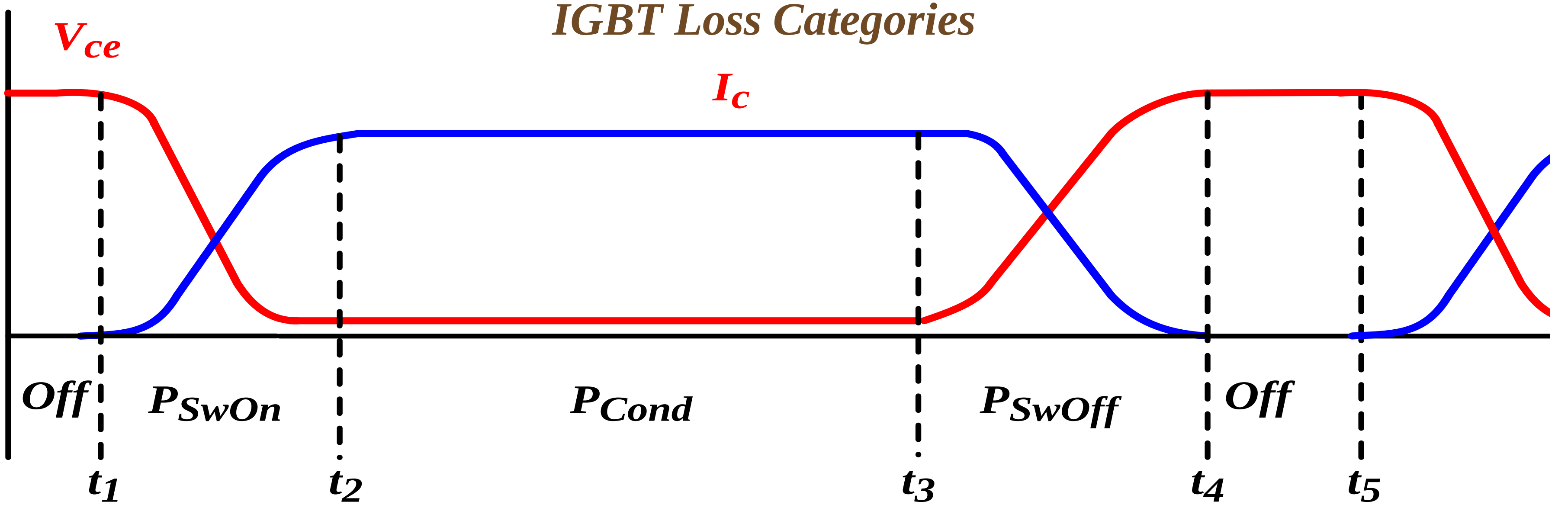
	Q1	Q3	Q2	Q4	V_{OC}
1	Off	On	Off	On	0 V
2	On	On	Off	Off	+10 V
3	On	Off	On	Off	0 V
4	On	On	Off	Off	+10 V

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 $$P_{SwOn} = \frac{1}{t_5 - t_1} * \int_{t_1}^{t_2} v_{CE}(t) * i_C(t) * dt$$

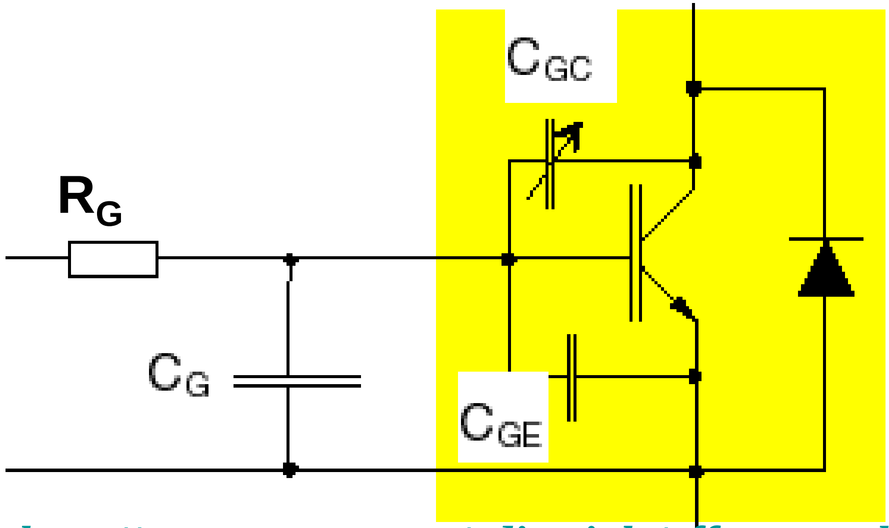
Conduction losses $$P_{Cond} = \frac{1}{t_5 - t_1} * \int_{t_2}^{t_3} V_{CE} * I_C * dt$$

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

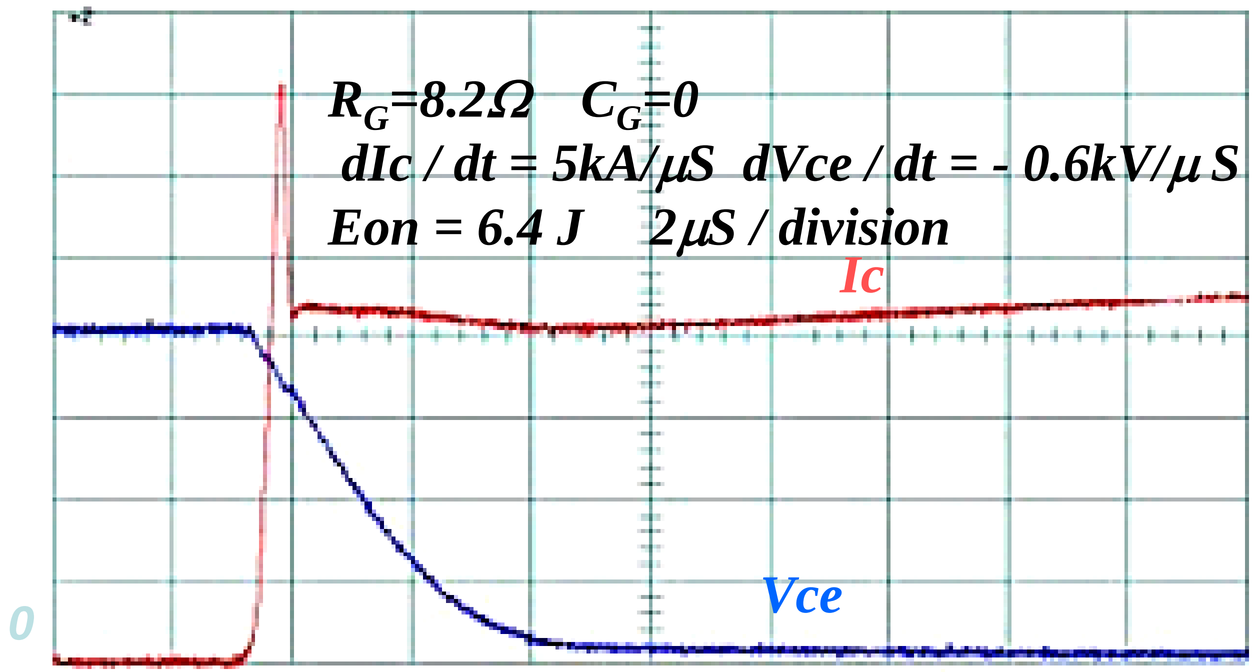
Reducing Losses

Reduce losses for greater efficiency and:

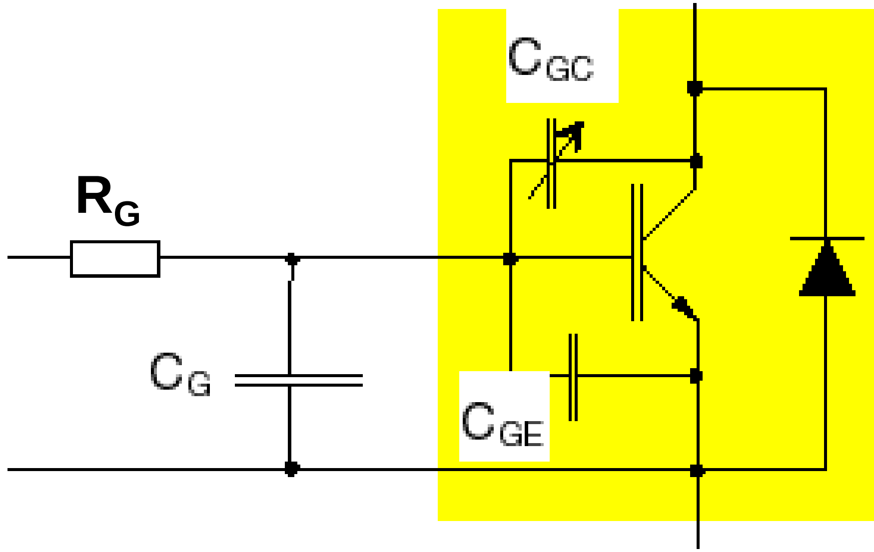
- *Smaller AC distribution system*
- *Less heat load into cooling water system*
- *Less heat into buildings and building HVAC*
- *Reduce IGBT dissipation*

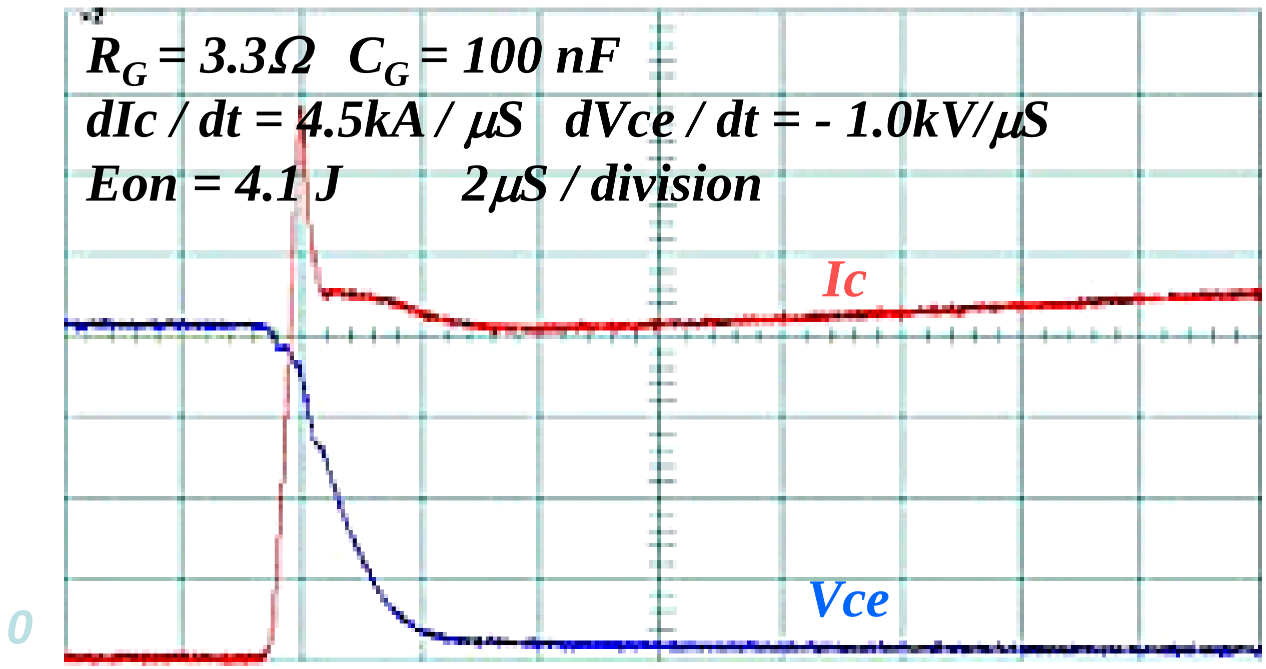


http://www.eupec.com/editorials/effect_cge.htm

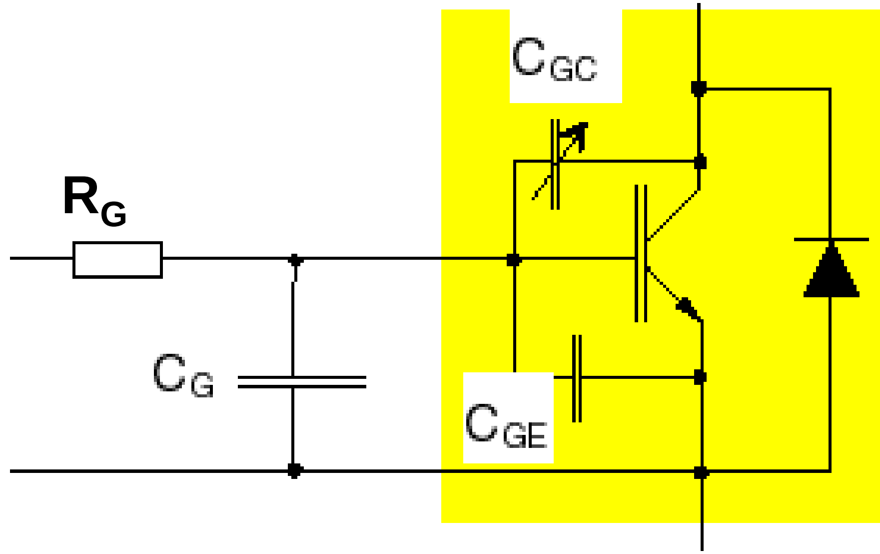


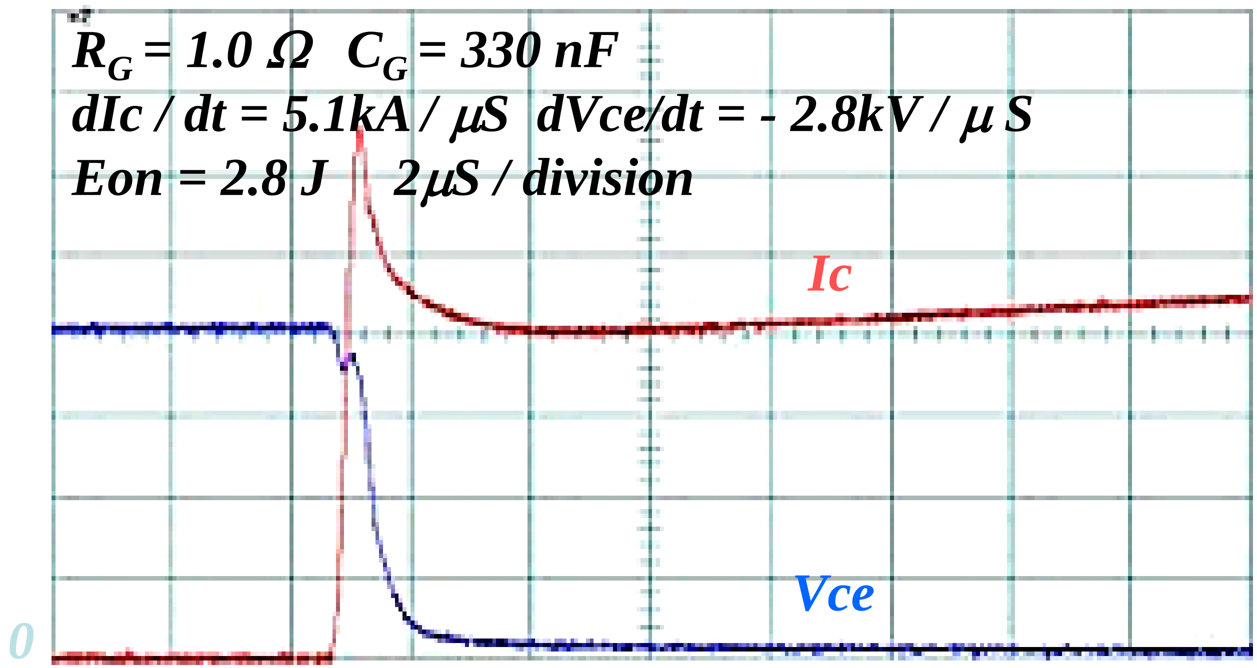
Reducing Turn On Losses By Varying R_G





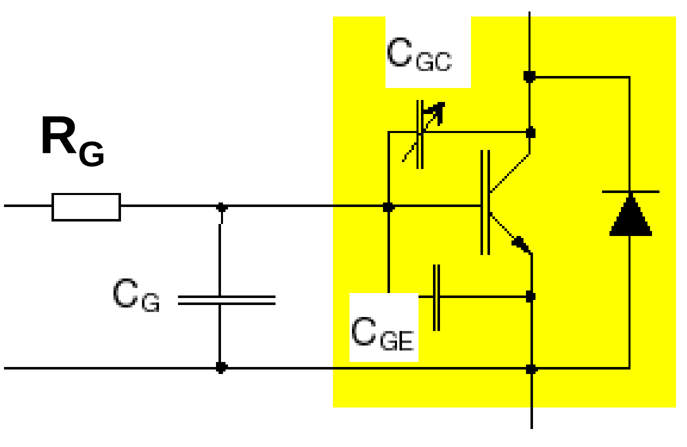
Reducing Turn On Losses By Varying R_G





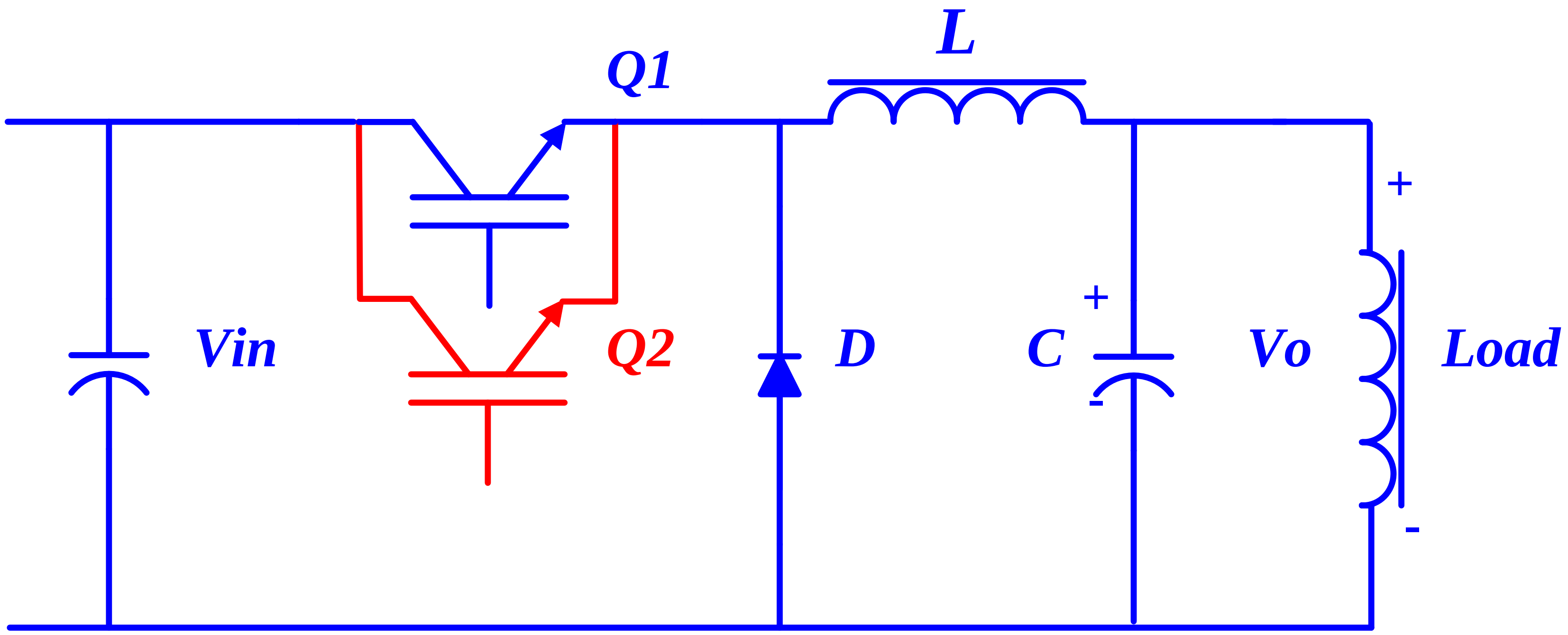
Reducing Turn On Losses By Varying R_G

Case	*R_G*	*dV_{CE} / dt*	*E_{On}*
1	*8.2 Ω*	*- 0.6 kV / μS*	*6.4 J*
2	*3.3 Ω*	*- 1.0 kV / μS*	*4.1 J*
3	*1.0 Ω*	*- 2.8 kV / μS*	*2.8 J*



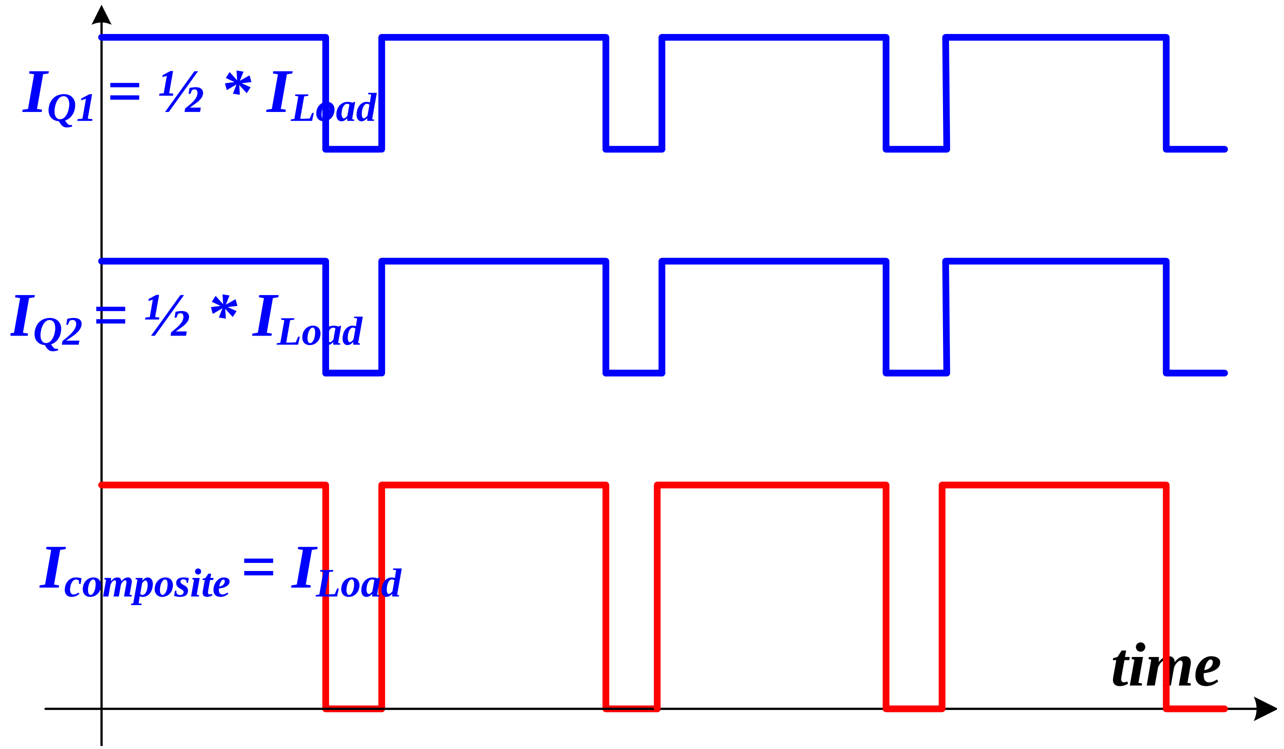
- *$P_{Diss} \propto^{-1} - dV_{CE} / dt$*
- *dV_{CE} / dt is controlled via R_G*
- *Lower losses but possibly increased EMI because of faster dV_{CE} / dt*

Reducing Conduction Losses



- *If the current rating of a single switch is insufficient (conduction loss is too great), add another switch in parallel.*
- *There are then 2 ways to switch Q1 and Q2, switch them ON and OFF together or stagger their On and OFF times*

Conduction Loss Reduction By Simultaneous Switching of Q1 and Q2



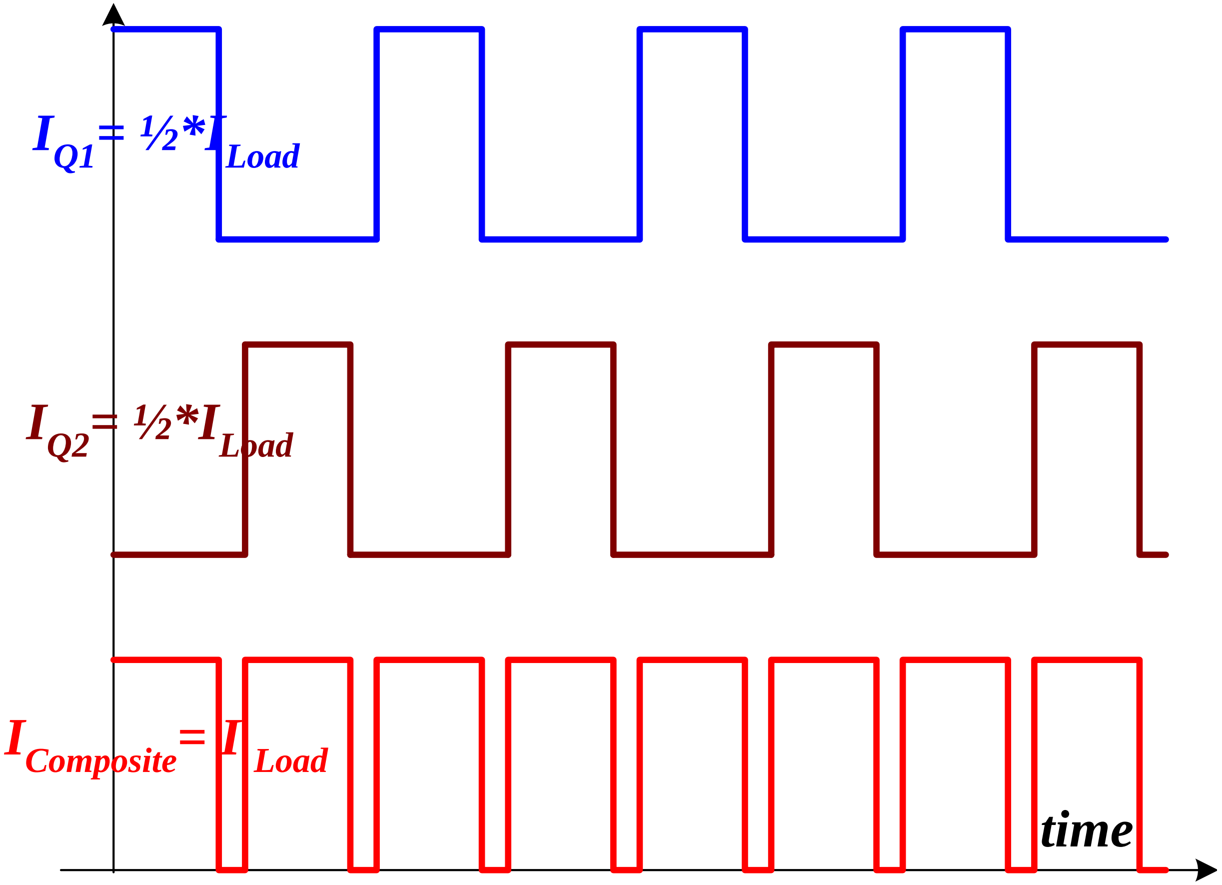
$$I_{RMS\,2Sw-EaSw} = \frac{1}{2} * I_{RMS-1Sw} \qquad V_{RMS\,2Sw-EaSw} = V_{RMS-1Sw}$$

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

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

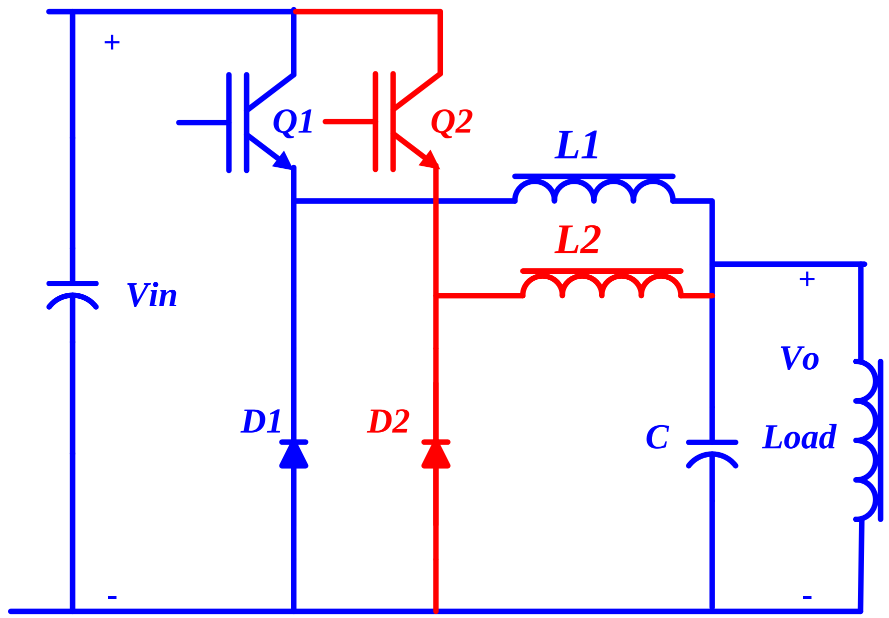
The composite frequency is the same as in Q1 and Q2

Conducted Loss Reduction By Staggered Switching of Q1 and Q2



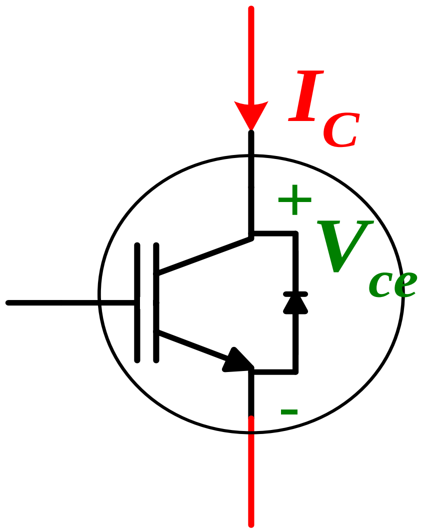
- *Duty factor is each switch is halved*
- *P_{ave} in each switch is 1/2 that of the single switch case*
- *The composite frequency is twice that of Q1 and Q2*

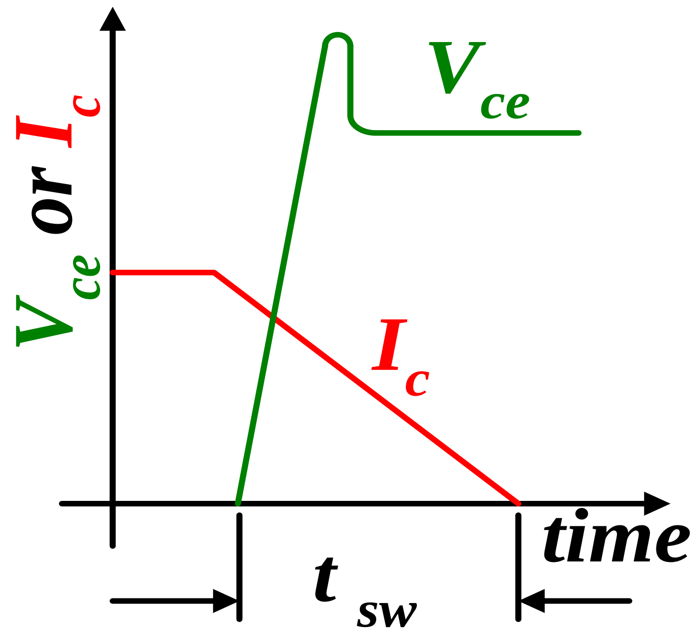
Conducted Loss Reduction By Paralleled Buck Regulators



Features:

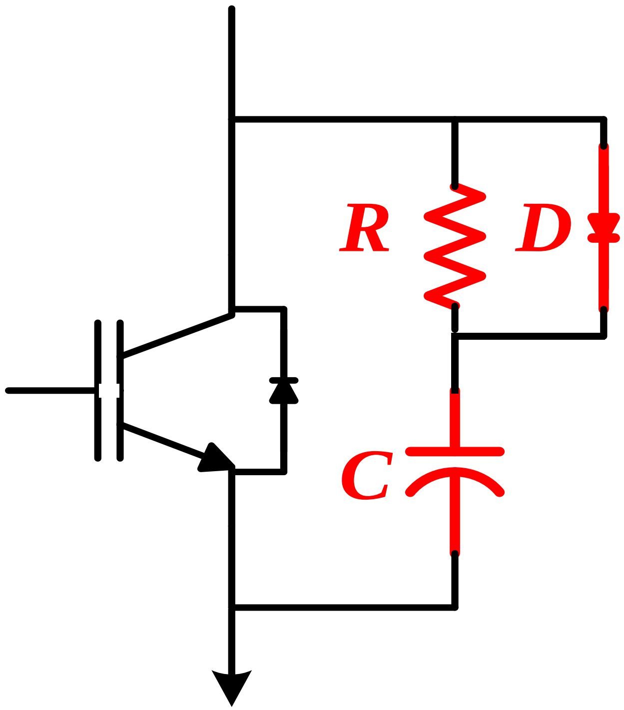
- *A second switch Q1 is added.*
- *Q1 and Q2 are staggered switched*
- *D2 is added, L2 is added*
- *Current in D1, D2 is 1/2 the load current*
- *Current in L1, L2 is 1/2 the load current*
- *L1, L2 energy 1/4 that of single inductor since* $E = 1/2 * L * I^2$

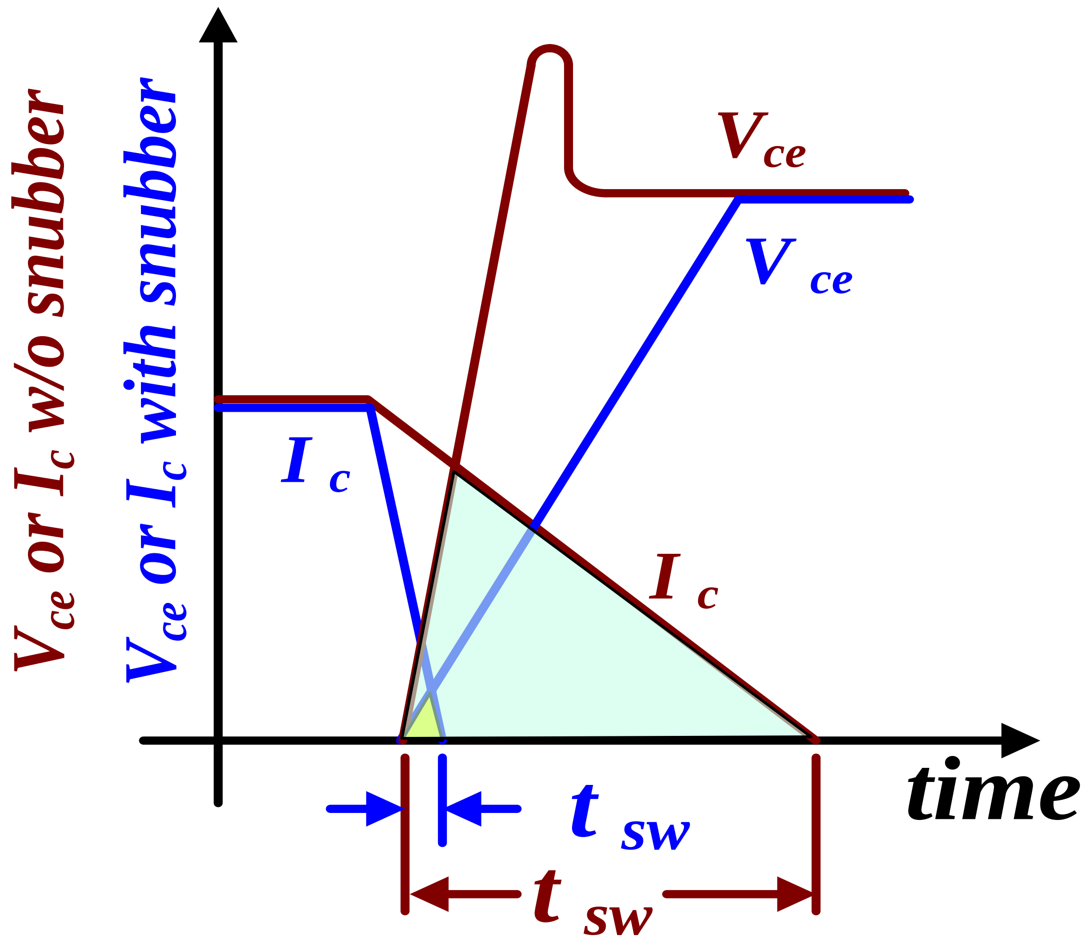




$$P_{SwOff} = \frac{1}{T} \int_0^{t_{Sw}} v_{CE}(t)\, i_C(t)\, dt$$

Switch Turnoff Loss Reduction By RCD Snubber

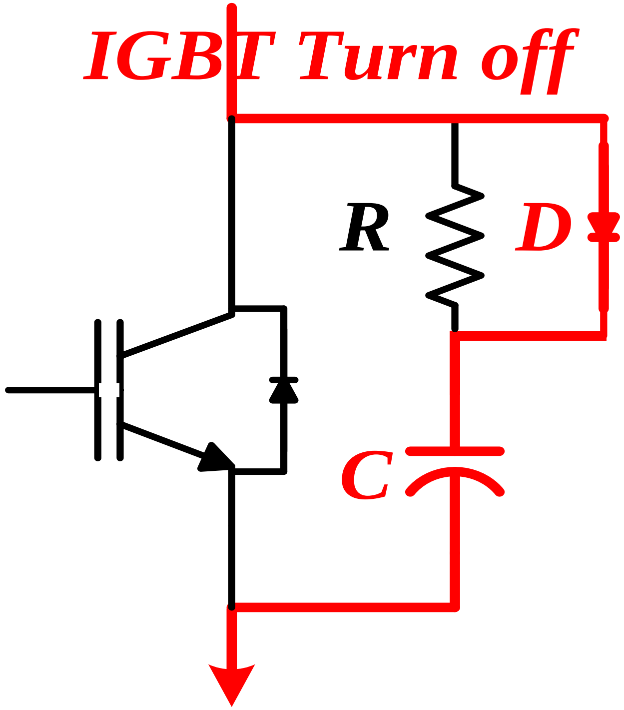




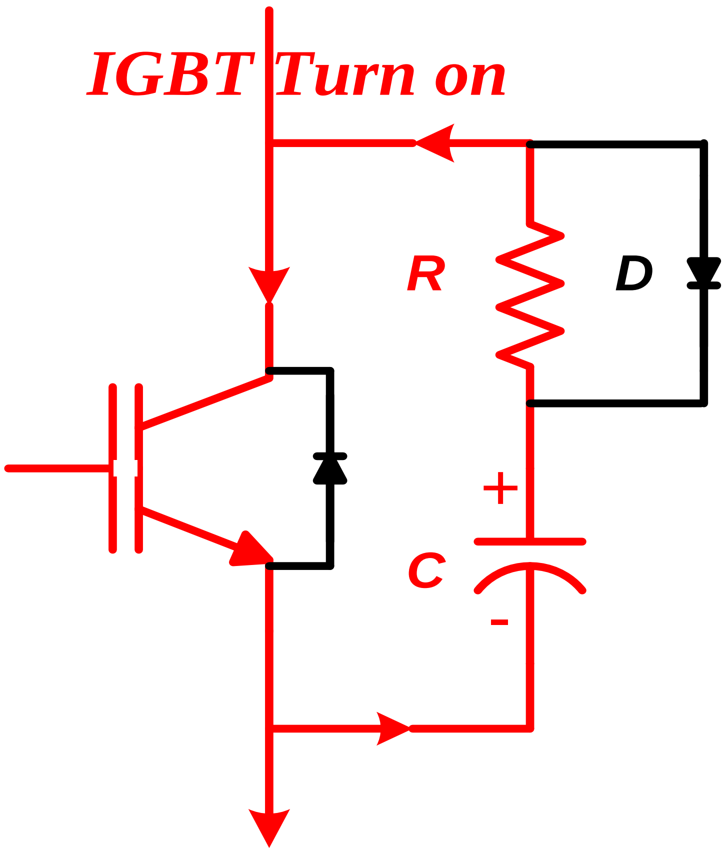
Goal:

- 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

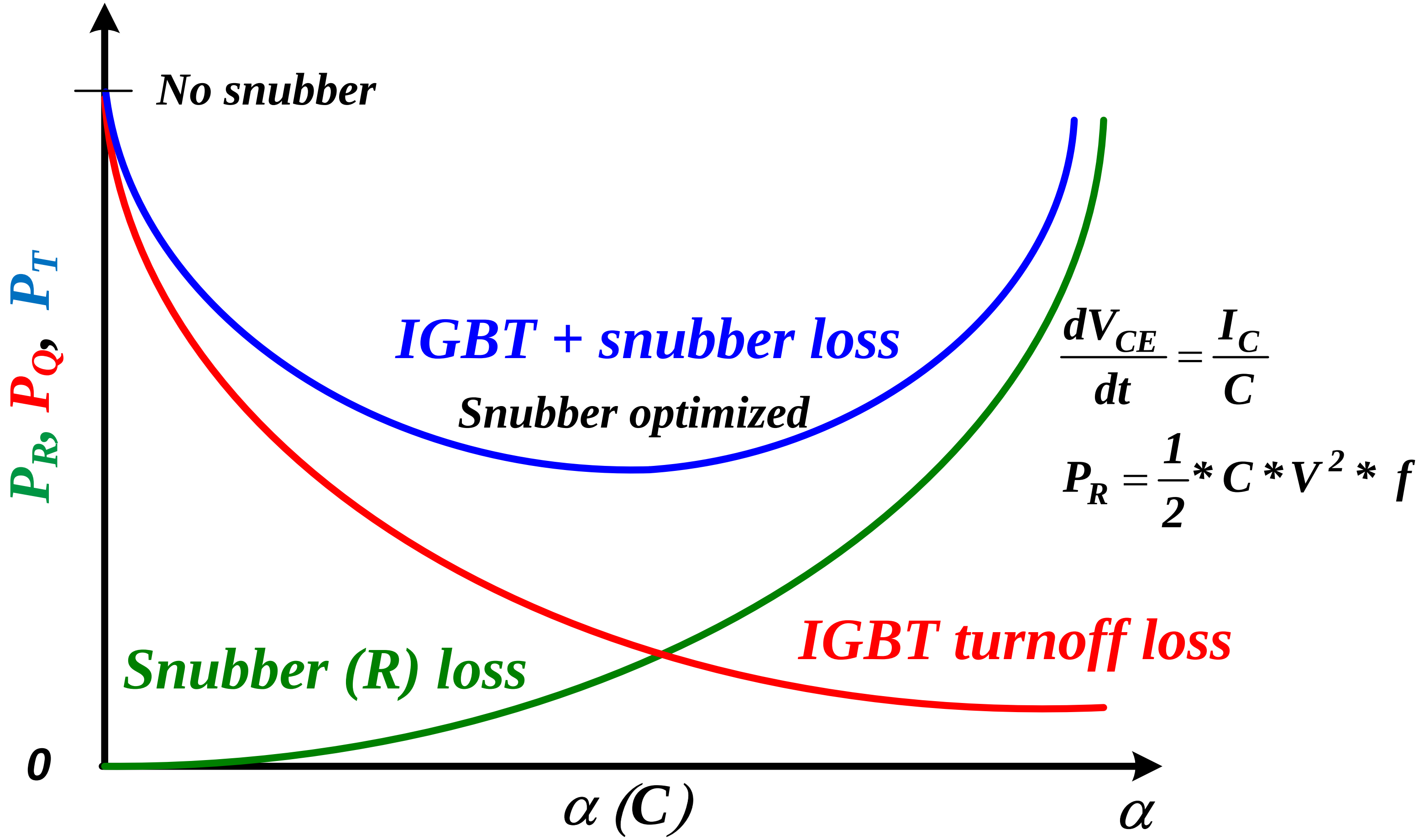


- When the IGBT turns off, current commutates out of the IGBT into the capacitor, C via the diode D
- This aids fast I_C current decay
- C becomes linearly charged to the bus voltage
- dV_{CE} / dt inversely proportional to C – this slows V_{CE} recovery



• *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

High Frequency Inductors and Transformers

Low and High Frequency Transformers Compared

	Low frequency	*High frequency*
Standards	*Well defined by ANSI, IEEE, NEMA and UL*	*Not as well defined* *Insulation standard followed*
Operation	*60 Hz* *Sine wave* *3 phase*	*10 kHz to 100 kHz* *Square wave – transformers Triangular wave – inductors* *Single phase*
Core material	*3 to 100 mil laminations of steel or Fe*	*0.5 to 3 mil laminations of Fe or Si-Fe* *Powdered Fe* *Powdered ferrites, Ni-Zn, Mn-Zn*
Winding material	*Single-strand Cu wire* *Layer or bobbin-wound*	*Multi-strand Cu Litz wire* *Cu foil, layer wound*

The power rating of a transformer is dependent upon the kollowing factors

$$V * A = K_1 * K_2 * f * A_C * A_E * J * B_M$$

where

$V * A$ = power rating of the transformer (V*A)

K_1 = waveshape factor (sine or square wave)

K_2 = copper fill factor (0 to 1)

f = excitation frequency (Hz)

A_C = core area (m^2)

A_E = winding area (m^2)

J = conductor current density $\left(\frac{A}{m^2}\right)$

B_M = peak flux density $\left(\frac{Wb}{m^2}\right)$ where a Weber = 1*volt*sec

The transformer area product = $A_C * A_E \propto \frac{V * A}{B_M * f * J}$

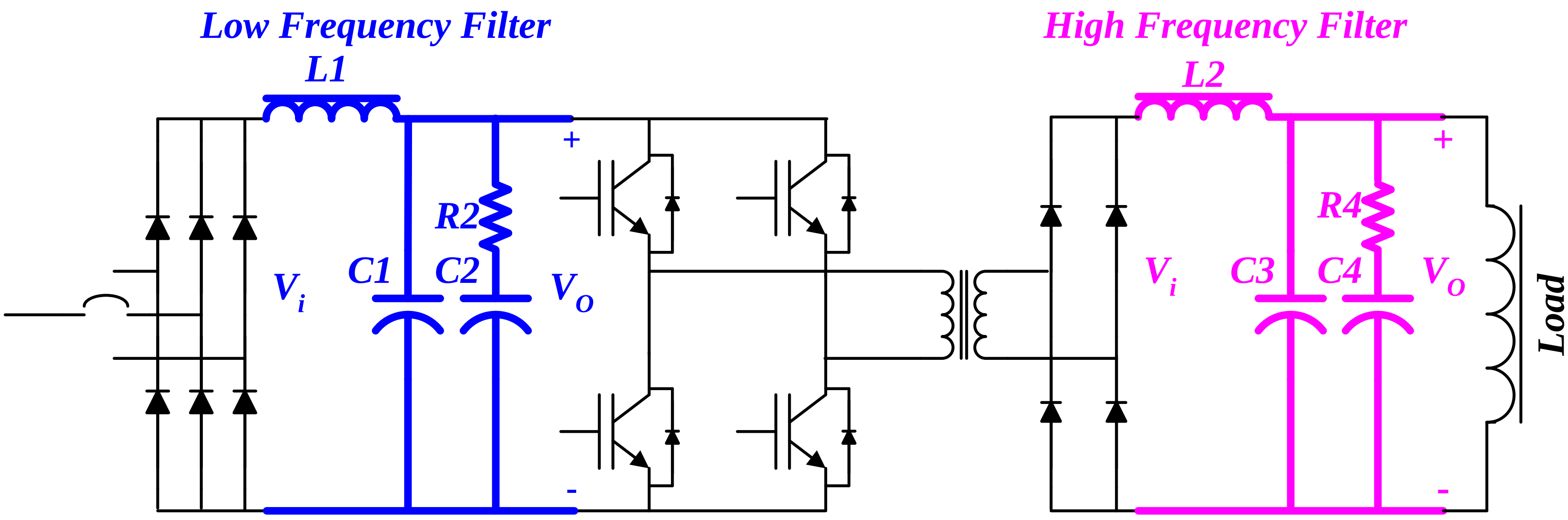
An example of a 10kVA, 480V : 208V Transformer At 60Hz the volume and weight would be					
f	*f* ratio to 60Hz	Volume (in ^{3})	Volume ratio to 60Hz	Weight (lb)	Weight ratio to 60Hz
60 Hz	1	18 X 18 X 18 = 5832 (in ^{3})	1	100	1
20 kHz	333	6H X 5.25W X 3.37D 118 (in ^{3})	1 / 50	5	1 / 20

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) ⊗ x (t) where ⊗ 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)*

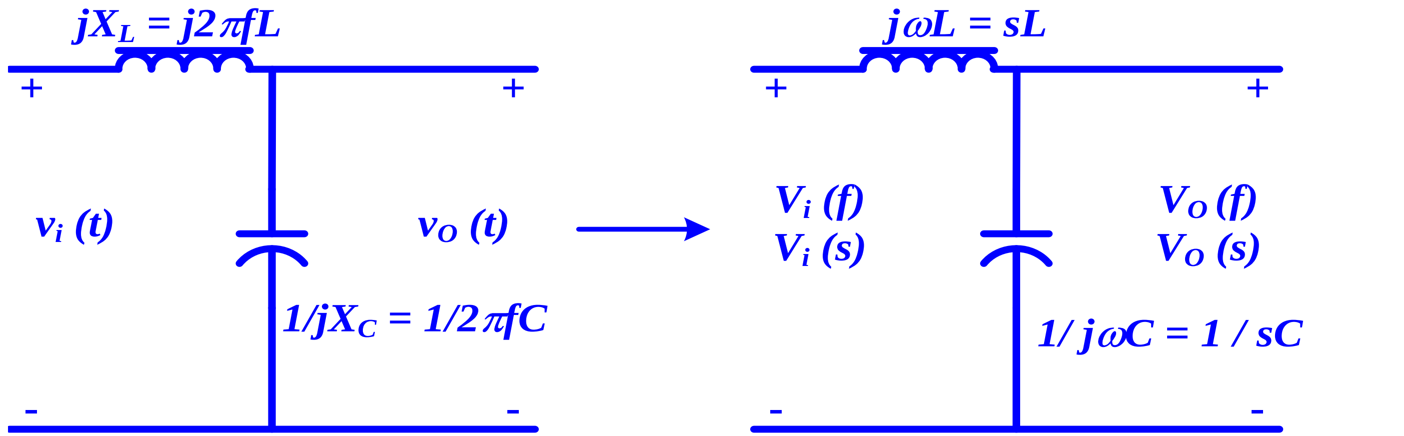
The “s” Operator

- *s is used in the frequency domain and in La Place analysis*
- $s = j\,\omega = j\,2\,\pi\,f$ $\qquad j = \sqrt{-1}$

Poles and Zeros

- Zero = 0 $\qquad$ Pole = ∞
- *Zeros occur at frequencies that cause the transfer function to go to zero. Transfer function = 0 is caused by a zero in the numerator and or a pole in the 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 a pole in the numerator or a zero in the 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 $$V_o = V_i * \frac{\frac{1}{sC}}{\frac{1}{sC} + sL} \qquad T = \frac{1}{s^2 LC + 1}$$

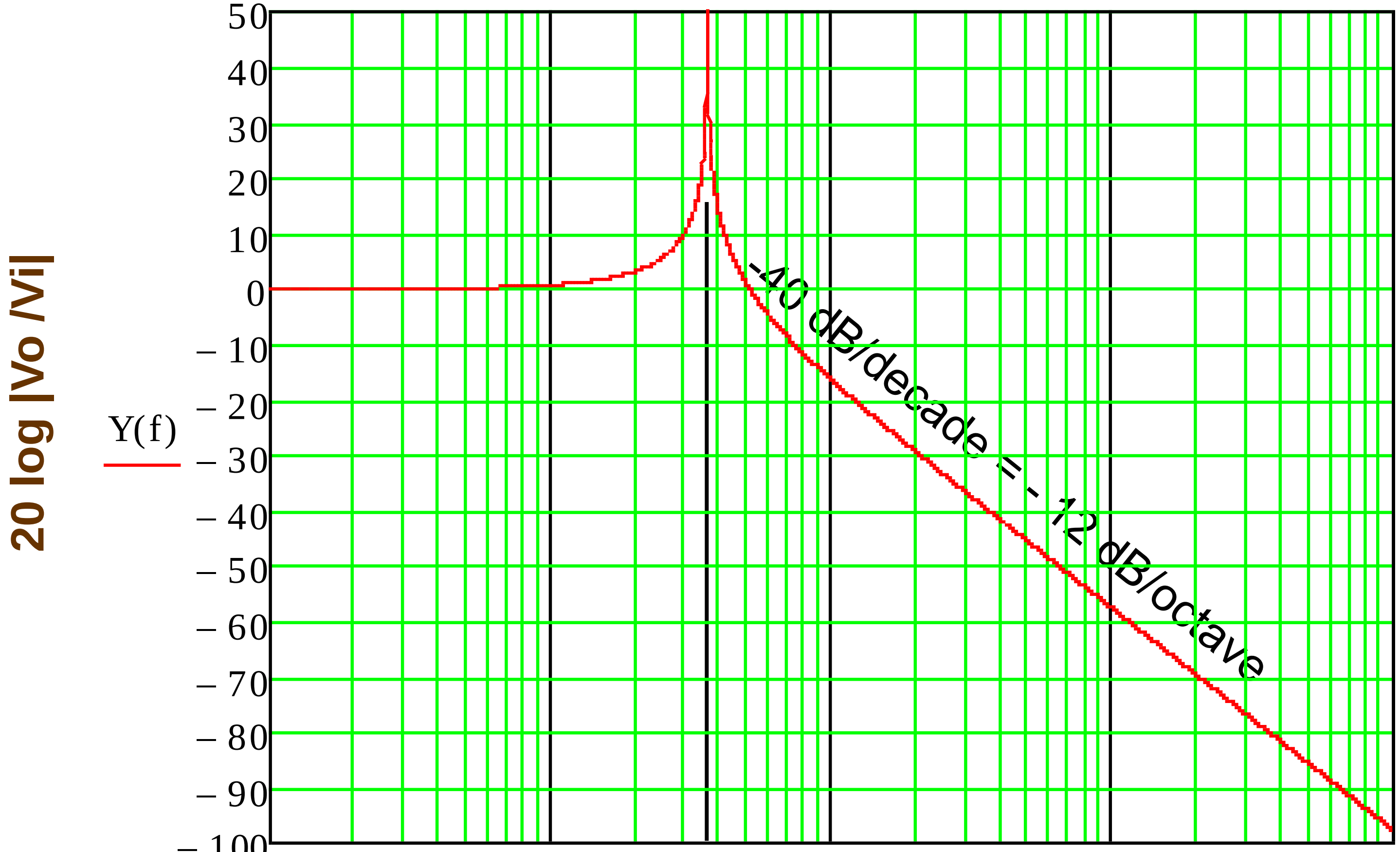
Pole $$s^2 LC + 1 = 0 \qquad (j2\pi f_p)^2 LC + 1 = 0$$

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 $$f_z = \infty$$

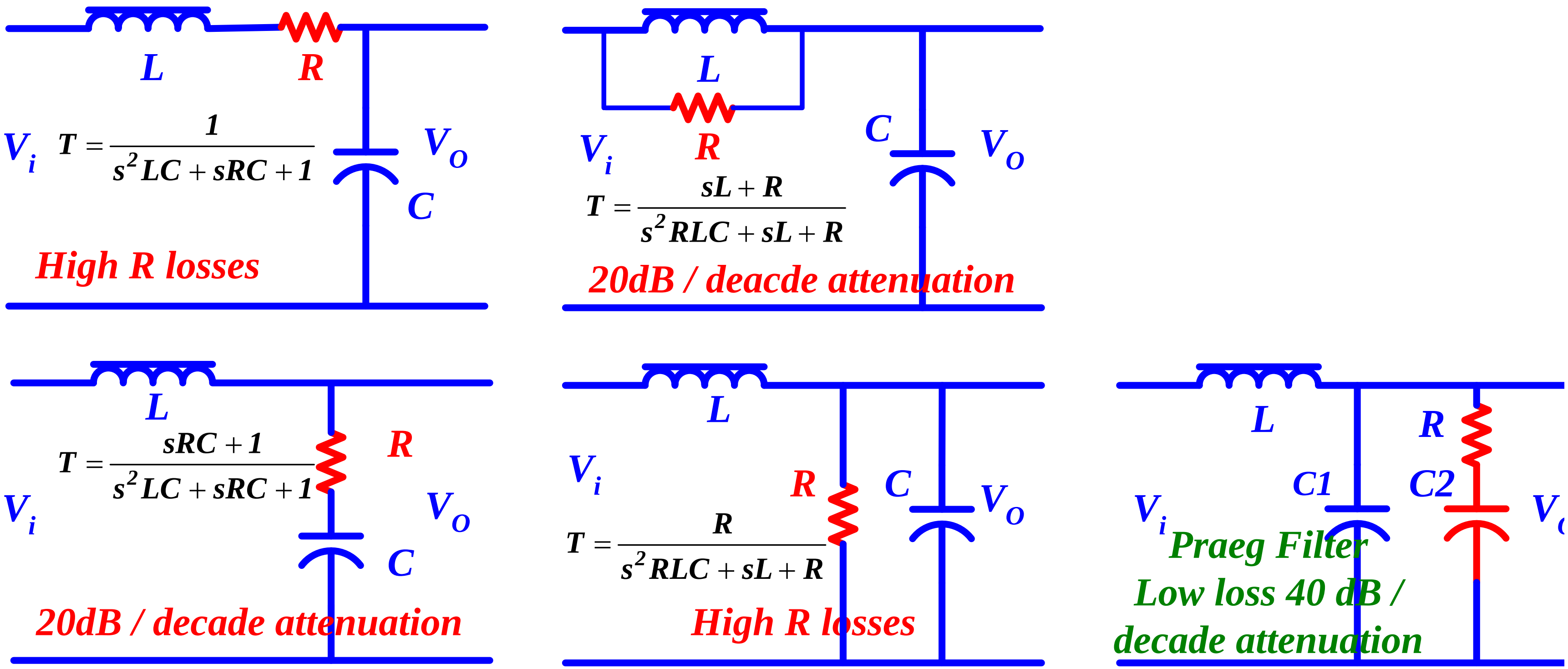
A Simple Low Pass Filter



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

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

The Praeg Low Pass Ripple Filter

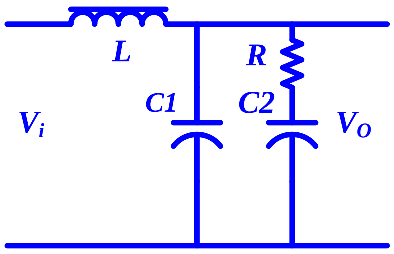


Why important:

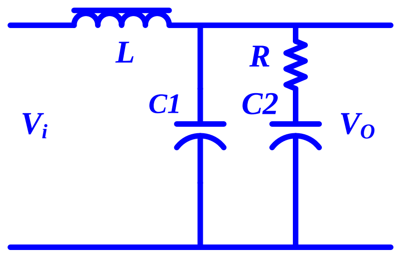
- *Used as low and high frequency filters in virtually every power supply*
- *Provides the filtering of the previous 2nd order filter*
- *Essentially critical damped*
- *No DC current in R, C2*

Component Selection Criteria

- L and C1 must be chosen to yield the desired breakpoint frequency (1/10 of the ripple frequency for 40 dB attenuation)
- C1 and C2 must 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
- $C2 \geq 5 * C1$
- $R = (L / C)^{1/2}$



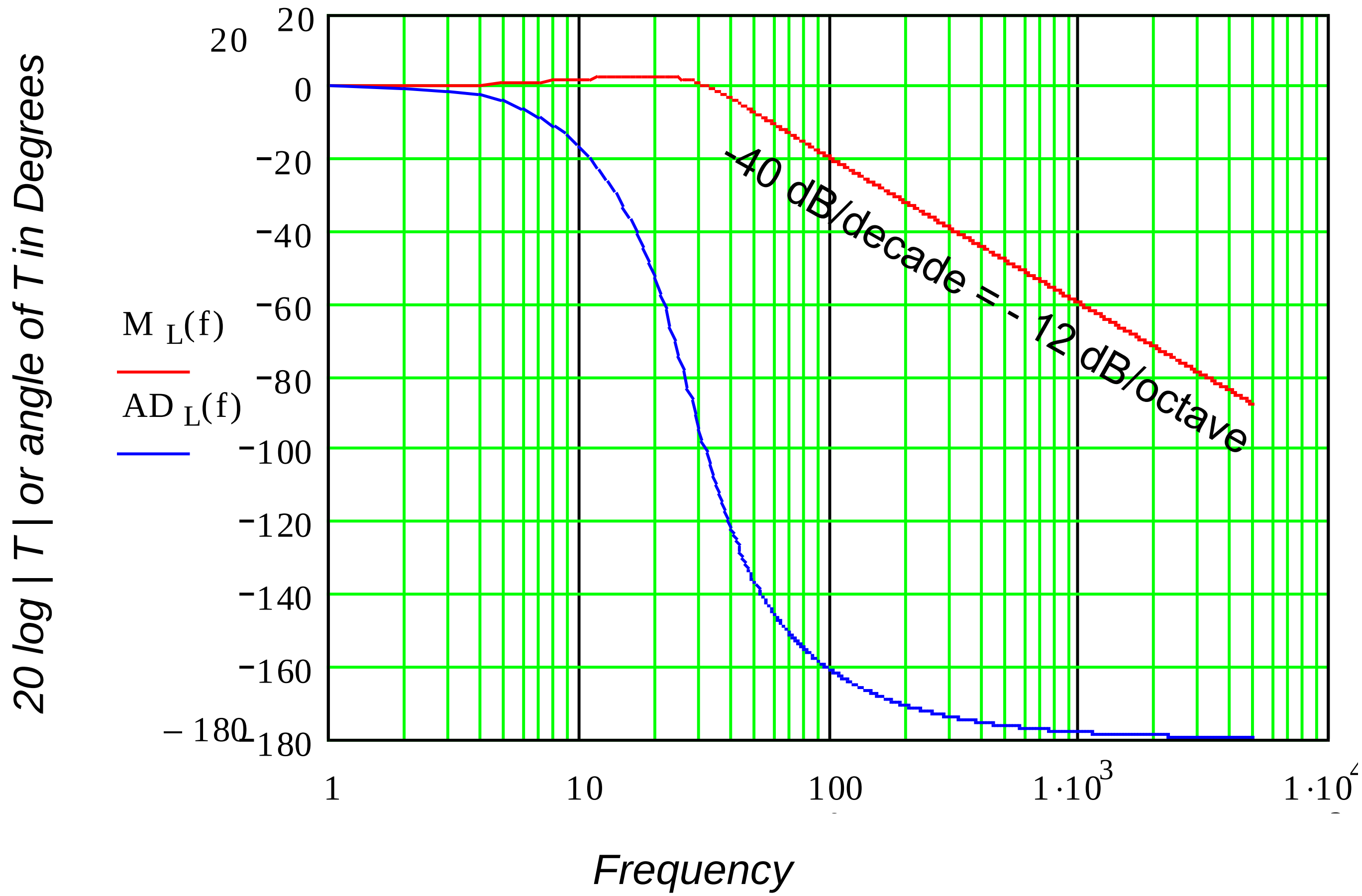
The Praeg Low Pass Ripple Filter



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

$$C_2 \geq 5 * C_1$$

$$R = \sqrt{\frac{L}{C_1}}$$



360 Hz Praeg Filter

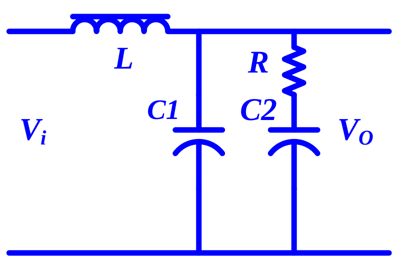
$f := 1\cdot Hz, 2\cdot Hz .. 1000\cdot Hz$ $\quad s(f) := j\cdot 2\cdot \pi \cdot f$ $\quad L := 1.5\cdot 10^{-3}\cdot H$ $\quad f_r := 36\cdot Hz$ $\quad C_1 := \dfrac{1}{4\pi^2\cdot L\cdot f_r^2}$ $\quad C_1 = 0.0130\,F$

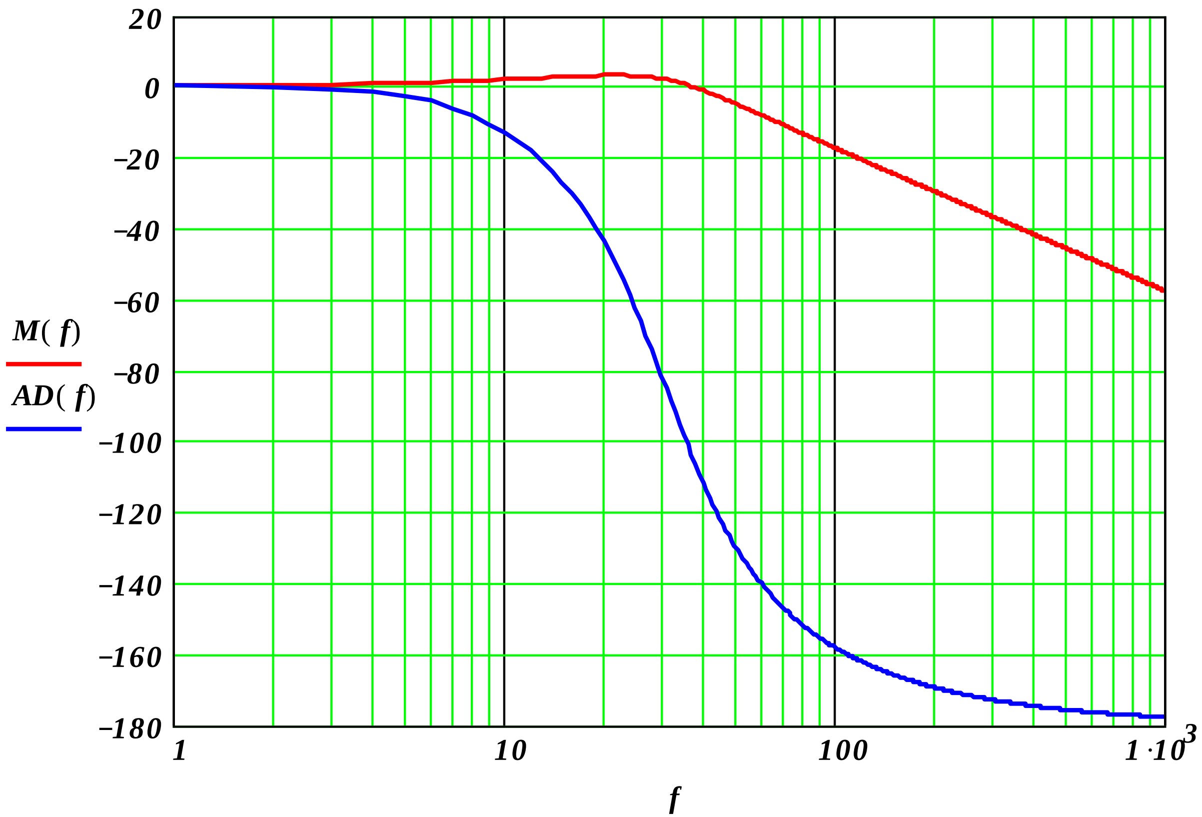
$R := \sqrt{\dfrac{L}{C_1}}$ $\quad R = 0.34\,\Omega$ $\quad C_2 := 5\cdot C_1$ $\quad C_2 = 0.065\,F$

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

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

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





36 kHz Praeg Filter

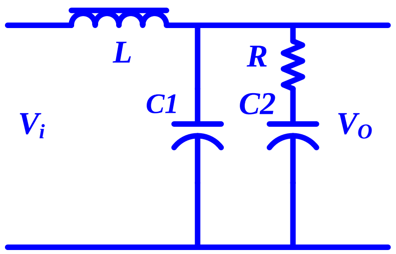
$f := 10 \cdot Hz, 20 \cdot Hz .. 100000 \cdot Hz \quad s(f) := j \cdot 2 \cdot \pi \cdot f \quad L := 1.5 \cdot 10^{-5} \cdot H \quad C_1 := 0.00013 \cdot F \quad f_r := \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot C_1}}$

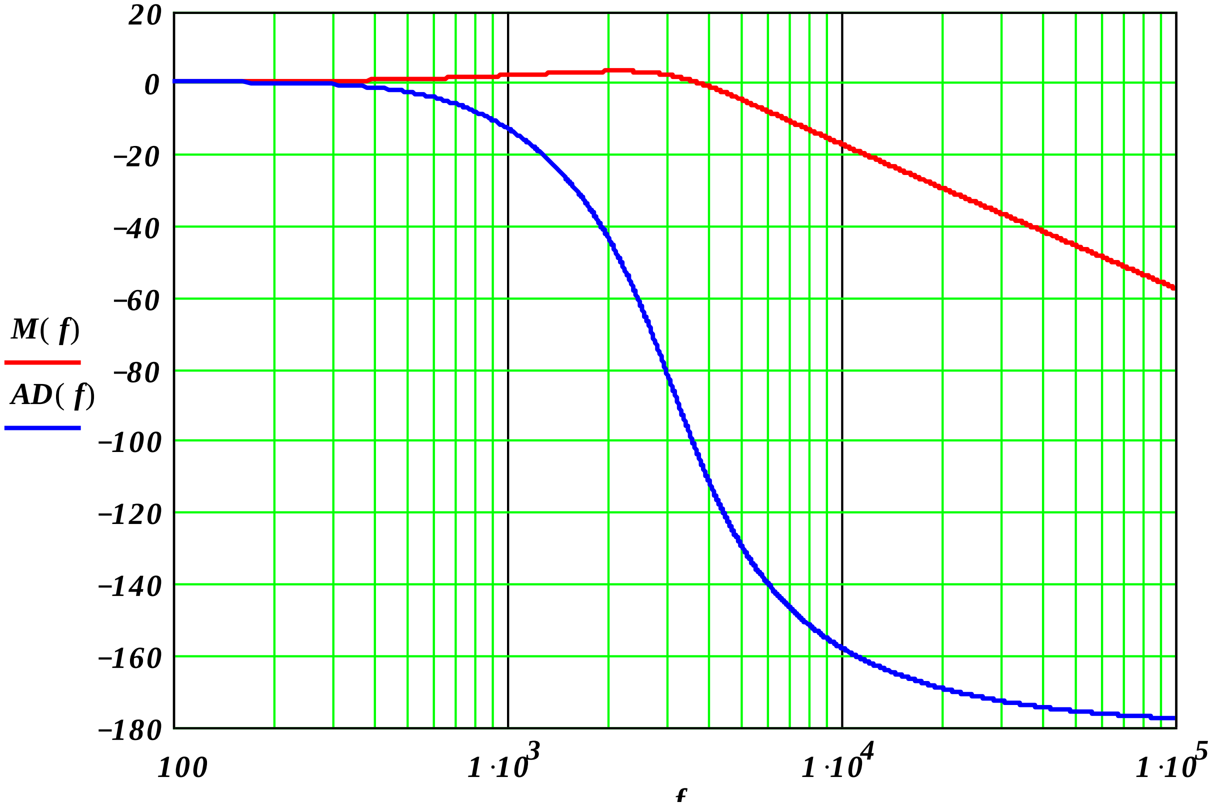
$R := \sqrt{\frac{L}{C_1}} \quad R = 0.34\,\Omega \quad C_2 := 5 \cdot C_1 \quad C_2 = 6.5 \times 10^{-4}\,F \quad f_r = 3604\,Hz$

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

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

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





Higher Frequency Operation Means a Smaller Filter

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

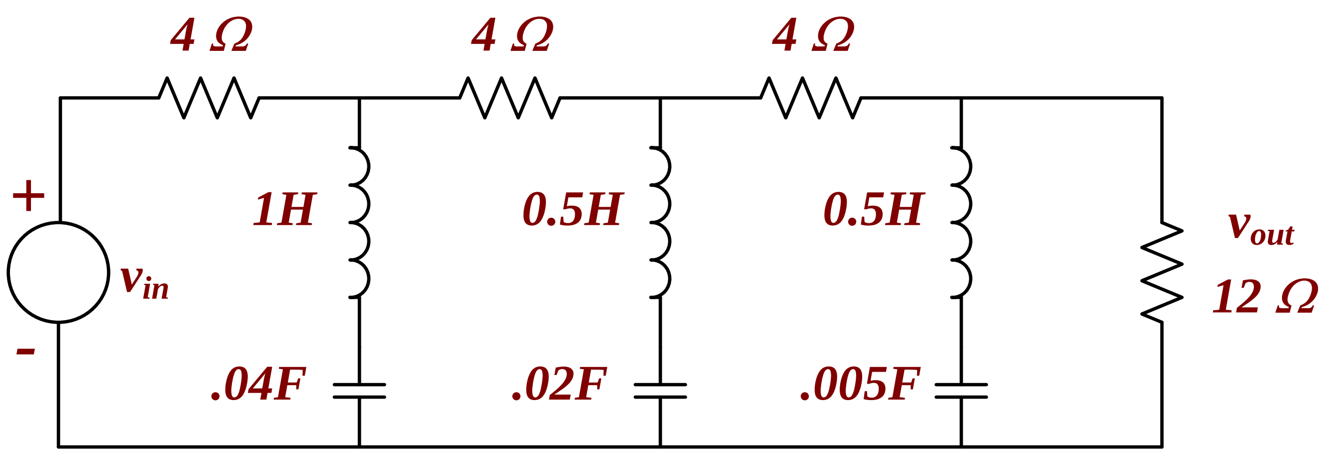
$$\text{Let } f_{r2} = nf_{r1} = \frac{n}{2\pi\sqrt{LC}}$$

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

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

- $AC\ equipment = \sum P_{switchgear} + P_{transformer} + P_{cables}$

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

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

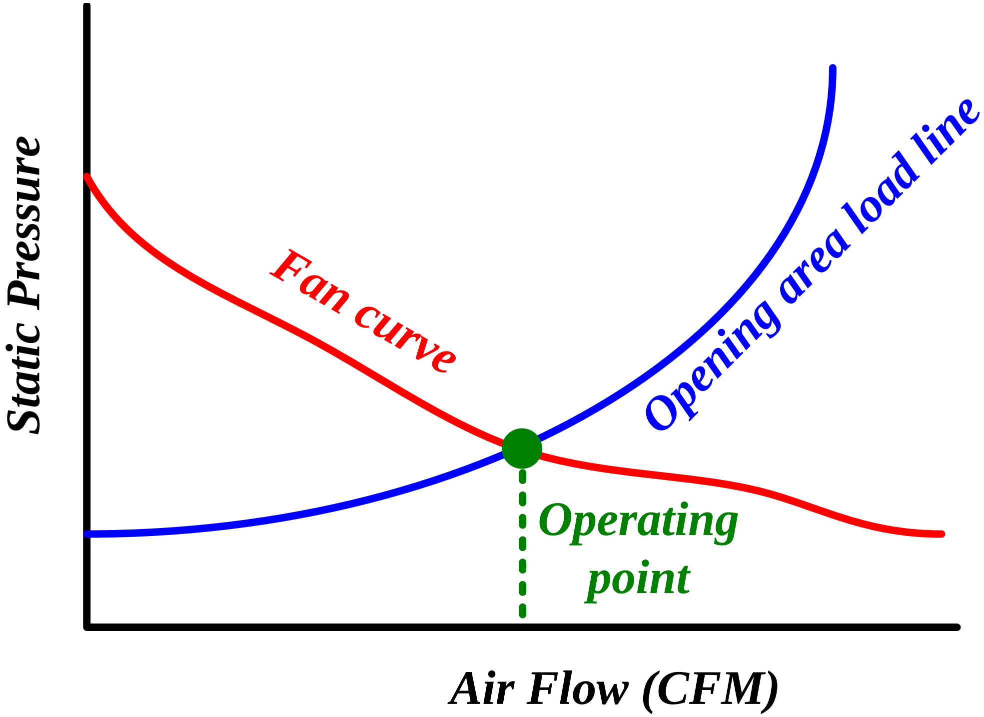
$$P_{AC\ cables} = \sum_j i_{RMS}^2 * \frac{R}{ft} * Length$$

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

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

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*



Heat Loading Into Building Water

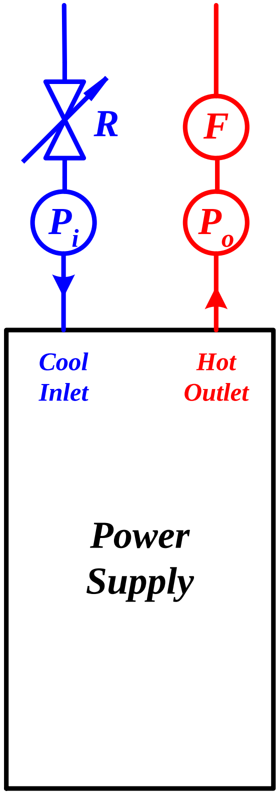
Power supply heat loss to water $= \sum$ electrical losses of all water-cooled components

Heat lost (dissipated) by PS water cooled components = Heat gained by cooling water system

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

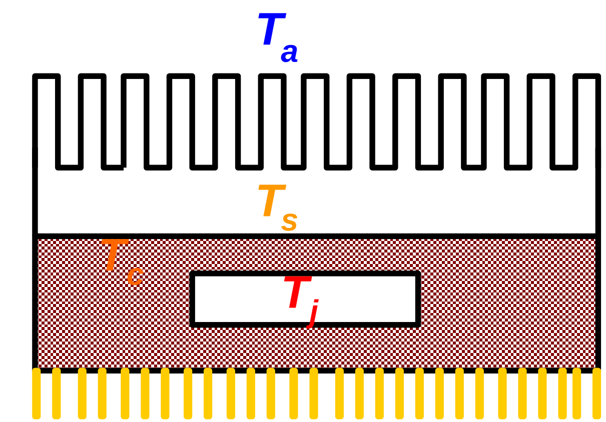
$$q = m * c * \Delta T \qquad watt = gpm * \frac{264\, watt}{gpm * {}^{O}C} * \left({}^{O}C_{Outlet} - {}^{O}C_{Inlet}\right)$$

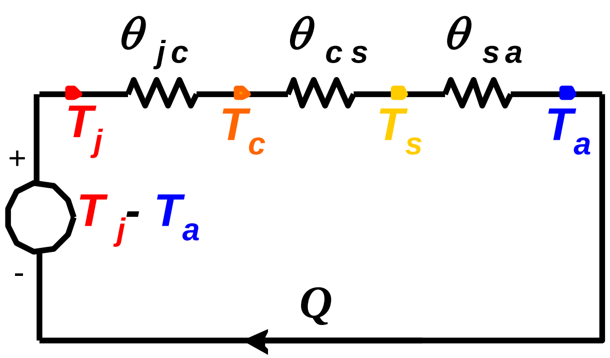
The system pressure drop is $\Delta P = \sum_i P_i$



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

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





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)

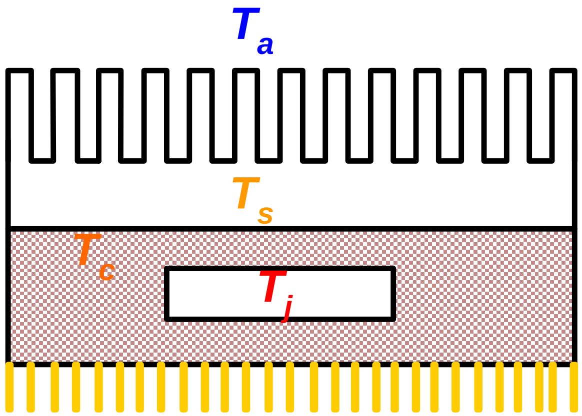
T_s = Heatsink temperature (^OC)

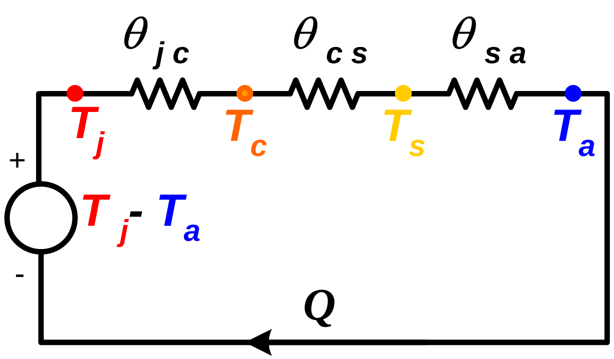
T_a = Ambient air or cooling water inlet temperature (^OC)

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 $q = m*c*\Delta T$

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

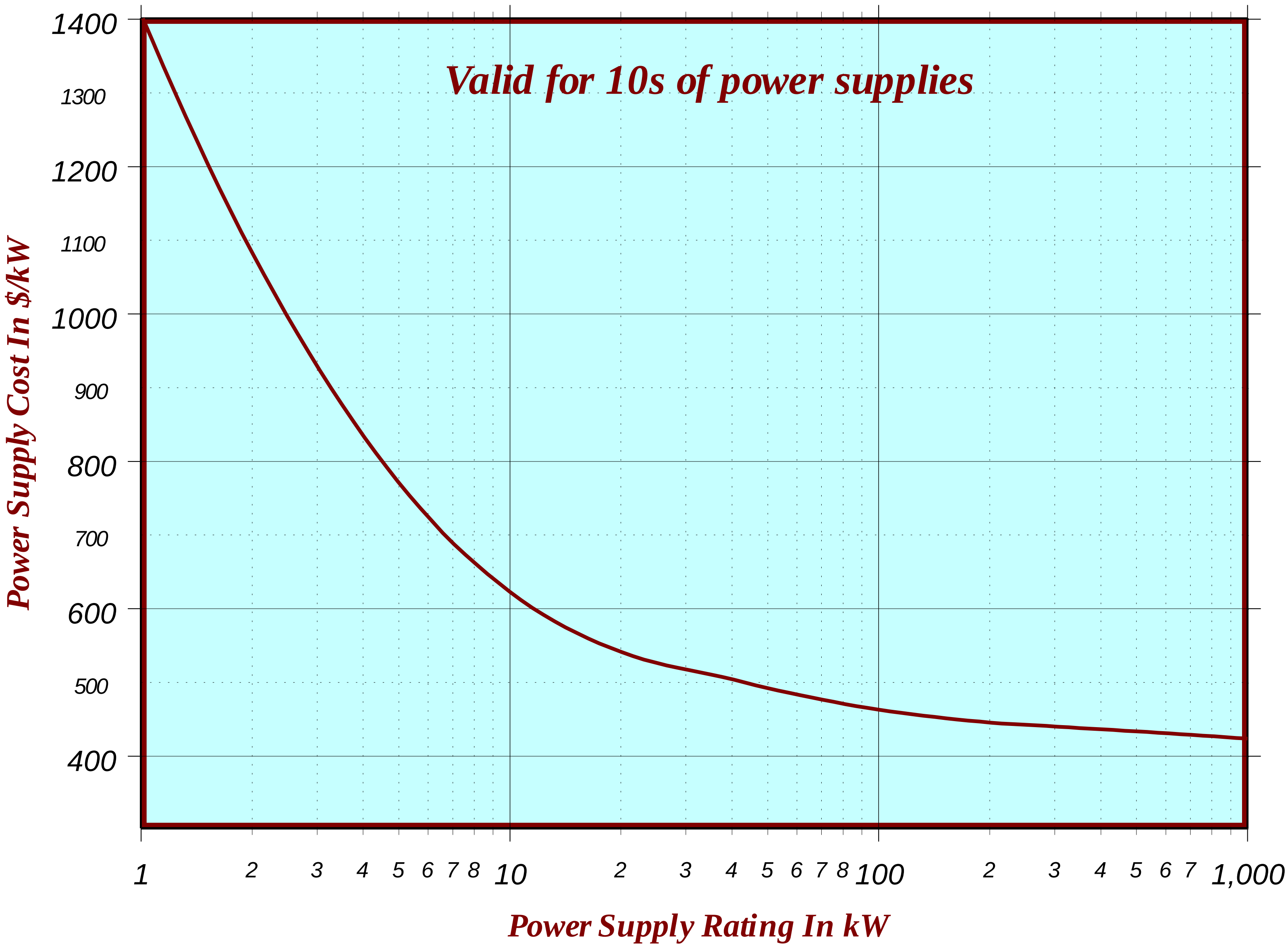
$\Delta T \leq$ *the maximum allowable temperature rise*

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

Cost Of Switchmode Power Supplies



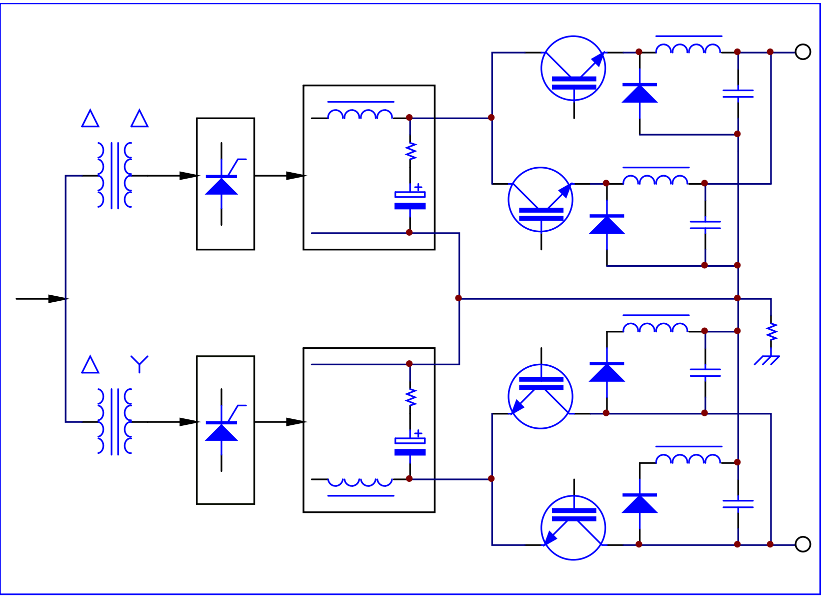
Homework Problem # 11

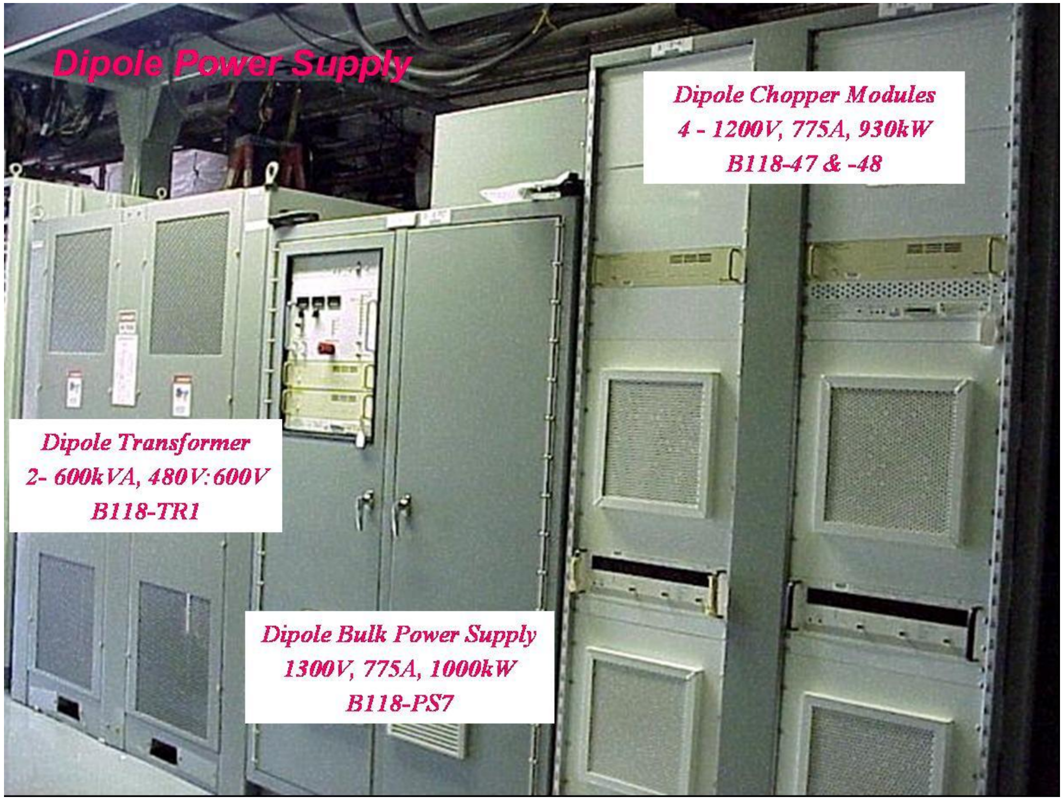
A 100kW power supply is 80% efficient. Approximately 50% of the power supply heat loss is removed by cooling water.

