Welcome!

High Efficiency Switch-mode Power Supply Design Overview

Contact Information

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Software (Simulator) Download

Free Microcap 12 full version for circuit simulation:
http://www.spectrum-soft.com/download/download.shtm

Simulation files available for upload from course website

- Use the CIR files

Course Outline

- **Module One:** Fundamentals of Switch-Mode Power Supply Design
- **Module Two:** Power Conversion Topologies with Simulation
- **Module Three:** Rectifiers & Active Power Factor Correction
- **Module Four:** Design of Magnetic Components
- **Module Five:** Design for High Efficiency & High Power Density
- **Module Six:** Practical Design Considerations (EMI, Safety, PCB)
- **Module Seven:** Power System Architecture & Digital Power Supply
- **Module Eight:** Practical Design of 30W Flyback Converter

Module One

Fundamentals of Switch-Mode Power Supply Design

Categories/Topologies of AC/DC Power Supplies

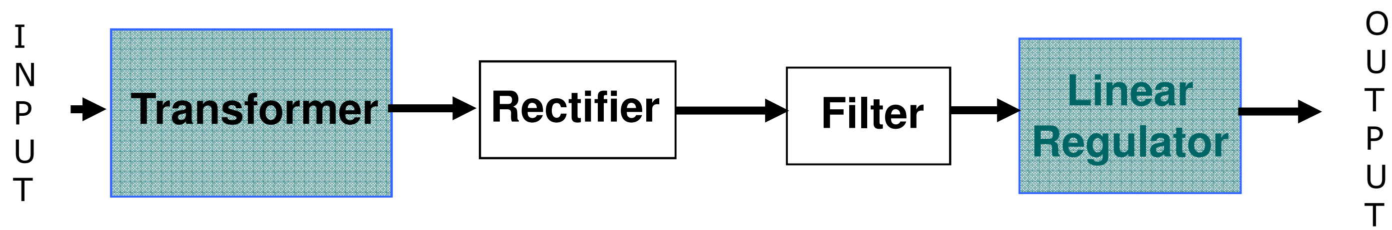
Switch-Mode		Linear
Isolated	***Non-isolated***	***Non-Isolated***
Flyback	Boost	Isolation is in AC transformer and not on DC section
Forward	Buck	
Half-Bridge	Buck-Boost	
Full-Bridge		

Popular Topologies

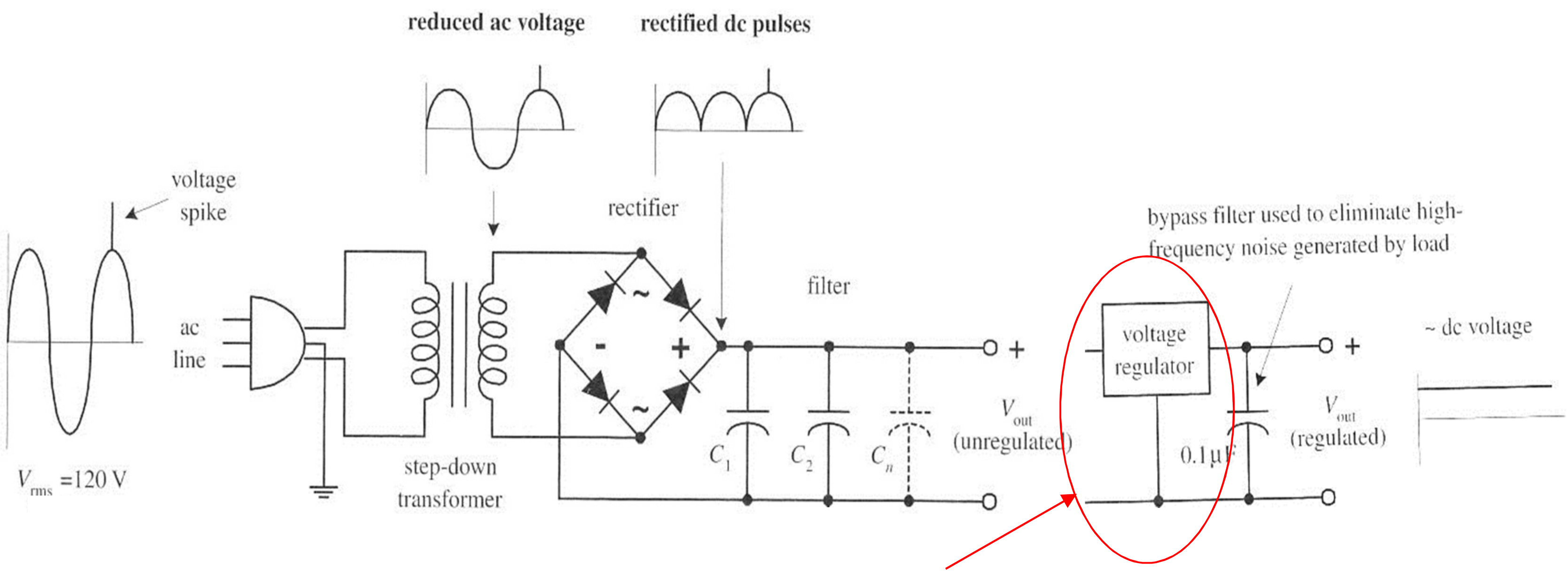
Topology refers to the particular arrangement/connection of components (Mosfet, diode, inductor, transformer, capacitor) in a power supply circuit

