TTM Technologies

Primer on Power Supply Topologies

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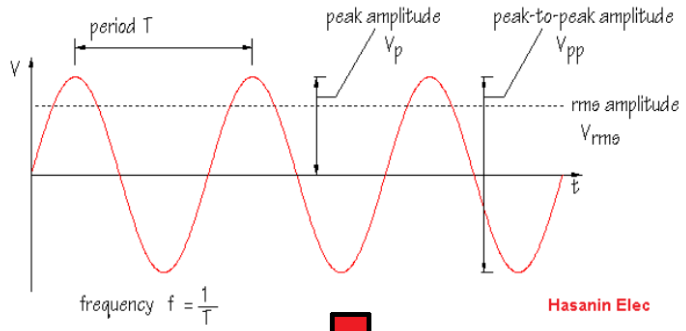
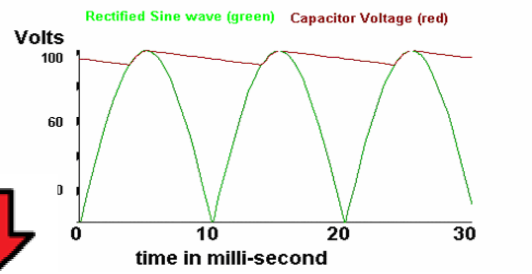
Director of Engineering

11/2/23

Inspiring Innovation

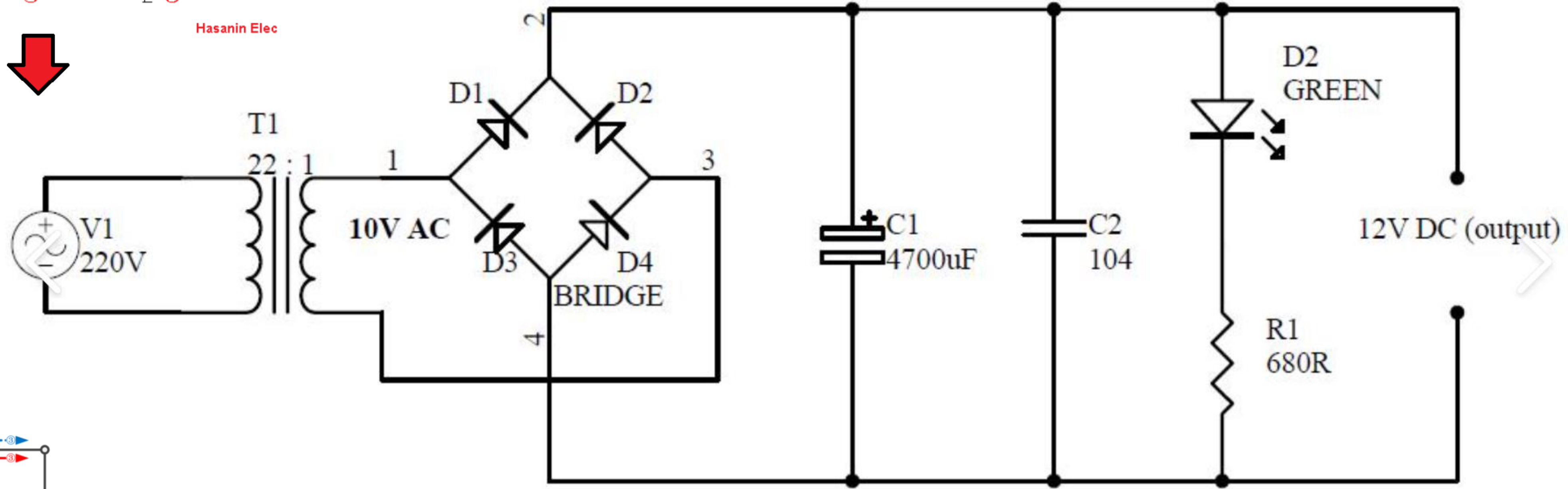
Transformer Coupled Rectifier Supply (AC to DC)

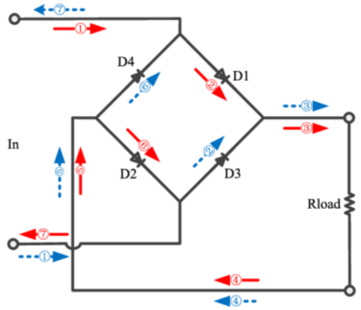




UNREGULATED
"MIDBUS"

AC INPUT





Inspiring Innovation

Single-phase full-wave bridge rectifier circuit with a C-filter

V_s rises

Supply provides load and simultaneously charges the capacitor

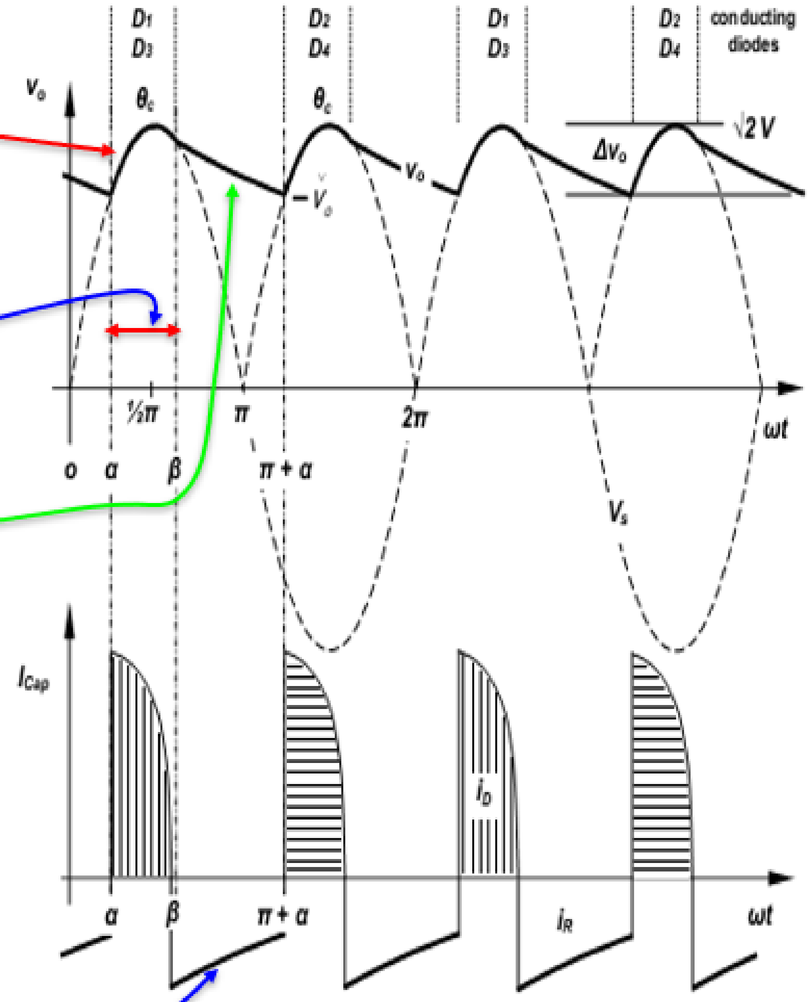
charging current period

capacitor voltage > V_s

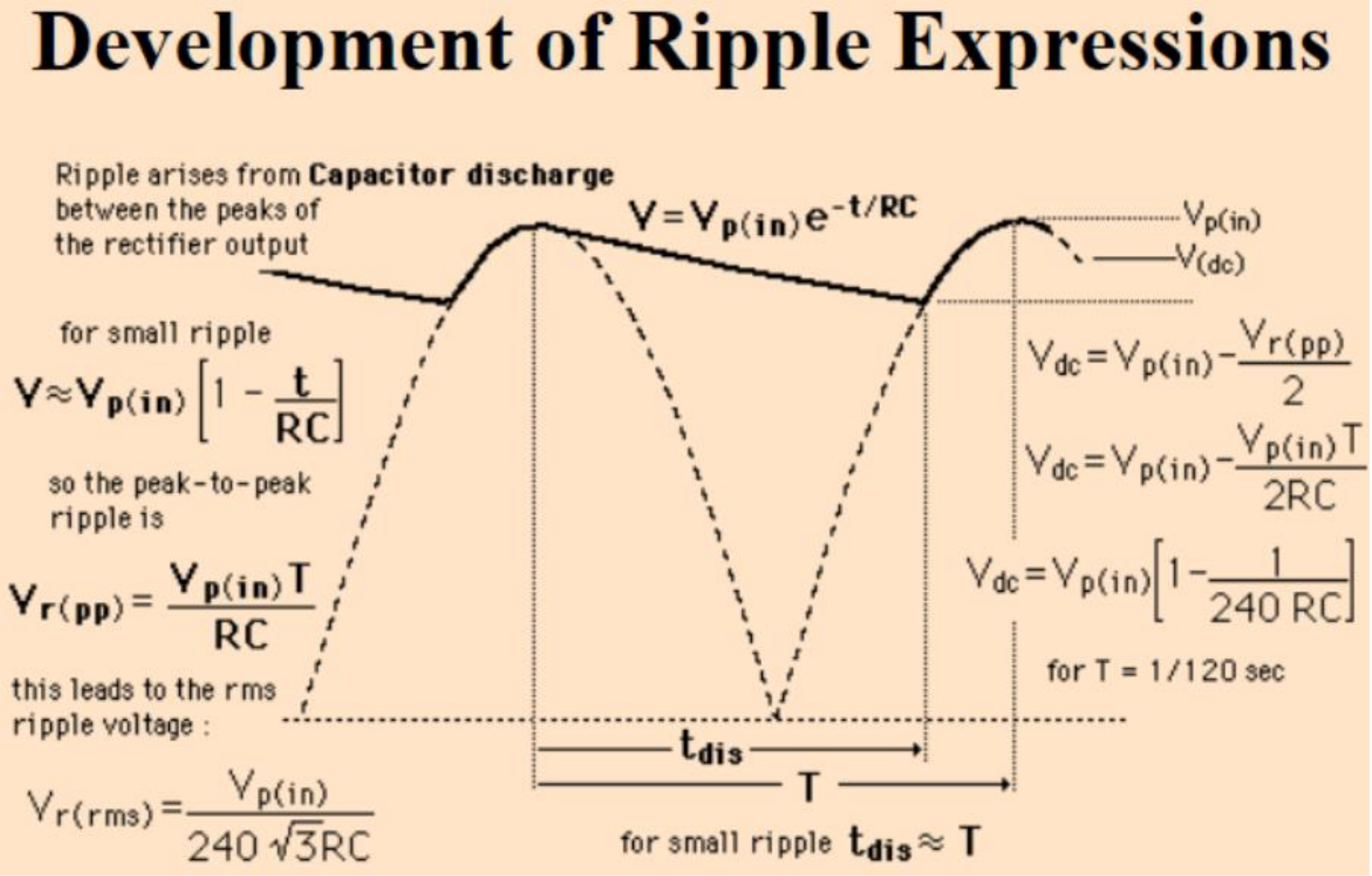
At ωt= β, D1-D2/D3-D4 OFF

capacitor supplies the load current

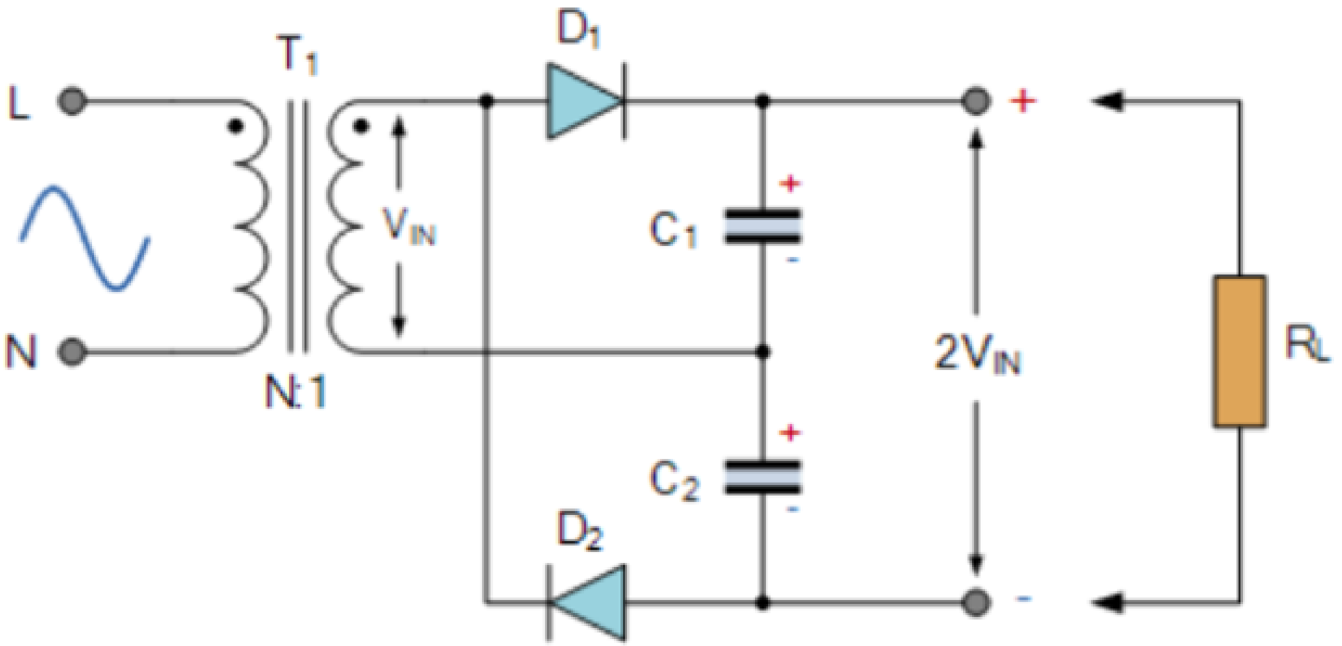
voltage decreases with an R-C time constant until ωt = π +α

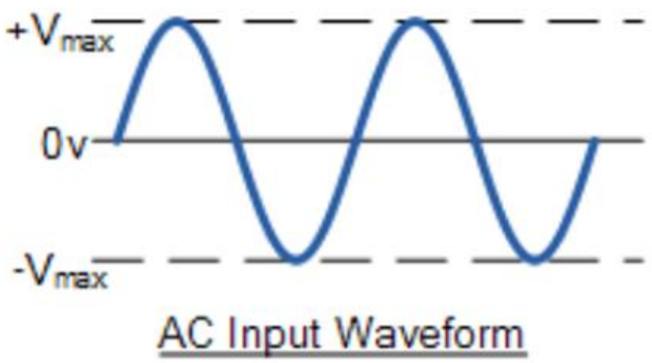


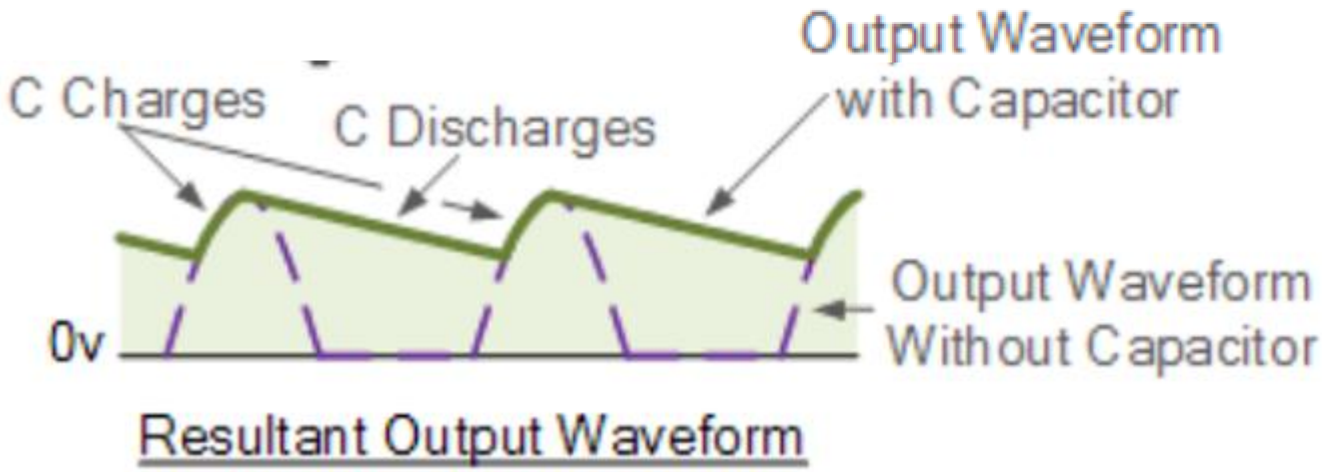
Single-phase full-wave bridge rectifier circuit with a C-filter



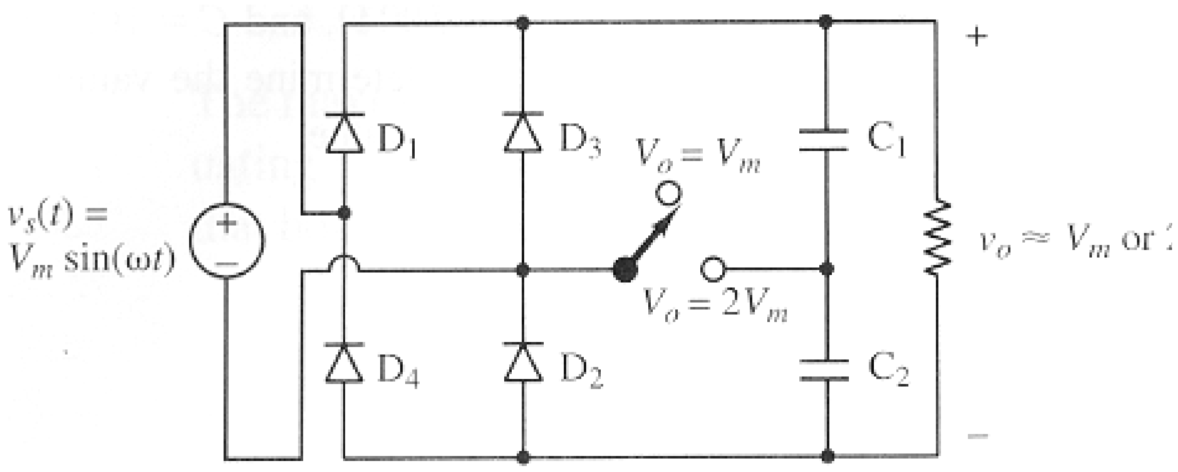
TRANSFORMER COUPLED VOLTAGE DOUBLER



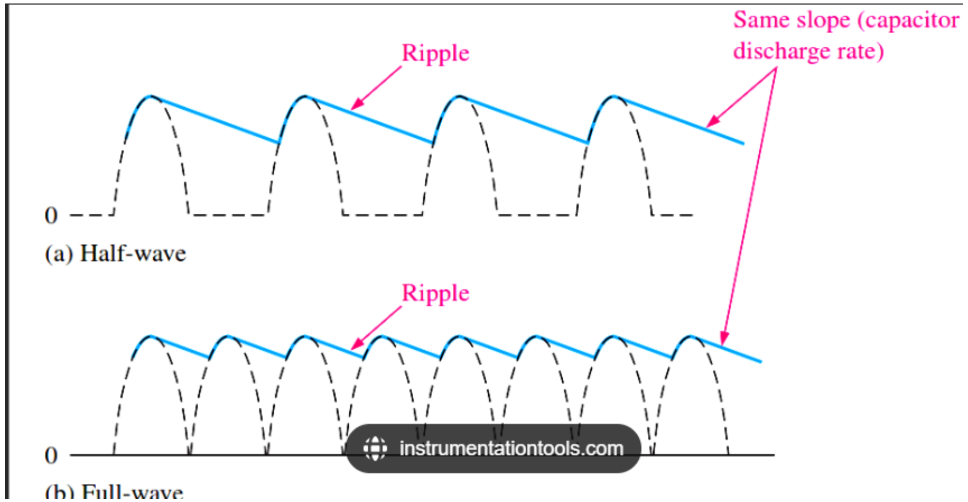




Voltage Doubler



Dual voltage rectifier = full-wave rectifier (sw. open) +voltage Doubler (sw. closed)



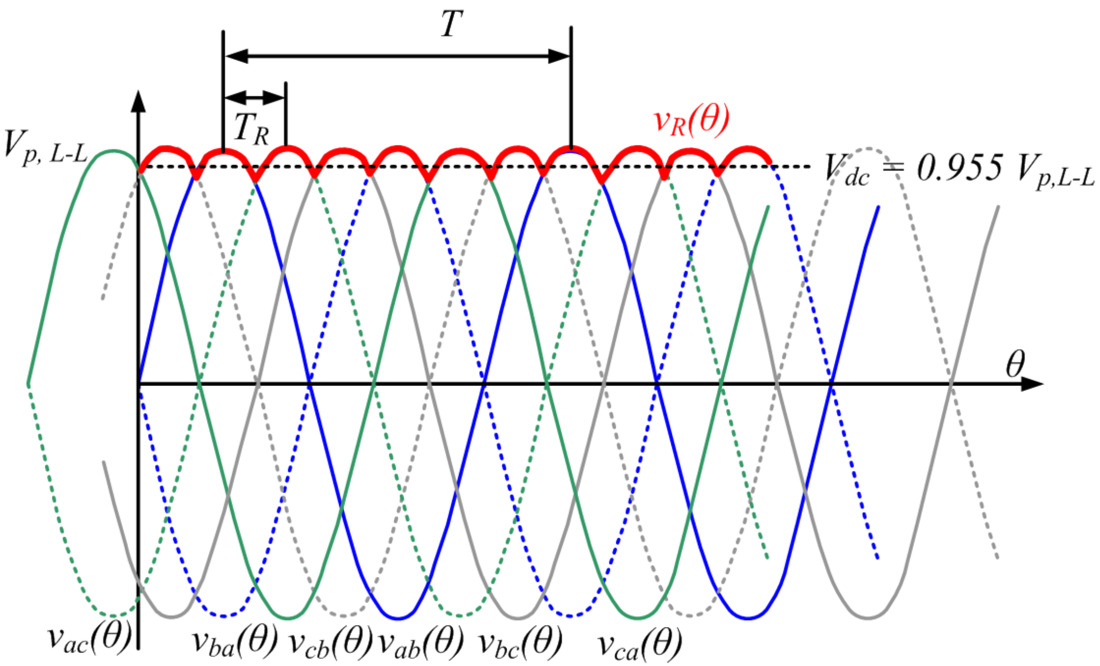
US Voltages 90VRMS-132VRMS
Switch closed Vo=2*SQRT(2)* VRMS
= 254V DC to 373 VDC

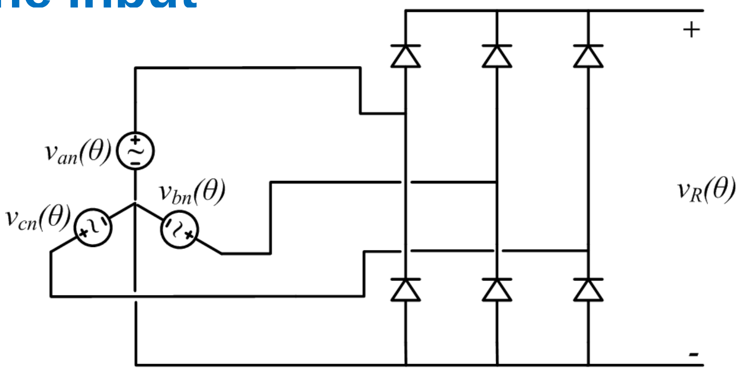
Europe 230V+/- 23V VRMS
Switch open Vo=SQRT(2)* VRMS
= 293V DC to 348 VDC

Three-phase Bridge Rectifier with Resistive Load

6 DIODES!

- The output voltage ripple frequency is six times that of the input voltage waveforms (60 degree intervals * 6 per cycle).