- *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.*

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*

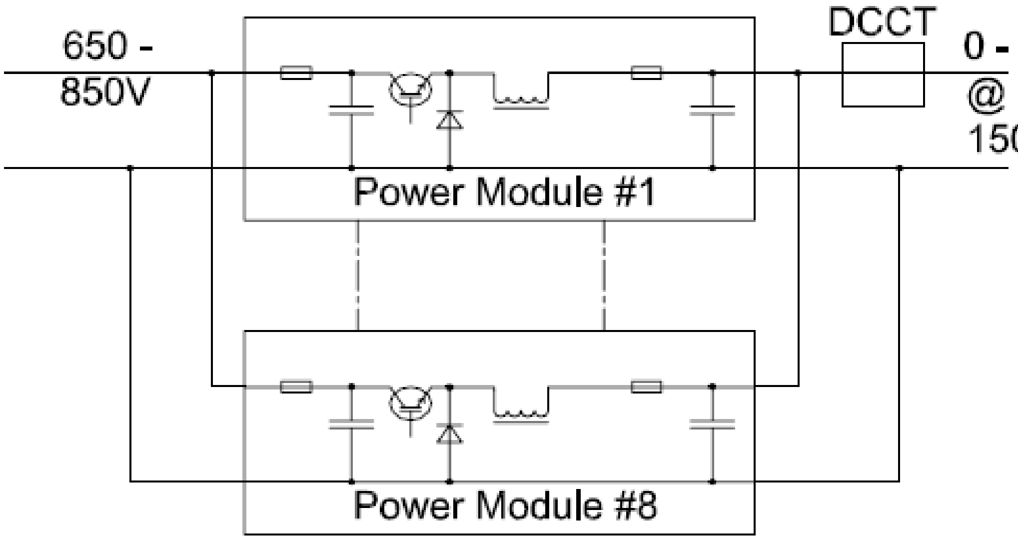


Figure 1: Dipole Converter Topology.

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*

Diamond Booster Dipole Power Converter

- *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*

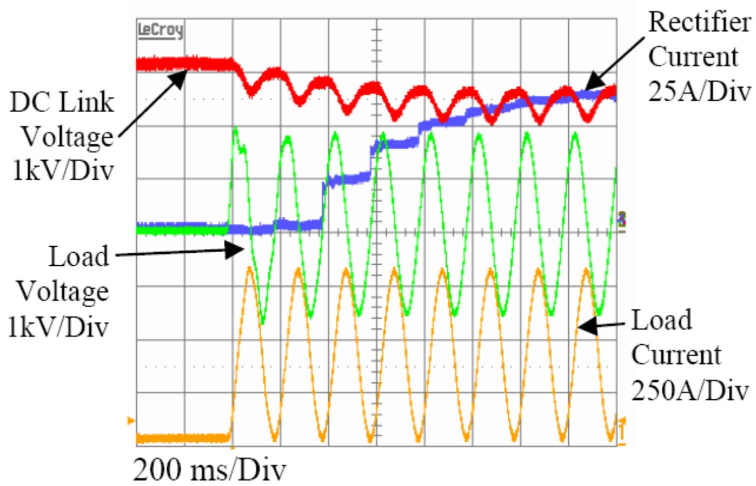


Figure 4: First few cycles after turn on.

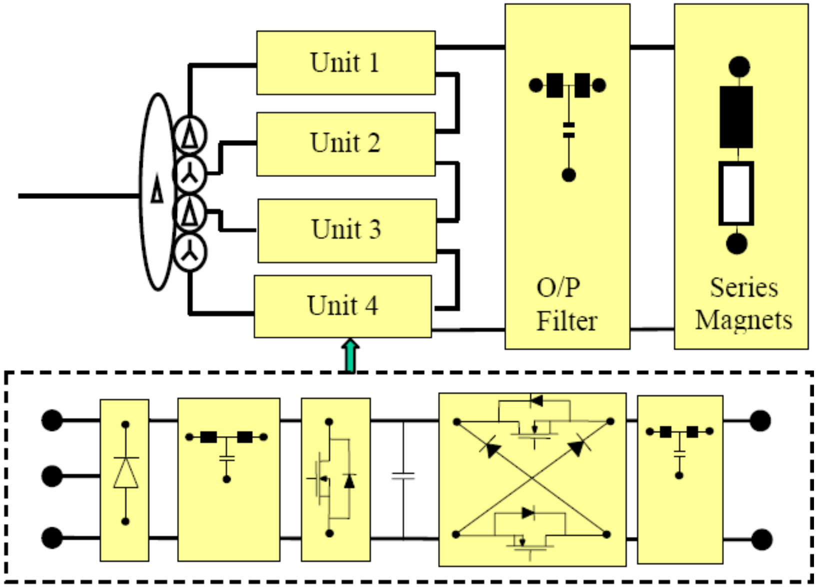
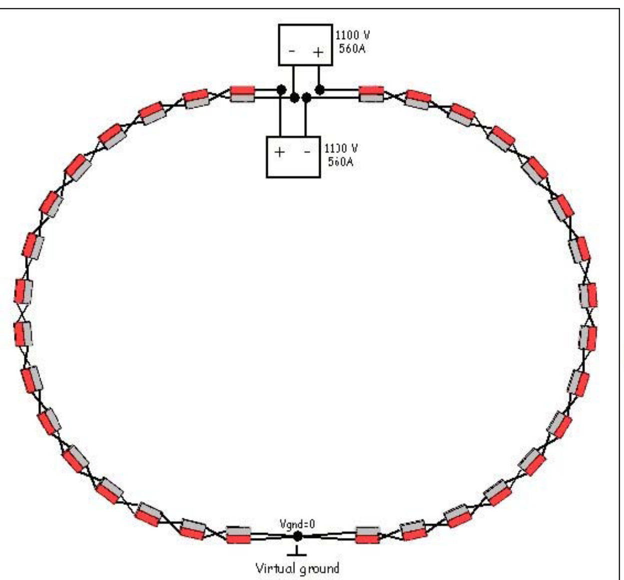


Figure 1: Booster dipole power circuit.

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



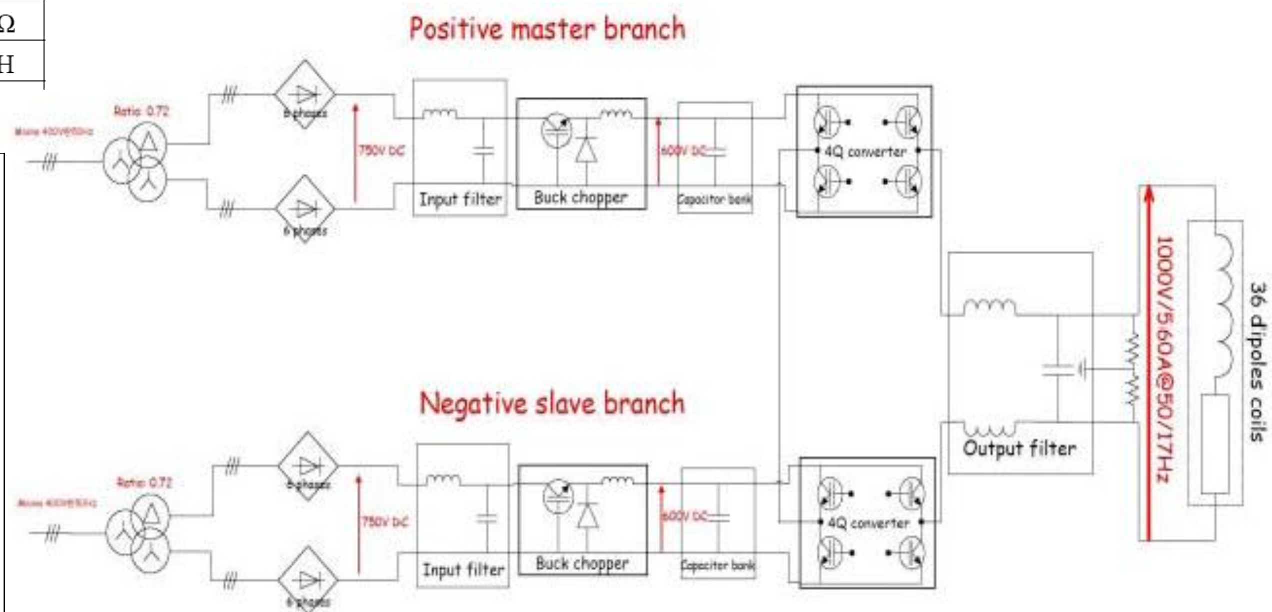
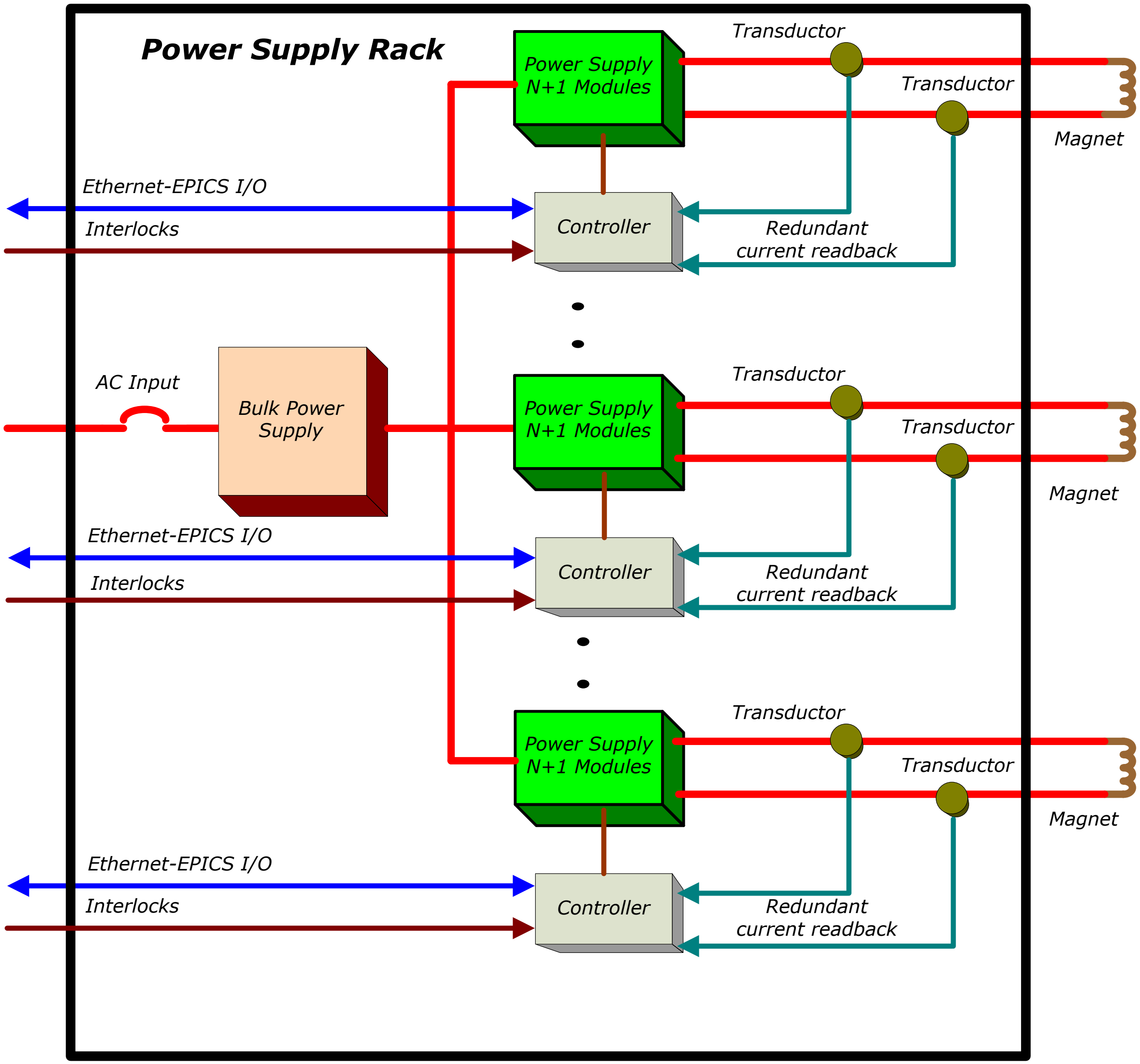


Figure 4: dipoles PS main schematics

Power Supplies for the ATF2



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

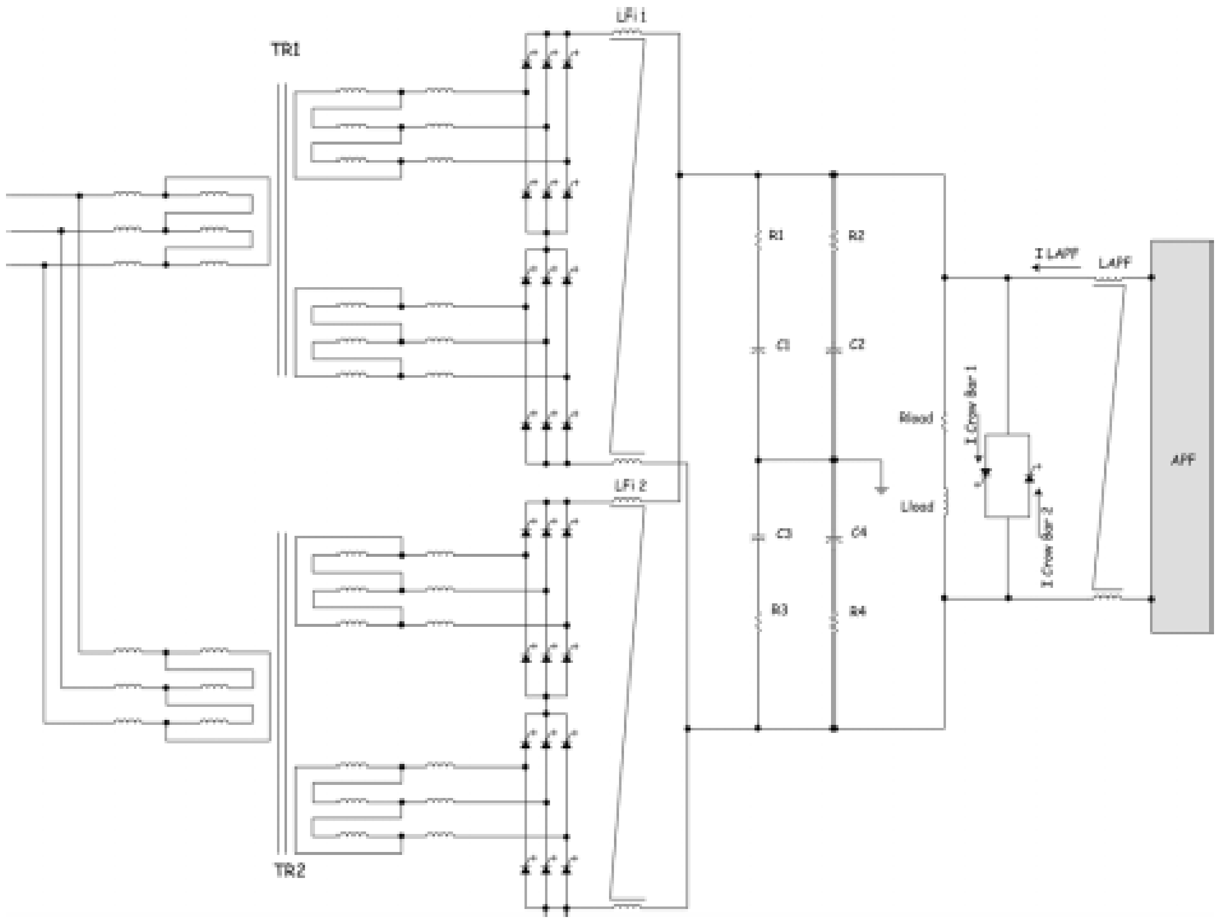


Figure 2: Topology of CNAO synchrotron power supply.

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

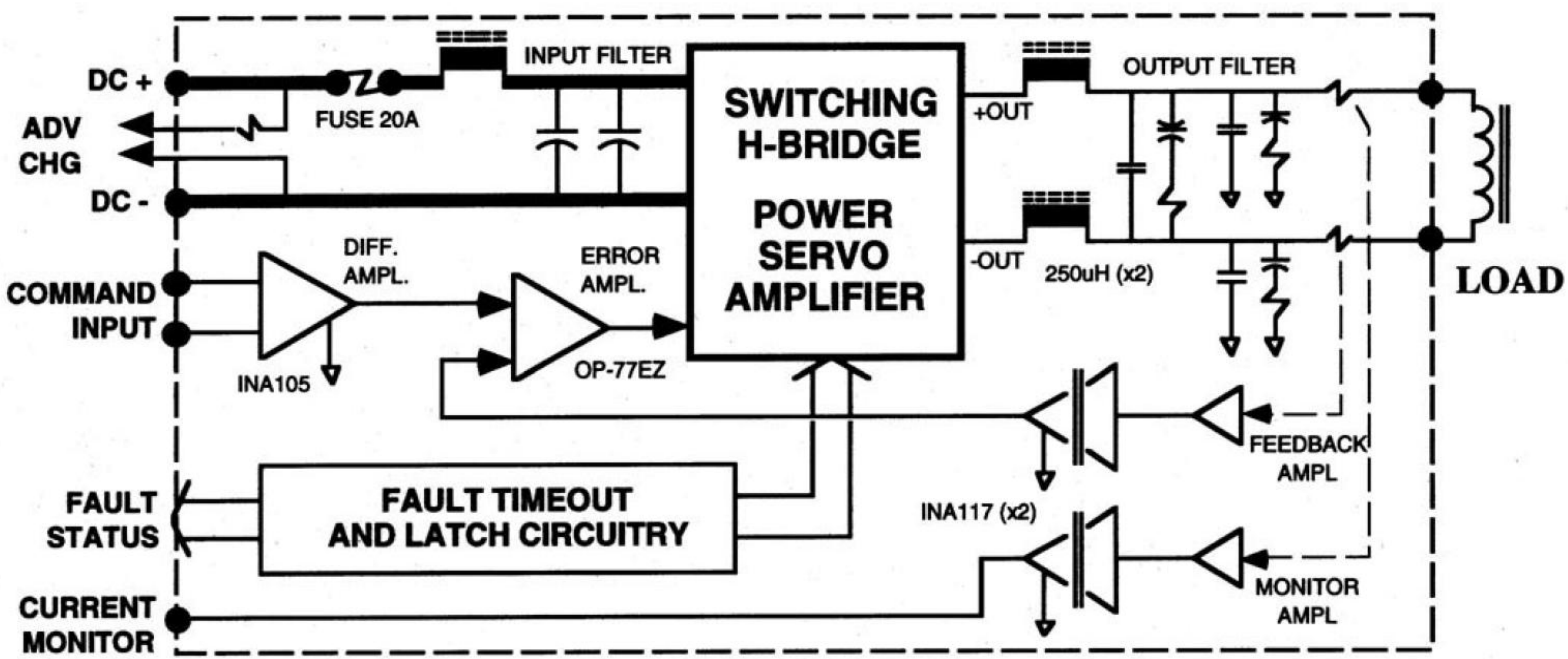


Figure 1.3. MCOR12 Block Diagram.

Bipolar Power Supplies at SPEAR3 and LCLS

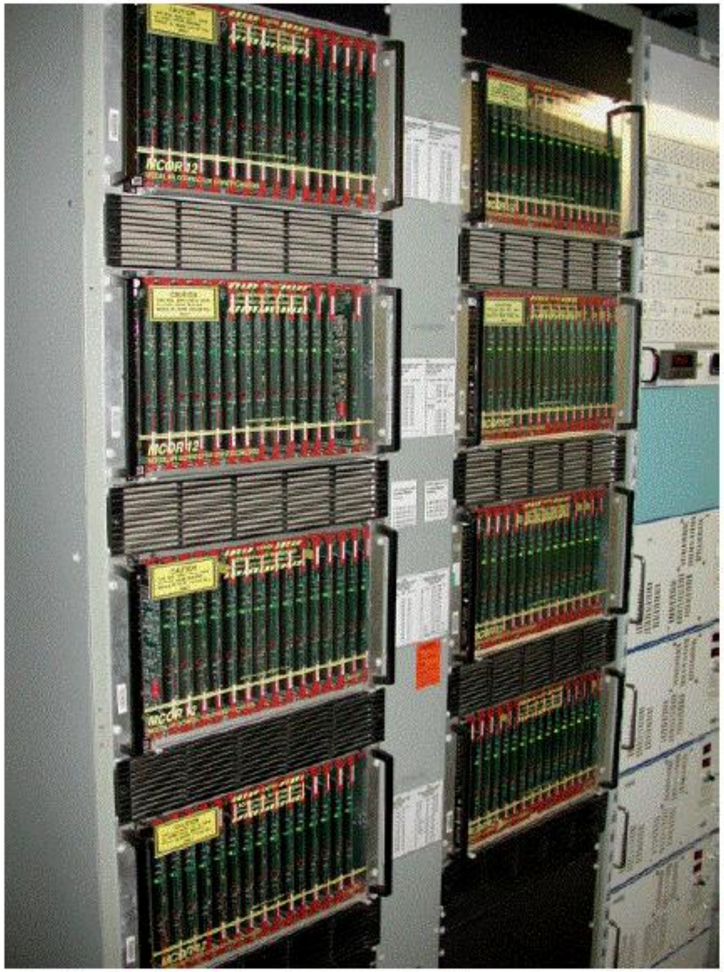
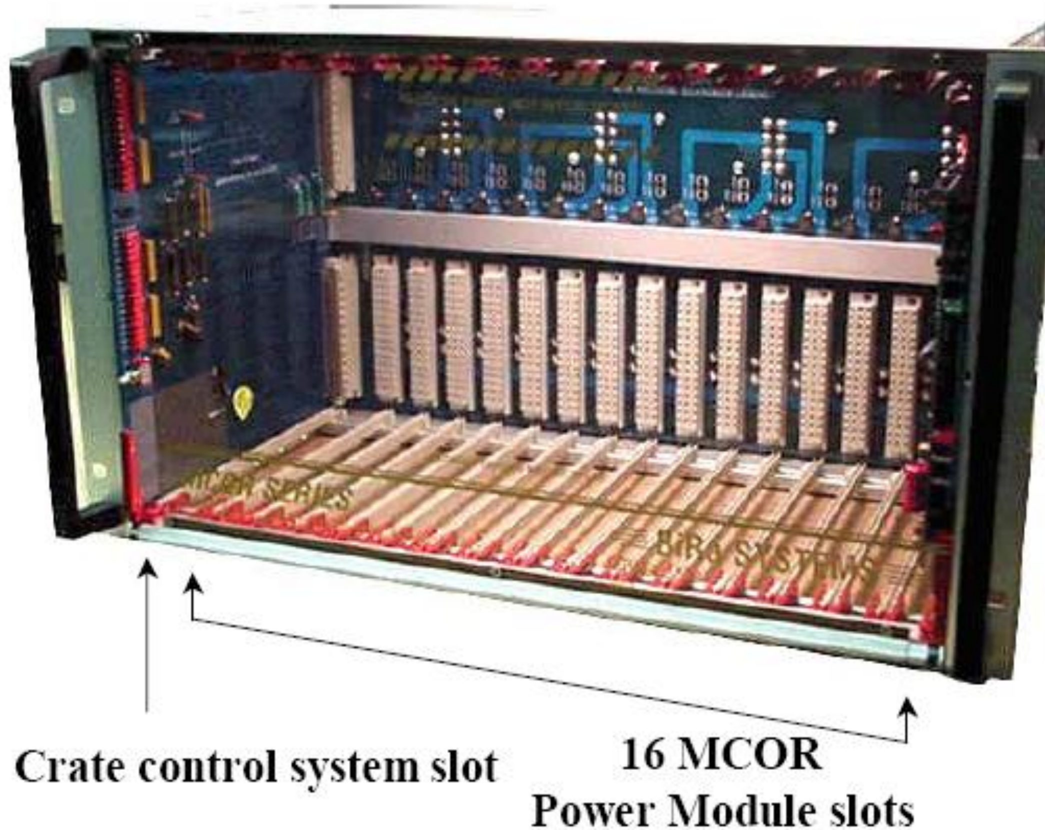


Figure 1.1. A typical MCOR installation



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

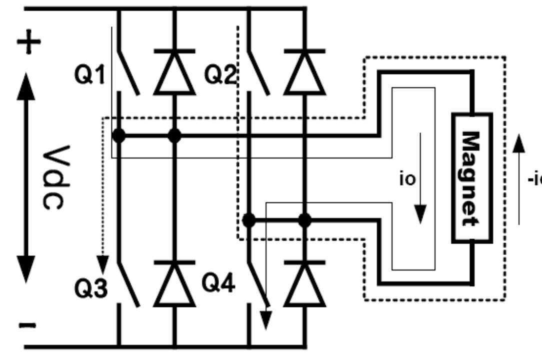


Figure 1: Bipolar MPS operation of full-bridge four-quadrant DC/DC converter.

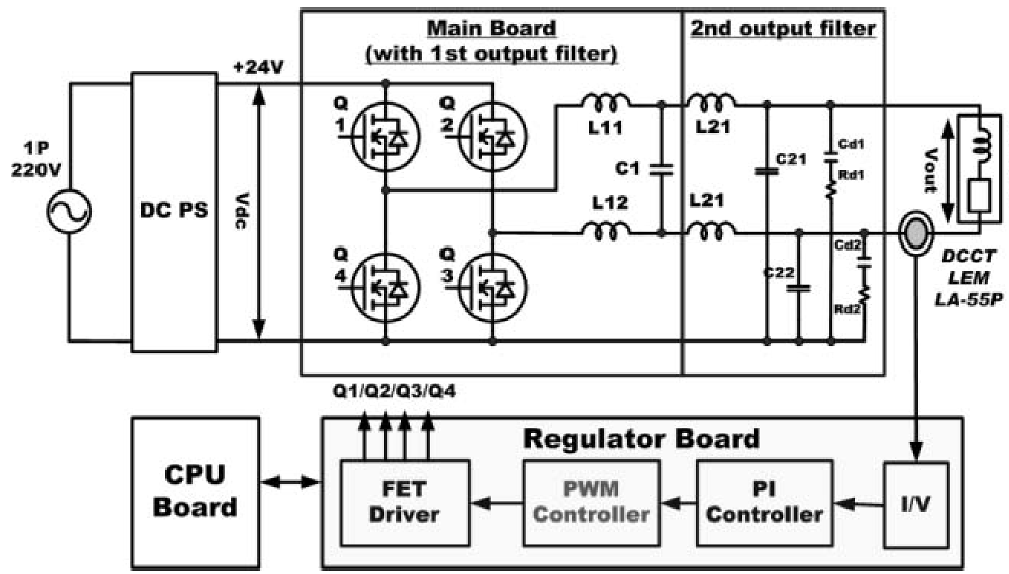
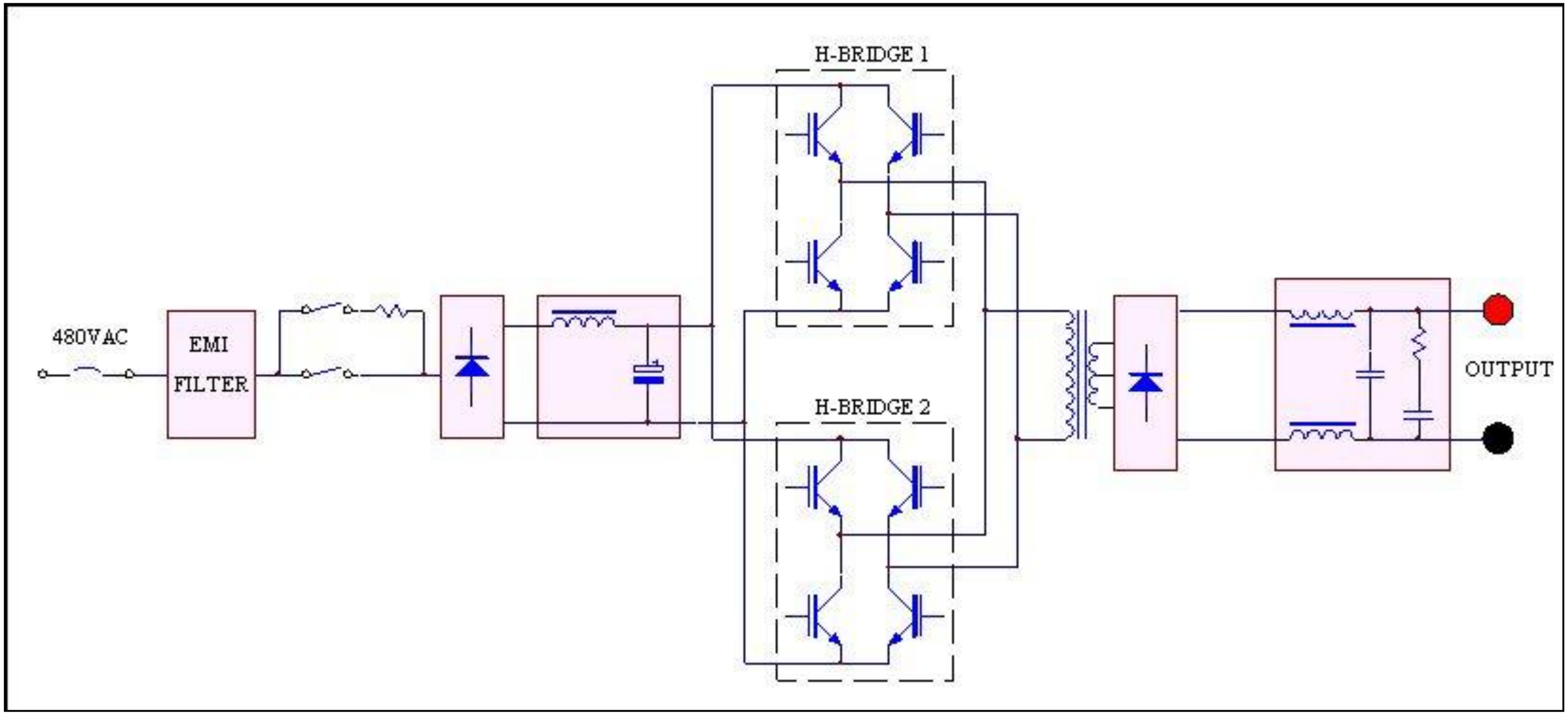


Figure 4: Circuit diagram of bipolar MPS.

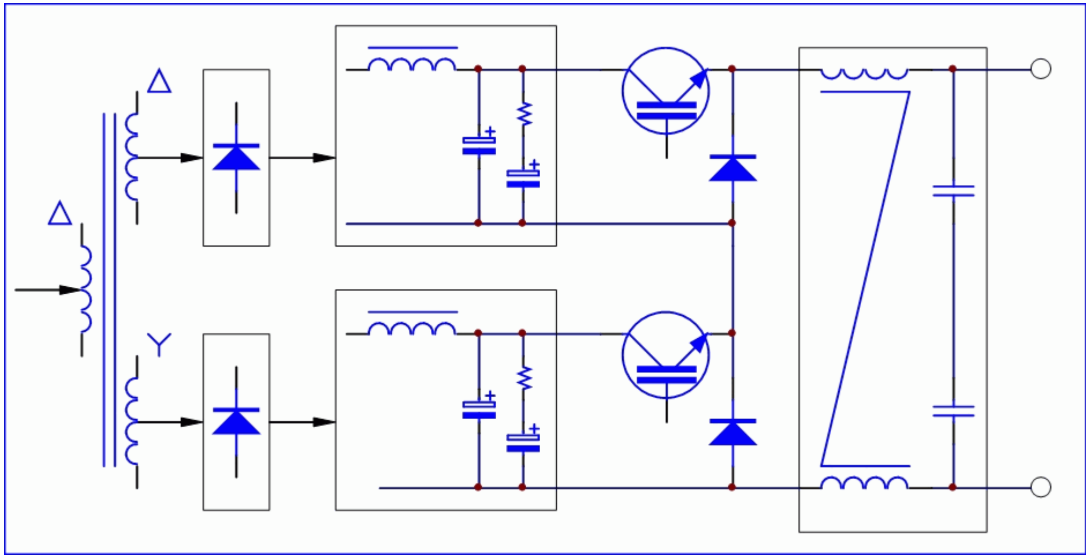
Table 1: LGPS ratings.

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

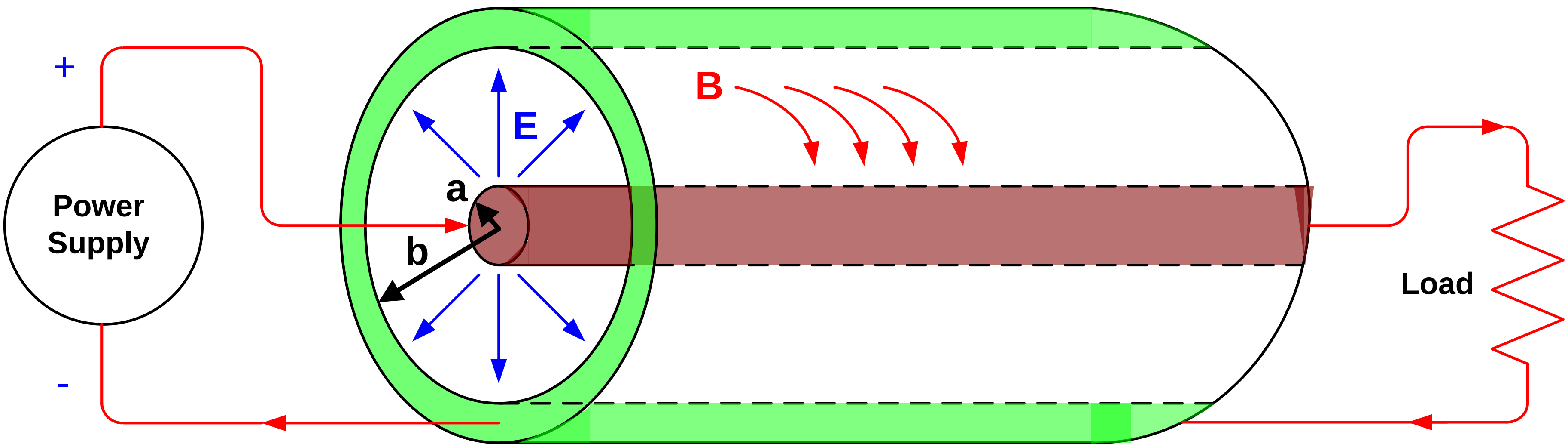
Transmission Line Basics

- *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*

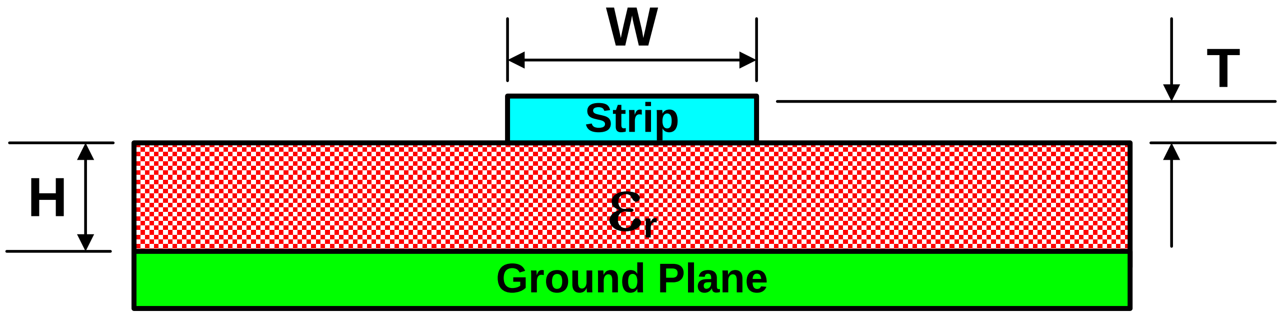
Transmission Line Types

- *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*



- *Planar transmission line - Microstrip line consists of a single strip on dielectric separated from a ground plane*



when $\left(\frac{W}{H}\right) < 1$ — Effective Dielectric Constant

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\left(1 + 12\left(\frac{H}{W}\right)\right)^{-1/2} + 0.04\left(1 - \left(\frac{W}{H}\right)\right)^2\right]$$

Characteristic Impedance

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

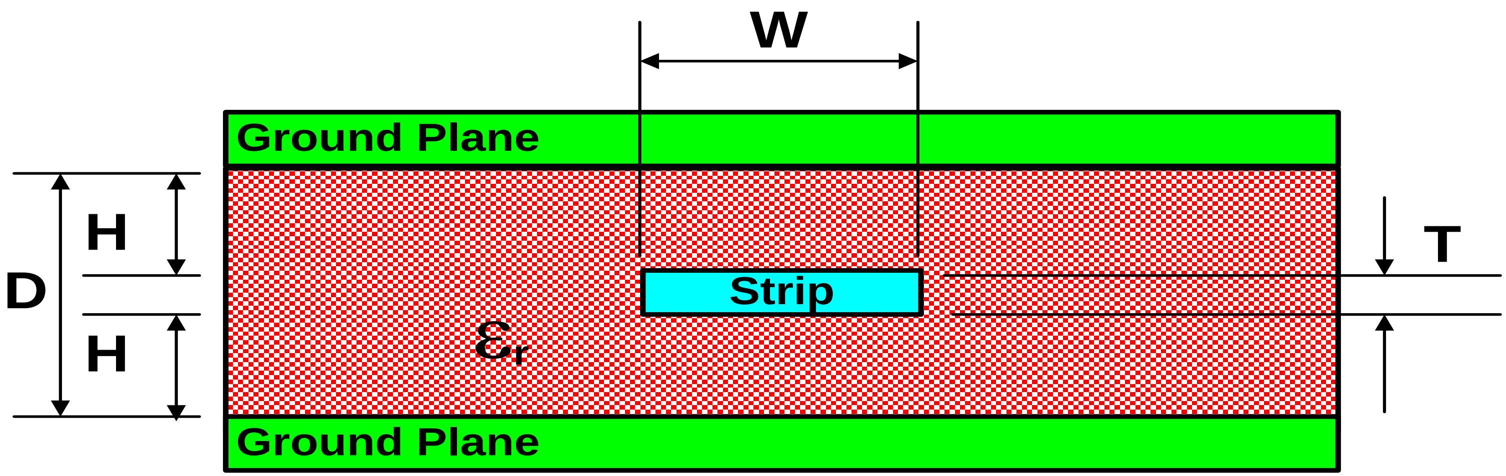
when $\left(\frac{W}{H}\right) \geq 1$ — Effective Dielectric Constant

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

Characteristic Impedance

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

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



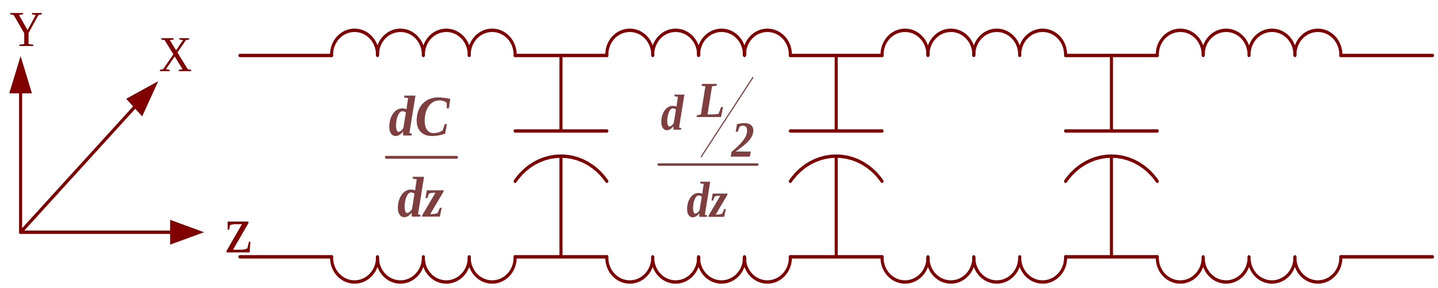
Characteristic Impedance

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

Transmission Line Types

- *Lumped element transmission lines*
  - *Combination of series inductors, shunt capacitors*
  - *Single inductor-capacitor combination is a resonant circuit*
  - *Series of an infinite combination of series L, shunt C turns into an ideal transmission line*
  - *Electric fields of lines stored in capacitors*
  - *Magnetic fields of lines stored in series inductors*

Lumped Element Transmission Lines

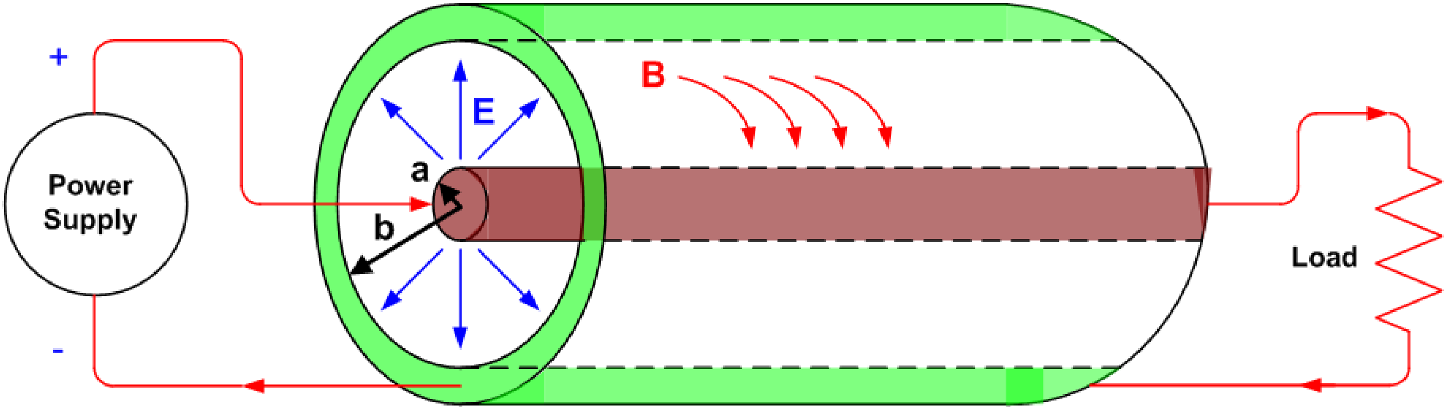


$E = \hat{y}E_y \quad H = \hat{x}H_x \qquad Z_0 = \sqrt{\frac{L}{C}}$ Characteristic impedance - 377 ohms for air (free space)

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

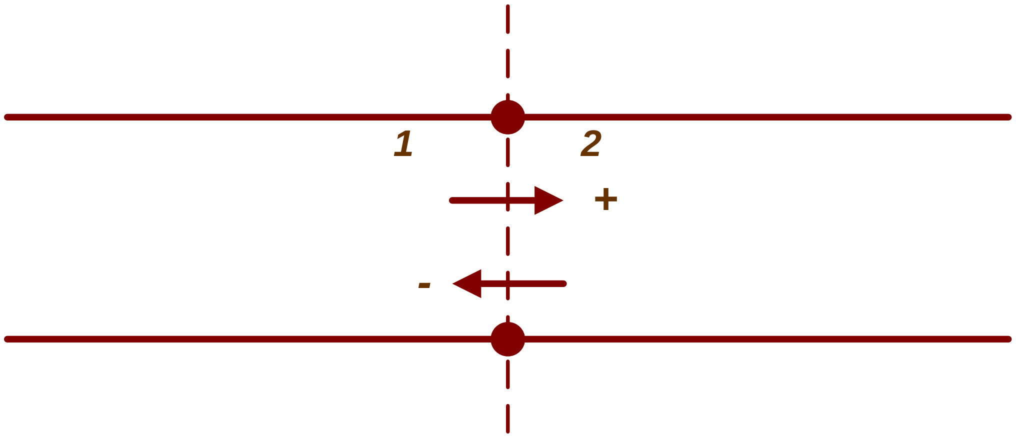
$$Z_0 = \frac{\ln b/a}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}$$ For coaxial line, $50\Omega \le Z_0 \le 80\Omega$

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



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 $V_1^- = Z_1 I_1^-$*



Equations at an Interface

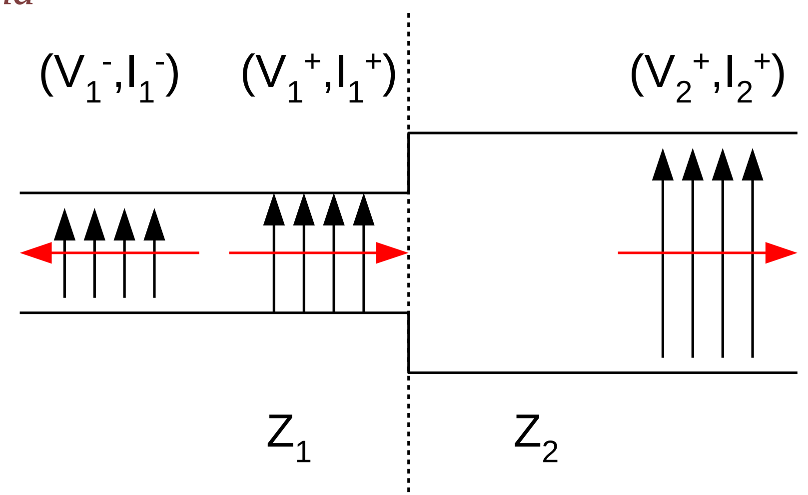
The voltages on each side of the interface must be equal.

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

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.

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

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

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

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

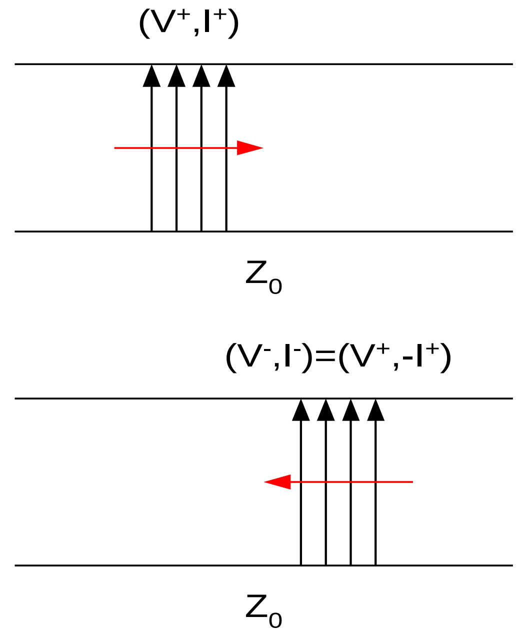
$$P_T + P_R = \frac{\left(4Z_2Z_1 + Z_2^{\,2} - 2Z_2Z_1 + Z_1^{\,2}\right)}{Z_1\left(Z_2 + Z_1\right)^2}\left(V_1^+\right)^2 = \frac{\left(V_1^+\right)^2}{Z_1}$$

$$= P_{IN}$$

Simple Examples

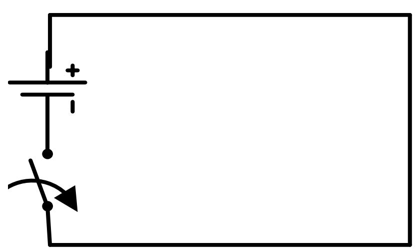
Open Line

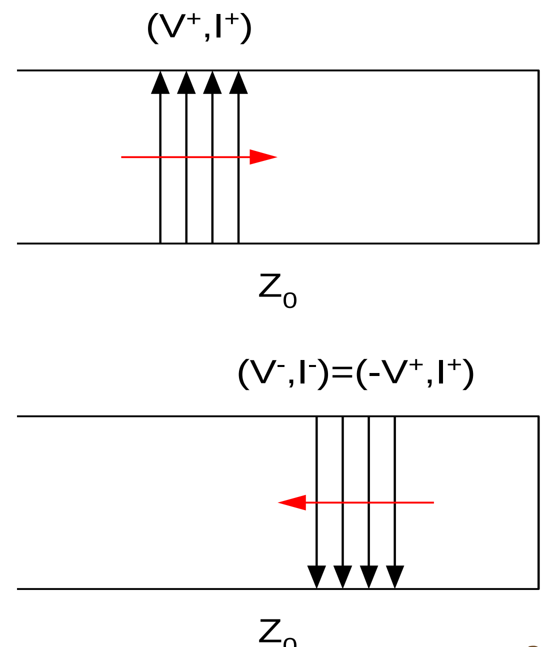
- $Z_1 = Z_0$, Z_2 *infinite*
- $\Gamma = 1$
- $I_2 = 0$
- *Voltage totally reflected without inversion*



Shorted Line

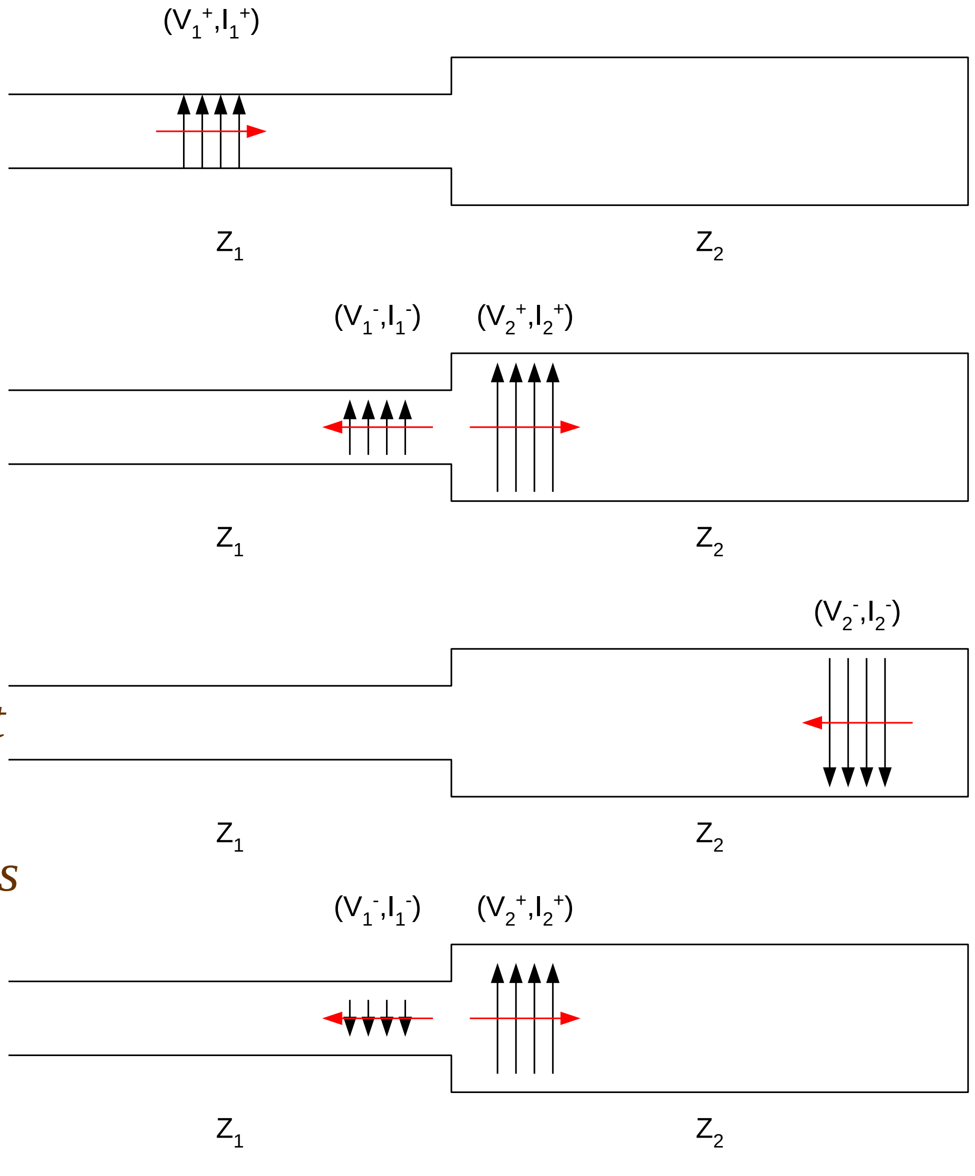
- Z_2 *zero*
- $\Gamma = -1$
- $V_2 = 0$
- *Voltage totally reflected with inversion*





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*



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.*

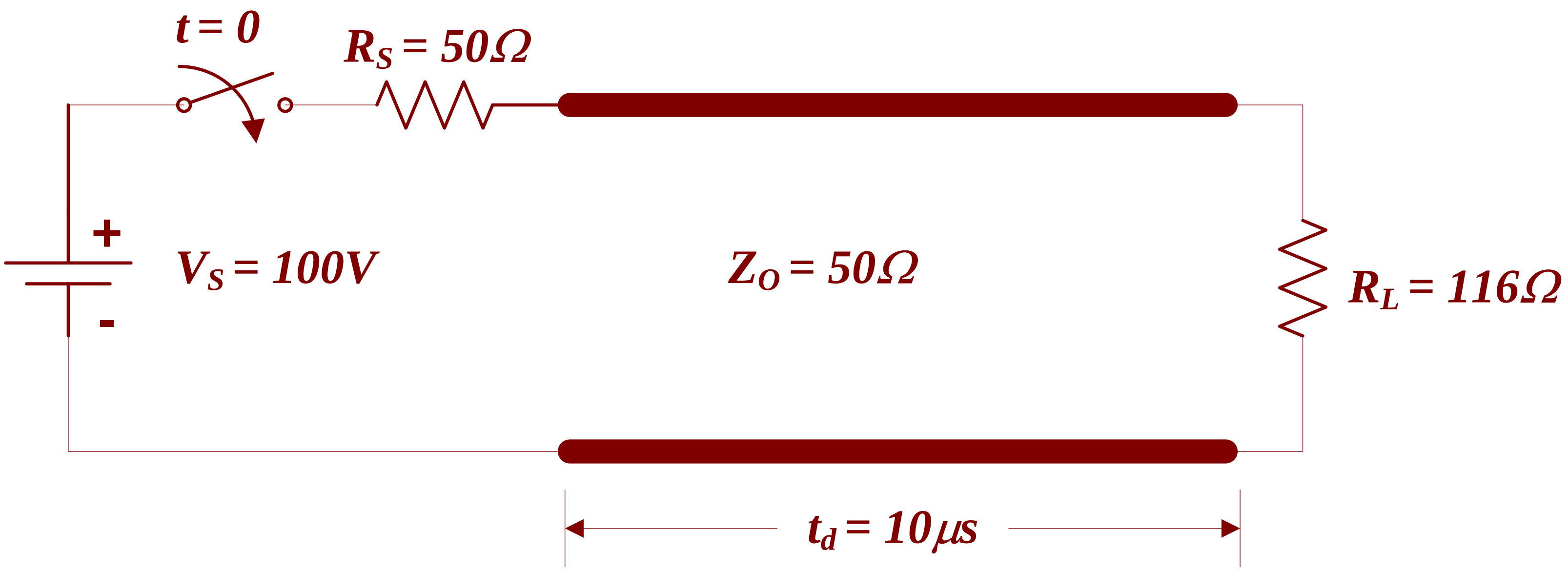
B. *The frequency of a signal applied to a two-wire transmission cable is 3GHz. What is the signal wavelength if the cable dielectric is air?*

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

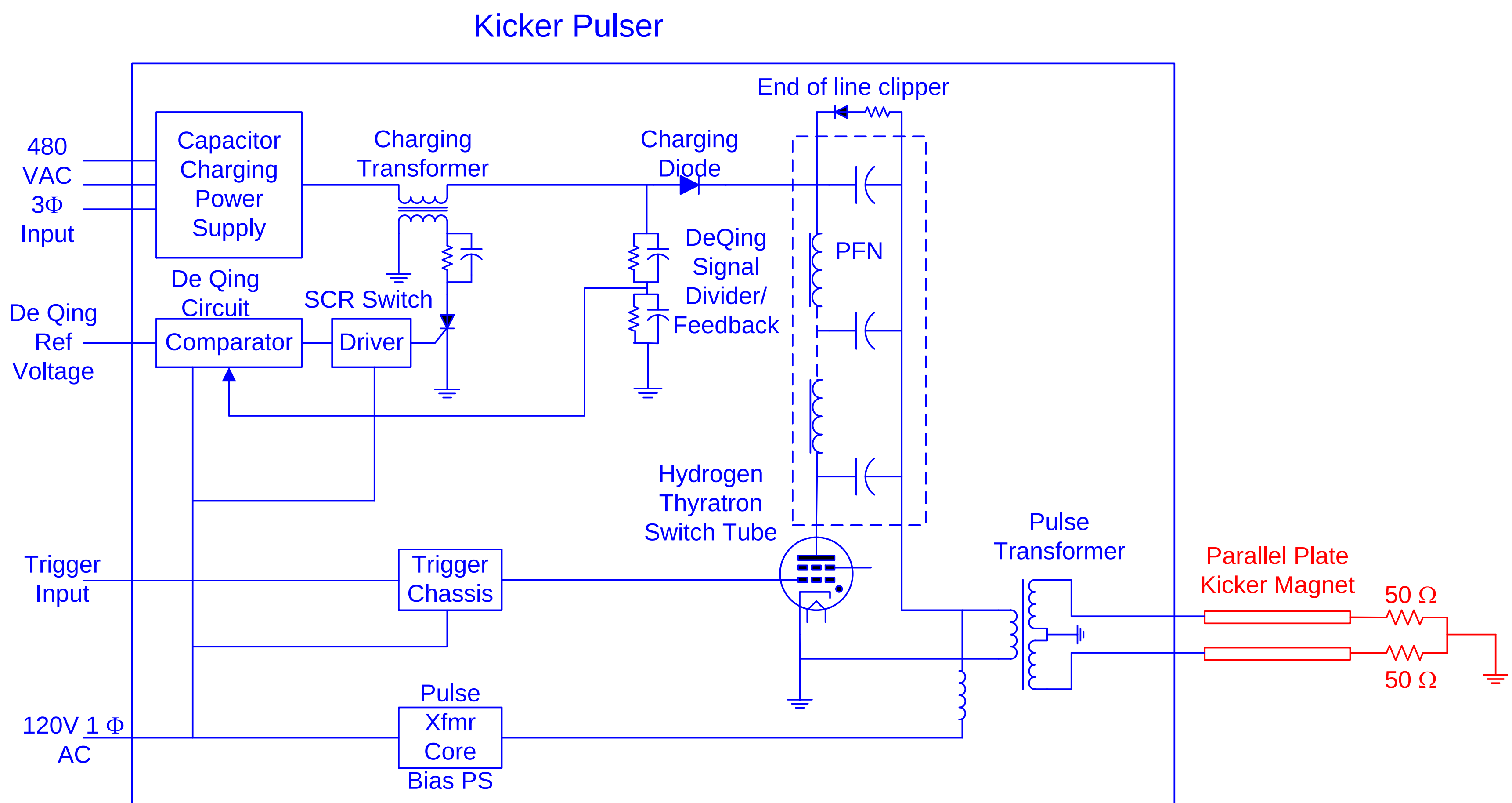
Hint – relative permittivity of air is 1

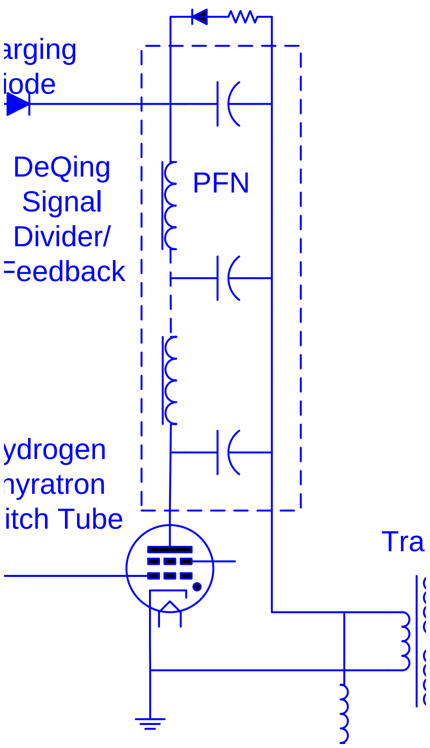
Homework Problem #13

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





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

$$t = \sqrt{L * C}$$

and the pulse width T is

$$T = 2 * \sqrt{L * C}$$

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.

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

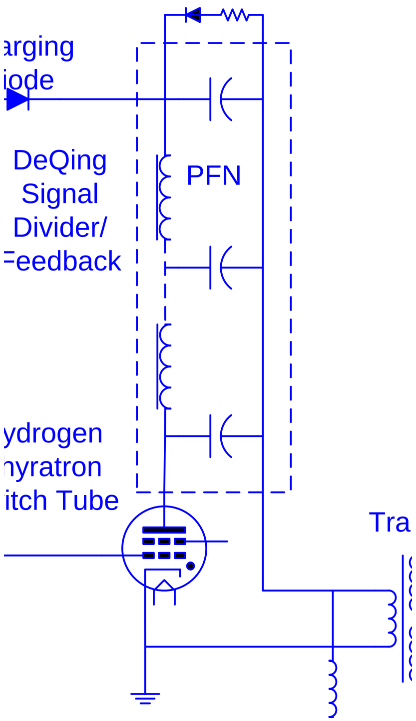
$$T = 2 * Z * C$$

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

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

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

The Pulse Forming Network (PFN)



The PFN is typically tuned to the impedance of the load in order to reduce voltage and current reflections. The effective output voltage at the load obeys the voltage divider law and is effectively

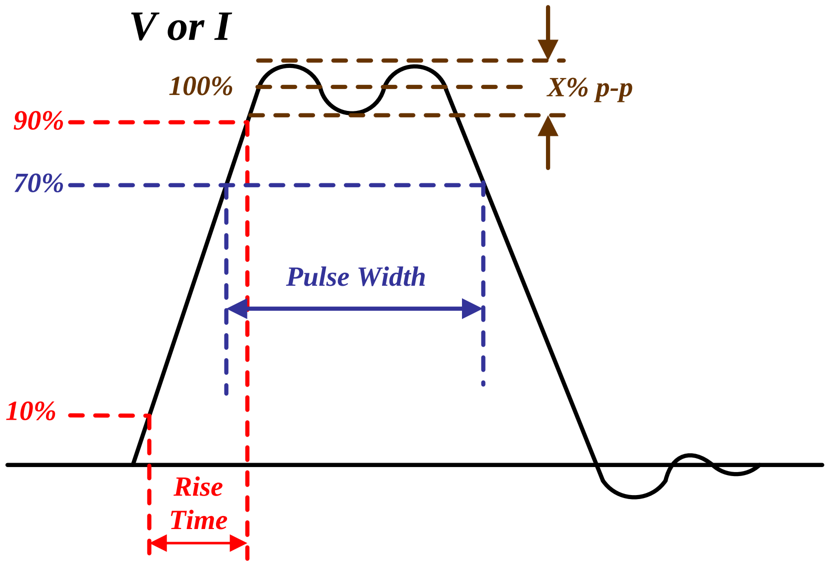
$$V_{load} = V_{pfn} * \frac{Z_{load}}{Z_{load} + Z_{pfn}}$$

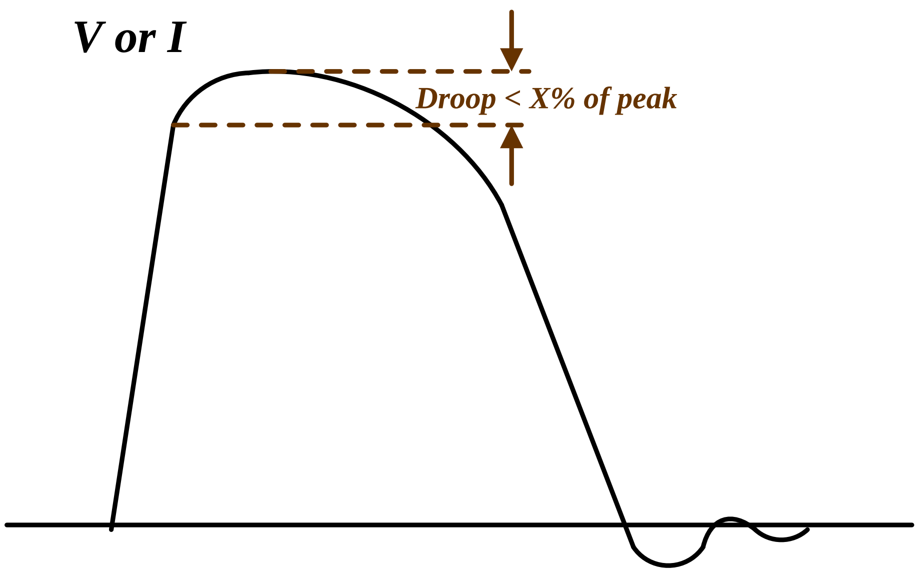
$$V_{pfn} = V_{load} * \frac{Z_{load} + Z_{pfn}}{Z_{load}}$$

Because typically the PFN has the same impedance as the load,

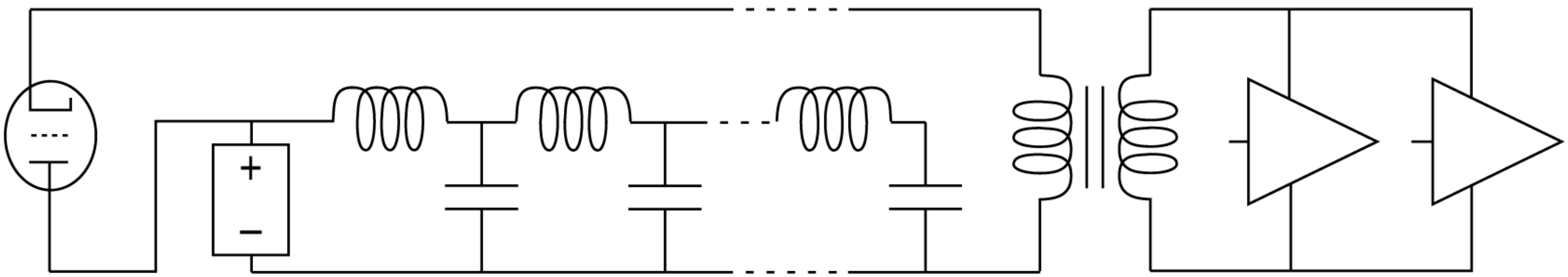
$$V_{pfn} = 2 * V_{load}$$

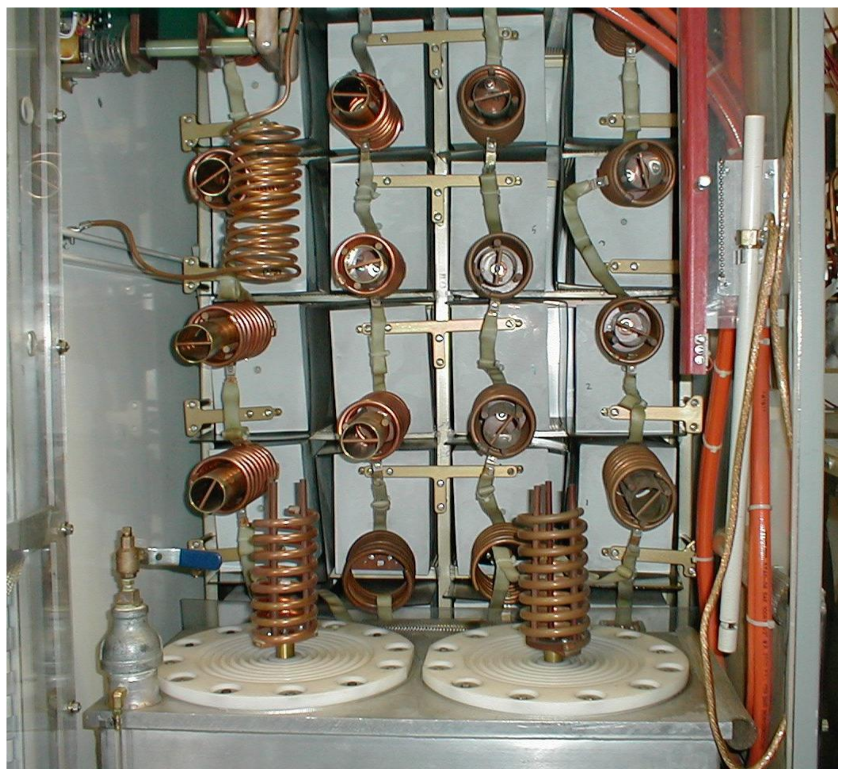
Therefore the PFN must be charged to twice the desired load voltage.