Block Diagram of Linear Power Supply

Simplified Block Diagram Showing the Different Stages



Linear Power Supply Circuit Diagram



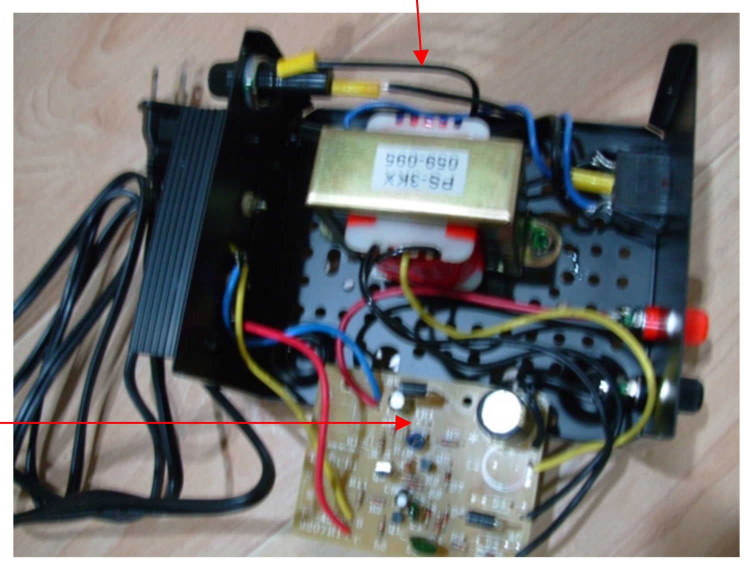
Linear regulator

Power dissipation: [Vout (unreg.) – Vout (reg.)] * Iout

Actual Example of Linear Power Supply

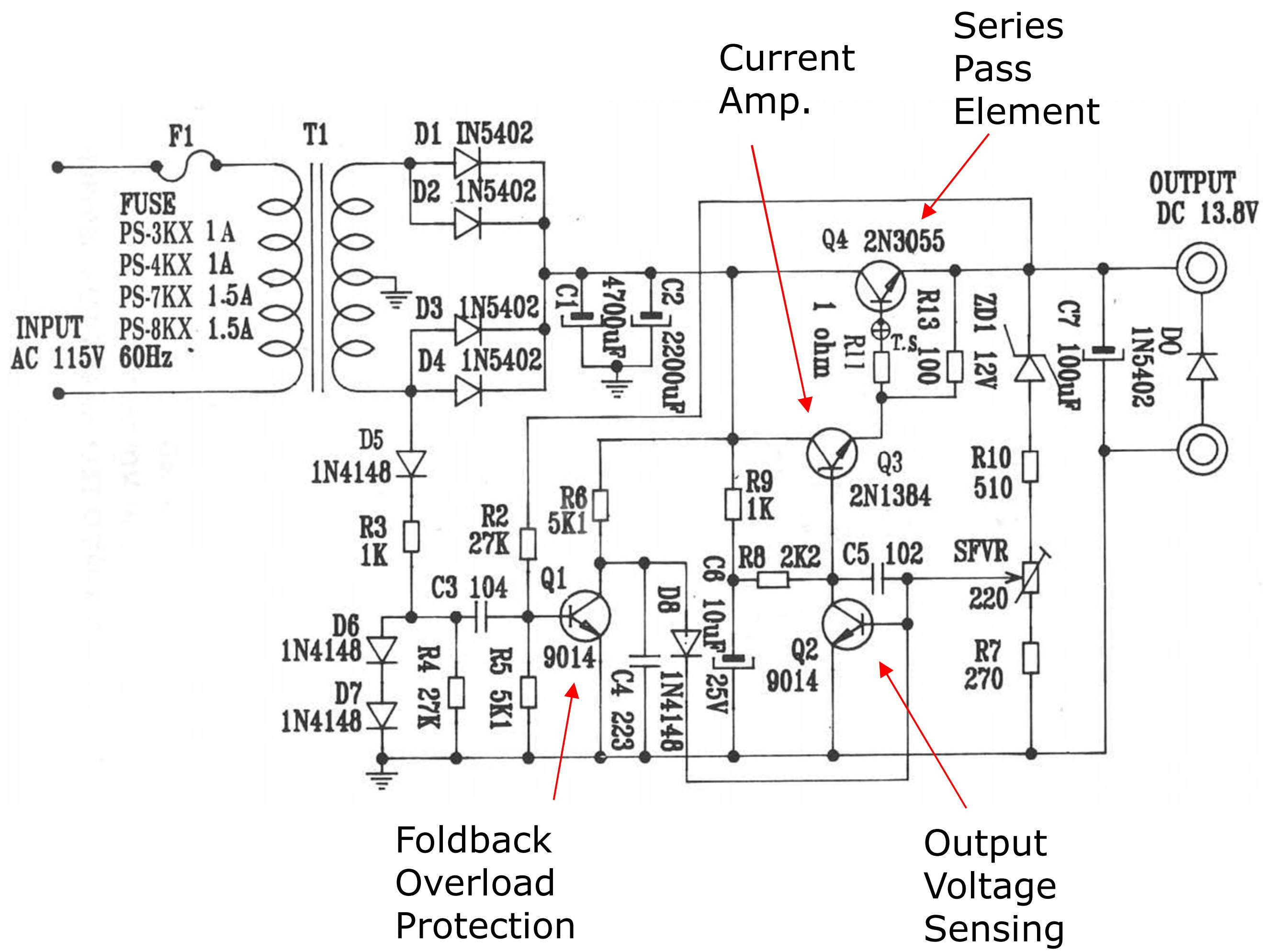
13.8VDC out 2.5A

Power transformer

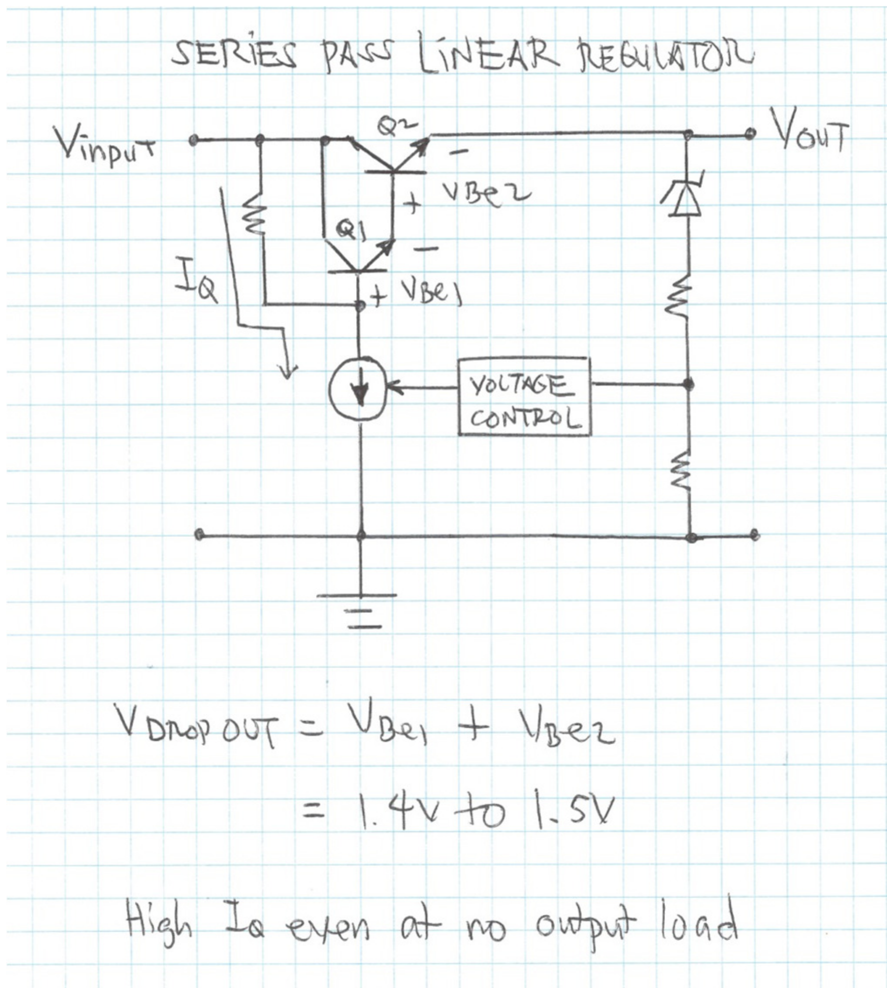


Board with rectifier, capacitor, and regulator

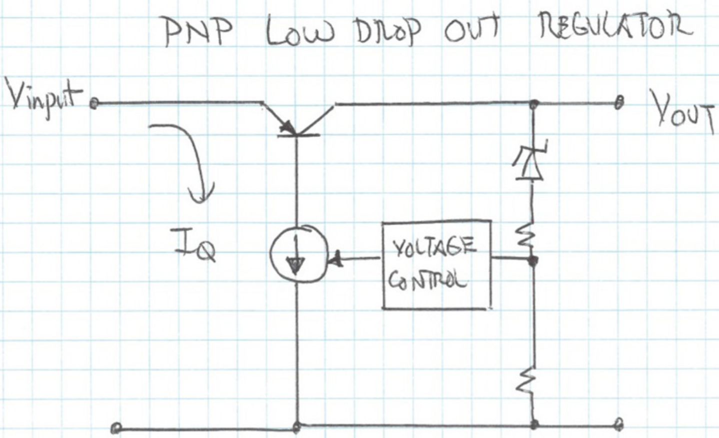
Schematic Diagram of Linear Power Supply



Linear Regulator

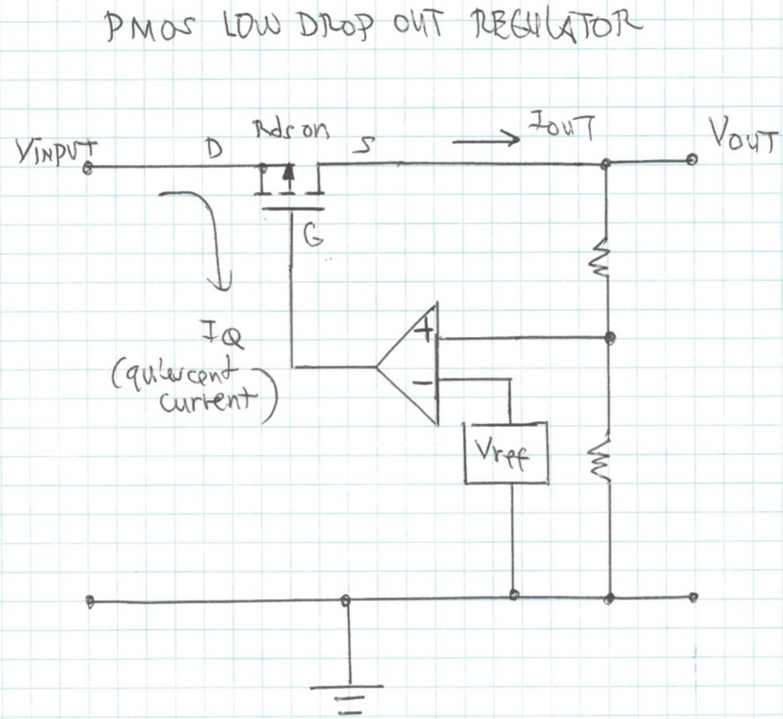


Low Drop Out Regulators



$V_{DROPOUT} = V_{CE(SAT)}$

High IQ even at no load

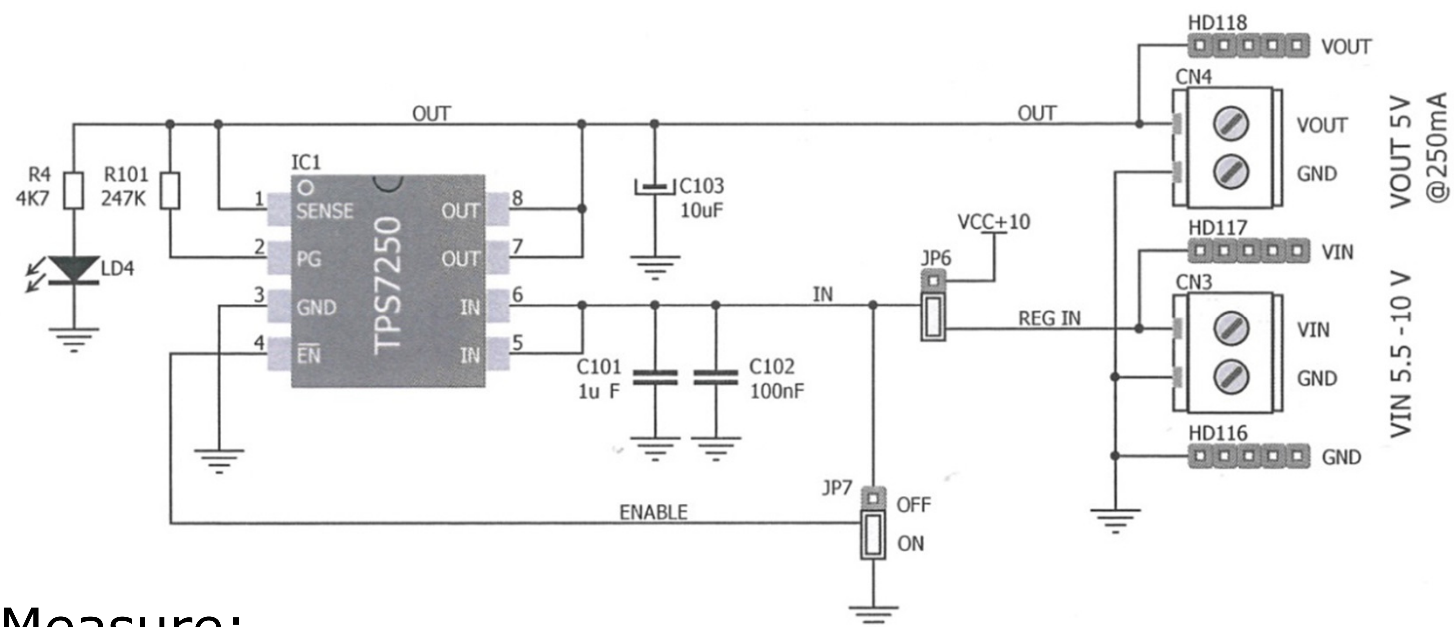


$V_{DROPOUT} = I_{OUT} \times R_{DS\,ON}$

Low quiescent current independent of load

- MOSFET ARE VOLTAGE CONTROLLED DEVICE

Low Drop-out Regulator Test

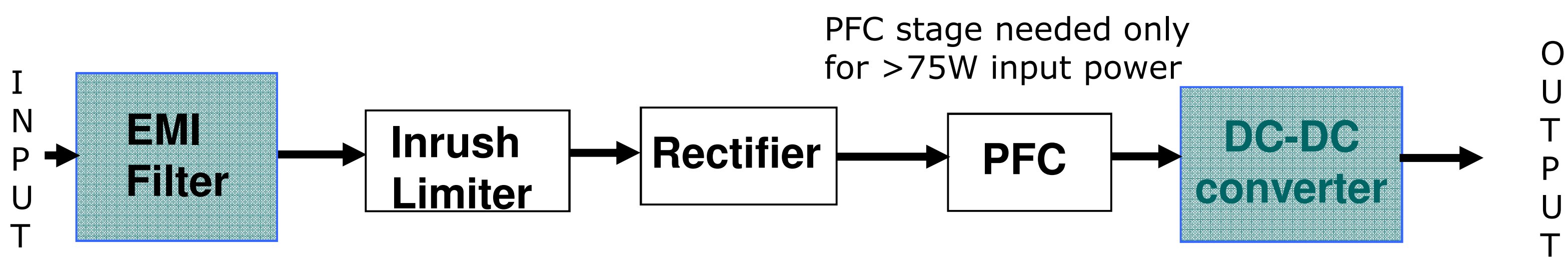


Measure:

- Drop-out voltage
- Quiescent current (full-load, no-load, and disabled)

Block Diagram of Off-Line (Isolated) Switching Power Supply

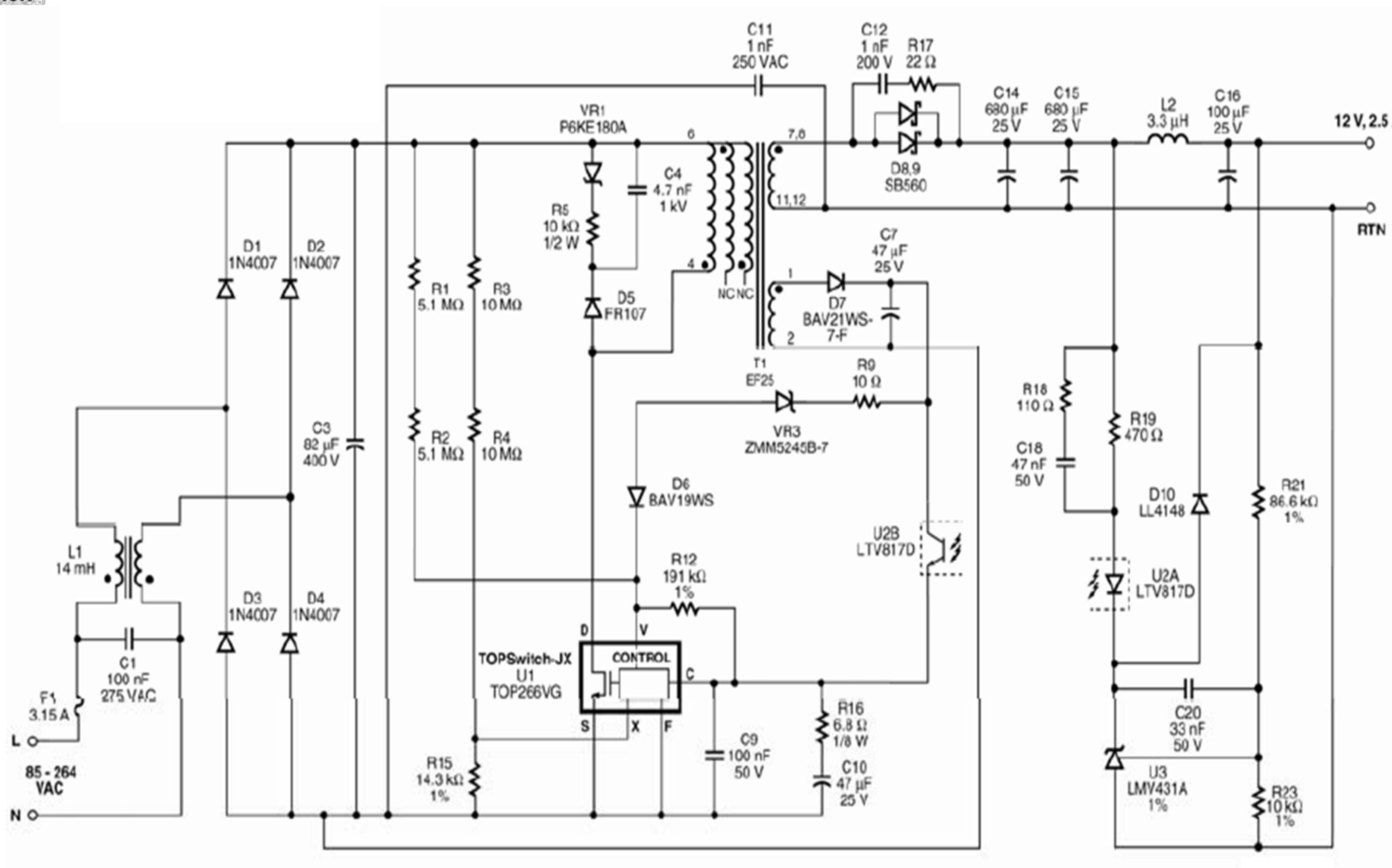
Simplified Block Diagram Showing the Different Stages



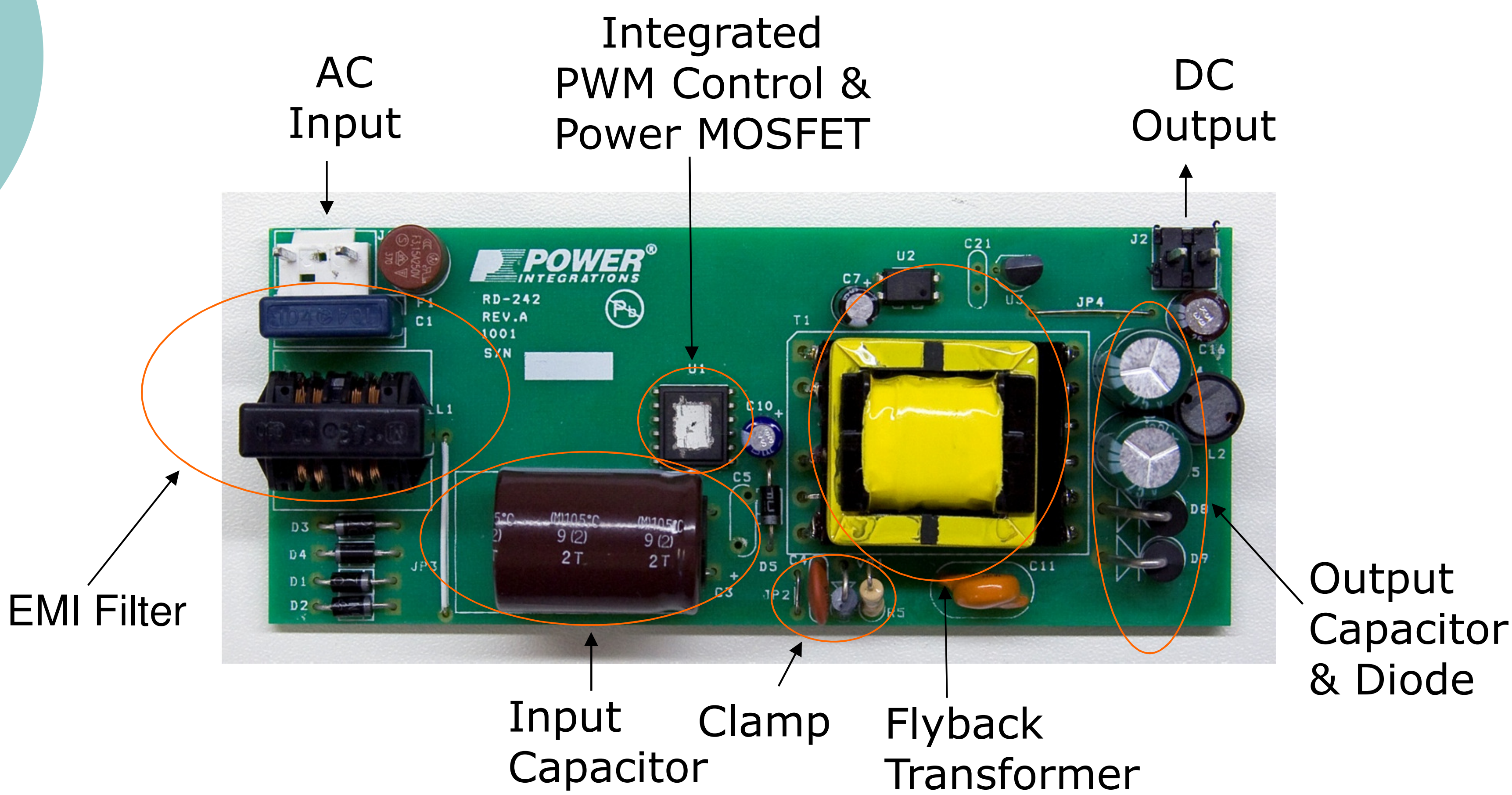
Different DC-DC Topologies:

- Flyback (1W to 150W)
- Forward (5W to 350W)
- Half Bridge (400W to 600W)
- Full Bridge (600W and above)

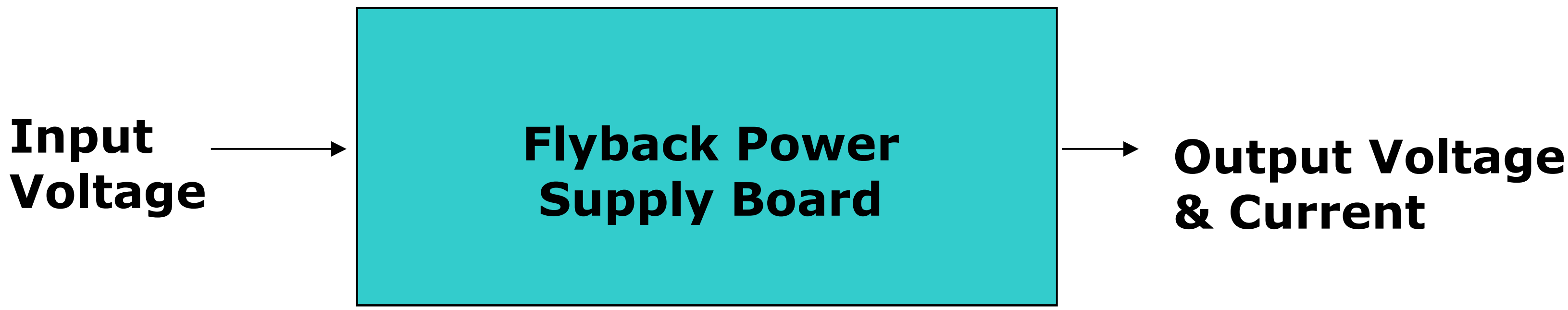
30W Switch-Mode Power Supply



Identifying the Blocks in the Flyback Board



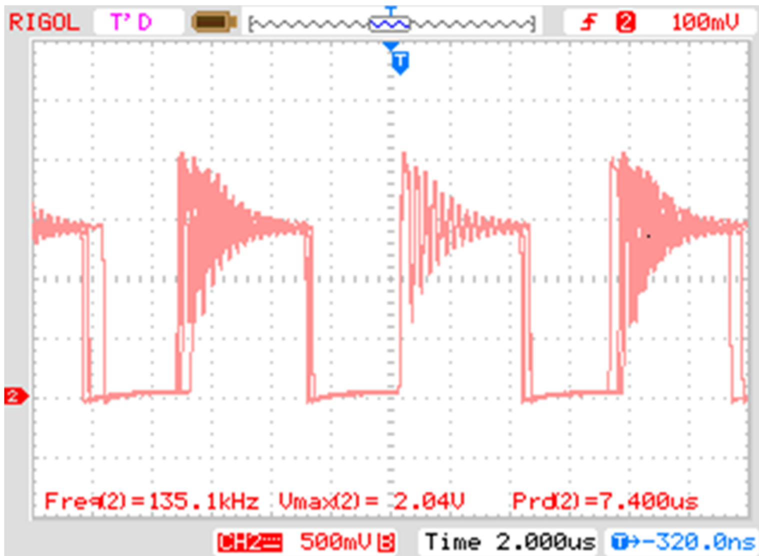
Understanding Effect of Input Voltage & Output Current in the Flyback Circuit