Supply Voltages Phase to Neutral (Peak):

$$v_a = \sqrt{2}V_{PH}\sin(\omega t)$$

$$v_b = \sqrt{2}V_{PH}\sin(\omega t - 2\pi/3)$$

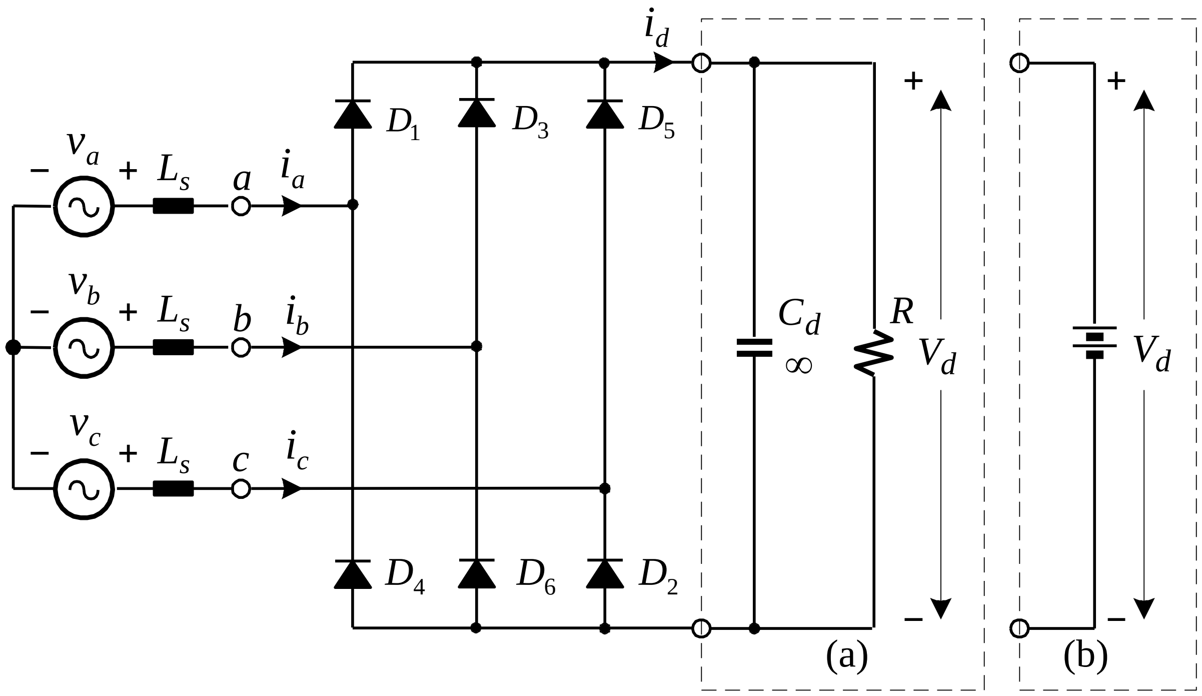
$$v_c = \sqrt{2}V_{PH}\sin(\omega t - 4\pi/3)$$

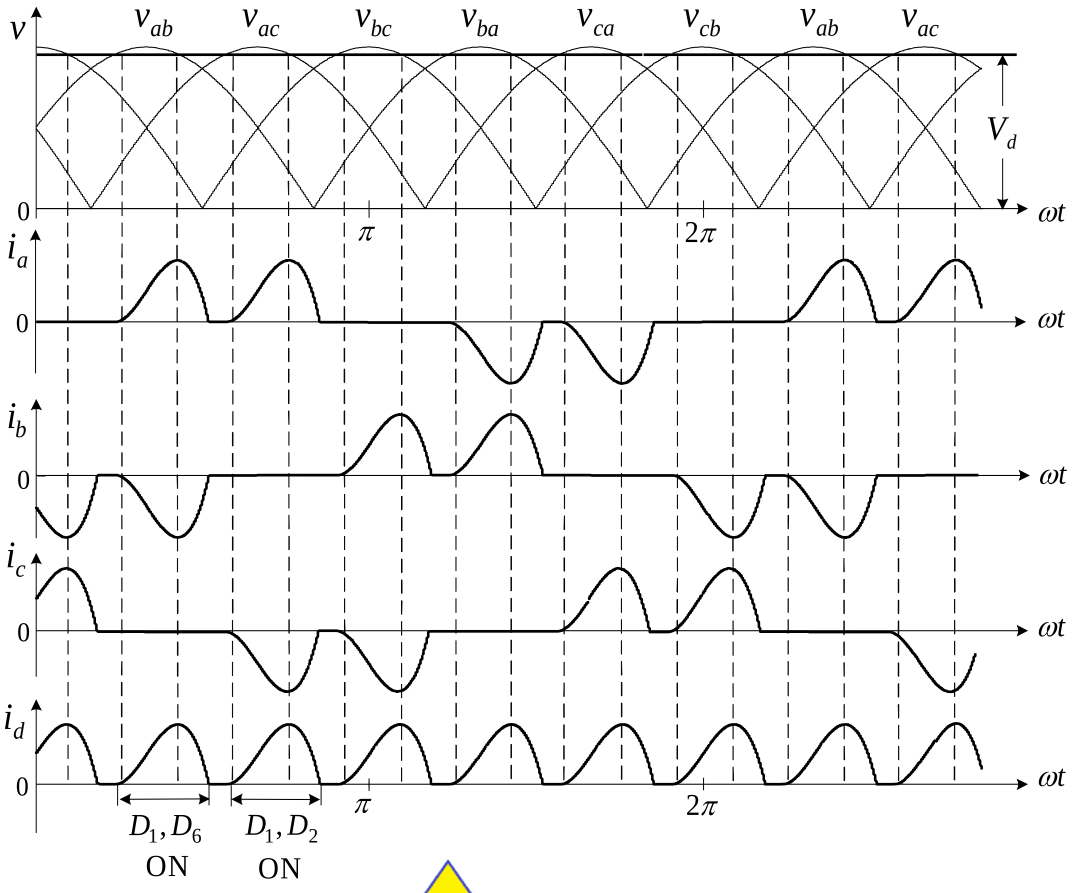
Vdc = 0.955* SQRT(6) * 115V RMS = 270VDC

$$V_{dc} = \frac{1}{T_R}\int_0^{T_R} v_R(t)dt = \frac{V_{p,L-L}}{2\pi/6}\int_{\pi/3}^{2\pi/3}\sin(\theta)d\theta = \frac{3V_{p,L-L}}{\pi} = 0.955V_{p,L-L} = \frac{3\sqrt{3}V_{p,L-n}}{\pi}$$

= 0.955* SQRT(6) * VRMS (L-N)

- **Capacitive + Resistive Load**





Assumption:

$$C_d = \infty \Rightarrow V_d = \text{constant}$$

Input Current Looks like a sinewave cap

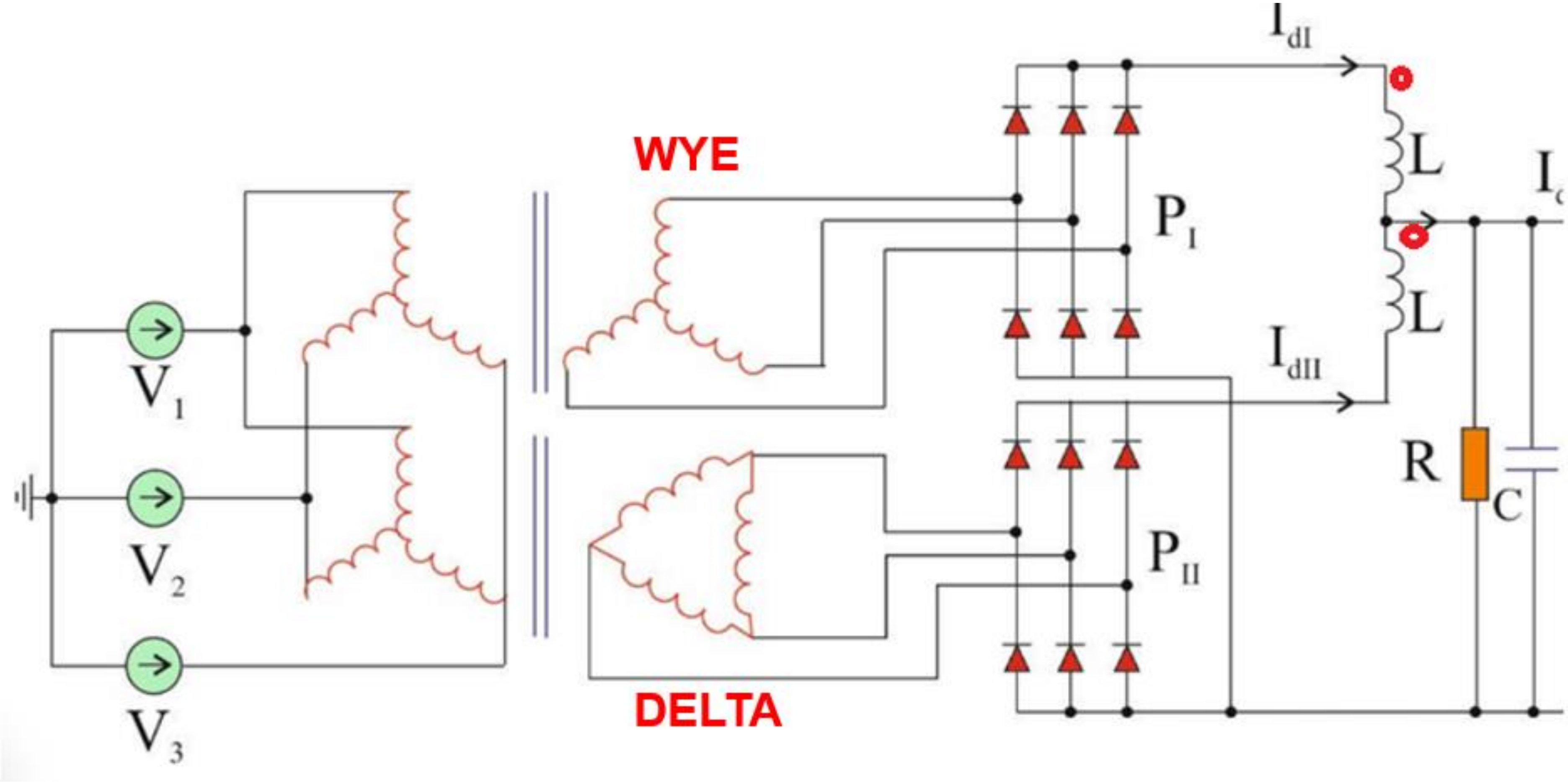
Multi-pulse Diode Rectifiers

Why Use Multi-pulse Diode Rectifiers?

- To reduce line current THD;
- To improve input power factor; and
- To avoid semiconductor devices in series.

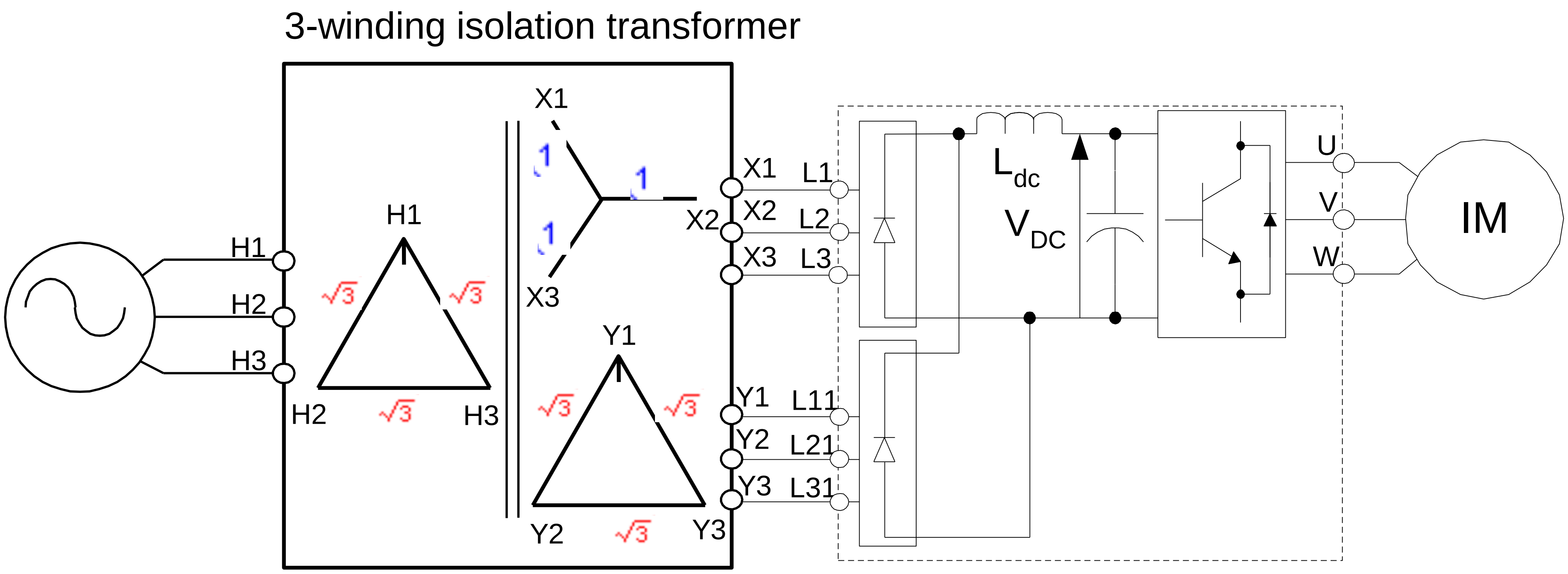
Three Phase Transformer Rectifier Supply

- The output voltage ripple frequency is 12 times that of the input voltage waveforms.

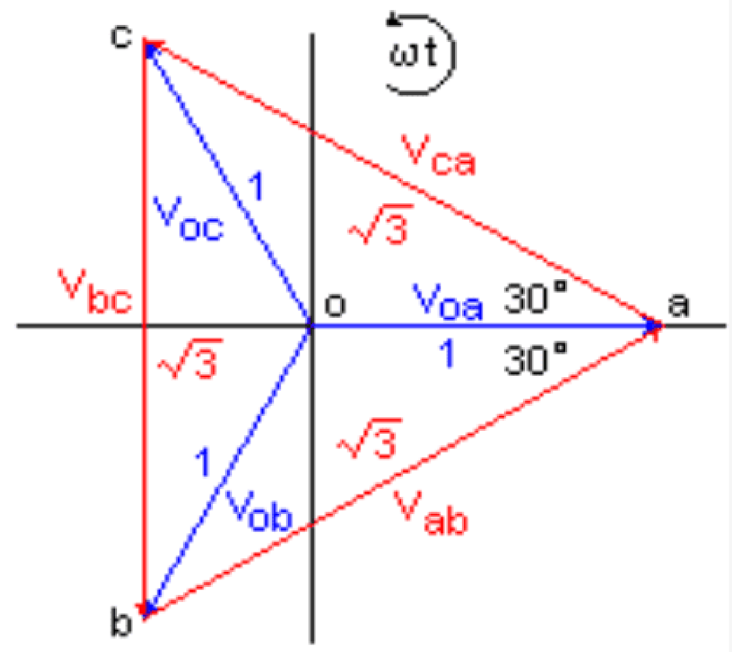


Three Winding 12-pulse Scheme (Transformer Rectifier)

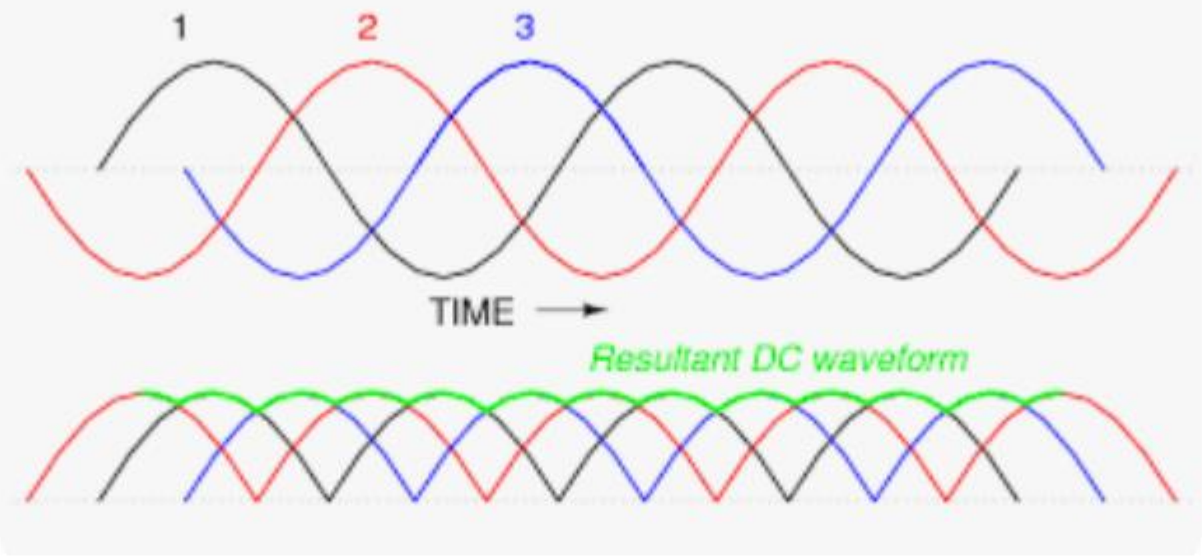
- Rated for full power operation – bulky but ONLY option when input is medium voltage and drive is of low voltage rating (very high power applications)



30 Degree Phase Shift between Delta and Wye



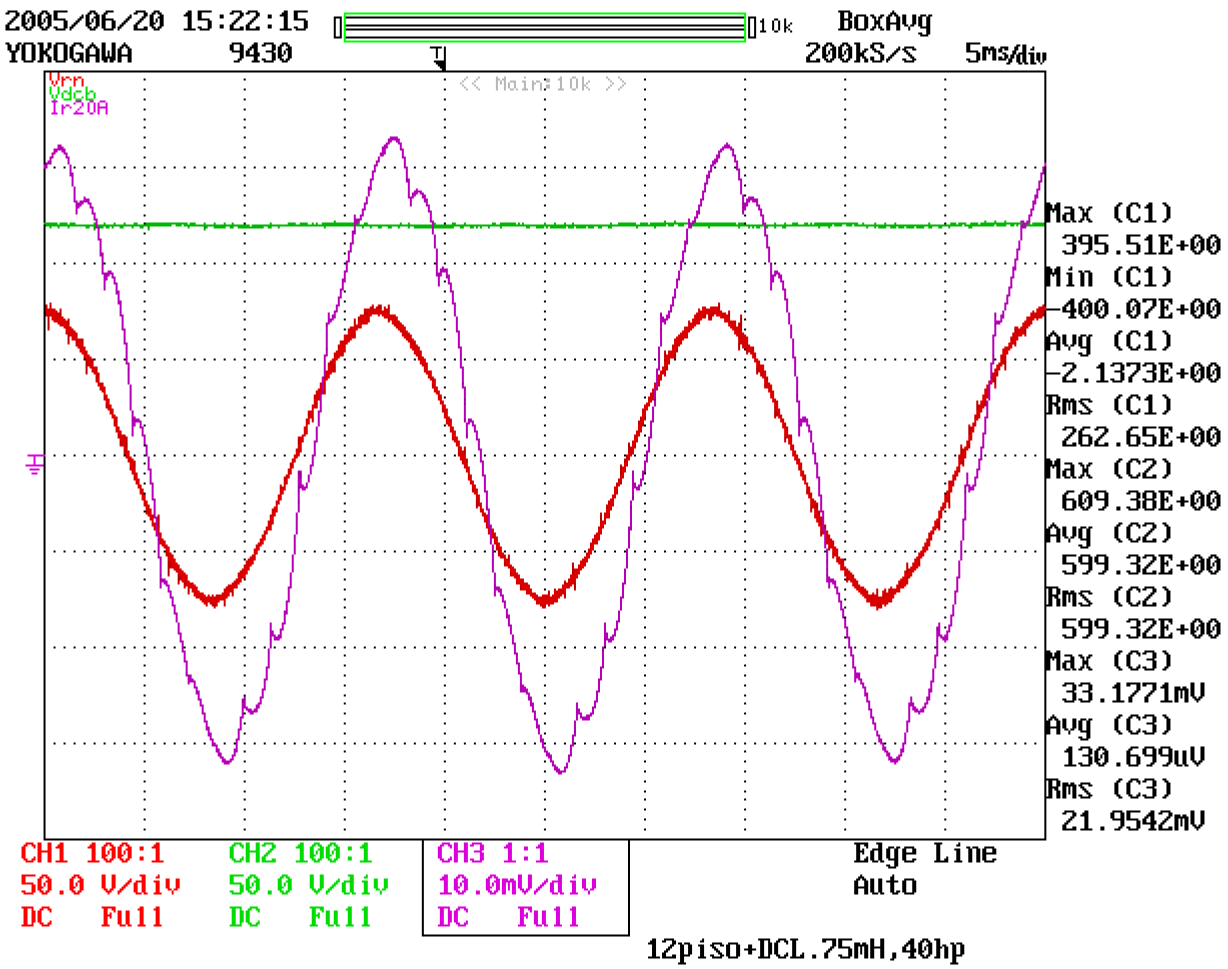
Three-Phase Wye and Delta



**With turns ratio Equalized

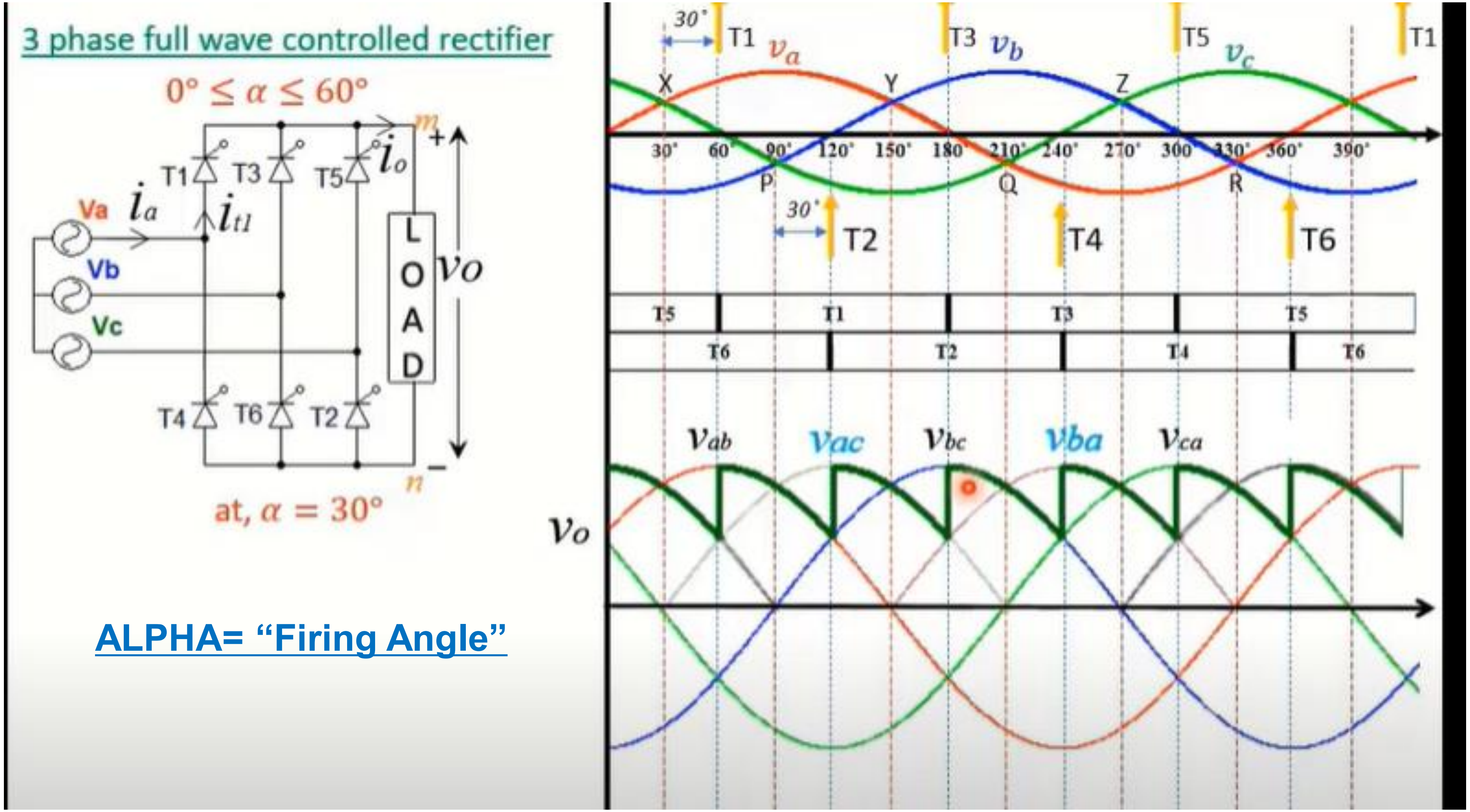
Line-to-neutral voltages are in blue and line-to-line voltages in red. Note that the magnitude of the line-to-line is $\sqrt{3}$ times larger, and ±30 degrees different in phase compared to line-to-neutral.