V or I
100%
90%
70%
10%
X% p-p
Pulse Width
Rise
Time


V or I
Droop < X% of peak

Klystron Modulator with PFN





Why Use a Modulator to Drive a Klystron?

$$Klystron\ perveance = \frac{I_{klystron}}{(V_{beam\ voltage})^{3/2}}$$

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%)

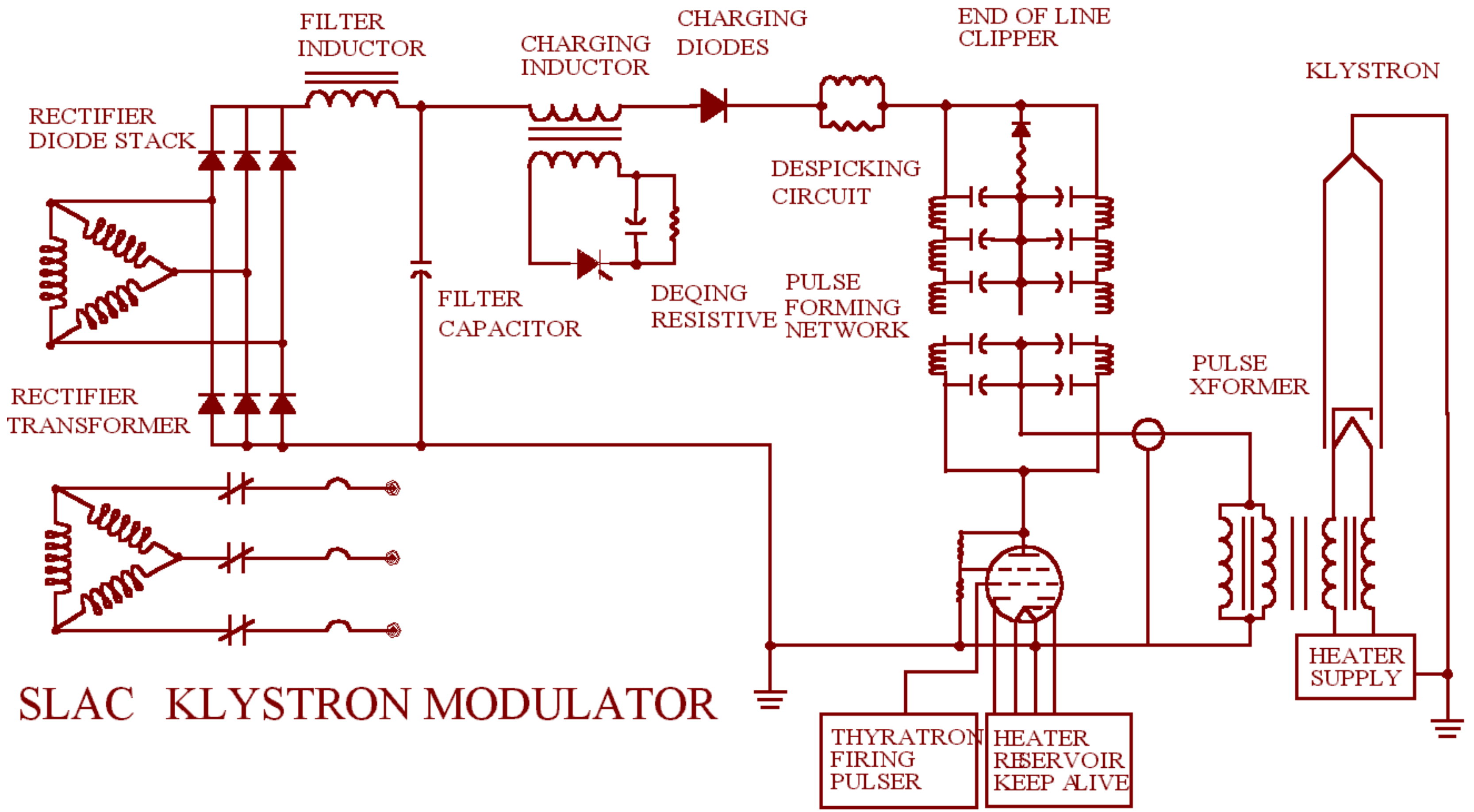
Average power = peak power *duty cycle(on-time*PRR)

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

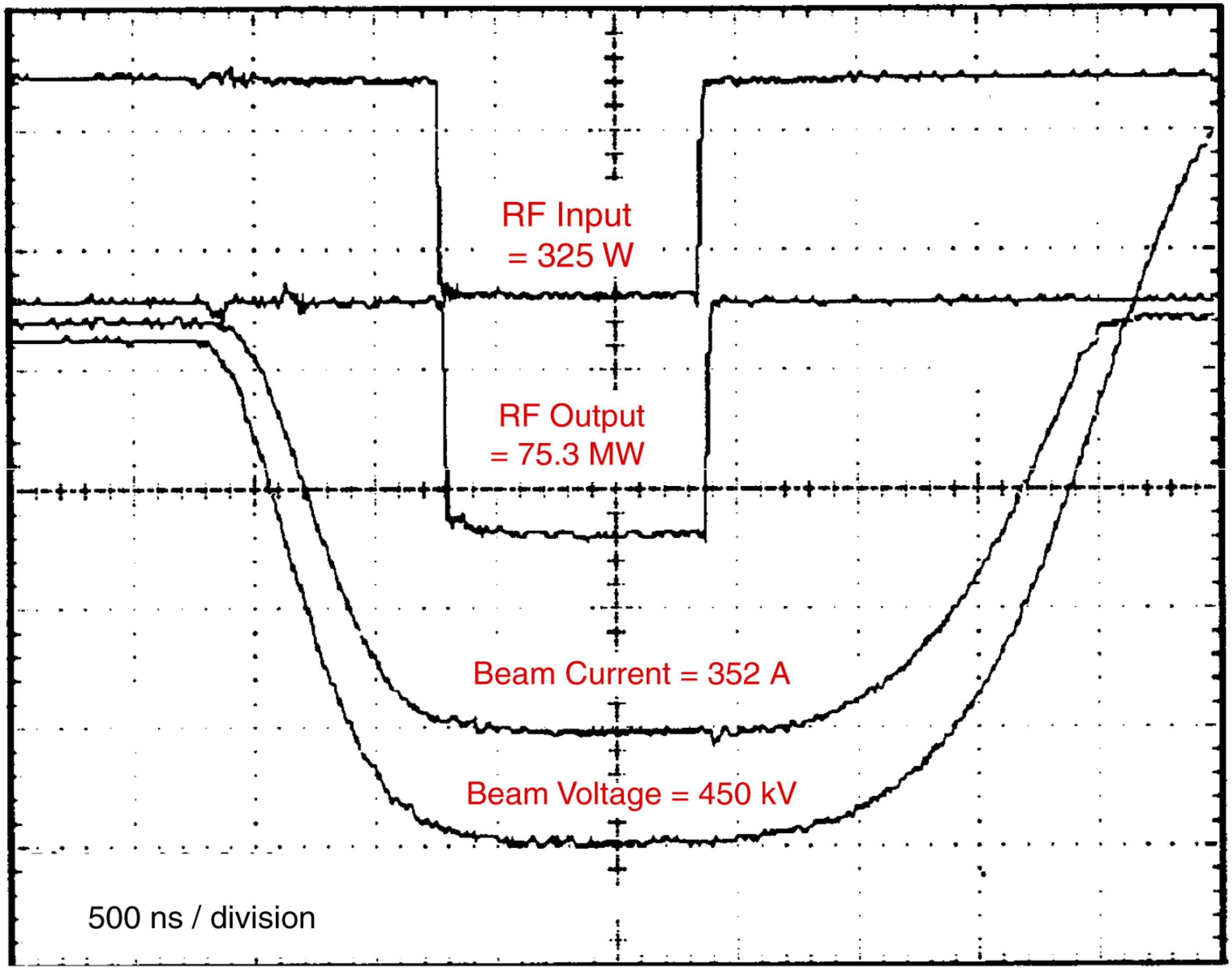
Transmission Line PFN

- *Open transmission lines are often used for Pulse Forming Networks (PFNs).*
  - *They are typically charged up from a high impedance source*
  - *Their open end is connected to a normally open switch that closes to connect the PFN to the load*
- *This situation can be viewed as a traveling wave reflecting back and forth off of two open ends*
  - *Total voltage on the line is the sum of the incident and reflected waves ($V_{PFN} = 2V_{LOAD}$)*
  - *Pulse has length 2 l / v, since the tail of the pulse must reflect off of the other open end before it reaches the load*

Present Klystron Modulator Power Supply

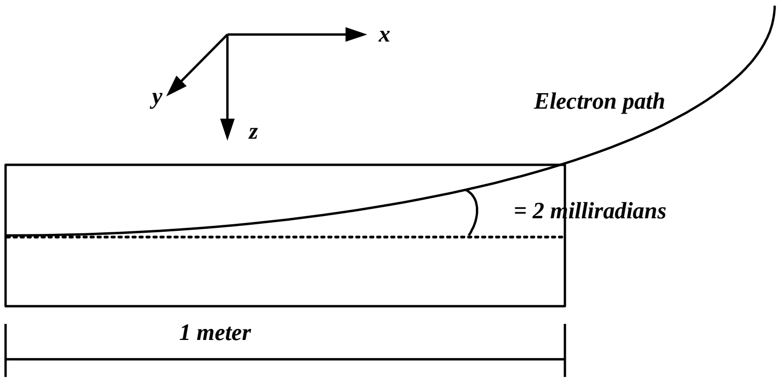


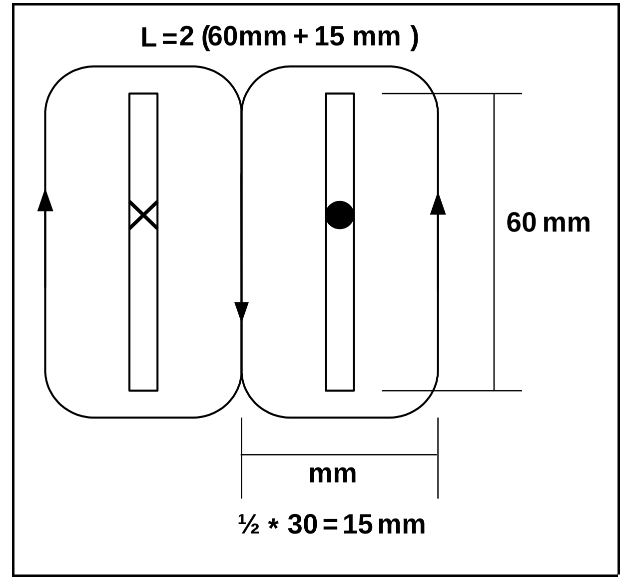
- *Primary VVT, with diode rectifier*
- *High voltage secondary with diodes and filter capacitor*
- *Protected against secondary faults*


RF Input
= 325 W
RF Output
= 75.3 MW
Beam Current = 352 A
Beam Voltage = 450 kV
500 ns / division

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

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

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

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

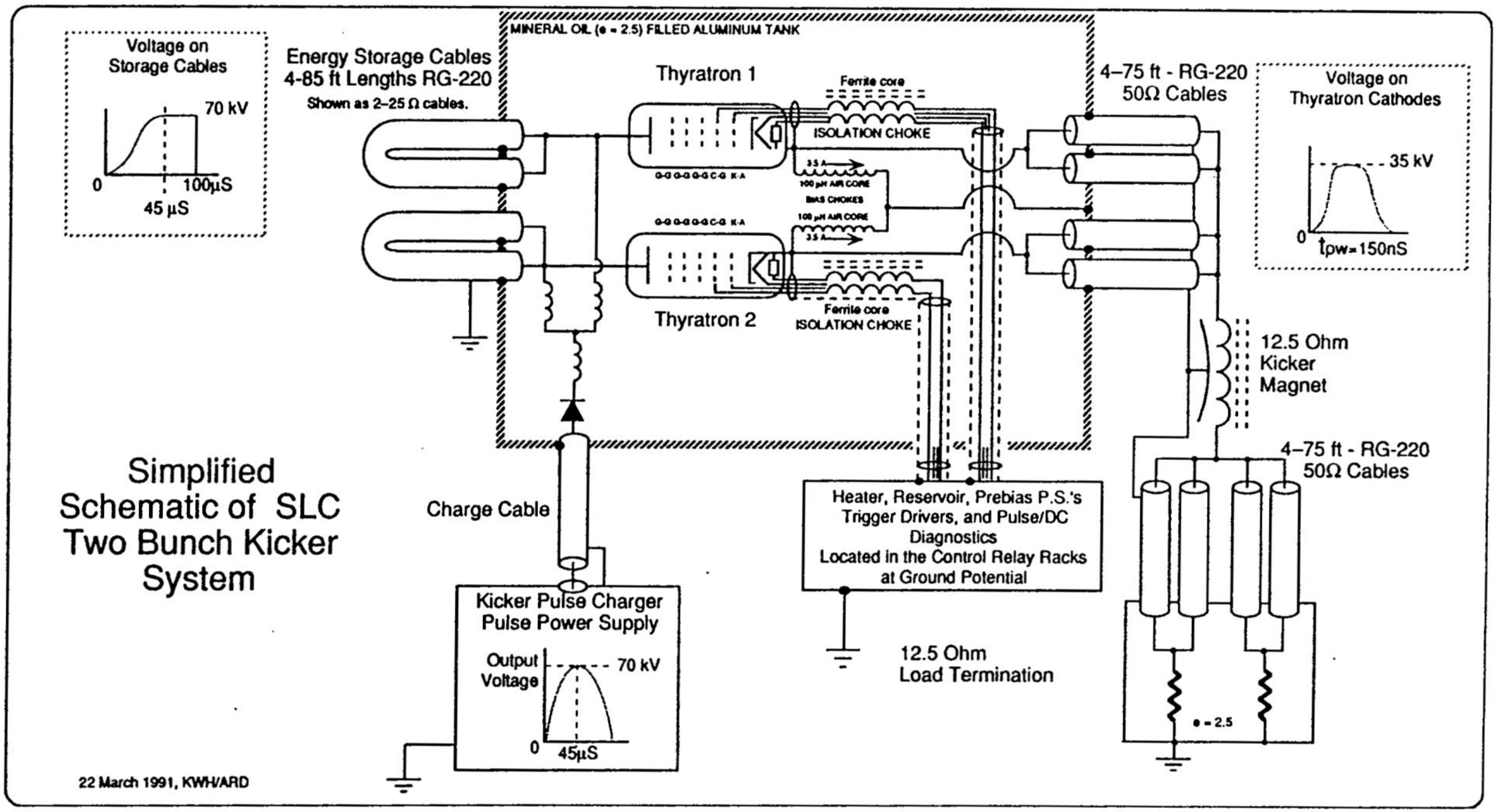
$E_x := 3 \cdot 10^{9} \cdot eV \quad E_y := E_x \cdot \tan(\theta) \quad E_y = 9.6 \times 10^{-13} J \quad E_y = 6 \times 10^{6} eV \quad F_y := \frac{E_y}{L_{mag}} \quad F_y = 9.6 \times 10^{-13} N$

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

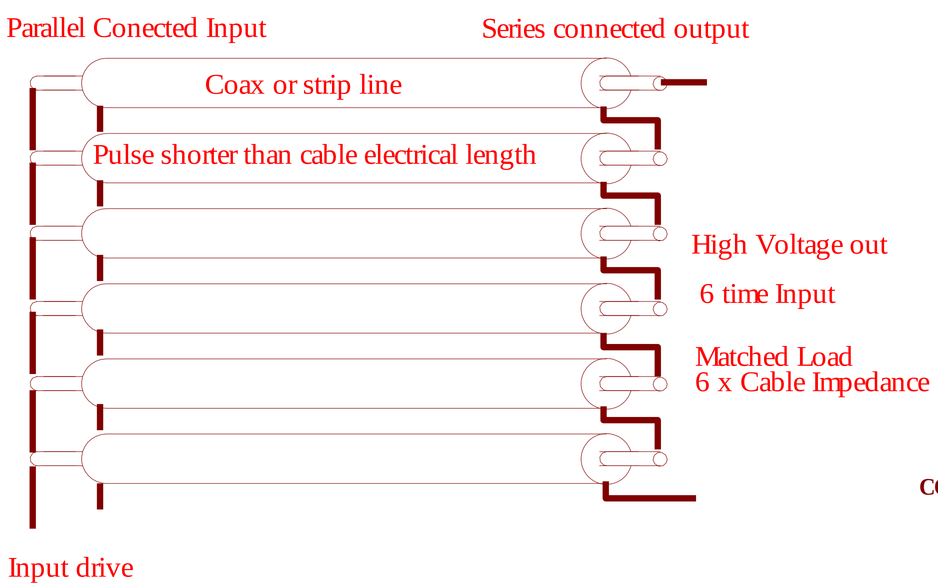
Kicker or Fast Modulator

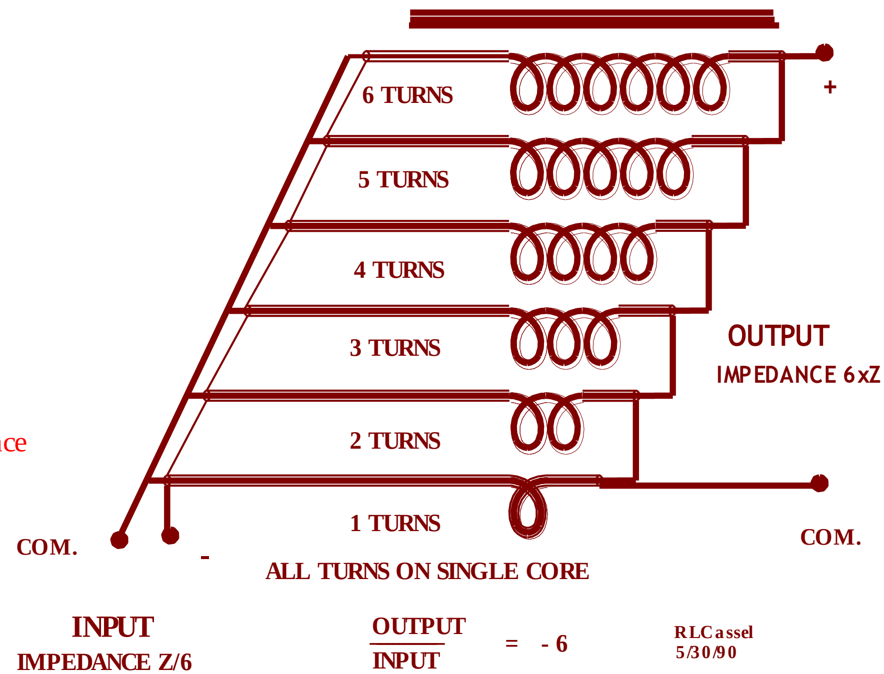
- *Improve the rise time of modulator pulse using Cable PFN*
- *In line Switch with PFN*
- *Blumline with Shunt Switch*

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



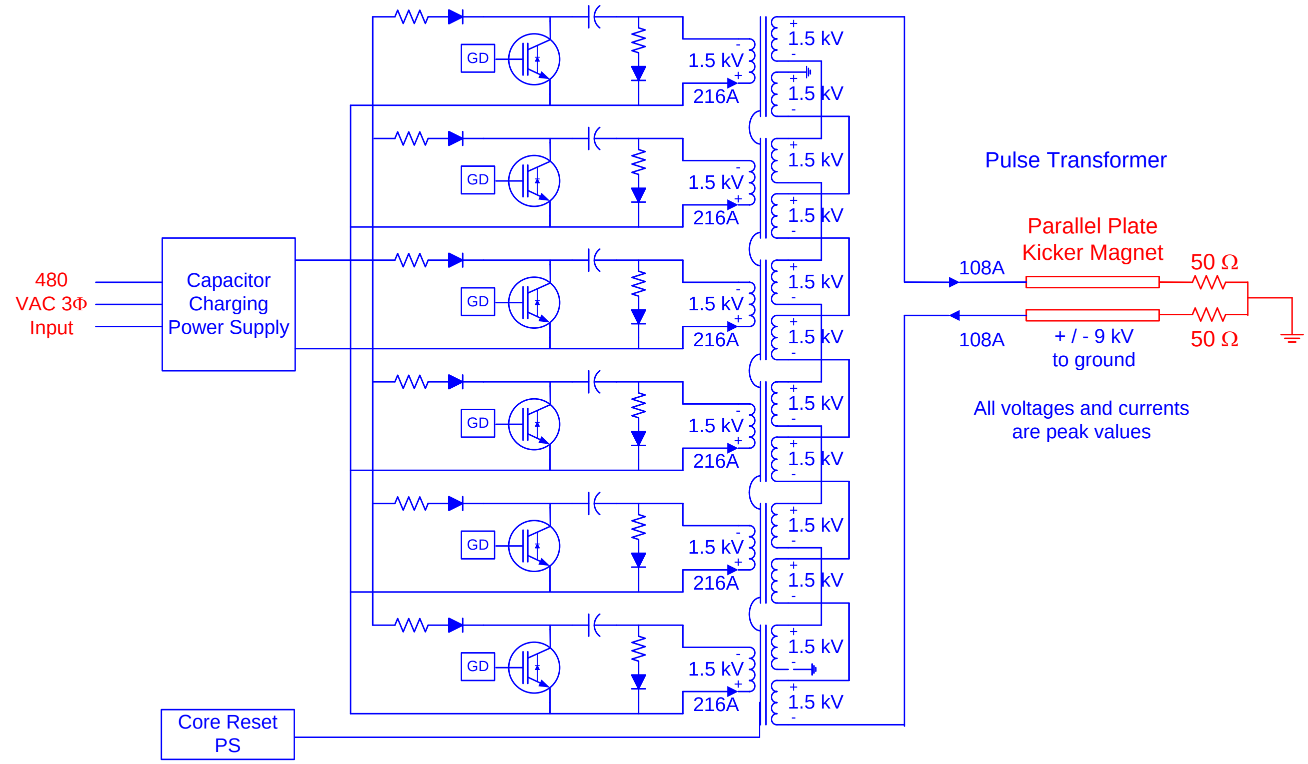
- *Cable Pulse transformer connecting the input of a cable in Parallel and the Output In Series and if the pulse is shorter than twice the electrical length of the cable and driving a matched load cable transformer works.*
- *Fast rise time with simple transformer*
- *Disadvantage stray capacitance and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





Solid-State Pulsers

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*

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*

Ongoing Developments

- *Replace Thyratron with solid-state switch SCR, IGBT, MOSFET, etc*
- *Having a high enough di/dt capability is the problem*
- *IGBTs without PFNs are being used at the present time*

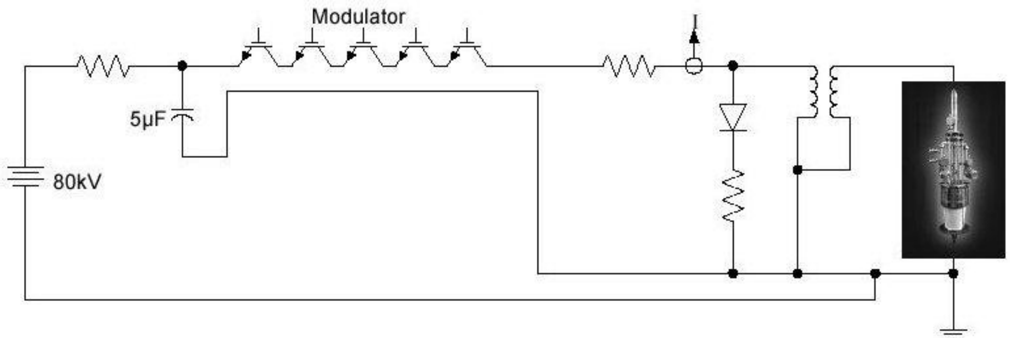
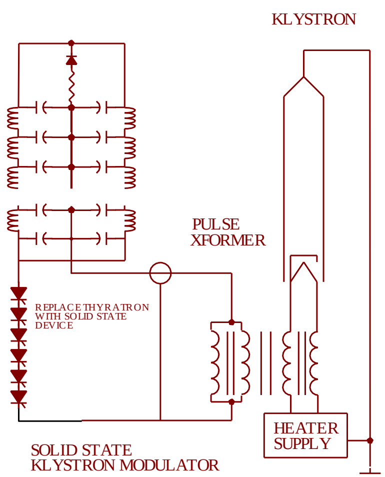


Figure 1 The hybrid modulator block diagram shows the high voltage power supply, the solid state modulator with energy storage capacitor, and the pulse transformer.



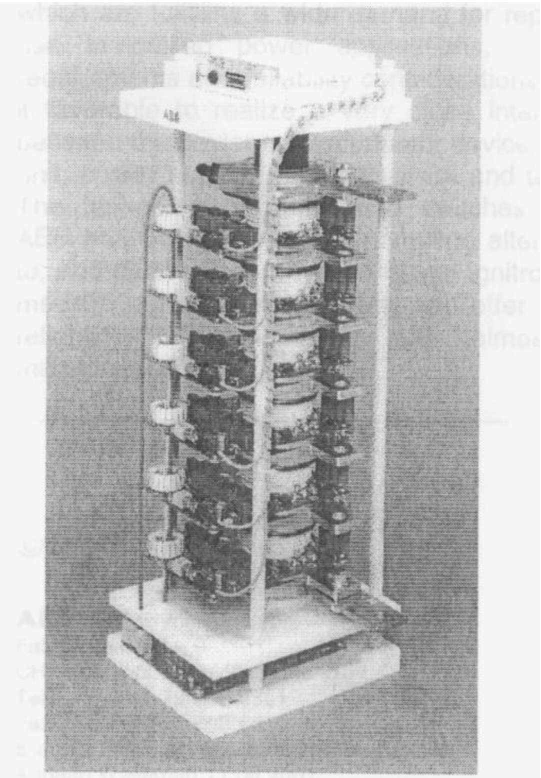
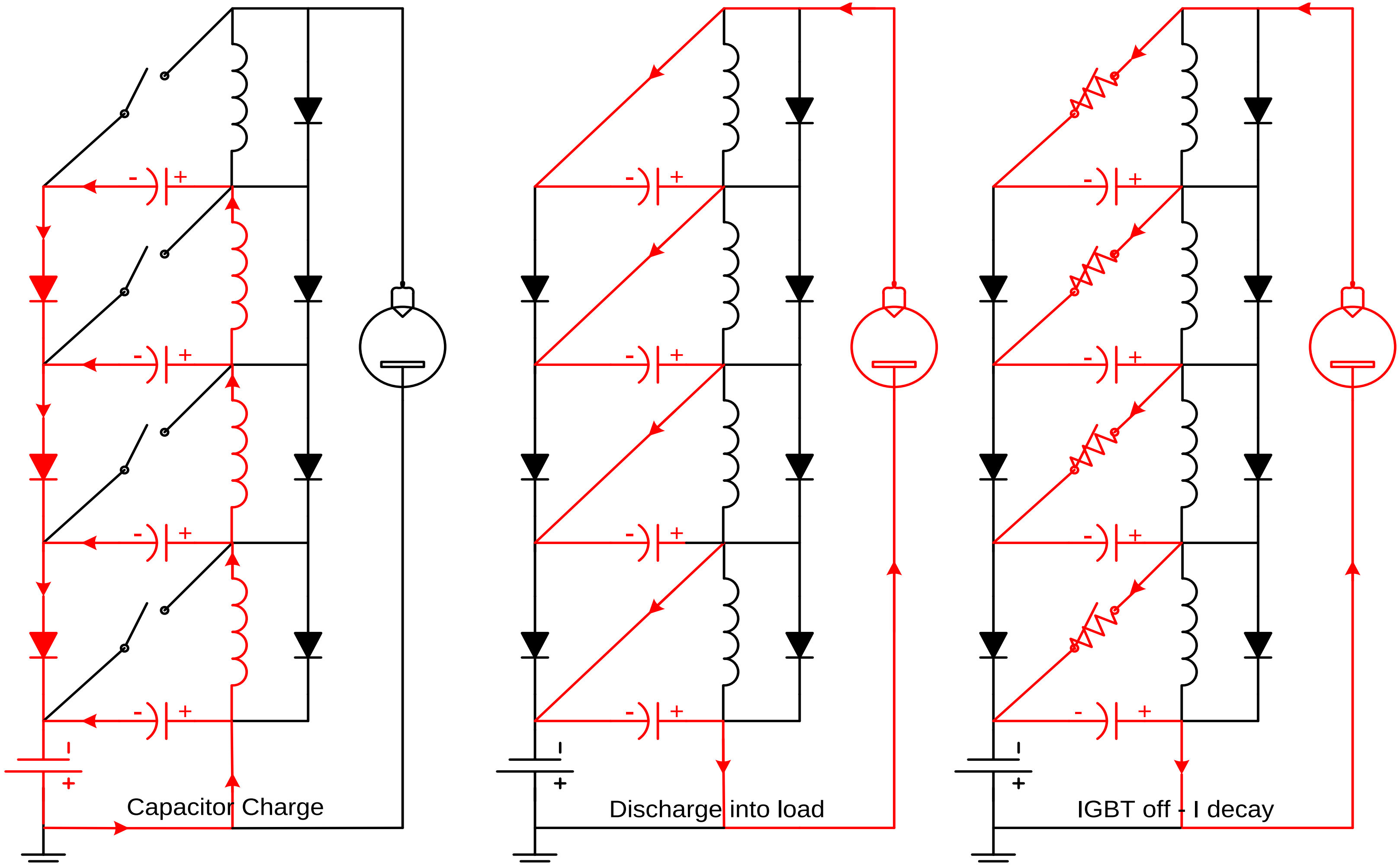


Fig. 11) Switch Assembly SPR-08F45-6-WC

ABB Semiconductor AG

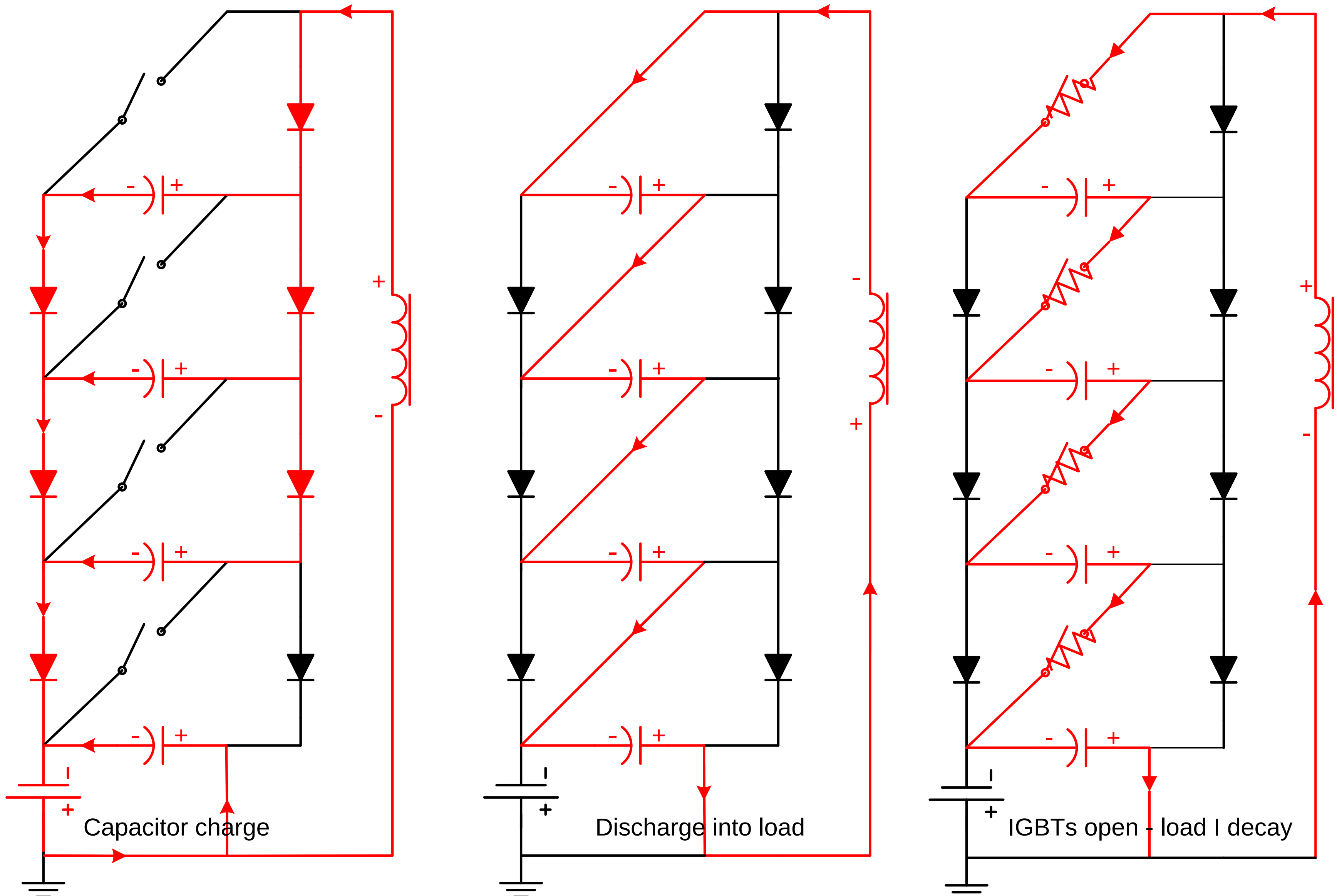
Solid-state Marx Generator for Modulators or Kickers

- 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



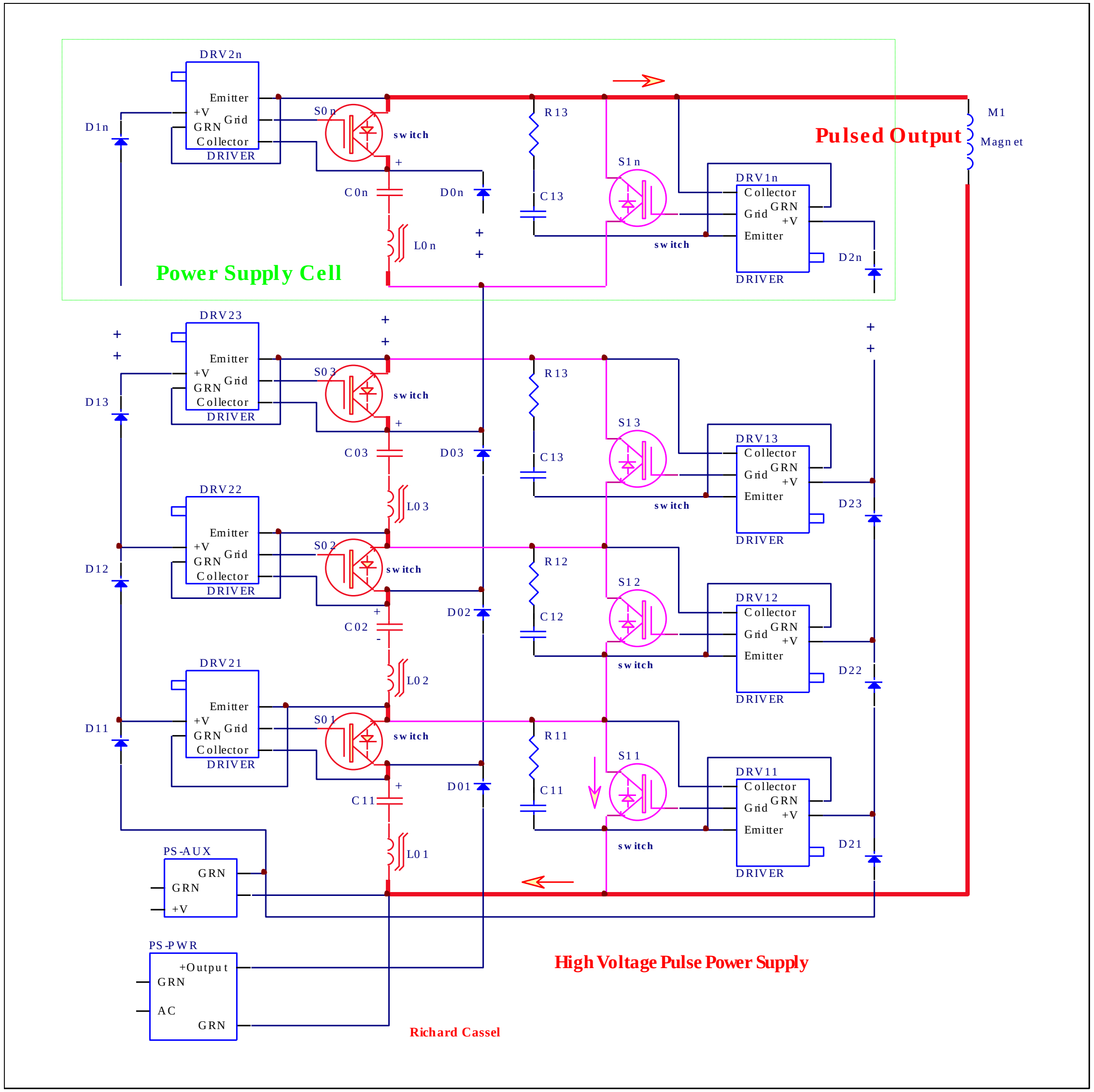
Solid-state Marx Generator for Modulators or Kickers

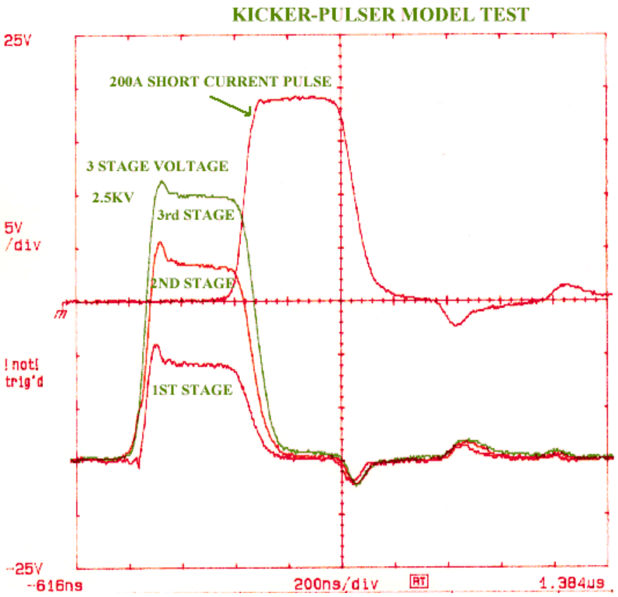
- *If the load is a magnet, the charging inductors are not required*



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*

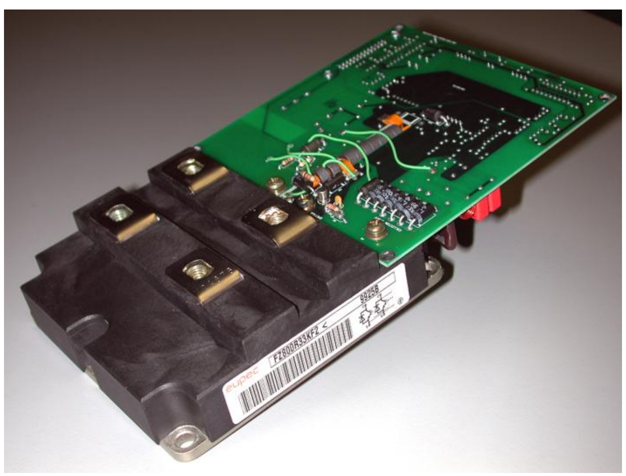


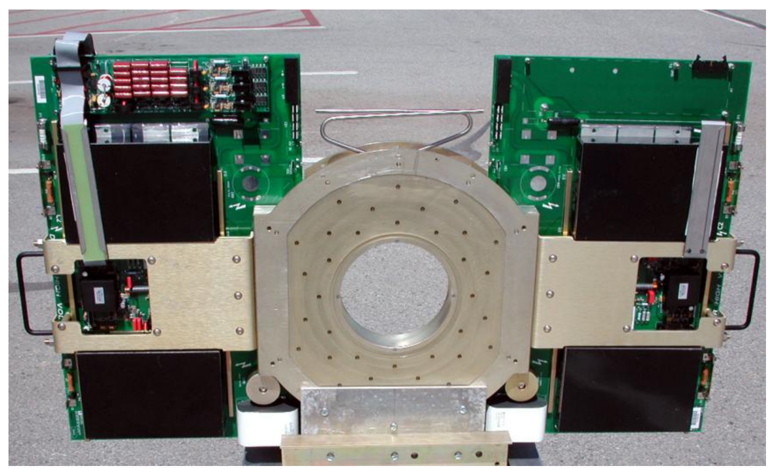


Solid State Induction Modulators

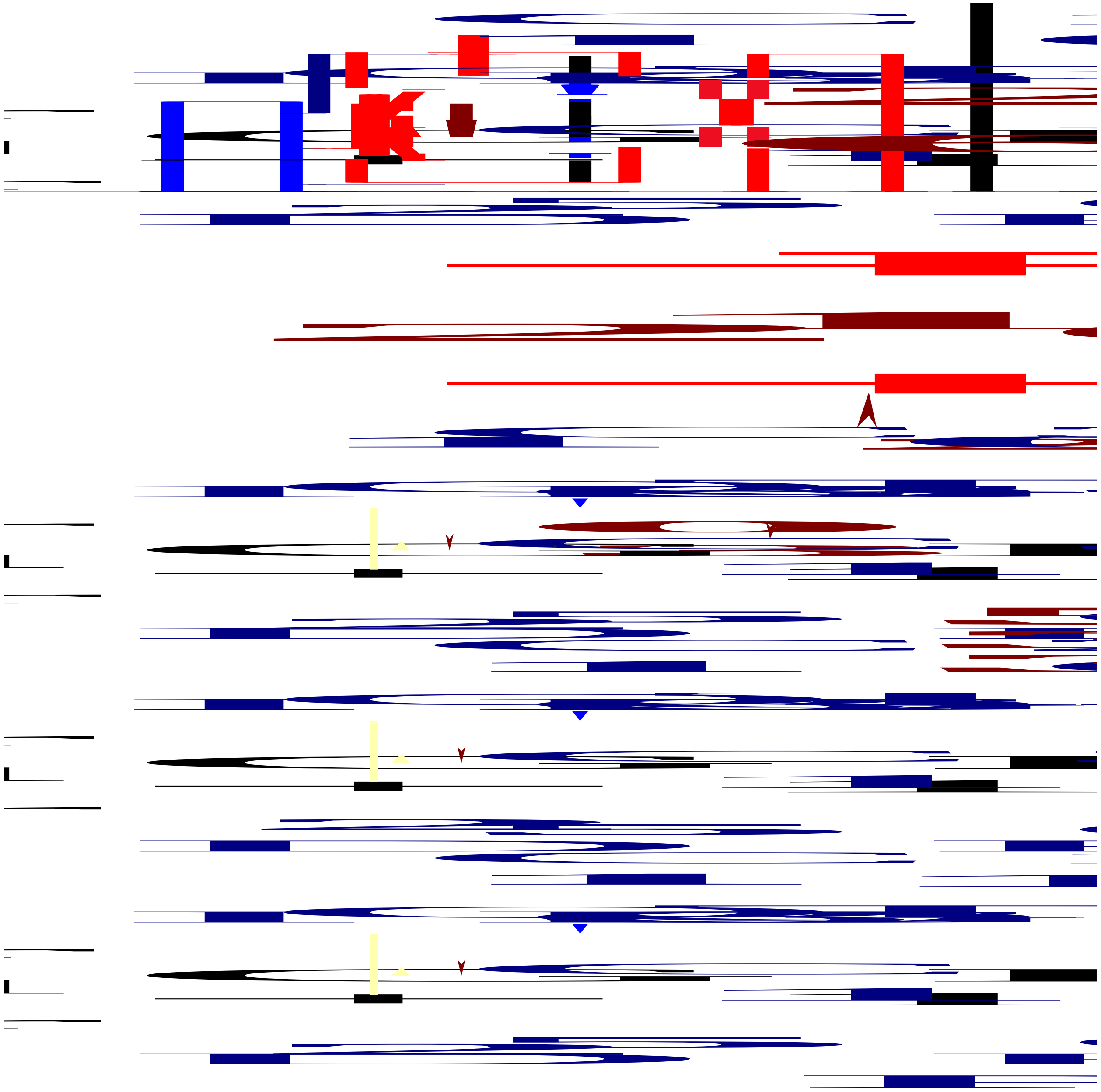
- *Fractional turn pulse transformer*
  - *–Similar to a induction accelerator*
  - *–Multiple primaries driven in parallel*
  - *–The secondary connected in series*

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

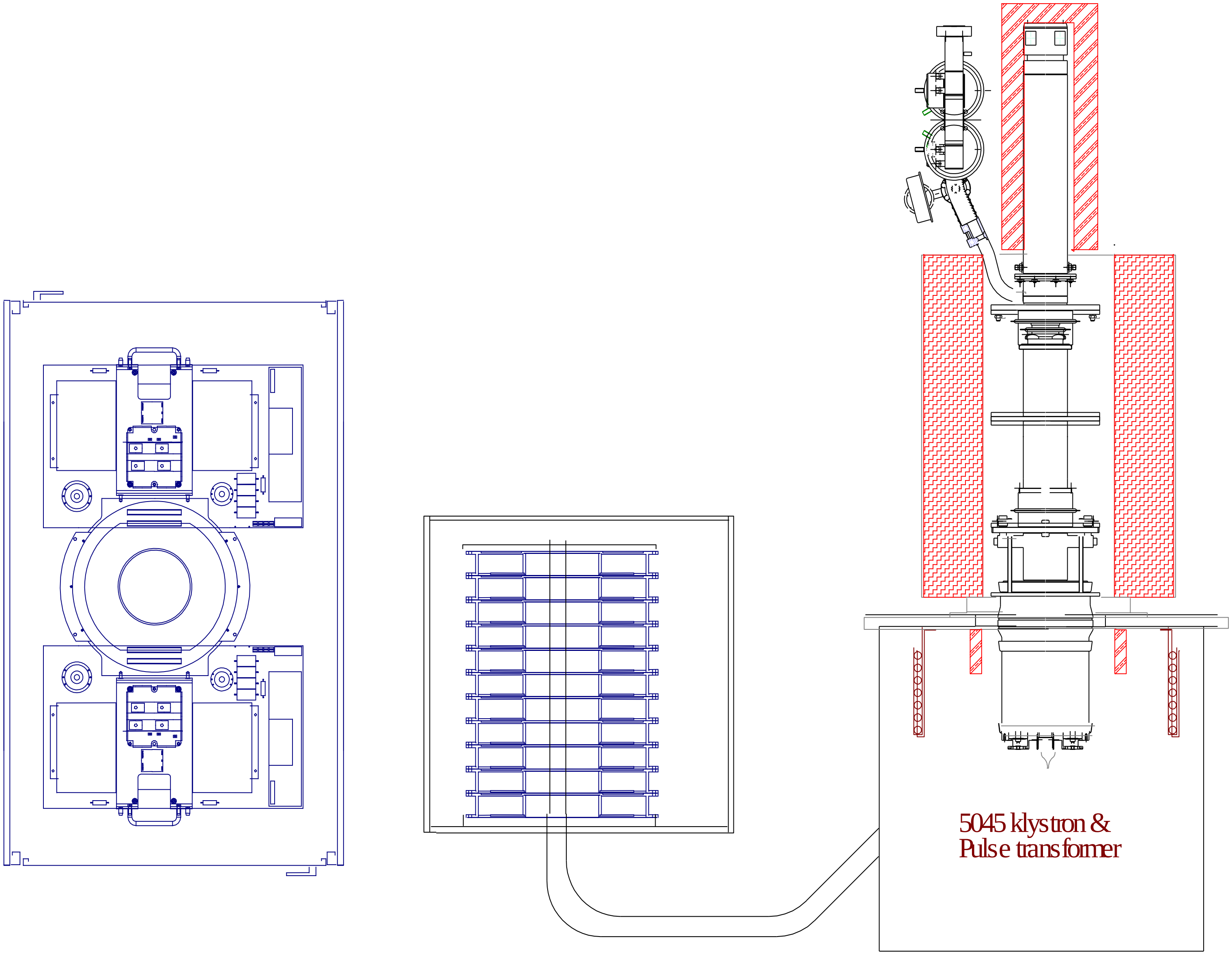




Solid State Induction Klystron Modulator



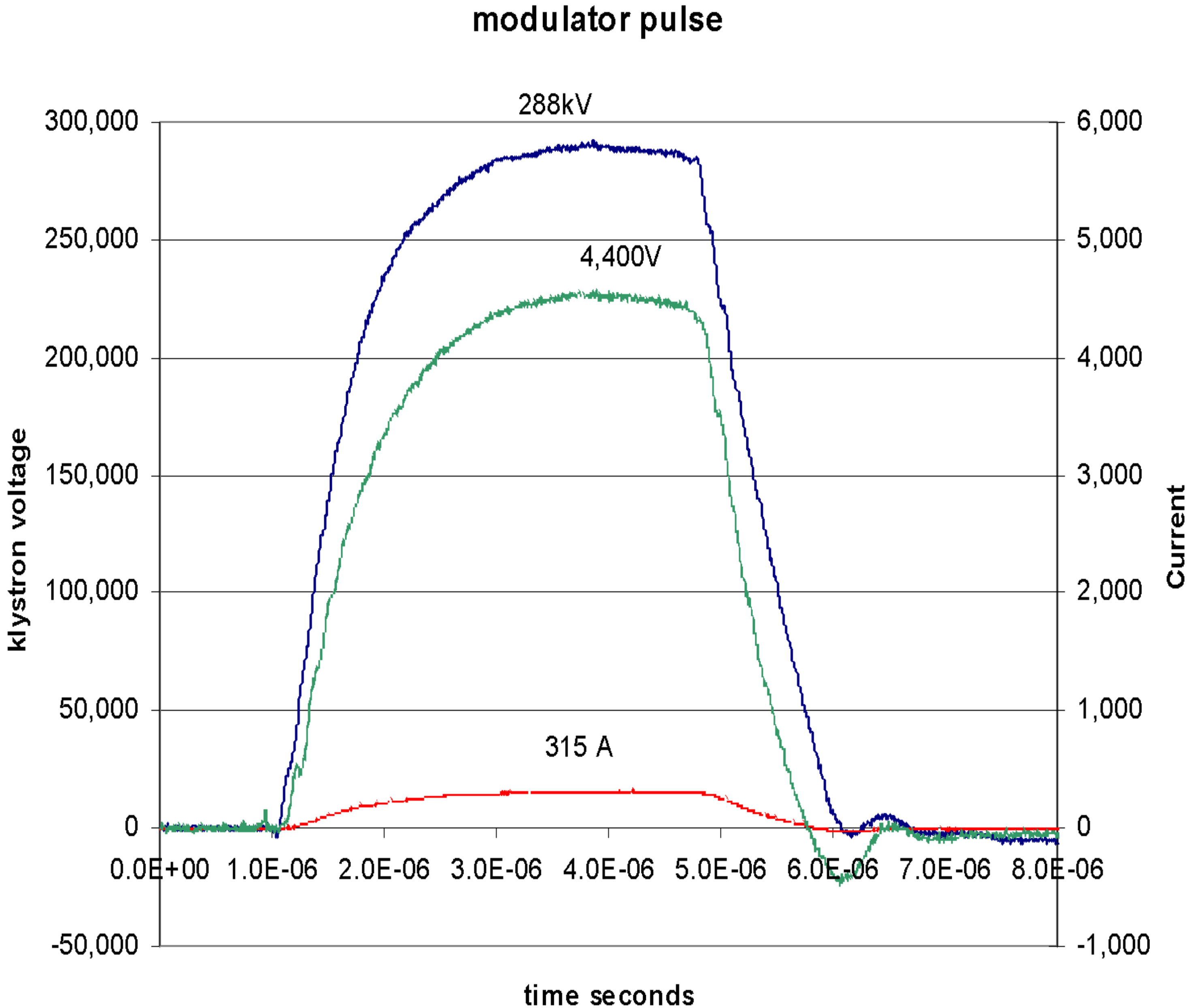
Solid State Induction Klystron Modulator



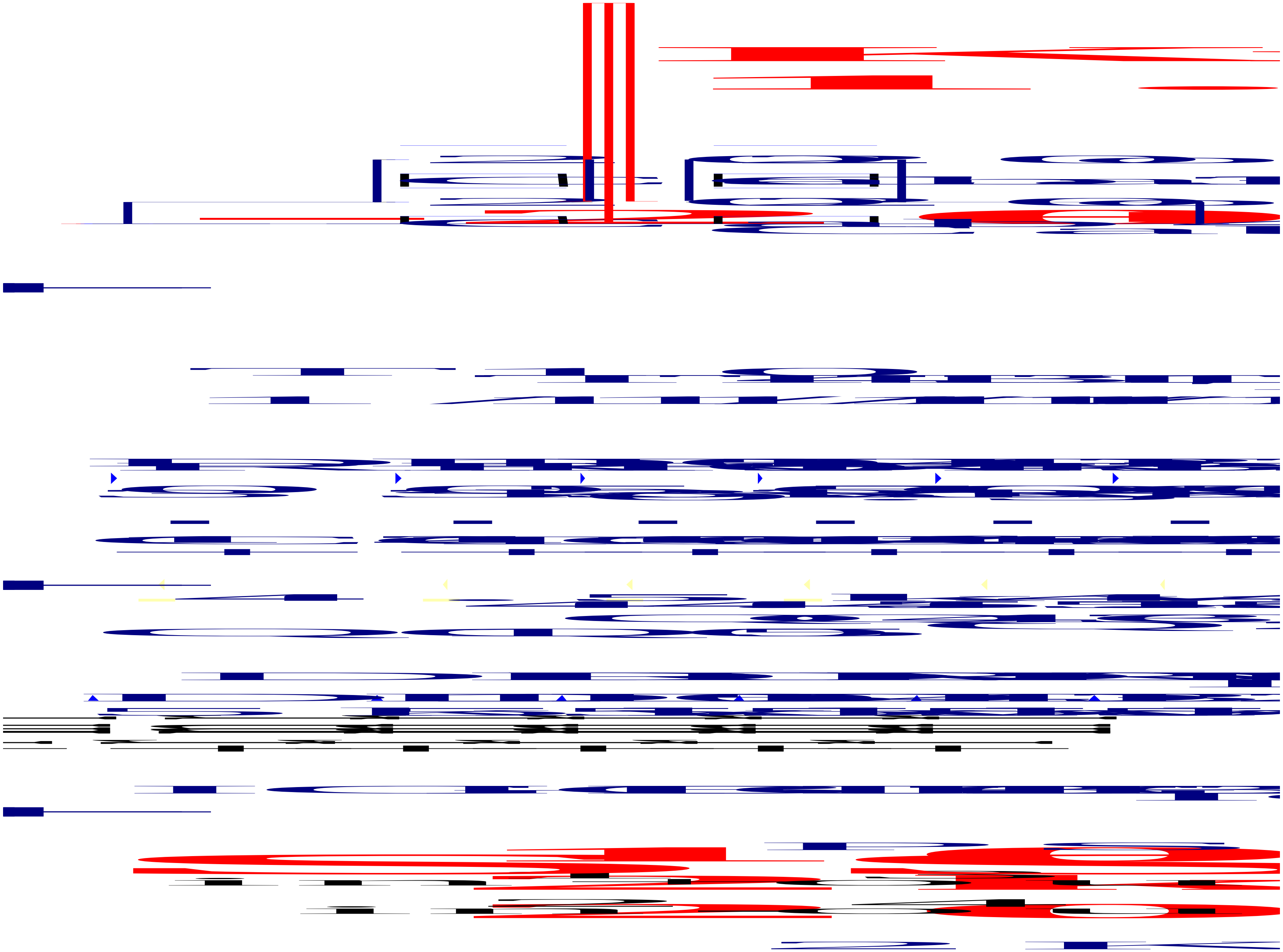
Solid - State Induction Klystron Modulator

- *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*

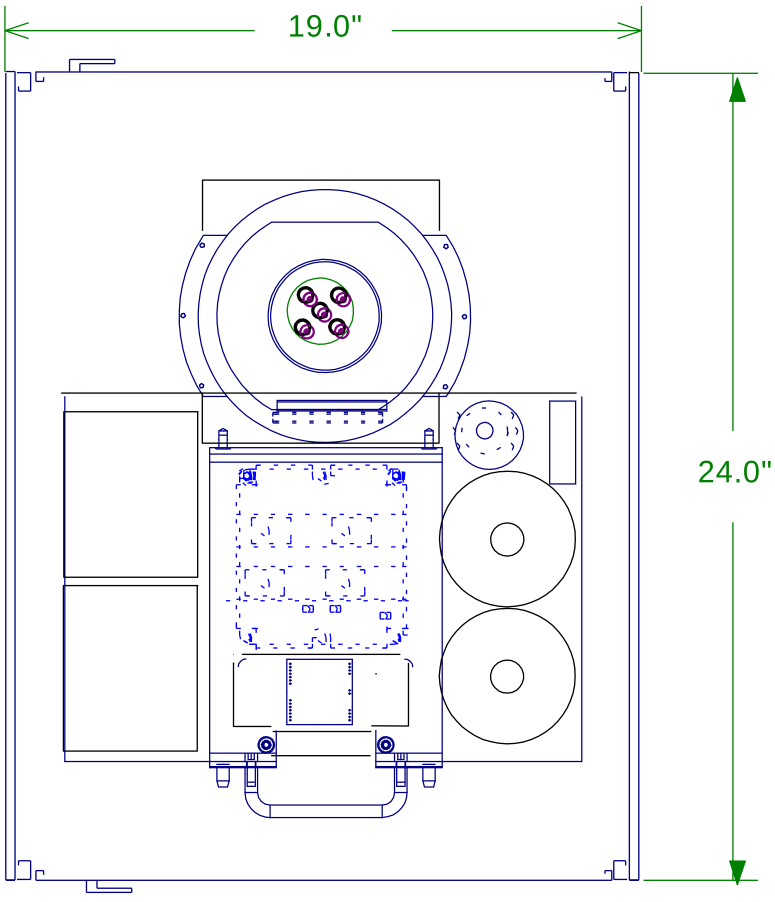
Solid - State Induction Klystron Modulator

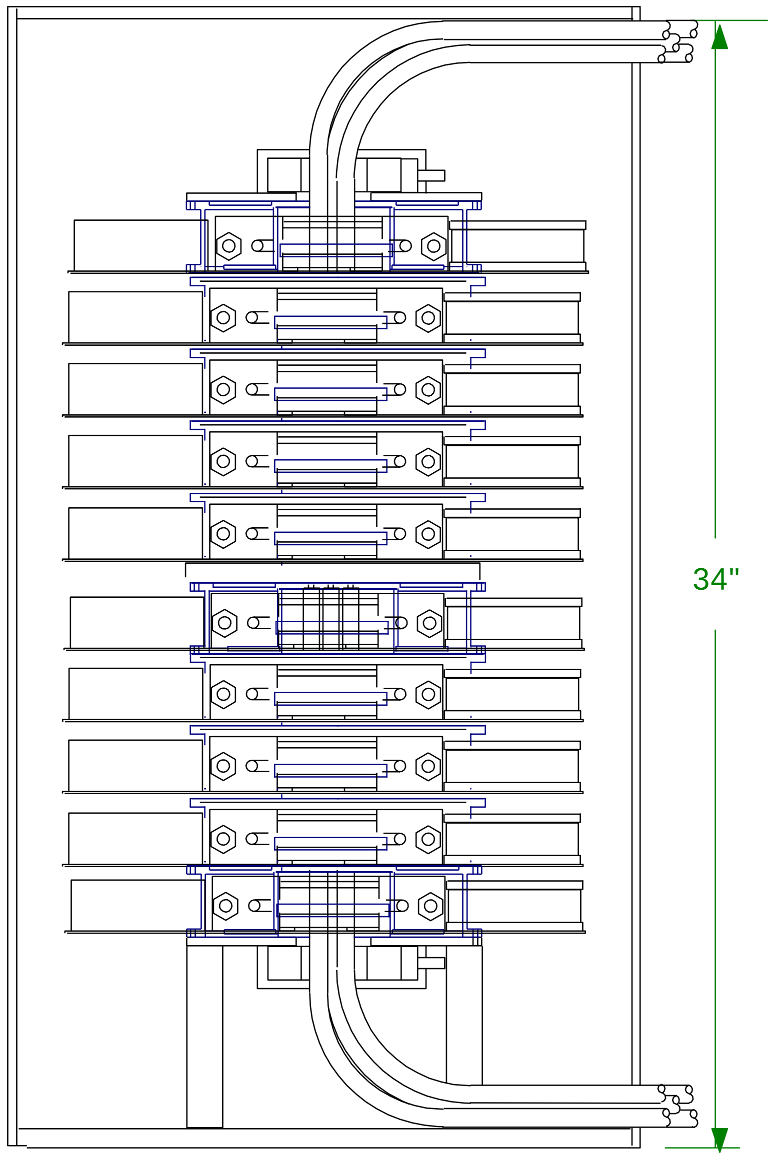


Induction Kicker Modulator



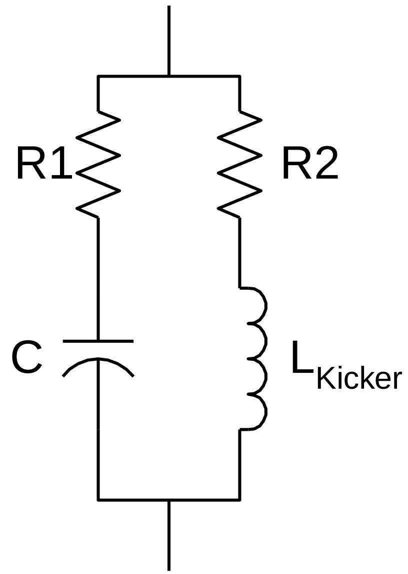
2 ea. 10 kV 2.5 kA
0.6 meters 1.5 mrad





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:
$\varepsilon_r = 1$ $\varepsilon_r = 2$ $\varepsilon_r = 4$ $\varepsilon_r = 8$ $\varepsilon_r = 16$

7. Magnetics

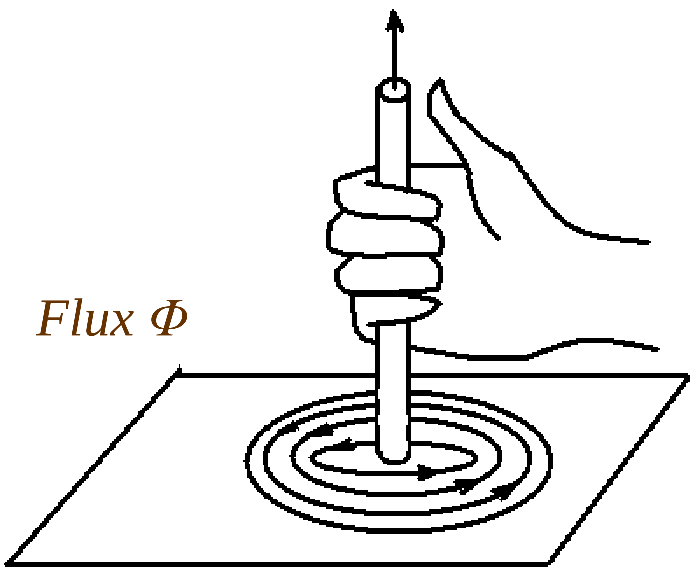
The Electric - Magnetic Equivalence

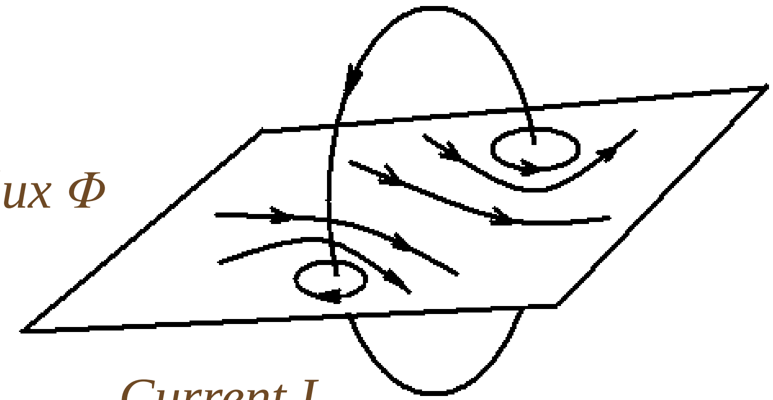
- *Magnetic circuits are analogous to electric circuits and are important for the analysis of magnetic devices. The equations for both electric and magnetic circuits show strong similarities*

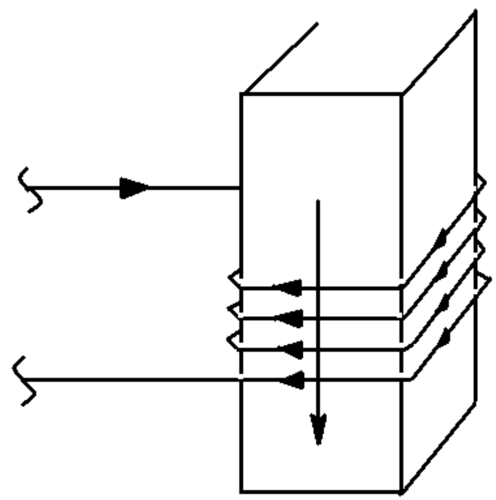
- *Various magnetic types, such as transformers and filter inductors, play a key role in many of the components used in power supplies*

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

Field Due to a Current







Right Hand Rule:

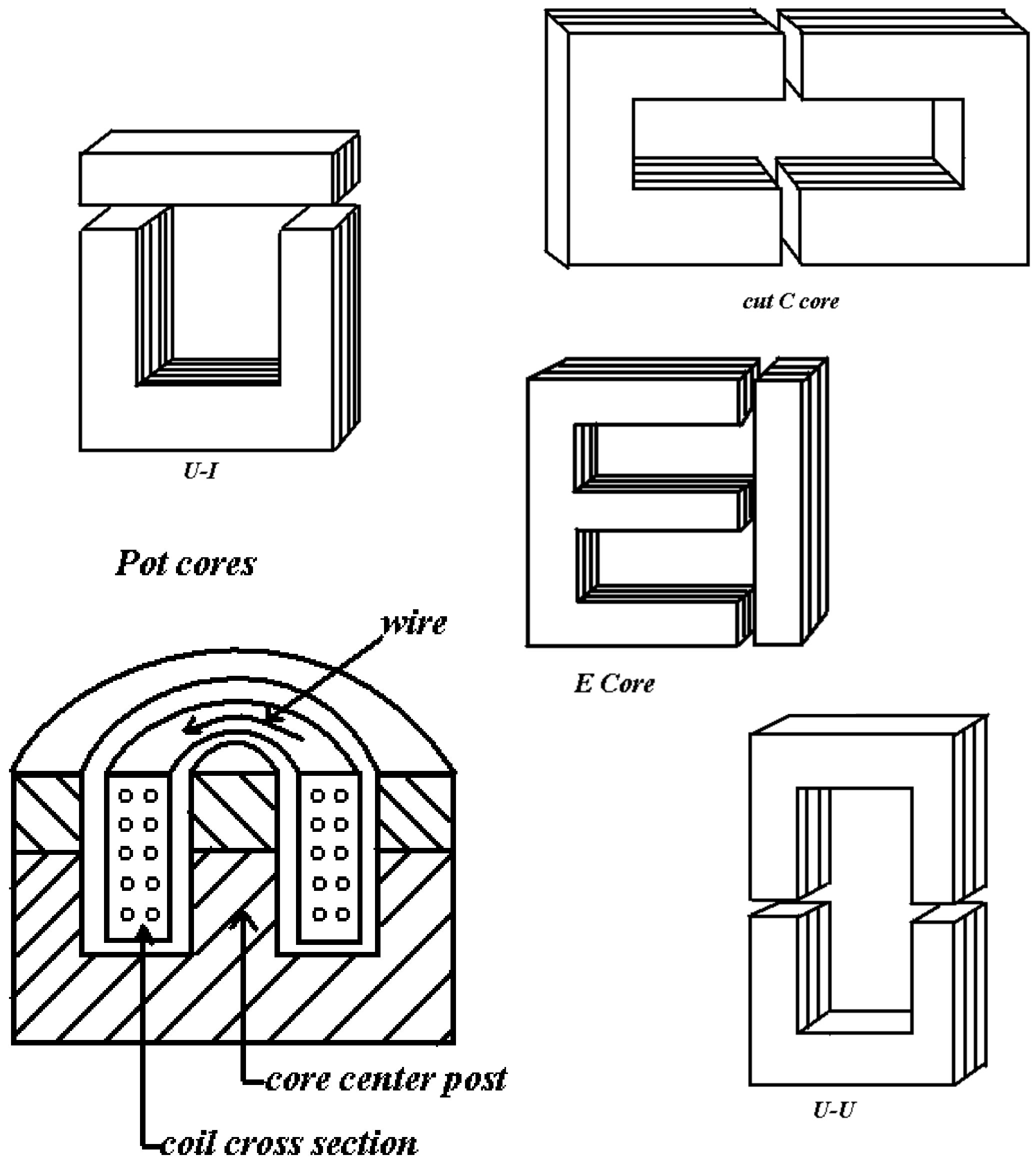
- *Thumb = Current*
- *Fingers Point in Direction of Magnetic Field*

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

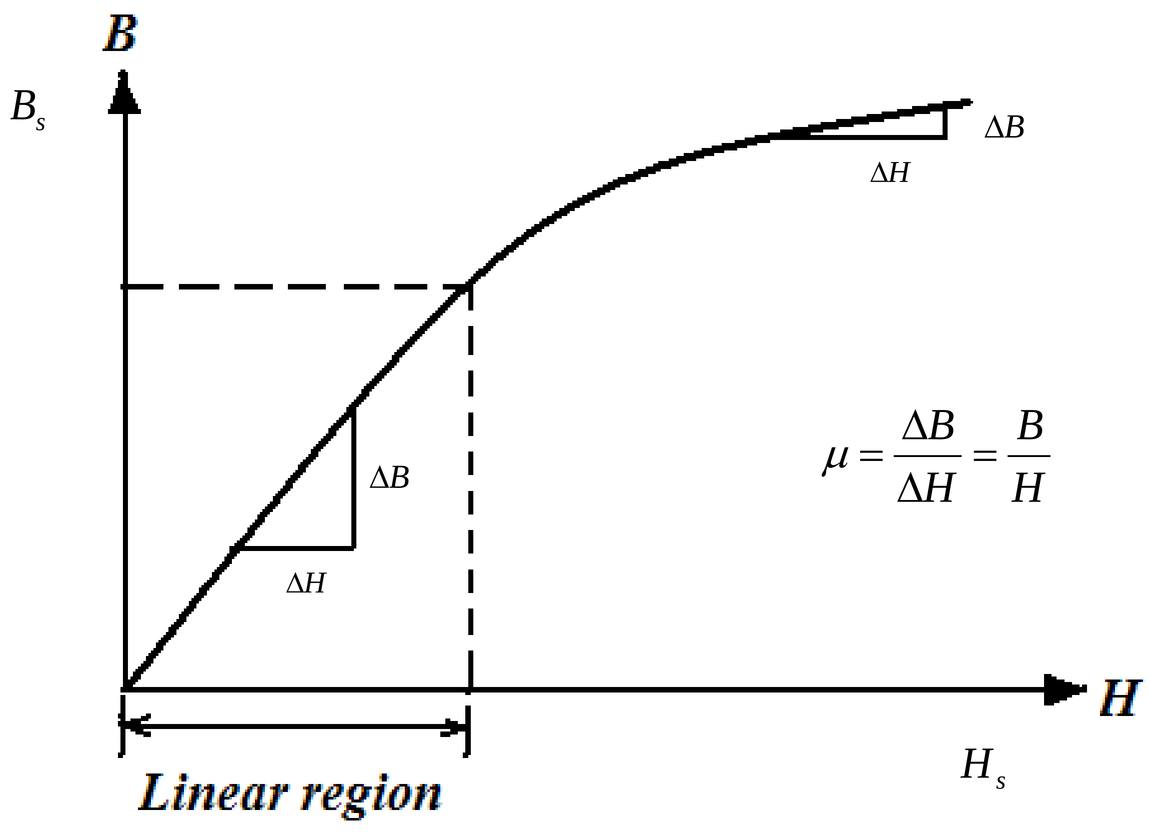
- U-U, U-I cores
- E-E, E-I, ETD cores
- POT cores
- RM cores
- PQ and PM cores
- EP, EFD and ER cores
- Toroid



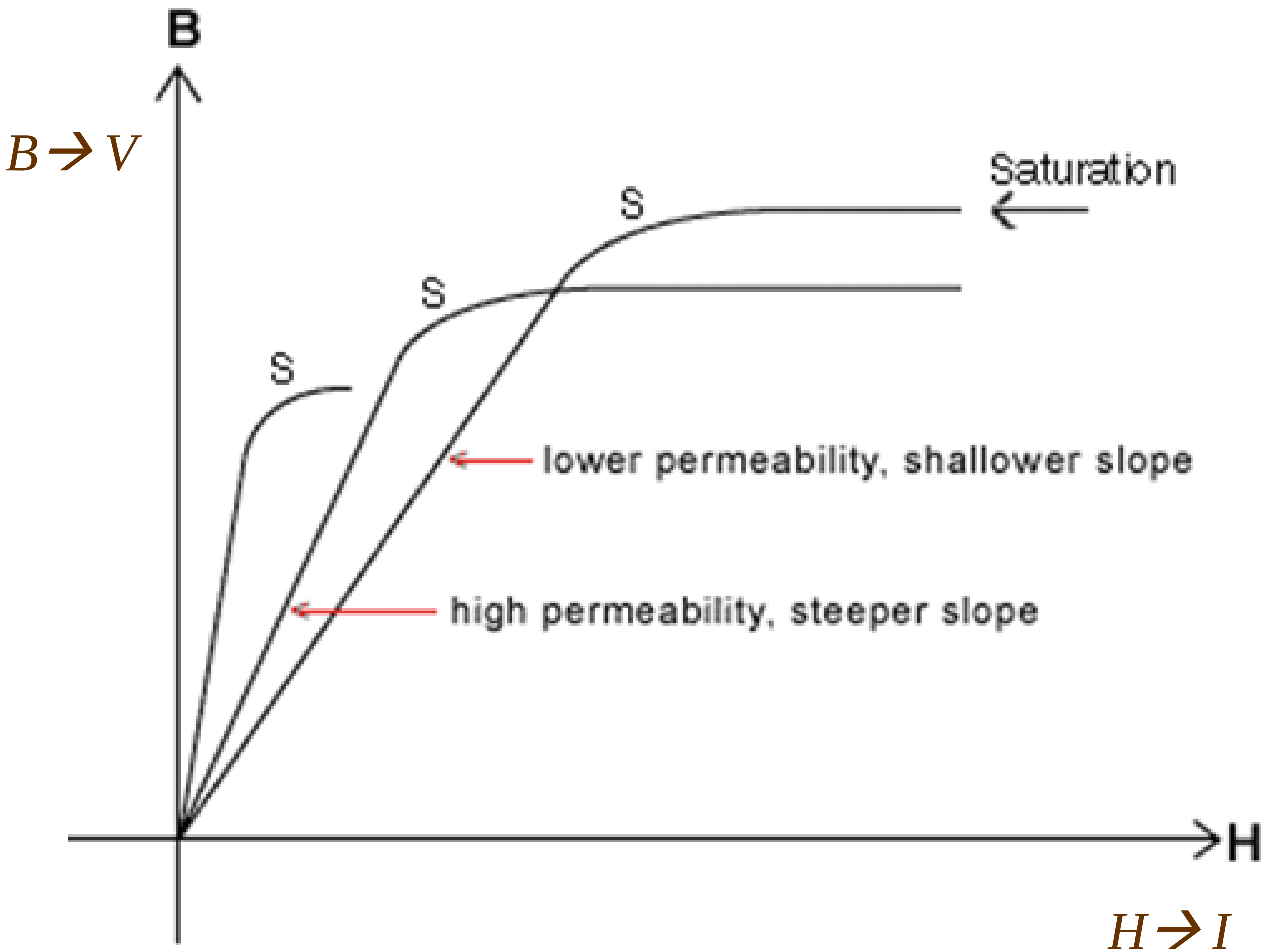
Permeability Definitions

- 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

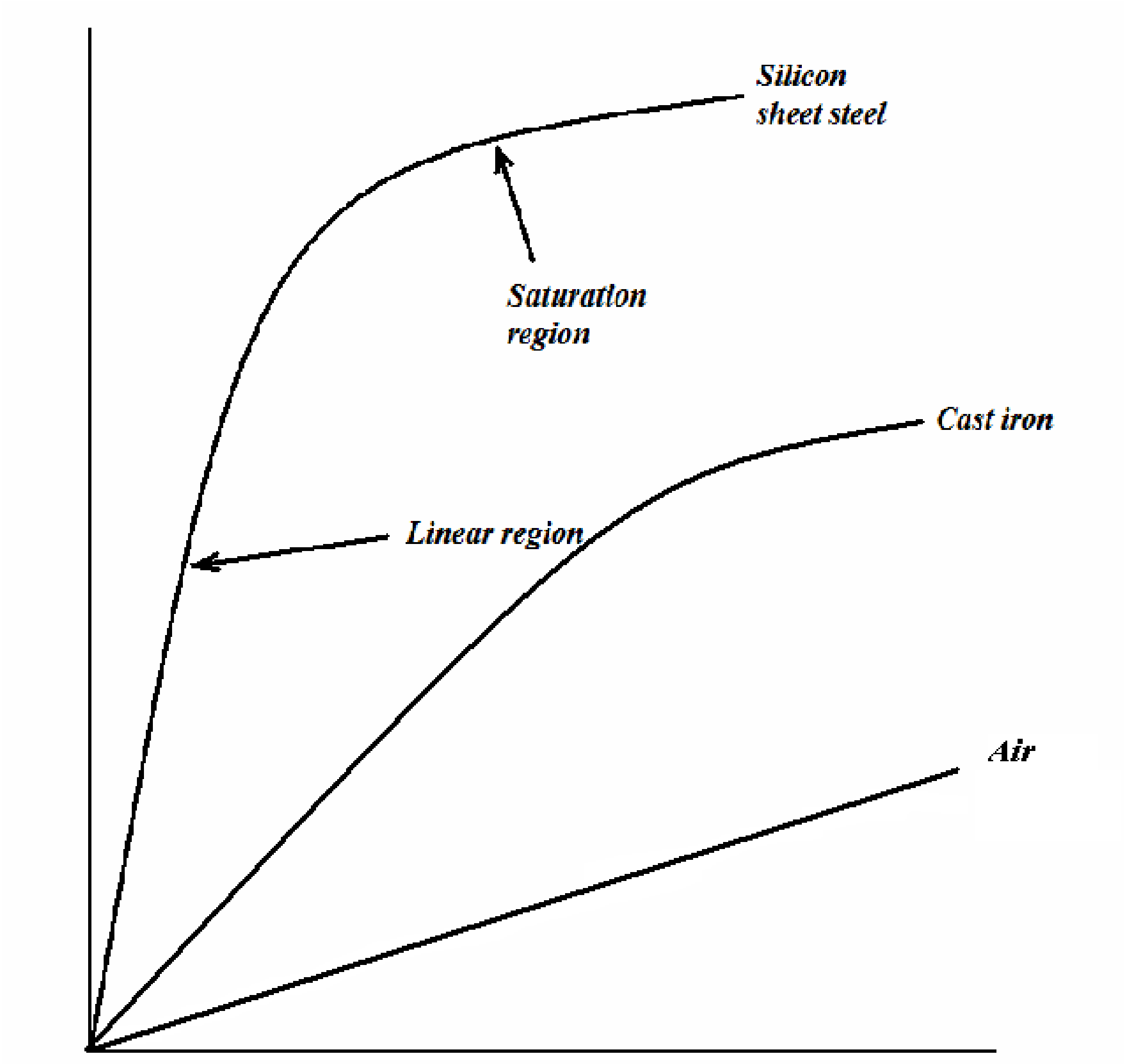
Core Materials
Air
Alloys
Amorphous
Iron Powder
Manganese-Zinc Ferrite
Molybdenum Permalloy Powder
Nickel-Zinc Ferrite
Sendust
Silicon Steel