What is the impact on:

- **Duty Cycle**
- **Voltage drain to source of MOSFET**
- **Output diode voltage & current**
- **Output ripple voltage & regulation**
- **Temperature of component**

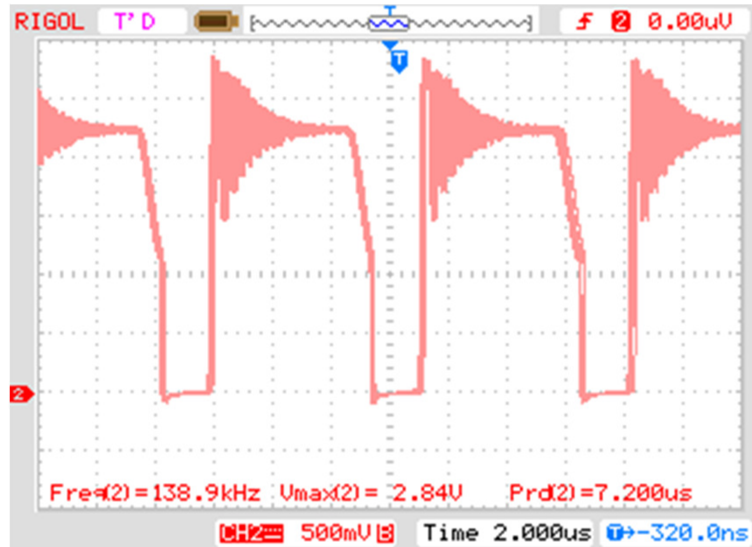
Duty Cycle & Vds V.S. Input Voltage



120VAC Input & 2A Output Load

Probe set X200, Vds(pk)=408V

41% Duty Cycle



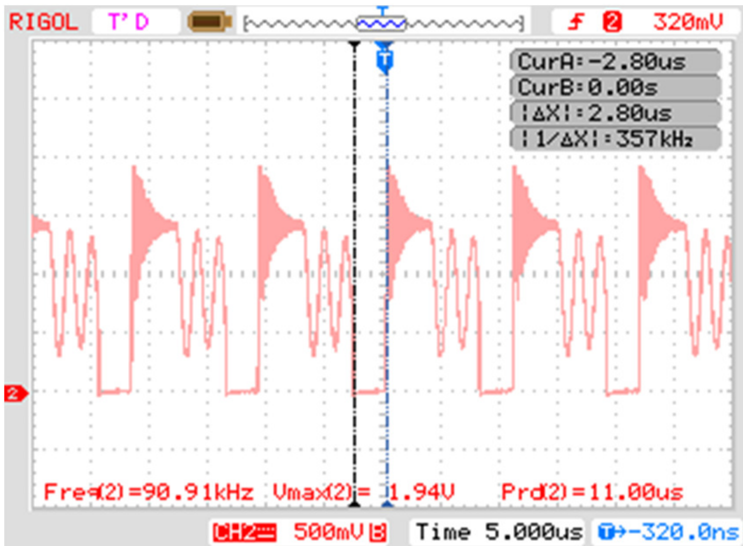
240VAC Input & 2A Output Load

Probe set X200, Vds(pk)=568V

22% Duty Cycle

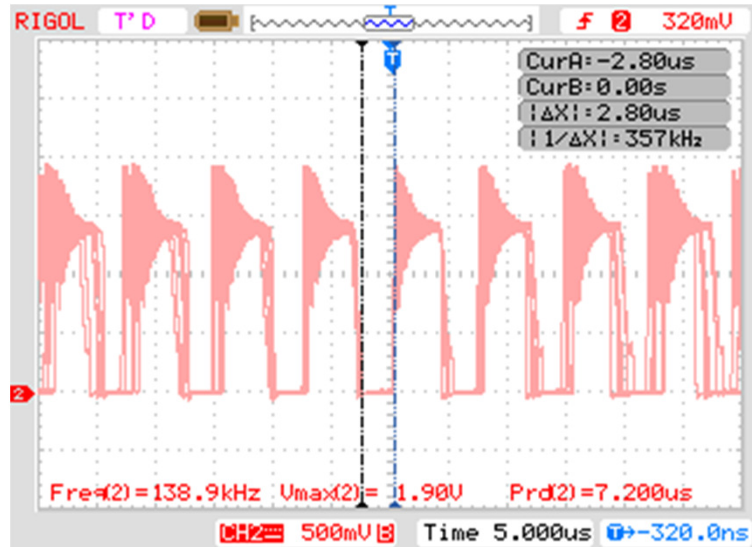
*Duty Cycle is constant with load of 1.5A and up (constant switching freq.)

Constant Turn-On Time with Load (Variable Switching Freq.)



120VAC Input & 1A Output Load

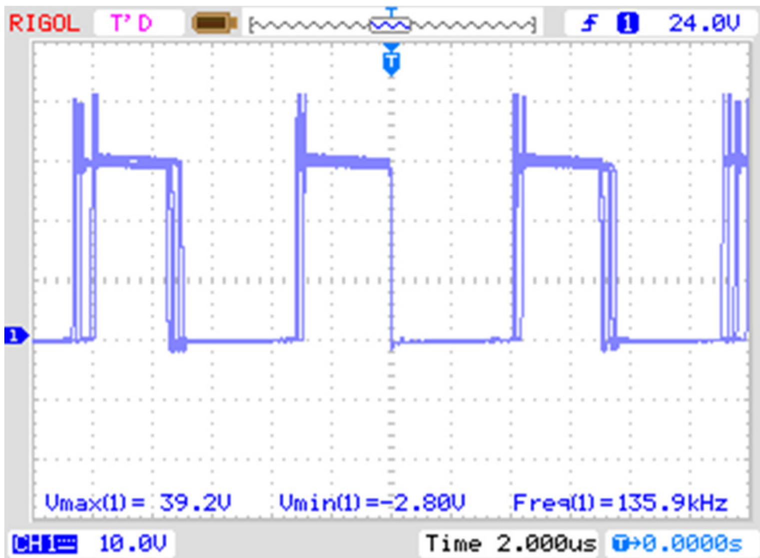
turn-on time=2.8uS



120VAC Input & 1.5A Output Load

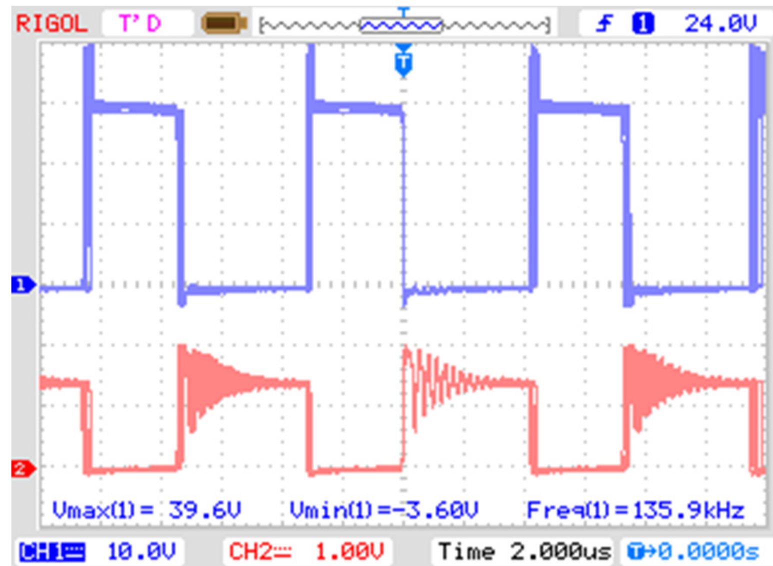
turn-on time=2.8uS

Output Diode Voltage & Comparison with the MOSFET Vds



120VAC Input & 2A Output Load

Output Diode Voltage

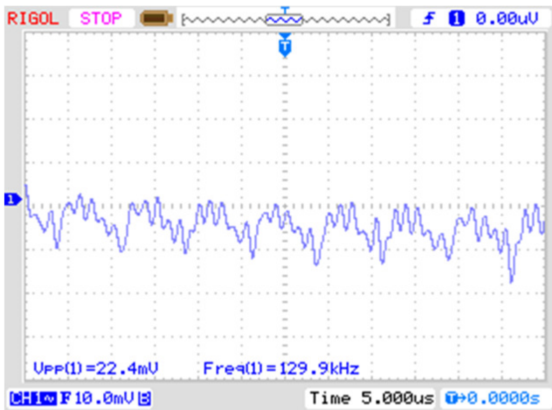


120VAC Input & 2A Output Load

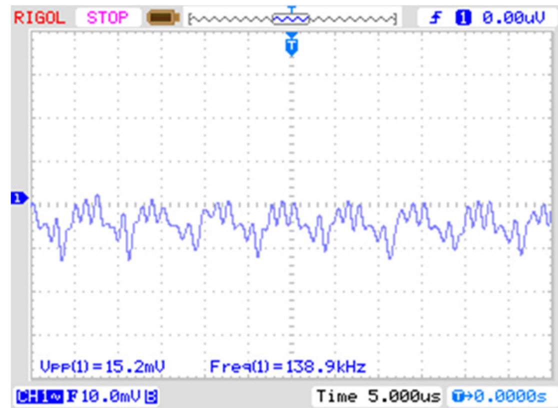
Output Diode Voltage Channel 1

MOSFET Vds Channel 2

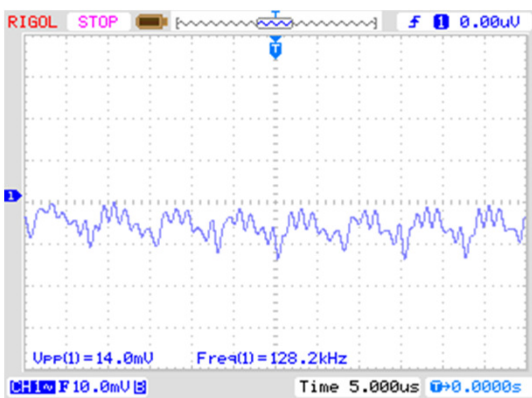
Output Ripple Voltage as Output Load Current Changes