Three Winding 12-Pulse Waveforms



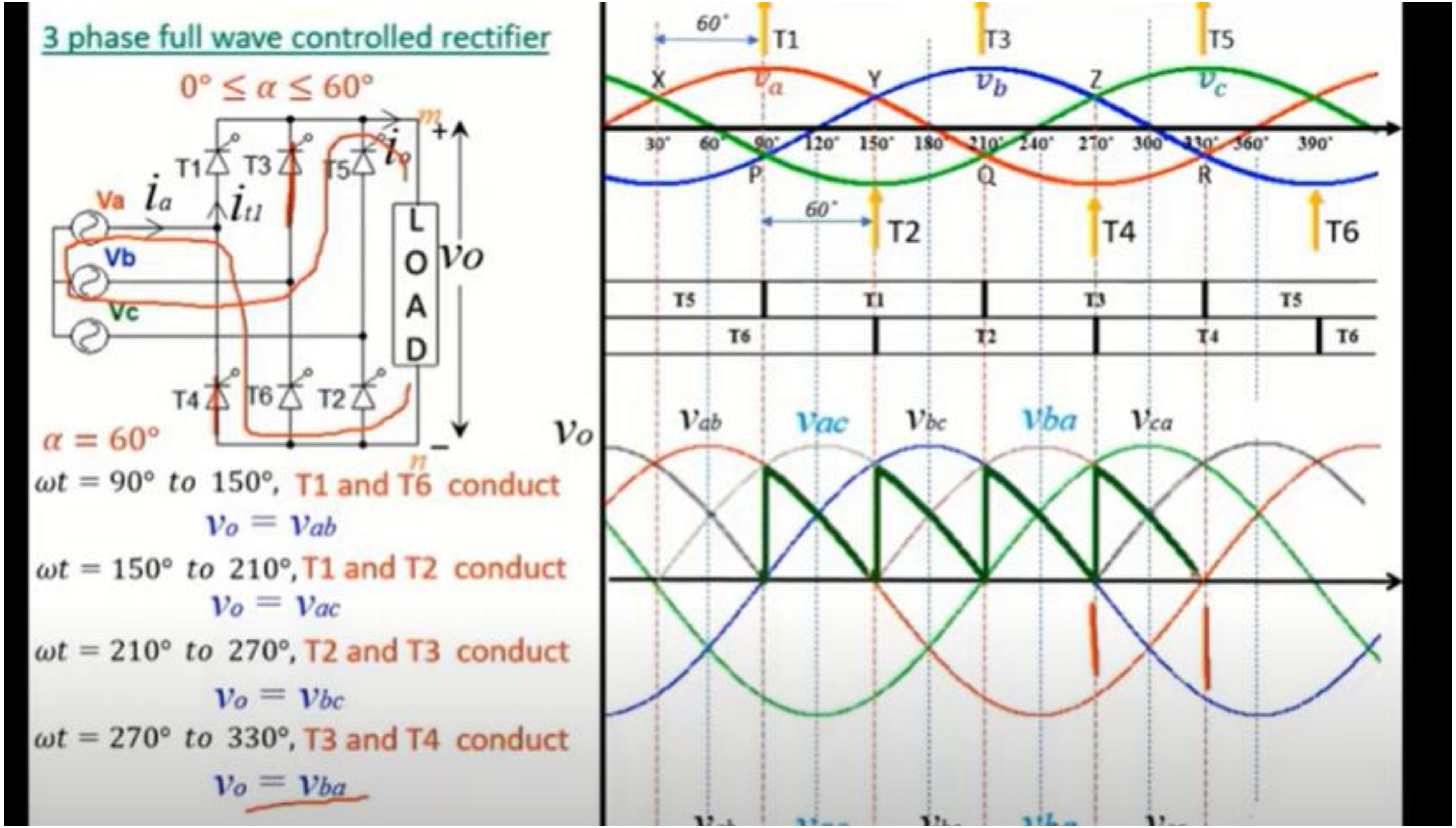
Load= 40hp
THD= 13.4%

Example: Three Phase 6-PULSE SCR Rectifier Supply (Alpha=30 degrees)



ALPHA= "Firing Angle"

Three Phase 6-PULSE SCR Rectifier Supply (Alpha=60 degrees)



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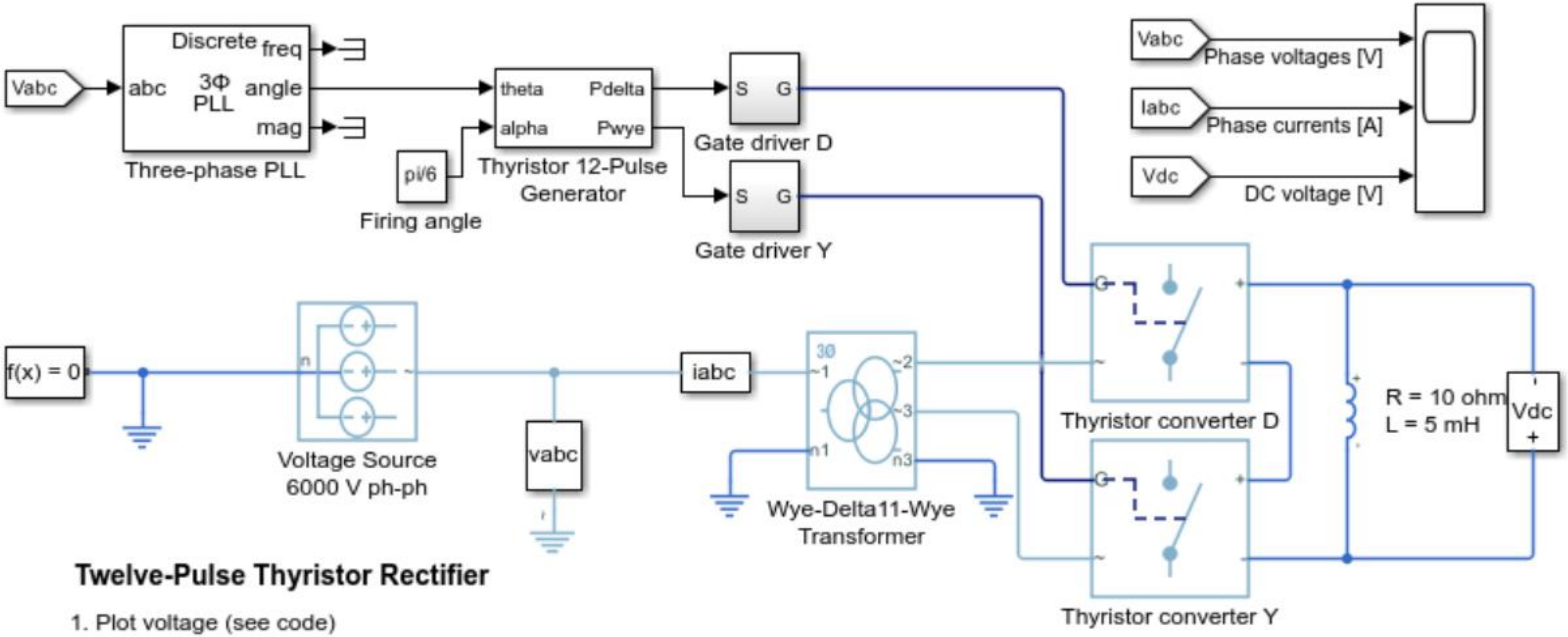
Programmable Three Phase 12-Pulse SCR Supply (MATLAB)

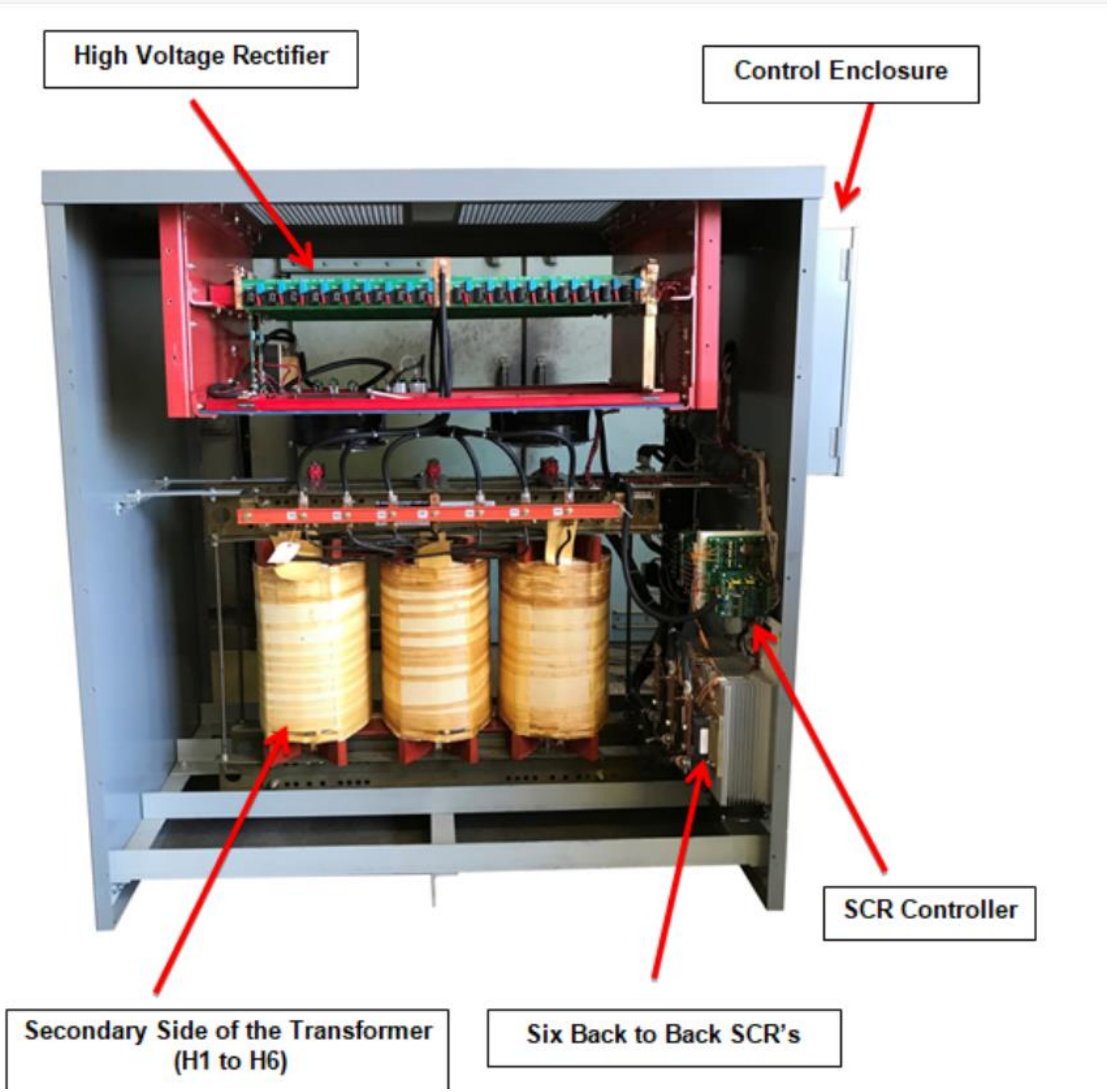
Model



Twelve-Pulse Thyristor Rectifier

1. Plot voltage (see code)
2. Explore simulation results using Simscape Results Explorer
3. Learn more about this example

Example: Three Phase 6 Pulse SCR Rectifier Supply



Linear Supplies

Why Use Linear Supplies?

- Simplicity
- Low Noise
- Reliability
- Low Cost
- Feedback Loop: Easy to Control

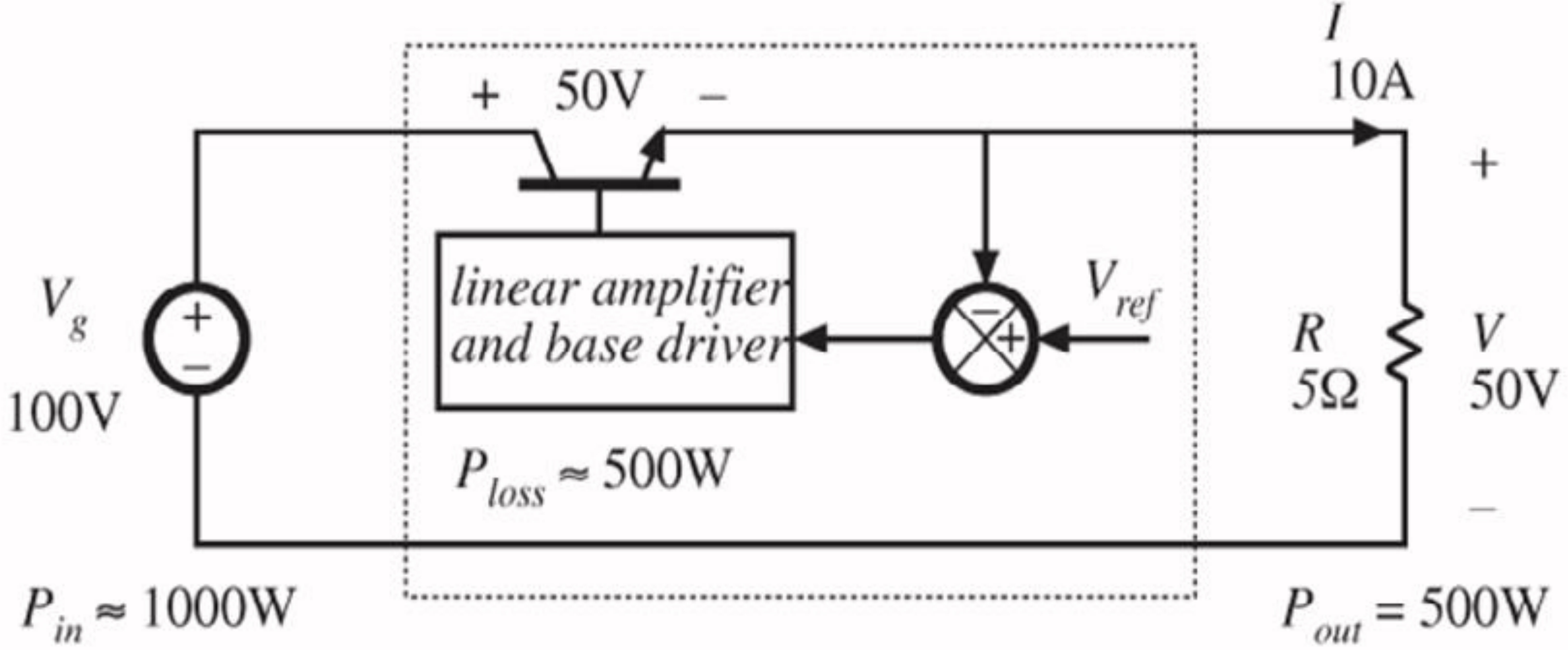
Disadvantages?

- Poor SWAP (Size, Weight and Power)
- Poor Efficiency

Low Efficiency of Linear Regulators

Dissipative realization

Series pass regulator: transistor operates in active region



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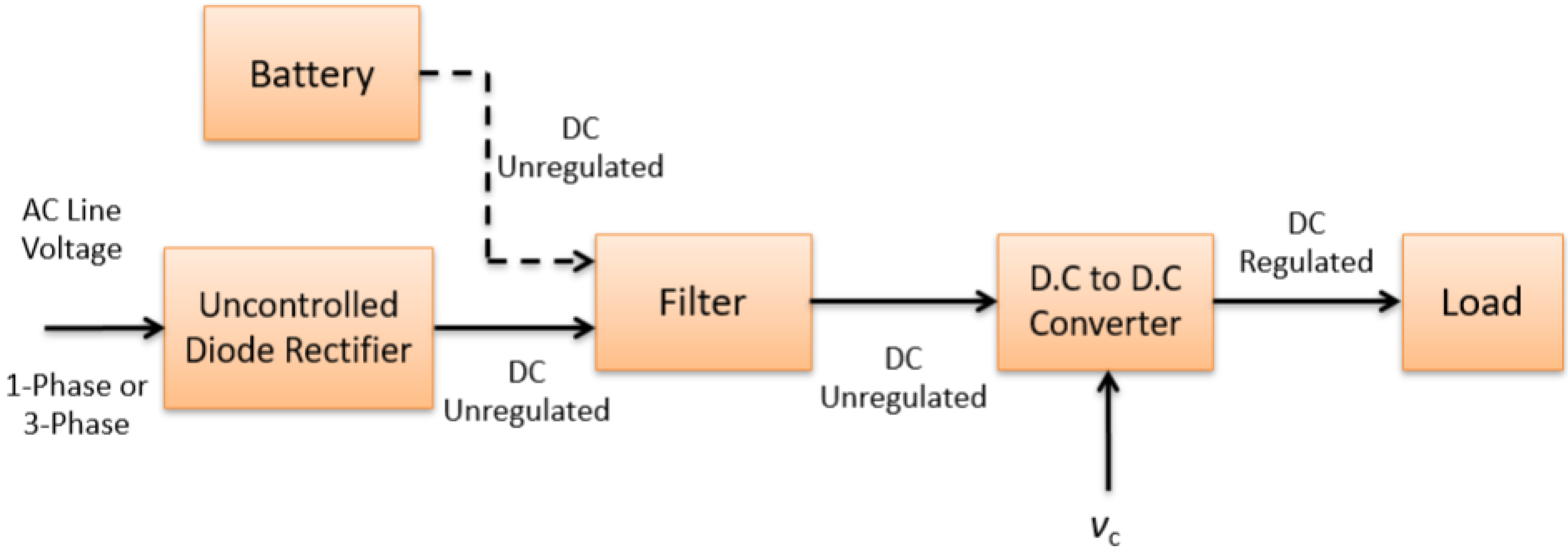
Introducing the Switch-Mode Supply

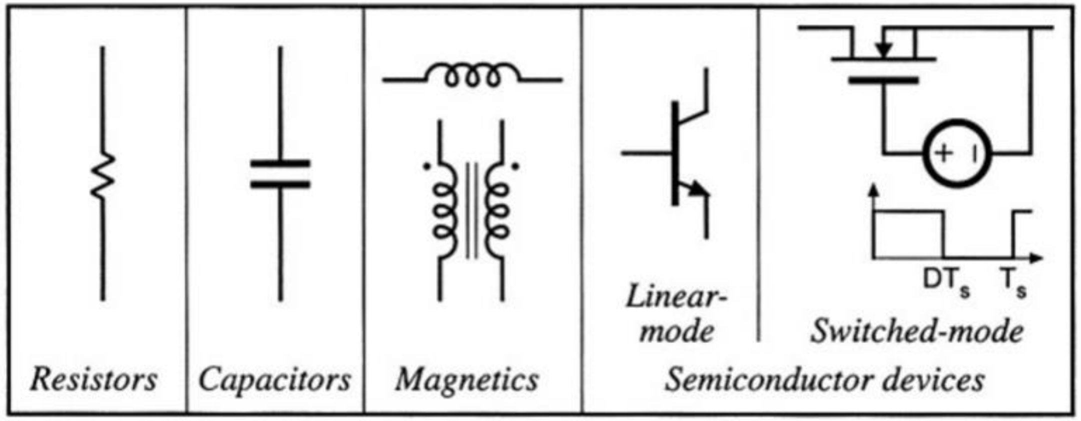


D.C to D.C Converter System

Typical Switch-mode Supply Topology Components

Efficiency & Power Losses

- The various conventional circuit elements are illustrated in Following figure.



- The available circuit elements fall broadly into the classes of resistive elements, capacitive elements, magnetic devices including inductors and transformers, semiconductor devices operated in the linear mode and semiconductor devices operated in the switched mode.