B
B_s
ΔB
ΔH
ΔB
ΔH
$\mu = \frac{\Delta B}{\Delta H} = \frac{B}{H}$
H
H_s
Linear region

Important Transformer Concepts



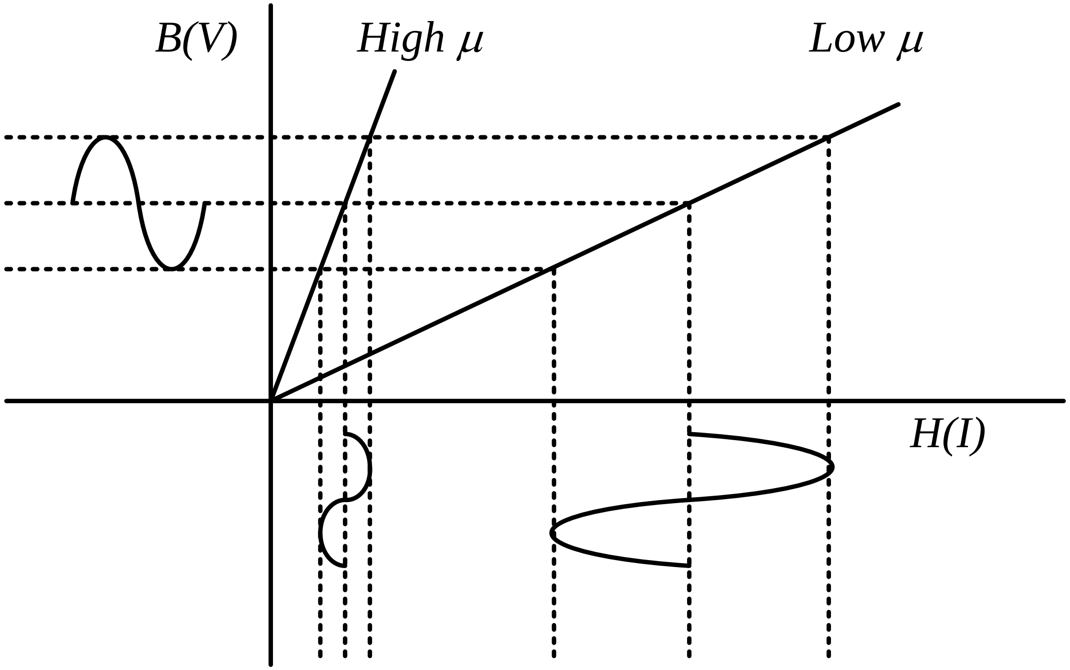
Material Comparison



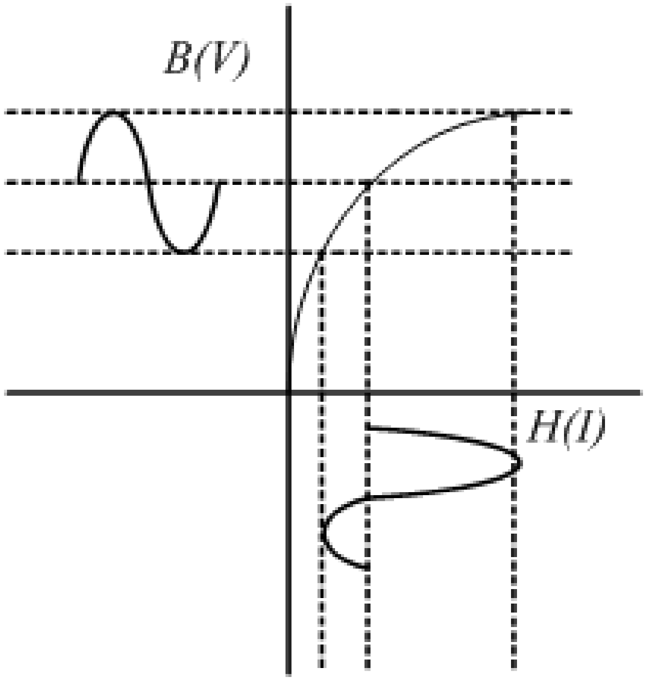
Core Material Guidelines

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 Φ(t)

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

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

$$\Phi(t) = -\int v_t(t) dt$$

$$\Phi(t) = \int_s B(t) \bullet da_c$$

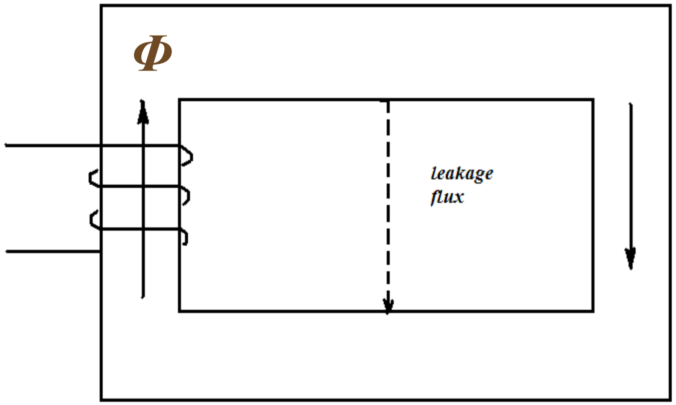
$$\int_s B(t) \bullet da_c = -\int v_t(t) dt = -\int \frac{V_{max} \cos 2\pi f t}{N_p} dt$$

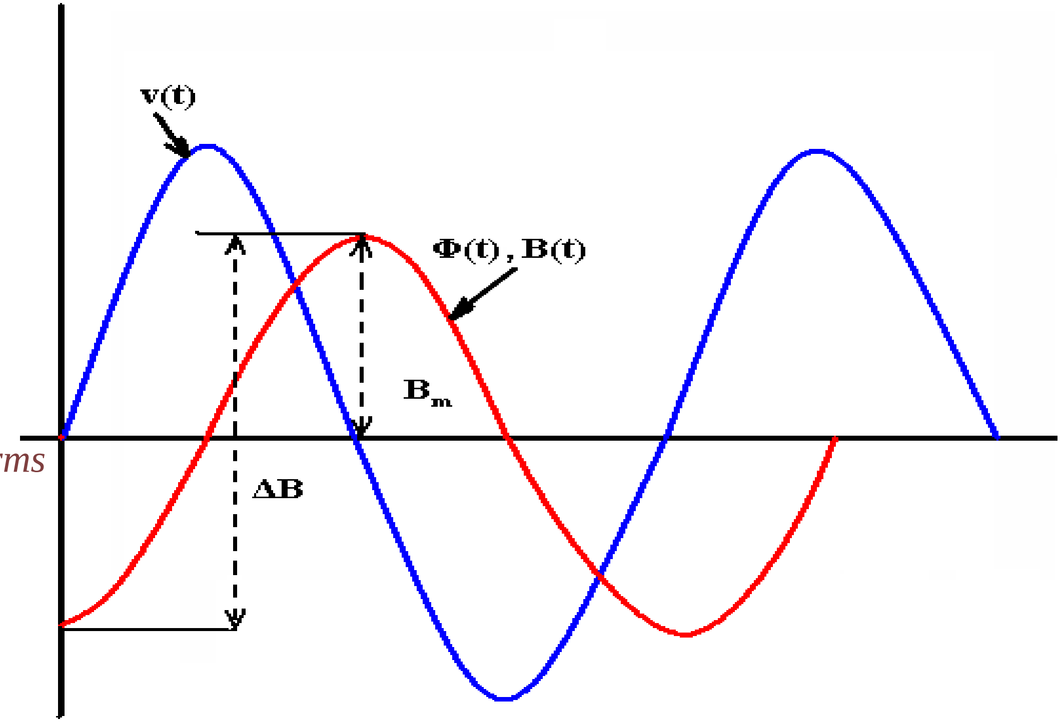
$$B(t) A_c = \frac{V_{max} \sin 2\pi f t}{2\pi f N_p}$$

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

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

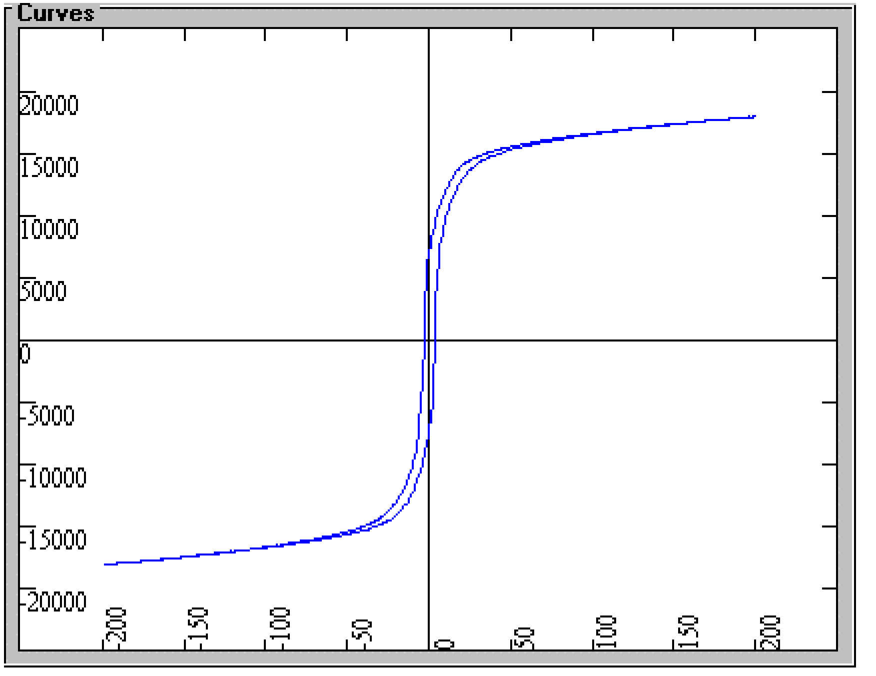
$4.44 = \frac{\sqrt{2}}{2\pi}$ converts peak AC to rms and ω to f

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

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

For square wave or rectangular wave excitation

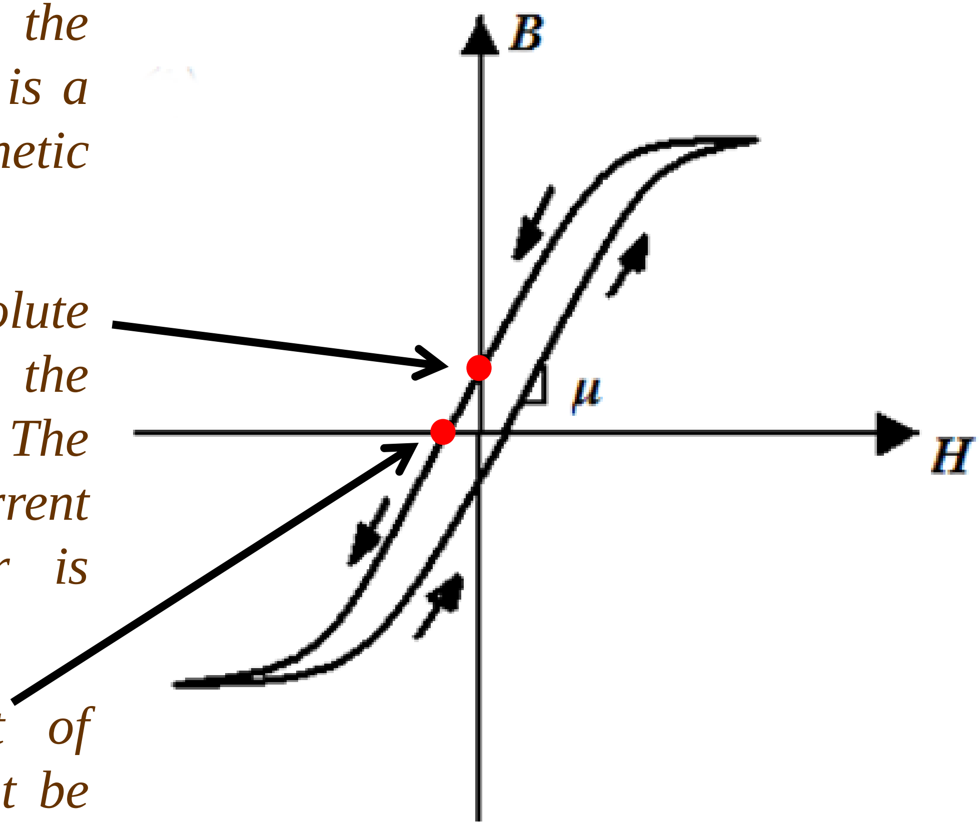
$$B_{max} = \frac{D * V_{peak}}{4 * f * A_c * N_p * 10^{-8}}$$

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 = 71 kilolines per square inch

B_r = residual flux density in kilolines (Maxwells) per square inch

= 60% of 1.05T, expressed as 43 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

$$i_{max} = \frac{10^3 * 40 * 46.5 * ((43 + 2 * 71) - 130)}{3.2 * 60 * 69.4} = 7.68kA$$

This is about 11X 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"*

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

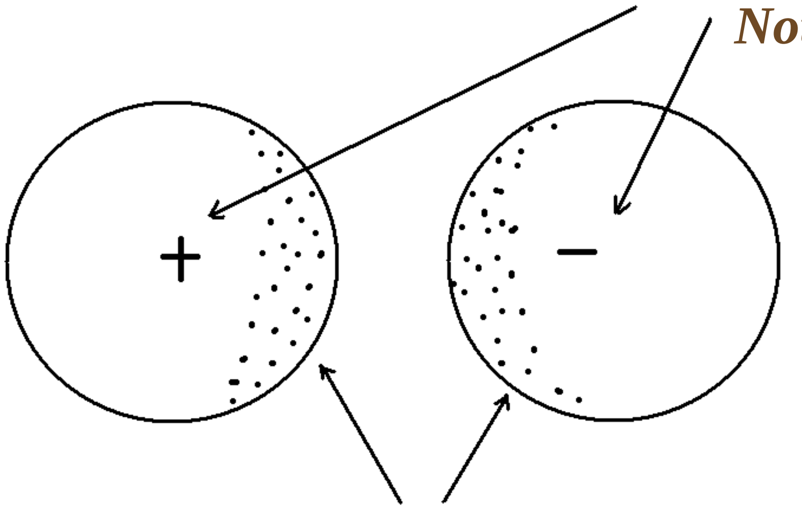
This is the depth where the fields or current in a conductor have decreased to 37% of their nominal value. In other words 63% of the current is carried in this depth.

Proximity Effect

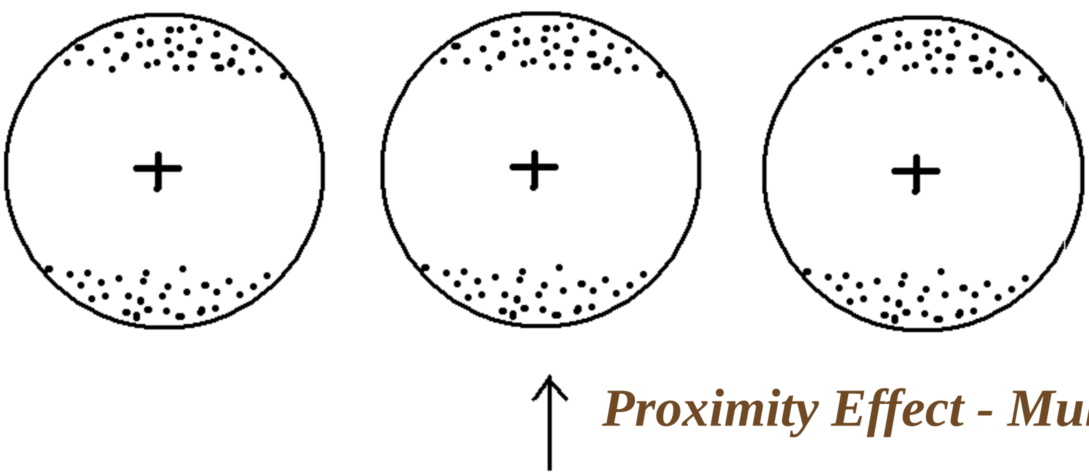
- *A current carrying conductor will generate a magnetic field*
- *This field can induce eddy currents in nearby conductors, increasing losses in addition to any skin effect. The eddy currents obey Lenz's Law. They flow in a direction that reduces the flux in the conductor*
- *This is referred to as "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

Note Opposing Currents

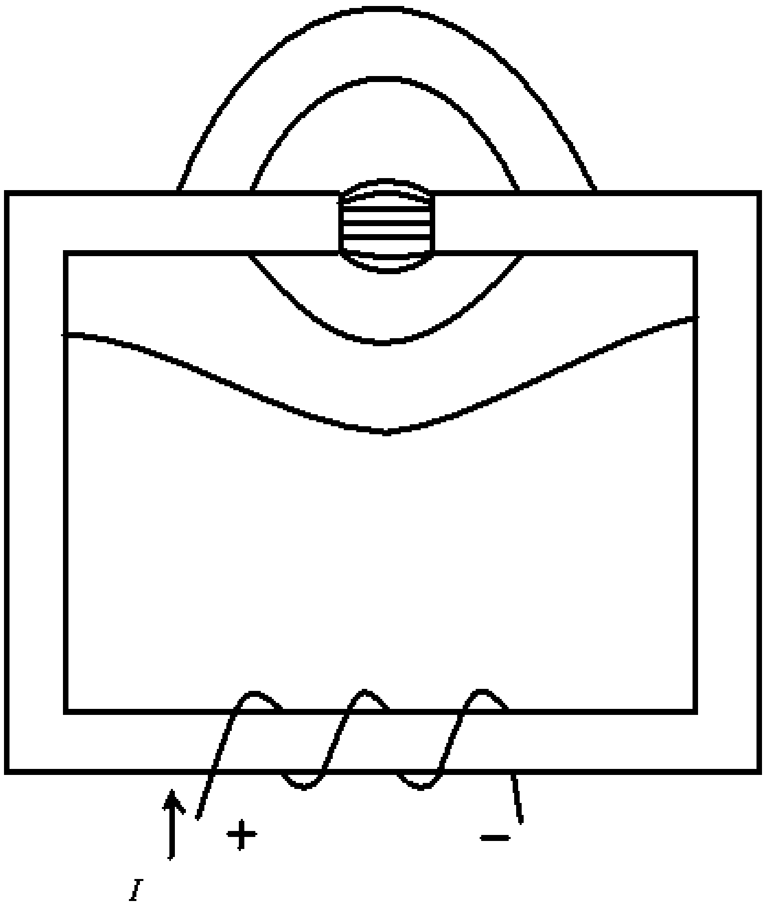


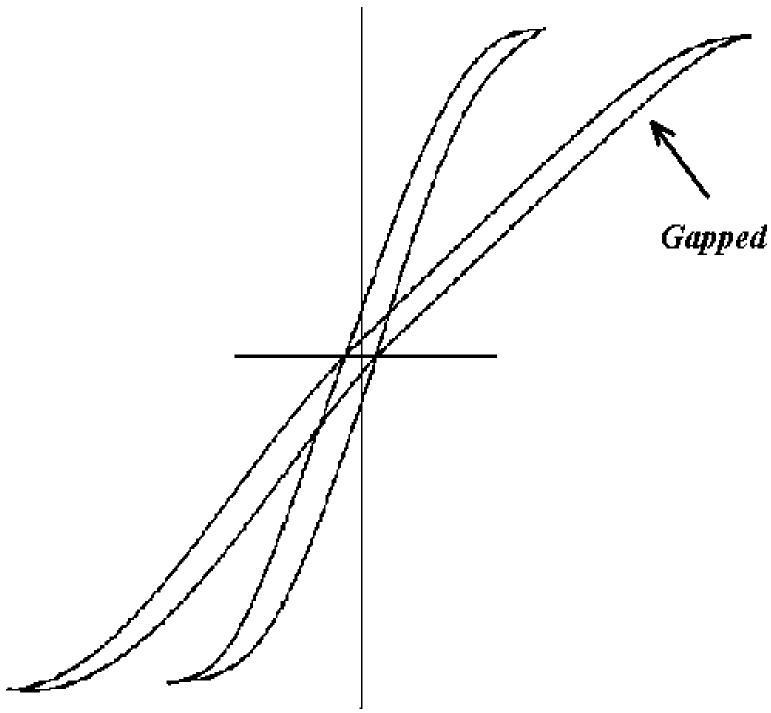
Current Concentrates At One Side



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*

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

Inductors

Purposes

- *Used as filters for smoothing power supply ripple*
- *Used as fault current limiting reactors in AC power currents*
- *Used to limit di/dt in certain pulsed circuits*

Requirements

- *Must carry high DC current*
- *Must select core size that is able to store the required magnetic energy (volt-seconds)*
- *An air gap is sometimes employed to extend DC current capability without saturating. Iron and Ferrites are manufactured with distributed air gaps.*

8. Controls

Controls Overview

- Purposes
- Voltage and Current Mode Control
- V – I Automatic Crossover Network
- Power Supply Controllers

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

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

Linear Systems

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

$y_1 = h[x_1]$ *and* $y_2 = h[x_2]$

then $ay_1 + by_2 = h[ax_1 + bx_2]$ *This is the principle of 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	$h_4[x] = \dfrac{dx}{dt}$

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

Example of a Nonlinear System

$$h[x] = e^{x}$$ *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

Impulse Function

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

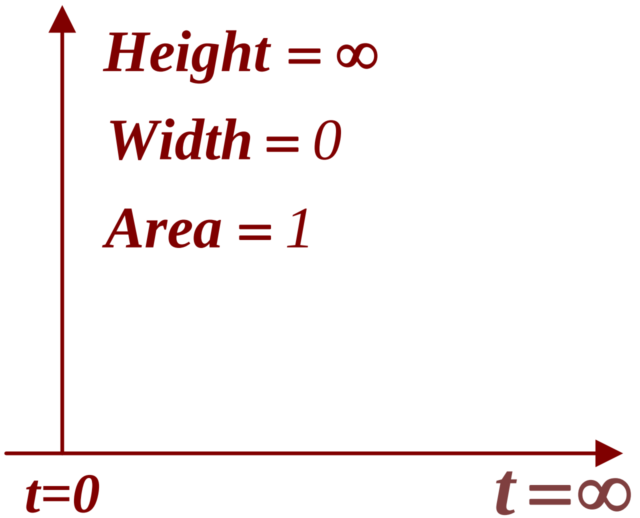
Continuous Dirac delta function, $\delta(t)$ properties

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

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

Functional representation

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

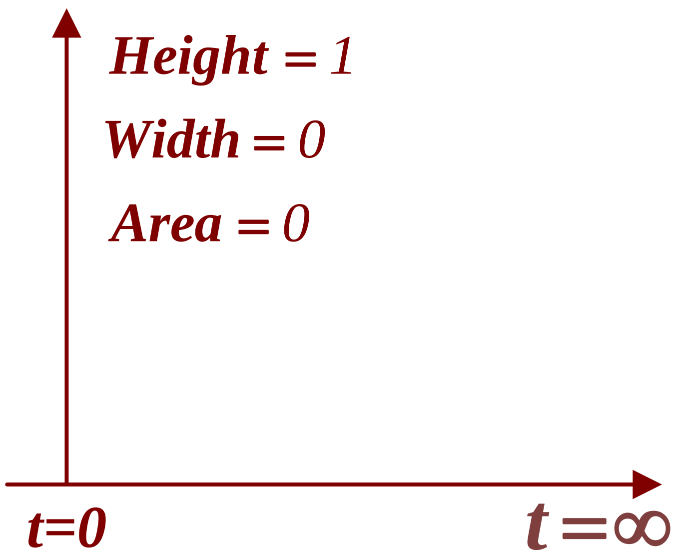


Discrete impulse function properties

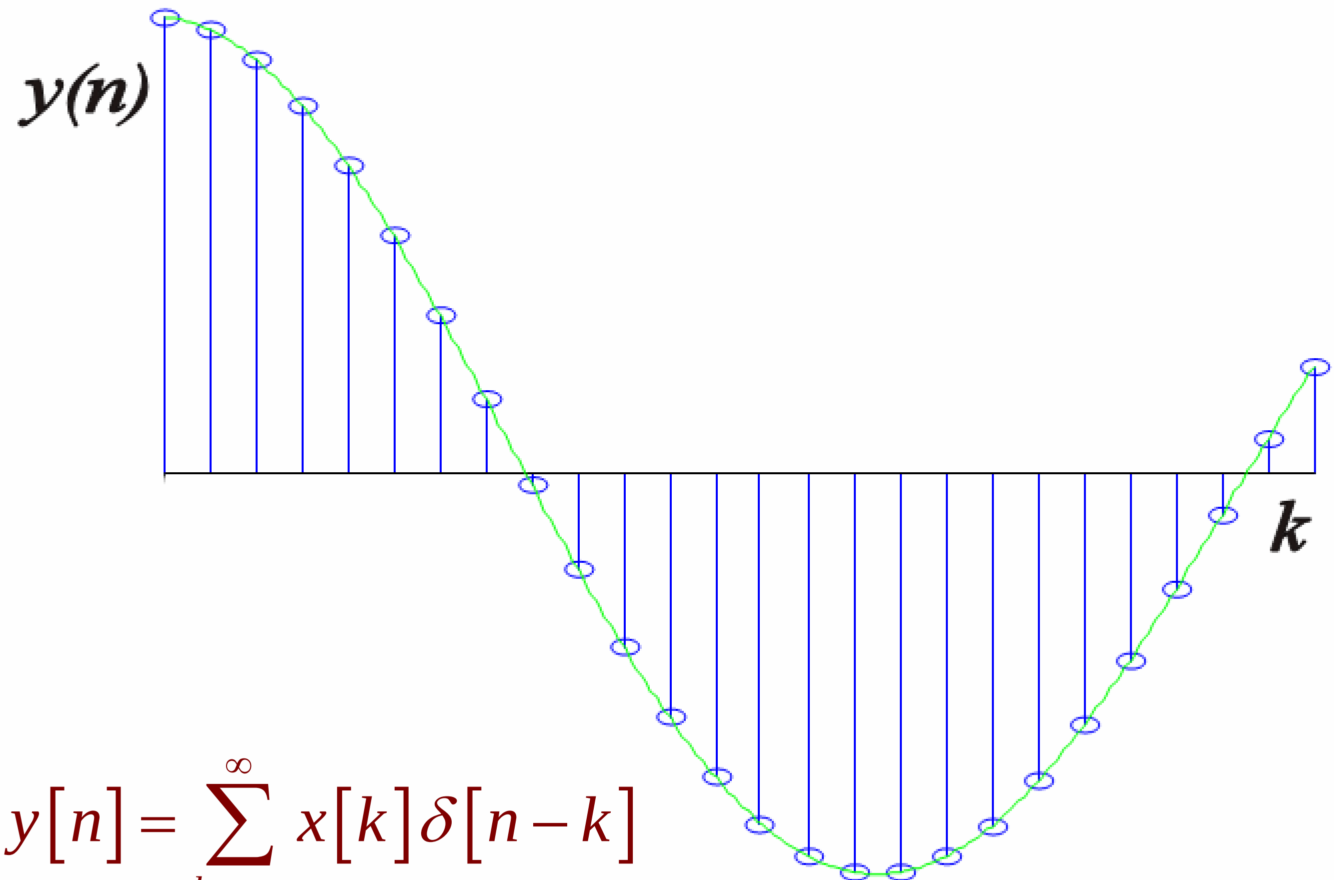
$$\delta[n] = 0, \quad n \neq 0 \qquad \delta[n] = 1, \quad n = 0$$

Functional representation

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



Function as Sum of Delta Functions



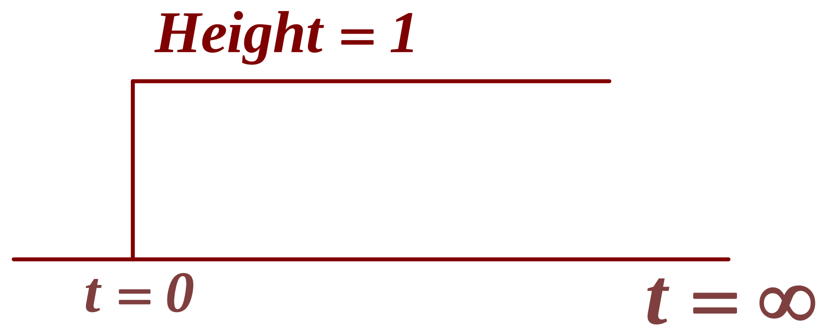
$$y[n] = \sum_{k=-\infty}^{\infty} x[k]\,\delta[n-k]$$

Continuous Step Function

Properties

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

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



Relation to impulse

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

Functional representation

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

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

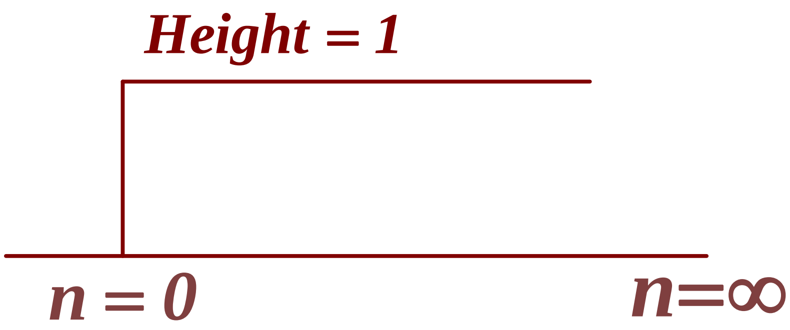
$$= \int_{-\infty}^{\infty} U(t_0 - t) \frac{dx(t)}{dt} dt + x(-\infty)$$

Heaviside step function

Properties

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

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



Relation to impulse

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

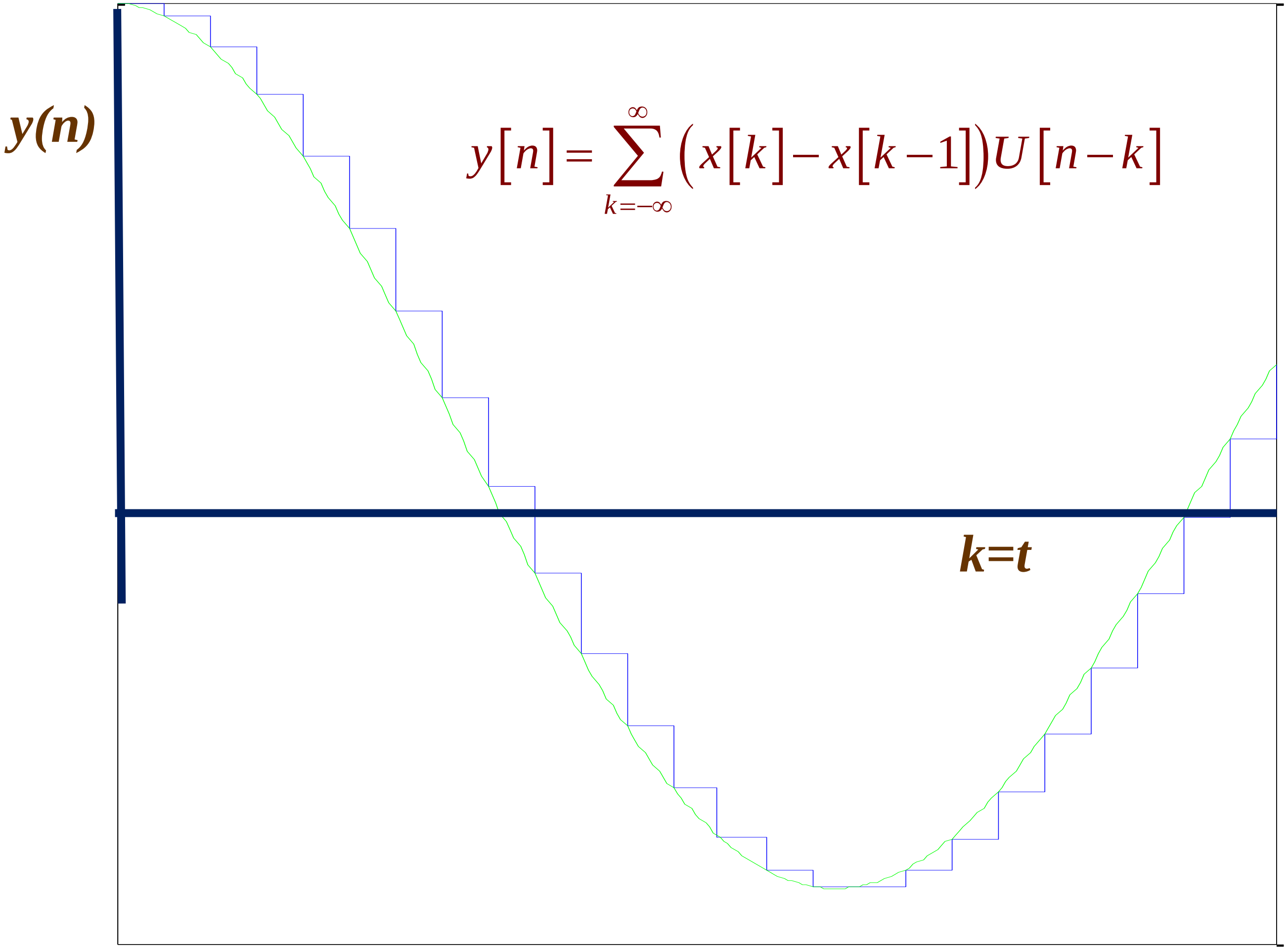
Functional representation

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

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

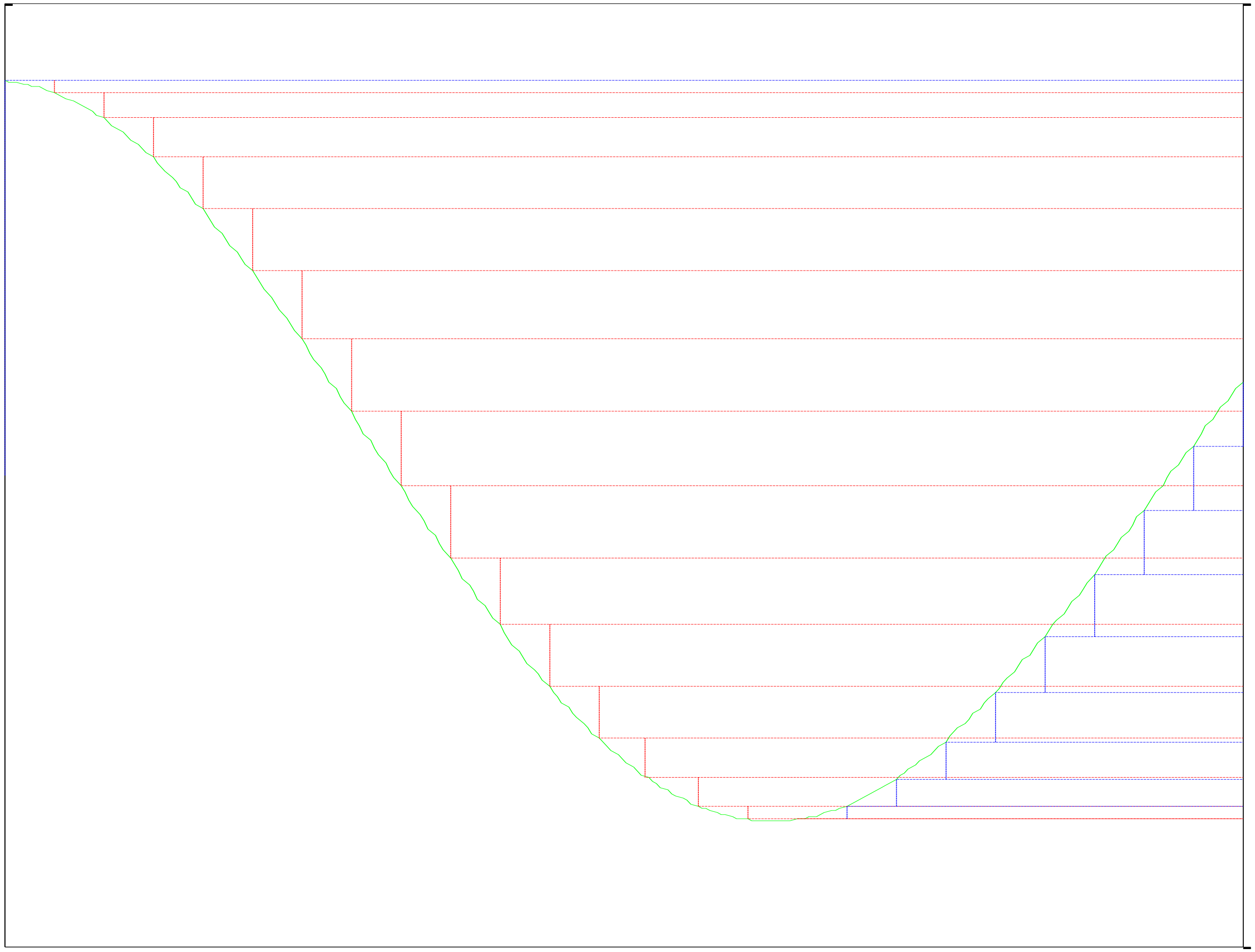
$$y[n] = \sum_{k=-\infty}^{\infty} \left(x[k] - x[k-1]\right)U[n-k]$$

Function Approximation with Steps



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

Function as Sum of Step Functions



Complex Exponentials

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

$$e^{j\omega t} = \cos \omega t + j \sin \omega t$$

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

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

- *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

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

$$V = R * I \qquad V = L * \frac{di}{dt} \qquad I = C \frac{dv}{dt}$$

$$v = Ri + L\frac{di}{dt}$$

Represent the current i as a complex exponential

$i(t) = I_0 e^{j\omega t}$ *then the equation for v becomes*

$$v = R I_0 e^{j\omega t} + L\, j\omega I_0 e^{j\omega t} = (R + j\omega L) I_0 e^{j\omega t}$$

$I_0 e^{j\omega t}$ *is the eigenfunction*

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

Fourier Transforms

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

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

- *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*

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

Fourier Series

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

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

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

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

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

Advantages of the Frequency Domain

- *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

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

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

Unit step with delay

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

Exponentially decreasing function, starting at t=0

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

Laplace transform of a derivative

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

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

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

System equation

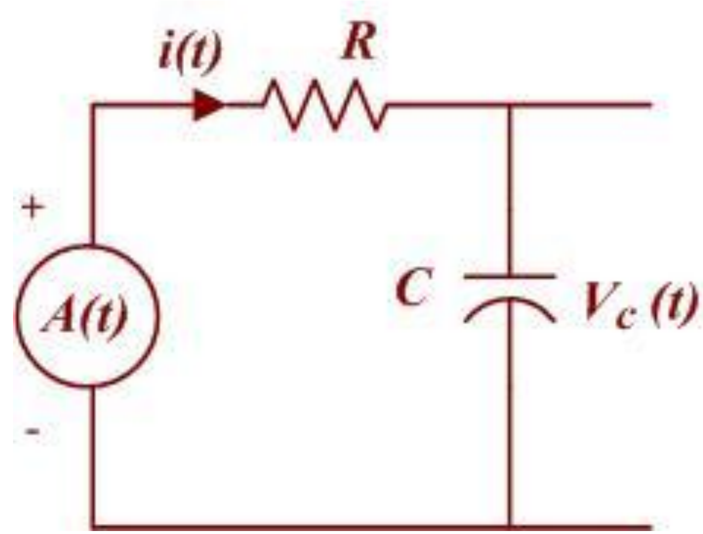
$$RC\frac{dv_c(t)}{dt} + v_c(t) = A(t) \qquad Let\ RC = \tau$$

Solution

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

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

Circuit Analysis Using Transforms

Repeat the same problem using Laplace transforms

$$C\frac{dv_c(t)}{dt} = \frac{\left[A(t)-v_c(t)\right]}{R}$$

Transform both sides

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

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

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

For the case when A is constant

$$= \frac{1}{s+\alpha}v_1(0)+A\frac{1}{s}\frac{\alpha}{s+\alpha}$$

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

$$v(t) = Ve^{-\frac{t}{\tau}} + \left(1 - e^{-\frac{t}{\tau}}\right)A, \text{ as before}$$

From the transform equation

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

we can immediately read off the system transfer function

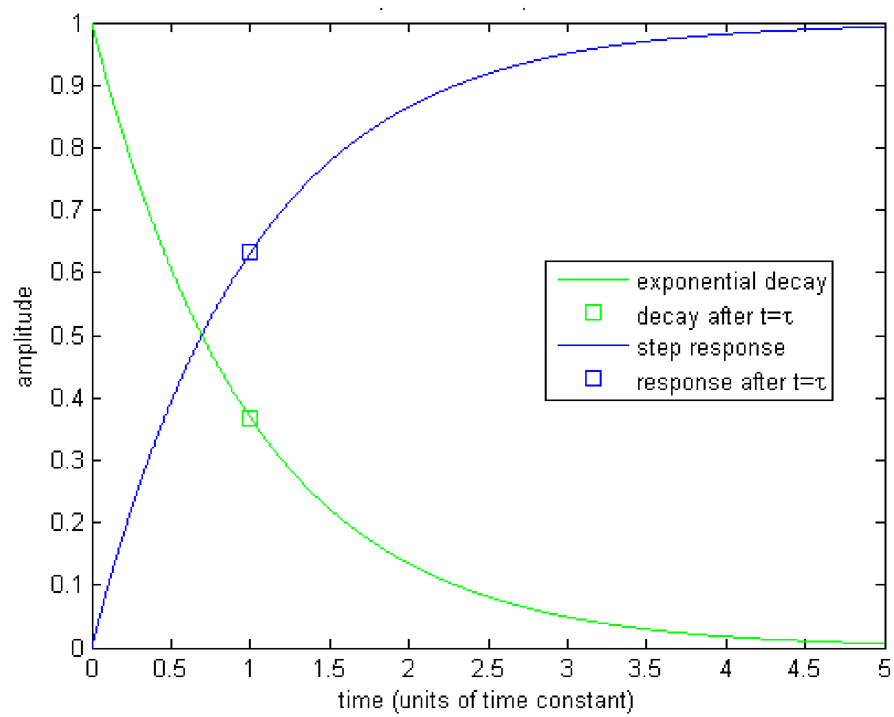
as the ratio of $\dfrac{V(s)}{A(s)}$ *when the initial conditions are zero.*

We also see that both the transfer function and the response to the initial conditions have the same poles and therefore similar frequency characteristics

One Pole Low-Pass Systems

- *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

$$H(s) = \frac{\tau^{-1}}{s + \tau^{-1}}$$



One Pole Low Pass Frequency Response

- *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*

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

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

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

One Pole LP Frequency Response

Magnitude $\quad |H(j\omega)| = \dfrac{1}{\sqrt{1+(\omega\tau)^2}}$

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

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

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

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

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

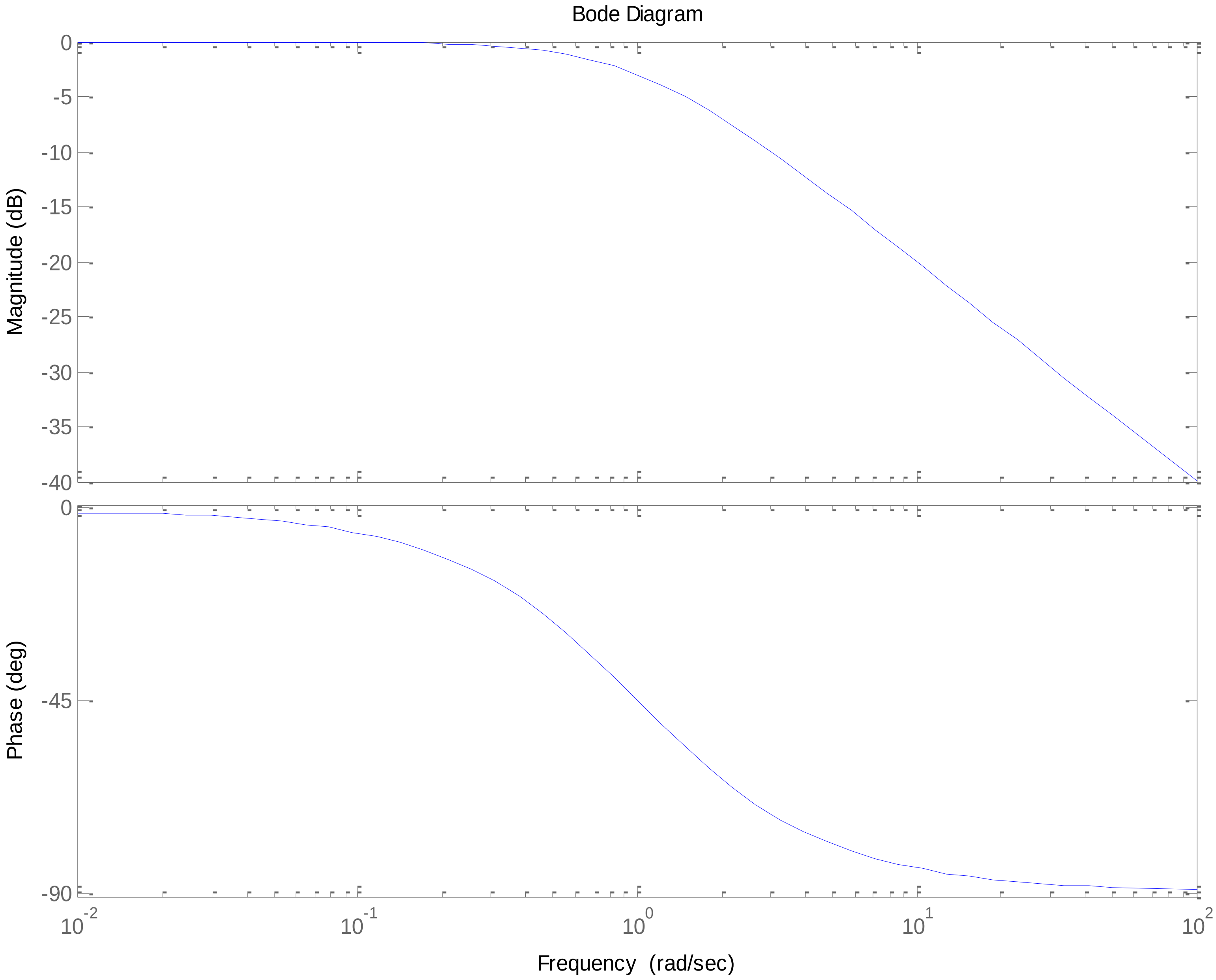
Phase $\quad \angle H(j\omega) = -\,arctan(\omega\tau)$

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

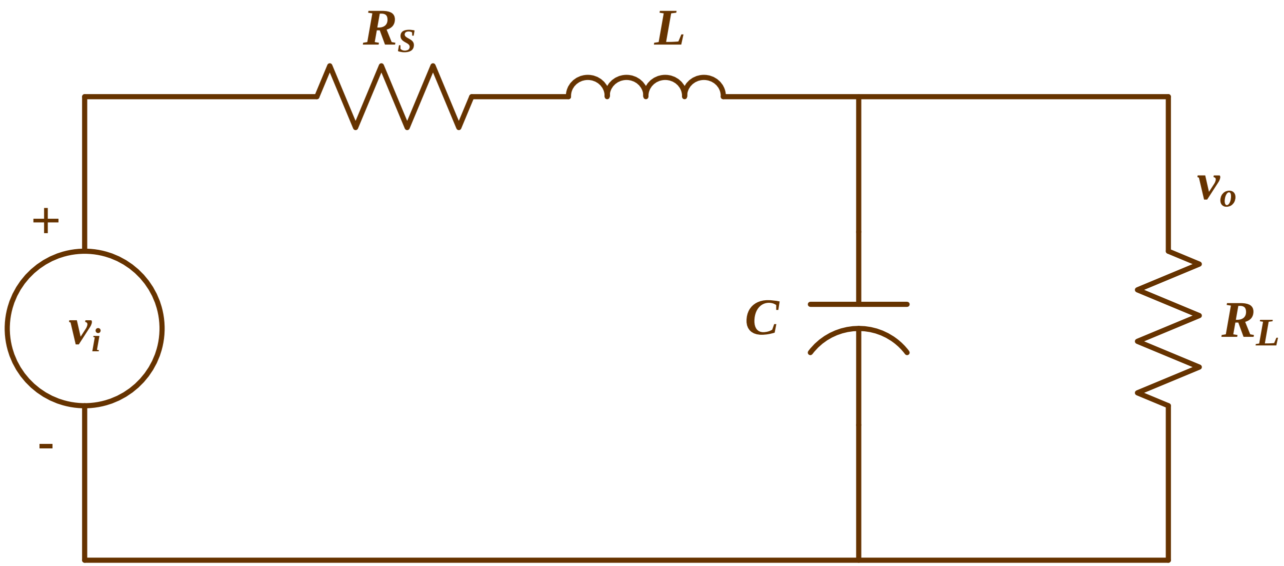
$$= -45^0 \qquad \omega\tau = 1$$

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

One Pole LP Frequency Response



Two Pole Low Pass Frequency Response



Two Pole Systems

Find transfer function of voltage divider

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

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

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

This has the form

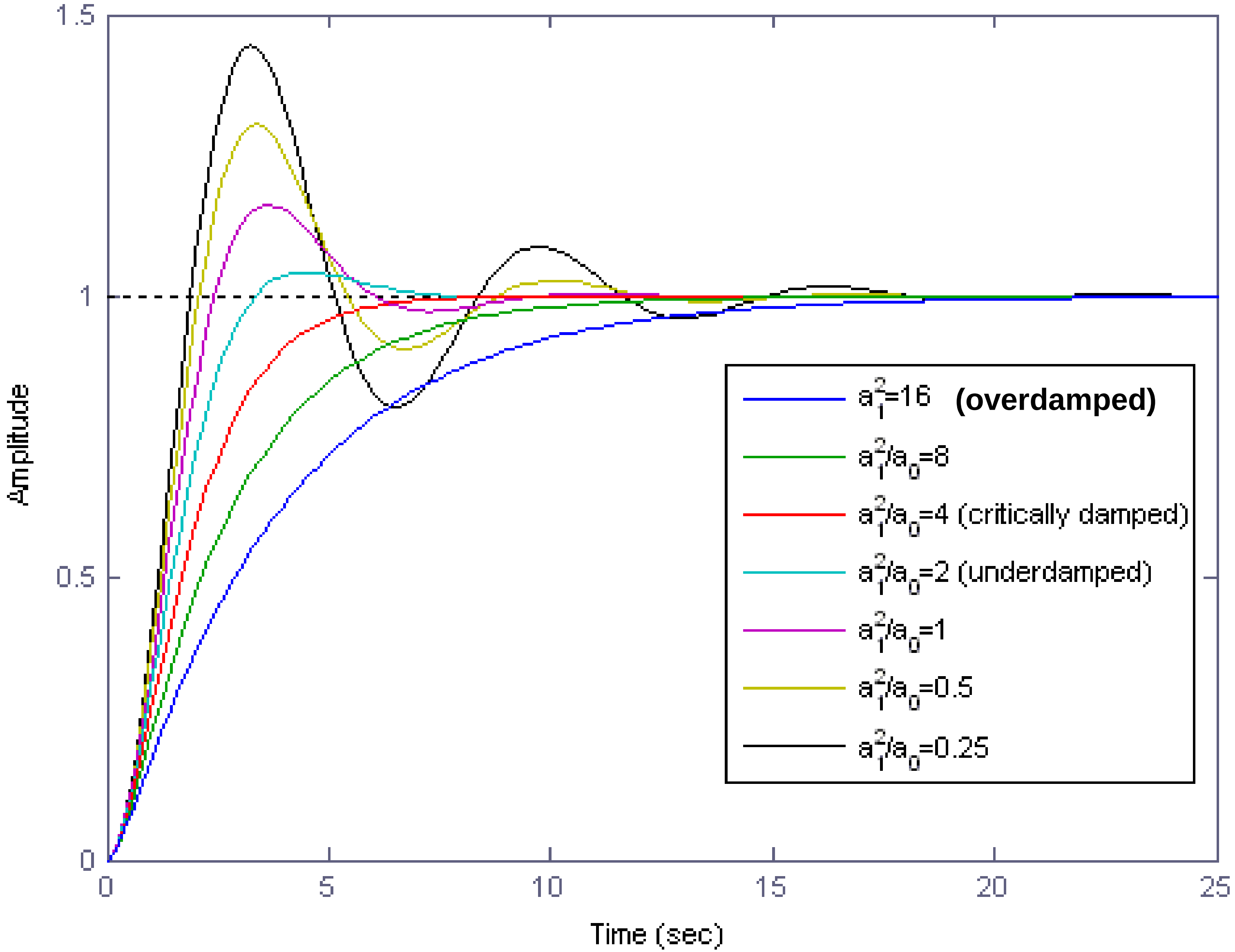
$$H(s) = \frac{a_0}{s^2 + a_1 s + a_0} = \frac{a_0}{\left(s - s_1\right)\left(s - s_2\right)}$$

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

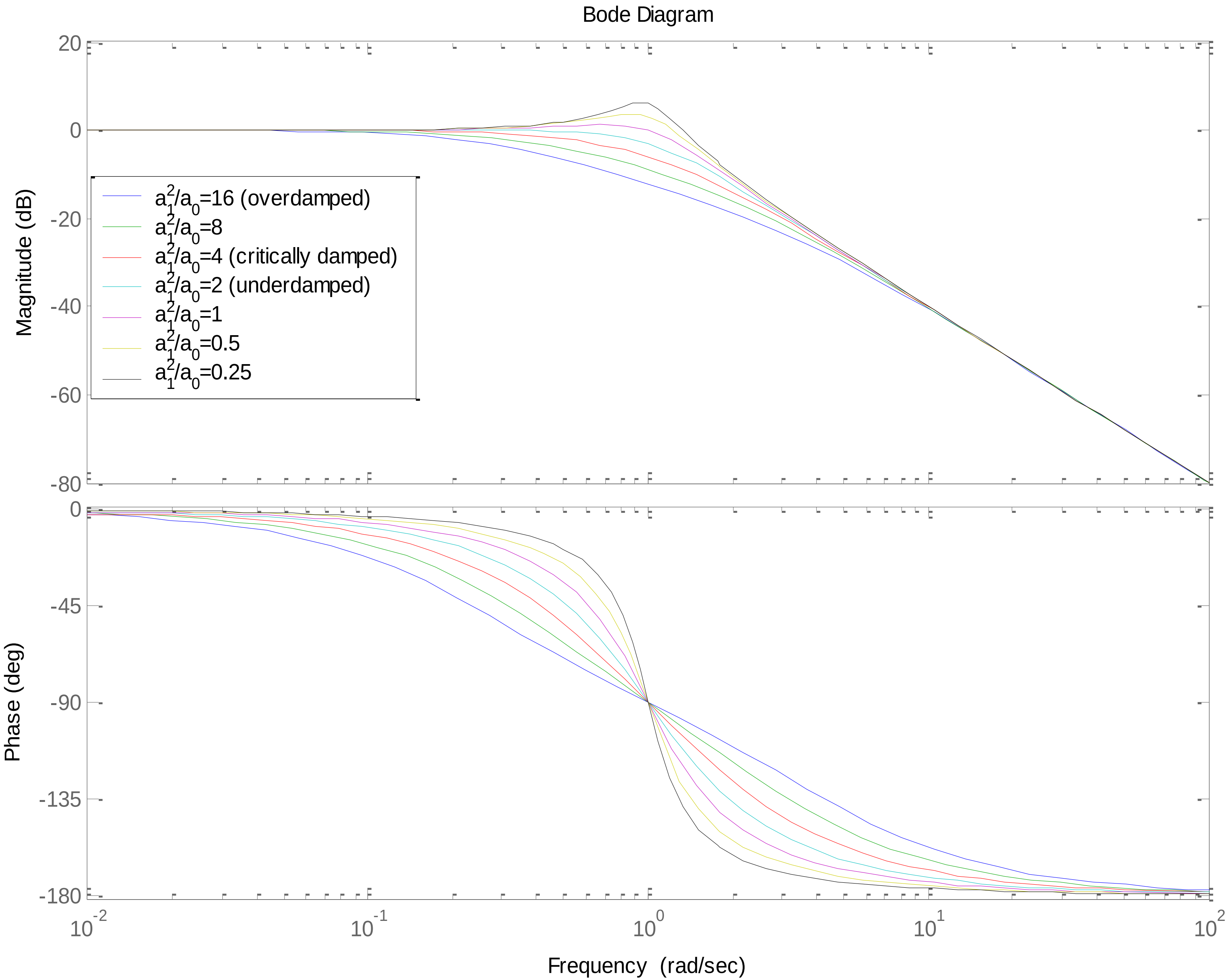
Two Pole Systems

- *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*

Two Pole System Step Response



Two Pole System Frequency Response



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

- 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 $10^* f_c$

Bode Plots

- *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

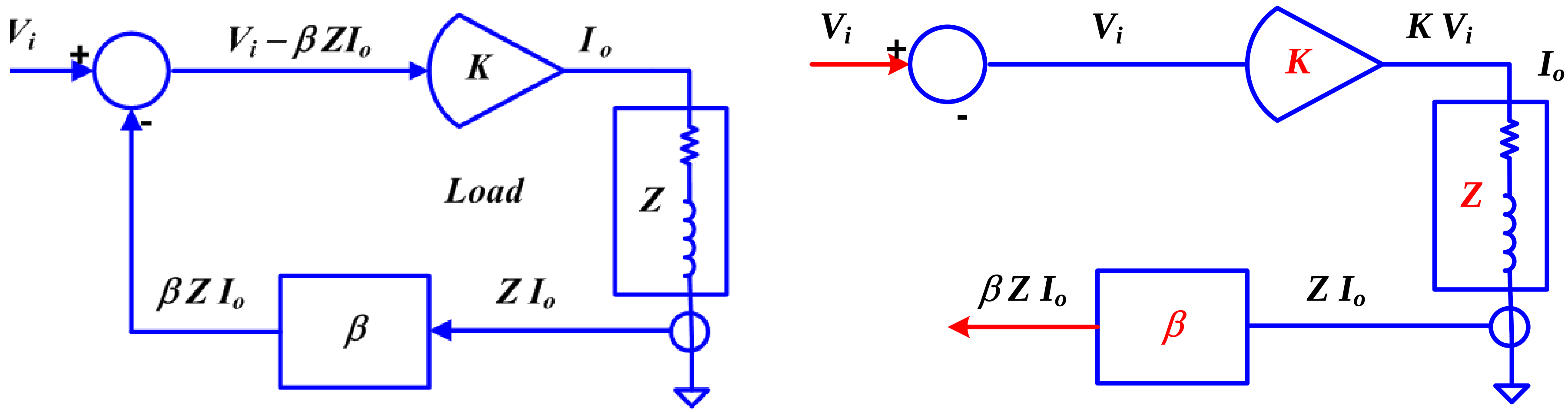
- *Similar rules exist for zeros*

  6 dB/octave increase in gain above zero

  +45 degree phase shift at the zero

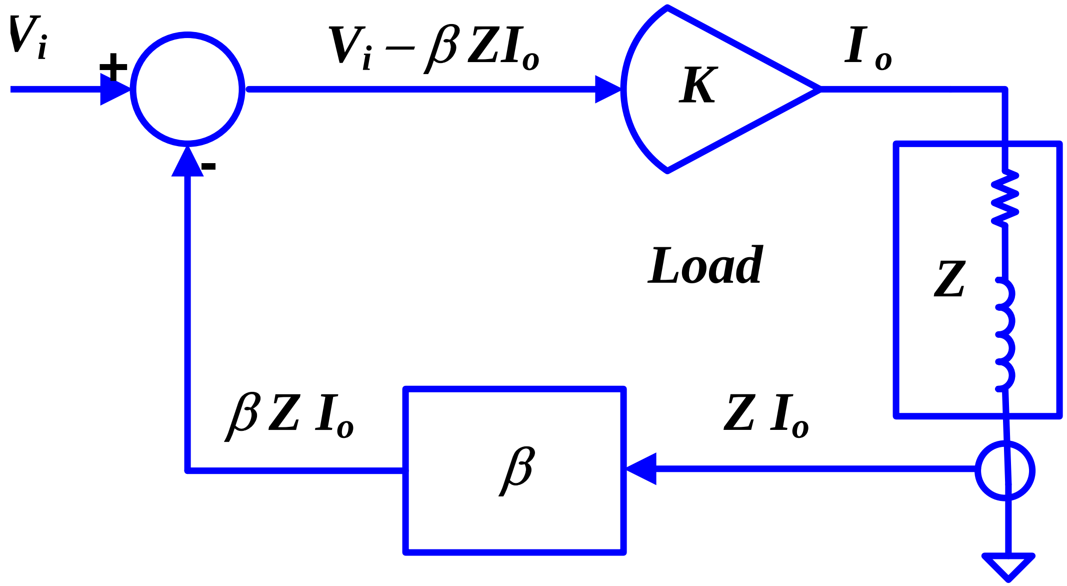
Feedback

- *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*



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

- A_{CL} *is called the closed loop gain,* β *is the feedback factor*
- $\beta Z K$ *is called the open loop gain*
- *For* $\beta Z K >> 1$ $\quad A_{CL} = \frac{1}{\beta Z}$
- *Power supply characteristics (K) unimportant, gain dependent upon* βZ



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

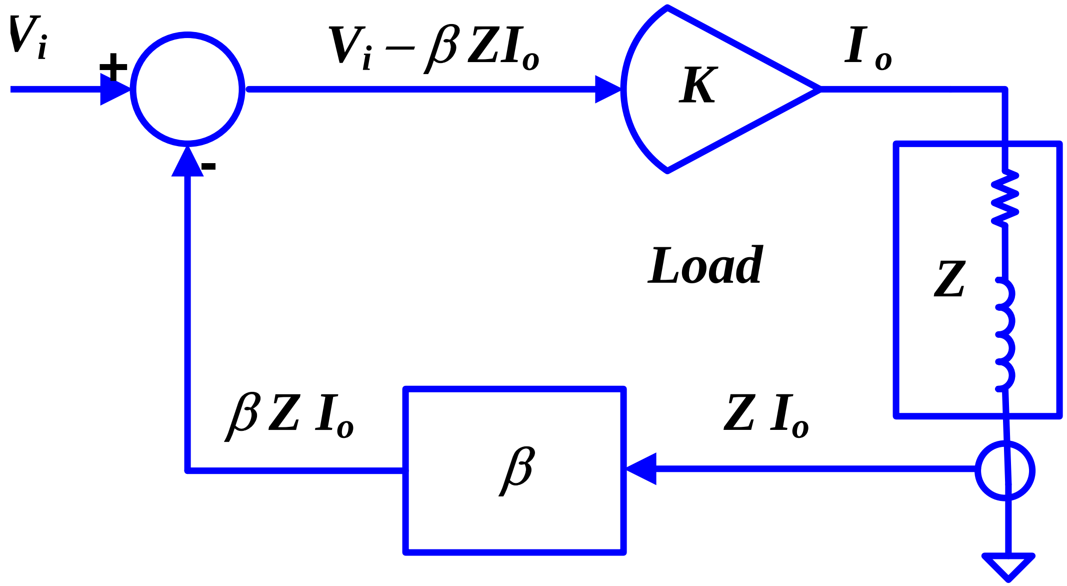
$I_o = K(V_i - \beta Z I_o)$		
V_i	$V_i - \beta Z I_o$	I_o
$V_i \downarrow$	$V_i - \beta Z I_o \downarrow$	$I_o \downarrow$
I_o	$V_i - \beta Z I_o \downarrow$	$I_o \downarrow$
$I_o \downarrow$	$V_i - \beta Z I_o$	I_o

Factors That Affect Power Supply Stability

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

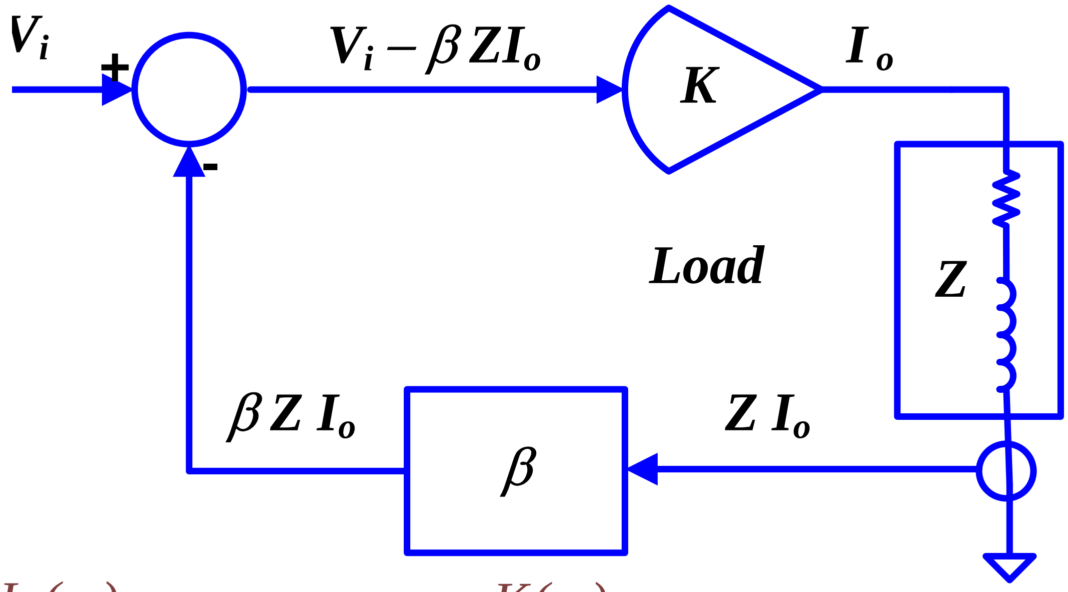


$$\frac{I_o}{V_i} = A = \frac{K}{1 + \beta Z K}$$

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

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



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

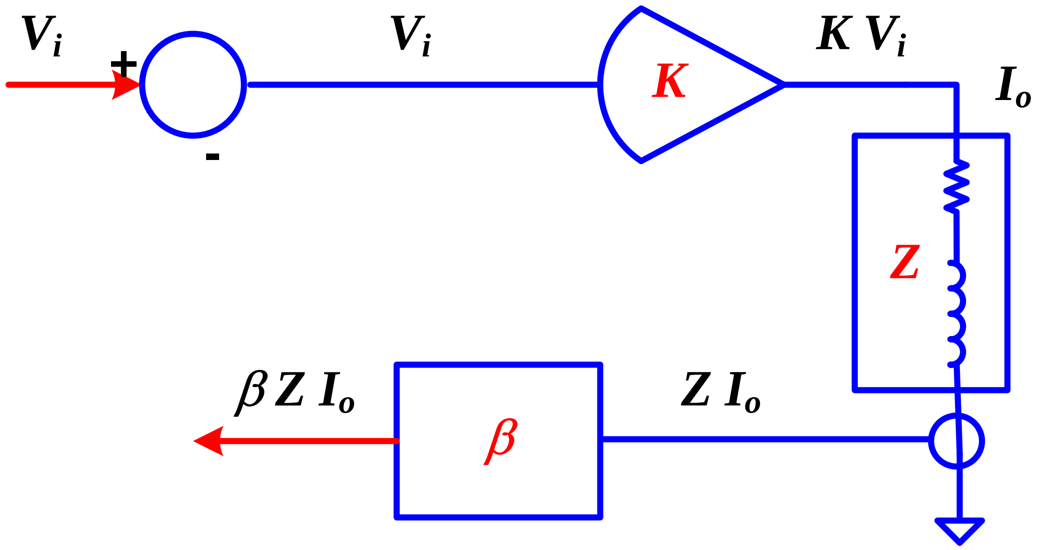
Very simply : 1+β(s) Z(s)K(s) must not = 0 or approach 0

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

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

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

Stability Against Oscillation

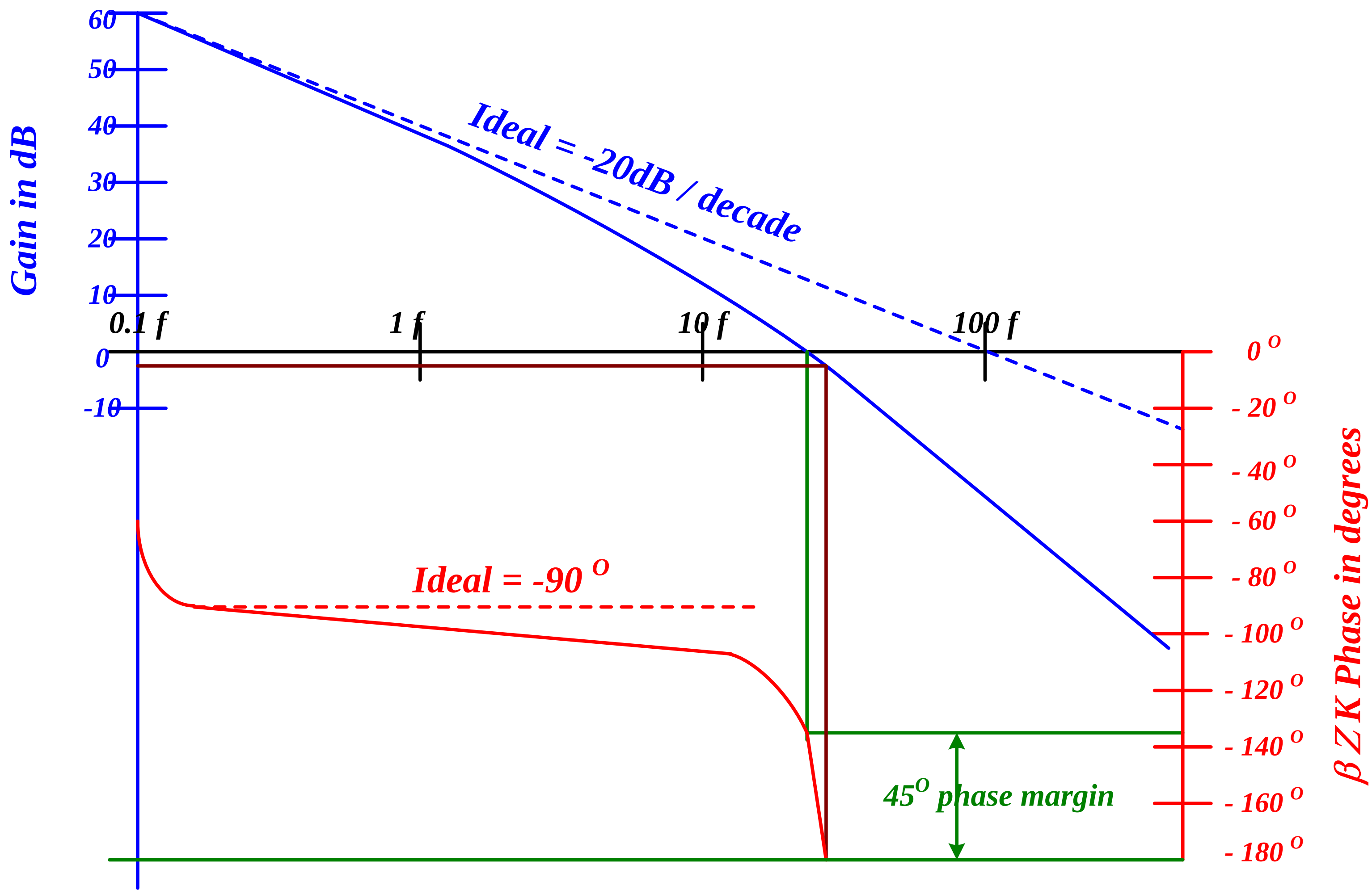


$$\frac{B(s)Z(s)I_o(s)}{V_i(s)} = \frac{B(s)Z(s)K(s)V_i(s)}{V_i(s)} = T(s) = \beta(s)\,Z(s)K(s)$$

Very simply :

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

Stability Against Oscillation



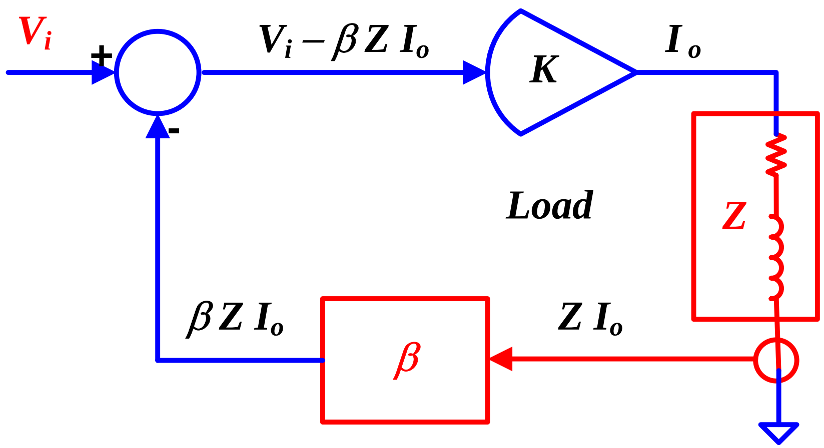
- For stability, the phase shift must be < 180 ^{O} when the |gain| =1
- For stability, the |gain| must be < 1 when the phase shift is 180 ^{O}

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

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

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

behavior dependent on load Z, 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)*

Zero Flux Current Transductors

Hitec (in Europe)

Danfysik Model 866
http://www.danfysik.com
0 - ±600 A
±400 mA out
0.3 ppm / ^{O}C
DC – 100 kHz
10 kA / mS
Separate burden resistor

Danfysik Model 860 Series
http://www.danfysik.com
0 - ±1000 A, ±2000 A, ±3000 A
±10 V out
0.3 ppm / ^{O}C
DC – 100 kHz
10 kA / mS

Isotek Model A-H, Manganin < 10 ppm/ OC Shunt Resistor

http://www.isotekcorp.com

Long-Term Stability

- *All parts are subject to aging.*
- *Resistors increase or decrease in value*
- *Capacitor dielectrics breakdown*
- *Capacitor electrolytes dry out or evaporate and leak*
- *Semiconductor bias points change*
- *Op-amp scale, linearity, monotonicity, gain and offsets change with time*

Stability Enhancement

- *Accelerate initial aging components prior to intended use by baking at elevated temperatures*
- *Accelerate aging by exposure to electron beam*

Factors that Affect Transient Stability (Regulation)

- *Two types of Regulation – Load and Line*
- *Classic definition of Load Regulation (0% is best)*

$$\%V_R = \frac{V_{NL} - V_{FL}}{V_{FL}} * 100\% \qquad \%I_R = \frac{I_{NL} - I_{FL}}{I_{FL}} * 100\%$$

- *Classic definition employing V_{NL} is usually not applicable. A limited version uses "decreased load or increased load" instead of a no-load condition*

$$\%V_R = \frac{V_{DL} - V_{FL}}{V_{FL}} * 100\% \qquad \%I_R = \frac{I_{DL} - I_{FL}}{I_{FL}} * 100\%$$

- *In addition, the recovery time for the power supply output voltage or current to return the original condition is also specified*

"The power supply shall have a voltage regulation of 0.5% for load changes of ± 5% from nominal with voltage recovery in ≤ 2 milliseconds"