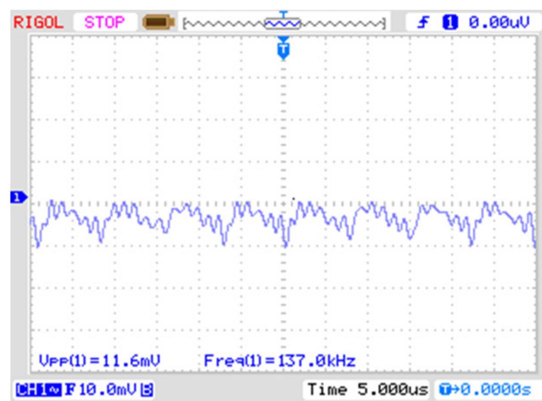
Iout= 3A, Vpk-pk= 448mV



Iout= 2.5A, Vpk-pk= 304mV

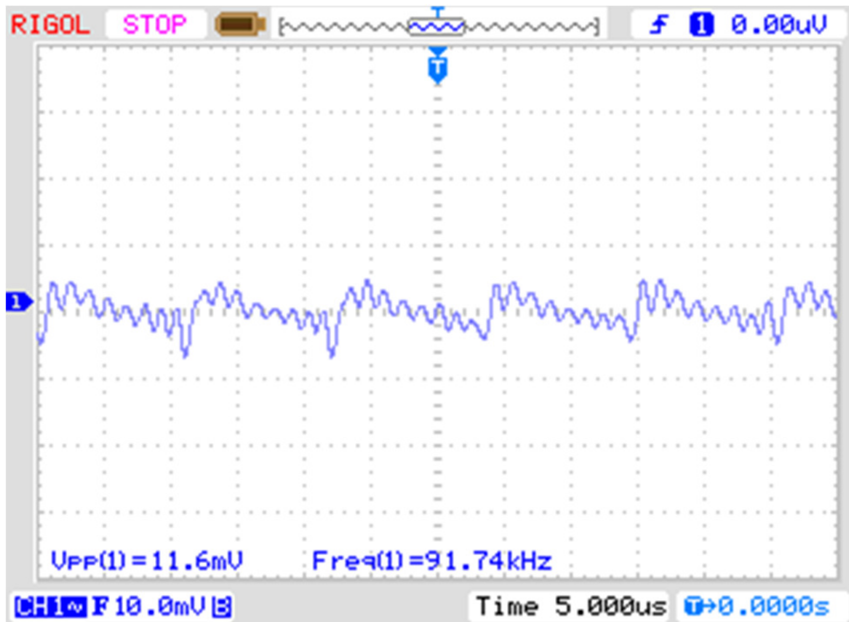


Iout= 2.0A, Vpk-pk=280mV



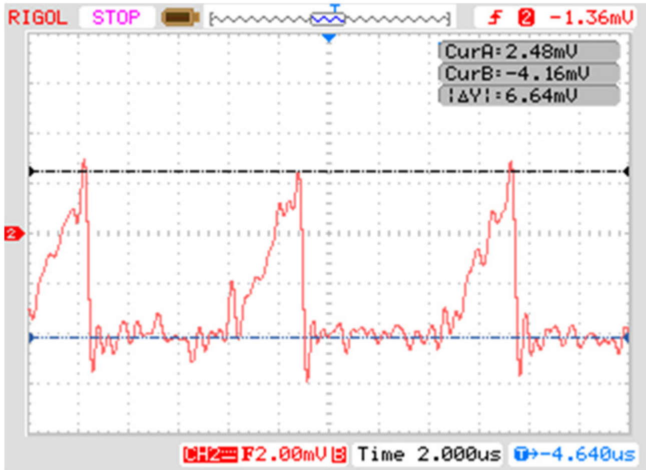
Iout= 1.5A, Vpk-pk= 232mV

Output Ripple Voltage at <1.5A Output (Variable Switching Freq.)

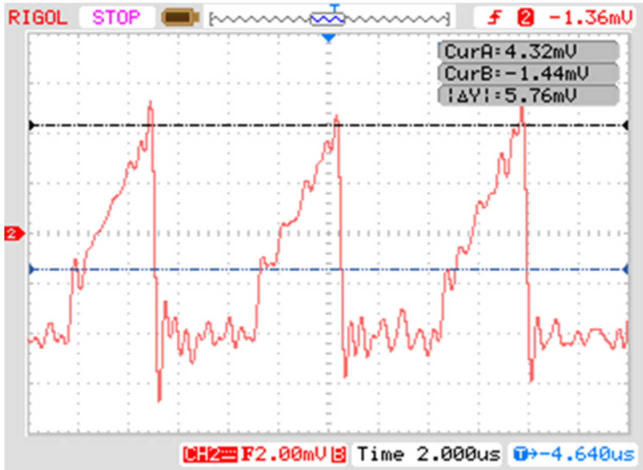


Iout= 1.5A, Vpk-pk= 232mV

Drain Current Waveform



Iout= 1.3A



Iout= 2.5A

$R_{\text{current sense}} = 0.2$ ohms

Comparing Efficiency of Linear and Switch-mode Power Supply

Power Supply	Input Power	Output Power	% Efficiency
Linear		30W	
Switch-Mode		30W	
Linear		0W (no-load)	-
Switch-Mode		0W (no-load)	-

% Efficiency = Output Power/Input Power X 100%

Output Power: $Pout = Vout \ x \ Iout$

- Compare the Linear and Switch-mode power supply
  - Weight & Size
  - Input voltage range & regulation
  - Temperature
  - Output voltage waveform

Line and Load Voltage Regulation

	IL=0A	IL=1.25A	IL=2.50A
Vin=120VAC	12.00V	11.98V	11.96V
Vin=240VAC	12.00V	11.98V	11.97V

Load Regulation:

$$\%\ Regulation = \frac{\text{Vout (No Load)} - \text{Vout (Full Load)}}{\text{Vout (nom)}} \text{ x } 100\%$$

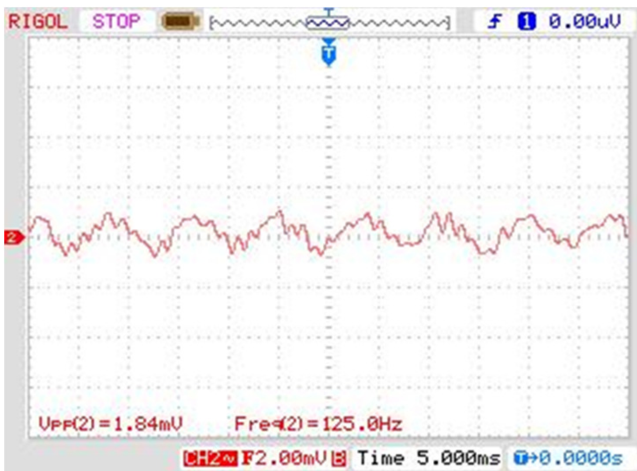
Line Regulation:

$$\%\ Regulation = \frac{\text{Vout (Line1)} - \text{Vout (Line2)}}{\text{Vout (nom)}} \text{ x } 100\%$$

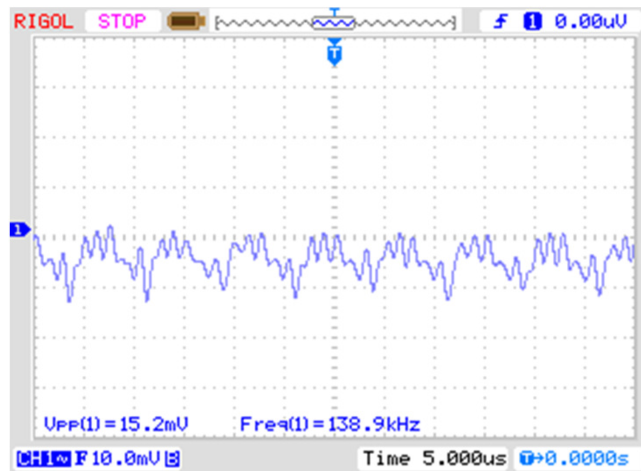
Temperature Measurements at Full Load

Vin=120VAC	Temp. in deg. C
Ambient	20 deg. C
IC (Mosfet + Control)	55 deg. C
Output Diode	47 deg. C
Transformer Core	48 deg. C