Maxwell's Equations

$$\oint_S \mathbf{E} \cdot d\mathbf{A} = \frac{q}{\varepsilon_o}$$ Gauss's law (electric) ⇨ electrostatic case

~~$$\oint_S \mathbf{B} \cdot d\mathbf{A} = 0$$ Gauss's law in magnetism~~ Don't need

Maxwellian Electrodynamics ⇩

⇨ V=L*dI/dt

$$\oint \mathbf{E} \cdot d\mathbf{s} = -\frac{d\Phi_B}{dt}$$ Faraday's law

volts

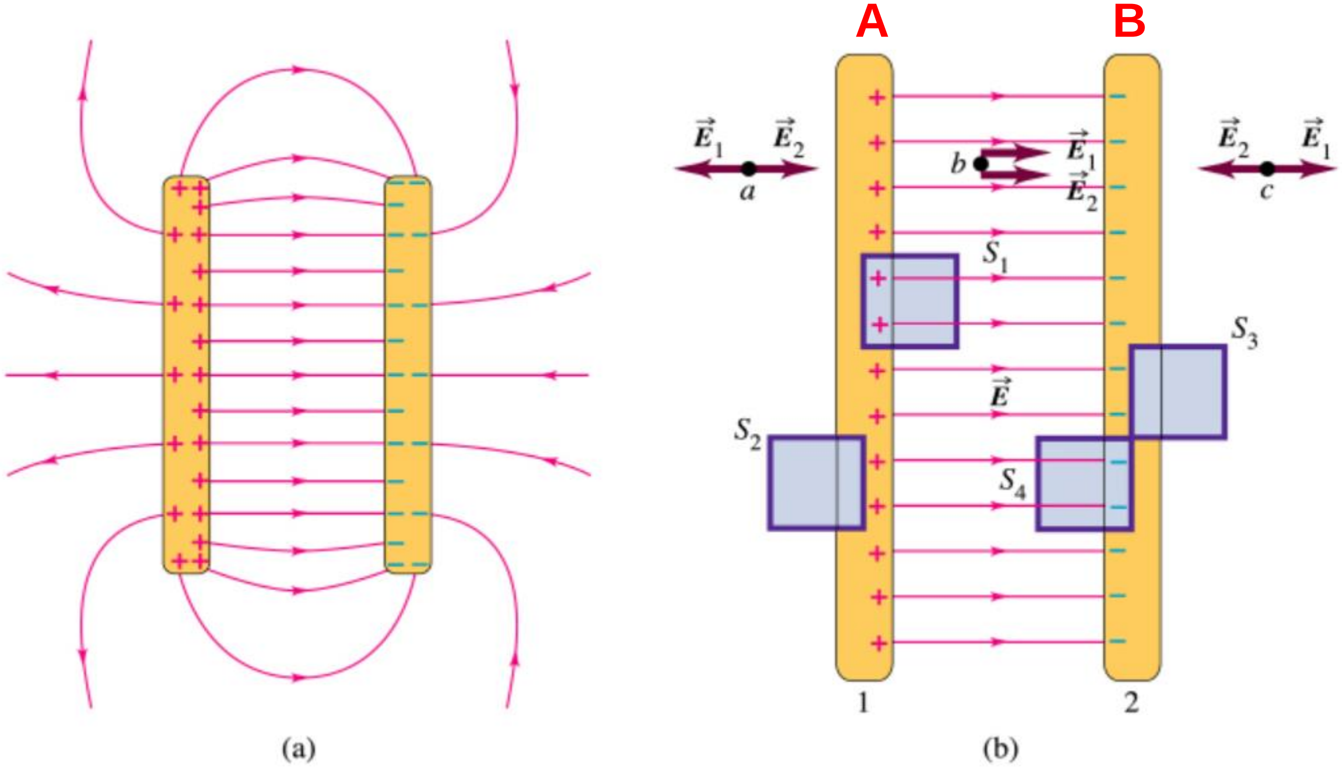
⇨ I=C*dV/dt

$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_o I + \varepsilon_o \mu_o \frac{d\Phi_E}{dt}$$ Ampere-Maxwell law

Basic Physics of a Capacitor

GAUSS's LAW

$$\oint_{S_1} \vec{E}\cdot dA = EA = \frac{\sigma A}{\varepsilon_0}$$



$$V_B - V_A = -\int_A^B \vec{E}\cdot d\vec{l},$$

$$\varepsilon = \varepsilon_0 \varepsilon_r;$$

$$C = \varepsilon \frac{A}{d};$$

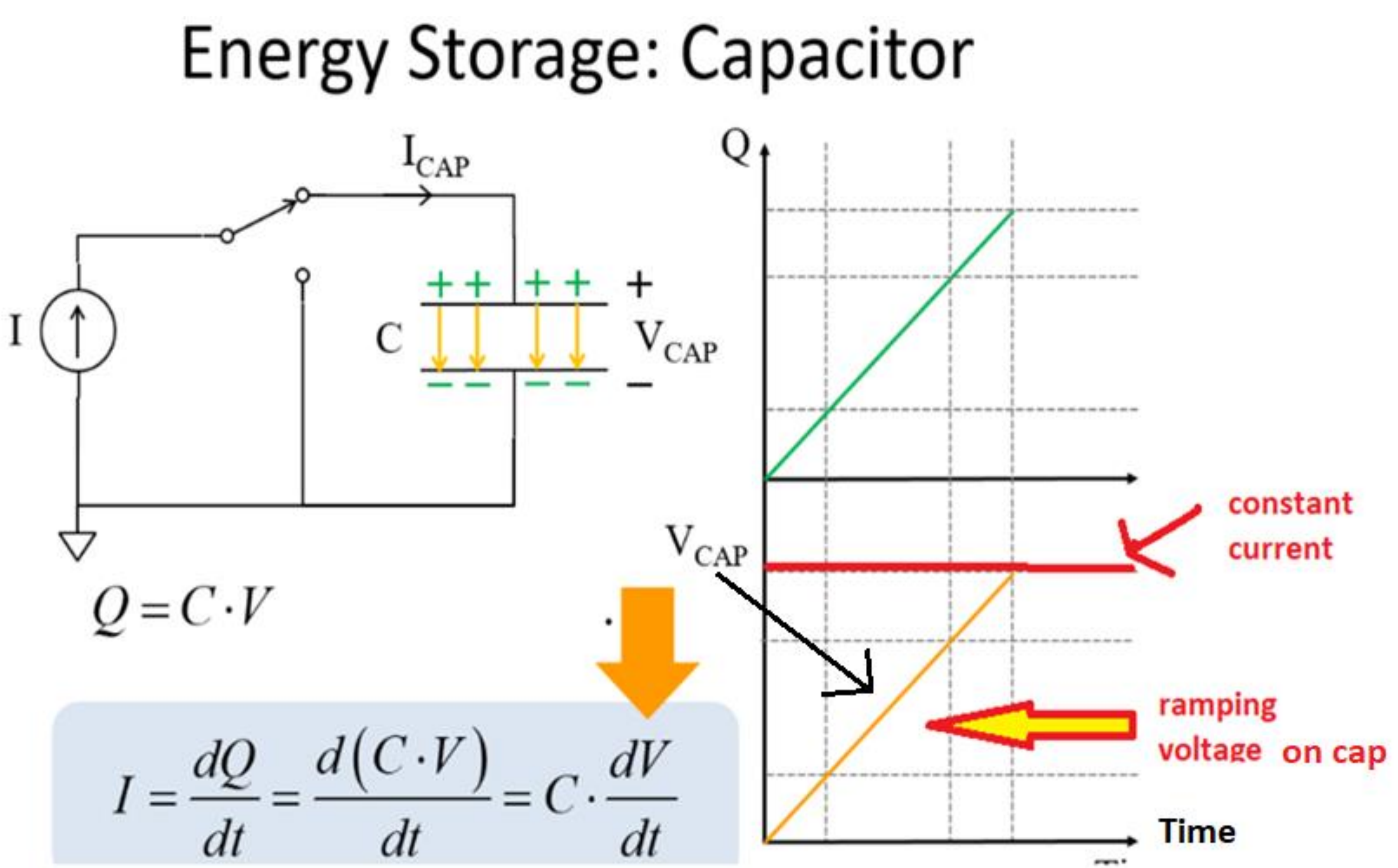
- Q = CV

$$1\,F = \frac{1\,C}{1\,V}.$$

$$i = C\frac{dv}{dt} = C*(\text{rate of change of voltage})$$

$$I = \frac{dq}{dt}$$

Waveforms of a Capacitor

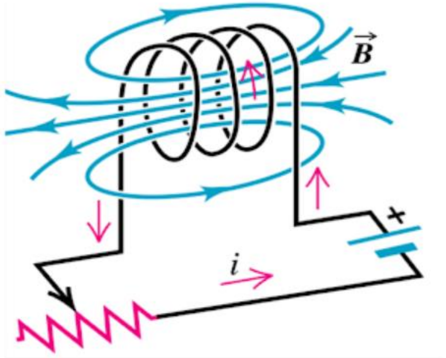


$$Q = C \cdot V$$

$$I = \frac{dQ}{dt} = \frac{d(C \cdot V)}{dt} = C \cdot \frac{dV}{dt}$$

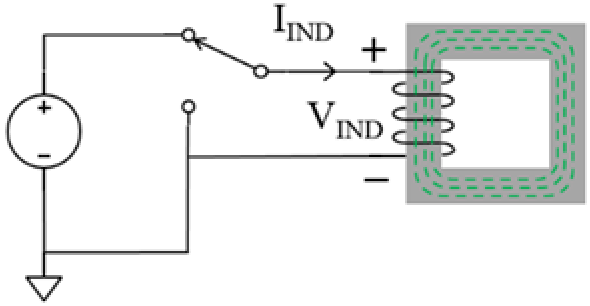
Basic Physics of an Inductor

Self Induction – the production of e.m.f. in a circuit due to the change of current in the circuit itself



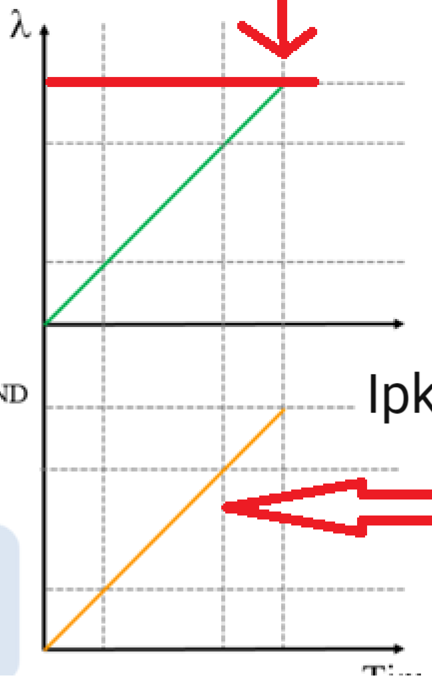
- Running a changing current (by changing R), creates a changing magnetic field, which creates an induced emf that fights the change
- Unit: Henry (V s A^{-1})

Energy Storage: Inductor



$$\lambda = L \cdot I \qquad E = \frac{1}{2} \cdot L \cdot I^2$$

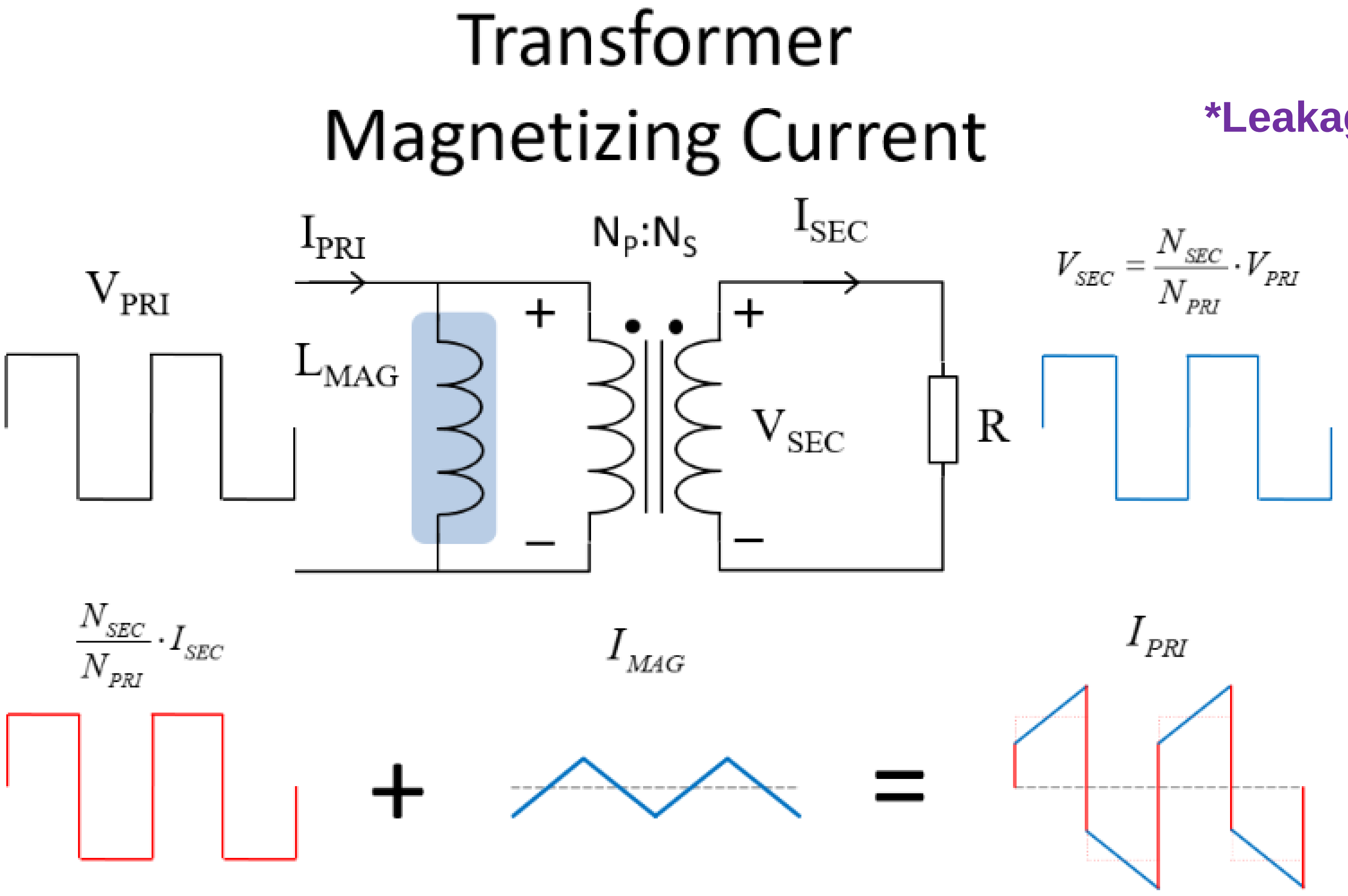
$$V = \frac{d\lambda}{dt} = \frac{d(L \cdot I)}{dt} = L \cdot \frac{dI}{dt}$$



NOTE: Real Inductor has series R which makes the current follow an exponential rather than linear function

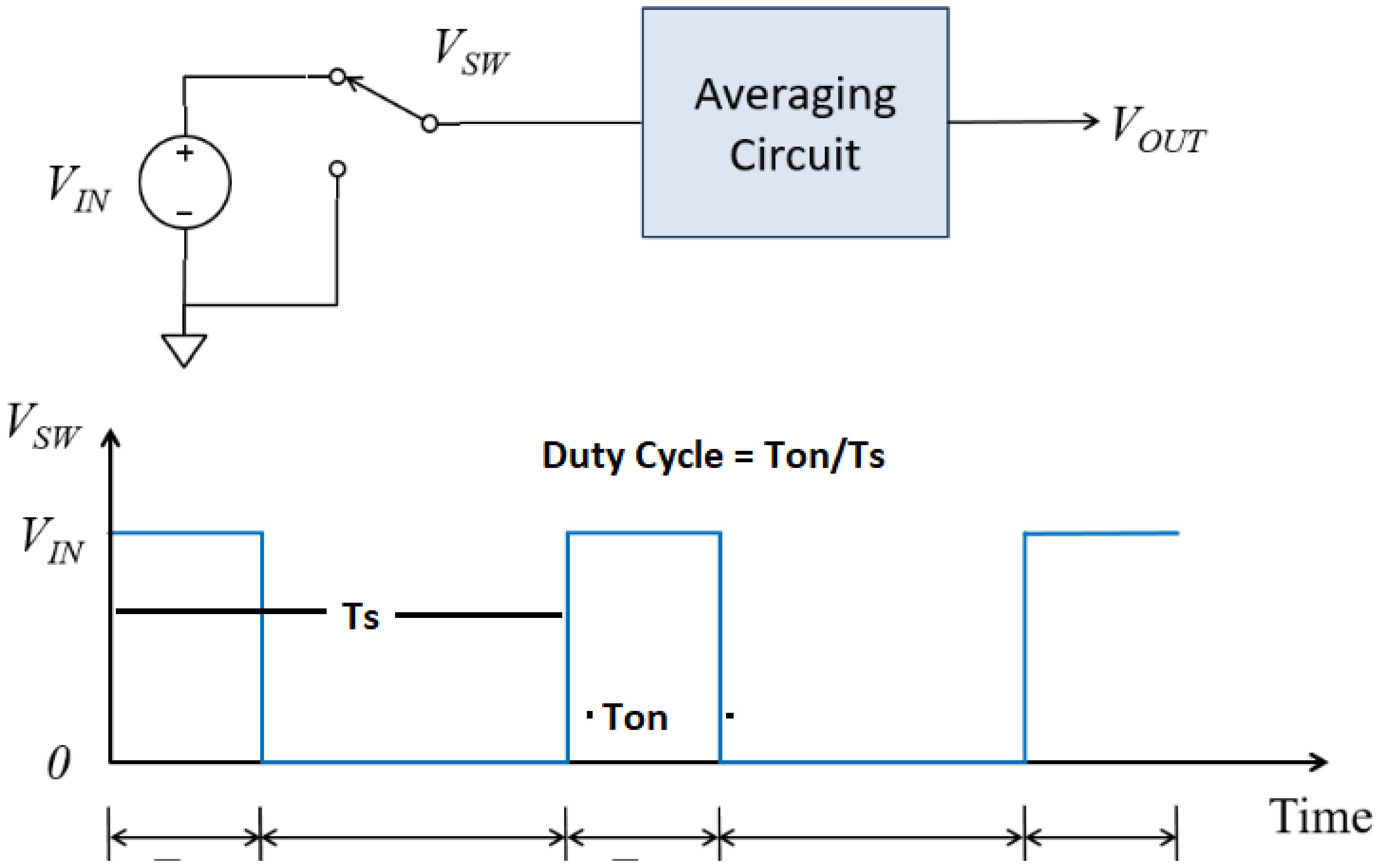
Basic Physics of an Transformer

*Leakage Inductance Omitted



Basic Switch-Mode Concept

Switch Mode Concept



D = switch duty cycle
$0 \leq D \leq 1$

T_s = switching period

f_s = switching frequency
$= 1 / T_s$

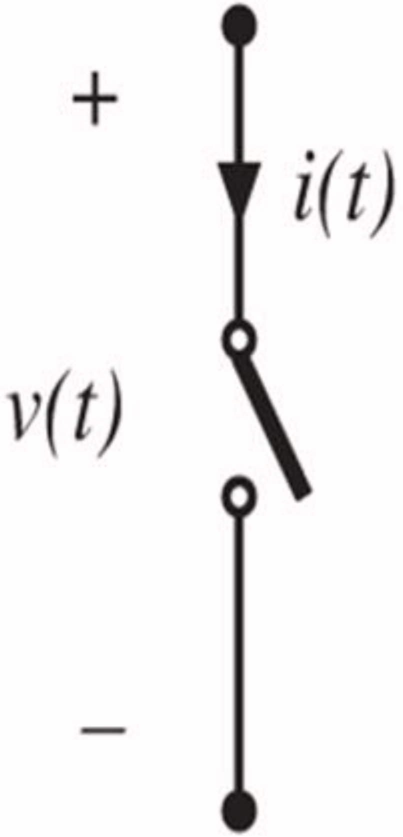
Power Loss in an Ideal Switch:

Switch closed: $v(t) = 0$

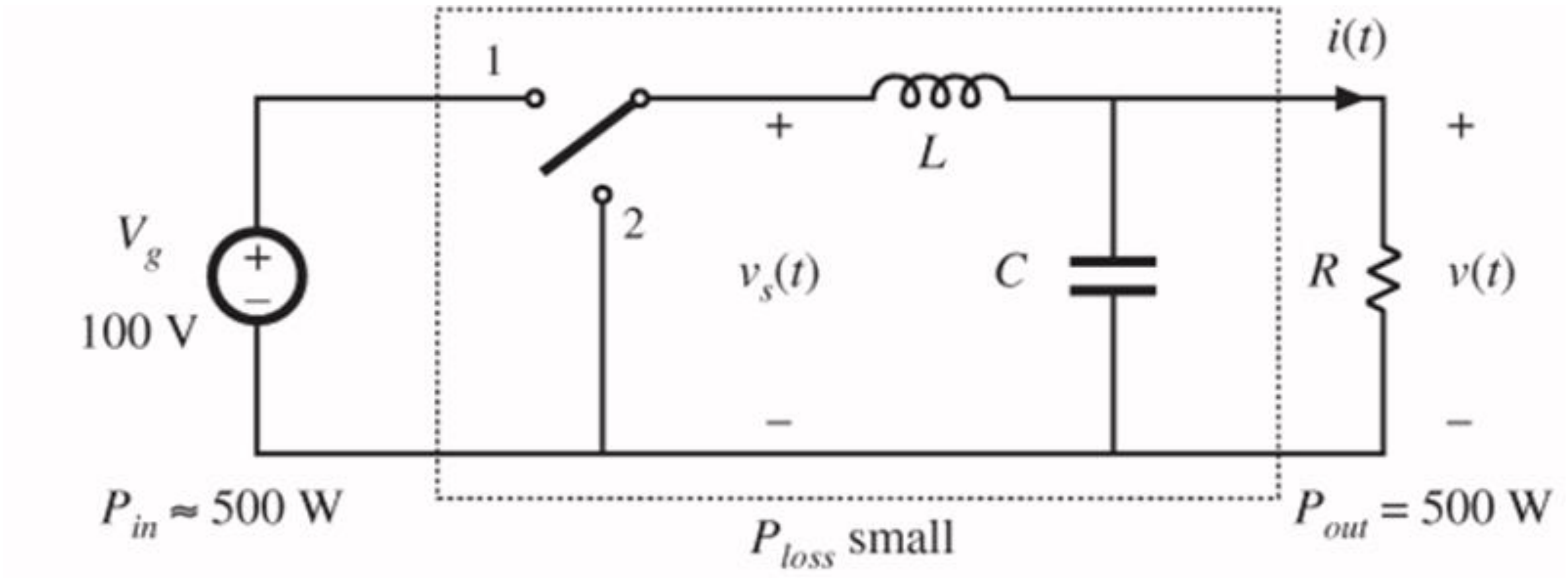
Switch open: $i(t) = 0$

In either event: $p(t) = v(t)\, i(t) = 0$

Ideal switch consumes zero power



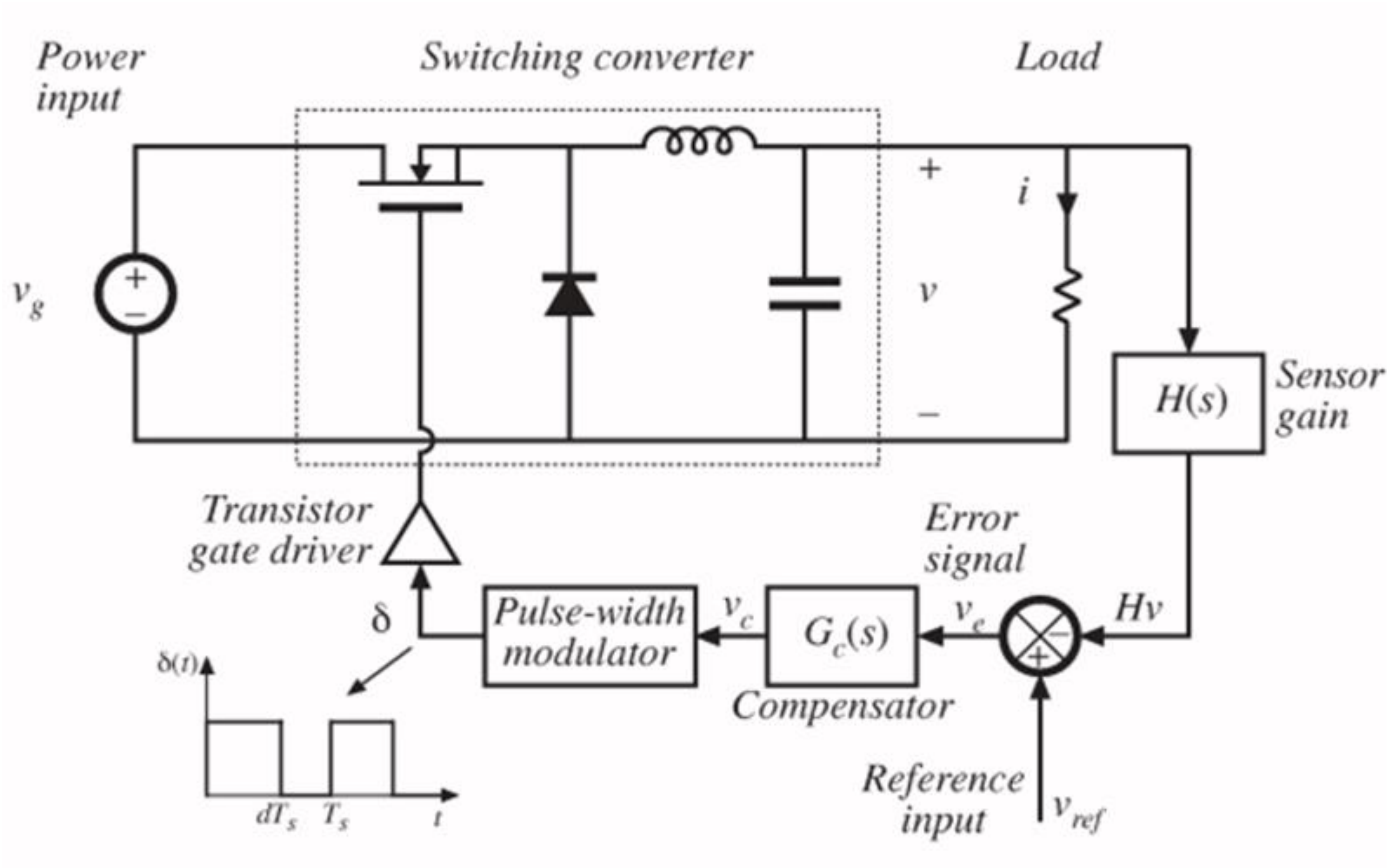
Now Add a Lossless L-C Low Pass Filter



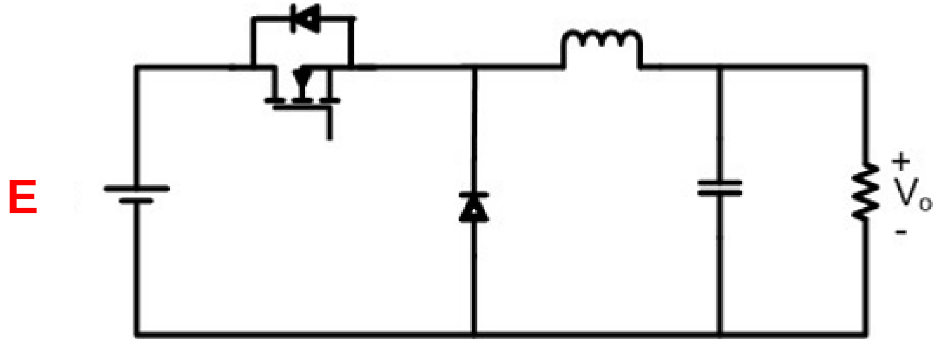
***Filter cutoff frequency is chosen to be significantly smaller than the Switching Frequency.*

This is called the "Buck Converter" in which we now have a "clean" DC output voltage!

Addition of Control System for Regulation of Output Voltage

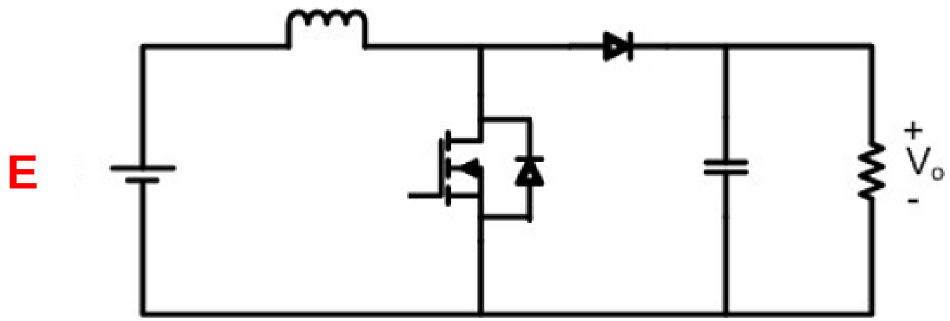


3 Basic Non-Isolated DC-DC Converters



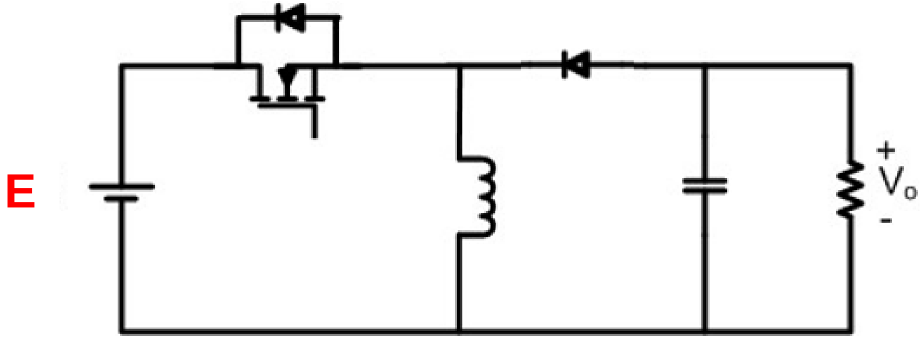
- *Buck converter*

$$V_o = DE$$



- *Boost converter*

$$V_o = \frac{E}{1-D}$$

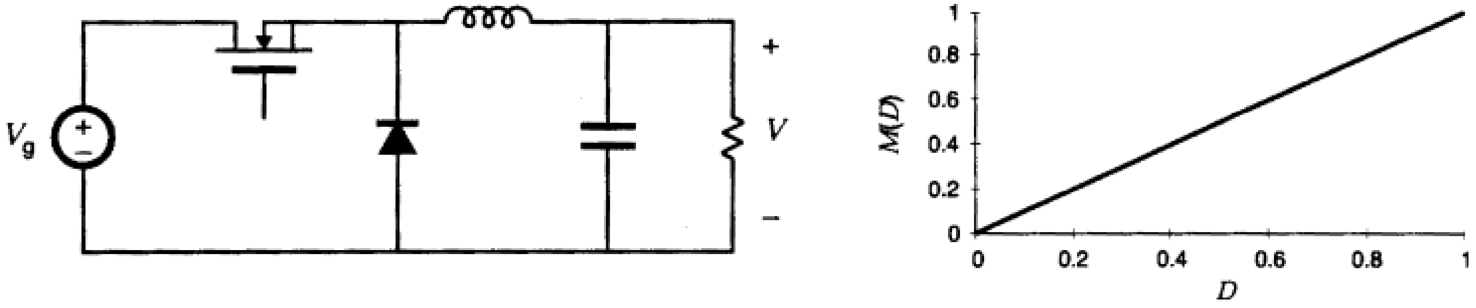


- *Buck-boost converter*

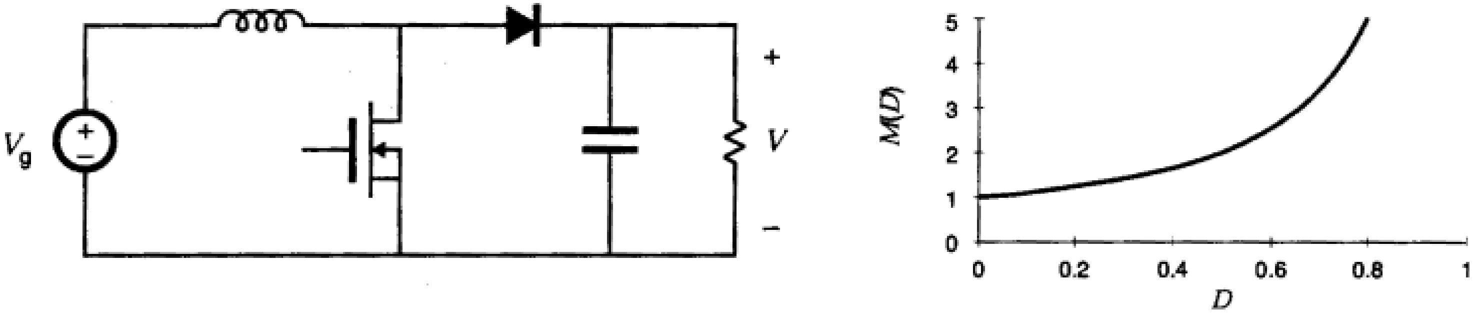
$$V_o = -\frac{DE}{1-D}$$

Non-Isolated DC-DC Converters (Continued)

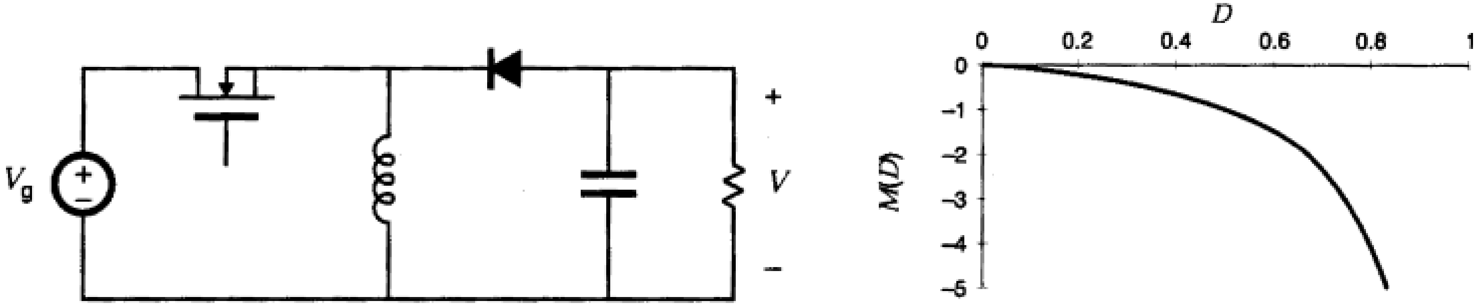
Buck converter



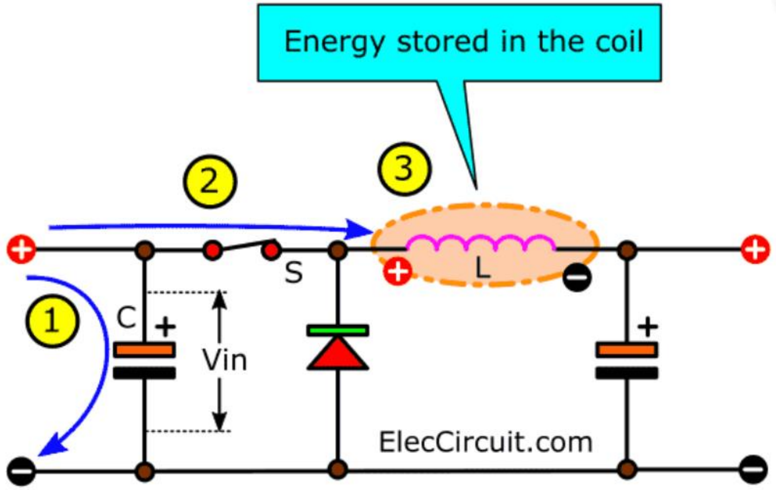
Boost converter



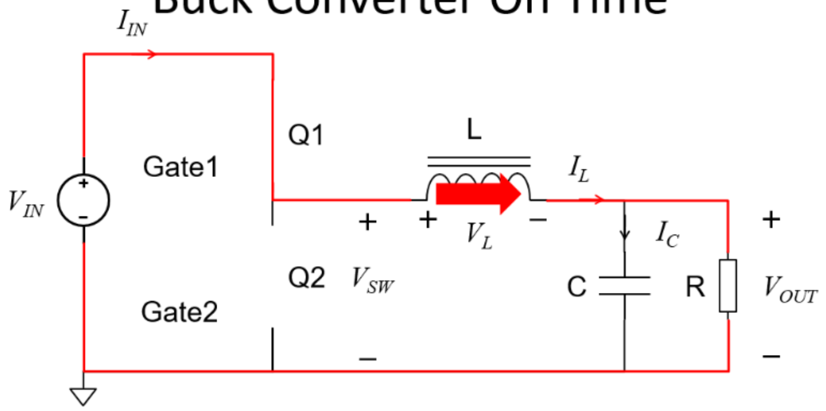
Buck-boost converter



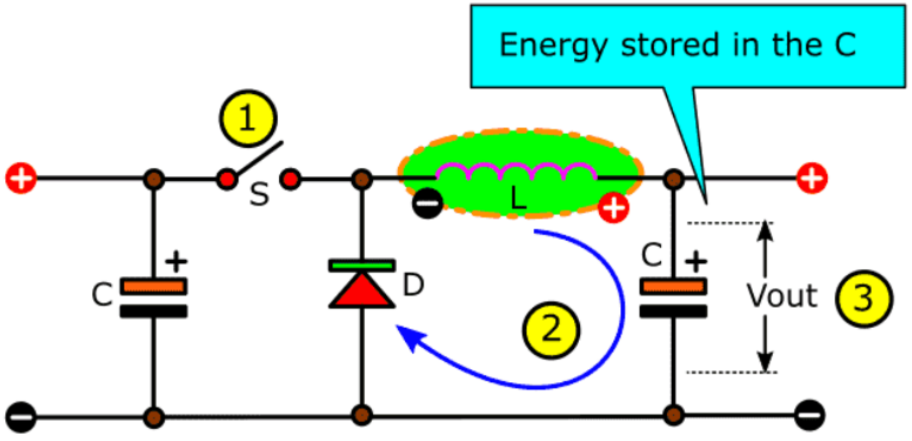
The “BUCK” - Most Basic Switch-mode Converter



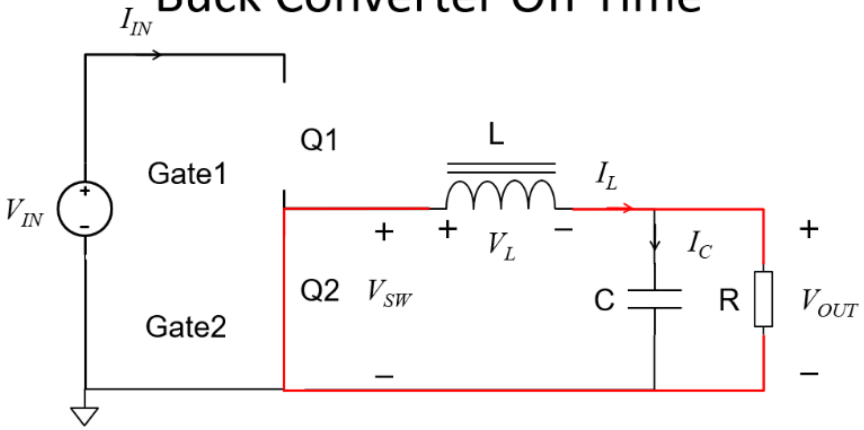
Buck Converter On Time



$$V_L = V_{IN} - V_{OUT}$$



Buck Converter Off Time

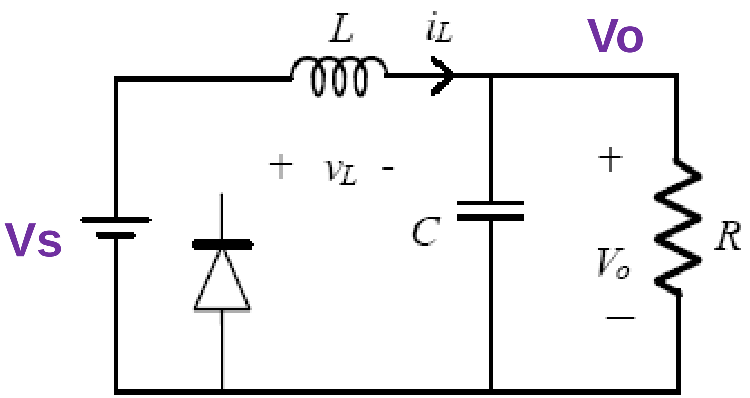


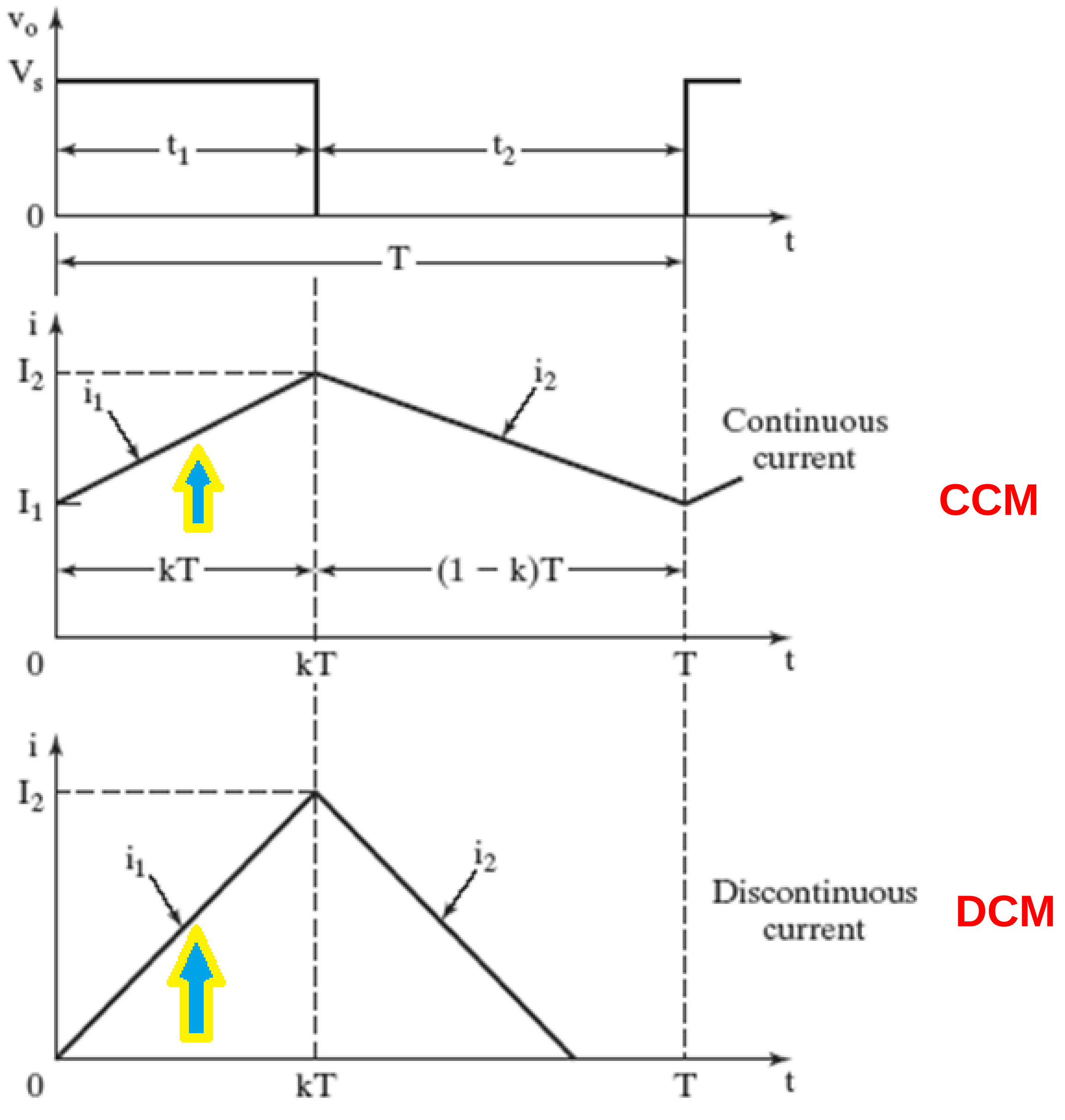
$$V_L = - V_{OUT}$$

BUCK (Continued)

Switch is CLOSED

- When switch is CLOSED
- $V_L = V_s - V_o = L\frac{di}{dt}$
- $\frac{di}{dt} = \frac{V_s - V_o}{L}$