Factors that Affect Stability (Regulation) Against Transient Effects

- *Line Regulation – Definition (HL= output voltage under high line, NL= output voltage under nominal line, LL = output voltage under low line)*

$$\%V_R = \frac{V_{HL} - V_{NL}}{V_{NL}} * 100\% \qquad \% I_R = \frac{I_{HL} - I_{NL}}{I_{NL}} * 100\%$$

$$\%V_R = \frac{V_{NL} - V_{LL}}{V_{NL}} * 100\% \qquad \% I_R = \frac{I_{NL} - I_{LL}}{I_{NL}} * 100\%$$

- *In addition, the recovery time for the power supply output voltage or current to return the original condition is also specified*

"The power supply shall have a voltage/current regulation of 0.5% for line changes of ± 5% from nominal with voltage/current recovery in ≤ 2 mS"

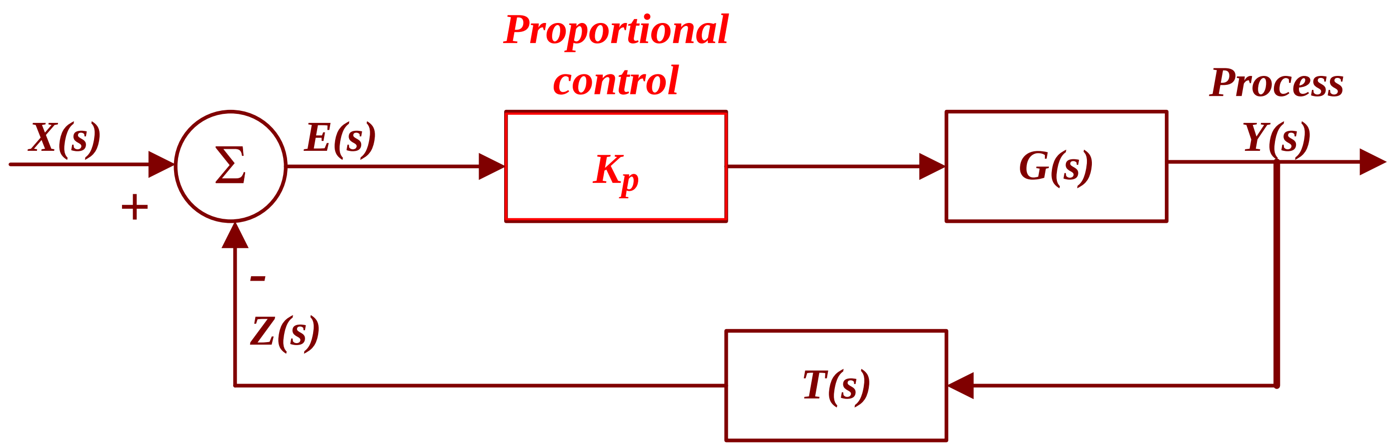
Factors that Affect Stability (Regulation) Against Transient Effects

The ability of a power supply to respond to a transient condition depends upon the speed, depth and duration of the transient. The transient can be mitigated by the use of:

- *Large filter capacitors and inductors in the input and output filters to maintain the input and output load voltage and current against line voltage changes and load changes..*
- *Employ fast regulating circuits. Regulating speed should be at least as fast as the fastest expected transient.*

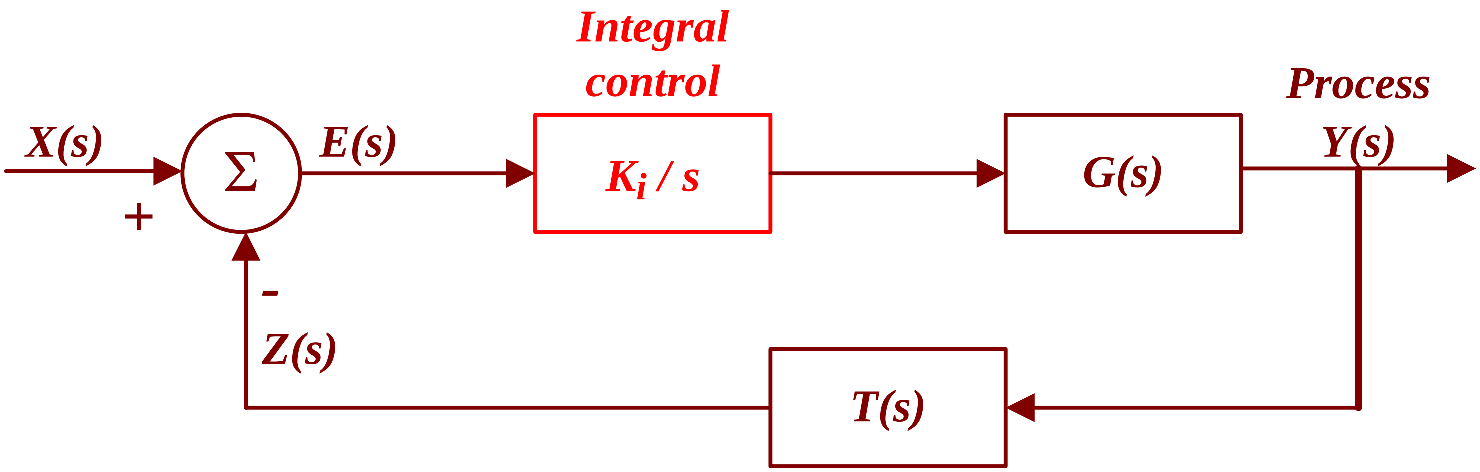
PID Loops - Proportional Control

- *Earliest controllers proportional only*
- *Proportional control consists of just a gain*
- *It has good response to instantaneous changes in the process or other cause of error*
- *Control effort is the product of the error and a finite gain Kp*
- *Eventually effort is too small to reduce error to zero*
- *There is always an error - it can never be eliminated*



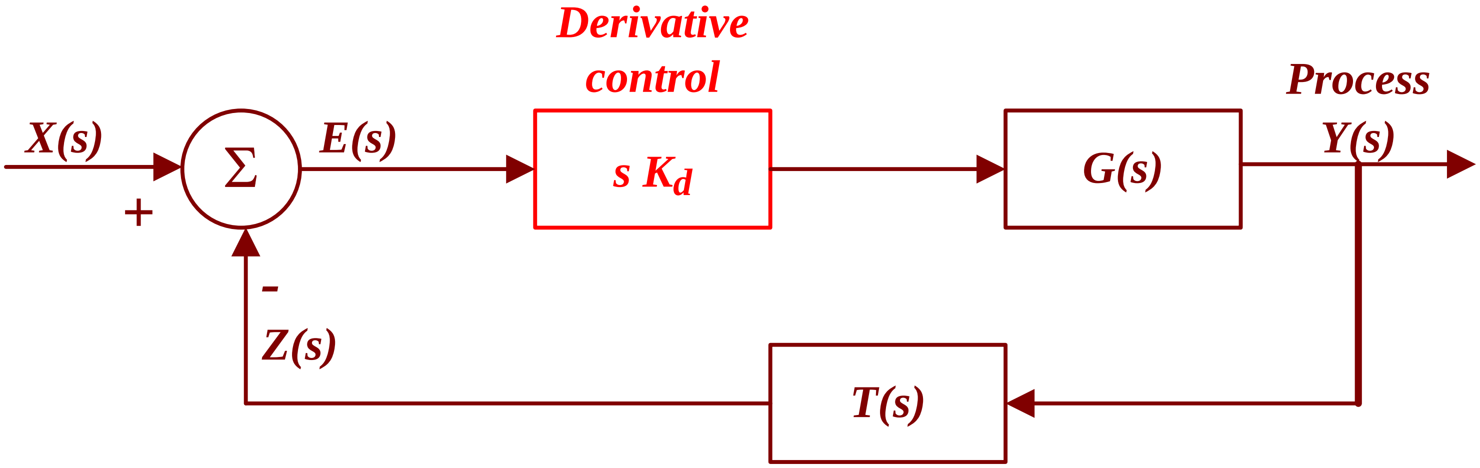
PID Loops - Integral Control

- *Integral control consists of a pure integrator*
- *The control effort is now* $\int e(t)dt$
- *Eliminates* DC *errors*
- *Limits high frequency response*
- *Introduces a phase delay that can cause sluggishness or oscillation*



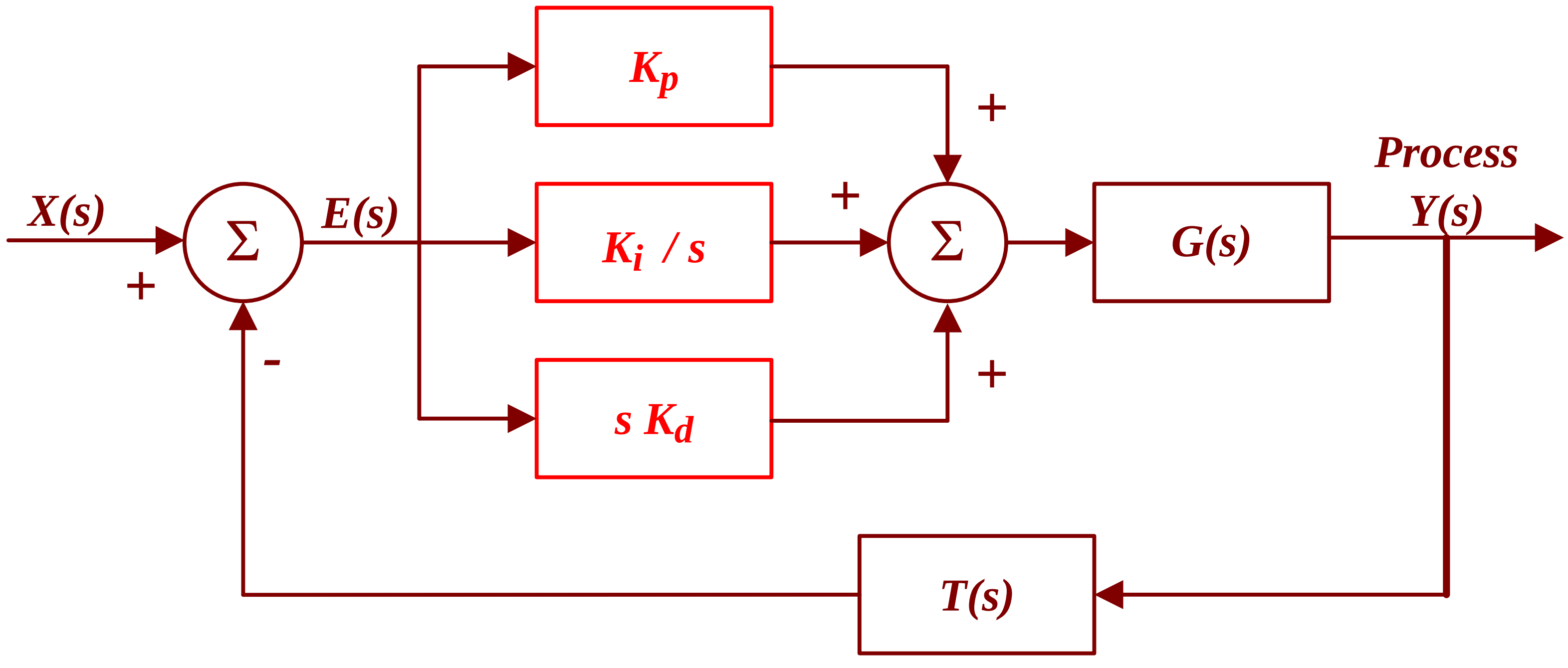
PID Loops - Derivative Control

- *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*



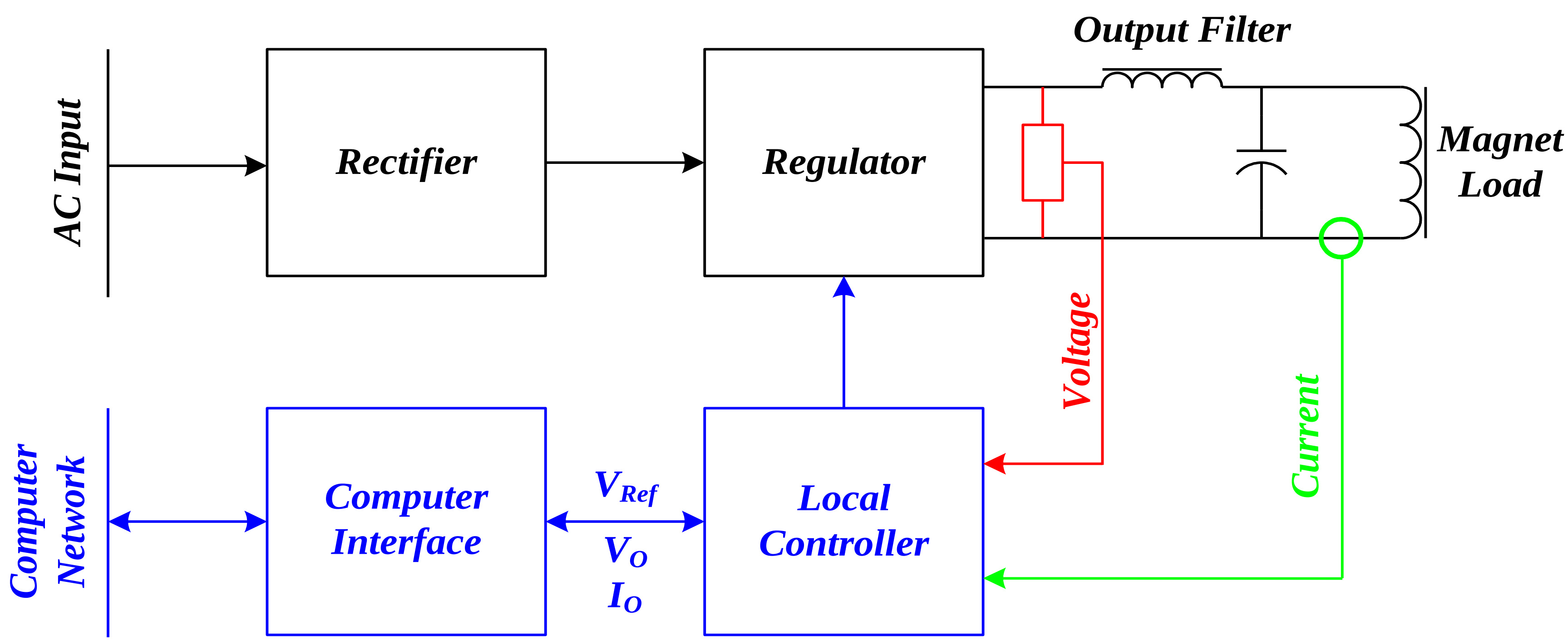
Stability and Feedback Summary

- *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*

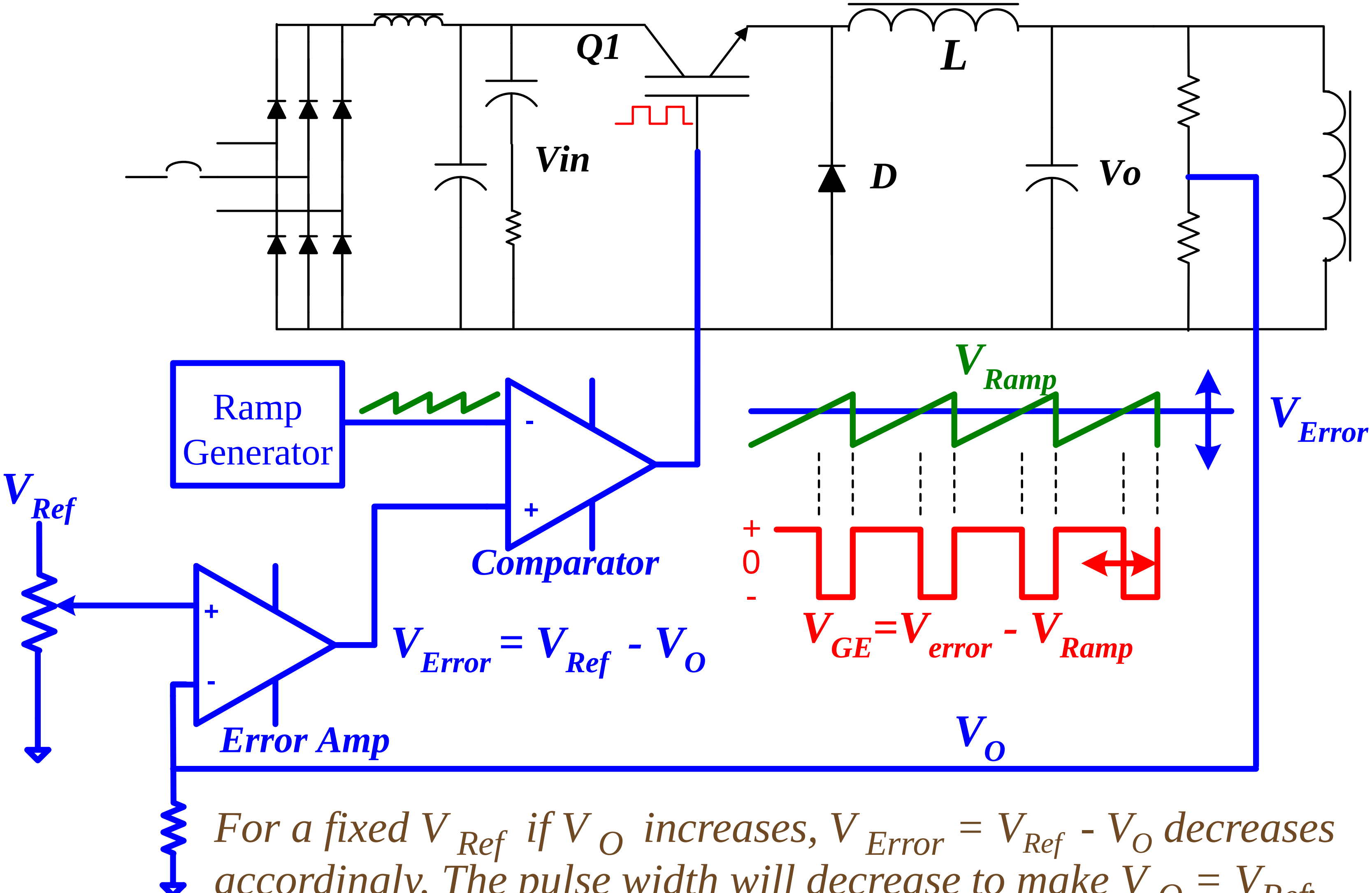
Controls

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



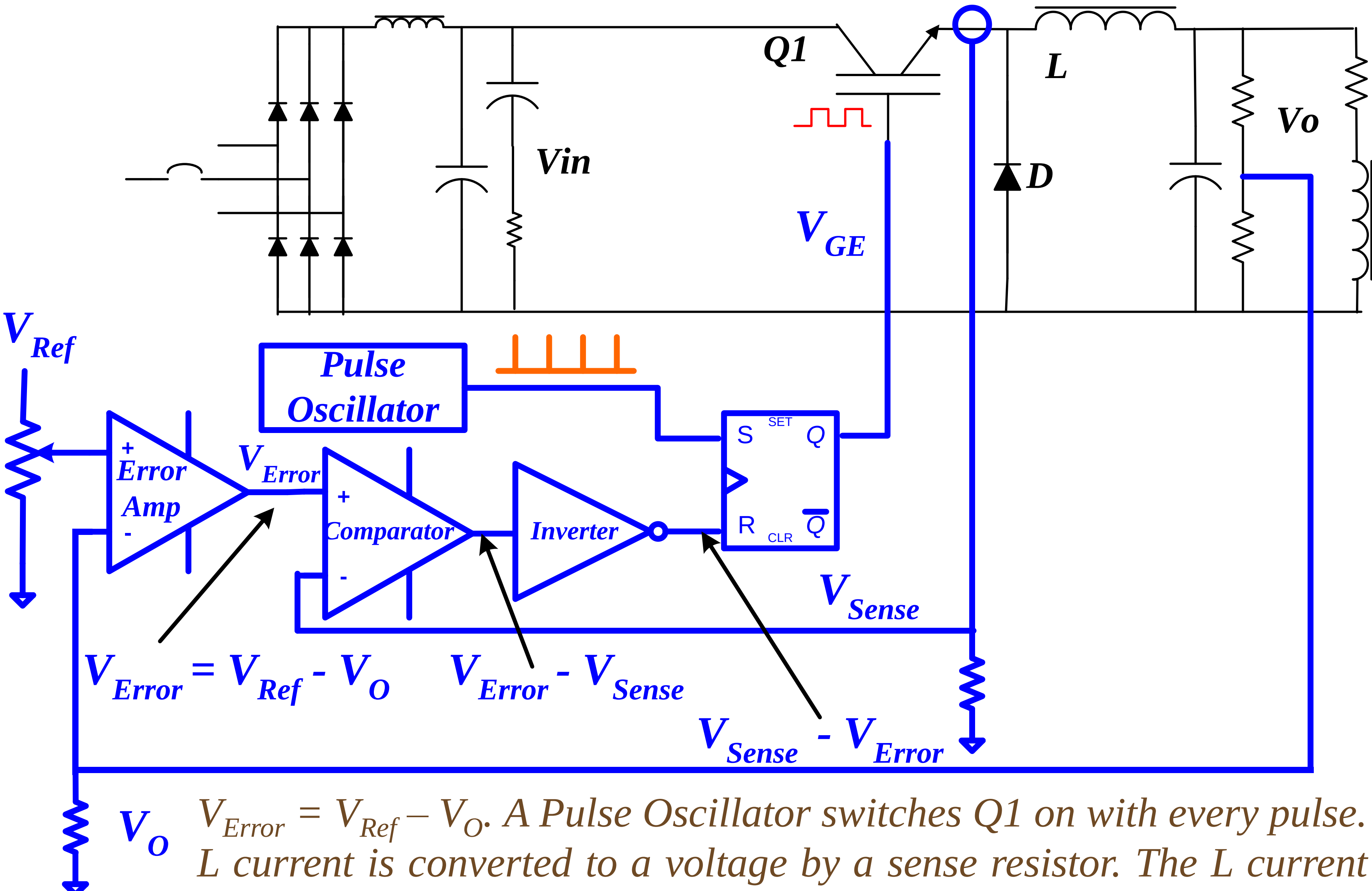
Voltage Mode Control



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

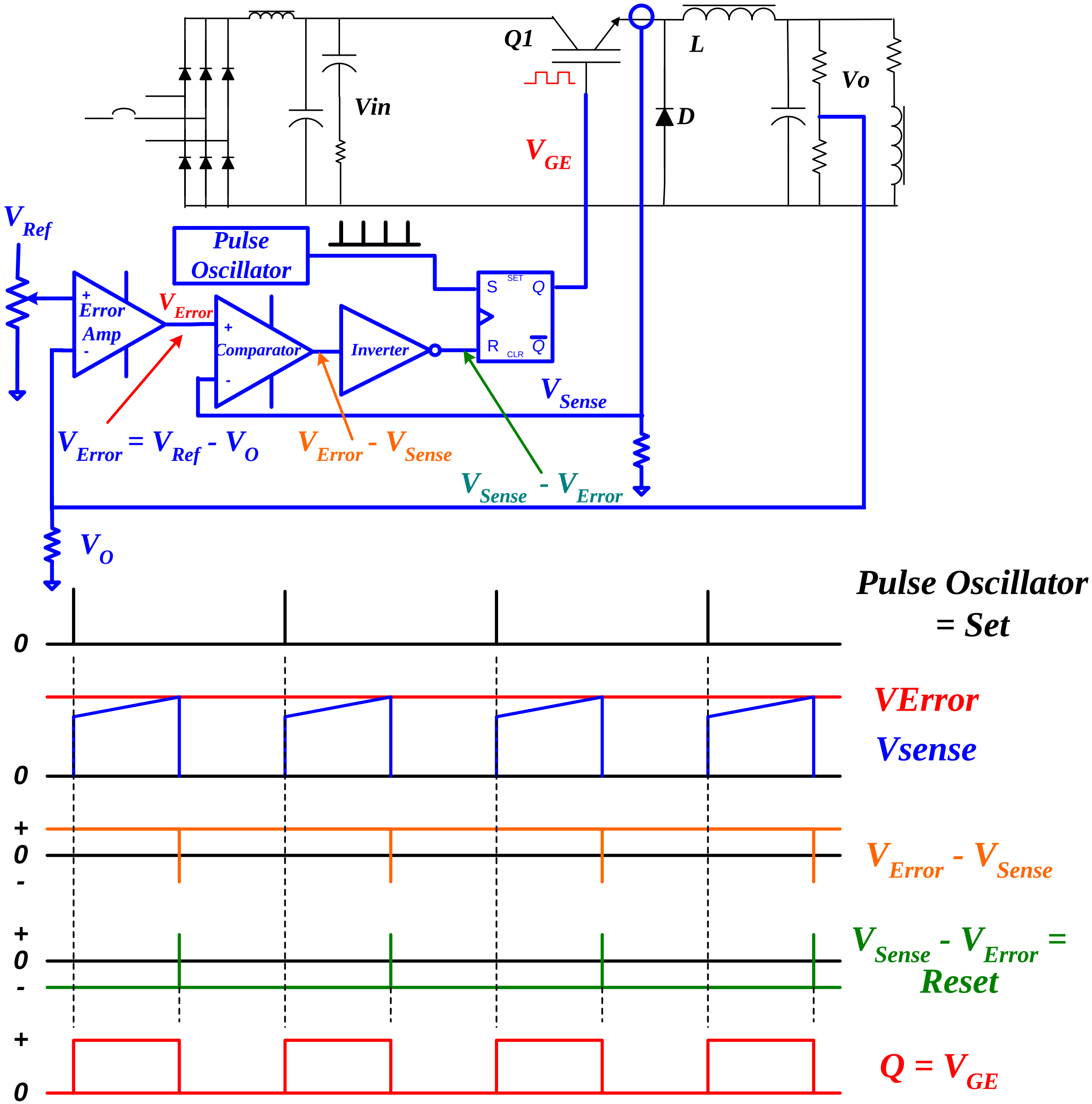
If V_O decreases, V_{Error} increases accordingly. The pulse width will increase to keep $V_O = V_{Ref}$.

Current Mode Control



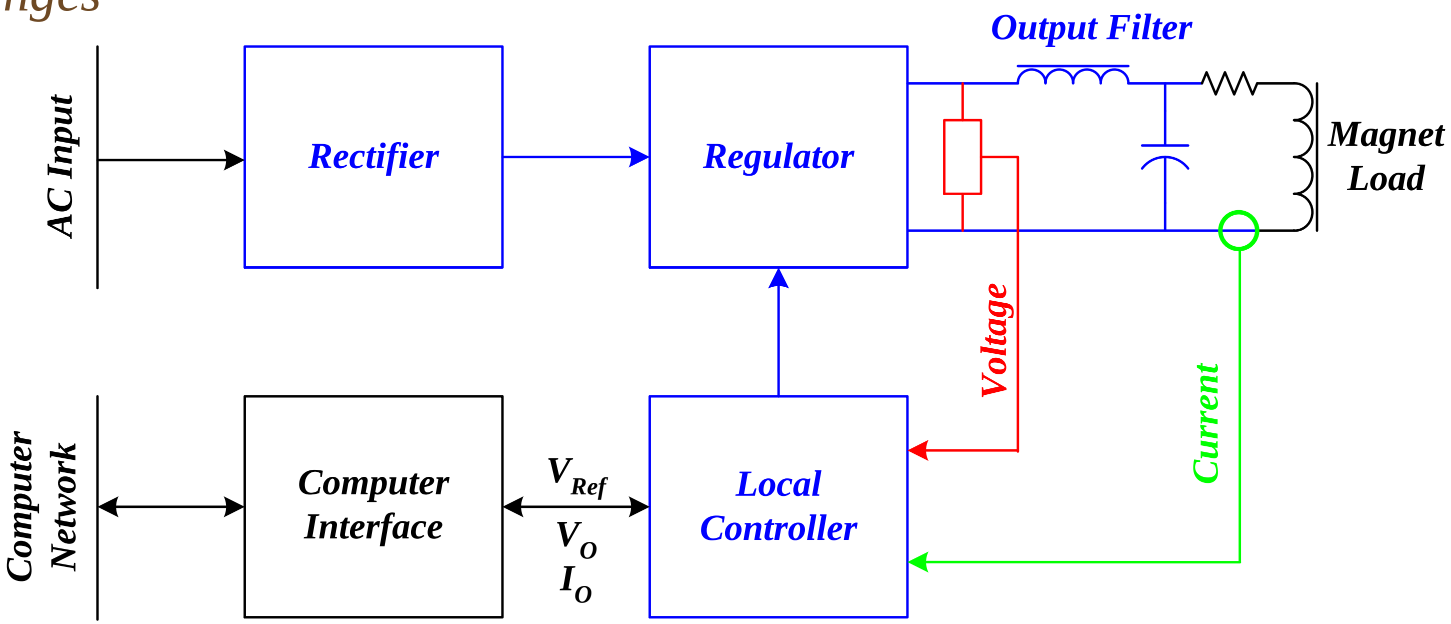
$V_{Error} = V_{Ref} – V_O$. A Pulse Oscillator switches Q1 on with every pulse. L current is converted to a voltage by a sense resistor. The L current builds up to the threshold set by the error voltage which then turns off Q1 in order to keep the output voltage or current constant.

Current Mode Control

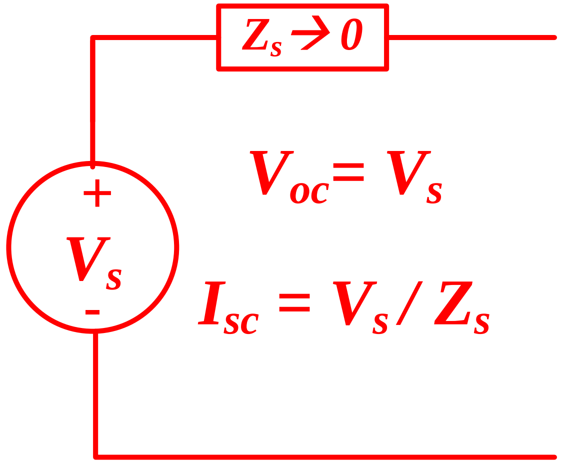


Summary

- 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

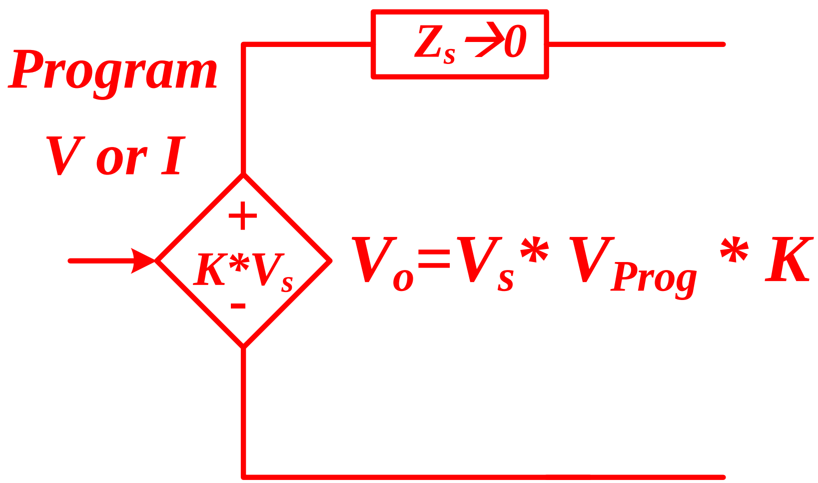


Independent



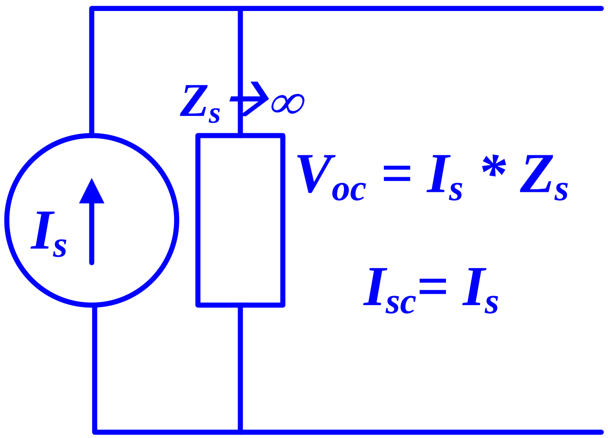
- Provides a constant output voltage regardless of the output current
- Fixed DC output voltage

Dependent



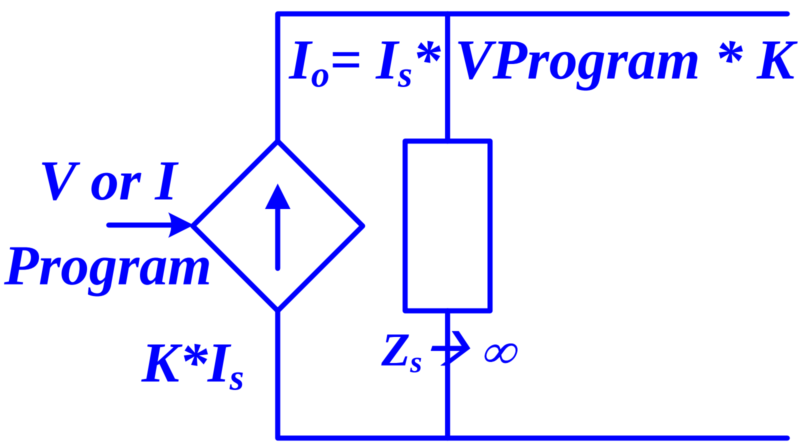
- Provides a constant output voltage regardless of the output current
- Continuously adjustable
- V_o dependent on V_{Prog} (V_{Ref})

Independent



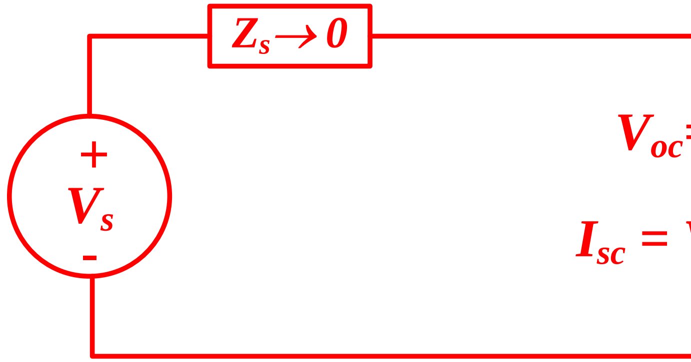
- *Provides a constant output current regardless of the output voltage*
- *Fixed DC output current*

Dependent



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

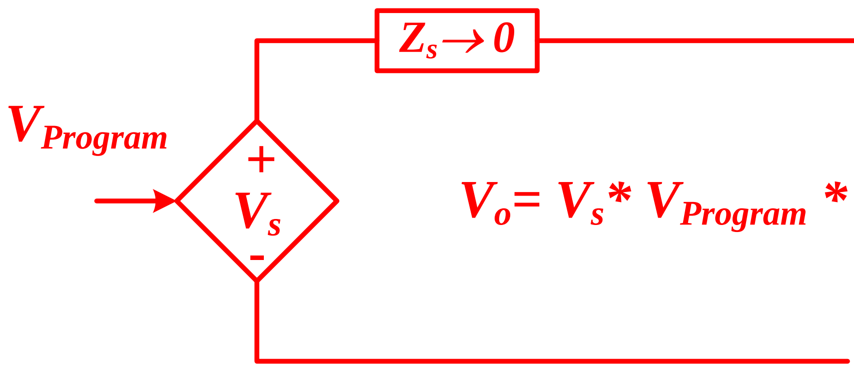
Independent



$$V_{oc} = V_s$$

$$I_{sc} = V_s / Z_s$$

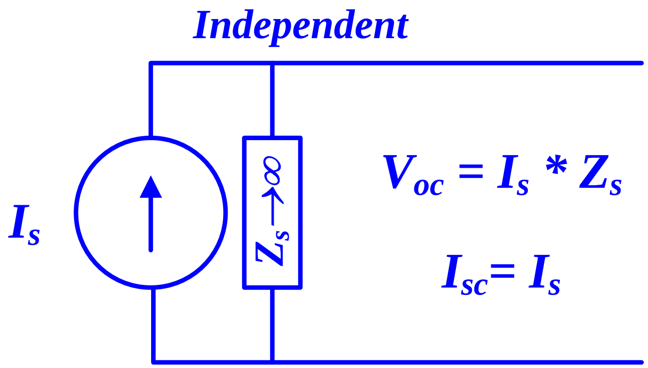
Dependent

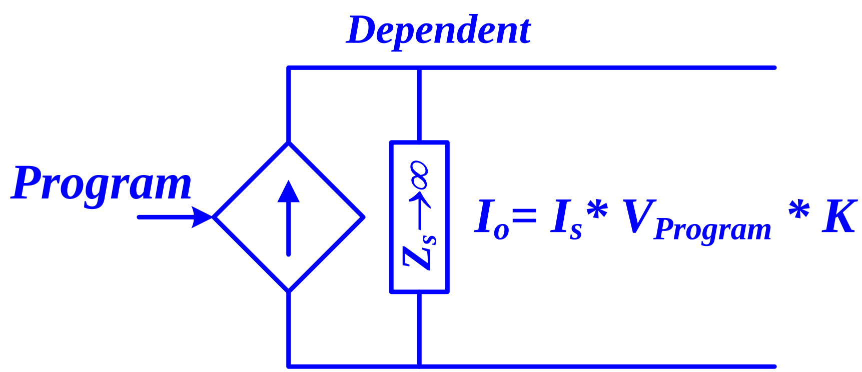


$$V_o = V_s * V_{Program} * K$$

V_O does not vary, regardless of I_O

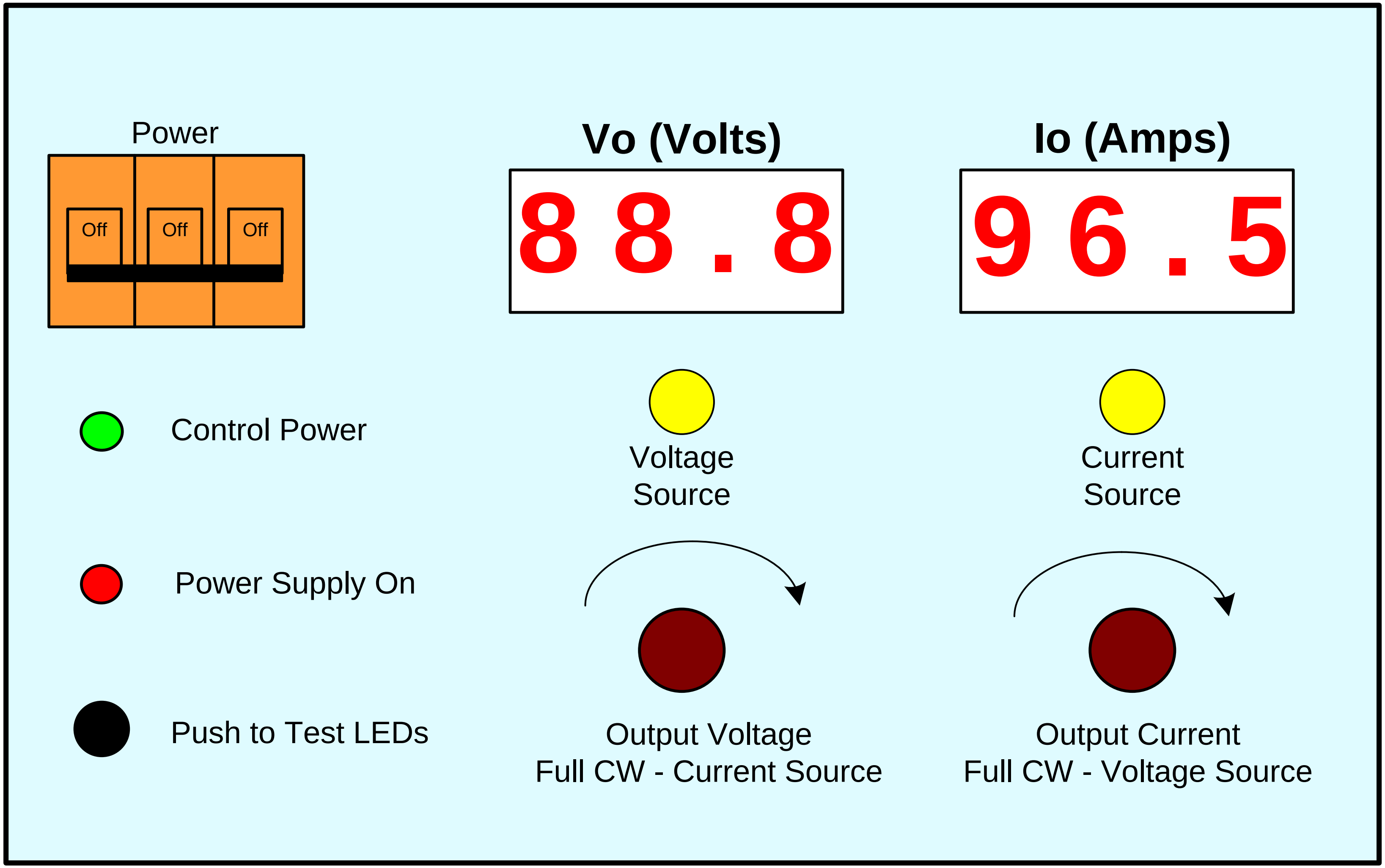
Voltage and Current Sources





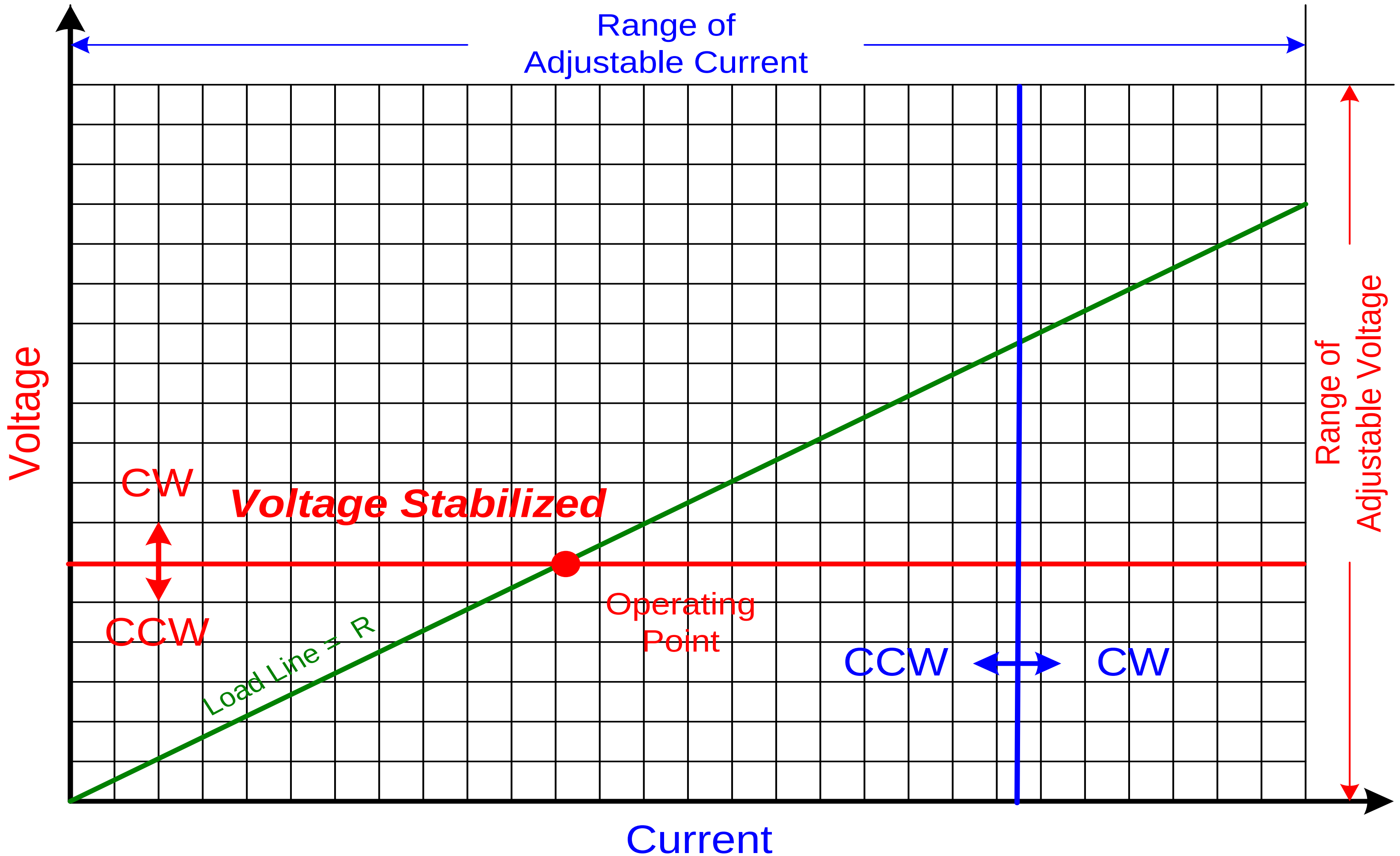
I_O does not vary, regardless of V_O

Automatic Voltage – Current Mode Crossover



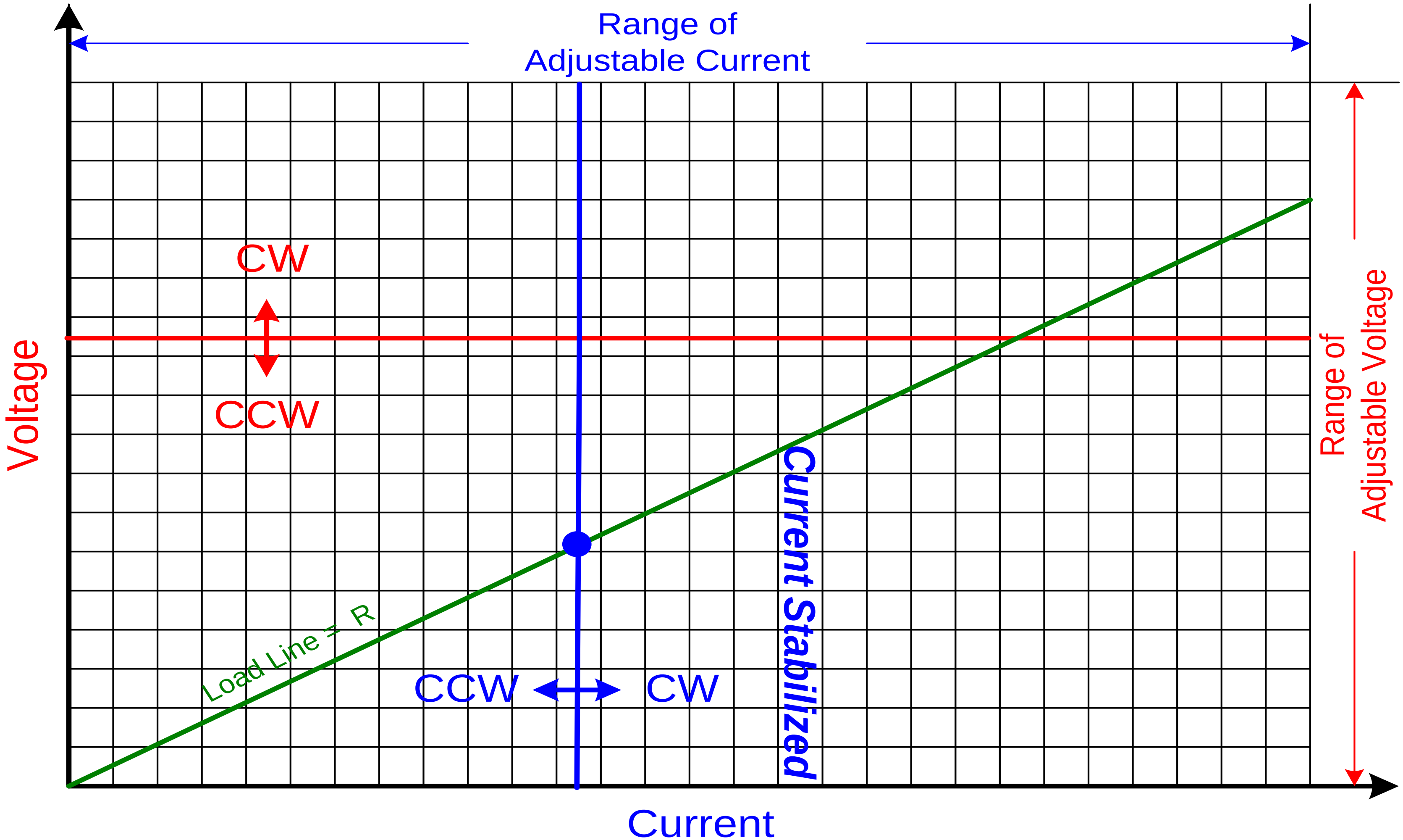
Power Supply Front Panel

Automatic Voltage/Current Crossover – Example 1



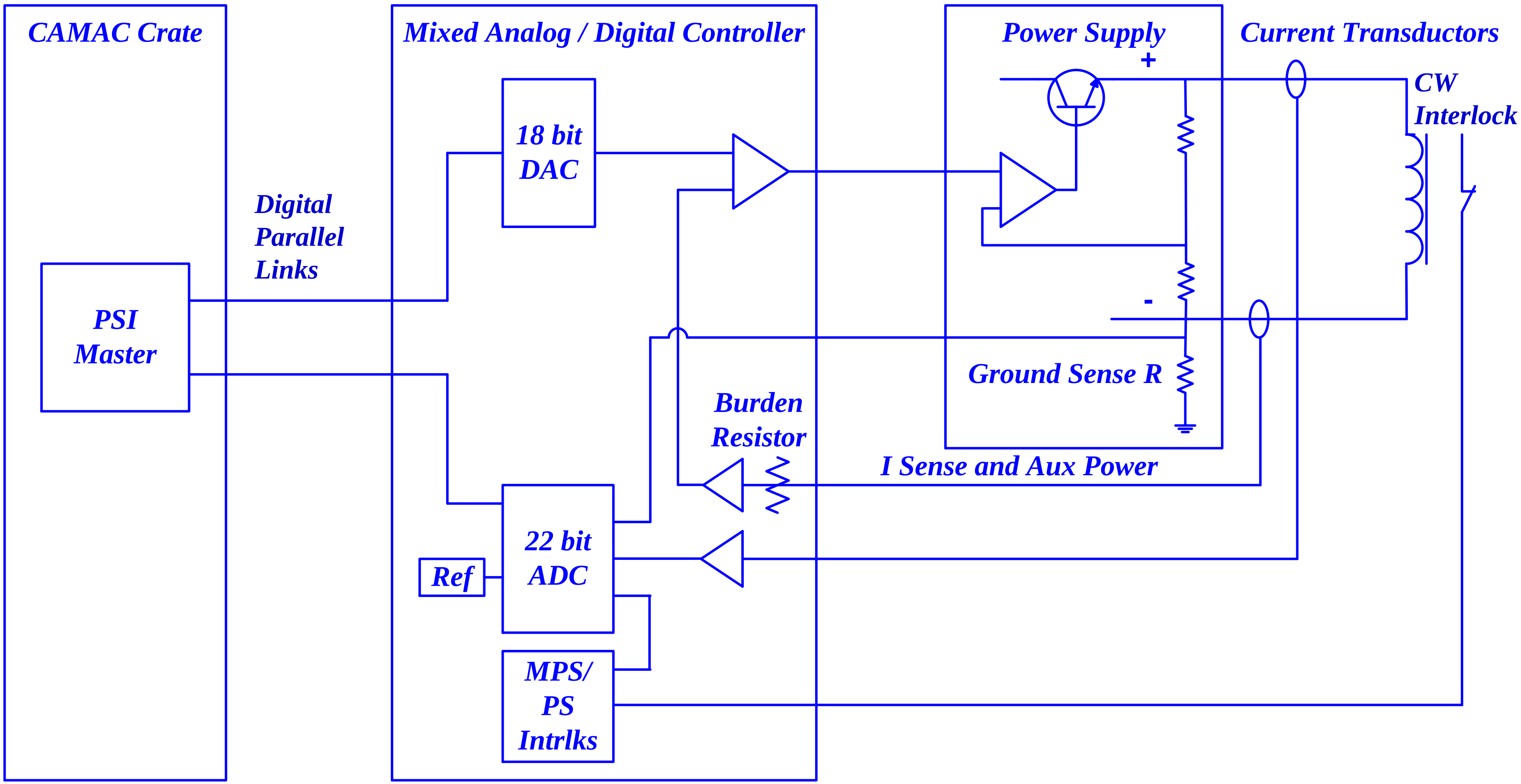
Constant Voltage Mode. *The power supply will operate in this mode whenever the current demanded by the load is less than that defined by the front panel current control. The output voltage is set by the front panel voltage control. The output current is set by the load resistance and the Vset.*

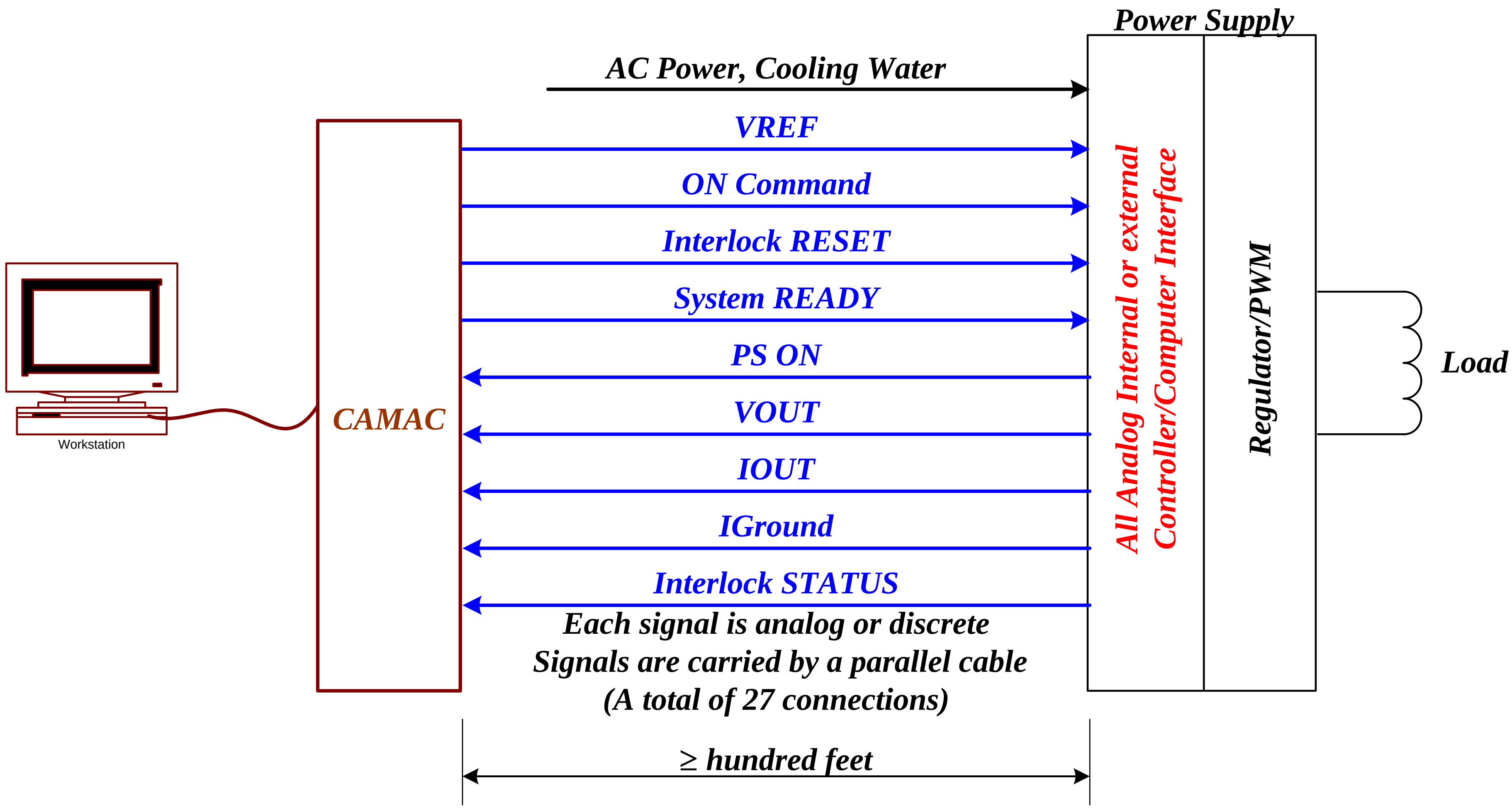
Automatic Voltage/Current Crossover – Example 2



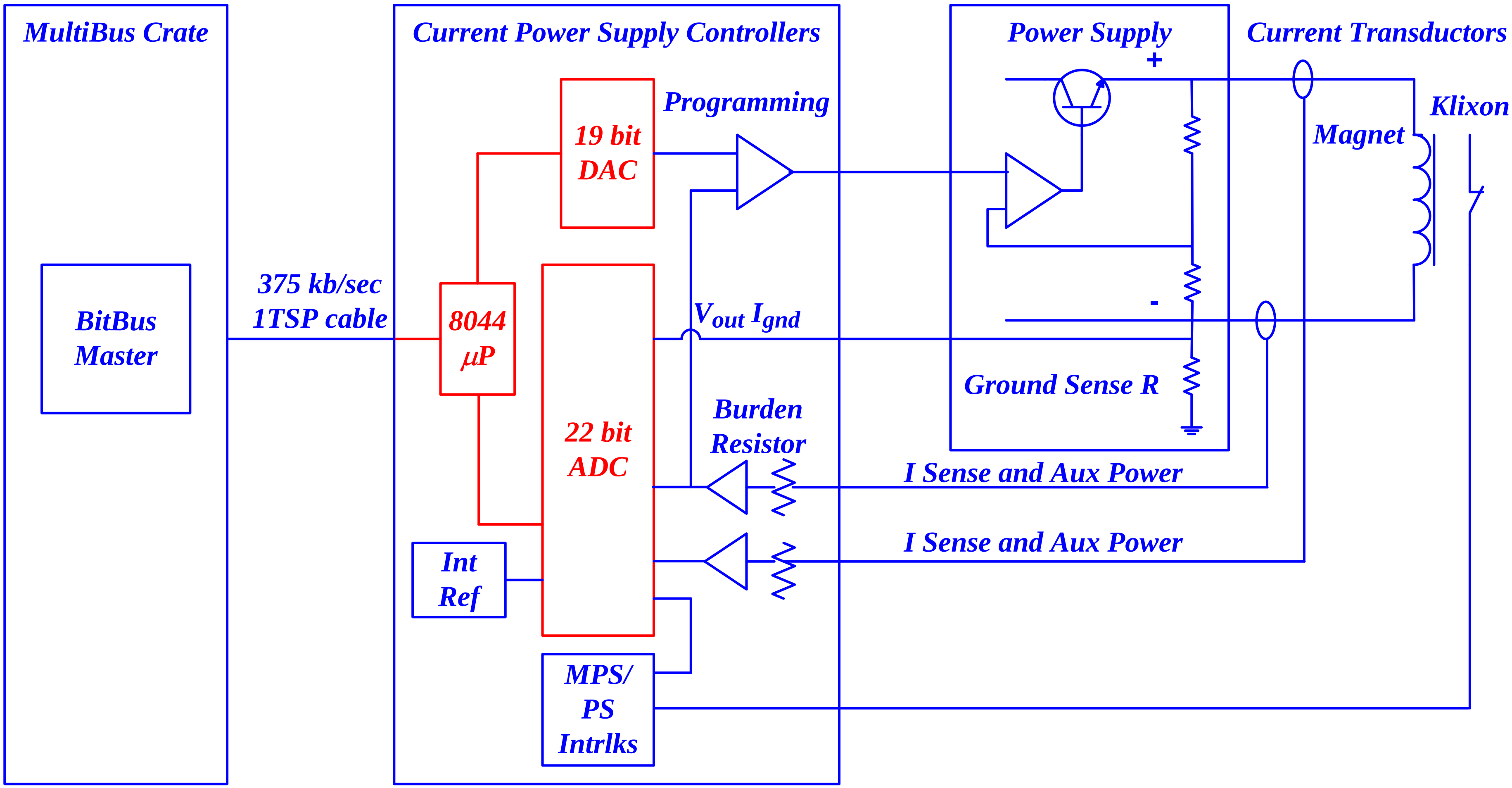
Constant Current Mode. *The power supply will operate in this mode whenever the voltage demanded by the load is less than that defined by the front panel voltage control. The output current is set by the front panel current control. The output voltage is set by the load resistance and the I set.*

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

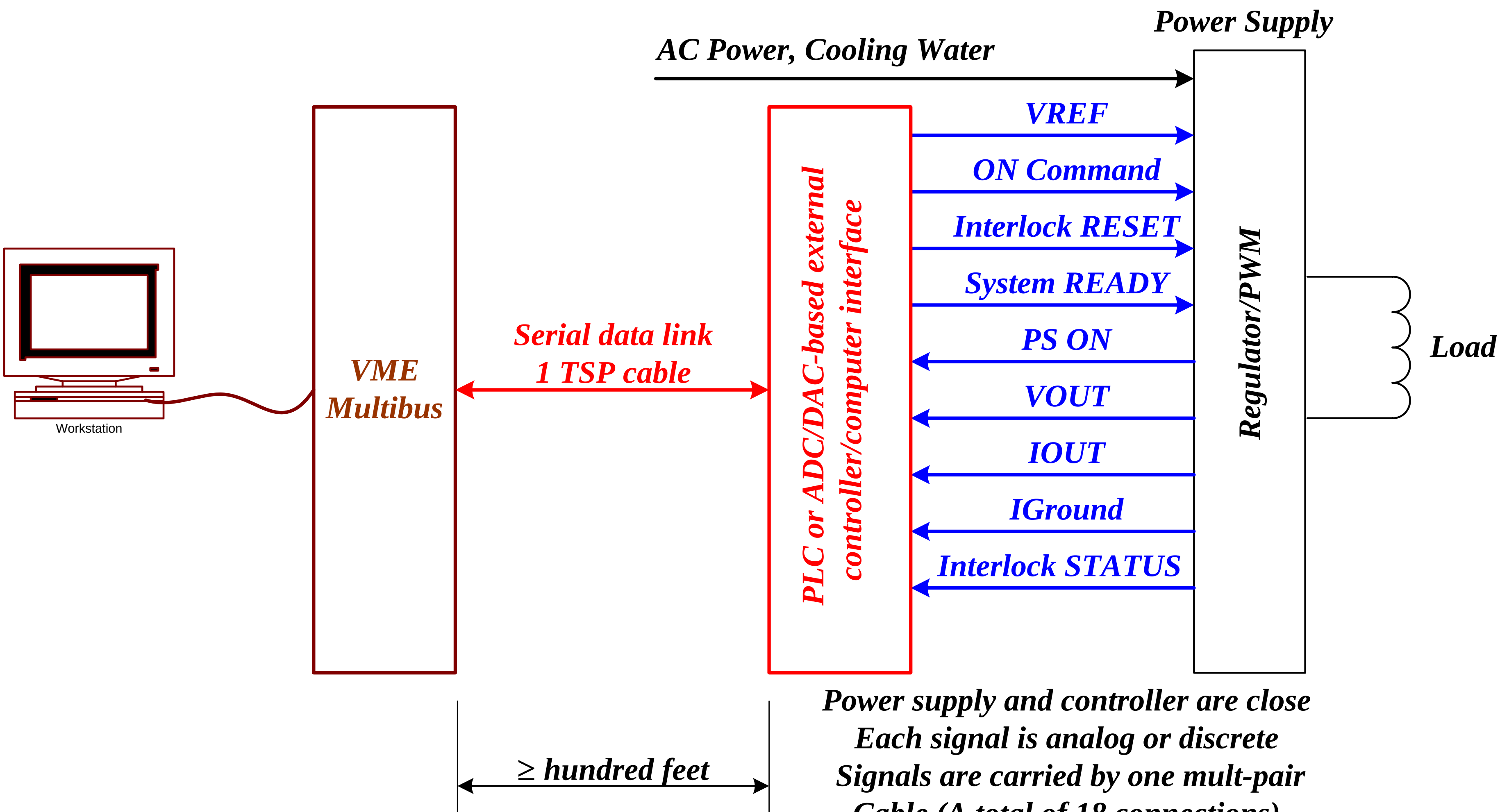



Power Supply
AC Power, Cooling Water
VREF
ON Command
Interlock RESET
System READY
PS ON
VOUT
IOUT
IGround
Interlock STATUS
CAMAC
Workstation
All Analog Internal or external Controller/Computer Interface
Regulator/PWM
Load
Each signal is analog or discrete
Signals are carried by a parallel cable
(A total of 27 connections)
≥ hundred feet

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

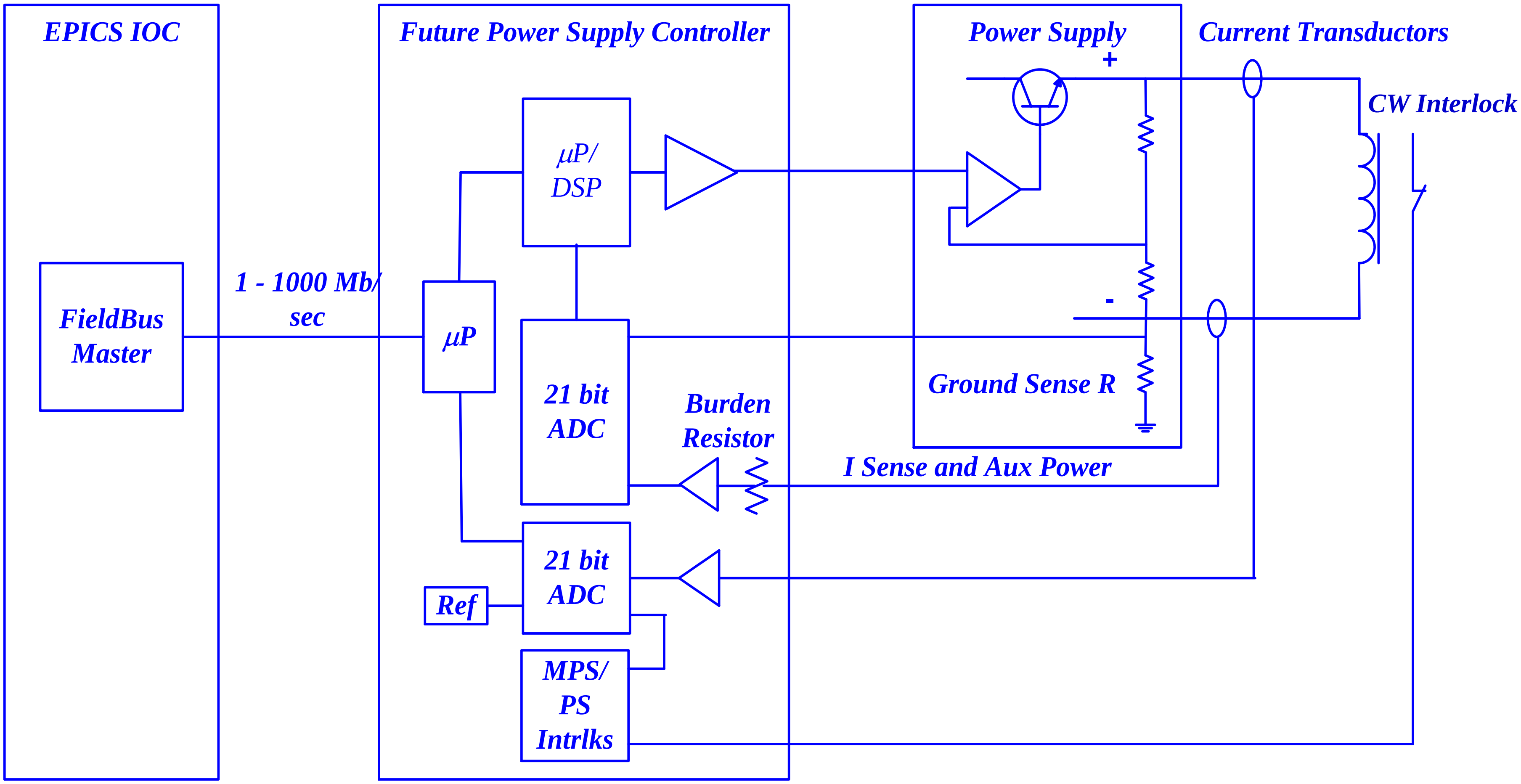


Hybrid Analog/Digital Power Supply Controllers – Circa 1980s to Present

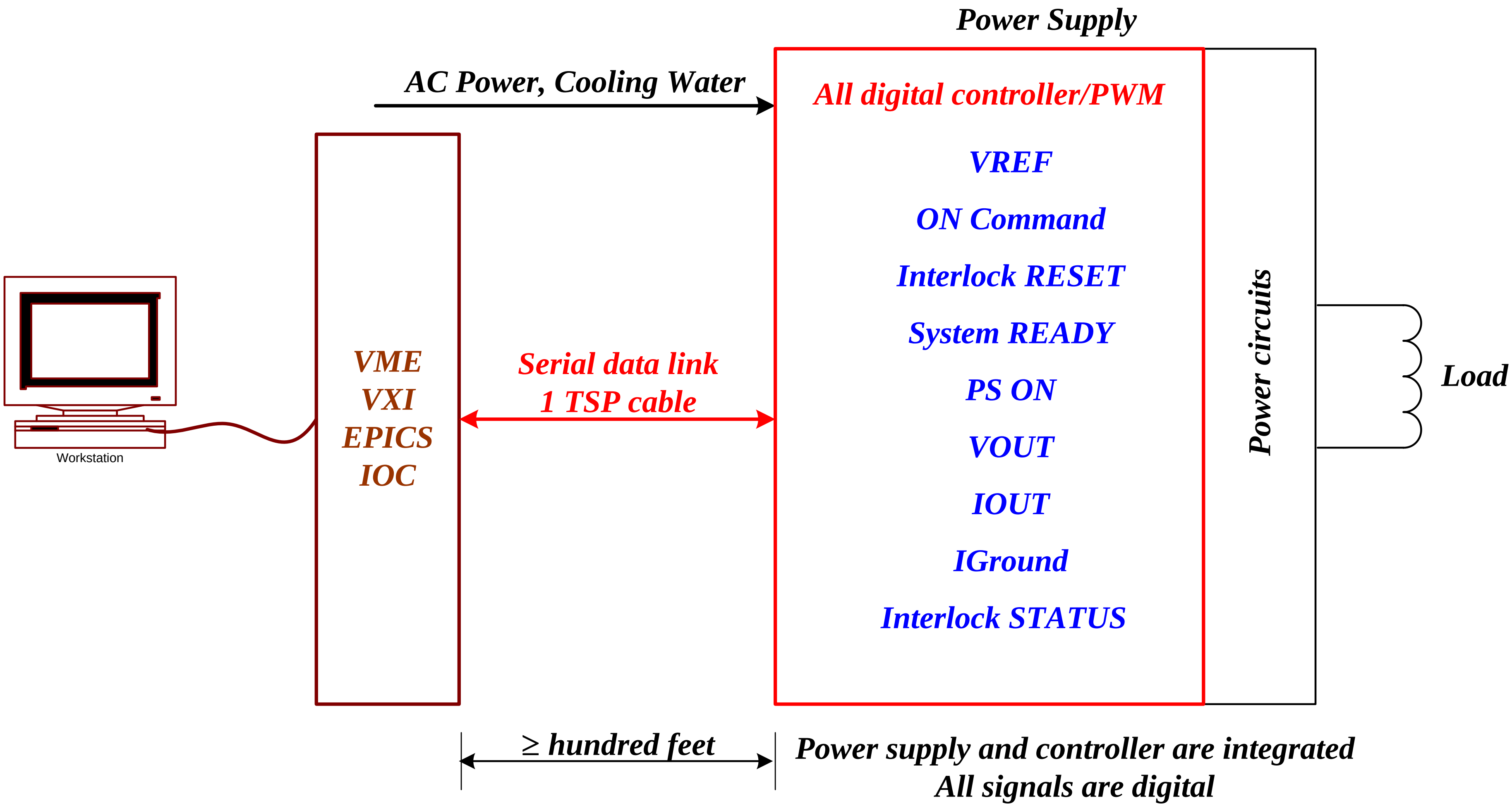


Power supply and controller are close
Each signal is analog or discrete
Signals are carried by one mult-pair
Cable (A total of 18 connections)

All Digital Power Supply Controllers – Circa the Future

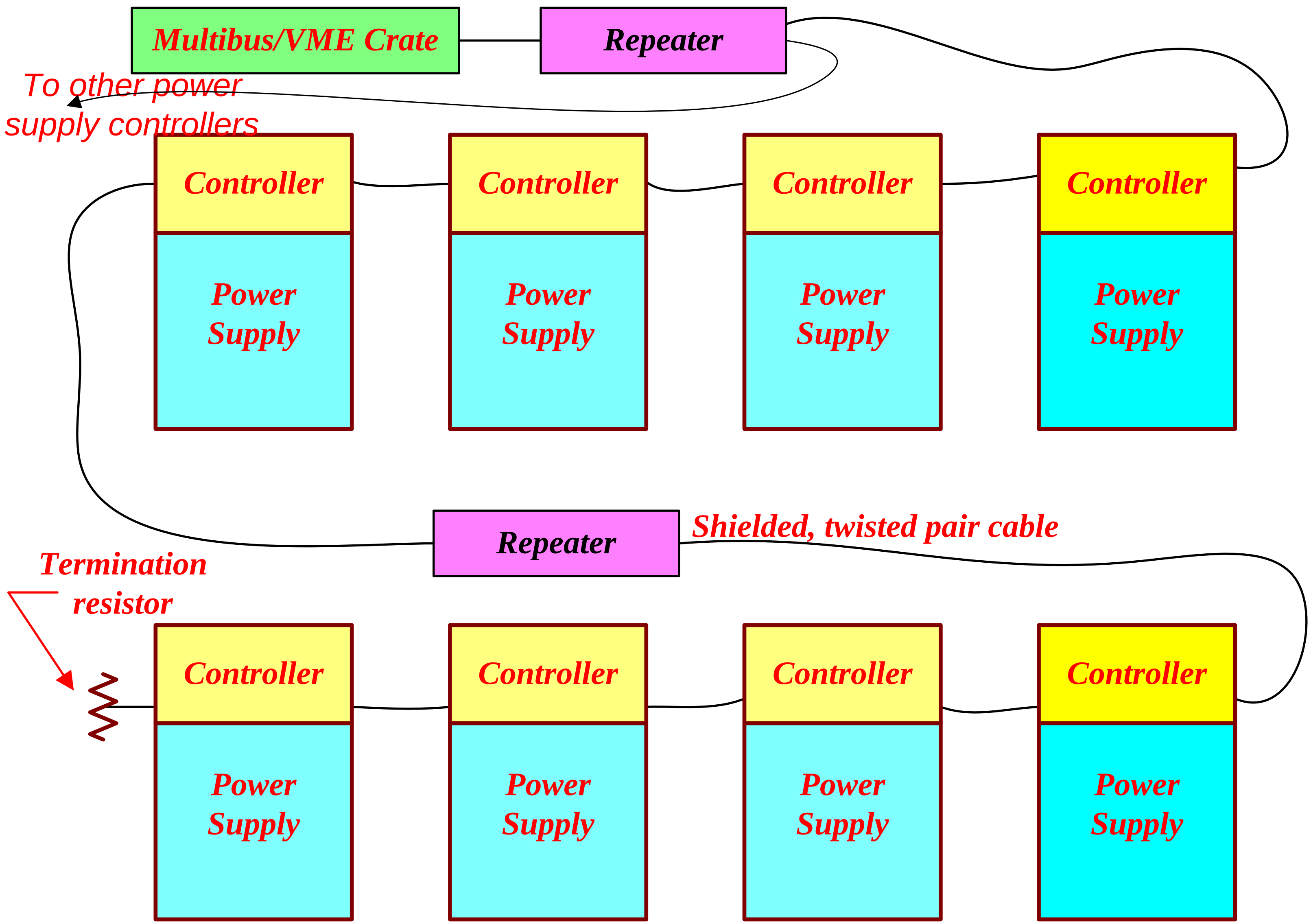


All Digital Power Supply Controllers – Circa the Future



Power supply and controller are integrated
All signals are digital

Daisy - Chaining of Power Supply Controls



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

9. Safety and Interlocks

Safety

National Fire Protection Association (NFPA)

- *NFPA 70 – 2008, National Electrical Code*
- *NFPA 70E – 2009, Standard for Electrical Safety in the Workplace*

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

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

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

Use 2-1/C500kcmil cables

Example of conduit sizing – Size a rigid metal conduit system to enclose 2-1/C4/0AWG cables with a 1-1/C#2AWG ground conductor. Conductors are THHN 600V rated. Conduit size and fill are covered by Article 344.22 and Table 1 of Chapter 9

Table 1 – Maximum % of Cross Section of Conduit and Tubing for Conductors	
Number of Conductors	All Conduit types
1	53%
2	31%
Over 2	40%

Chapter 9 Table 5 area of 1/C#4/0 = 0.32 in^2 and 1/C#2AWG = 0.12 in^2. Total cable area = 0.76in^2

0.76in^2/ 0.4 = 1.9in^2 From Chapter 9, Table 4 a 1-1/2 diameter conduit has an internal area of 2.071 in^2. Use this size

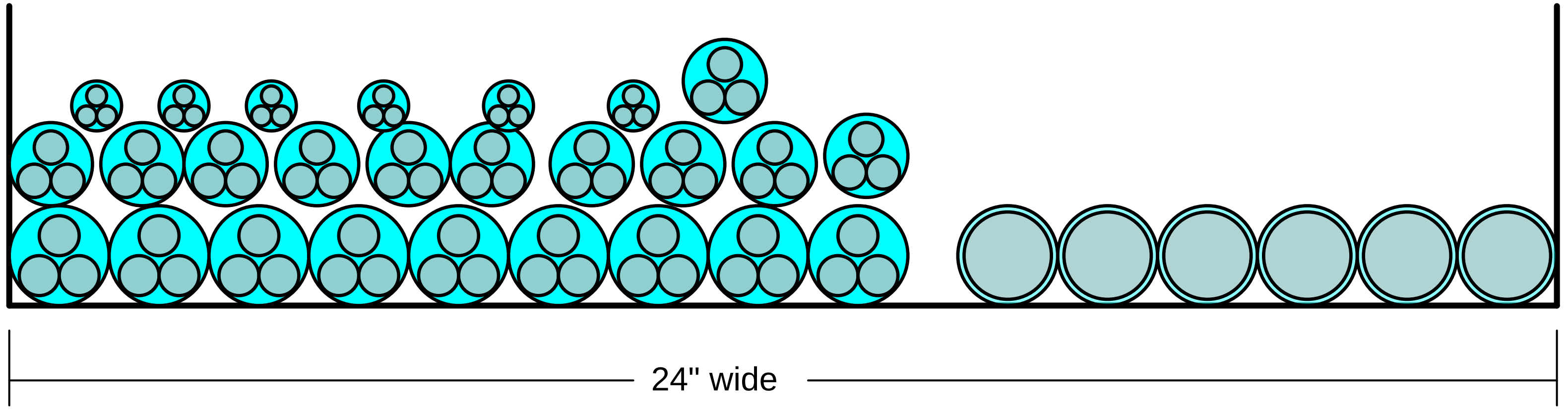
Example of raceway sizing

Cable	Diameter (in)	Area (in^2)	Quantity	Total Area
3/C#8AWG	0.600	0.283	3	0.848
3/C#6AWG	0.684	0.367	4	1.470
3/C#4AWG	0.876	0.603	4	2.411
3/C#2AWG	1.005	0.793	5	3.966
3/C#1/0AWG	1.231	1.190	5	5.951
3/C#2/0AWG	1.328	1.385	4	5.540
3/C#4/0AWG	1.556	1.902	2	3.803
				23.990

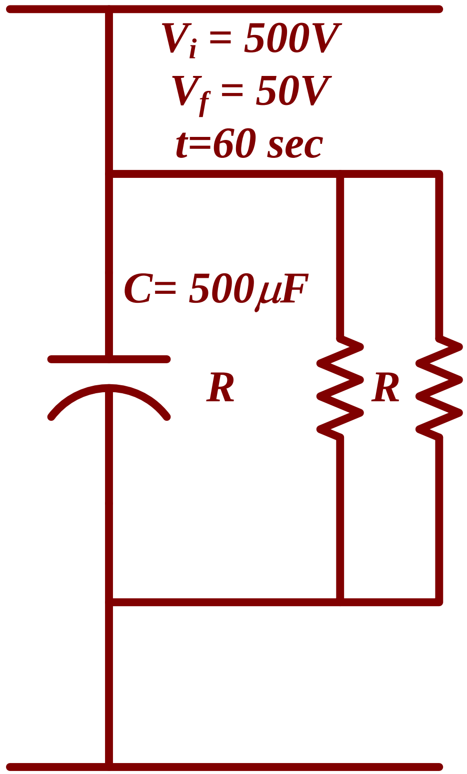
Cable	Diameter (in)		Quantity	Sd (in)
1/C#4/0AWG	0.642		6	3.852

Example of raceway sizing

- *Article 392.9(A)(3) mixture of multiconductor cables and 1/C#4/0AWG cables*
- *Article 392.9, Column 2 sum of single conductor diameters*
- *6 - 1/C4/0 (ea 0.642" diameter) cables placed in a single layer and no other cables on top of them*
- *24" wide tray. The allowable area reserved for multiconductor cables per Column 2, 28-1.2Sd = 28 - 6 * 0.642" = 28 - 3.852" = 24.148 in* ^{2}
- *The total crossectional area of all the multiconductor cables is 23.990 in* ^{2} *which is less than the cable tray area reserved for the multiconductor cables - OK*



- 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



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

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

$$R = 50\,kohm$$

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

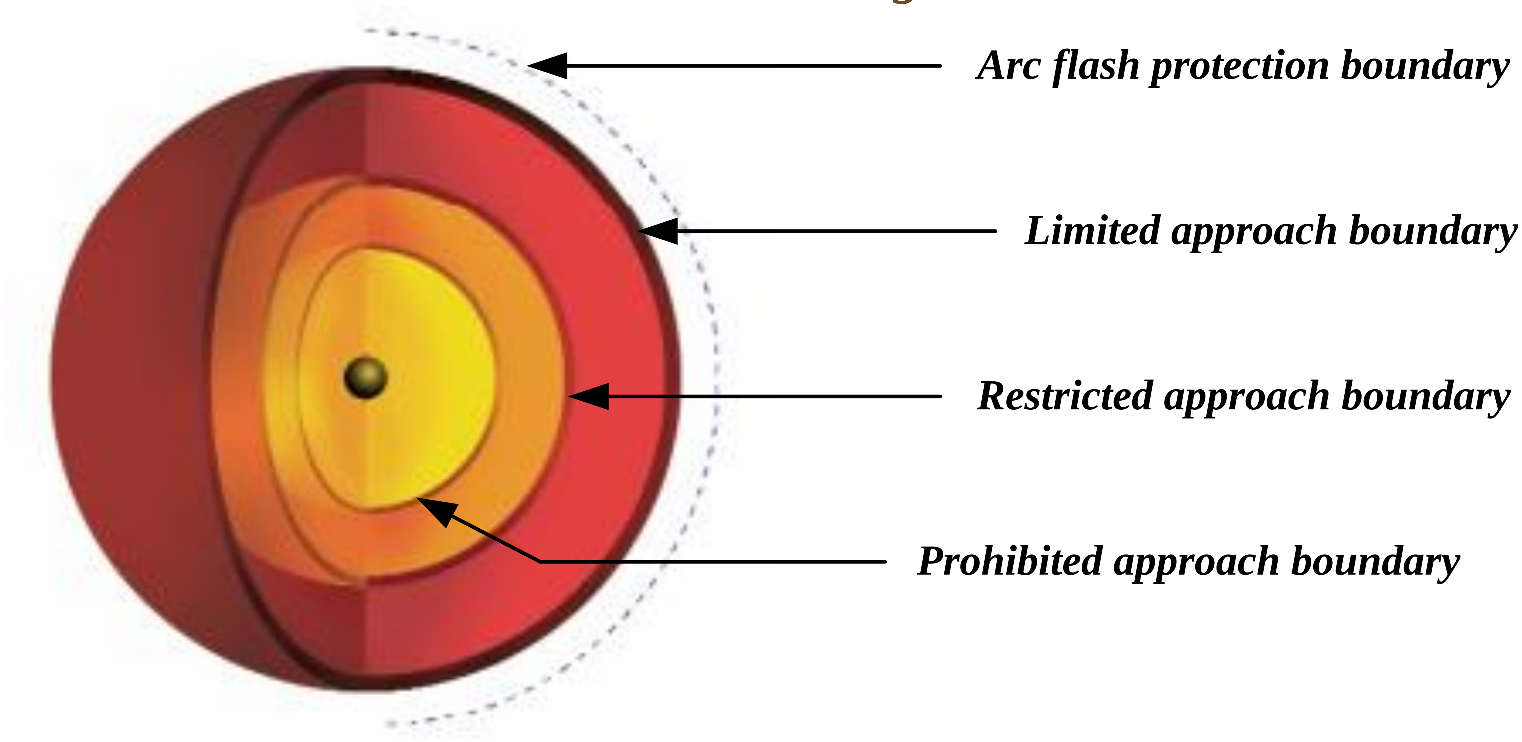
Use two 5W, 100kΩ resistors in parallel

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

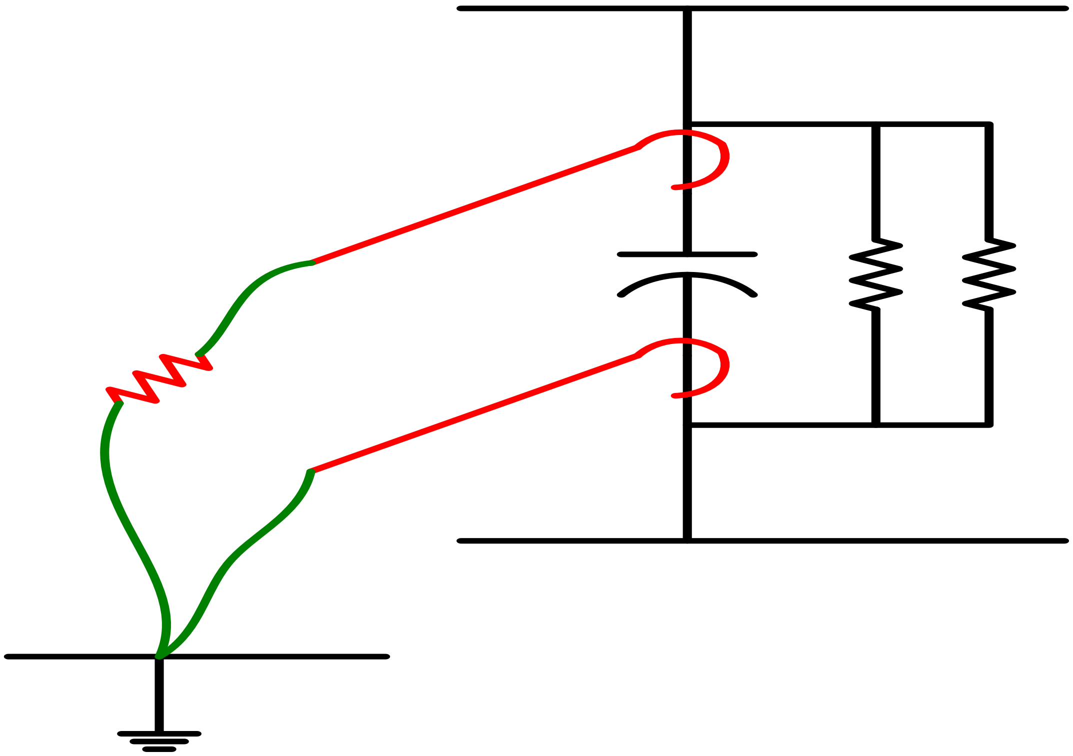
- *They are marked with the class appropriate for the voltage, and should be subject to periodic electrical tests*
- *Leather protective gloves should be worn outside the rubber gloves to provide protection from cuts, abrasions, or punctures.*
- *Before each use, check for signs of damage or color change. Replace if contamination or sustain any physical damage is evident.*
- *Gloves should be stored in a closed, dry container.*

Mitigating the Voltage Hazard

Insulating Glove Class	*Rated Use Voltage AC [1]/DC [2,3]*	*Proof Test Voltage AC [1]/DC [2,3]*
00	*500 / 750*	*2,500 / 10,000*
0	*1,000 / 1,500*	*5,000 / 20,000*
1	*7,500 / 11,250*	*10,000 / 40,000*
2	*17,000 / 25,500*	*20,000 / 50,000*
3	*26,500 / 39,750*	*30,000 / 60,000*
4	*36,000 / 54,000*	*40,000 / 70,000*

1. *American Society for Testing and Materials (ASTM) Standard D-120*
2. *International Electrotechnical Commission (IEC) Standard 60903*
3. *DC applications: when gloves do not have an IEC DC voltage rating, use the AC rating as the DC rating*

The possibility of residual voltage on capacitors is high. Use one or more ground stick to remove the voltage (stored energy)



What is Arc Flash?