Comparing Output Voltage Waveform of Linear & Switch-mode



Linear



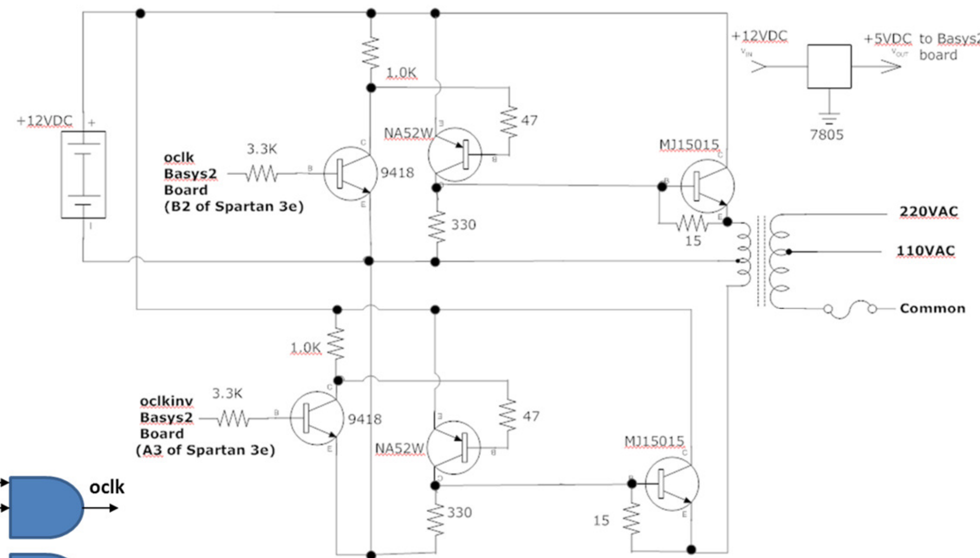
Switch-mode

Probe Set X 20= 36.8mV

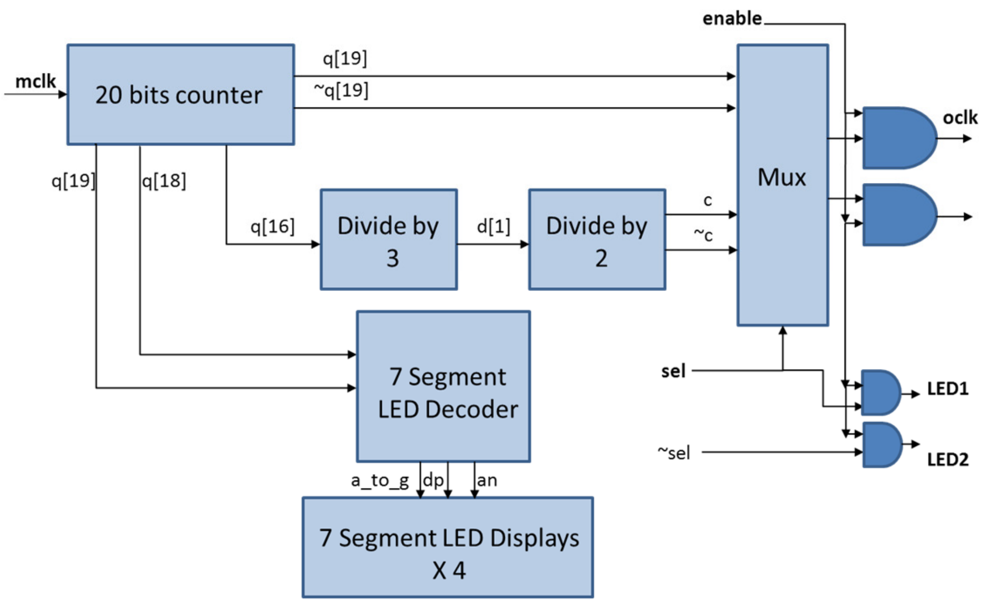
Probe Set X 20= 304mV

Iout = 2.5A

FPGA Based DC to AC Converter



Block Diagram of Power Controller



List of References

Brown, M. (2008). *Power Sources and Supplies.* Boston: Newnes.

Power Integrations (2010). RDR-242 Reference Design for a 30W Power Supply. Retrieved on Dec. 19, 2011 at www.powerint.com.

Scherz, P. (2000). *Practical Electronics for Inventors.* New York: McGraw-Hill.

Spiazzi, G. & Buso, S. (2002). Comparison Between two Single-Switched Isolated Flyback and Forward High-Quality Rectifiers for Low Power Applications. *APEC 2002 Conference Proceedings.* Retrieved on Dec. 19, 2011 at dei.unipd.it/~pel/Pagine_Personali/Simone/Articoli%20pdf/2002/APEC2002.pdf

High Efficiency Switch-mode Power Supply Design Overview

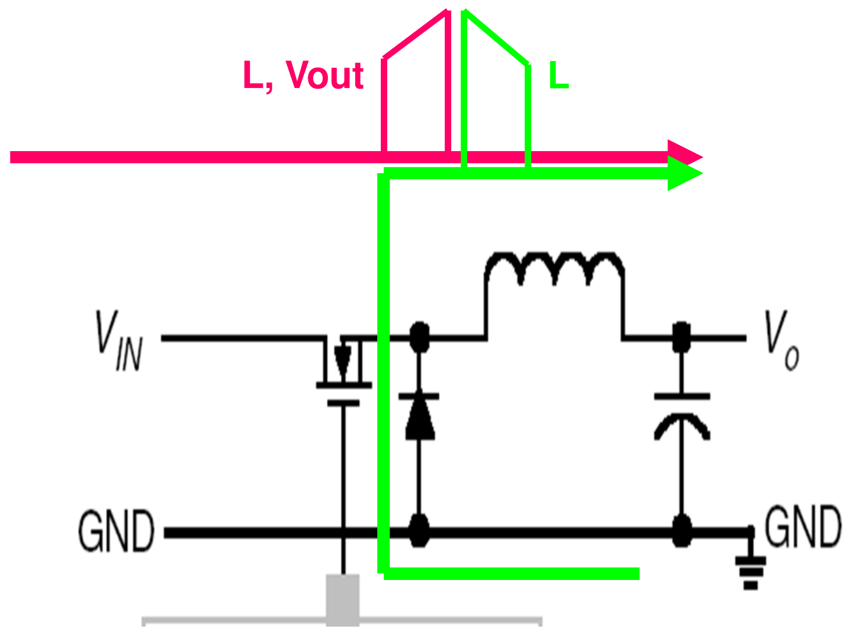
Module Two

Power Conversion Topologies

Review of Relevant Component Formulas

	Volts & Amps.	Energy	DC	AC (LF)	& AC (HF)
Resistor:	$V = I * R$	$I^2 * R * t$	R	R	R + L + C + Rskin effect
Capacitor:	$I = C\ dV/dt$	$½\ C * V^2$	Dielectric Resistance	C + ESR	C + ESR + Series L
Inductor:	$V = L\ di/dt$	$½\ L * I^2$	ESR	L + ESR	L + ESR + Parallel C

The Buck Converter



Vo/Vin= D

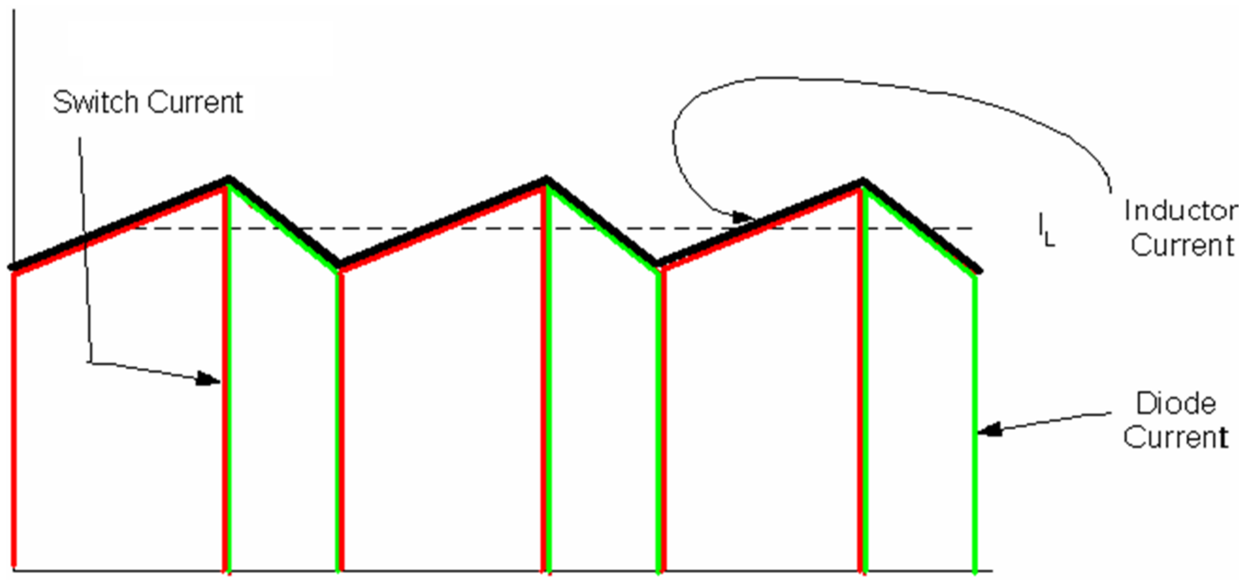
- **Input Cap Current 'choppy'**
- **Output Cap Current smooth**
- **Average Inductor Current = Load Current**

The Voltage Across the Inductor

- A 'steady state' in power conversion can be defined as $\Delta I_{ON} = \Delta I_{OFF}$

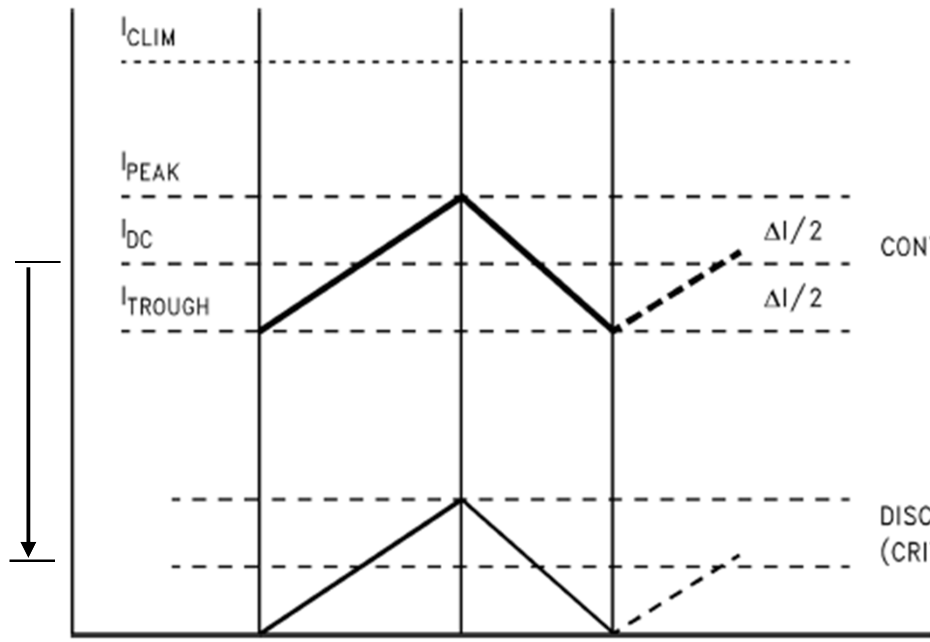
$$V_{ON} = L\frac{\Delta I_{ON}}{t_{ON}}$$