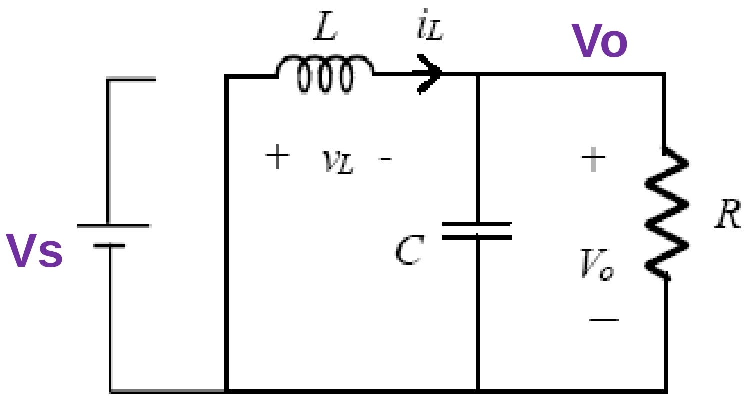


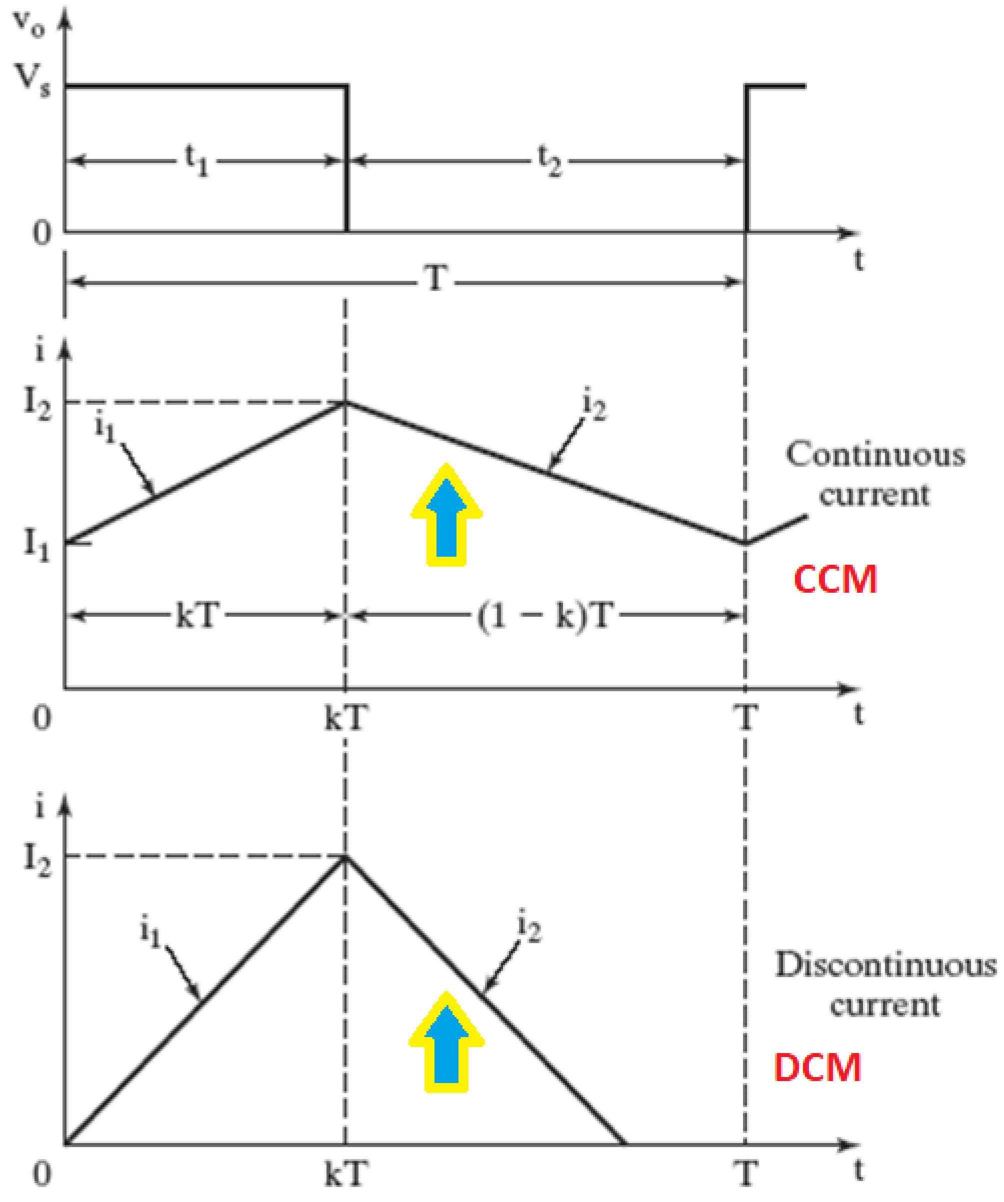
(b) Waveforms

BUCK (Continued)

Switch is OPEN

- When switch is OPEN
- $V_L = -V_o = L\frac{di}{dt}$
- $\frac{di}{dt} = -\frac{V_o}{L}$





(b) Waveforms

BUCK (Continued)

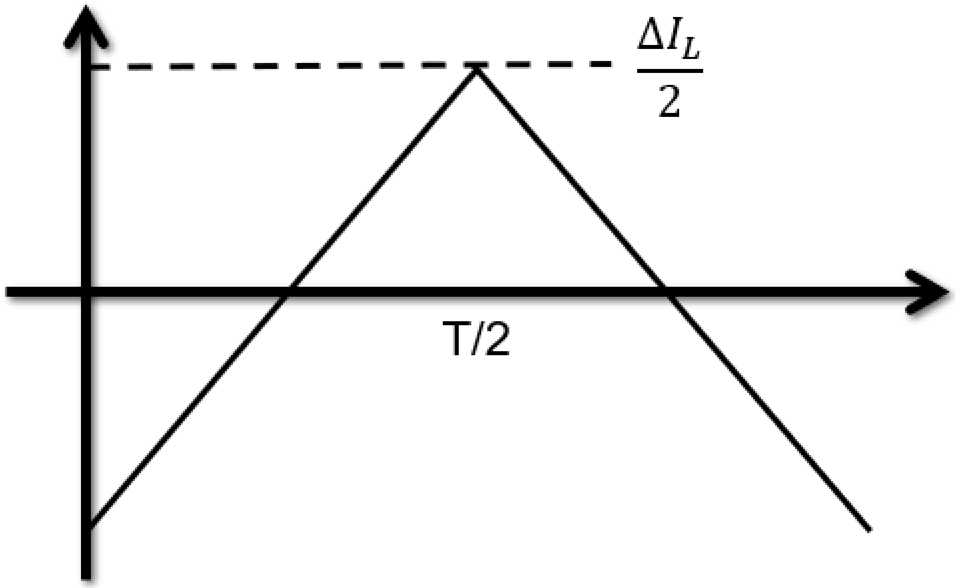
Buck Converter Math

$$V_O = DV_S$$

$$\Delta I_L = \frac{(1-D)V_o T}{L}$$

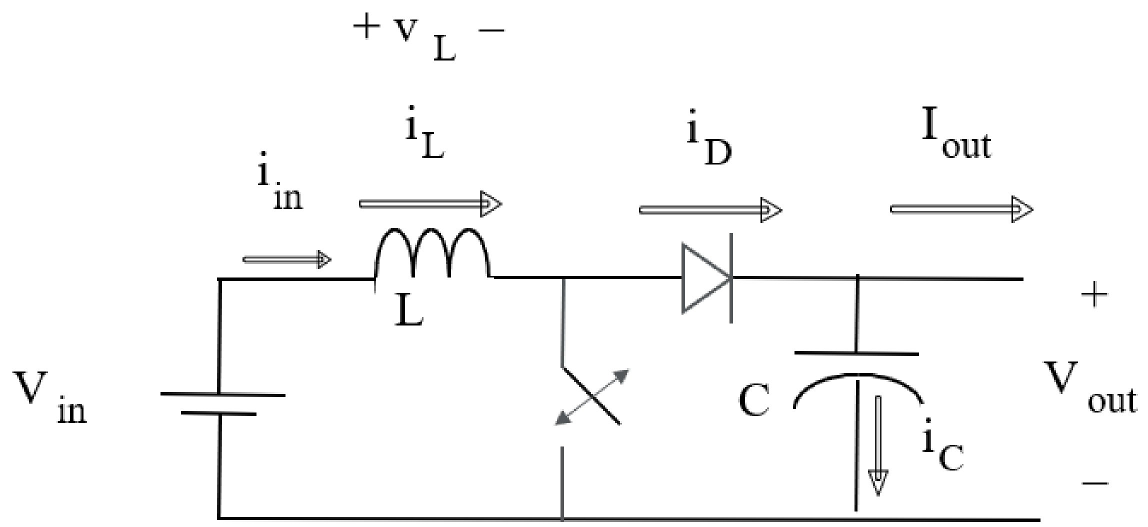
$$L_{min} = \frac{(1-D)R}{2f}$$ **for continuous operation**

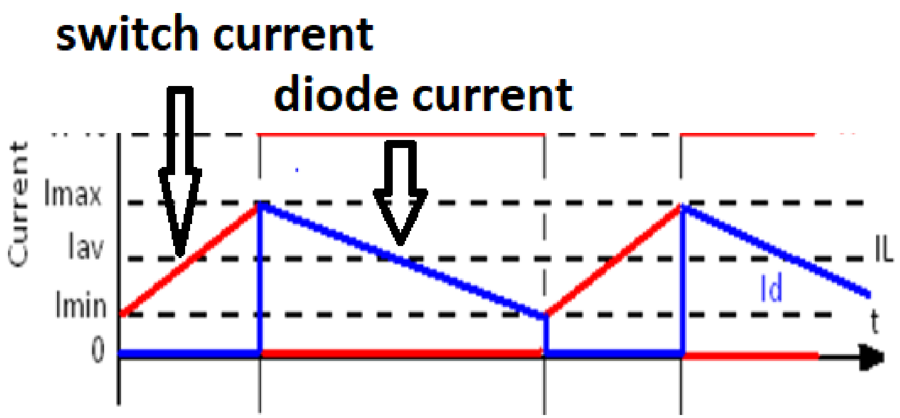
- $I_{max} = V_o\left(\frac{1}{R} + \frac{(1-D)T}{2L}\right)$

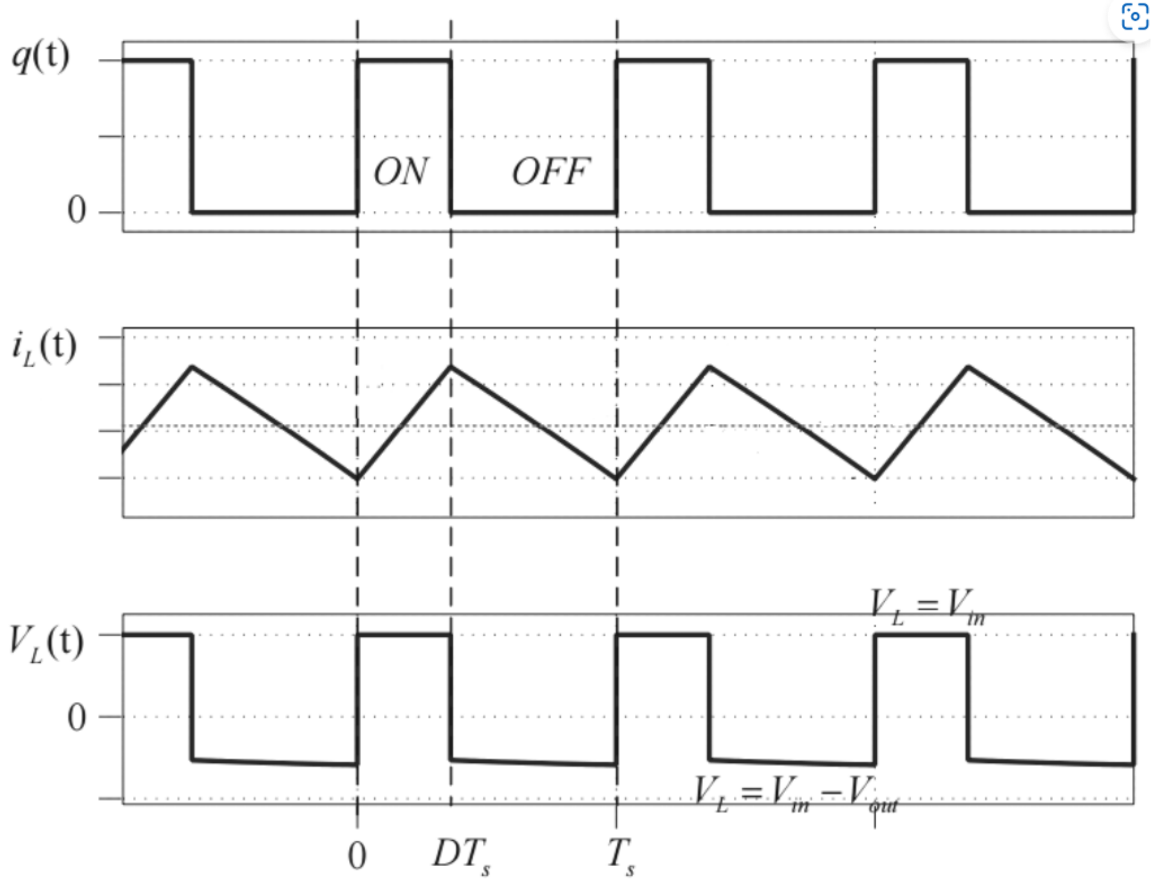


- $I_{min} = V_o\left(\frac{1}{R} - \frac{(1-D)T}{2L}\right)$

Boost Converter Waveforms

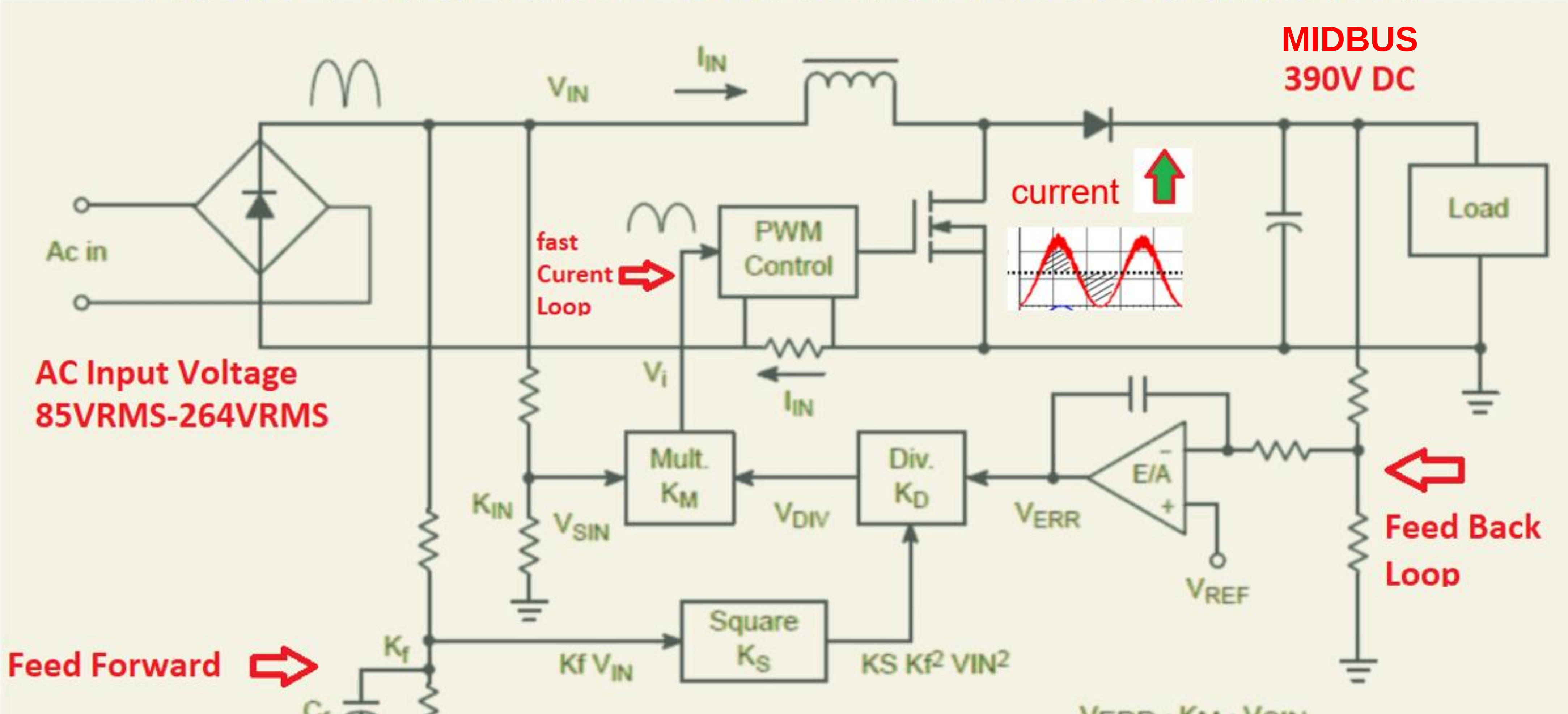






$$V_{out} = \frac{V_{in}}{1-D}$$

Active Power Factor Correction (Boost converter)

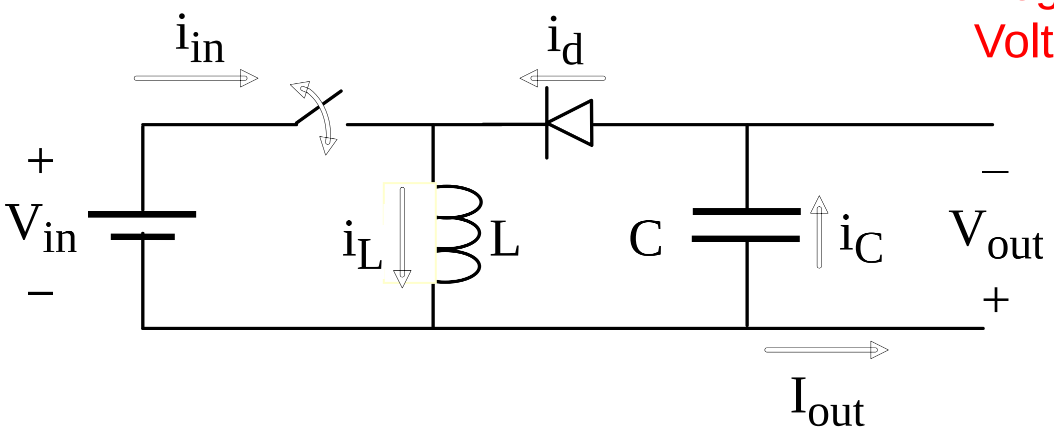


$$V_i = V_{DIV} \cdot K_M \cdot V_{SIN} = \frac{V_{ERR} \cdot K_M \cdot V_{SIN}}{K_D \cdot K_S \cdot K_f^2 \cdot V_{IN}^2}$$

Continuous Conduction Mode (CCM), and controlled by Average Current Mode Control (ACMC)

The Buck-Boost converter (CCM)

Negative Output Voltage



Output Voltage Boost (Up) or Buck(Down) (relative to input voltage)

$$V_{out} = \frac{DV_{in}}{1-D}$$

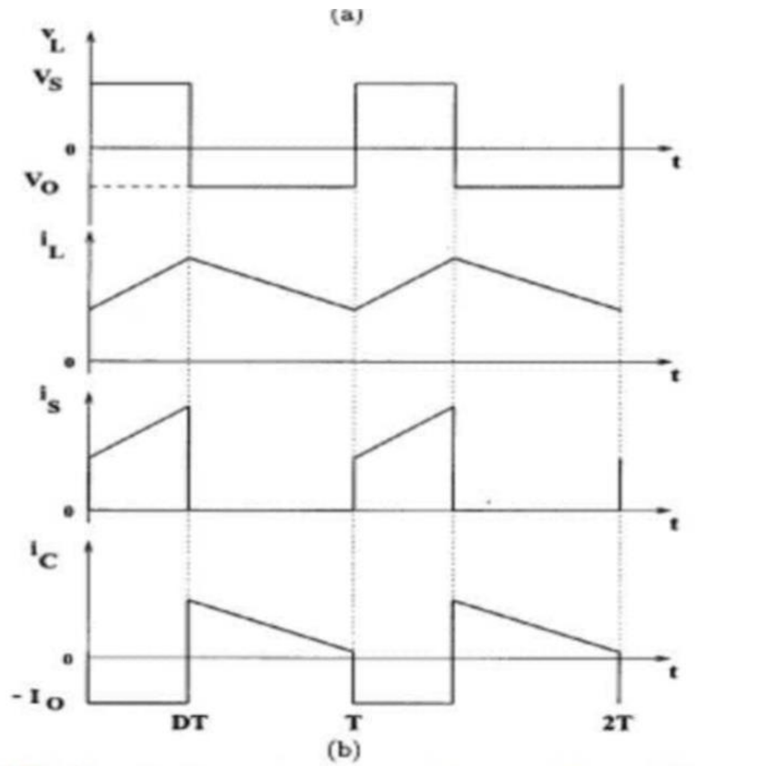


Fig.1 Buck-boost converter: (a) circuit diagram; (b) wav

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Power Supply Control Discussion

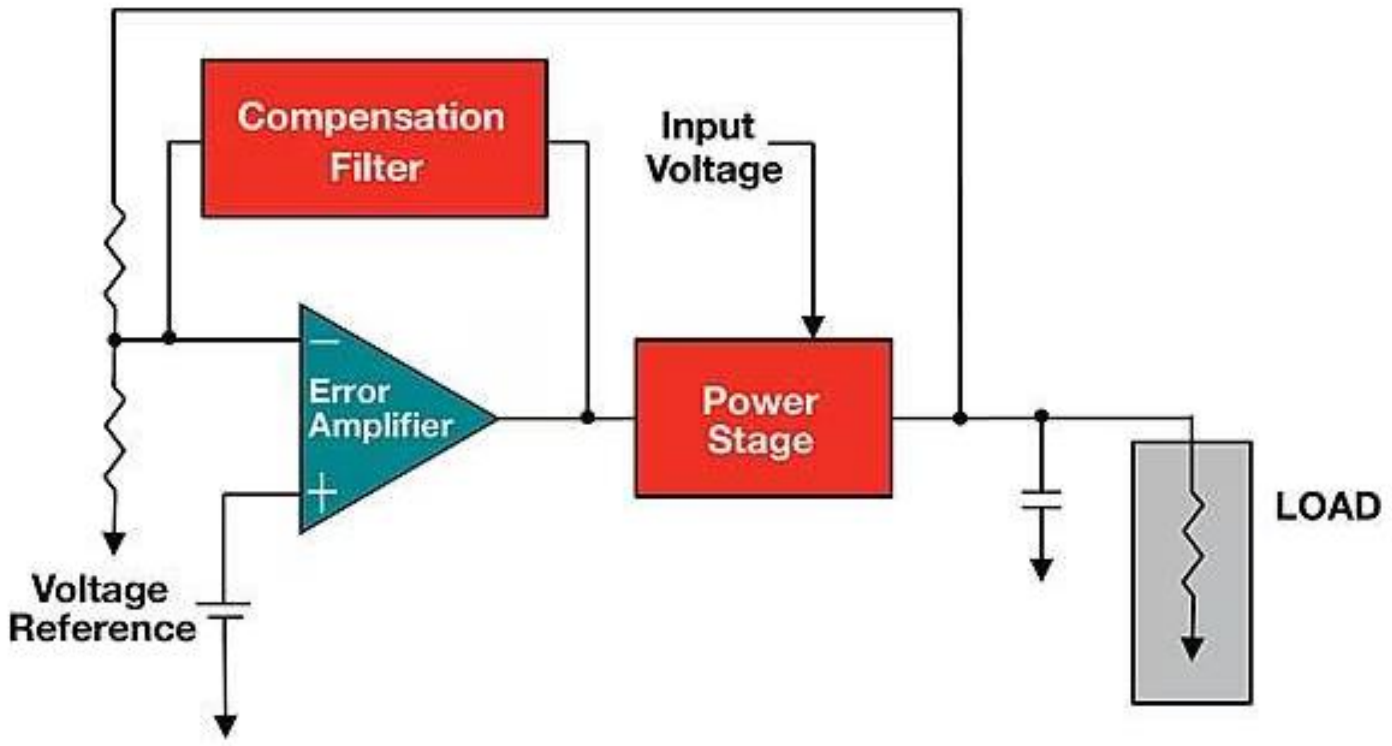
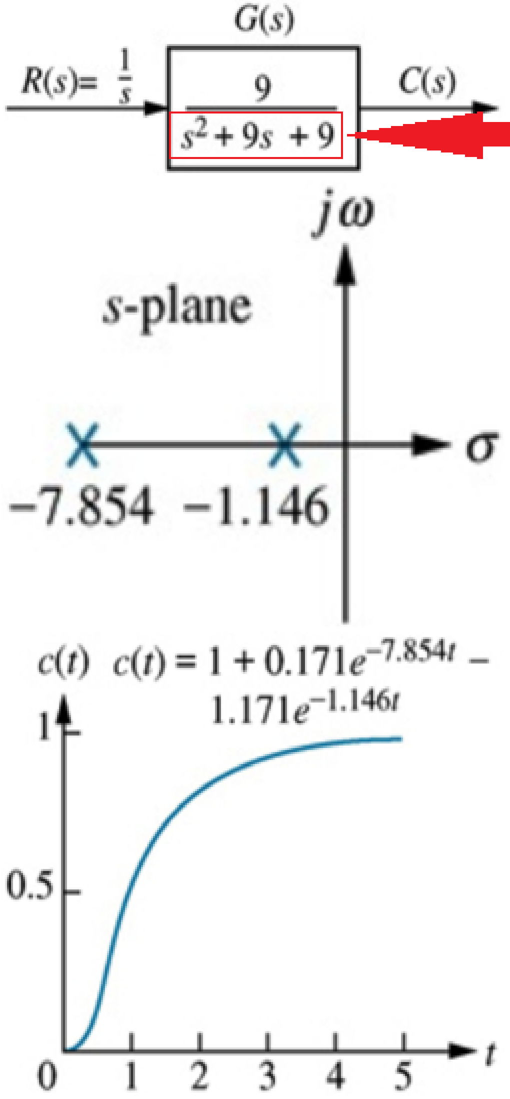


Figure 1. A typical power supply control loop.