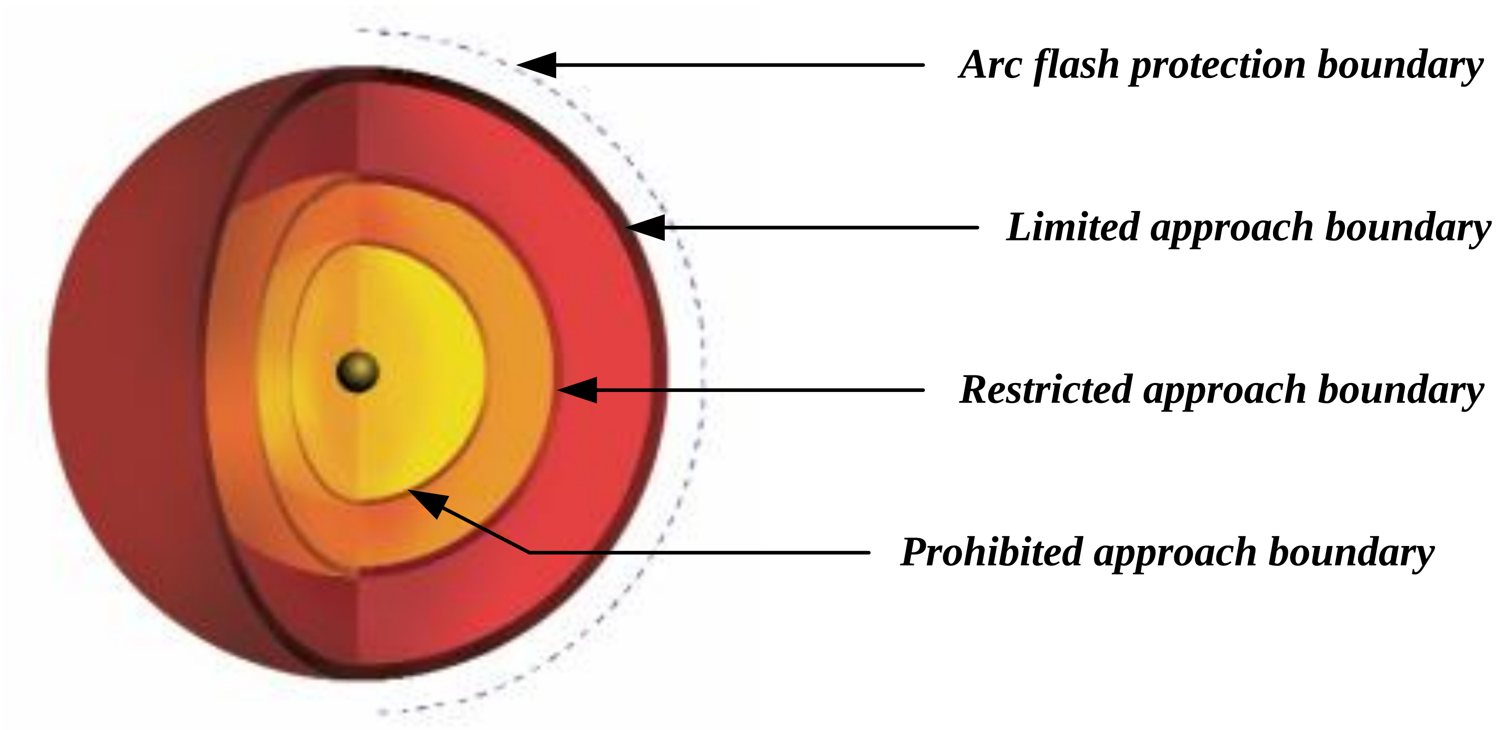
- *Short circuit through air*
- *Caused when circuit insulation or isolation is compromised*
- *A burn and explosion hazard, not an electrocution hazard*
- *Temperature can greatly exceed 5000 F*
- *Instantaneous, almost too fast for the eye to comprehend*
- *Arc flashes occur 5 – 10 times a day in electric equipment in US alone.*

Possible Causes of Arc Flash

- *Tool inserted or dropped into a breaker or service area*
- *Equipment cover removal causes a short*
- *Loose connections on bus work*
- *Improper bus work fabrication*
- *Insulation breakdown due to environmental factors or equipment aging*
- *Failure to ensure equipment is de-energized before work*
- *Primarily applications above 208 VAC*

Injuries Associated with Arc Flash

- *Third Degree Burns, Blindness, Hearing Loss, Nerve Damage, Cardiac Arrest, Concussion, Death*



- *Arc flash hazard - a dangerous condition associated with the release of electrical energy caused by an electrical arc. Typically due to the molten plasma formed by the melting of conductors during an electrical short circuit*
- *Arc flash protection boundary - The distance form exposed live parts within which a person could receive a second degree (curable) burn (1.2 cal/cm ^{2} = 5 J/cm ^{2})*

- *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)*

Arc Flash Hazard

- *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.*

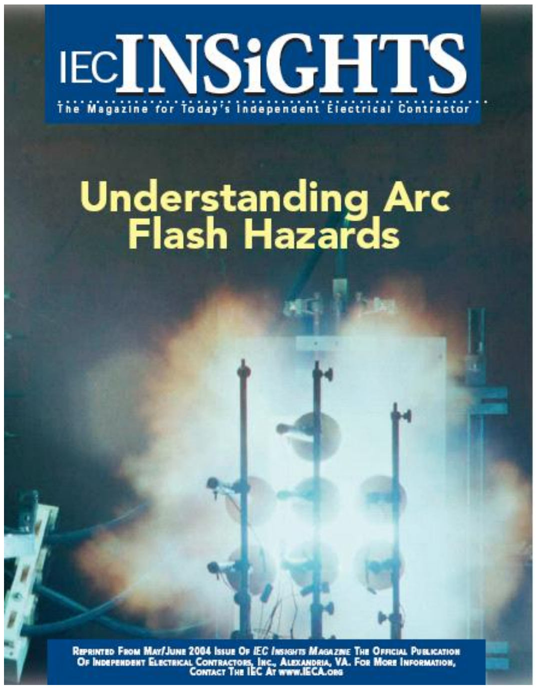
  Note: This is comparable to holding the flame from a cigarette lighter on your skin for 1 second

In 1982, the first calculations concerning arc-flash were published by Ralph Lee

- *Calculated the maximum available power from an arc*
- *Assumed the power density dropped off with the inverse square of the distance from the arc*
- *Related the energy to biological studies that determined the second-degree burn threshold*
- *Formula for working distance to avoid second-degree burns reproduced in 130.3(A) of NFPA 70E*

$$D_c = \sqrt{2.65 MVA_{bf}\, t}$$

First Empirical Models



- *Mid 1990's, other teams from DuPont, Doughty, et. al., and an IEEE Working Group IEEE1584, performed a set of experiments to measure the heat generated by an arc.*
- *Wanted empirical data to quantify arc flash hazards*
  - *Measured dependence on arcing current*
  - *Measured dependence on distance from arc*
  - *Measured dependence on some enclosure configurations*
  - *Measured voltage dependence*
  - *Detailed configuration dependencies*
  - *Found that enclosures focus the pressure blast from the arc and focus the energy*
- *Flash protection boundary for enclosures more conservative than Lee's*
- *Formulae reproduced in Annex D.6 of NFPA 70E*

IEEE 1584 208 VAC Exemption

- *Arc needs to sustain itself in order to generate enough heat to cause burns*
- *Empirical evidence from studies showed that it was extremely difficult to sustain an arc from a 208VAC system*
- *Statement from IEEE 1584 "The arc-flash hazard need only be considered for large 208 V systems; systems fed by transformers smaller than 125 kVA should not be a concern."*

NFPA 70E Table 130.7(C)(9)(a)

- *NFPA Technical Committee also addressed the arc-flash hazard issue from a parallel point of view*
- *Used common industrial experience to determine the level of protection required to prevent second-degree burns for certain well-defined operations*
- *Table 130.7(C)(9)(a) summarizes this experience*
- *Distinguishes between types of equipment*
- *Switchgear, MCCs, panelboards, and switchboards*
- *In order for table to be applicable for most low voltage systems, the fault current must be below a maximum allowed current and the fault clearing time must be less than a maximum allowed time*

Calculation Assumptions

- *Nothing in the panel being operated, including the main breaker, will protect us in case of an arc-flash during the operation of any part of that panel*
  - *Main breaker could fail on line side during operation*
  - *Arc-flash originating at operated breaker could spread to line side of main breaker*
- *The fronts of the panelboards and switchboards provide no protection against arc-flash*
- *Independent of the clearing time of the upstream protective device, the worker will move away from exposure in less than 2 seconds, so that "two seconds is a reasonable maximum time for calculations"*

Bolted Fault Current Calculation

- *Power from a three-phase Wye or Delta transformer is*

$$S_{3P} = \frac{V_{LL} * I_L}{\sqrt{3}}$$

- *The full load line current is*

$$I_{FL} = \frac{MVA * 10^6}{\sqrt{3} * V_{LL}}$$

- *Available short circuit current using the transformer rating and circuit impedances (mainly leakage inductance of transformer)*

$$I_{BF} = \frac{MVA * 10^6 * 100}{\sqrt{3} * V_{LL} * Z(\%)}$$

$$I_{BF} = \frac{MVA * 10^6 * 1}{\sqrt{3} * V_{LL} * Z(pu)}$$

Arcing Current

- Empirical formula from IEEE 1584
- Flash hazard is due to total energy absorbed by skin
- Bolted fault current (I_{bf} in kA)
- Must calculate arcing current (I_a in kA) at which the flash energy is generated

$$I_a = 10^{K + 0.662 \log I_{bf} + 0.0966 V + 0.000526 G + 0.5588 V \log I_{bf} - 0.00304 G \log I_{bf}}$$

- I_a lower than I_{bf} therefore may last a longer time than I_{bf} since it may take longer for the protective device to clear
- K is the value for the arc ambient (0.153 for open air, 0.097 for boxes)
- V is the system voltage in kV
- G is the conductor gap in mm (25mm for 480VAC MCCs and panels)
- Use I_a and $0.85I_a$ for clearing times from breaker or fuse time-current curves

Clearing Times

- *Once the arcing currents are determined, the clearing times must be determined*
- *The upstream fuse or breaker that will clear the fault must be identified*
- *The manufacturer's time-current curves for the appropriate device are identified*
- *The arcing current is found on the x axis and the clearing time is read from the y axis*

Protective Devices

- *Protective devices act to clear fault currents*
- *Fuses (fixed time-current curves)*
- *Molded Case Circuit Breakers (MCCB)*
  - *Thermal*
  - *Magnetic (adjustable)*
  - *Electronic (adjustable)*
- *Low Voltage Power Circuit Breakers (adjustable)*
- *Vacuum Contactors with Protective Relays (adjustable)*

Molded Case Circuit Breakers

- *Panelboard with 4 800A MCCBs*
- *Thermal-magnetic*
- *Adjustable with front panel rotary switches*

Molded Case Circuit Breaker

- *Motor Control Center (MCC) main breaker (2000A)*
- *Separate Frame and Trip units*
- *Adjustable with front panel rotary switches*
- *Electronic Trip Control LSIG*
  - *Long Time*
  - *Short Time*
  - *Instantaneous*
  - *Ground Current*

Low Voltage Power Circuit Breaker

- First breaker downstream of transformer
- Separate frame and trip unit
- Rated up to 4000A
- Trip units are adjustable via front panel controls
- Typically inside a substation

Medium Voltage Breaker and Protective Relay

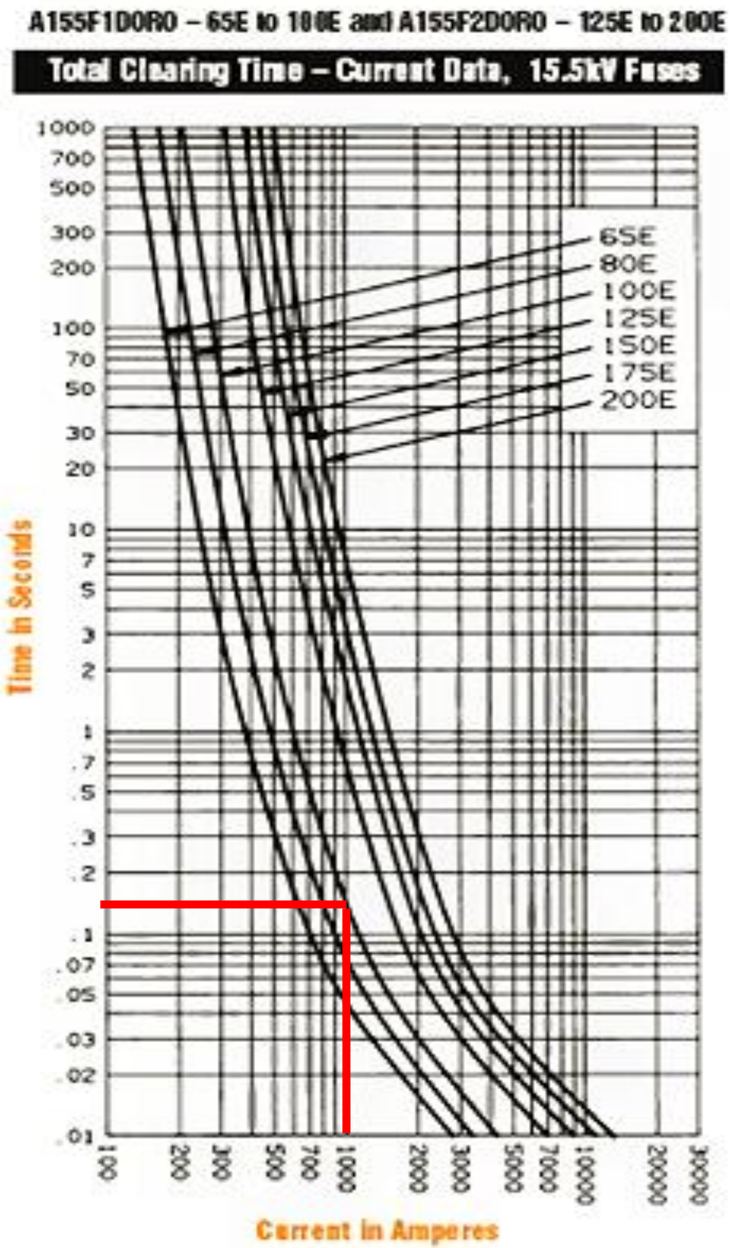
- *Protects primary side (12.47kV) of transformer*
- *Breaker has tripping mechanism but no sensor*
- *Protective relay*
  - *Connected to current transformers on bus*
  - *Activate breaker tripping mechanism*
  - *Adjustable via DIP switches*

Linac VVS with LVPCB, Relays, XFMR, MCCBs

Time-Current Curves

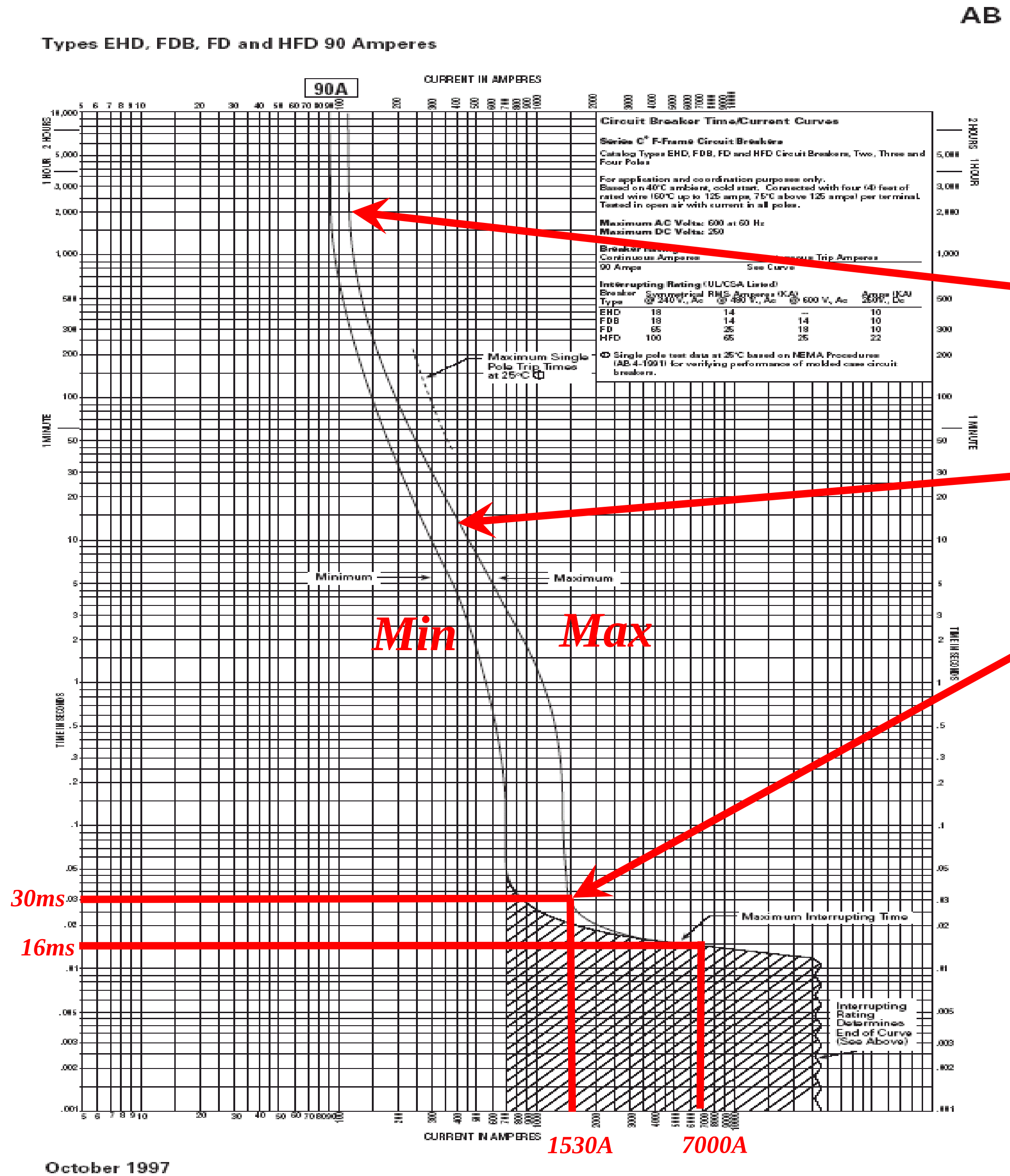
- *Each protective device has a time-current curve*
  - *Current on x-axis*
  - *Time on y-axis*
- *Currents below the trip value will not open the device*
- *Currents slightly above the trip value will trip after a long time to prevent fires from heating in the wires*
- *Currents very much larger than the trip setting signal a fault and trip the device as quickly as possible*
- *Adjustments set these values and, if applicable, the intermediate behavior of the breaker*

Typical medium voltage fuse time-current curve (Ferraz-Shawmut)



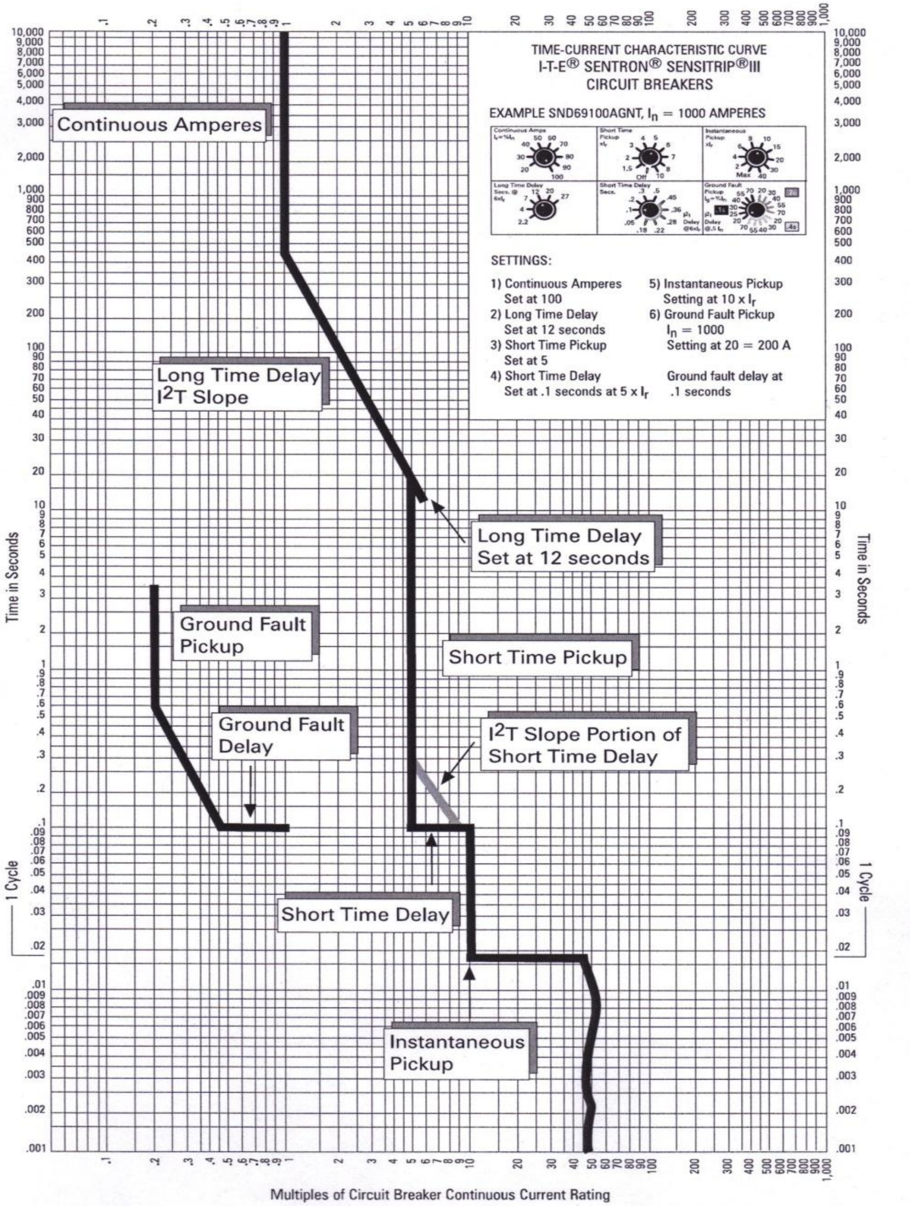
- *Non-adjustable*
- *Top of y-axis is 1000 seconds and fuses not yet open on 2X overcurrents*
- *These fuses take more than 0.1 second to open on 10X overcurrent*
- *Different classes of fuses for different voltages and currents*

Typical breaker time-current curve (Cutler Hammer)



- *Thermal breaker (90A)*
- *Small overcurrent takes > 30 minutes to trip*
- *Lines of constant I^2t (constant energy) protect against thermal damage*
- *17X (1530A) overcurrent trips in 30 msec*
- *Very high currents trip in 16 msec*
- *Note that curve gives Min, Max tolerance band*

Adjustable MCCB (LSIG) Time-Current Curve(C-H)



Adjustable breaker can set various parameters

- *Long time moves left hand side vertical bar*
- *Short time pickup sets intermediate vertical bar*
- *Short time delay sets intermediate pedestal*
- *Instantaneous setting determines current at which instantaneous trip occurs*

Normalized and Actual Incident Energies

Once the system configuration and arcing currents are known, the "normalized" and actual arcing energies can be calculated (IEEE 1584 formulas)

$$E_n = 10^{K_1 + K_2 + 1.081 \, Log \, I_a + 0.0011 \, G}$$

$$E_{85n} = 10^{K_1 + K_2 + 1.081 \, Log \, I_{85a} + 0.0011 \, G}$$

$$E_a = C_f \, E_n \left(\frac{t_a}{0.2}\right)\left(\frac{610}{D}\right)^x$$

$$E_{85a} = C_f \, E_{85n} \left(\frac{t_{85a}}{0.2}\right)\left(\frac{610}{D}\right)^x$$

- K_1=-0.555 for arcs in a box, K_2=-0.113 for a grounded system
- En, E_{85n}, E_a, E_{85a} are expressed in cal/cm2
- C_f = 1.5 (voltages below 1 kV and = 1.0 for voltages above 1 kV)
- t_a and t_{85a} are arcing time in seconds, obtained from the appropriate time-current curve
- D is working distance in mm
- x is a system-dependent distance factor from Table 4 of IEEE 1584 or Table D.7.2 of NFPA 70E

Working Distance

- *The "safe" working distance is defined as the minimum distance at which the worker's body and torso receives a second degree burn (E or Ea=1.2 cal/cm²)*
- *Invert the above formulas to obtain the Flash Protection Boundary distances*

$$D = \left[C_f \left(\frac{E_n}{1.2}\right)\left(\frac{t_a}{0.2}\right)\right]^{1/x}(610)$$

$$D_{85} = \left[C_f \left(\frac{E_{85n}}{1.2}\right)\left(\frac{t_{85a}}{0.2}\right)\right]^{1/x}(610)$$

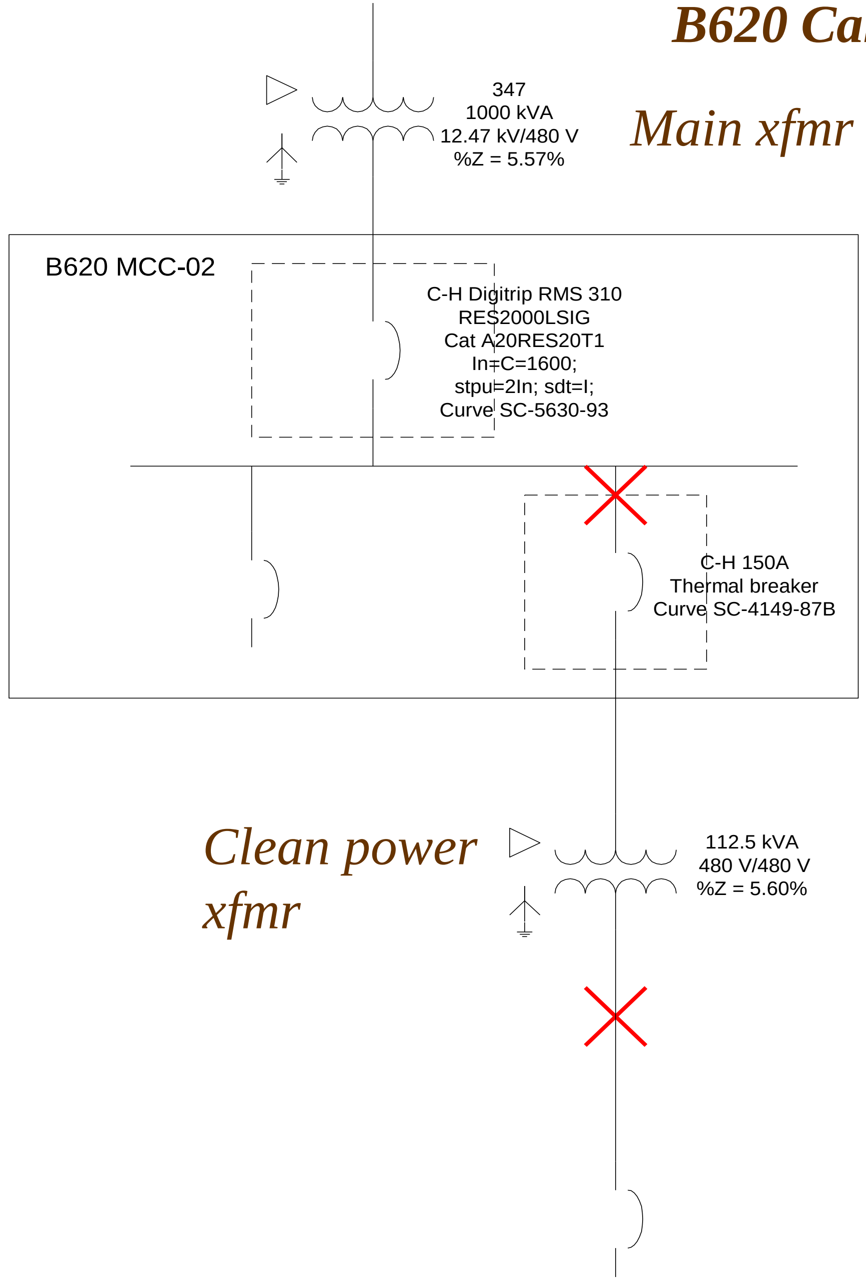
- *Take the larger of the arcing energies and distances for use on the arc flash hazard labels*

- *The hazard/risk category is determined by selecting the row for which $E_{min} \leq E < E_{max}$ at the working distance.*

E_{min}	E_{max}	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*

B620 Calculation



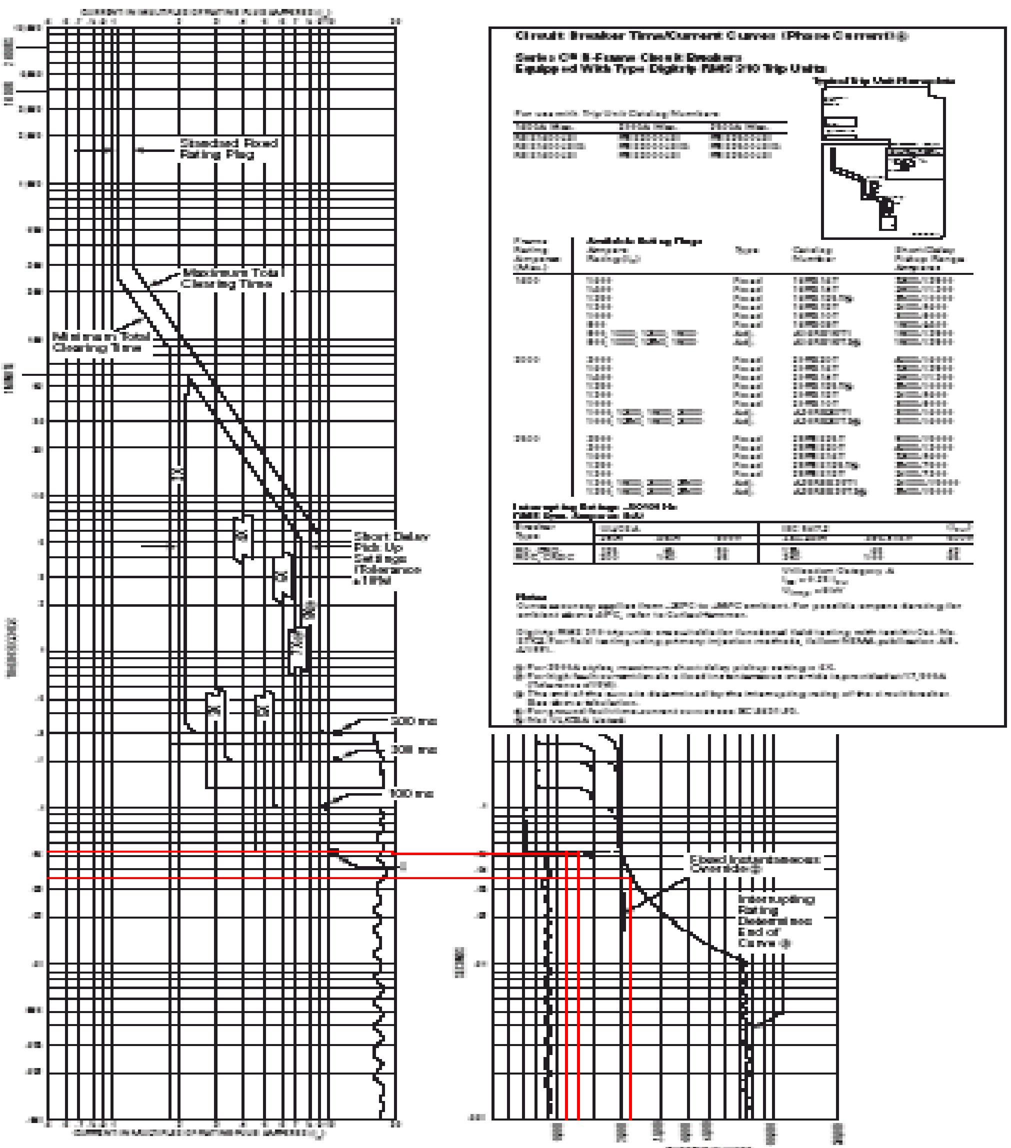
- *Calculate two arc-flash energies*
  - *Operate feeder breaker in MCC*
  - *Operate breaker downstream of "clean" transformer*

- *Main xfmr*
  - *1 MVA 12470V/480V*
  - *Z = 5.57%*

- *"Clean power" xfmr*
  - *112.5 kVA 480V/480V*
  - *Z = 5.60%*

MCC Feeder Breaker Calculation

Types RD, CRD, RDC, CRDC Equipped With Digitrip RMS 310 Trip Units. Typical Long Delay/Short Delay Time-Phase Current Characteristic Curve Based on I_n

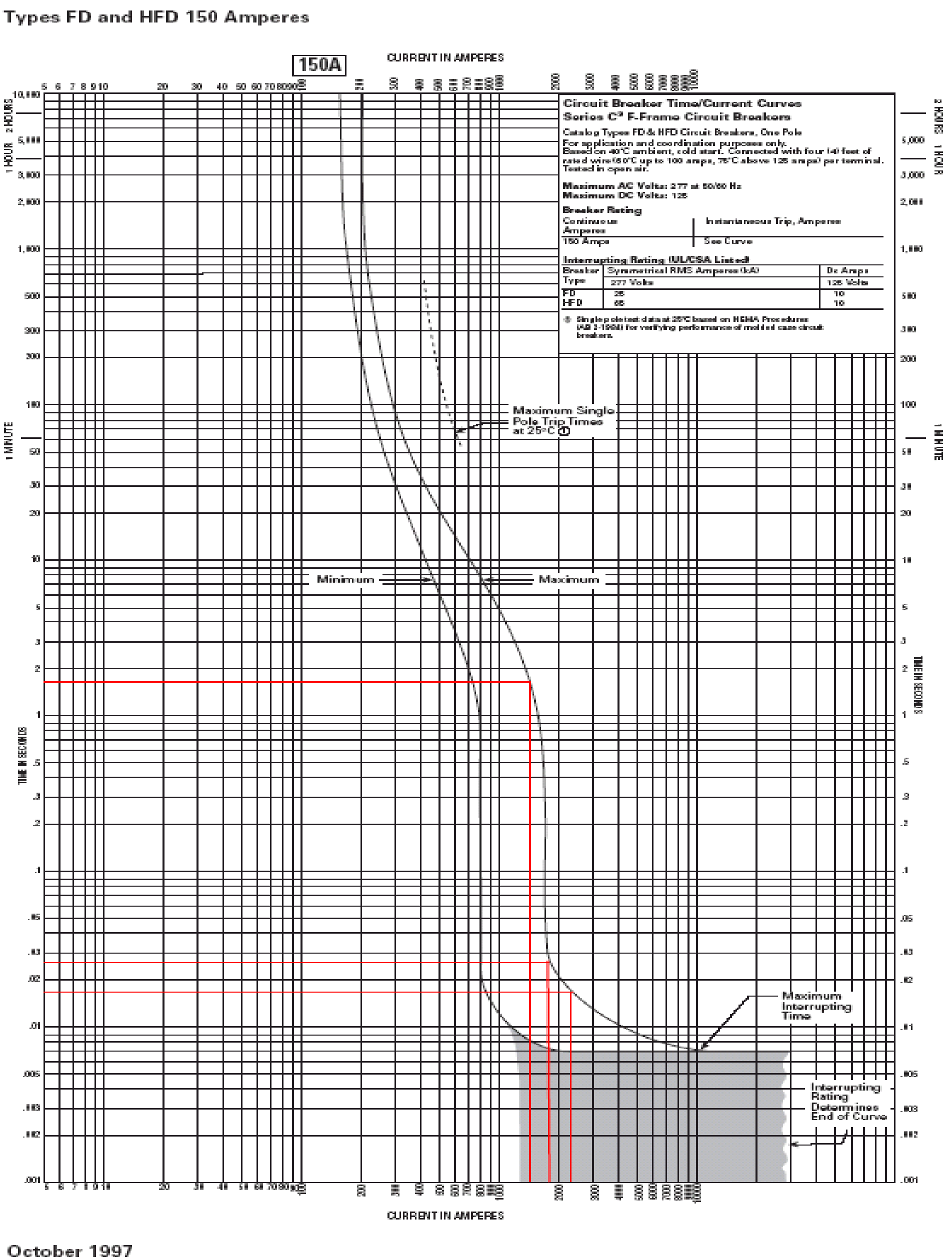


- I_{fl} = 1.2 kA
- Z = 5.57%
- Fault currents
  - I_{bf} = 21.6 kA
  - I_a = 12.7 kA
  - $0.85I_a$ = 10.8 kA
- Clearing times from C-H AD 29-167R Curve SC-5630-93
  - t_{bf} = 0.040 s
  - t_a = 0.051 s
  - $t_{0.85a}$ = 0.051 s
- Times are short because breaker is set at its fastest setting

MCC Feeder Breaker Calculation

- *Working distance is 30" (because breaker is recessed from handle)*
- $E_a = 0.94\ cal/cm^2$
- $E_{0.85a} = 0.79\ cal/cm^2$
- *Maximum energy (0.94 cal/cm²) less than 1.2 cal/cm² so operation of this circuit breaker is Hazard/Risk Category 0*
- *Table 130.7(C)(9)(a) not applicable because*
  - $I_{bf} < 65\ kA$
  - $t_{clear} > 0.030$ *seconds*

Clean Power Breaker Calculation



- I_{fl} = 135 A
- Z = 6.23%
- Fault currents
  - I_{bf} = 2.2 kA
  - I_a = 1.8 kA
  - $0.85I_a$ = 1.5 kA
- Clearing times from C-H AD 29-167F Curve SC-4438-88A
  - t_{bf} = 0.017 s
  - t_a = 0.024 s
  - $t_{0.85a}$ = 1.6 s
- Time is large because system is not properly coordinated

Clean Power Breaker Calculation

- *Working distance is 18” (NFPA70E standard)*
- $E_a = 0.12\ cal/cm^2$
- $E_{0.85a} = 6.9\ cal/cm^2$
- *Maximum energy (6.9 cal/cm²) between 4 and 8 cal/cm² so operation of this circuit breaker is Hazard/Risk Category 2*
- *Table 130.7(C)(9)(a) not applicable*
  - $I_{bf} < 25\ kA$
  - $t_{clear} > 0.030$ *seconds*
- *112.5 kVA transformer in circuit led to long clearing times of upstream breaker*
- *Reduce arc-flash by*
  - *Using faster clearing time upstream breaker*
  - *Adding separate downstream breaker or fuse*

Mitigating the Arc Flash Hazard

Minimum Protective Clothing - Abridged NFPA 70E Table 130.7(C)(11)		
Hazard Risk Category	Clothing Description	Required Minimum Arc Rating of PPE [J/cm2 (cal/cm2)]
0	Long sleeve shirt, long pants, safety glasses	5 (1.2)
1	Long pants, FR long sleeve shirt, hard hat, safety glasses	16.74 (4)
2	T-shirt, FR long sleeve shirt, FR long pants, hard hat, safety glasses or goggles, face shield, hearing protection, leather gloves, leather work shoes	33.47 (8)
3	T-shirt, FR long sleeve shirt, FR long pants, FR coveralls, hard hat, safety glasses or goggles, flash suit hood, hearing protection, leather gloves, leather work shoes	104.6 (25)
4	T-shirt, long pants, FR long sleeve shirt, FR long pants, flash suit jacket and pants, hard hat, safety glasses or goggles, flash suit hood, hearing protection, leather gloves, leather work shoes	167.4 (40)

Mitigation

- *Decrease available energy by using smaller upstream transformer (208V transformers less than 125 kVA pose no arc-flash hazard)*
- *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*

Mitigation

- *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*

Arc flash protection boundary determination from energy stored in capacitors

Developed by Jim Sebek of SLAC and based on R. H. Lee in NFPA70E

$D_c = \sqrt{2.65\, MV_{source}\, A_{bf}\, t}$ where D_c is the arc flash boundary in feet

Recall that $E_{stored} = \frac{1}{2} C V^2$ is the stored capacitor energy in joules

According to Lee the maximum energy dissipated in a fault occurs when

the fault voltage is $\frac{\sqrt{2}}{2}$ of the supply voltage and the arc current is $\frac{\sqrt{2}}{2}$

of the available fault current (the arc is resistive). Therefore, $P_{max} = \frac{1}{2} M V_{source} A_{bf}$

or, to keep D_c inviolate, $2 P_{max} = M V_{source} A_{bf}$ substituting yields

$$D_c = \sqrt{5.3\, M V_{source}\, A_{bf}\, t} = \sqrt{5.3\, P_{max}(MW)\, t} = \sqrt{5.3 * 10^{-6}\, P_{max}(W)\, t}$$

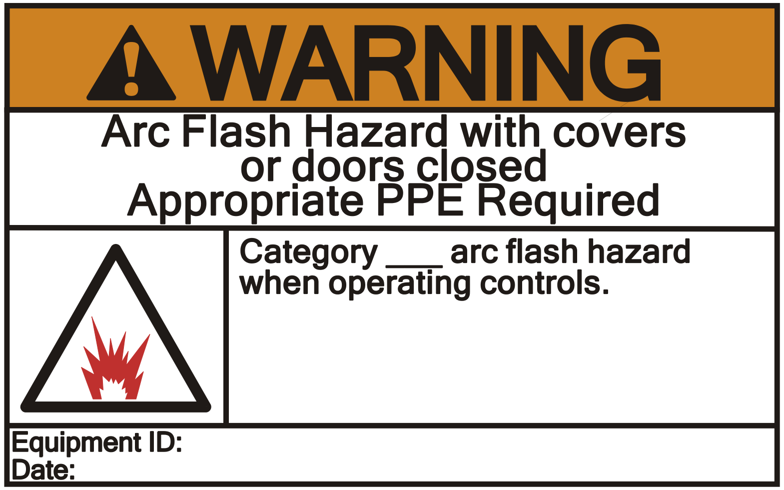
Recognizing that watts*time = energy in joules yields

$$D_c = \sqrt{5.3 * 10^{-6}\, E_{stored}}$$

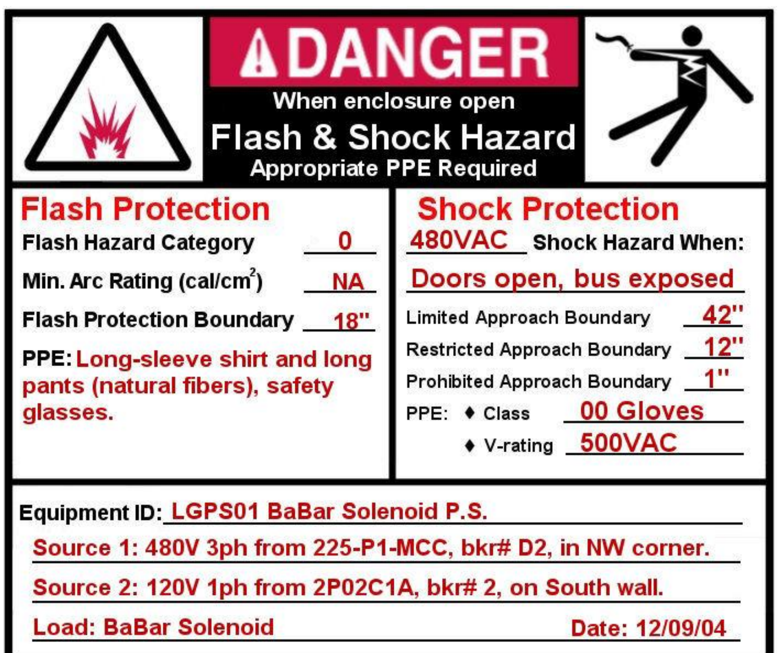
More Information

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*



The WARNING label is for operating ***enclosed*** *circuit breakers. No shock hazard listed. Note the requirement for identification of the equipment to which it will be affixed*



The DANGER label is for ***exposed, energized*** *work. Shock and arc flash hazards listed. Arc flash hazard category typically higher than for the Warning Label. Note the requirement for identification of the equipment to which it will be affixed*

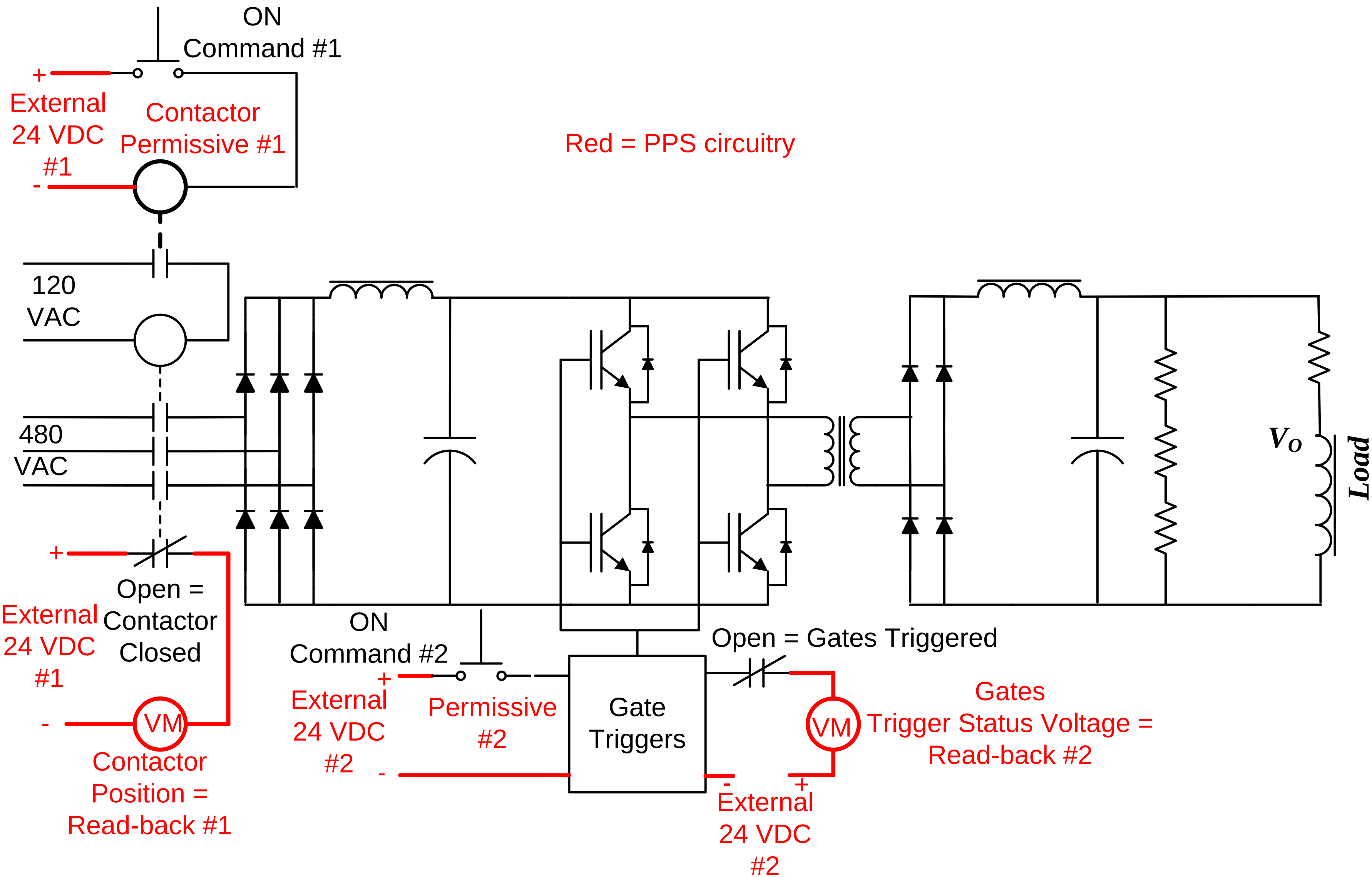
4 Types

- *Personnel protection - Personnel Protection System (PPS)*
- *Personnel protection - Lock and Tag (LOTO)*
- *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*

PPS Example



Many variations of this example

Lock & Tag for Personnel Safety During Maintenance

- *Procedures and requirements for servicing and maintaining machines and equipment in which unexpected energization, startup or release of energy could cause injury to personnel*
- *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*

Required by

- *Occupational Safety and Health Administration (OSHA) under 29CFR1910.147*

Applicability

- *All types of equipment containing electrical, mechanical, hydraulic, pneumatic, chemical and/or thermal active or stored energy*
- *For working on exposed electrical circuits that would expose personnel to any electrical hazard operating at > 50 V, >50A, >10J*

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

Types

General Lock and Tag Procedure (GLP) - used when there is only one source of energy and there is no stored energy

Equipment Specific Procedures - used for systems or equipment with more than one energy source or equipment with stored energy (e.g.; capacitor banks)

Interlocks As LOTO

Interlocks are not used as a substitute for lock and tag

Steps To Lockout – Tagout (LOTO)

1. *Preparation and notification*
2. *Location and isolation of energy sources*
3. *Shutdown*
4. *Lock and tag application*
5. *Verification of isolation*
   a. Attempt to start the locked-out equipment
   b. Remove all stored energy
   c. Use appropriate test equipment (e.g. voltmeter) to verify that the circuit elements and parts have been de-energized

Notes:

- *Use only easily recognizable, dedicated, facility-approved locks and tags*
- *Never attempt to operate equipment that has been locked out*
- *Do not attempt to remove another person's lock*

Types of Lock-out Devices

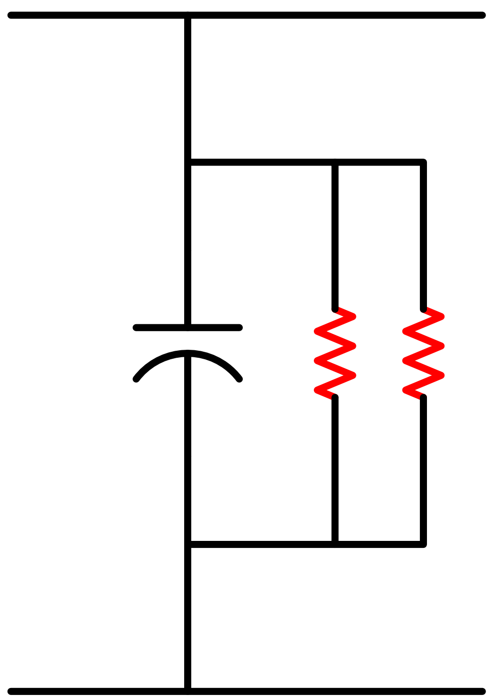
For Locking and Tagging

- *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*

Removal of Energy Storage

• Capacitor bleeder resistors per 2008 NEC, Article 460

Removal of Energy Storage



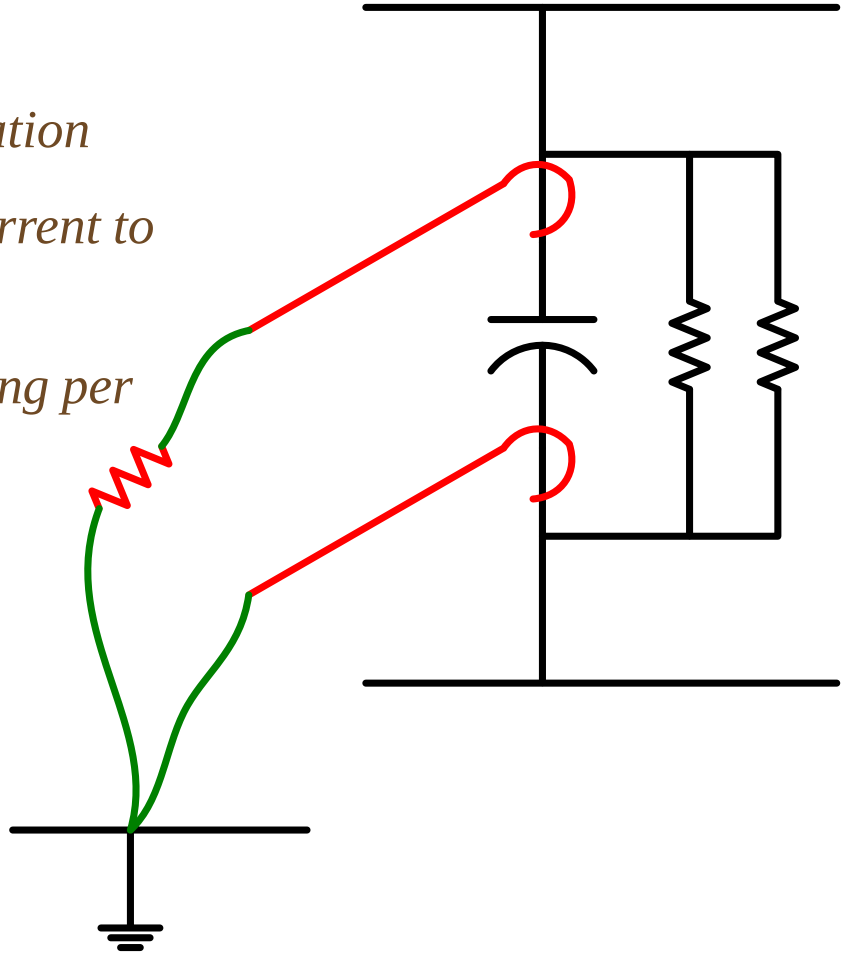
• Working voltage ≤ 600 V , discharge to 50 V or less in 1 minute

• Working voltage . 600 V , discharge to 50 V or less in 5 minutes

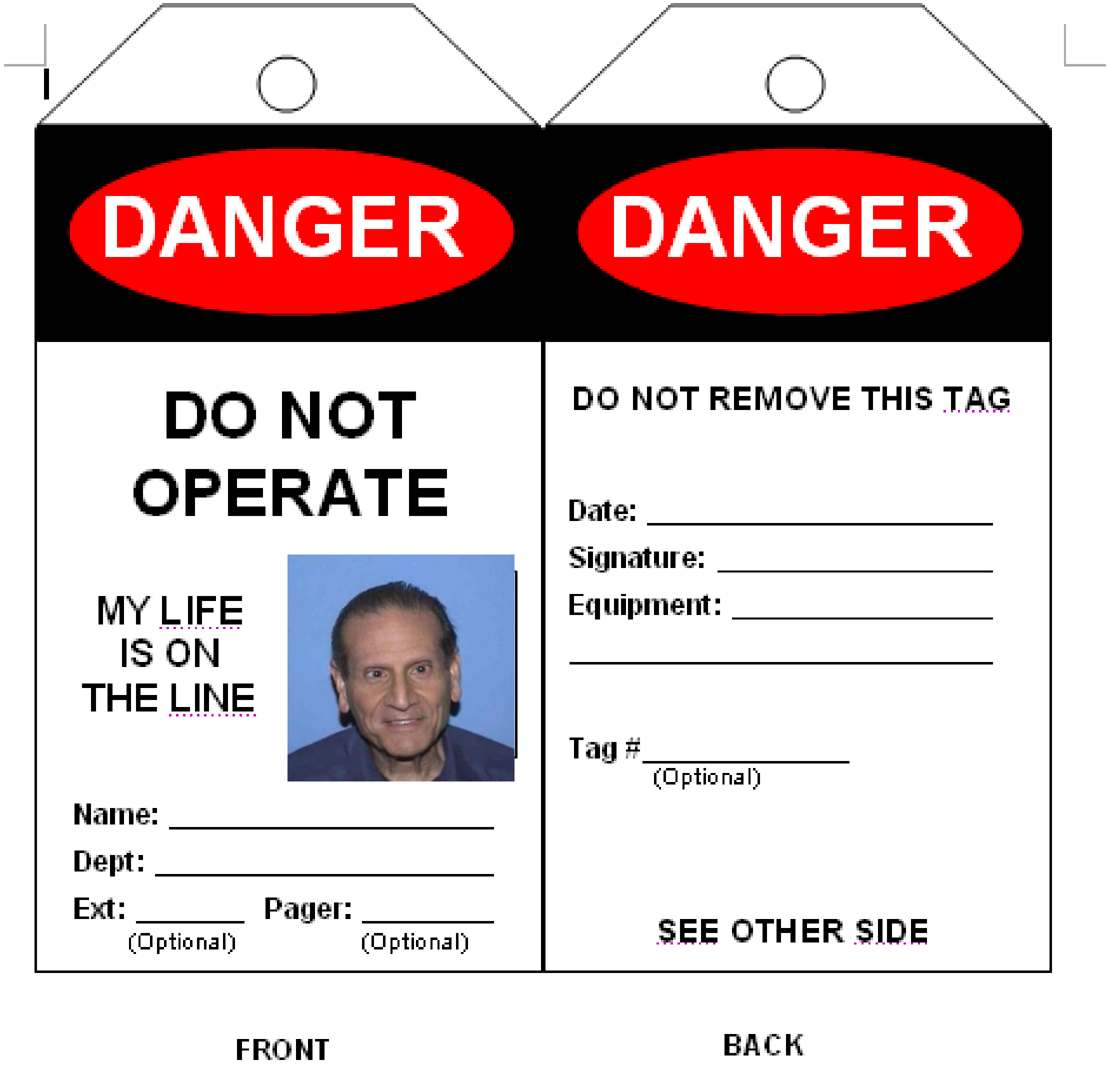
• Redundant resistors recommended

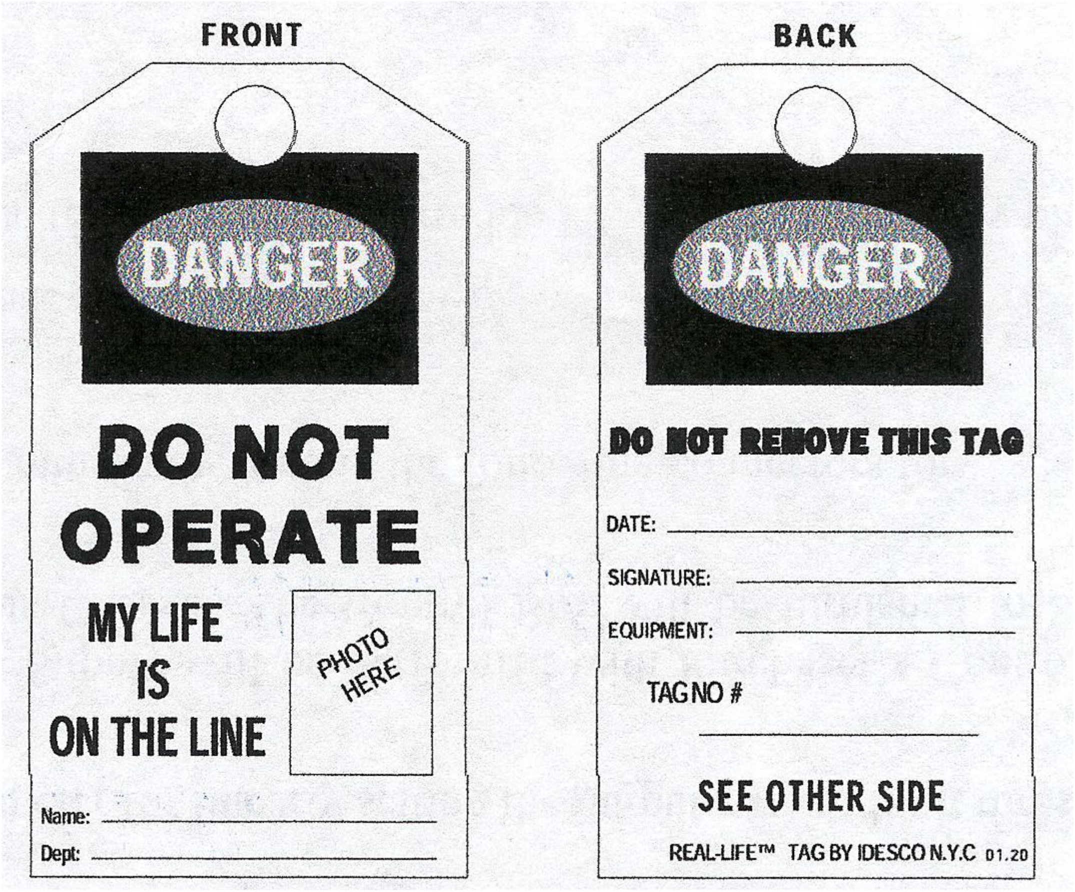
Removal of Energy Storage

- *Grounding hooks*
- *Clear or green-colored insulation*
- *Resistor to keep discharge current to safe value*
- *Electrical equipment grounding per 2008 NEC, Article 250*




Keyed-Alike Locks


DANGER
DO NOT OPERATE
MY LIFE IS ON THE LINE
Name:
Dept:
Ext: (Optional)
Pager: (Optional)
DANGER
DO NOT REMOVE THIS TAG
Date:
Signature:
Equipment:
Tag # (Optional)
SEE OTHER SIDE
FRONT
BACK


FRONT
DANGER
DO NOT OPERATE
MY LIFE IS ON THE LINE
PHOTO HERE
Name:
Dept:
BACK
DANGER
DO NOT REMOVE THIS TAG
DATE:
SIGNATURE:
EQUIPMENT:
TAG NO #
SEE OTHER SIDE
REAL-LIFE™ TAG BY IDESCO N.Y.C 01.20

Machine (or magnet) protection systems protect loads from damage.