$$V_{OFF} = L\frac{\Delta I_{OFF}}{t_{OFF}}$$



Continuous Conduction Mode CCM & Discontinuous Conduction Mode DCM

As the output current I_{DC} decreases the operation transitions from CCM to DCM



Power supply can be designed to specifically operate in CCM or in DCM

CCM VS DCM Operation

CCM

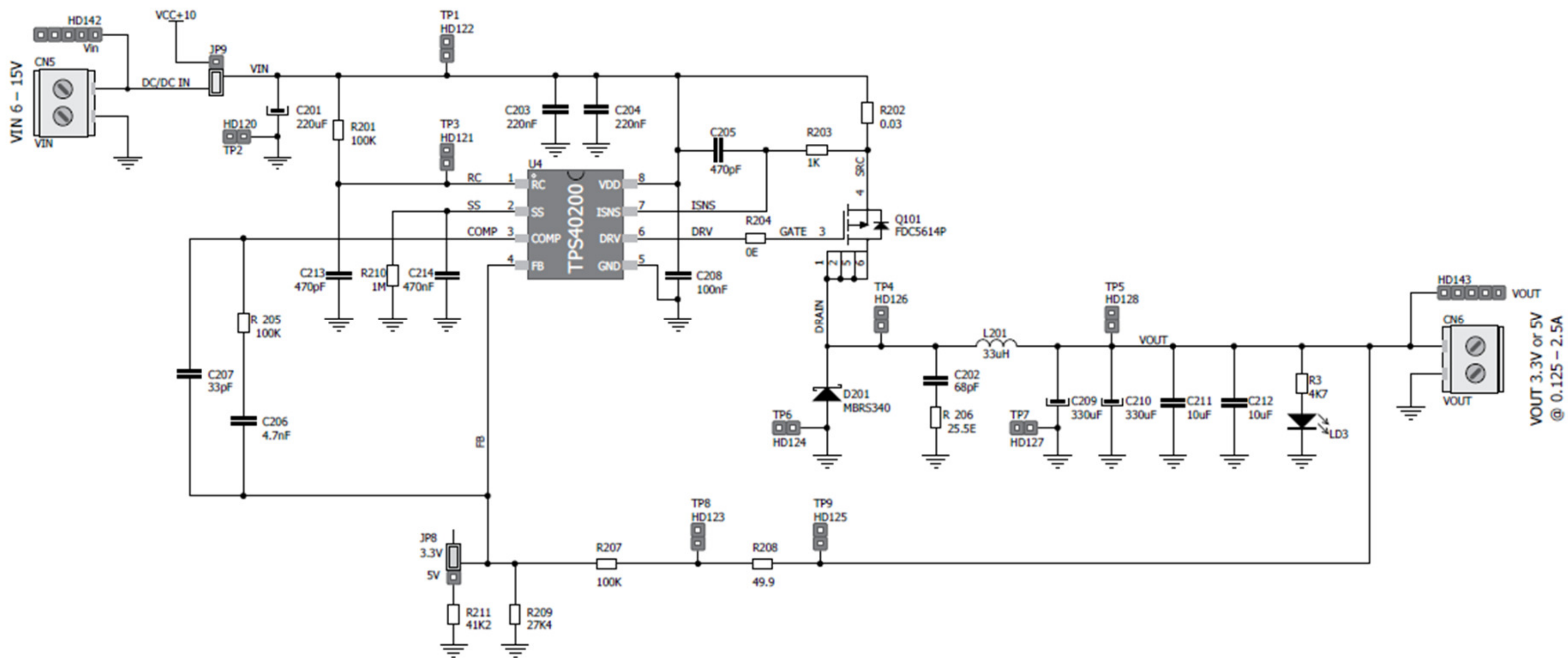
- Low peak current
- Low inductor ripple current
- Slower dynamic load resp.
- Difficult to stabilize
- Higher inductance

DCM

- High peak current
- High inductor ripple current
- Fast dynamic load step resp.
- Easier to stabilize
- Smaller inductance

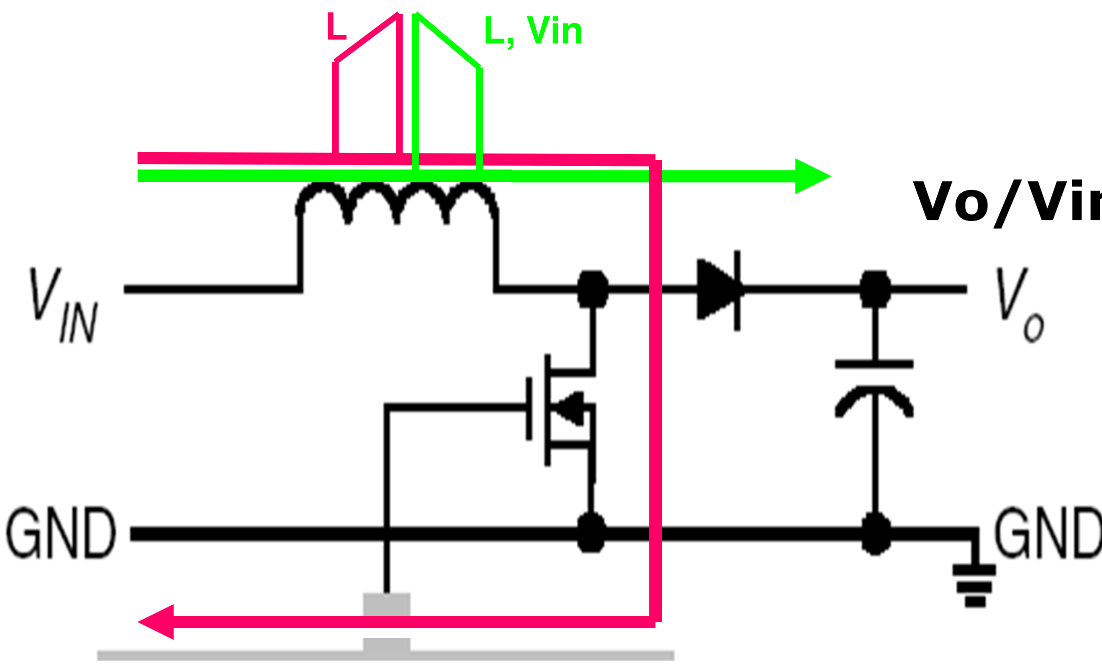
Based on the above what applications should we use CCM over DCM and vice versa?

Buck Converter Board Evaluation



- Measure efficiency with Iout 0.1A to 1.5A for 3.3V & 5V output
- Monitor duty cycle & IL (inductor current) with Iout =0.5A and Vin from 6V to 12V
- Monitor sawtooth waveform and compare with Mosfet switching
- Vary output voltage by modifying voltage divider

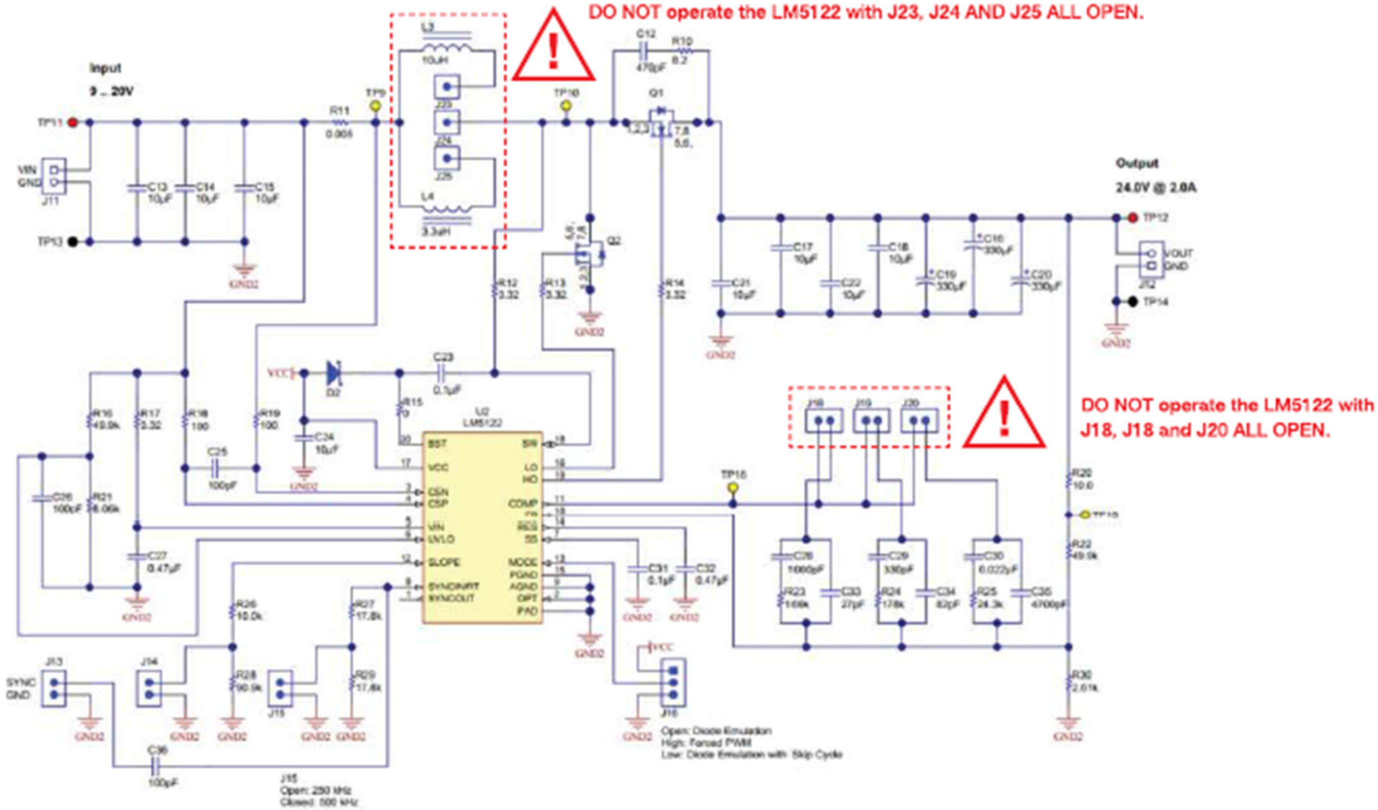
The Boost Converter



Vo/Vin= 1/(1-D)

- **Input Cap Current smooth**
- **Output Cap Current choppy**
- **Average Diode Current = Load Current**