Solving the "Characteristic Equation"



Poles

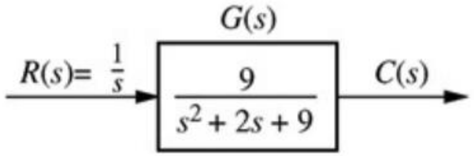
Roots of this denominator goes into the exponent of the equation that represents the output waveform

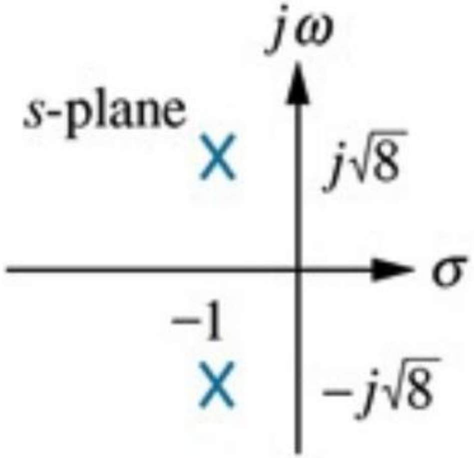
$$c(t) = K_1 e^{-\sigma_1 t} + K_2 e^{-\sigma_2 t}$$

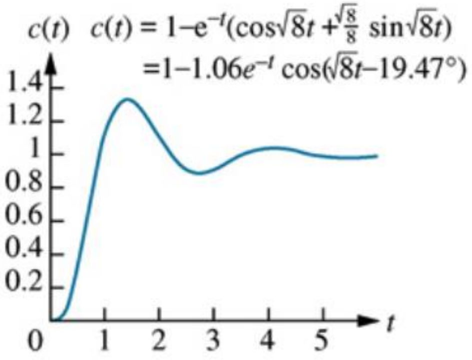
Inverse Laplace Transform

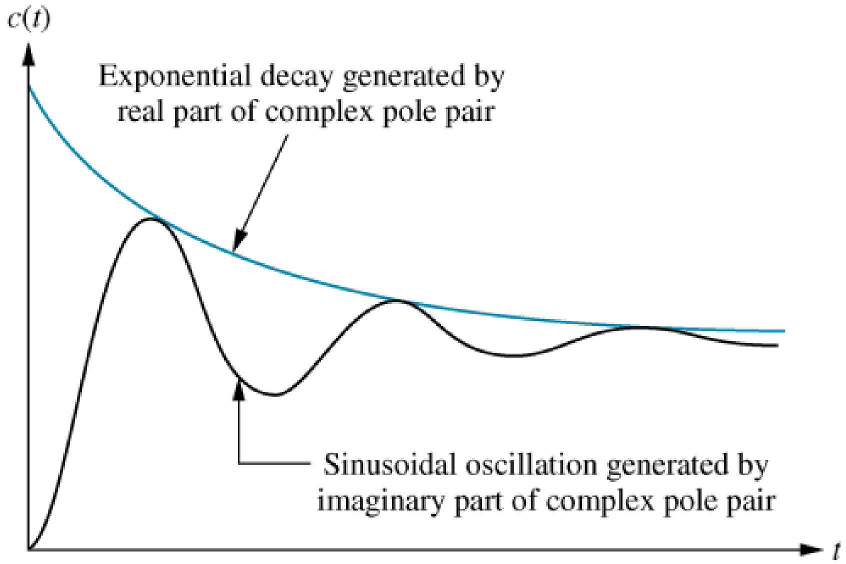
This is a damped response (Asymptotically Stable) since all poles lie in the left half plane (LHP).

SOLVING the “Characteristic Equation”







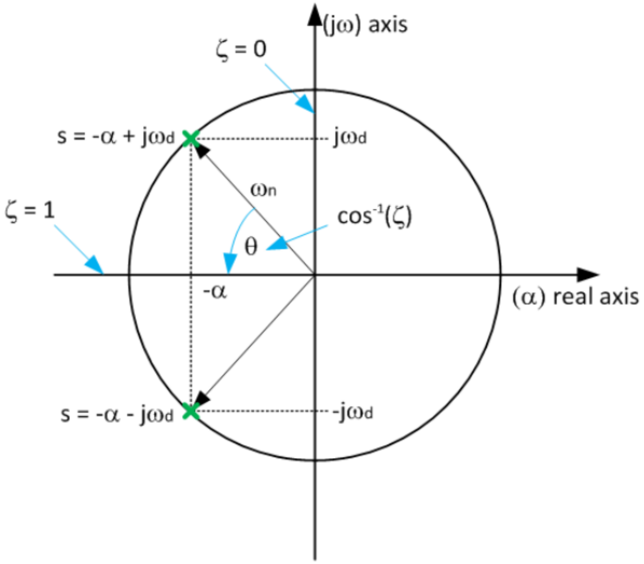


- Natural response: Damped sinusoid with an exponential envelope

Inverse Laplace Transform

$$c(t) = K_1 e^{-\sigma_d t} cos(\omega_d t - \phi)$$

Roots of "Characteristic Equations"- 2nD Order Systems



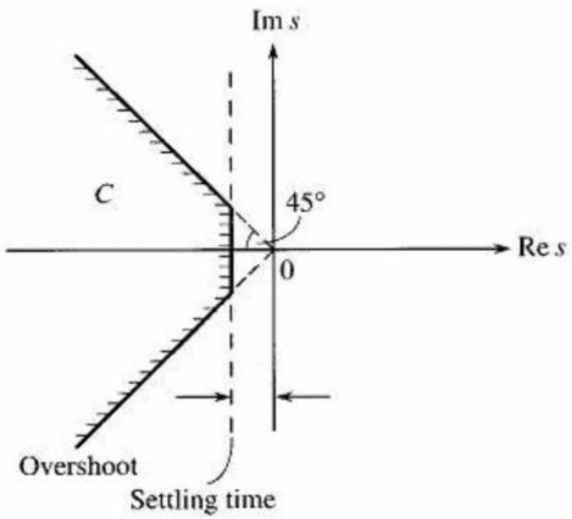
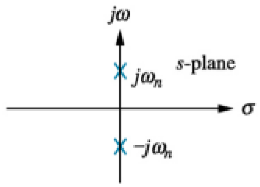
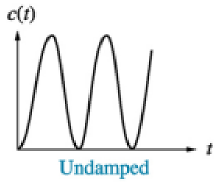
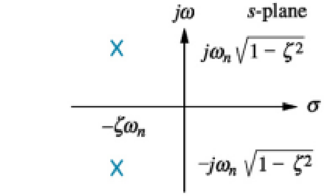
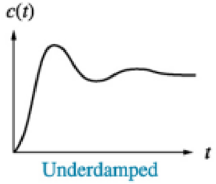
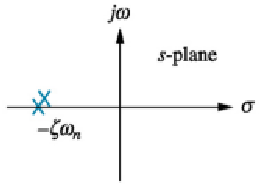
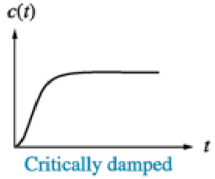
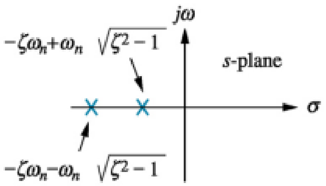
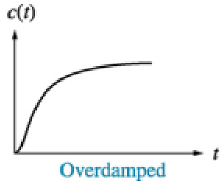
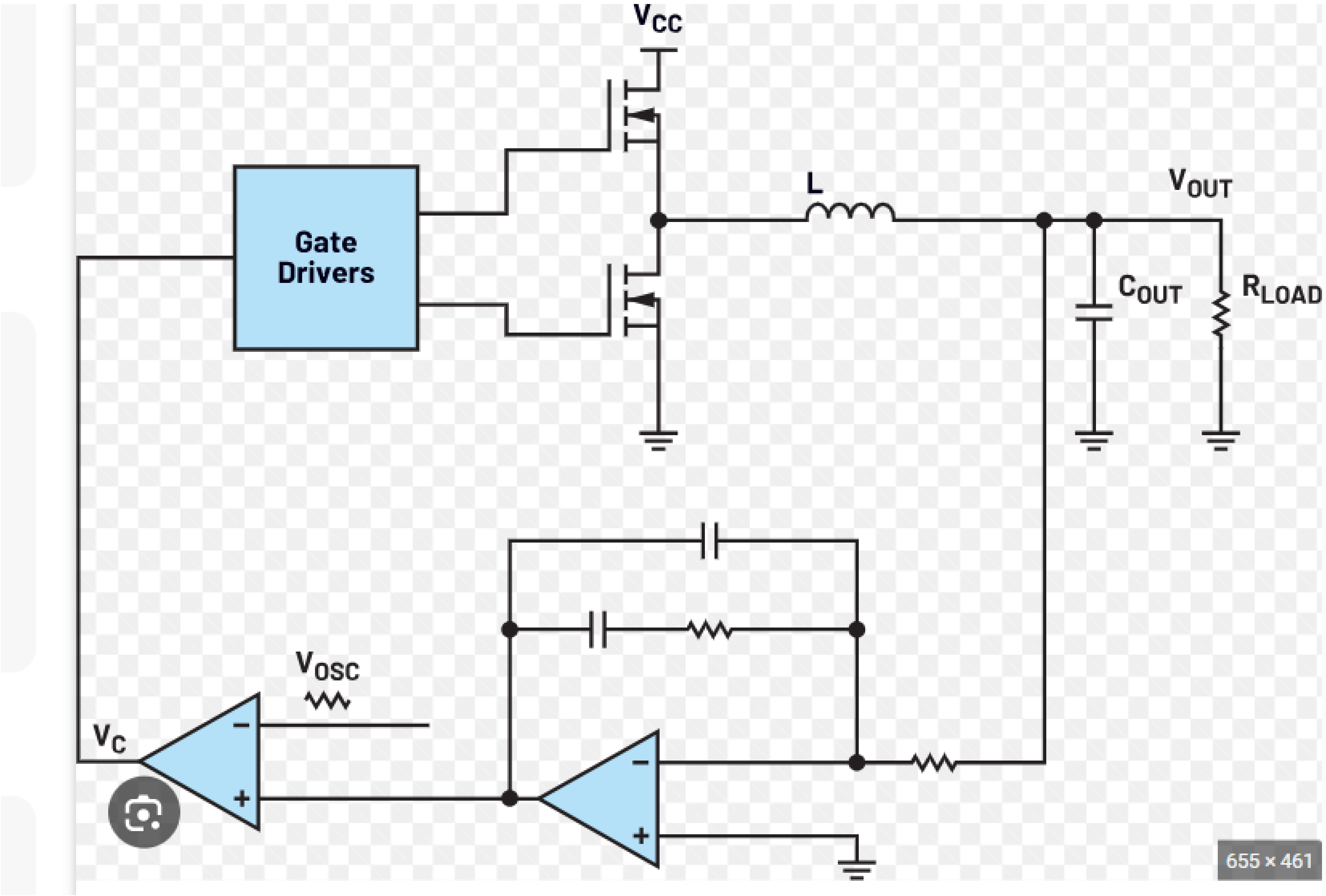


Table: 2^{nd}-order response as a function of damping ratio

ζ	Poles	Step response
0		
0 < ζ < 1		
ζ = 1		
ζ > 1		

Practical Feedback Realization (Buck)



Simple "Proportional" Feedback

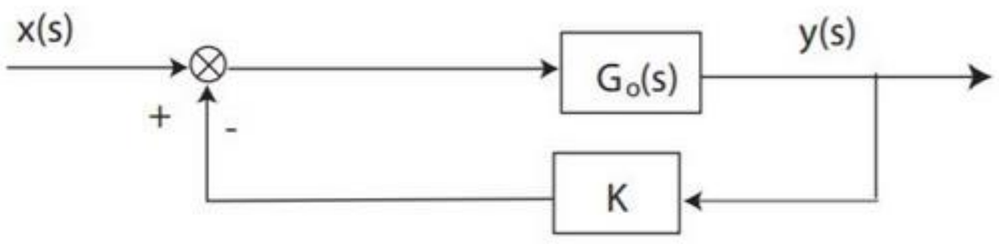


Figure 1: The proportional feedback control system.

Linearized Boost CCM model

$$\frac{V_{out}(s)}{D(s)} = H_0 \frac{\left(1+\frac{s}{\omega_{z_1}}\right)\left(1-\frac{s}{\omega_{z_2}}\right)}{1+\frac{s}{\omega_0 Q}+\left(\frac{s}{\omega_0}\right)^2} \qquad \omega_{z_1} = \frac{1}{r_C C_2} \qquad \omega_{z_2} \approx \frac{(1-D_0)^2 R_{load}}{L_1}$$

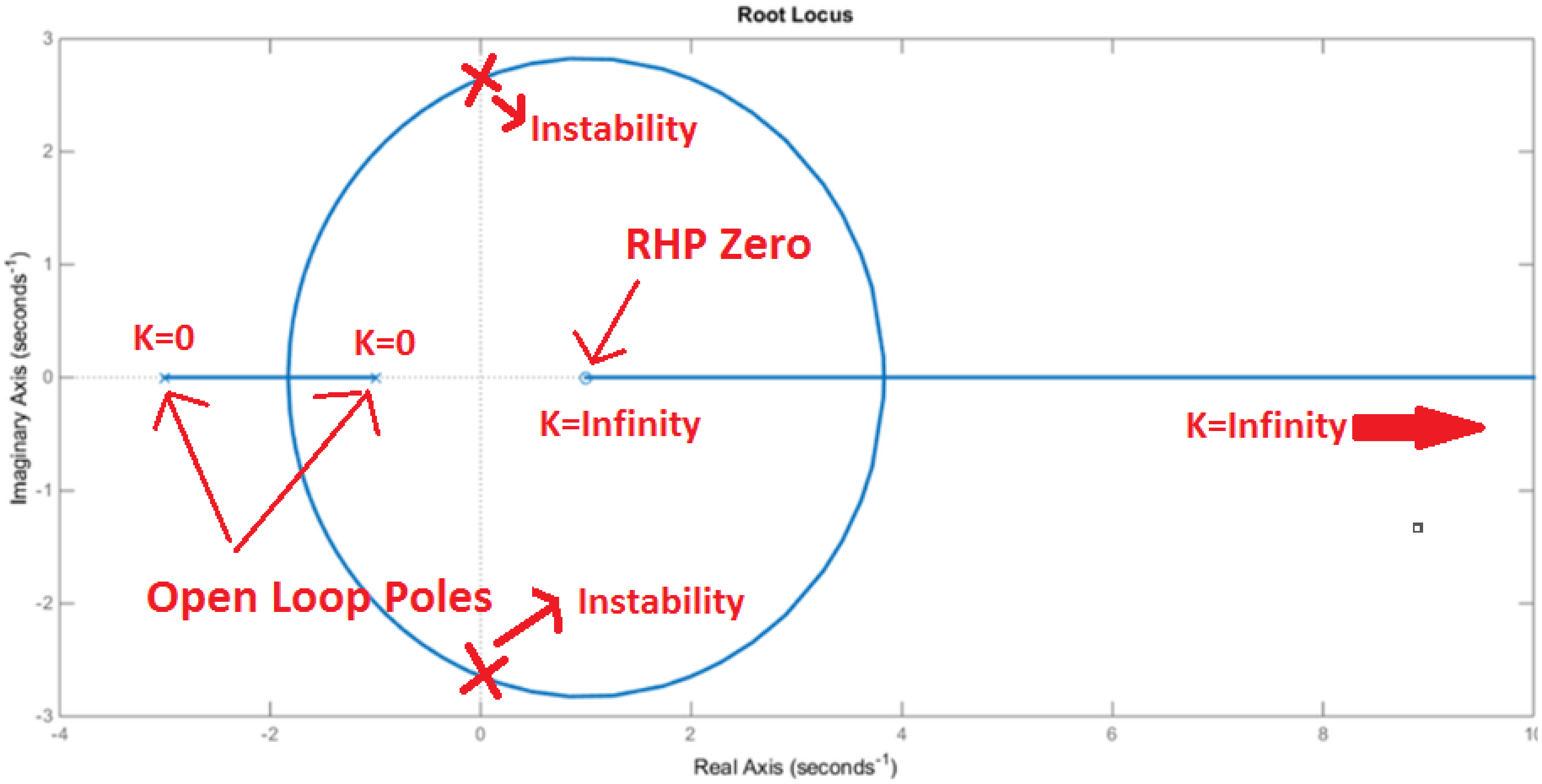
$$f_{RHP\_zero} = \frac{R}{2\pi L} \cdot \left(\frac{V_{IN}}{V_o}\right)^2$$

$Go(s) = N(s)/D(s)$ → **OPEN LOOP (No Feedback))**

$$T(s) = \frac{KN(s)}{D(s)+KN(s)}$$ → **CLOSED LOOP TRANSFER FUNCTION (Feedback)**

Important NOTE: At K = 0 the roots of the "Characteristic Equation" start at the Open Loop Poles and migrate towards the Open Loop Zeros at K = Infinity.

Boost Converter Root Locus (CCM) with Proportional Feedback

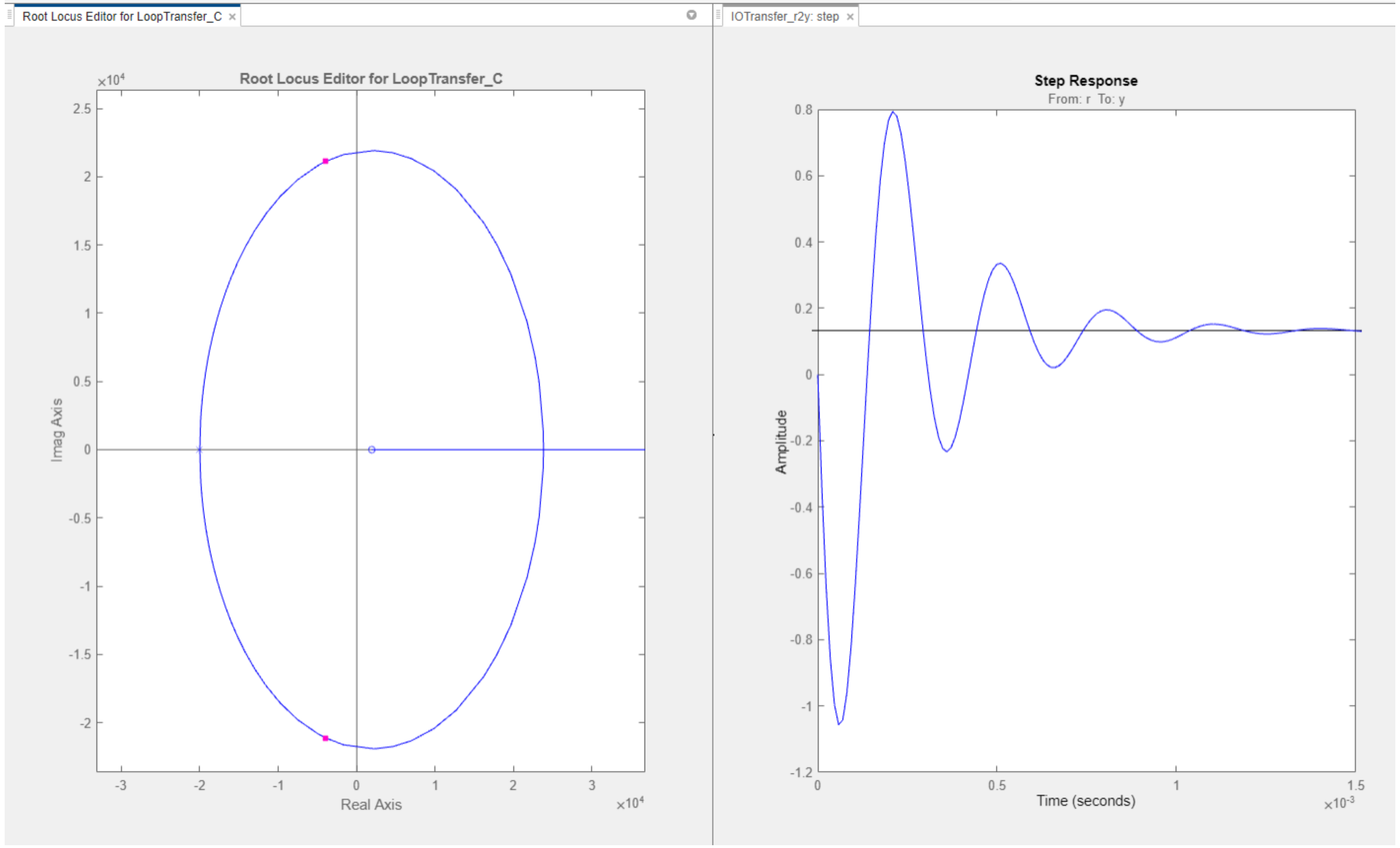


Root locus of the closed loop system of boost converter with proportional controller and two real negative roots.