Magnet Cooling Water Temperature / Flow Sensors

- *Usually employ a simple normally closed (NC) contact that opens when a pre-determined temperature has been reached.*

- *Water flow monitoring switches open when flow drops below a pre-established safe value*

- *Temperature / Flow switches are wired to the source power supply. If the water temperature is too high or if the flow drops the contacts open and turn the power supply off*

Vacuum Interlock System

- *Sensors are similar to that described in the magnet cooling water system*

Orbit Interlock System

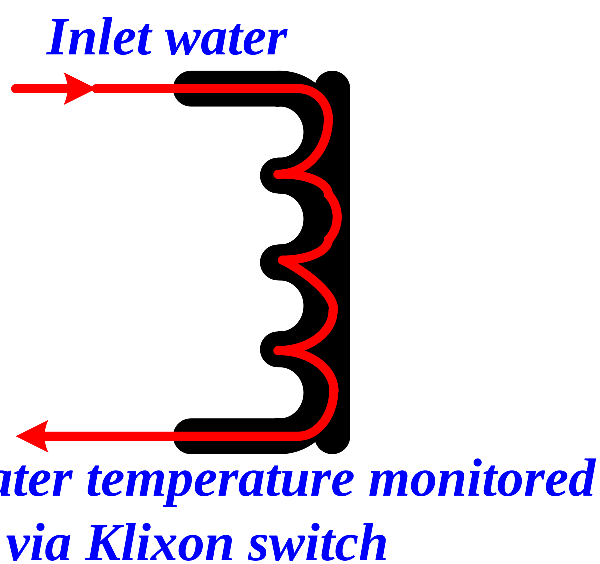
- *Sensors consist of Beam Position Monitors and switches. Function is essentially the same in the magnet cooling water system*

Water Temperature Sensors

- *Thermal switches - Klixons (a trade name) are NC contact bimetal switches mounted on the load cooling water outlet line. Their contacts open when temperature exceeds a pre-established safe value*

- *Multiple-winding, multiple water path magnets employ simple series connected Klixons.*

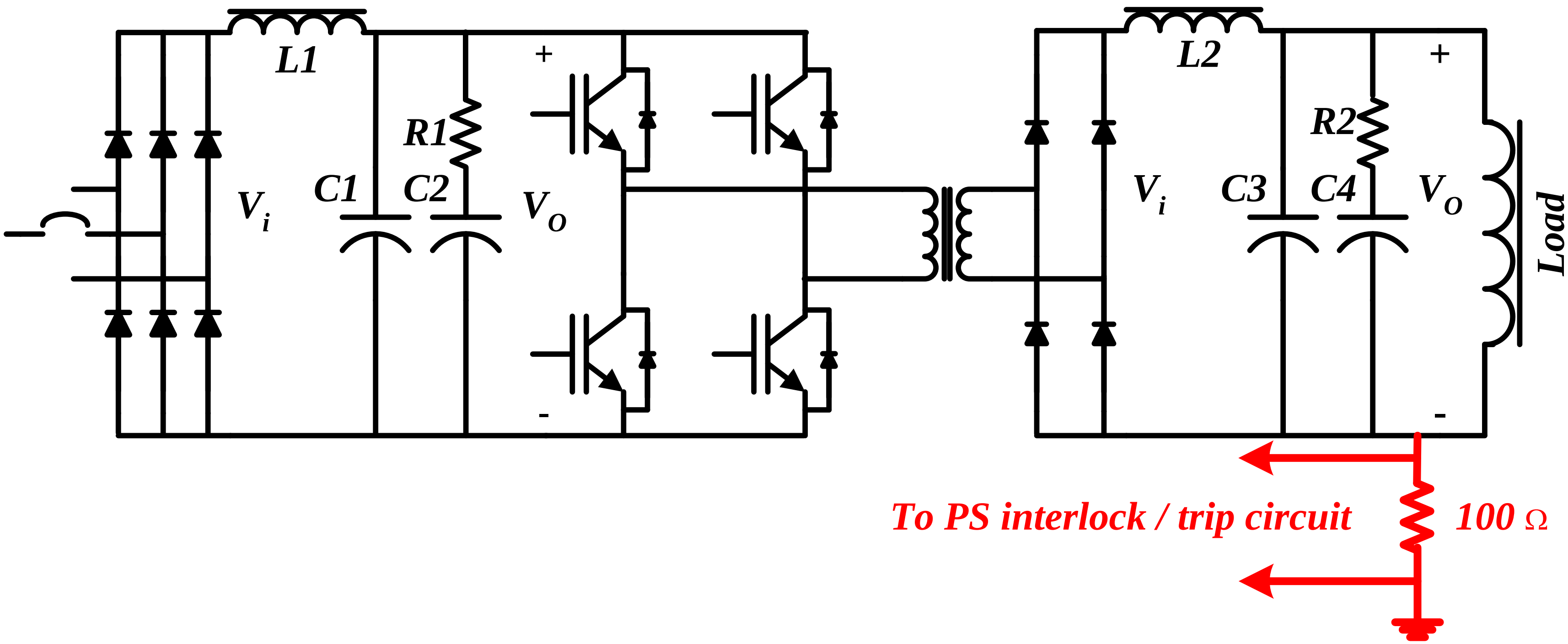
- *Klixons are wired to the source power supply. If the load overheats, the contacts open and turn off the power supply*



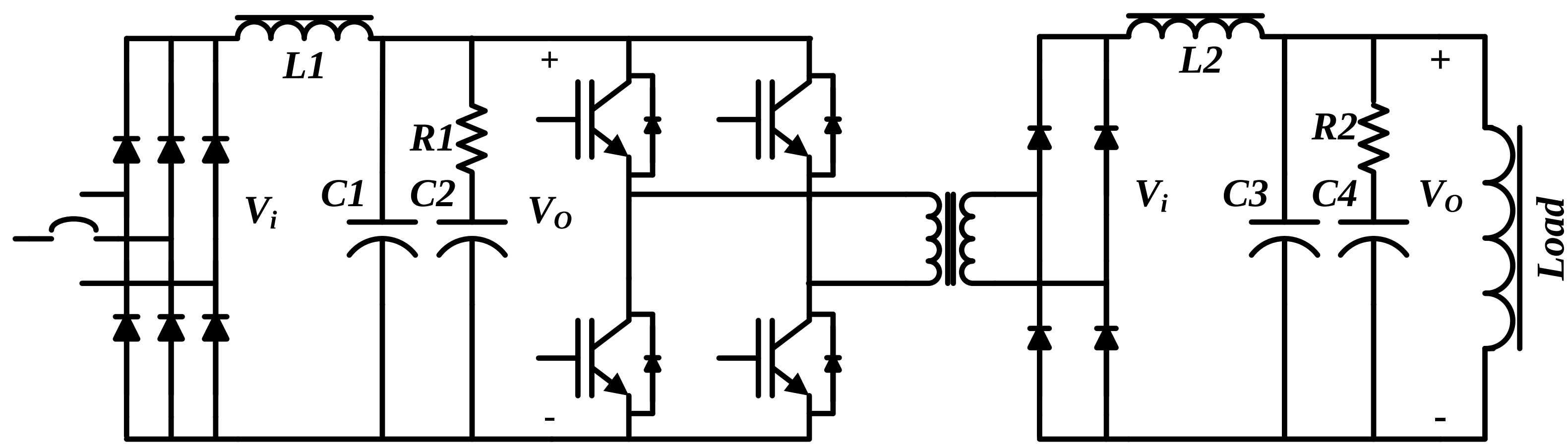
Klixon switches

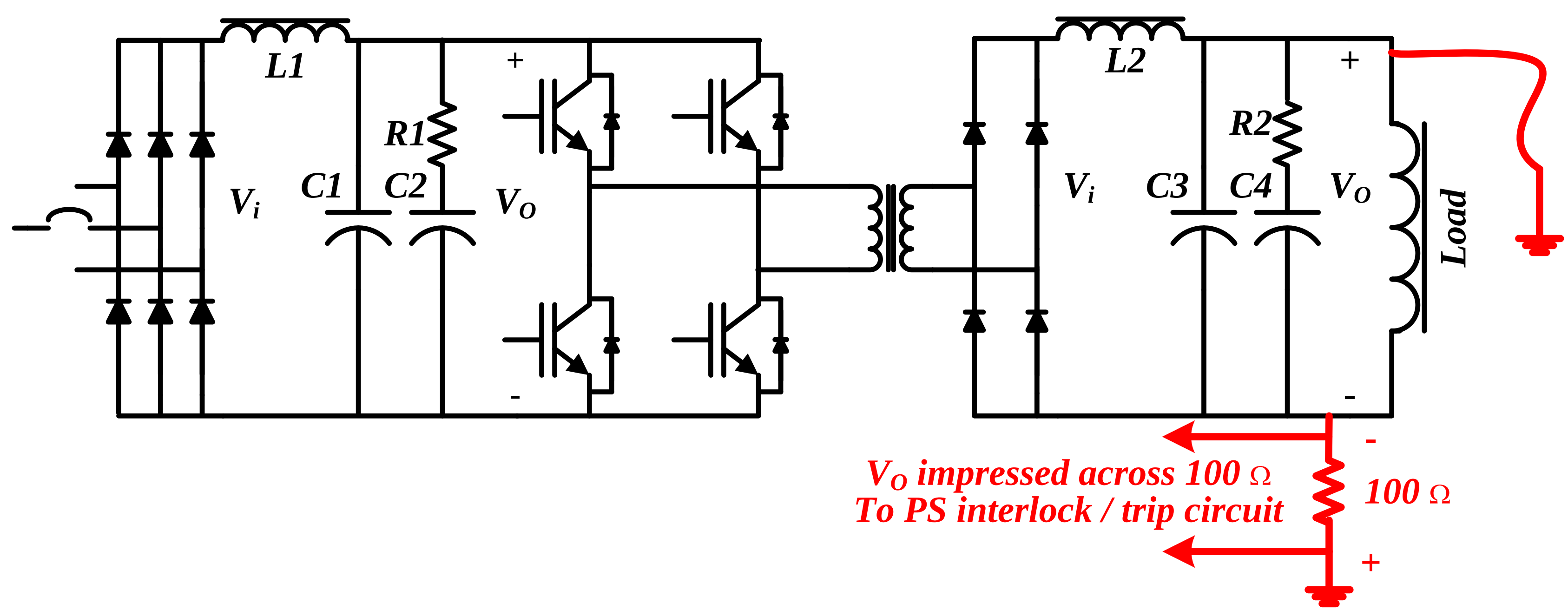
Ground Fault Detection / Protection Systems

- *Loads are usually located in crowded, dense areas with a multitude of other equipment. This makes them vulnerable to ground faults*
- *Power supplies are usually isolated from ground so that a single ground fault does not cause load-catastrophic ground fault current. Fix first fault before the second fault occurs*



Ground Fault Detection / Protection Systems





Some Internal Interlocks

Internal interlocks protect the power supply itself

- *Low input supply voltage*
- *Phase loss detection*
- *Output DC over-current*
- *Low frequency filter inductor temperature*
- *Heat-sink temperature or heat-sink cooling water flow*
- *IGBT temperature*
- *IGBT over-current*
- *Ground Fault current*
- *Output over-voltage*
- *Cabinet or chassis over-temperature*

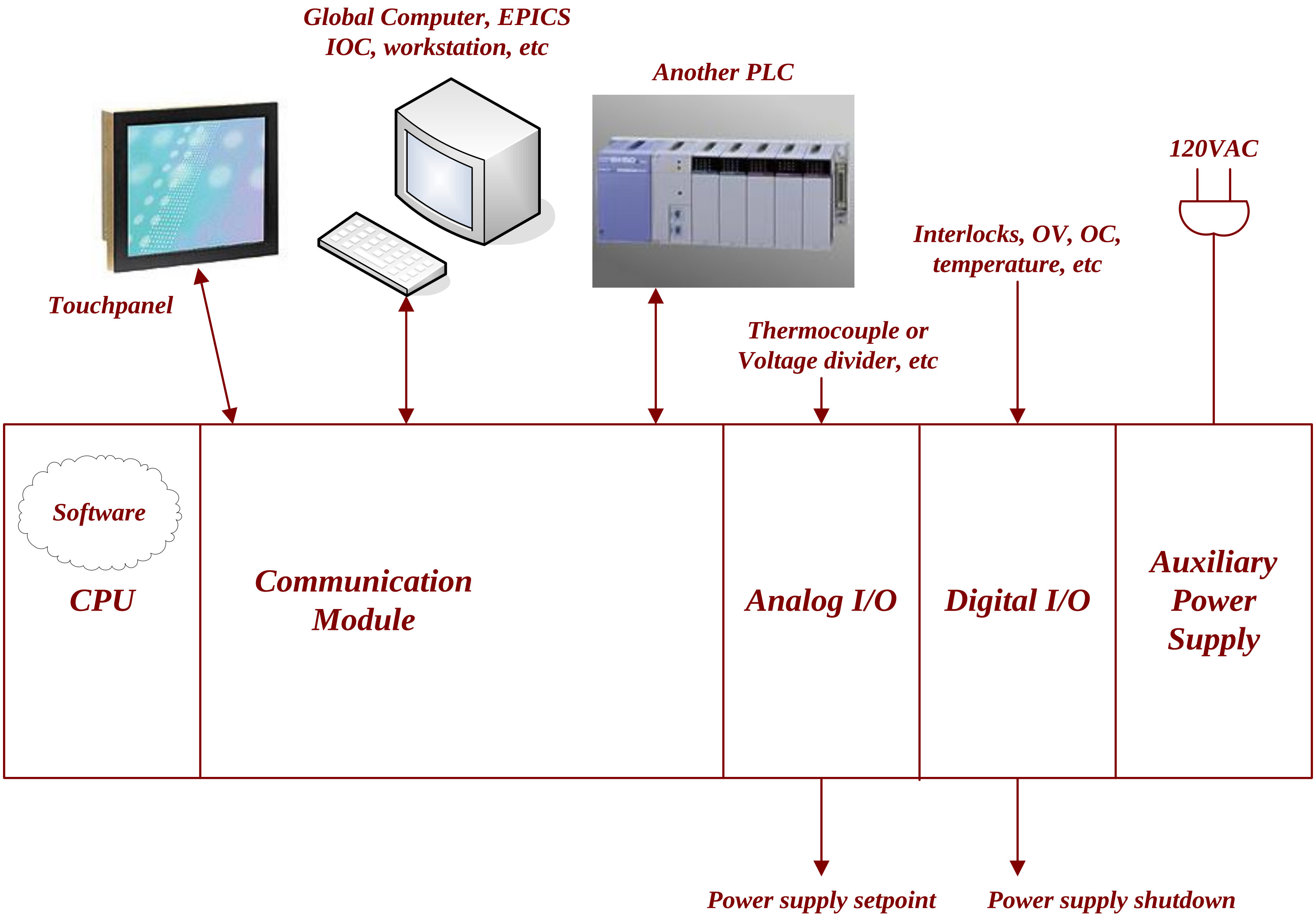
Example of a PLC and its Use

Manufacturers are many

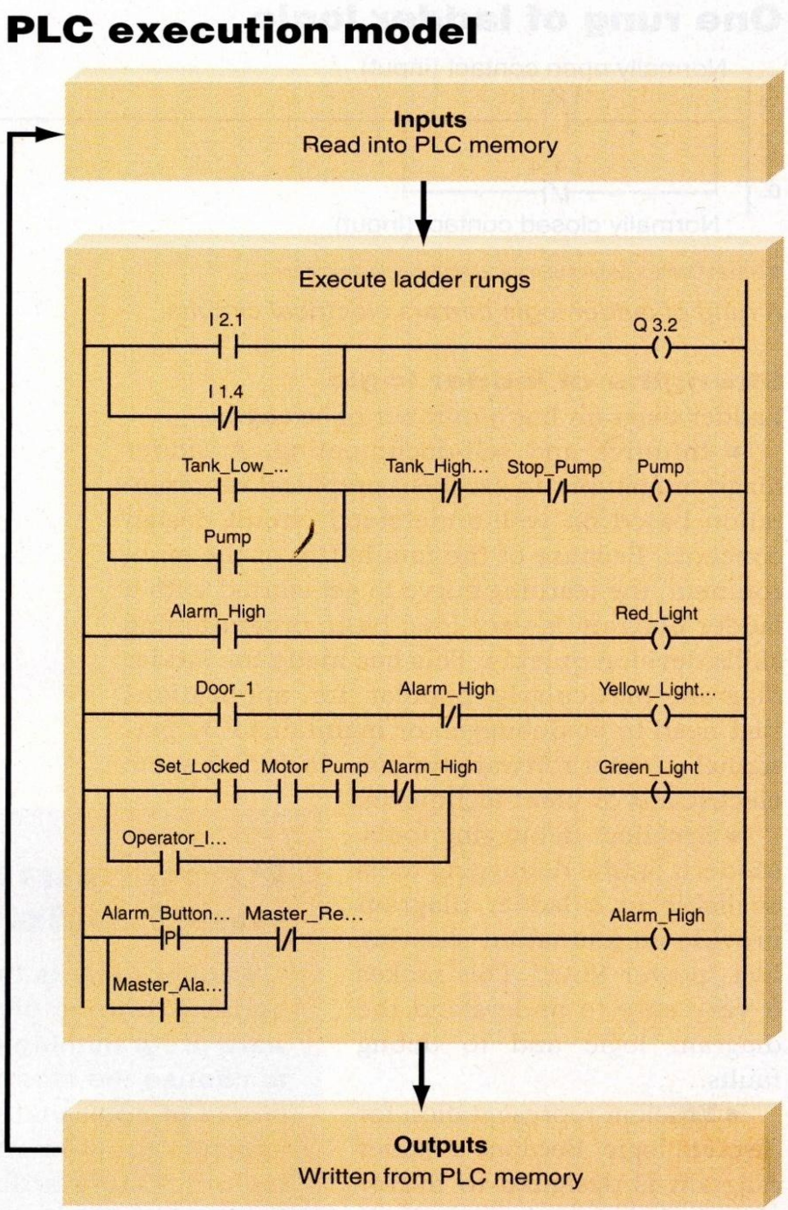
- *Allen-Bradley*
- *Rockwell International (AB)*
- *Siemens*
- *General Electric*
- *IDEC*

Programming logic

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


Global Computer, EPICS
IOC, workstation, etc
Another PLC
120VAC
Interlocks, OV, OC,
temperature, etc
Touchpanel
Thermocouple or
Voltage divider, etc
Software
CPU
Communication
Module
Analog I/O
Digital I/O
Auxiliary
Power
Supply
Power supply setpoint
Power supply shutdown

Ladder Logic



Source: Control Engineering *and National Instruments*

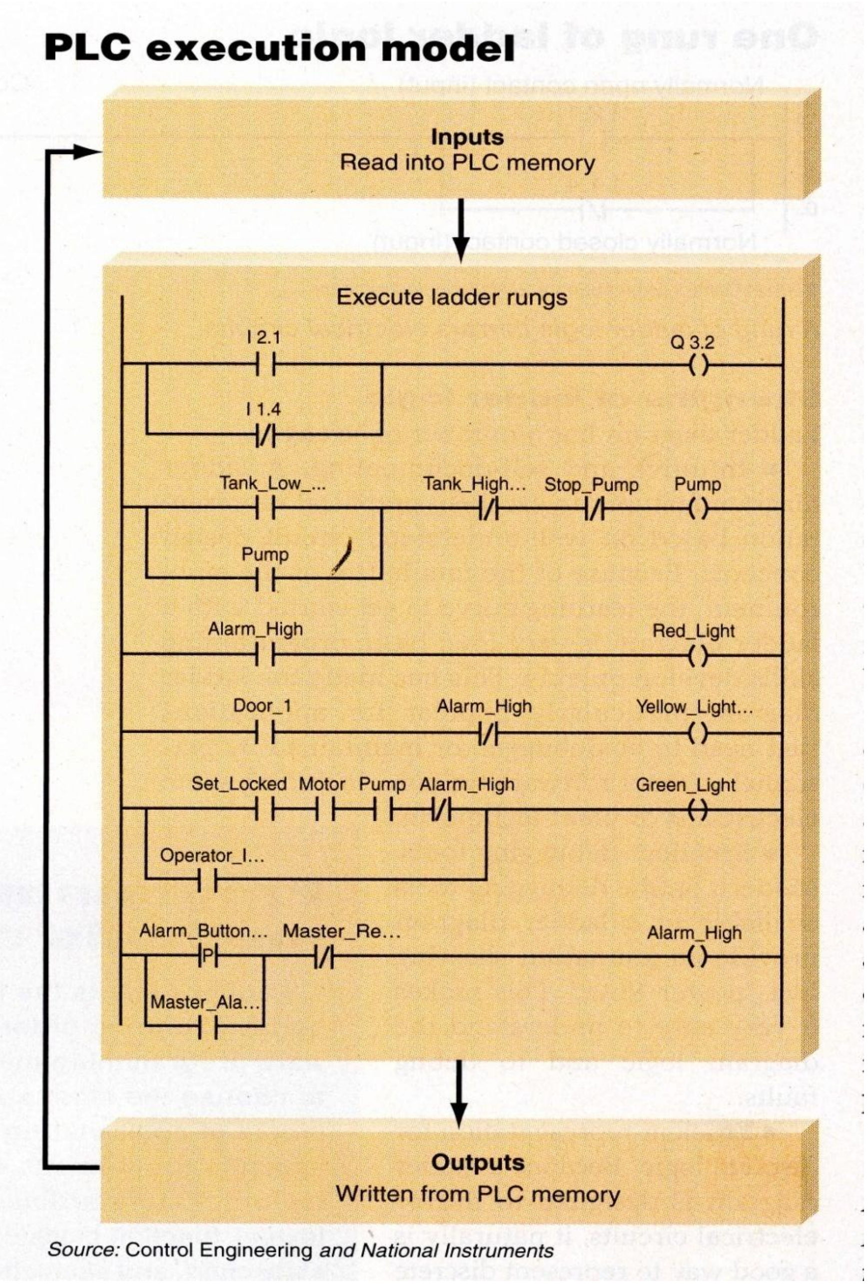
Ladder diagrams evolved in the 1960s when the automobile industry needed a more flexible and self-documenting alternative to relay and timing cabinets. A microprocessor was added and software designed to mimic the relay panels.

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



Inherent in Ladder Logic is an unseen scanning engine and memory management stack.

Physical inputs are read and stored in a memory table

The ladder logic is run by reading and writing from the memory table for inputs, outputs and intermediary values.

At the end of the logic cycle, all the physical outputs are updated with the values from the memory table. More complex tasks (math, timers, etc) are handled by calls to built-in functions on the ladder rungs

Ladder Logic

Most widely used application to program PLCs

Strengths

- *Intuitive and self-documenting. Can be learned very quickly by personnel with little or no software training*
- *Excellent debugging tools, include animation showing live "power flow". This makes the logic easy to understand and to debug faults*
- *Efficient representation for discrete logic*

Weaknesses

- *Hierarchical data and logic flow. Is supplemented by functions, function blocks and subroutines*
- *Poor data structure. Rungs are executed in a left-to-right, top-to-bottom order. Timing is defined 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*

10. Reliability, Availability and Maintainability

Reliability Overview

- *Definition and Importance*
- *Glossary of Terms*
- *Calculation Standards*
- *Calculations - Power Supply/Power System*
- *Improvements by Redundancy - Examples*
- *Fault Modes And Effects Criticality Analysis (FMECA)*
- *The Reliability Process*
- *Maintainability - Cold-Swap, Warm-Swap and Hot-swap*

Reliability and Availability Definitions

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)*
λ, λ_O, λ_R	*Failure rates in* hr^{-1}*. These are the reciprocals of the MTBFs*
1/1	*One full rated power supply. Rated power = delivered power*
1/2	*One out of two redundant power module configuration*
2/3	*Two out of three redundant power module configuration*
3/4	*Three out of four redundant power module configuration*
4/5	*Four out of five redundant power module configuration*

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

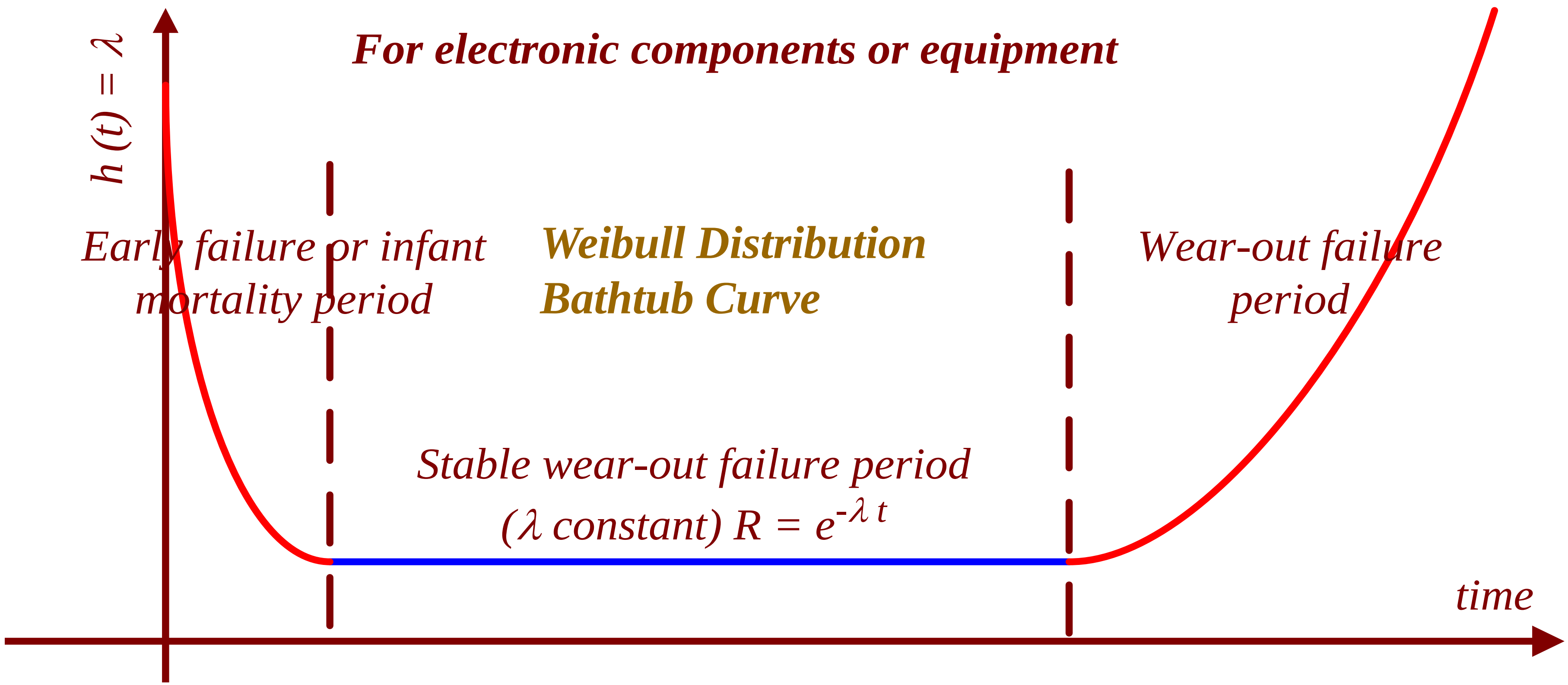
B. Solve for three out of four for success

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* $0 < \Pi_{GB} < \infty$

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

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

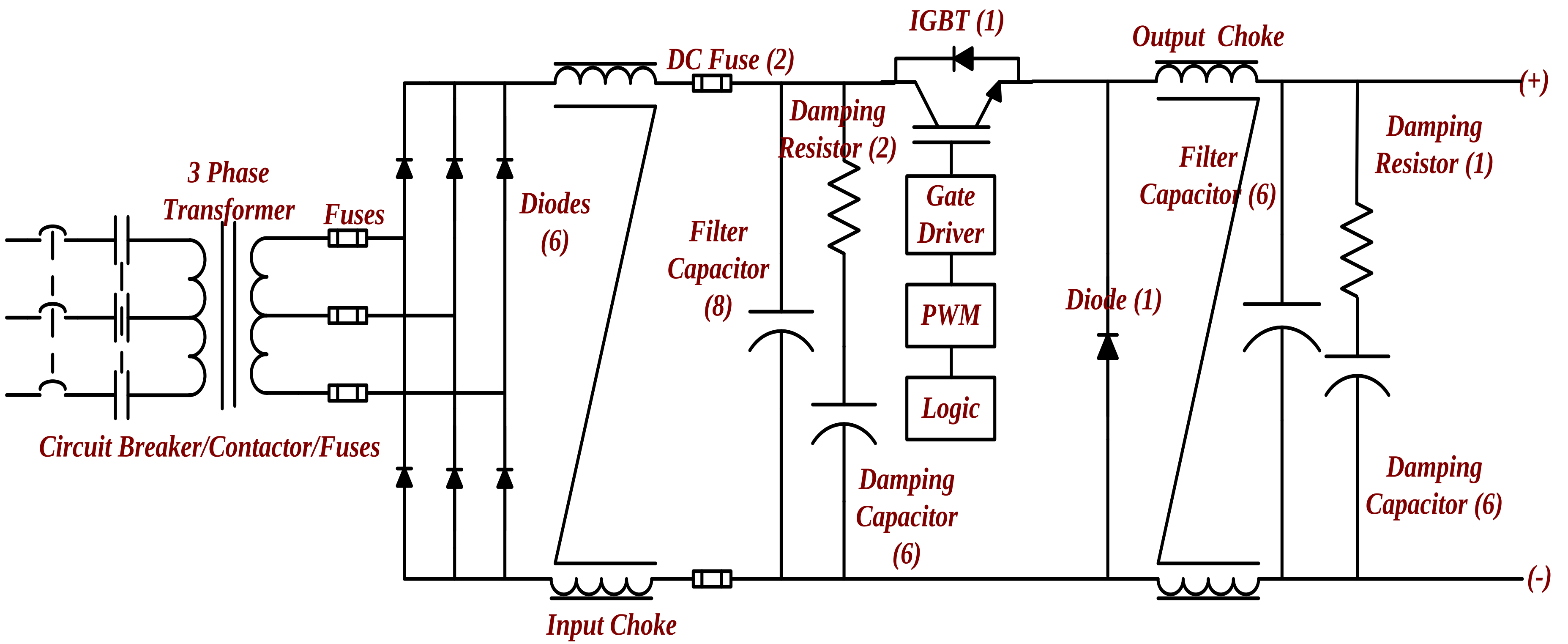
Π_{VS} = *voltage stress factor* $0 < \Pi_{VS} < \infty$

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

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

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

Example of Reliability Calculation – Power Supply



Example of Reliability Calculation – Power Supply

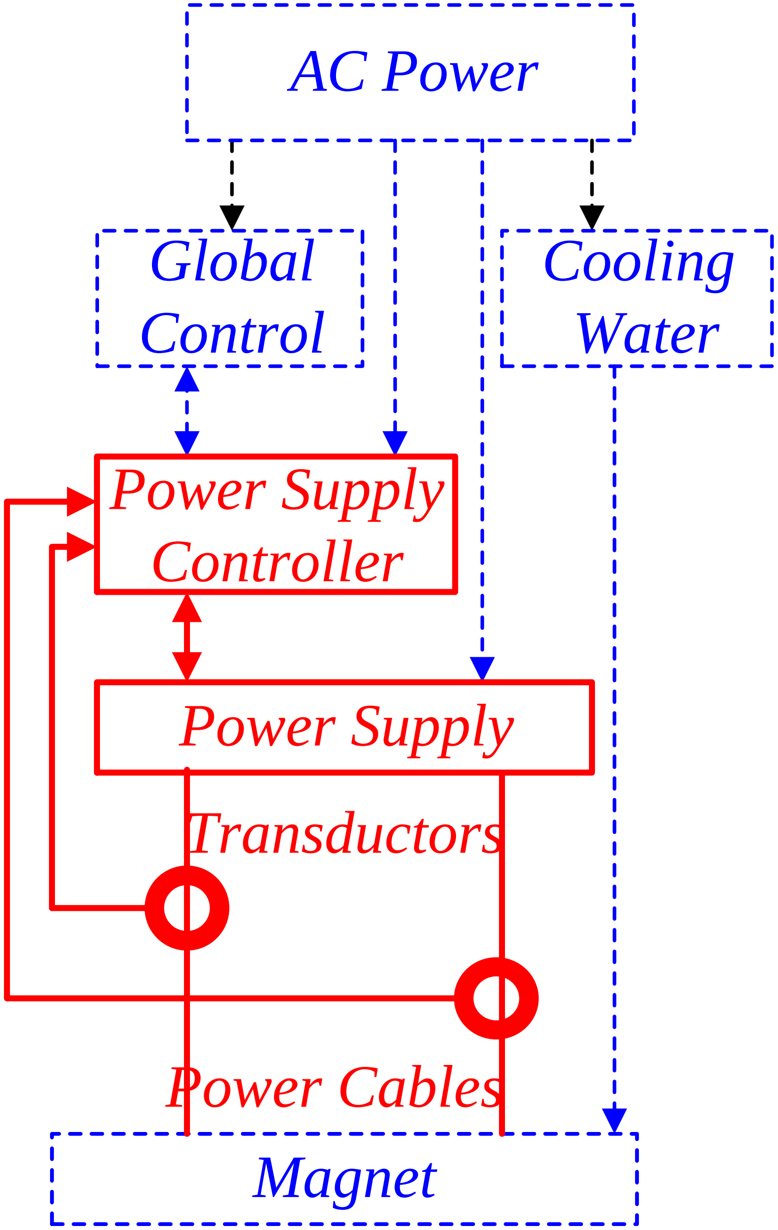
Component Description	Qty	λ	π_{GB}	π_{T}	π_{MQ}	π_{VS}	π_{IS}	π_{PS}	Mission Loss	Total Rate $\lambda_T\ 10^{-6}$
Circuit Breaker/Contactor/Fuse	5	0.42	1.00	1.10	1.00	1.01	1.05	1.10	Yes	2.695
3 Phase Transformer	1	0.05	1.00	1.10	1.00	1.50	1.50	1.50	Yes	0.186
Input/Output Filter Choke	2	0.02	1.00	1.10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

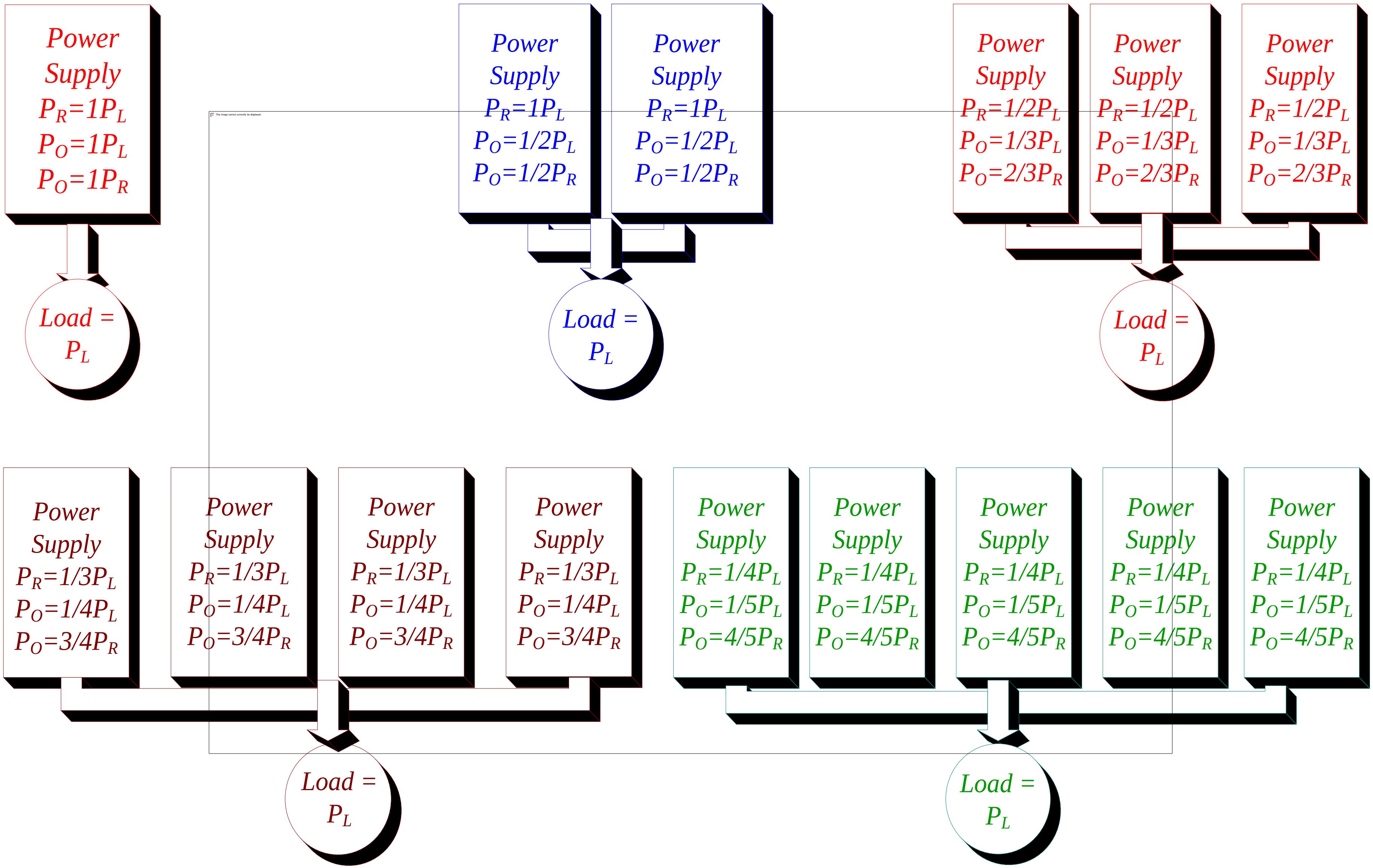
Relex by Relex Software

See Reference Appendix for web link to this manufacturers products

RelCalc by T-Cubed

See Reference Appendix for web link to this manufacturers products

Reliability/Availability Improvement By Redundancy



Reliability/Availability Improvement By Redundancy

- *Two types - Standby and Active*

1. Standby - the redundant parts are off and only operate when the first part fails. This requires more vigilance on the part of the control system and is not covered here.

2. Active - the redundant part(s) are on, albeit operating at a reduced power level until asked to assume increased or full load. This is easier to implement than Standby redundancy and is the more common method. We will examine this further

Availability Improvement By Oversizing and Redundancy

The general, exponential form of the Binomial Distribution for m out of n parts is

$$R(t) = \sum_{k=m}^{n} \left(\frac{n!}{(n-k)!\,k!} \right) \left(e^{-\lambda t} \right)^{k} \left(1 - e^{-\lambda t} \right)^{n-k}$$

λ = constant=failure rate

k= index counter

m= minimum number of power modules needed for operation

n = total number of power modules in the system

Special cases occurs when m = n or when m=n=1

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

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**

$$R_{2/3}(t) = 3e^{-2\lambda t} - 2e^{-3\lambda t}$$

Availability Improvement By Oversizing and Redundancy

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

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

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

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

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

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

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

$$P_R = P_O$$

$$MTBF_R = MTBF_O$$

$$\lambda_R = \lambda_O$$

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

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

For the m=1 out of n=2 case

2- full rated rated power supplies. *Each power supply operates at* $\frac{1}{2}$ *rated* P_R

$$MTBF_O = \frac{P_R}{P_O} MTBF_R = 2\,MTBF_R \qquad \lambda_O = \frac{1}{2}\lambda_R$$

$$R_{O1/2}(t) = 2e^{-\lambda_O t} - e^{-2\lambda_O t}$$

$$MTBF_{O1/2}(t) = \frac{2e^{-\lambda_O t} - e^{-2\lambda_O t}}{2\lambda_O e^{-\lambda_O t} - 2\lambda_O e^{-2\lambda_O t}}$$

$$A_{O1/2}(t) = \frac{MTBF_{O1/2}(t)}{MTBF_{O1/2}(t) + MTTR}$$

For the m=2 out of n=3 case

3-1/2 rated power supplies. Each power supply operates at 2/3 rated P_R

$$MTBF_O = \frac{P_R}{P_O} MTBF_R = \frac{3}{2} MTBF_R \qquad \lambda_O = \frac{2}{3}\lambda_R$$

$$R_{O2/3}(t) = 3e^{-2\lambda_O t} - 2e^{-3\lambda_O t}$$

$$MTBF_{O2/3}(t) = \frac{3e^{-2\lambda_O t} - 2e^{-3\lambda_O t}}{6\lambda_O e^{-2\lambda_O t} - 6\lambda_O e^{-3\lambda_O t}}$$

$$A_{O2/3}(t) = \frac{MTBF_{O2/3}(t)}{MTBF_{O2/3}(t) + MTTR}$$

Active Redundancy - Three Out of Four Case

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

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

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

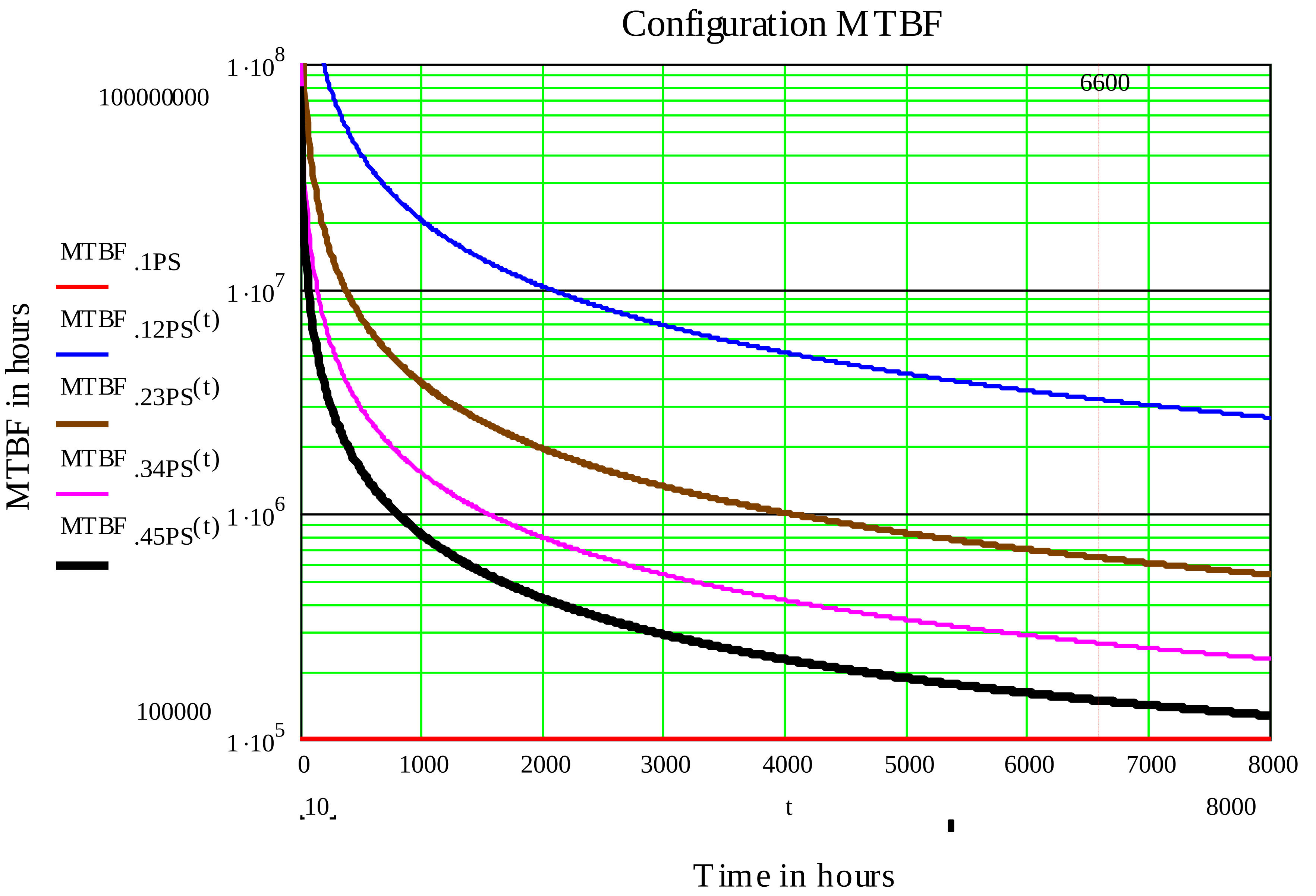
$$MTBF_{O4/5}(t) = \frac{5e^{-4\lambda_O t} - 4e^{-5\lambda_O t}}{20\lambda_O e^{-4\lambda_O t} - 20\lambda_O e^{-5\lambda_O t}}$$

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

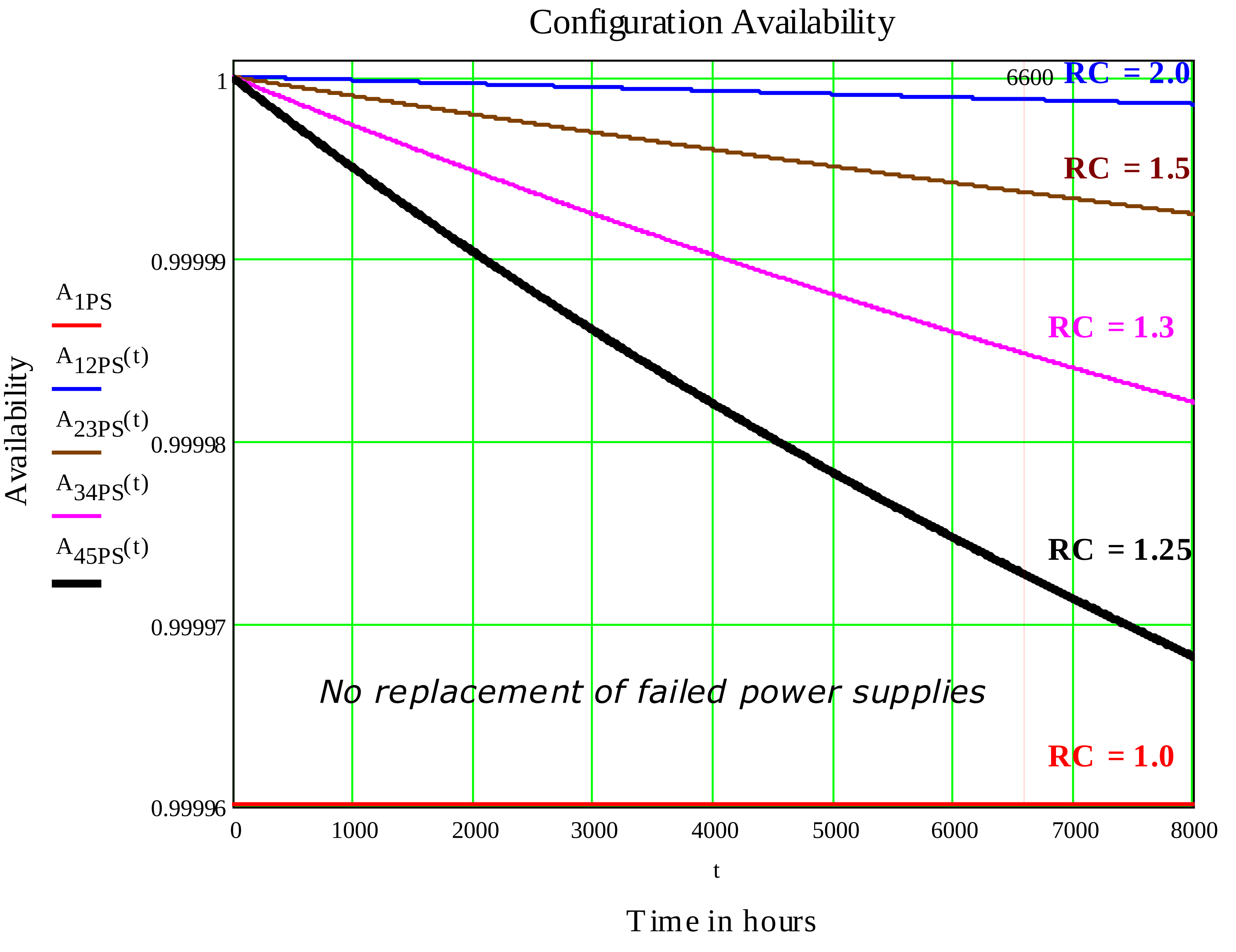
Active Redundancy Power Supply Reliability Summary

PS		Redundant Power Supplies		
1FR	$\lambda_O = \lambda_R$	$R_O = e^{-\lambda_O t}$	$MTBF_O = MTBF_R$	$A_O = \frac{MTBF_O}{MTBF_O + MTTR}$
1/2	$\lambda_O = \frac{1}{2}\lambda_R$	$R_{O1/2} = 2e^{-\lambda_O t} - e^{-2\lambda_O t}$	$MTBF_{O1/2}(t) = \frac{2e^{-\lambda_O t} - e^{-2\lambda_O t}}{2\lambda_O e^{-\lambda_O t} - 2\lambda_O e^{-2\lambda_O t}}$	$A_{O1/2}(t) = \frac{MTBF_{O1/2}(t)}{MTBF_{O1/2}(t) + MTTR}$
2/3	$\lambda_O = \frac{2}{3}\lambda_R$	$R_{O2/3} = 3e^{-2\lambda_O t} - 2e^{-3\lambda_O t}$	$MTBF_{O2/3}(t) = \frac{3e^{-2\lambda_O t} - 2e^{-3\lambda_O t}}{6\lambda_O e^{-2\lambda_O t} - 6\lambda_O e^{-3\lambda_O t}}$	$A_{O2/3}(t) = \frac{MTBF_{O2/3}(t)}{MTBF_{O2/3}(t) + MTTR}$
3/4	$\lambda_O = \frac{3}{4}\lambda_R$	$R_{O3/4} = 4e^{-3\lambda_O t} - 3e^{-4\lambda_O t}$	$MTBF_{O3/4}(t) = \frac{4e^{-3\lambda_O t} - 3e^{-4\lambda_O t}}{12\lambda_O e^{-3\lambda_O t} - 12\lambda_O e^{-4\lambda_O t}}$	$A_{O3/4}(t) = \frac{MTBF_{O3/4}(t)}{MTBF_{O3/4}(t) + MTTR}$
4/5	$\lambda_O = \frac{4}{5}\lambda_R$	$R_{O4/5} = 5e^{-4\lambda_O t} - 4e^{-5\lambda_O t}$	$MTBF_{O4/5}(t) = \frac{5e^{-4\lambda_O t} - 4e^{-5\lambda_O t}}{20\lambda_O e^{-4\lambda_O t} - 20\lambda_O e^{-5\lambda_O t}}$	$A_{O4/5}(t) = \frac{MTBF_{O4/5}(t)}{MTBF_{O4/5}(t) + MTTR}$

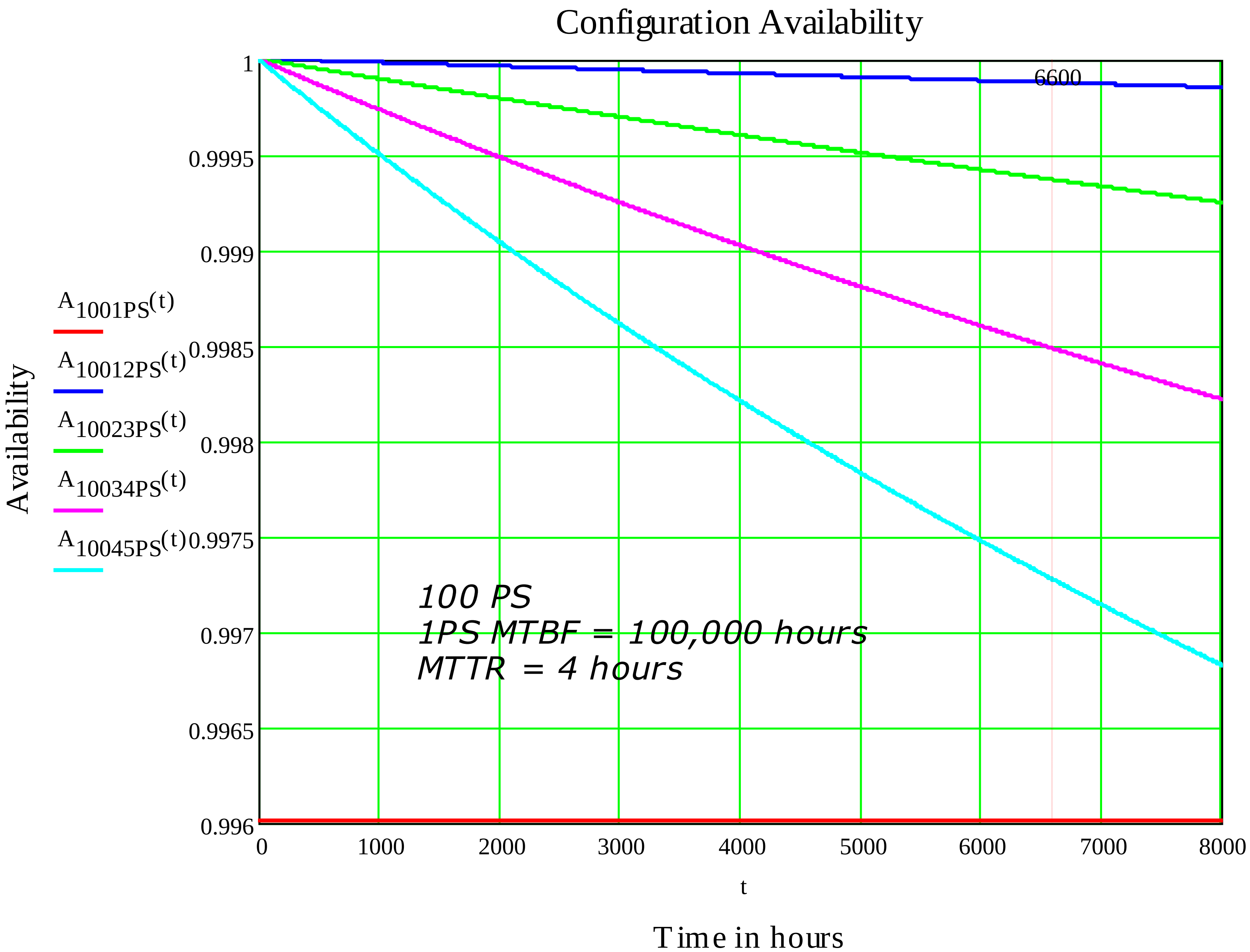
Active Redundancy MTBF Plot



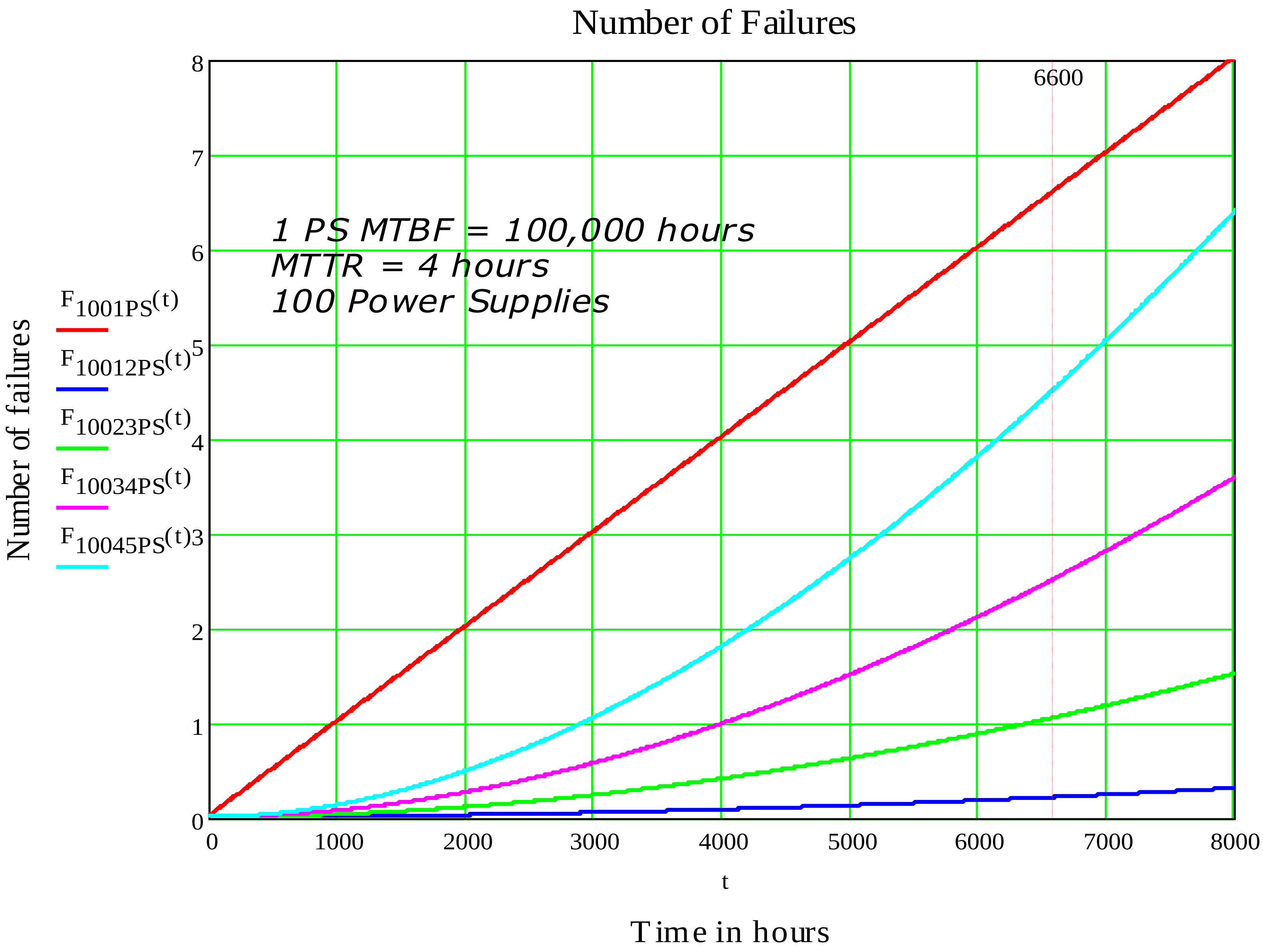
Active Redundancy - Availability



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

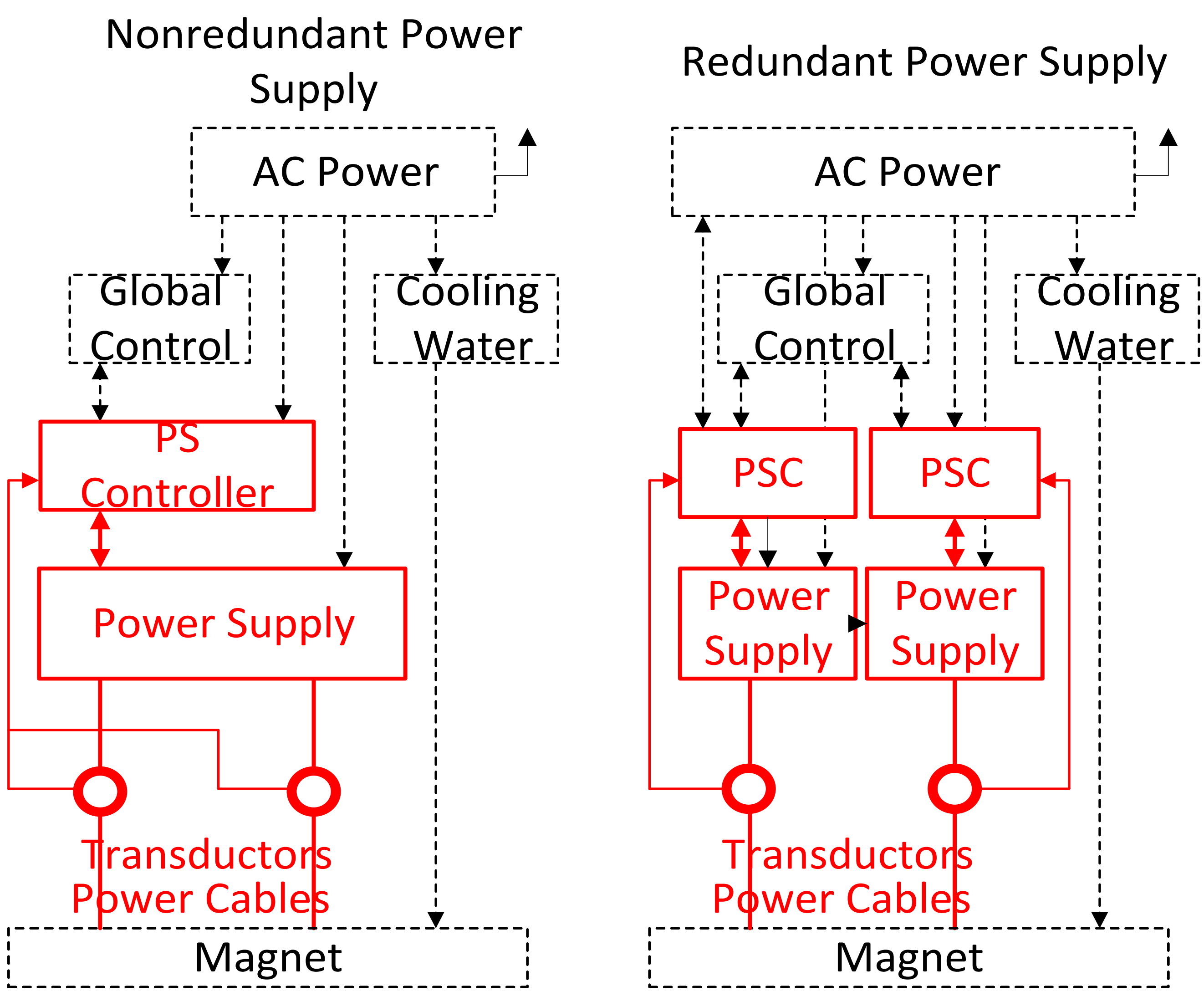
For a critical mission, 3 power supplies, each capable of supplying the total required output, are to be paralleled. The power supplies are also decoupled such that a failure of any power supply will not affect the output. The calculated failure rate of each power supply is 4 per million hours.

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

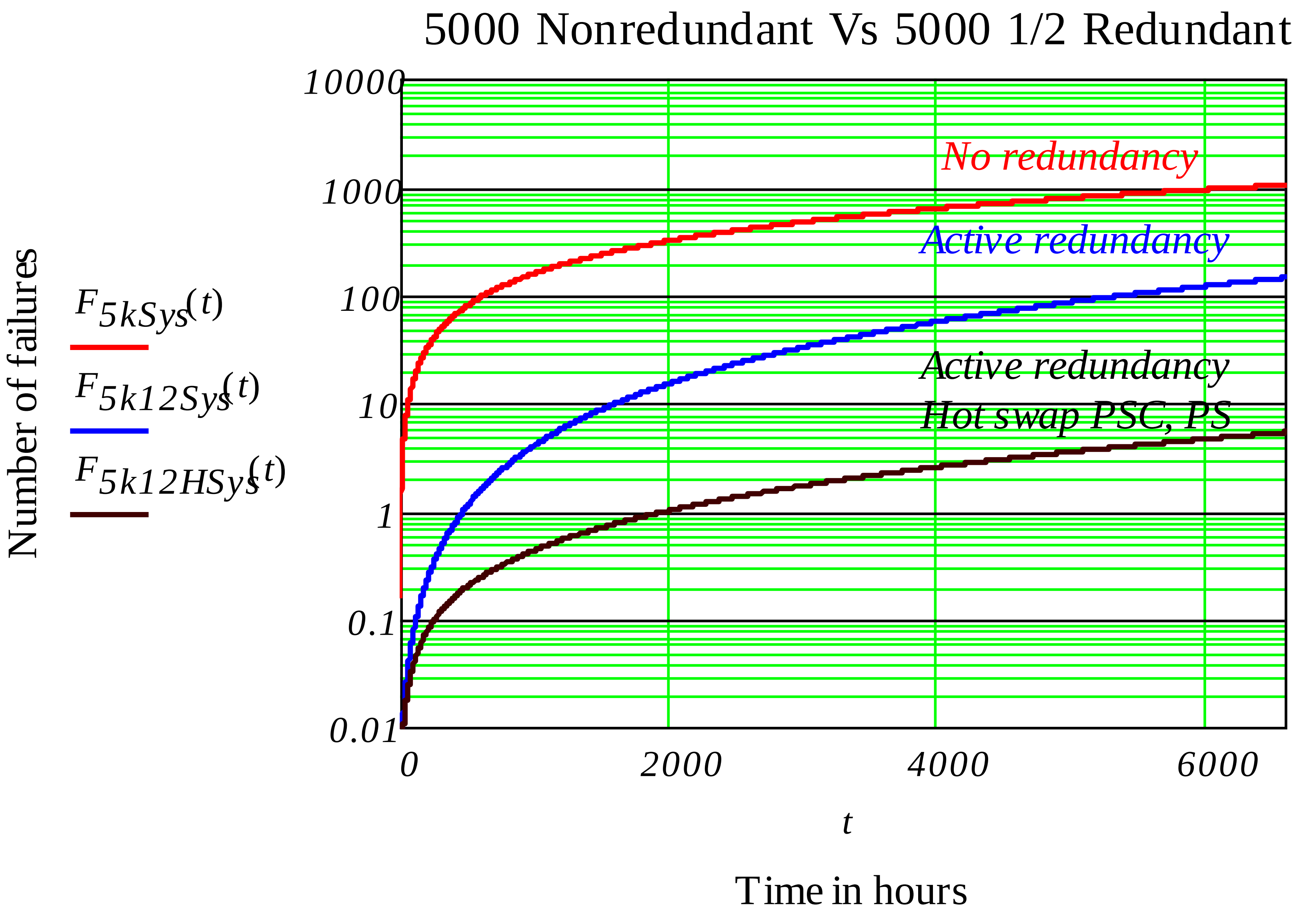


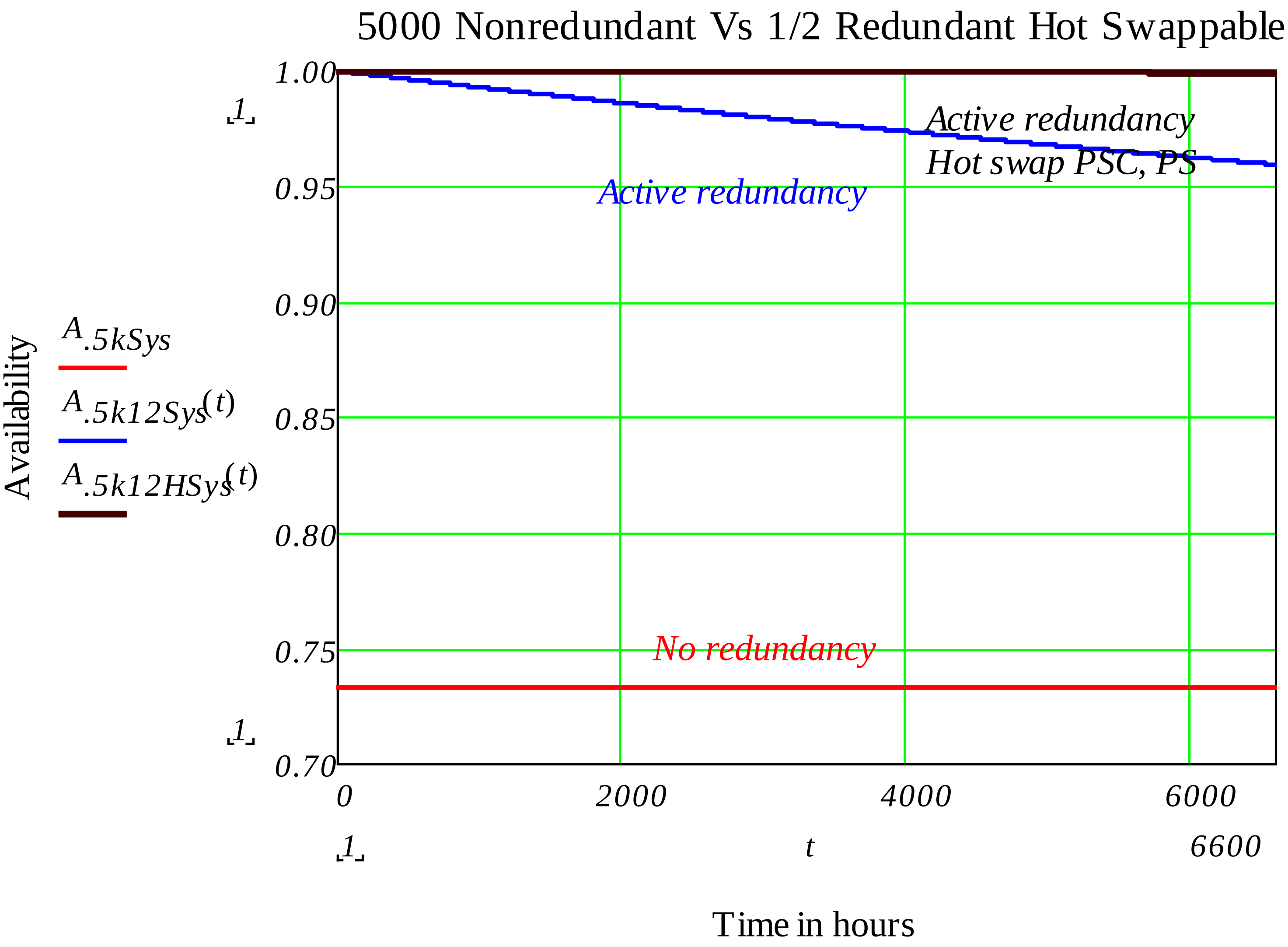
Item	MTBF kHrs
PSC	110
PS	60
Transductor	381.5
Cables/ Connectors	14000

MTTR = 2 Hours

PAC 2001 Chicago, Illinois

Bellomo, Donaldson, MacNair


5000 Nonredundant Vs 5000 1/2 Redundant
10000
1000
100
10
1
0.1
0.01
0
2000
4000
6000
t
Time in hours
Number of failures
F5kSys(t)
F5k12Sys(t)
F5k12HSys(t)
No redundancy
Active redundancy
Active redundancy
Hot swap PSC, PS



It is clear that redundancy and hot swap are needed

SLAC Projects with Non-redundant or Redundant Power Supplies

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

•Power supply quantity is hundreds, not thousands

• Power supply availability budget is modest 98%

• Non-redundant supplies satisfied availability budget

• Redundant power systems not readily available from industry

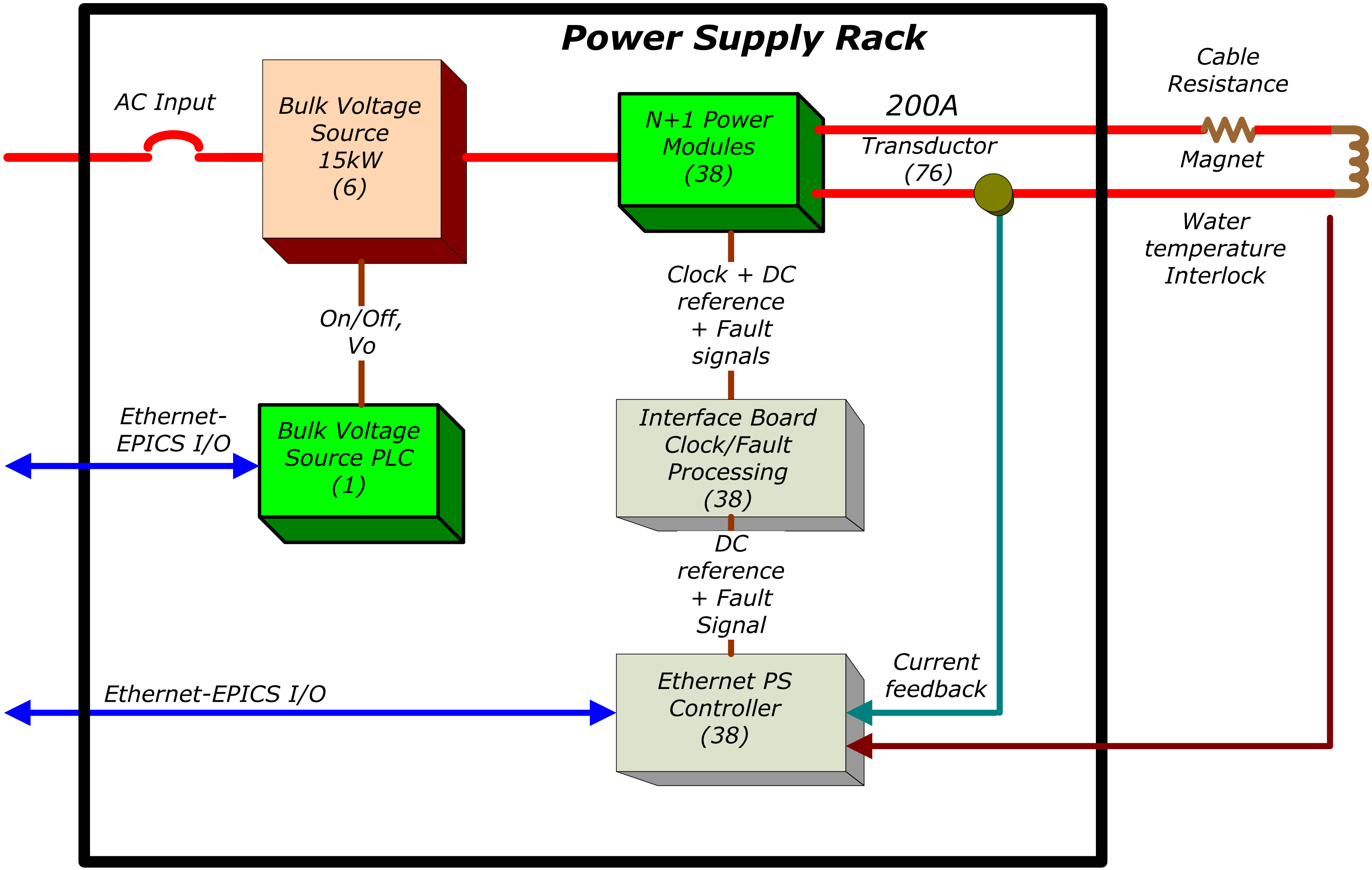
• Redundant systems would not fit within cost and schedule constraints

Redundant - KEK ATF 2 (2006 – 2008)

• Mock-up of ILC Final Focus accelerator

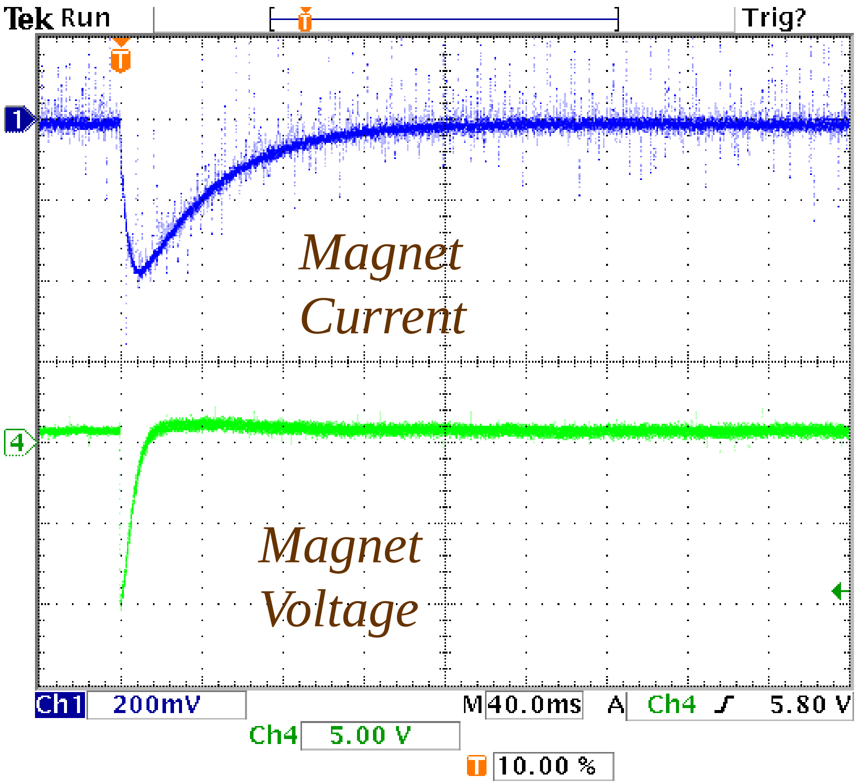
• Magnet power supplies ILC-like

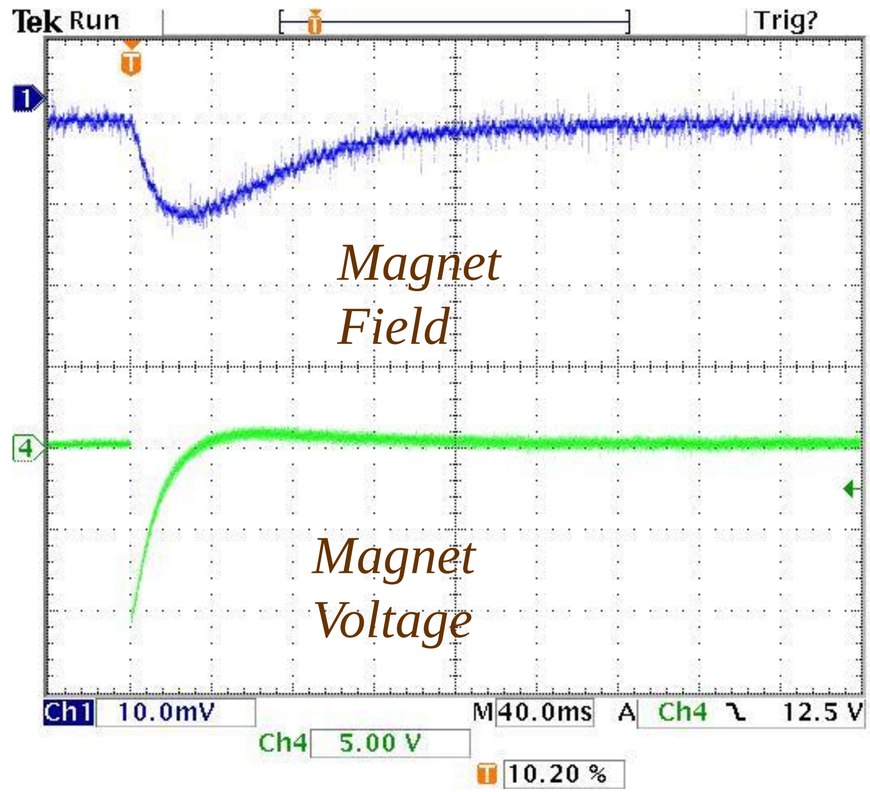
ATF2 Block Diagram



ATF2 – at KEK

ATF2 Current and Field Recovery Plots





- *During power module loss measured 6A magnet current drop at 150A*
- *100 Gauss drop at 3.1 kilogauss. 200mS recovery with no overshoot, no re-standardize needed*

Next Generation High Availability Power Supply (HAPS)

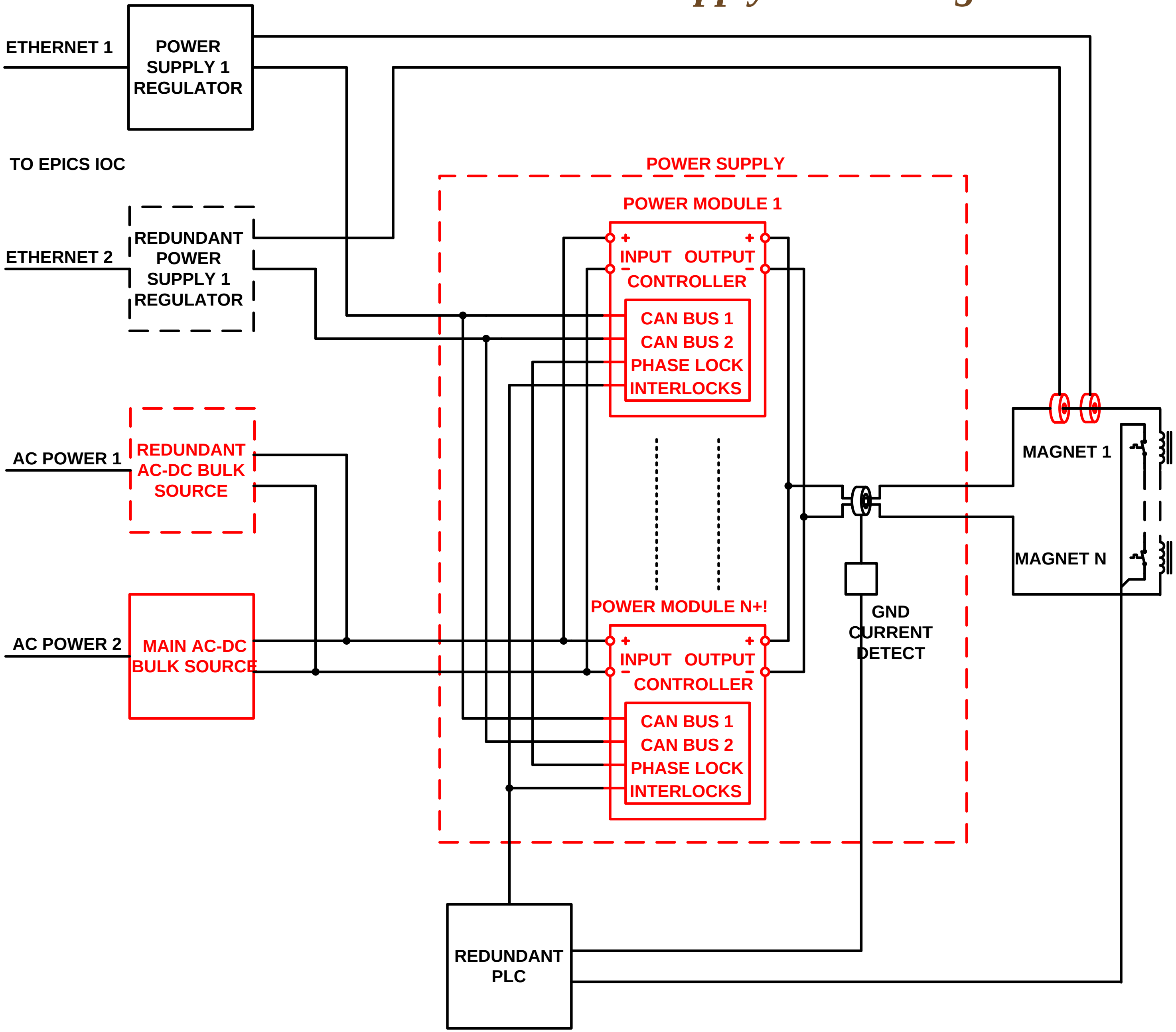
Goals

- *All components N+1 modular and redundant*
- *Power module hot-swappable*
- *Unipolar or bipolar output from a single unipolar bulk voltage source*
- *Imbedded controller with digital current regulation*
- *Capable of driving superconducting magnets*
- *High bandwidth for use in BBA or closed orbit correction systems*
- *High stability and precision output current*
- *High accuracy read-backs*
- *Scalable to higher output levels*

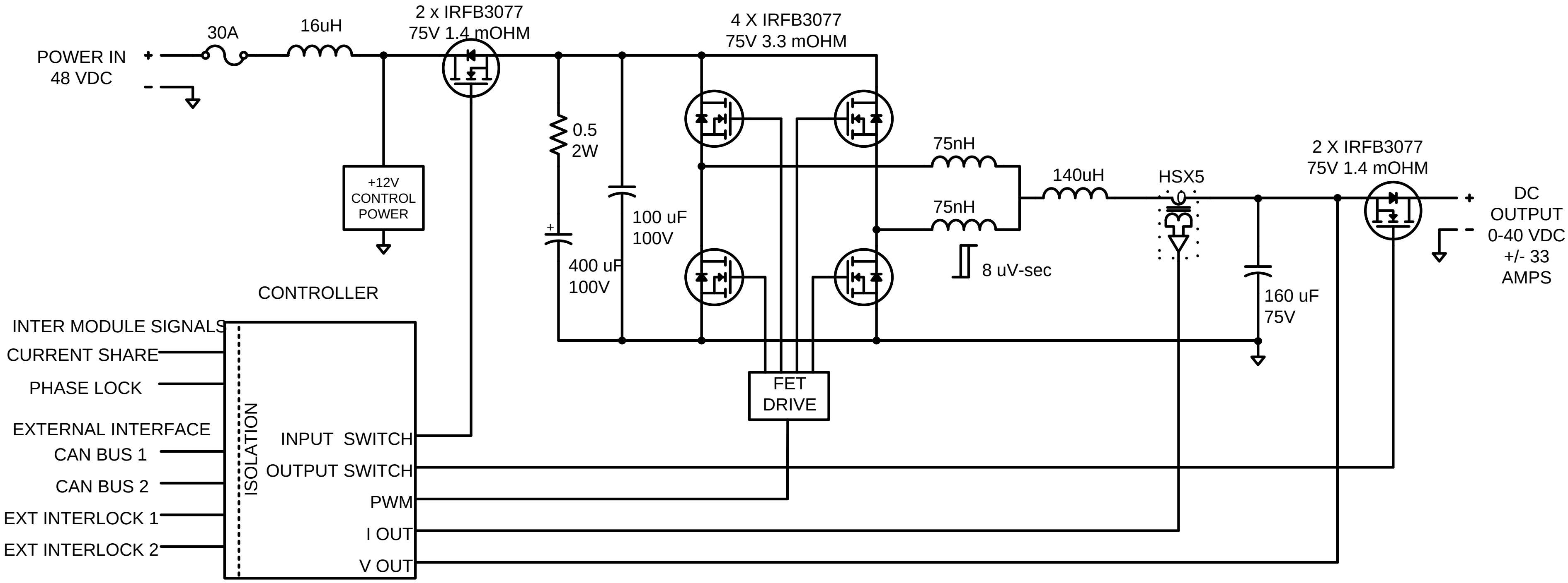
Applications

- *ILC and other future accelerators*

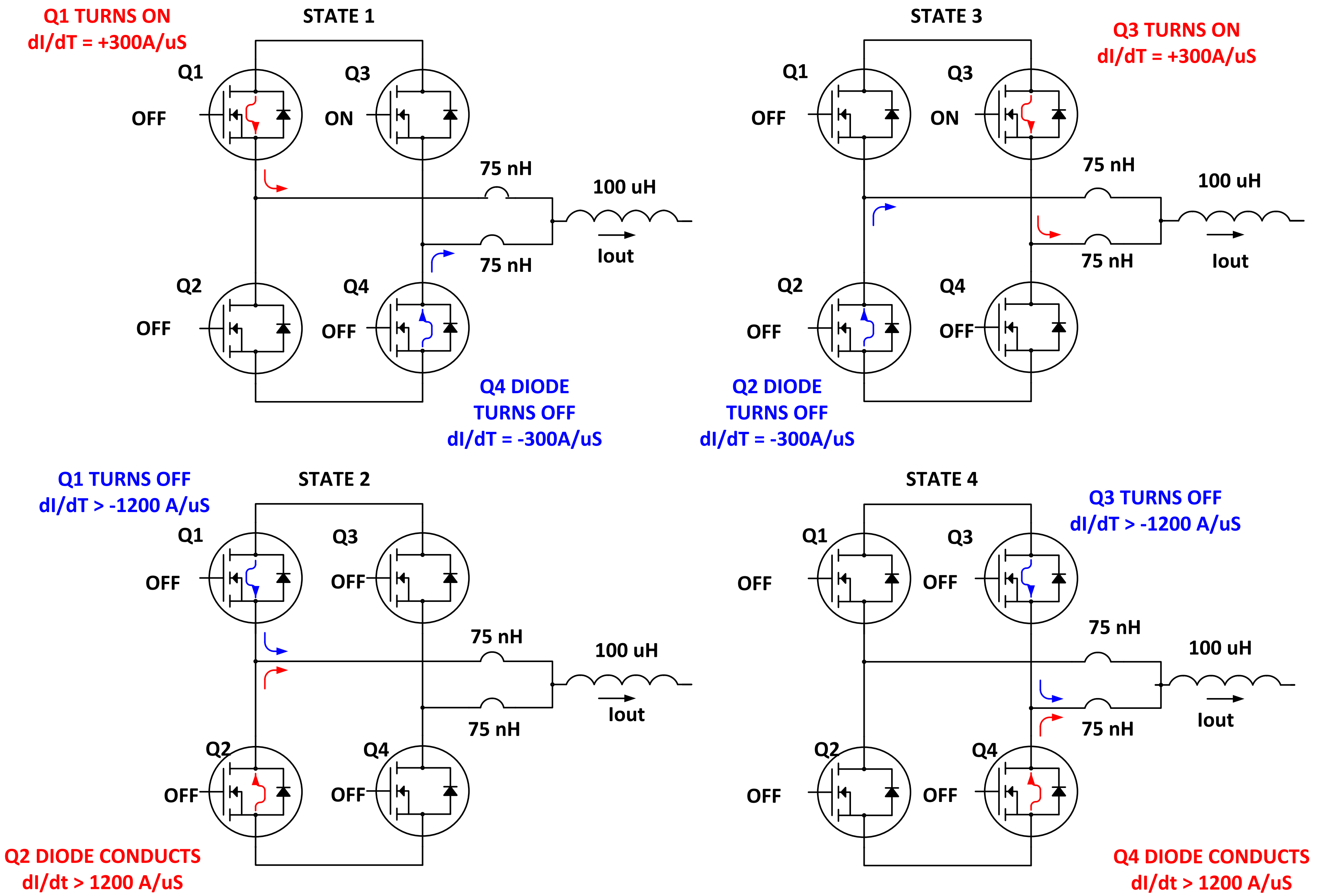
Next Generation Power Supply Block Diagram



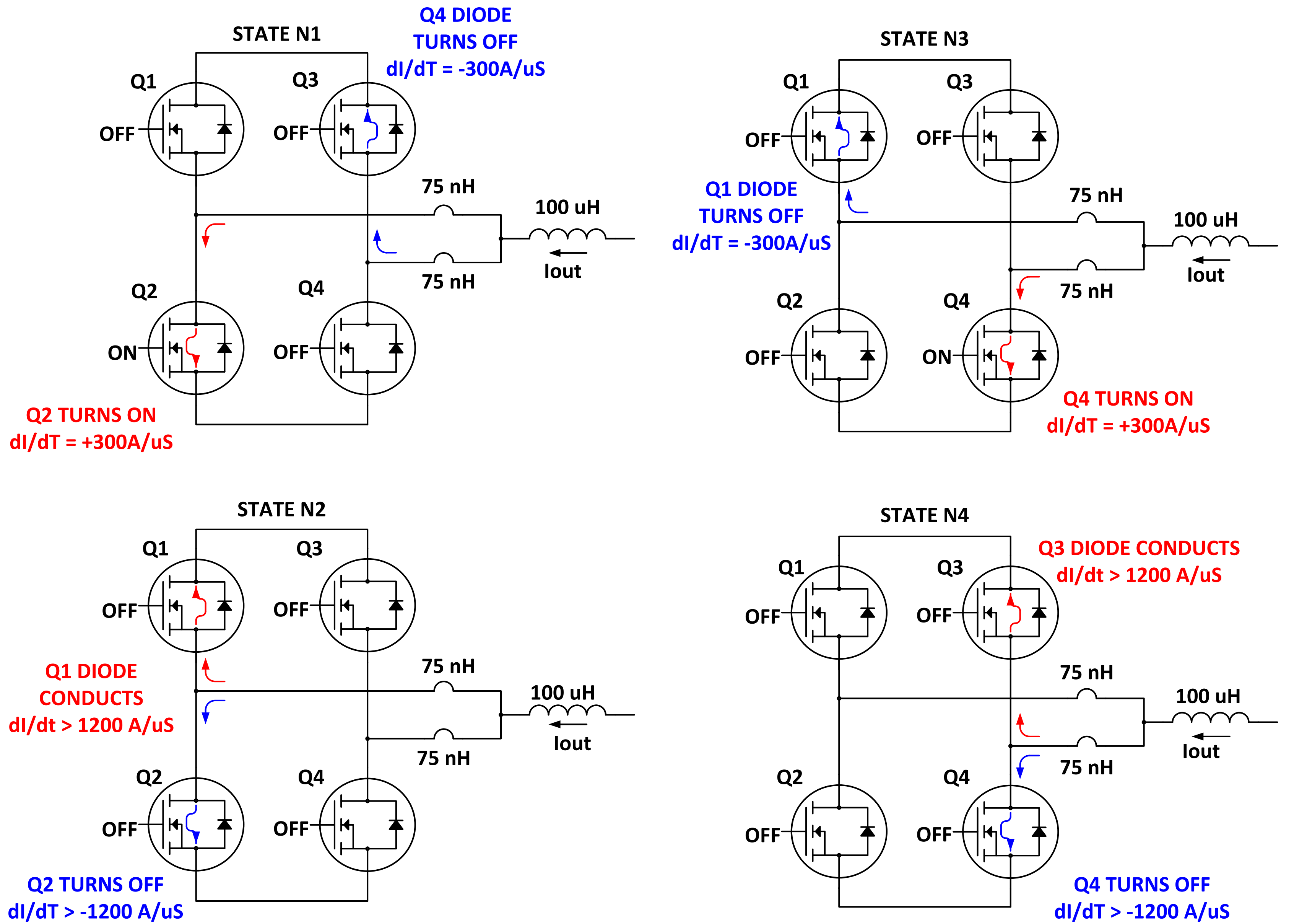
Next Generation Power Module Schematic



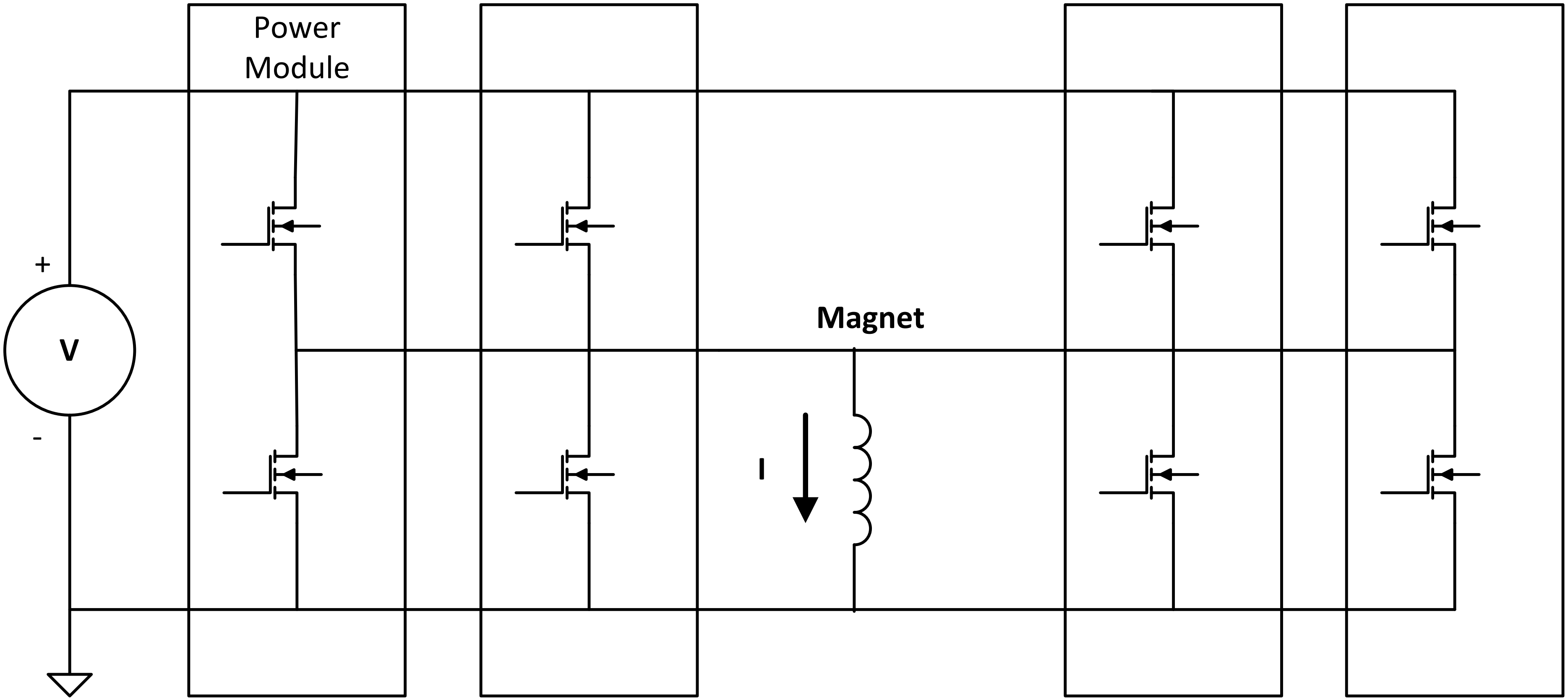
Next Generation Positive Output Current (Q1 – Q2 – Q3 – Q4)



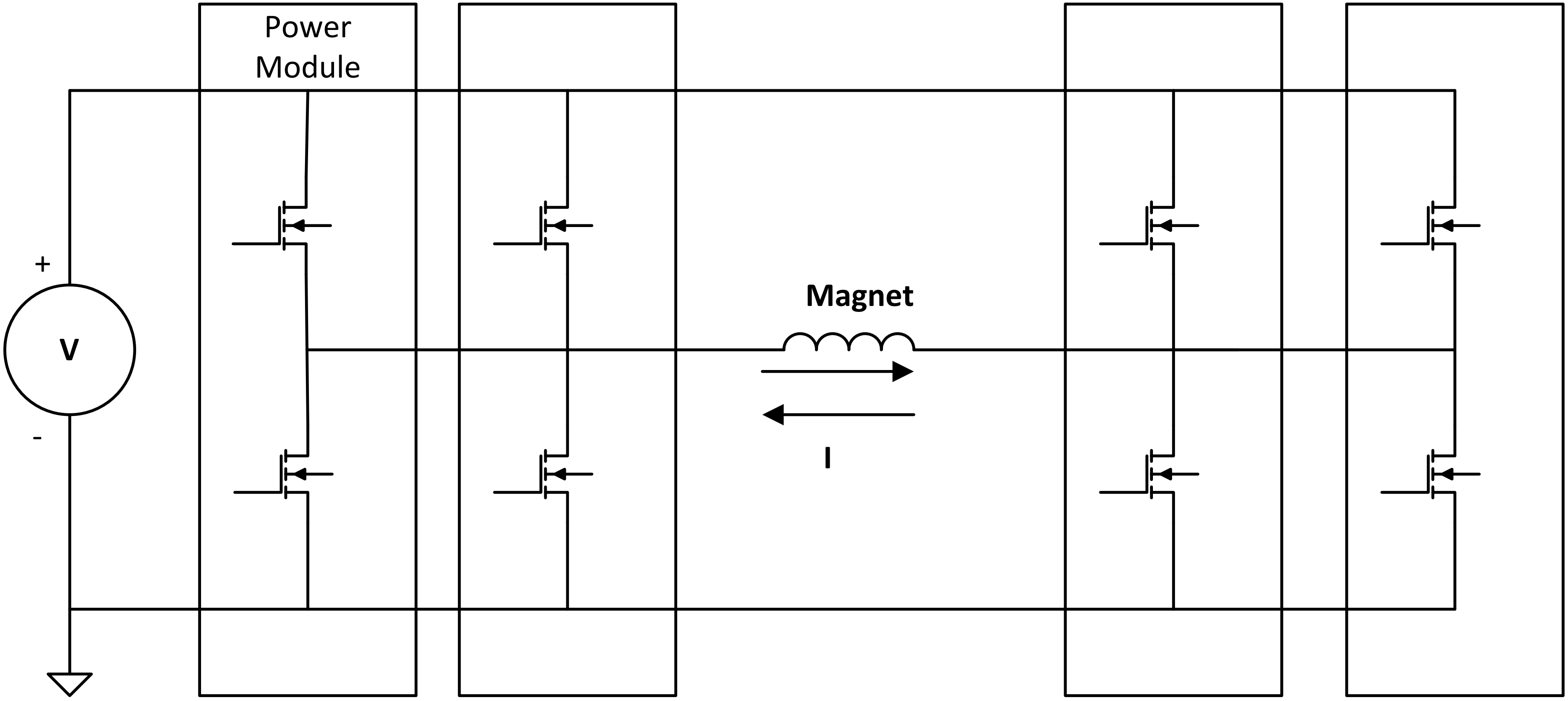
Next Generation Negative Output Current (Q2 – Q1 – Q4 – Q3)



Power Modules Connected for Unipolar Output

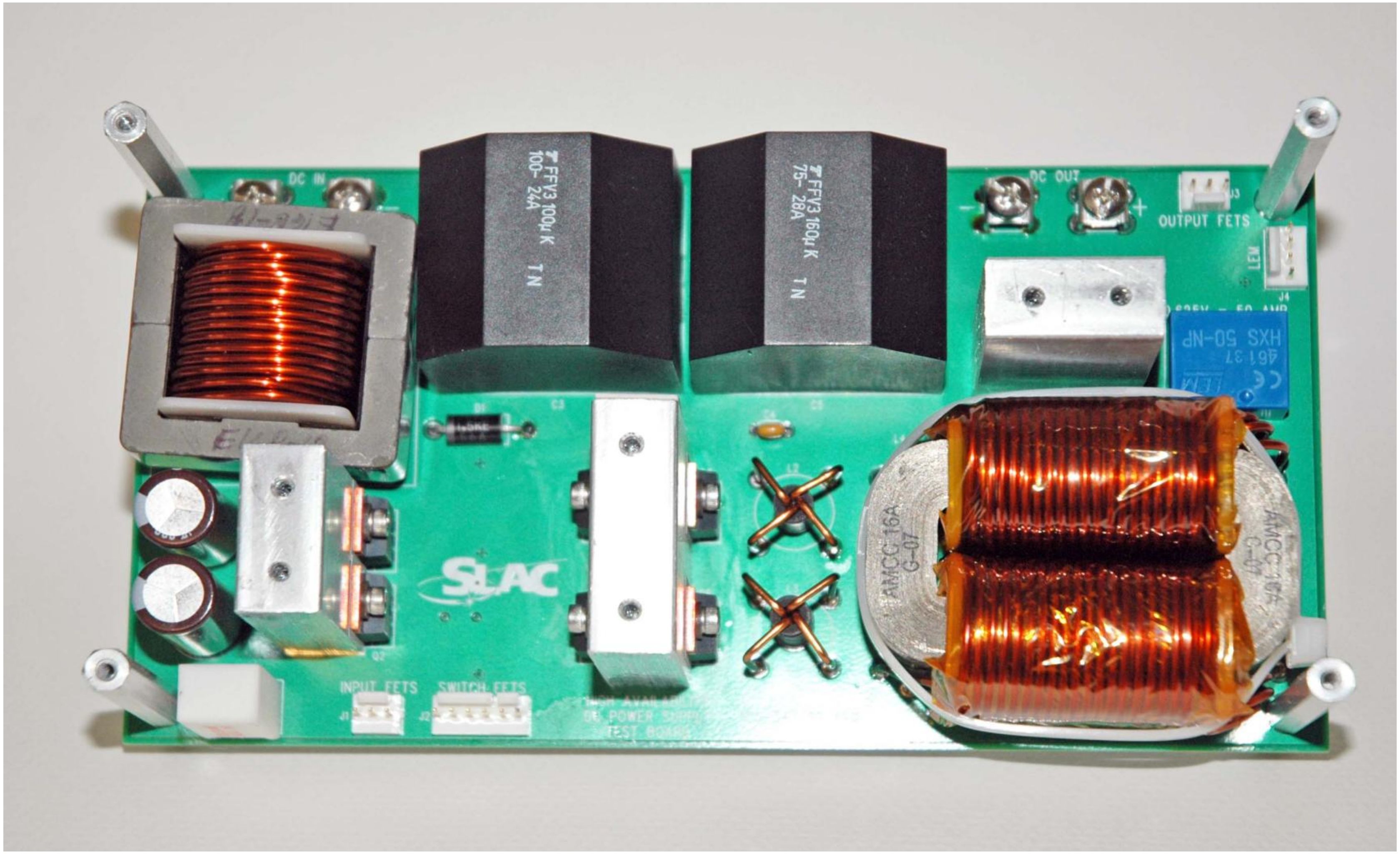


Power Modules Connected for Bipolar Output

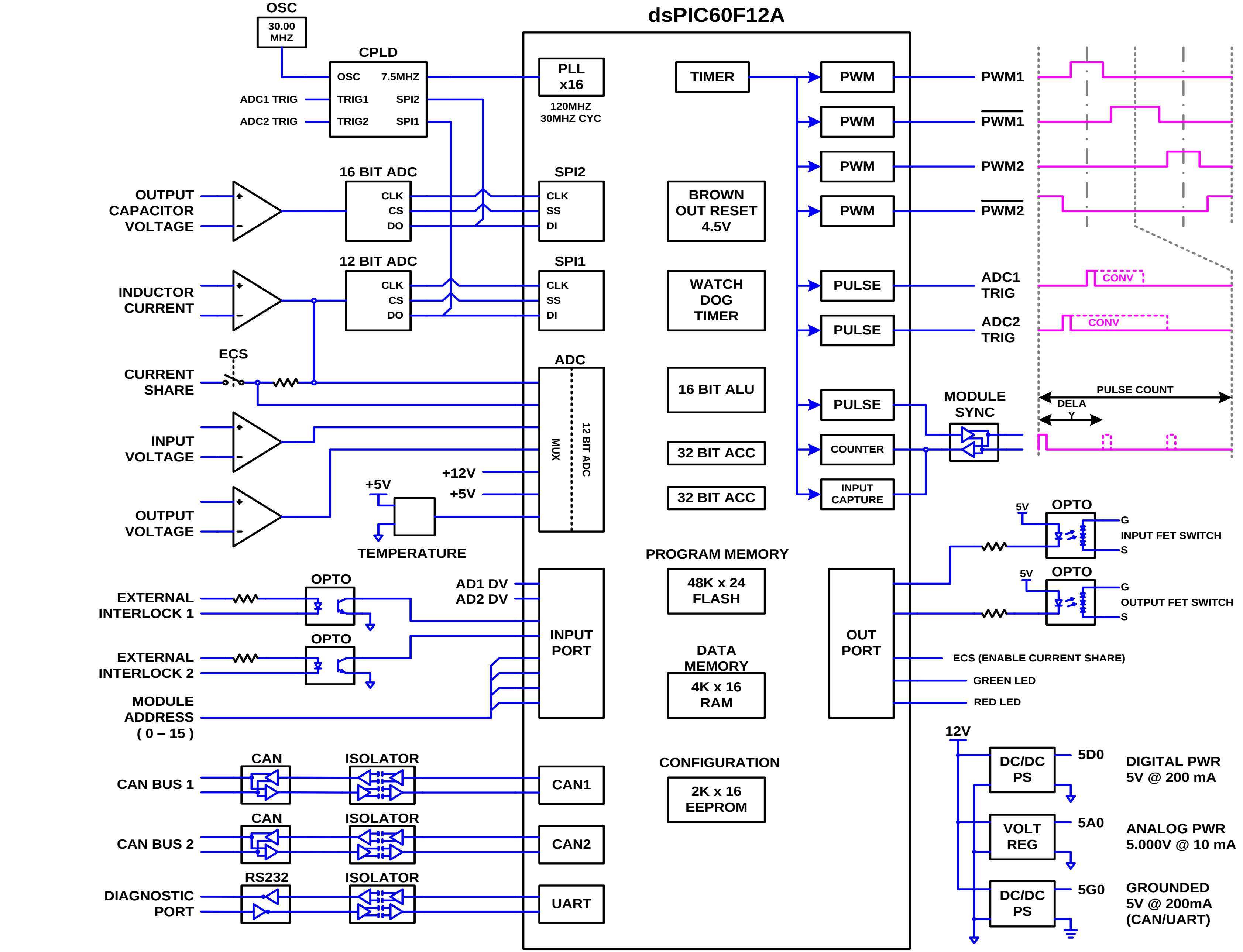


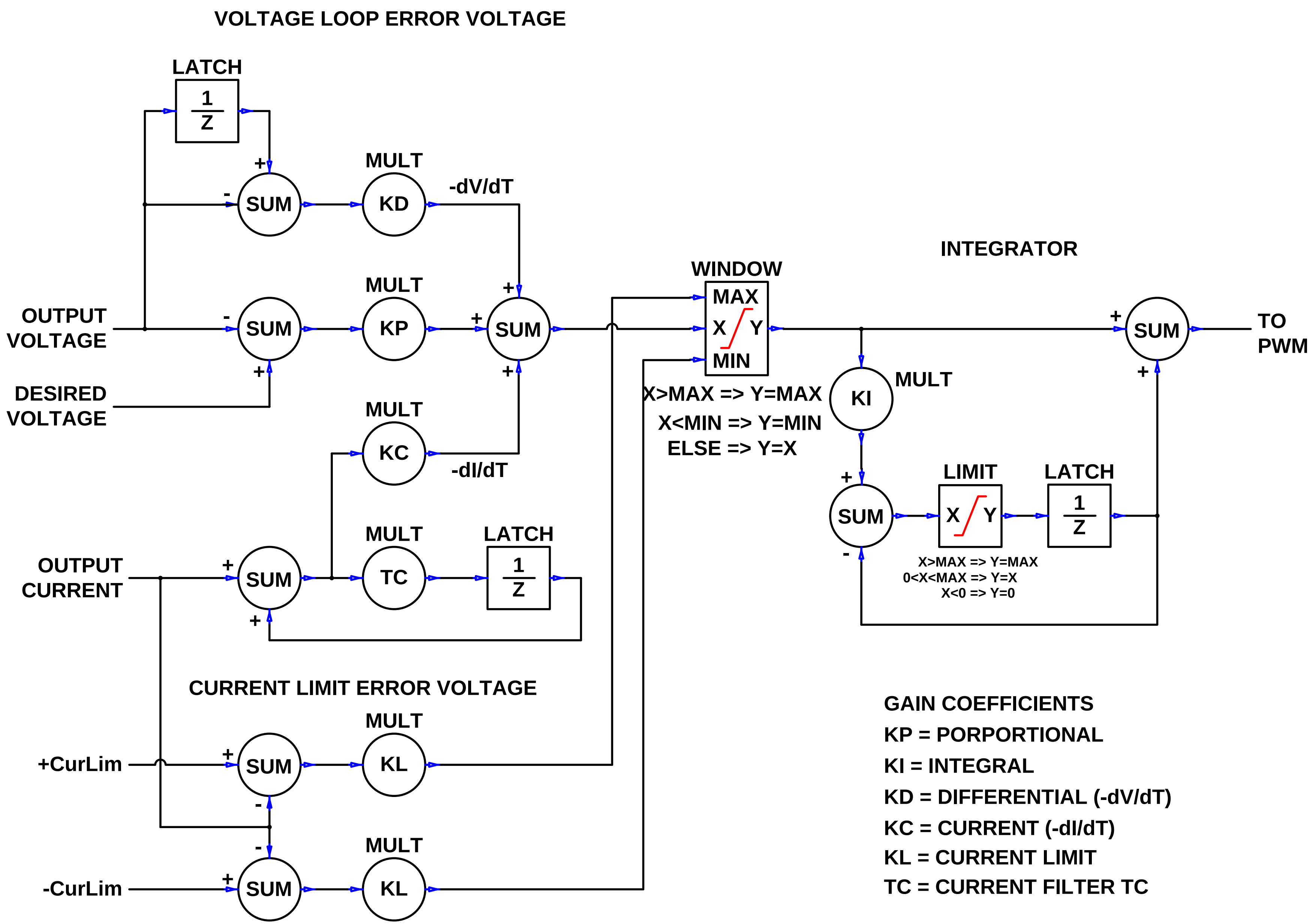
Next Generation Power Modules are "Bricks"

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


DC IN
DC OUT
OUTPUT FETS
INPUT FETS
SWITCH FETS
SLAC
HXS 50-NP

Next Generation Controller





GAIN COEFFICIENTS

KP = PORPORTIONAL

KI = INTEGRAL

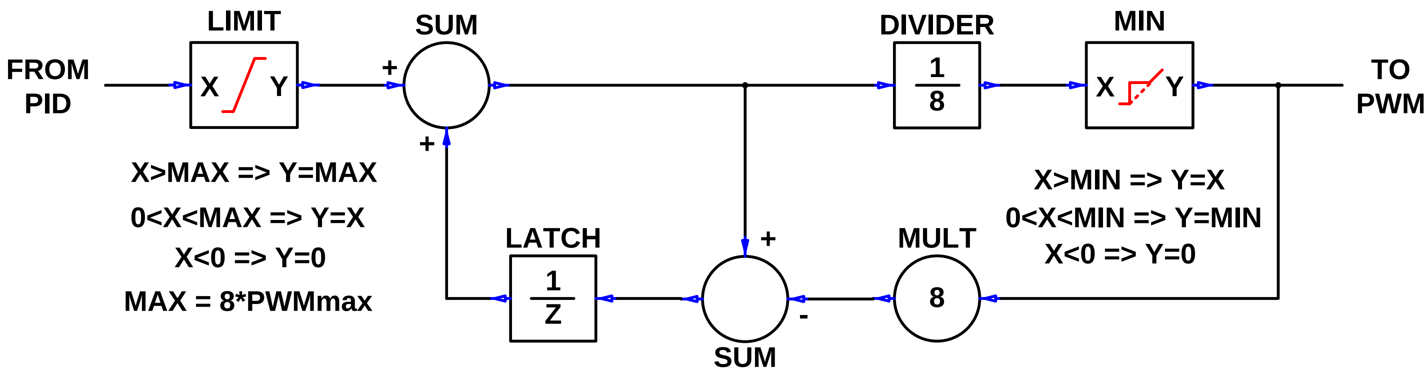
KD = DIFFERENTIAL (-dV/dT)

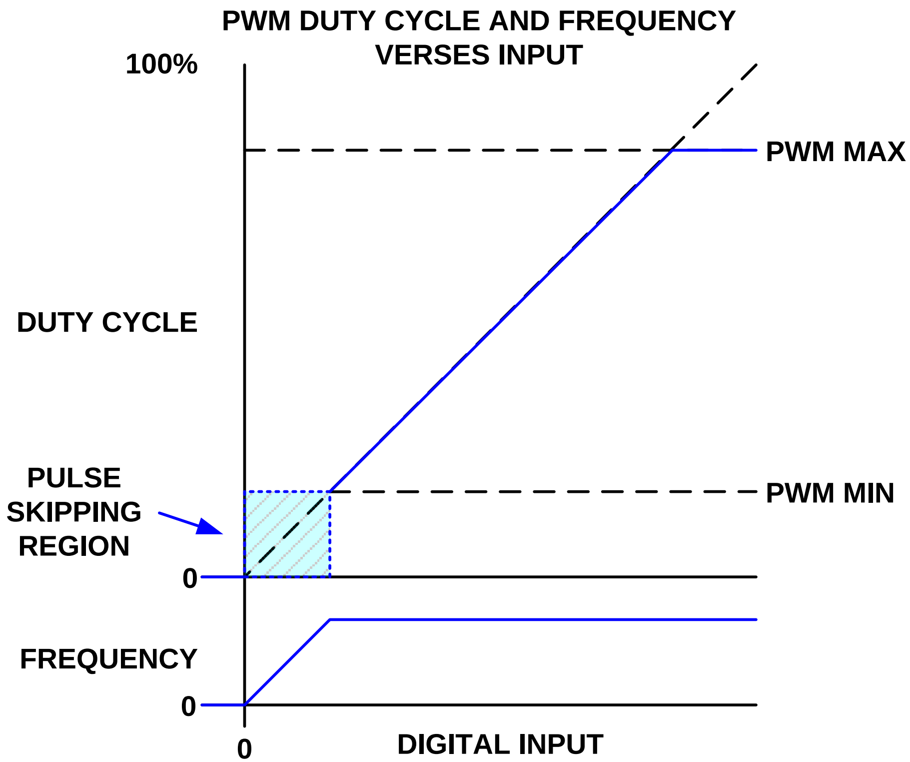
KC = CURRENT (-dI/dT)

KL = CURRENT LIMIT

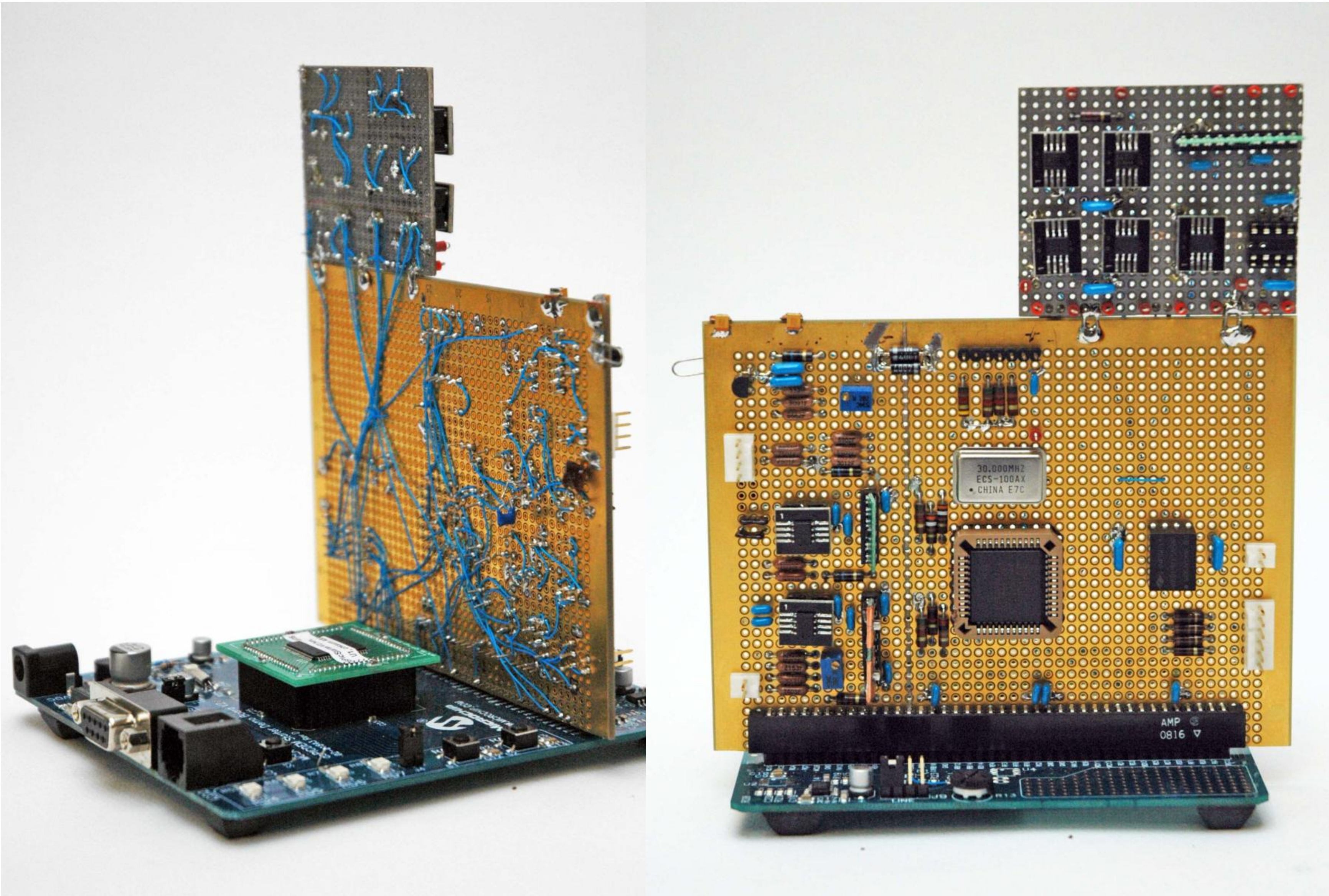
TC = CURRENT FILTER TC

Next Generation PWM Control

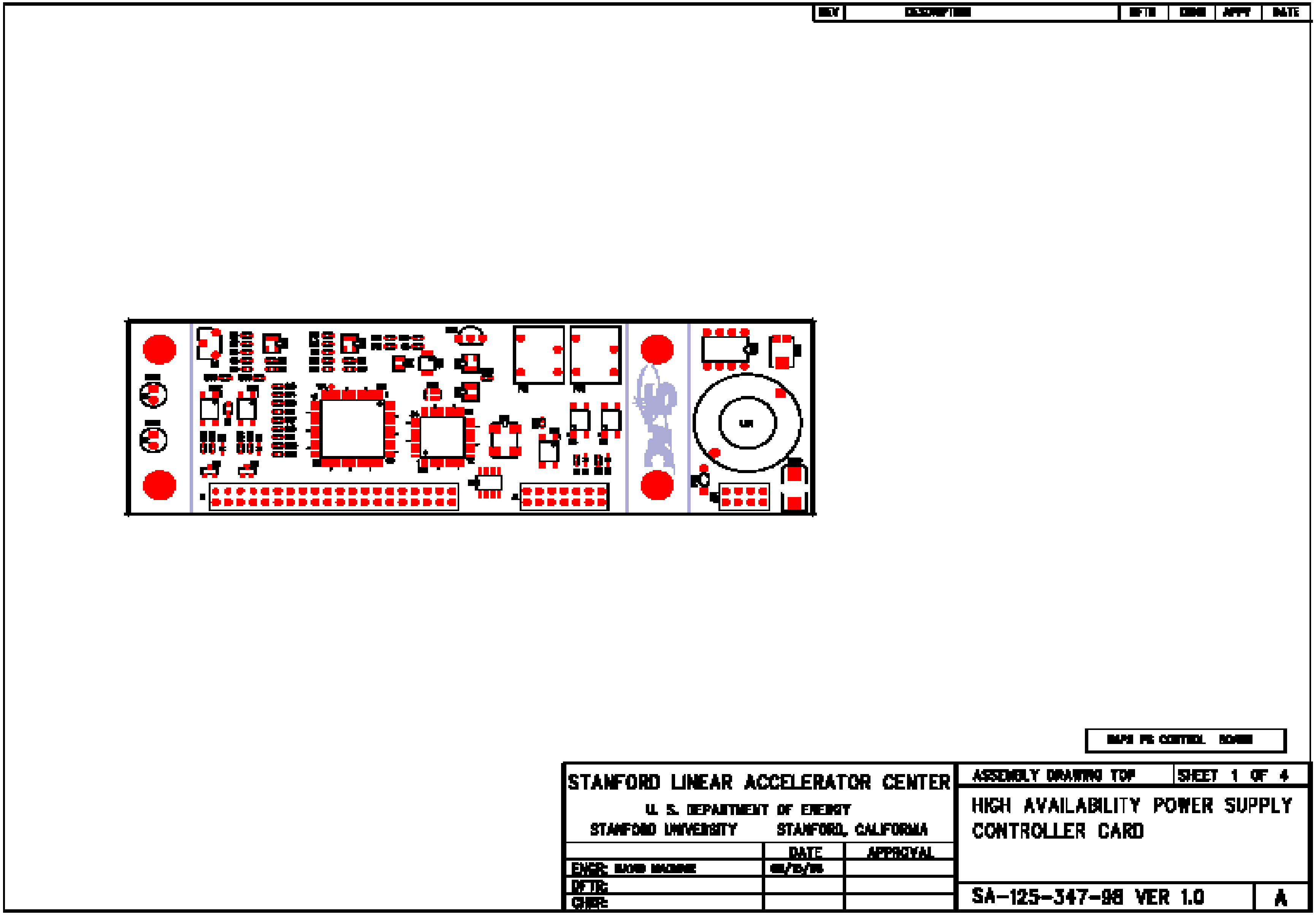




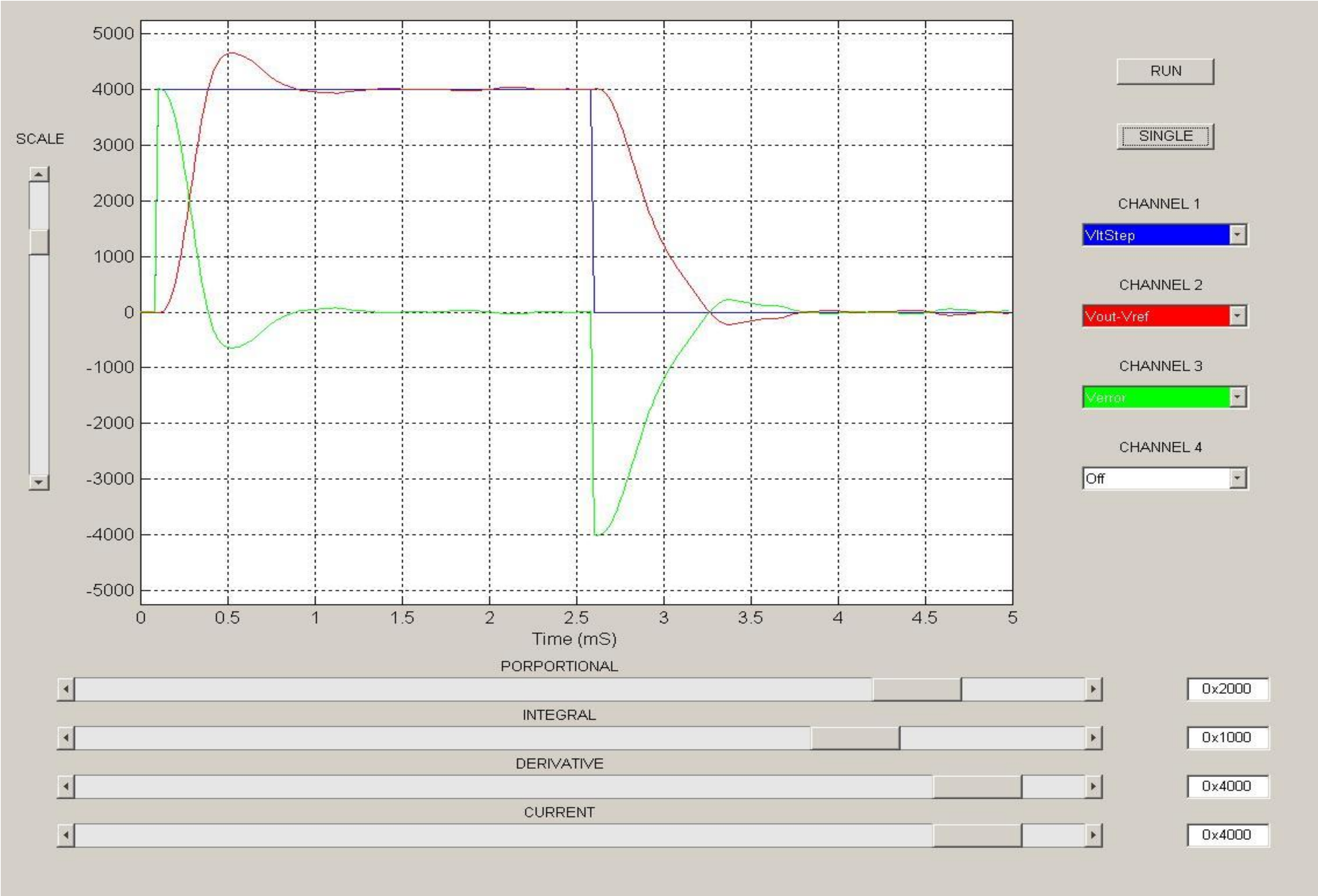
Next Generation Prototype Controller with Development Board



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

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:

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

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

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

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

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.*

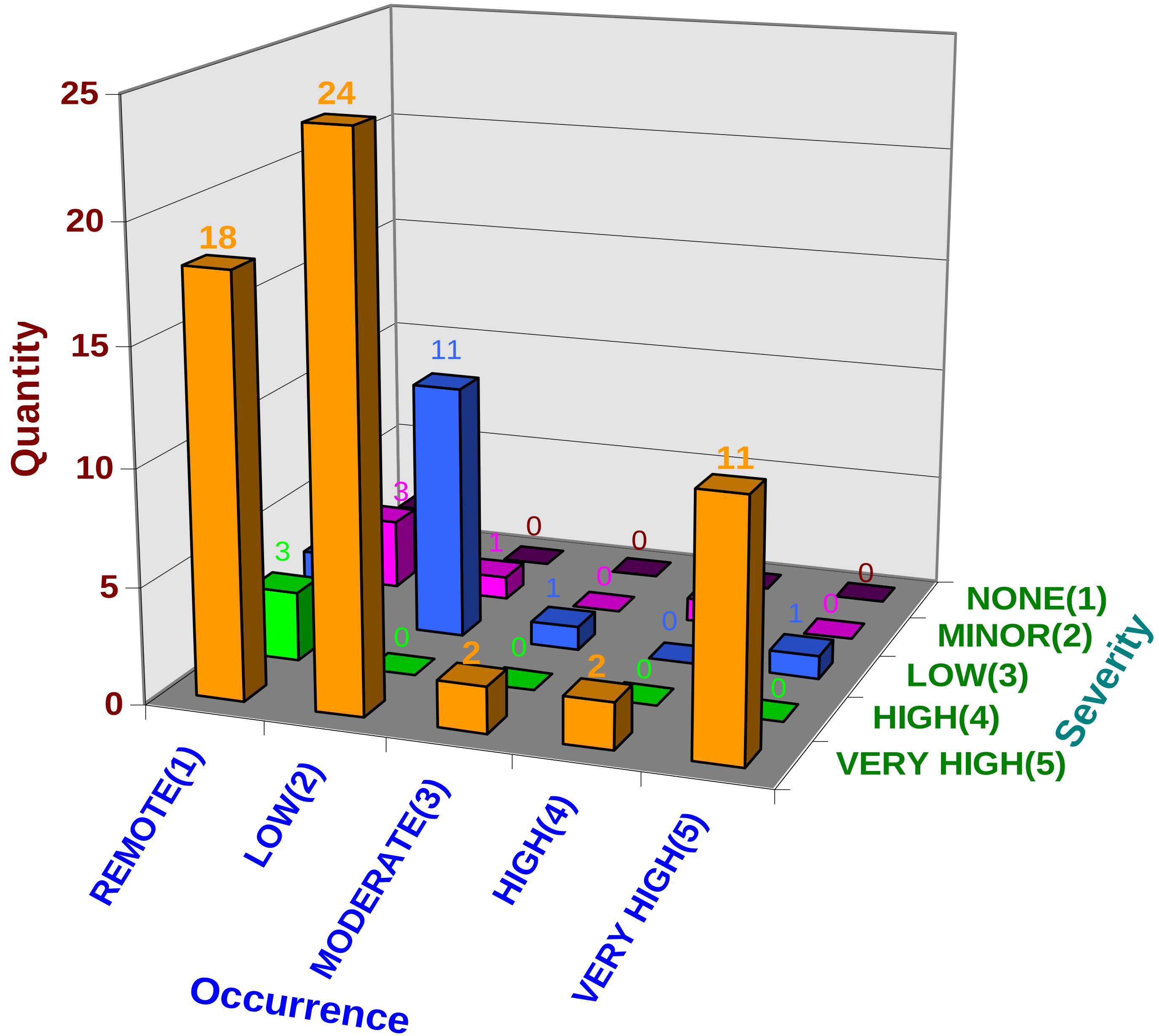
3 Major Iterations

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

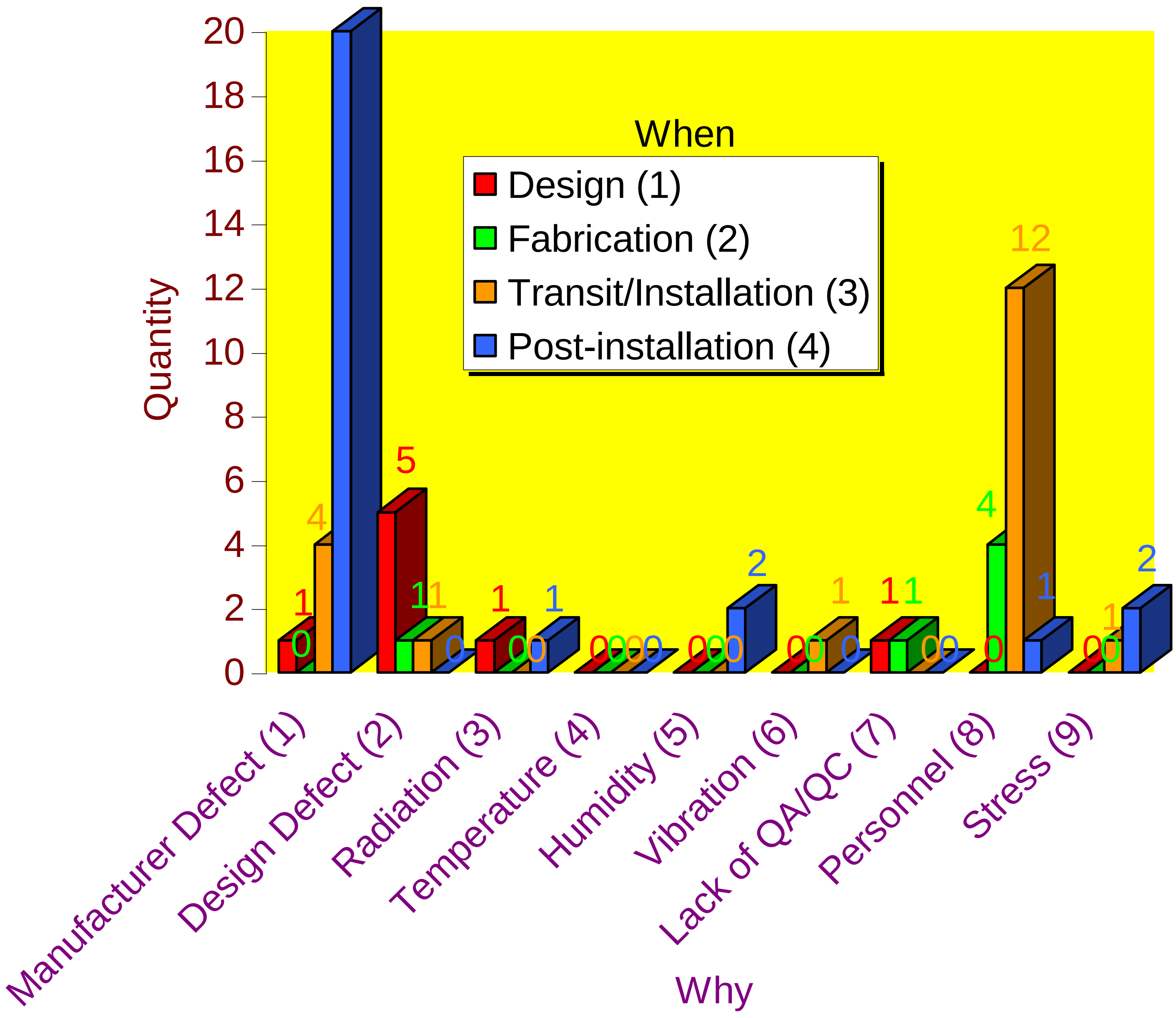
Fault Modes And Effects Criticality Analysis (FMECA)

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

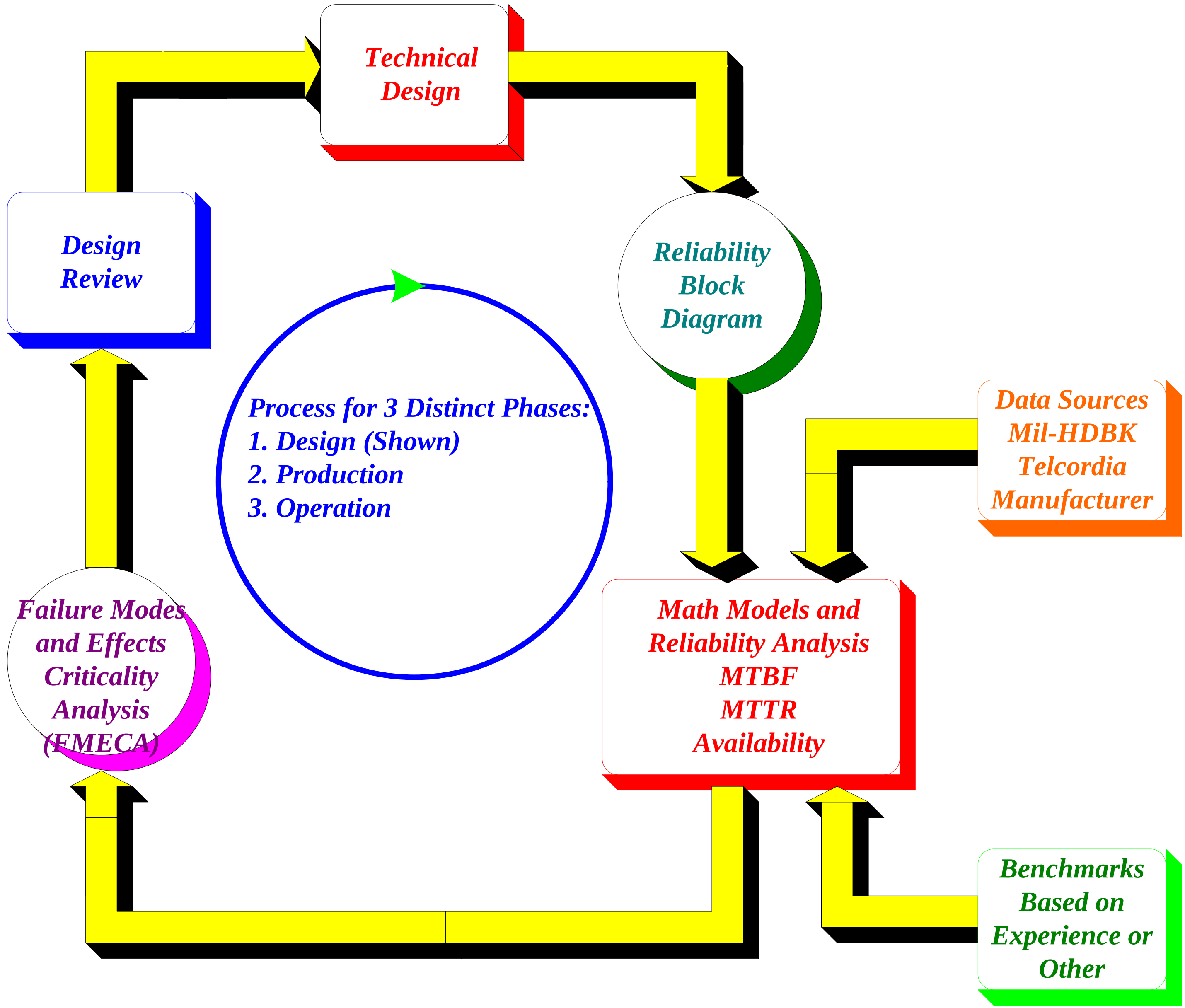
Fault Modes And Effects Criticality Analysis (FMECA)



FMECA When and Why Plot



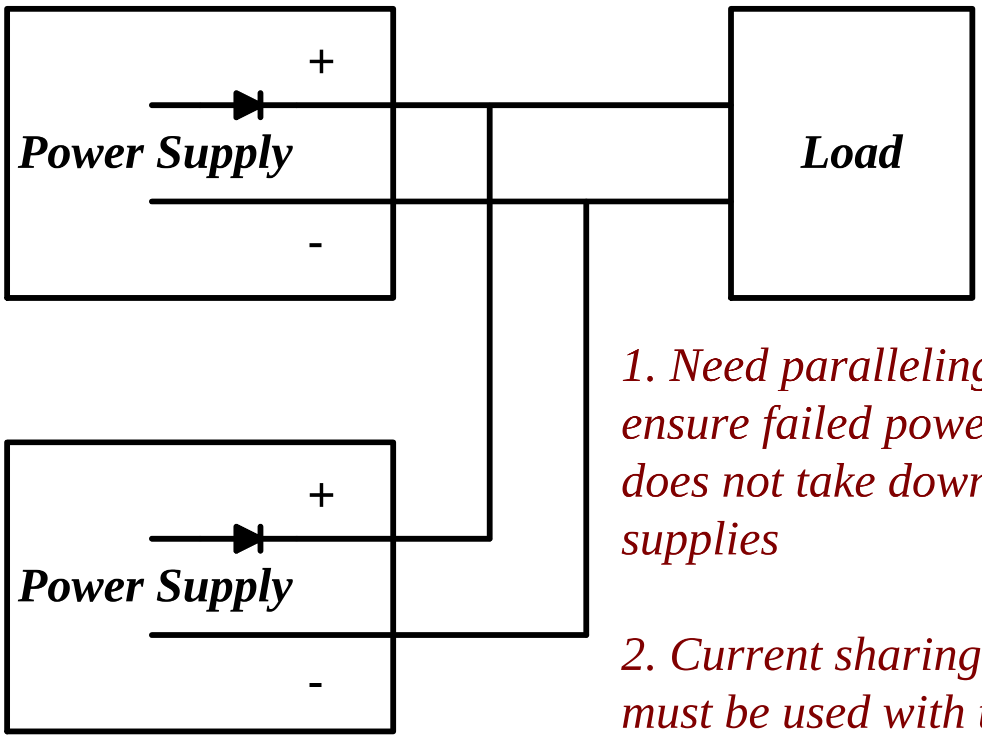
Reliability Process Diagram



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

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 500μ S*
17. Type of control system	*Analog, mixed analog-digital, all digital* *Communication bus*
18. Interlocks	*•Low input voltage - loss of input phase* *•Output over voltage – over current* *•Excessive ground current* *•Insufficient cooling air flow – cabinet over temperature* *•Insufficient cooling water flow – cooling water over temperature*

List of Specifications 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*

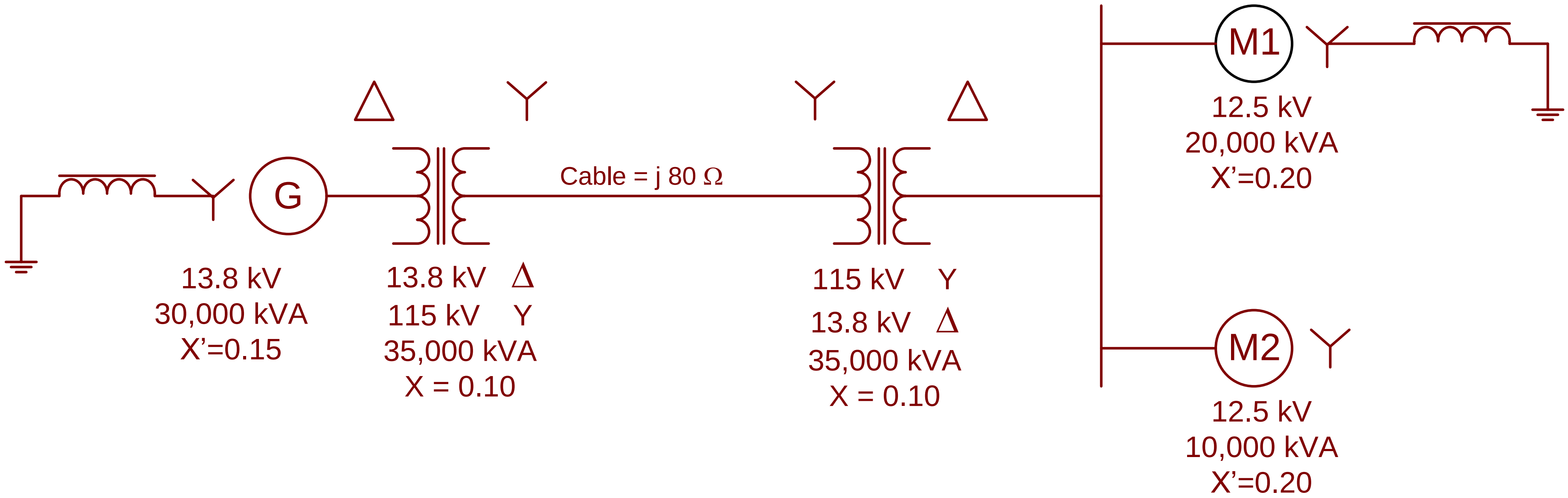
Useful Textbooks And References

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

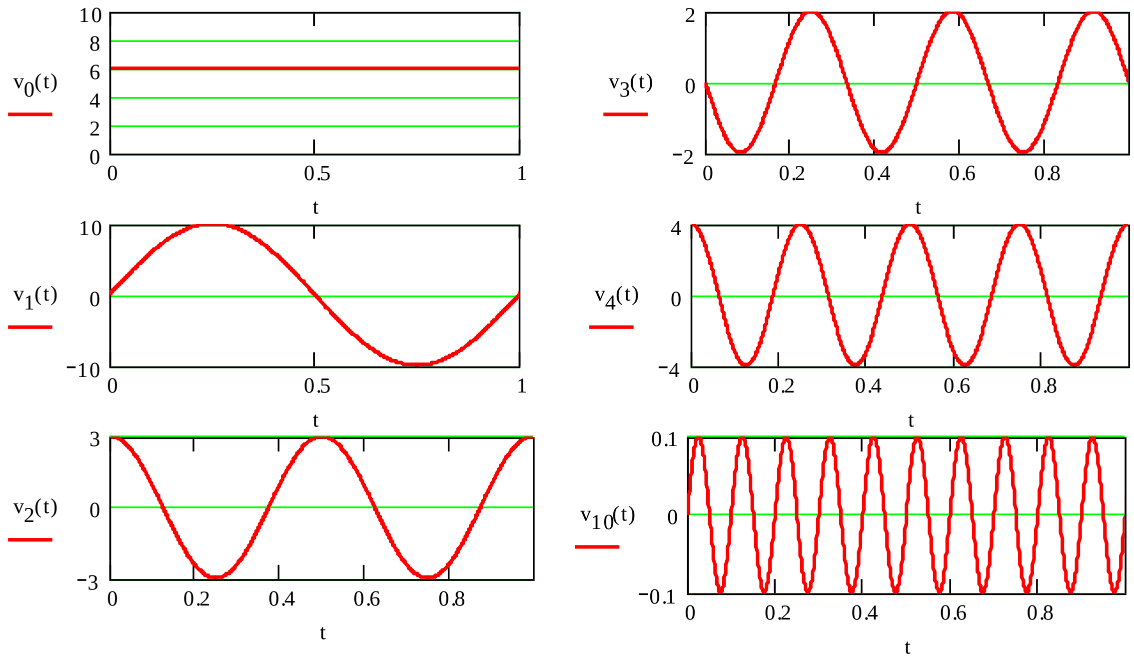
Referring to the one-line diagram below, determine the line currents in the:

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 ω=(2*π)/T*

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

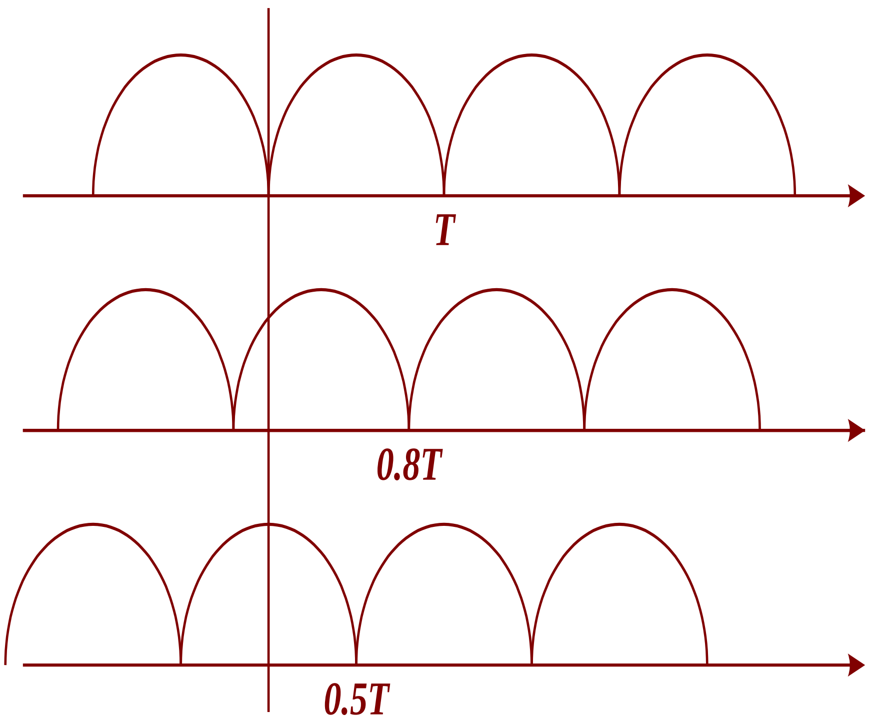
c. Give the numerical result of

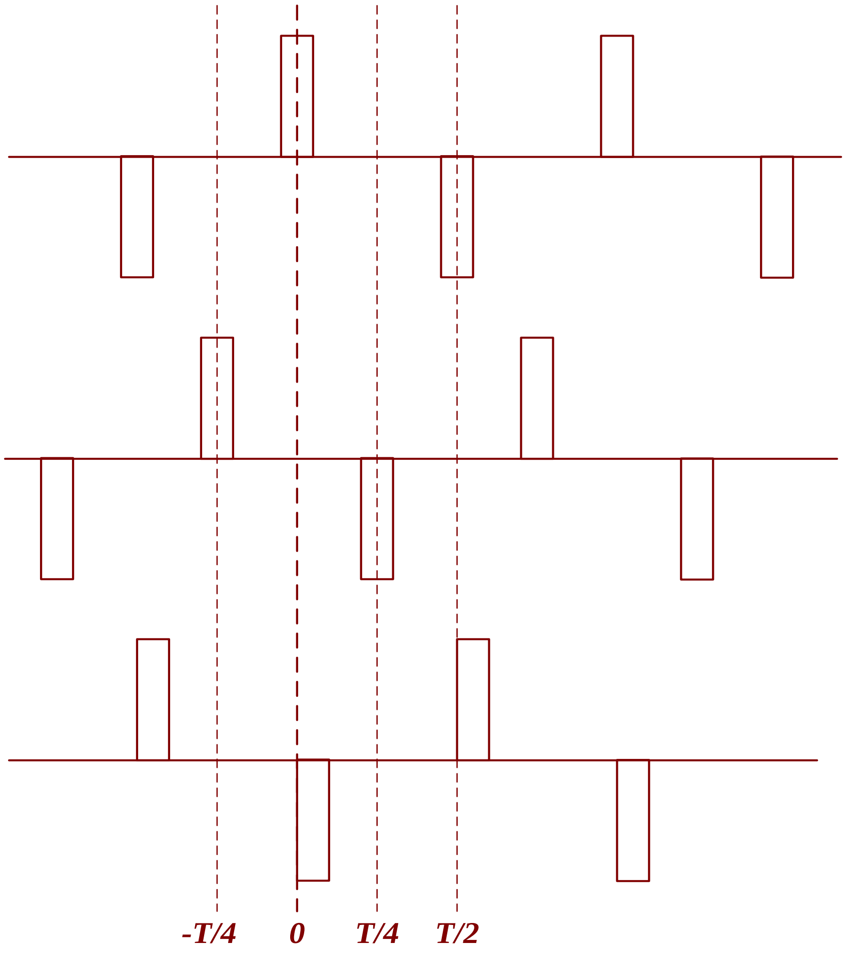
$$b_3 = \frac{2}{T}\int_0^T v(t)\sin 3\omega t\,dt \qquad \text{Help}: \int \sin^2(3\omega t)\,dt = \frac{1}{3} * \frac{\frac{1}{2}\cos(3\omega t)\sin(3\omega t) + \frac{3}{2}\omega t}{\omega}$$

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

Homework Problem # 3

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 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 # 5

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 $\mu\,\Omega - cm$.

Homework Problem # 6

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

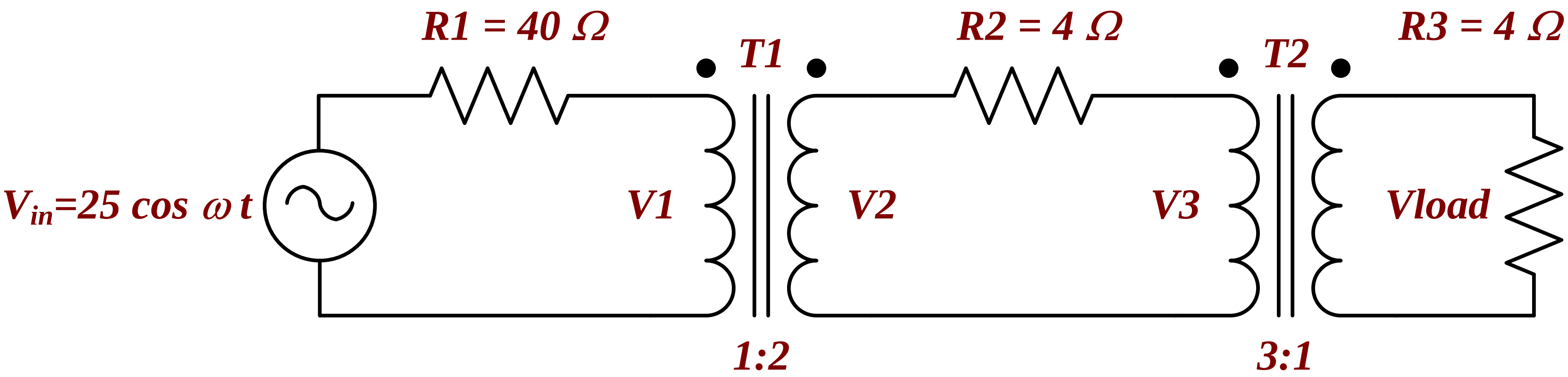
a. The actual impedance and leakage inductance referred to the primary winding

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

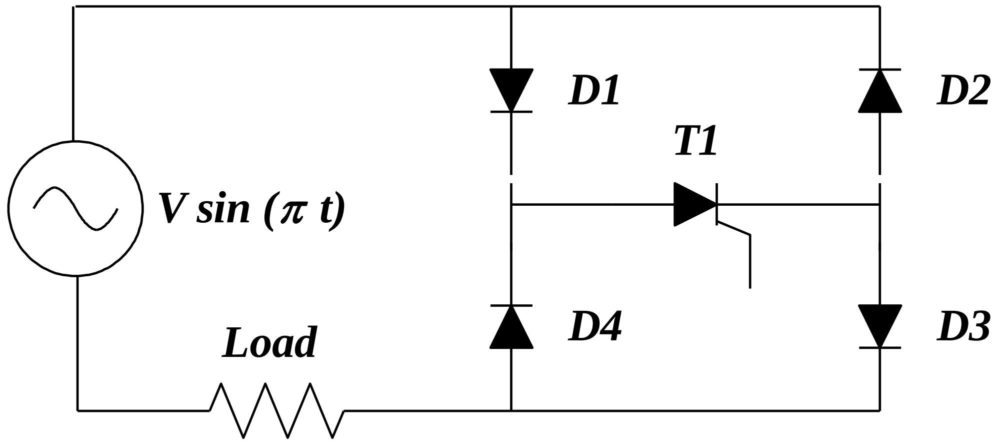
c. The magnetizing inductance referred to the primary winding

Homework Problem # 7

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:

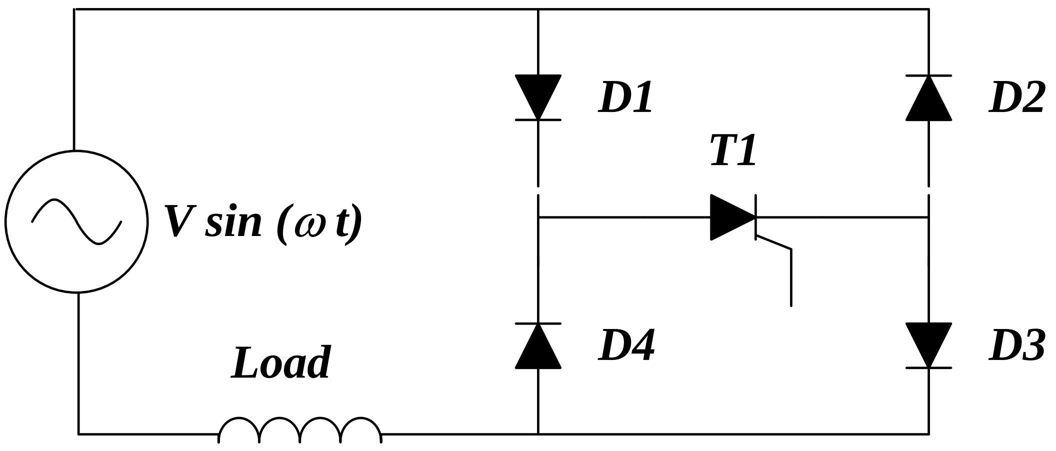
A. Explain how the circuit operates

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:

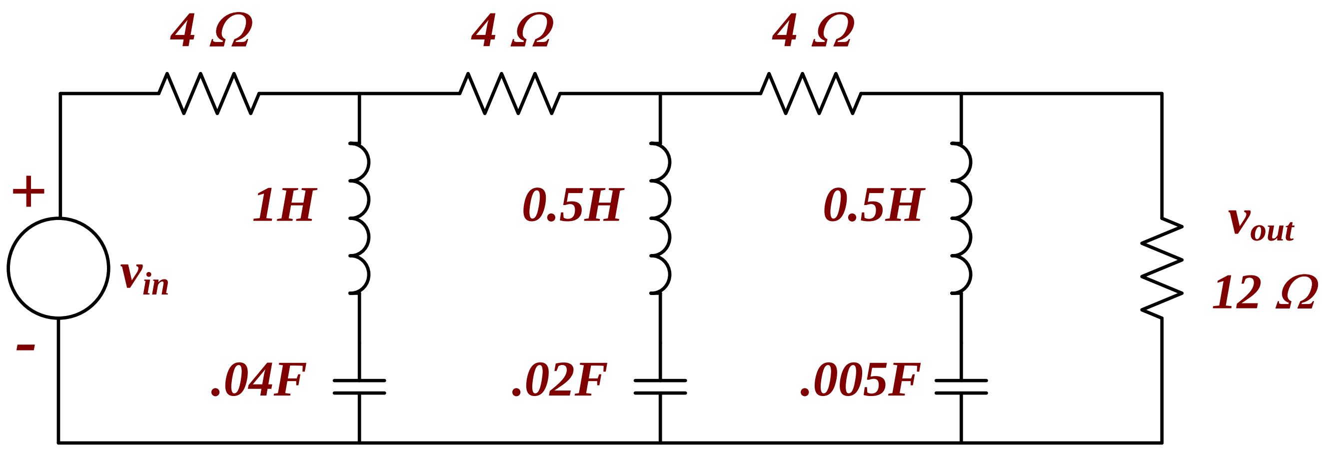
A. Explain how the circuit operates.

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.*

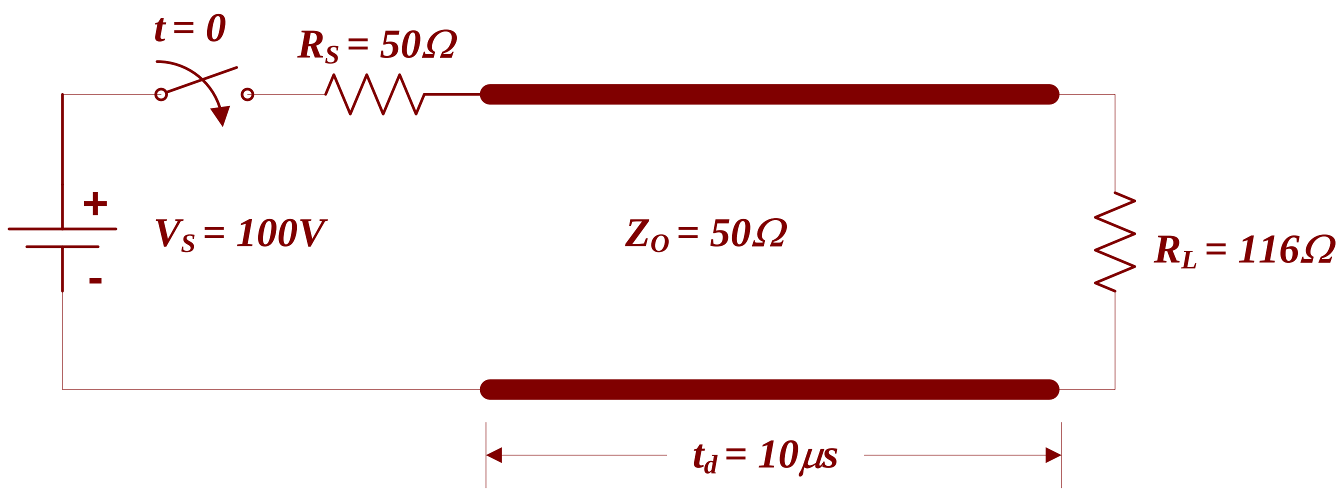
B. *The frequency of a signal applied to a two-wire transmission cable is 3GHz.*

What is the signal wavelength if the cable dielectric is air? Hint – relative permittivity of air is 1

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

Homework Problem #13

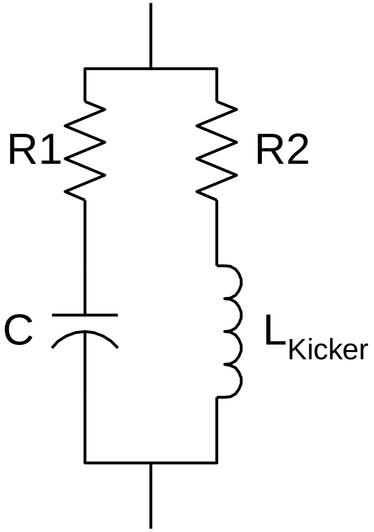
For the transmission line shown below, calculate the Reflection Coefficients Γ, the reflected voltages and the voltage and current along the line versus time.



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.



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?