MATLAB Boost Converter Root Locus (CCM)

```
>> controlSystemDesigner('rlocus',tf_boost);
>> tf_boost=(Ro*(1-d)/(2*Rsense))*(1-s/(2*3.14*Frhpz))/((1+s/(2*3.14*Fp))^2)
```

$$G_{PS}(S) = \frac{R_O \times (1 - D)}{2 \times R_{sense}} \times \frac{\left(1 + \frac{S}{2 \times \pi \times f_{ESRZ}}\right)\left(1 - \frac{S}{2 \times \pi \times f_{RHPZ}}\right)}{\left(1 + \frac{S}{2 \times \pi \times f_P}\right)^2}$$



Note: Plot does not contain the ESR Zero

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Stability Summary (Voltage Mode)

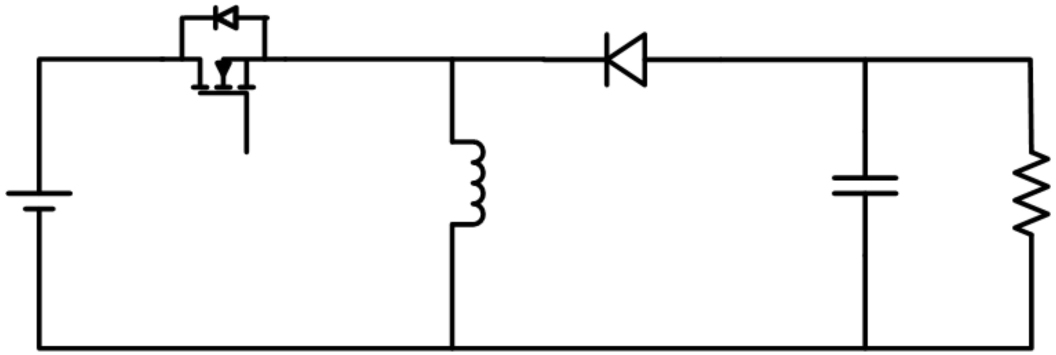
Buck, Boost and Buck Boost (DCM- Discontinuous Conduction Mode) are all single Pole Functions for dVout(s)/dVin(s) and dVout(s)/dD(s) → **EASY**

BUCK (CCM):
Fixed Pole Pair for both dVout(s)/dVin(s) and dVout(s)/dD(s) located near 1/SQRT(L*C)
No RHP
→ **Medium Difficulty**

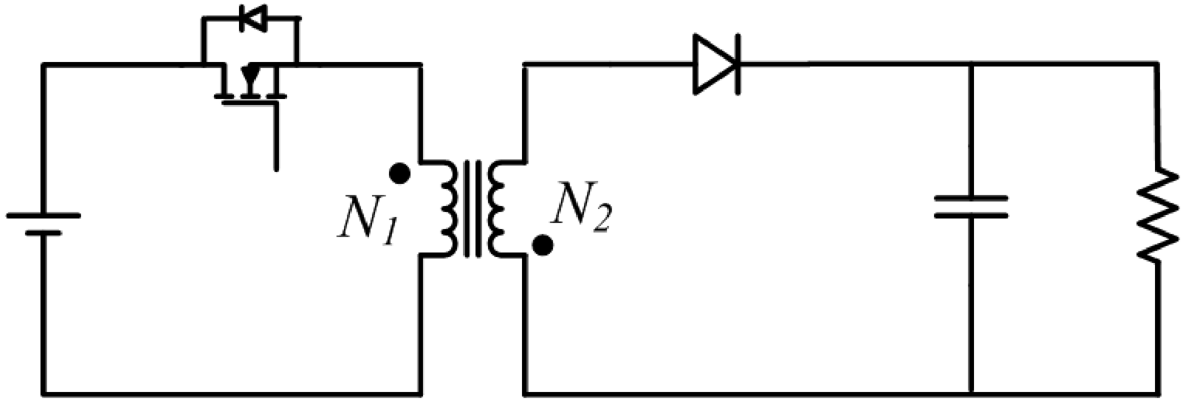
Boost and Buck-Boost: (CCM- Continuous Conduction Mode)
dVout(s)/dVin(s) -Variable Pole Pair near (1-D)^2/SQRT(L*C) and RHP Zero for dVout(s)/dD(s)
→ **Most Difficult**

The Fly-back converter

- Buck-Boost converter:

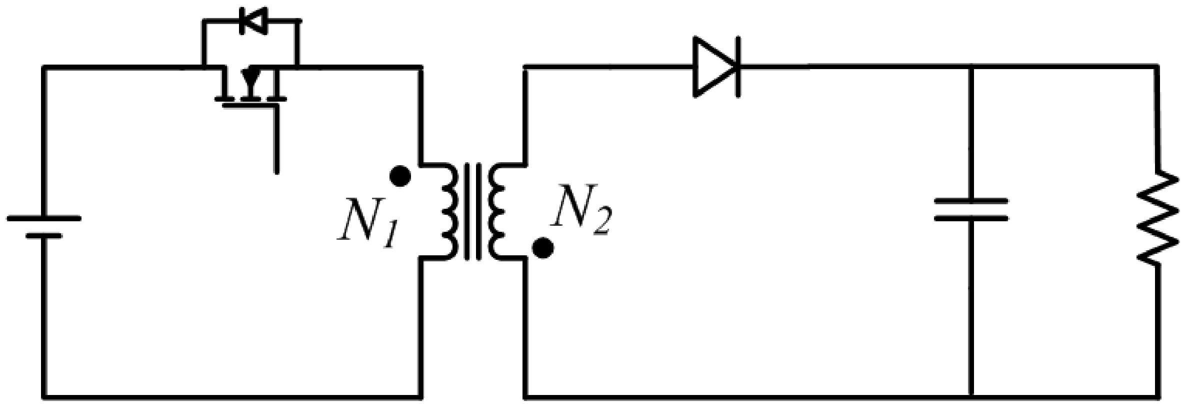


Equivalent (isolated) version using magnetically coupled inductors:



Flyback Converter

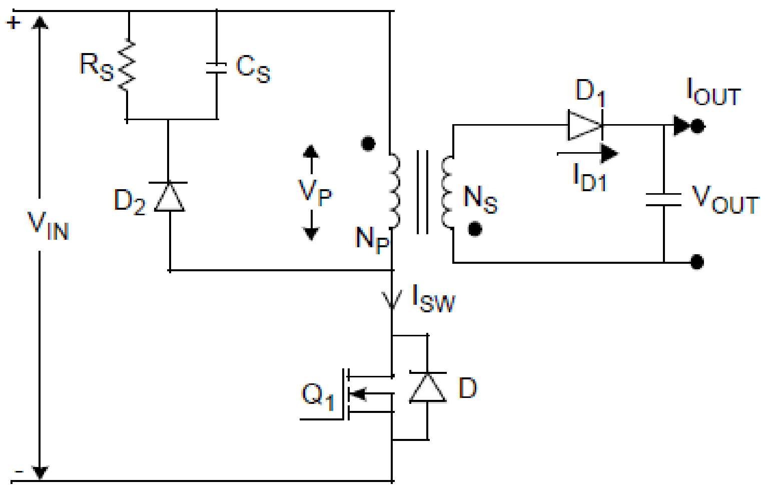
The Fly-back converter (Continued)

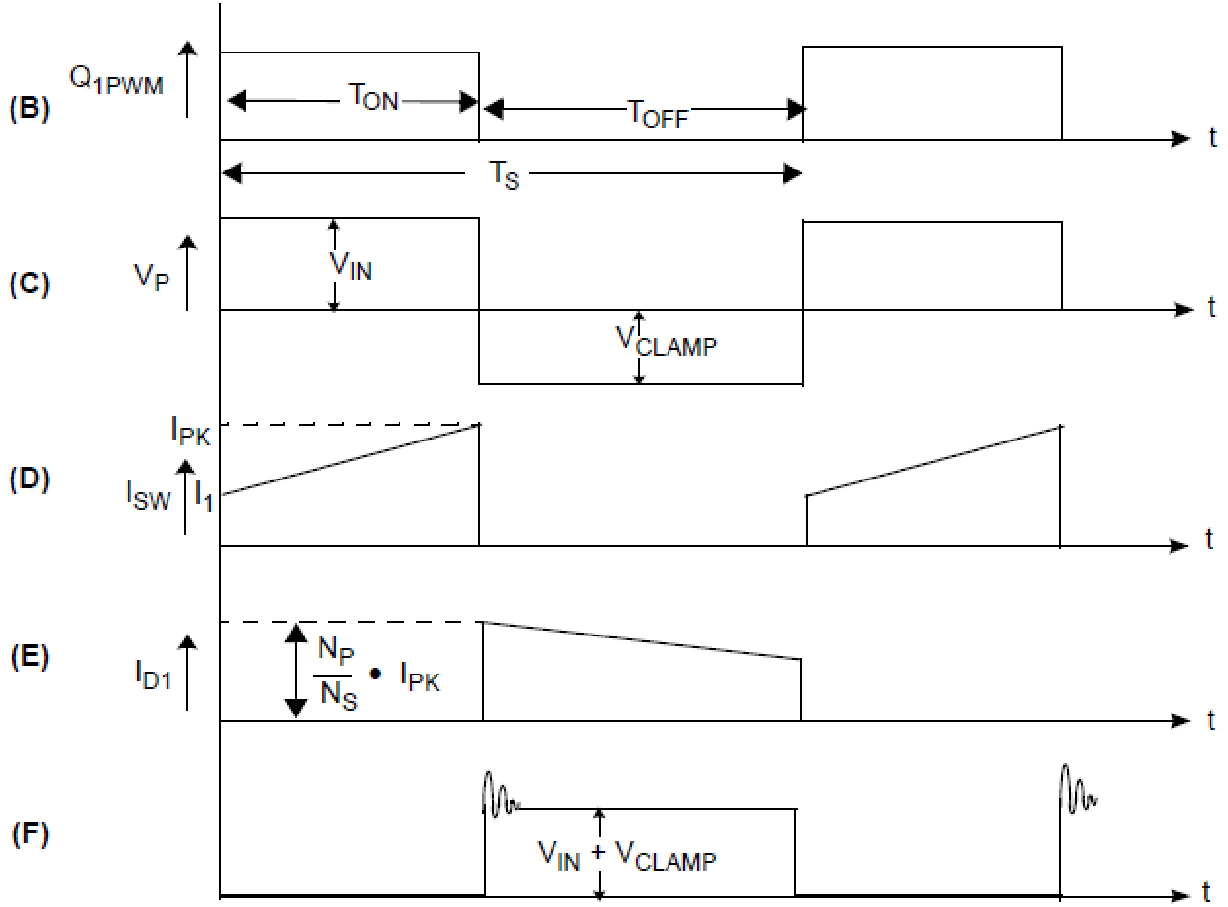


- The coupled inductors is an energy storage device (ass opposed to a traditional transformer)
- Output side is galvanically isolated from the input side

$$V_{out} = \frac{N_2}{N_1} \frac{DV_{in}}{1 - D}$$

Fly-back Converter Waveforms (CCM)





(A) = Flyback converter power circuit

(B) = Gate pulse for the MOSFET Q_1

(C) = Voltage across the primary winding

(D) = Current through MOSFET Q_1

(E) = Current through the diode D_1

(F) = Voltage across the MOSFET Q_1

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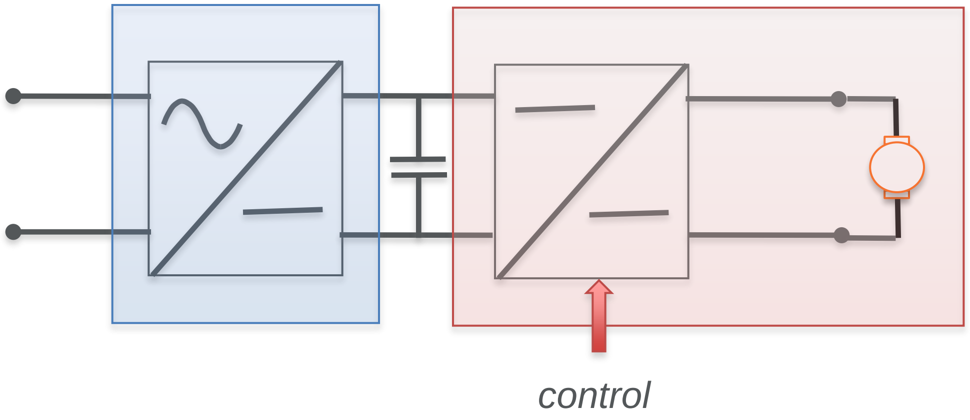
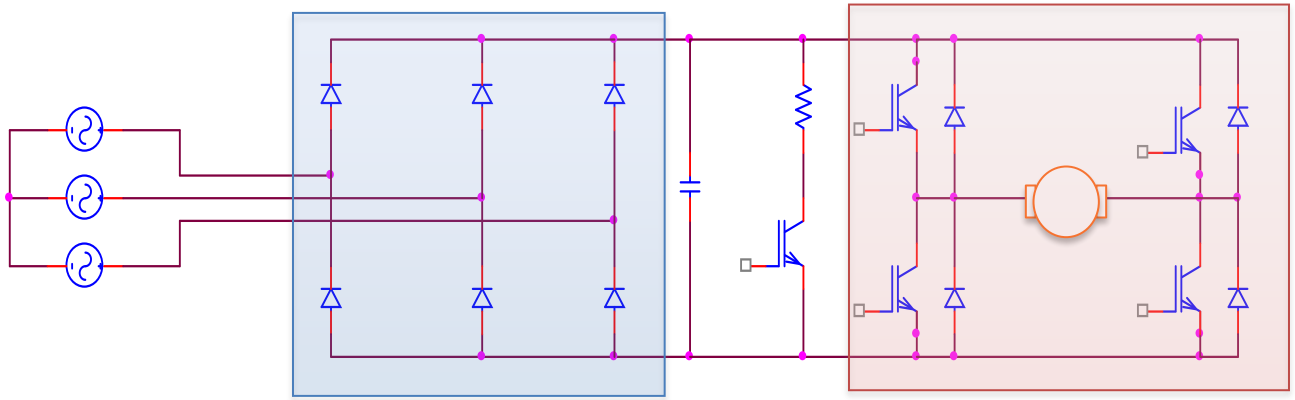
Power Electronic Converters in Electric Drive Systems

DC DRIVES

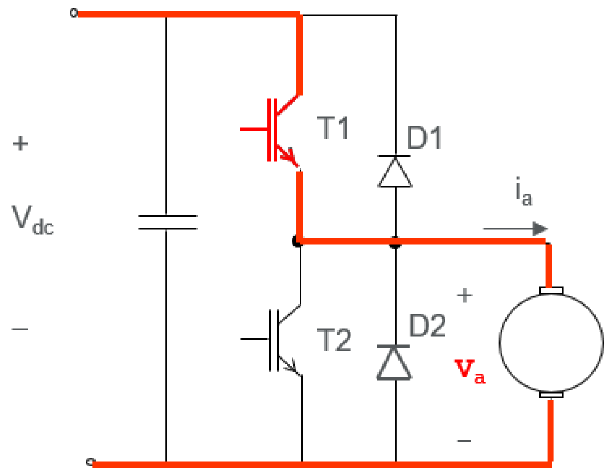




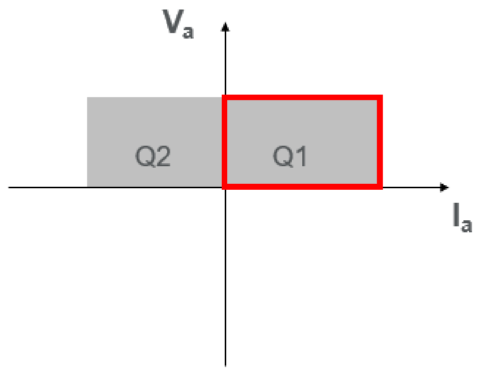
Power Electronic Converters in Electric Drive Systems

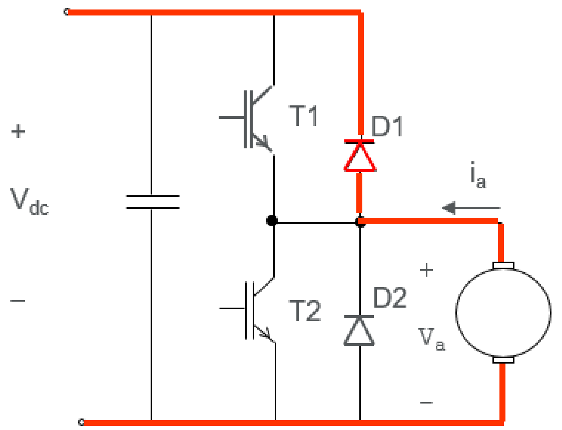
Two-quadrant Converter

Motor can deliver energy to the supply input bus!

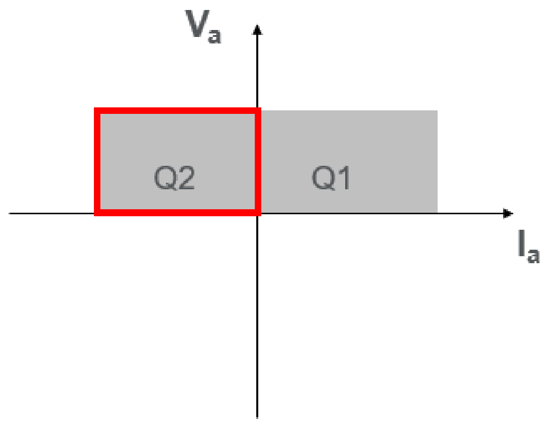


T1 conducts → $v_a = V_{dc}$



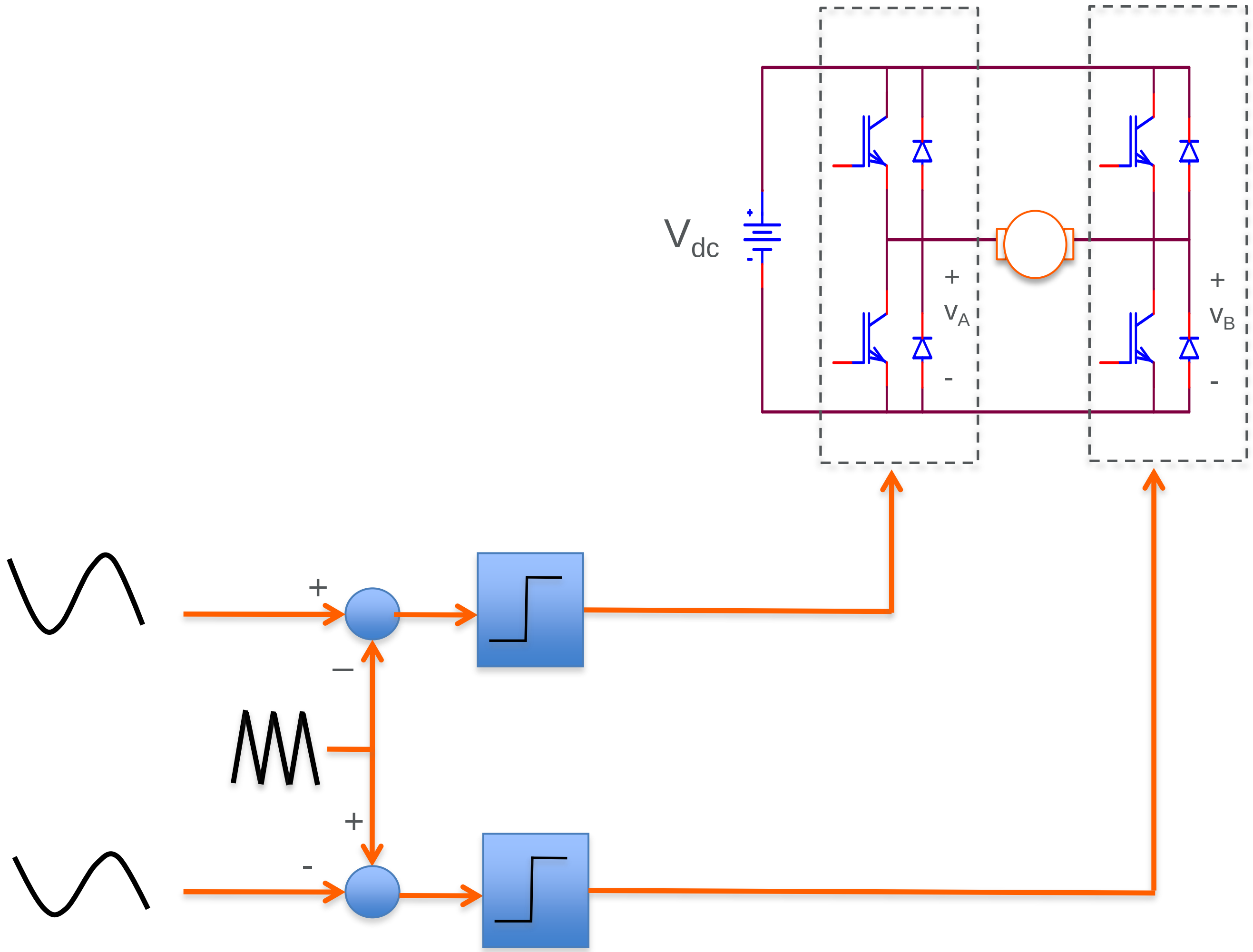


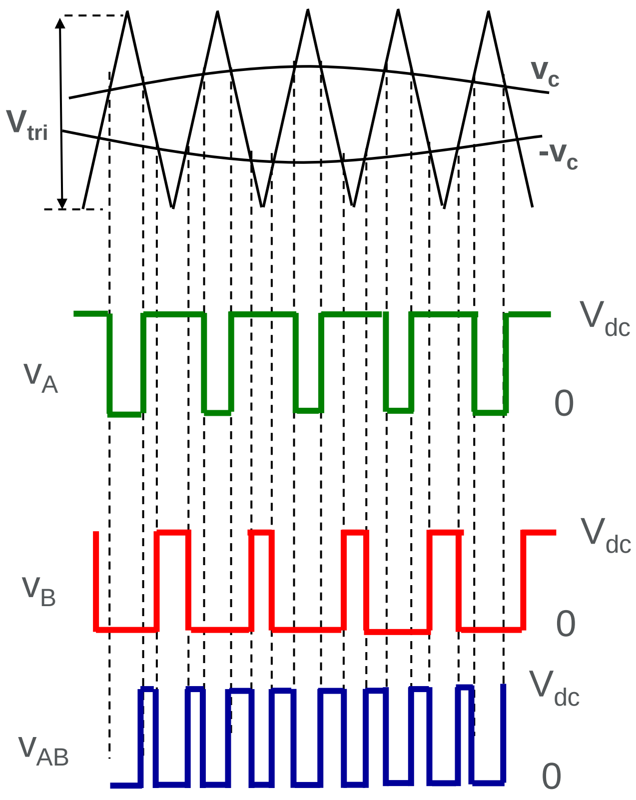
D1 conducts → $v_a = V_{dc}$



Power Electronic Converters in Electric Drive Systems

DC-DC: Four-quadrant Converter





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