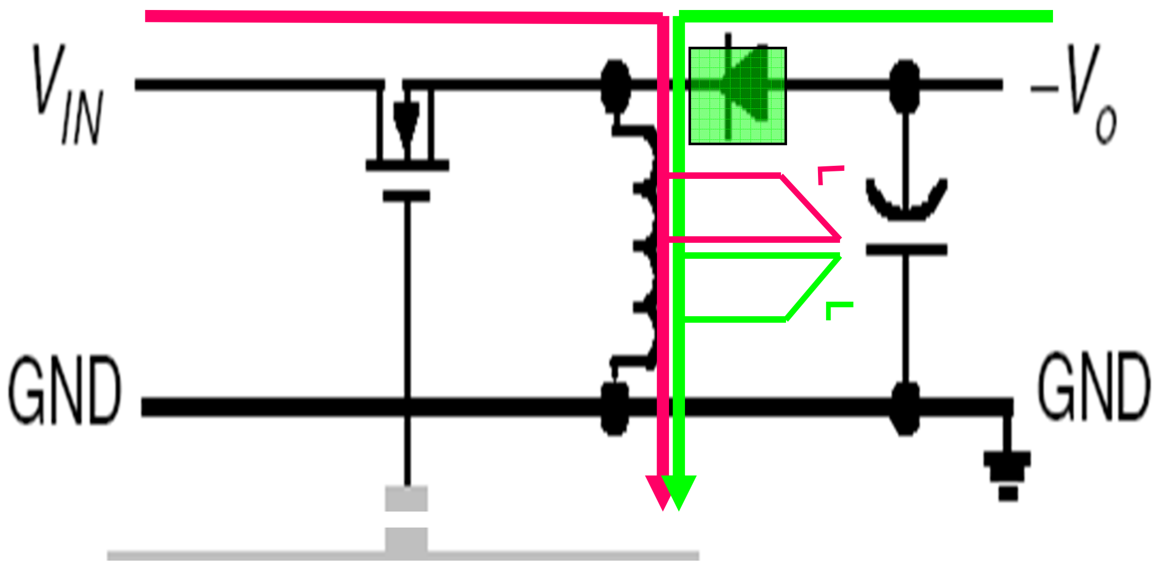
The SR Boost Converter Exercise



- Measure efficiency in SR and in Diode Emulation mode
- Monitor duty cycle as Vin is adjusted
- Monitor output ripple voltage

The Buck-Boost Converter

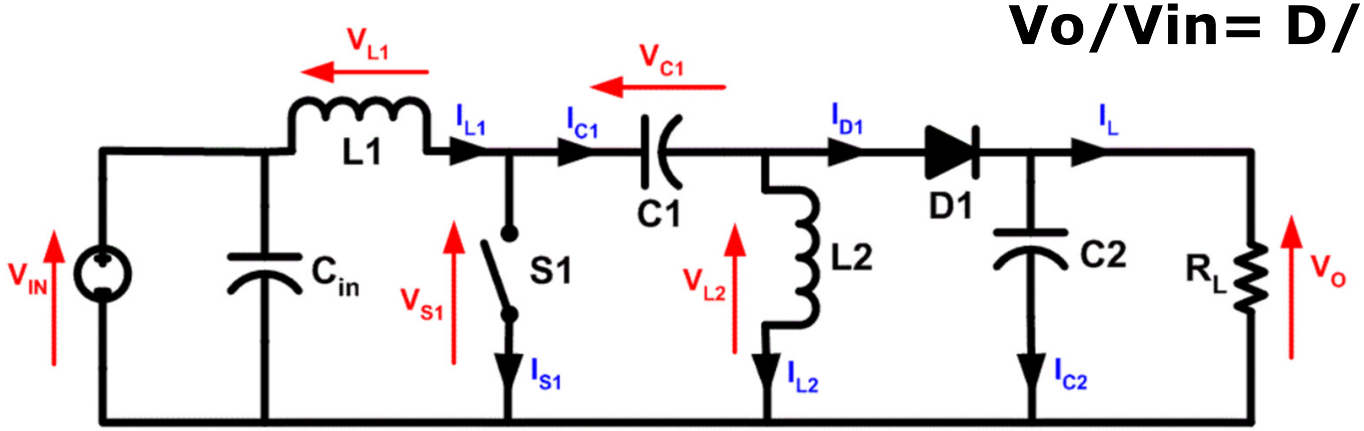
Vo/Vin= -D/(1-D)



- **Input Cap Current choppy**
- **Output Cap Current choppy**
- **Average Diode Current = Load Current**

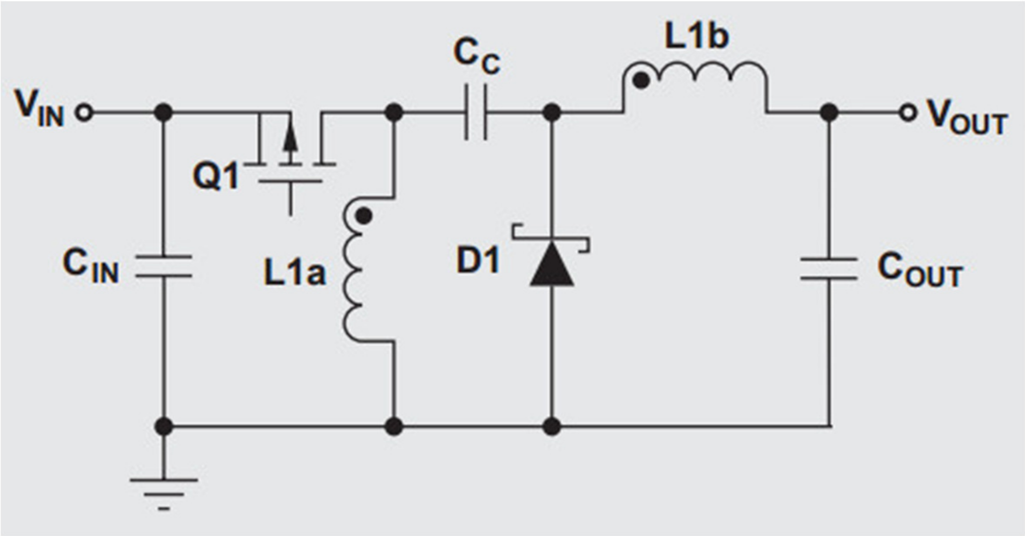
The SEPIC Converter

Vo/Vin= D/(1-D)



- **Input Cap Current smooth**
- **Output Cap Current choppy**
- **Non inverting output**
- **Interchange D1 & L2 becomes cuk converter**
    - **-D/(1-D)**
- **Zeta is another non inverting variant**

The Zeta Converter



$$Vo/Vin = D/(1-D)$$

Duty Cycle Equation at CCM Based on Volt-Sec. Law

	Buck	Boost	Buck-Boost
V_{ON}	$\mathbf{V_{IN} - V_O}$	$\mathbf{V_{IN}}$	$\mathbf{V_{IN}}$
V_{OFF}	$\mathbf{V_O}$	$\mathbf{V_O - V_{IN}}$	$\mathbf{V_O}$
t_{ON}	$\mathbf{D/f}$		
t_{OFF}	$\mathbf{(1-D)/f}$		
Voltseconds	$(V_{IN} - V_O)D = V_O(1-D)$	$V_{IN}D = (V_O - V_{IN})(1-D)$	$V_{IN}D = V_O(1-D)$
'$AB = CD$' $\frac{A}{C} = \frac{D}{B}$	$\frac{V_{IN} - V_O}{V_O} = \frac{1-D}{D}$	$\frac{V_{IN}}{V_O - V_{IN}} = \frac{1-D}{D}$	$\frac{V_{IN}}{V_O} = \frac{1-D}{D}$
$\frac{A+C}{C} = \frac{D+B}{B}$	$\frac{V_{IN} - V_O + V_O}{V_O} = \frac{1-D+D}{D}$	$\frac{V_{IN} + V_O - V_{IN}}{V_O - V_{IN}} = \frac{1-D+D}{D}$	$\frac{V_{IN} + V_O}{V_O} = \frac{1-D+D}{D}$
therefore	$\frac{V_{IN}}{V_O} = \frac{1}{D}$	$\frac{V_O}{V_O - V_{IN}} = \frac{1}{D}$	$\frac{V_{IN} + V_O}{V_O} = \frac{1}{D}$
reciprocal	$D = \frac{V_O}{V_{IN}}$	$D = \frac{V_O - V_{IN}}{V_O}$	$D = \frac{V_O}{V_{IN} + V_O}$

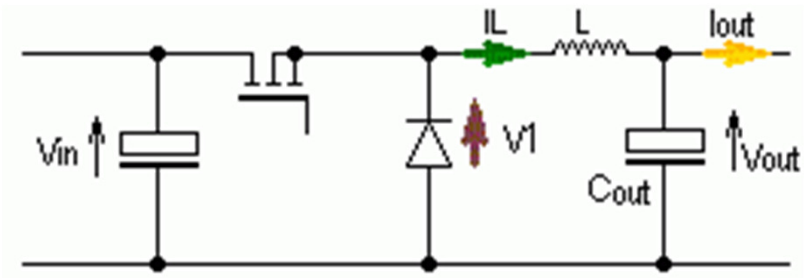
Online Simulation Site

http://schmidt-walter.eit.h-da.de/smps_e/smps_e.html

Allows user to create simple design based on specified parameter and simulate circuit performance

Topologies Covered

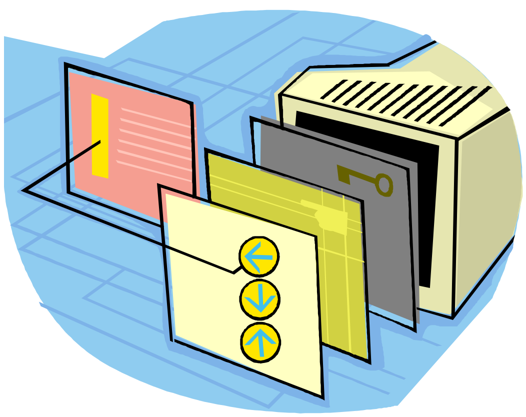
- Buck
- Boost
  - •PFC Boost
- •Buck-Boost
- •Flyback Converter
- •Forward Converter (Basic design)



Steps to Exercise (Part 1)

Part 1 Understanding the Topology

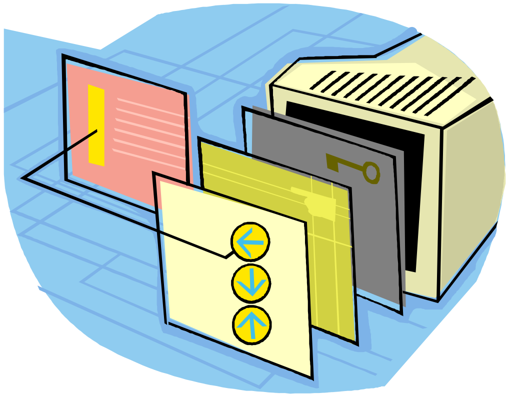
- Choose the topology
- Sweep across time line to see sequence of operation
  - Understand circuit operation and corresponding waveforms
- Change parameter to transition between CCM and DCM
  - Understand the factors involved in CCM & DCM operation



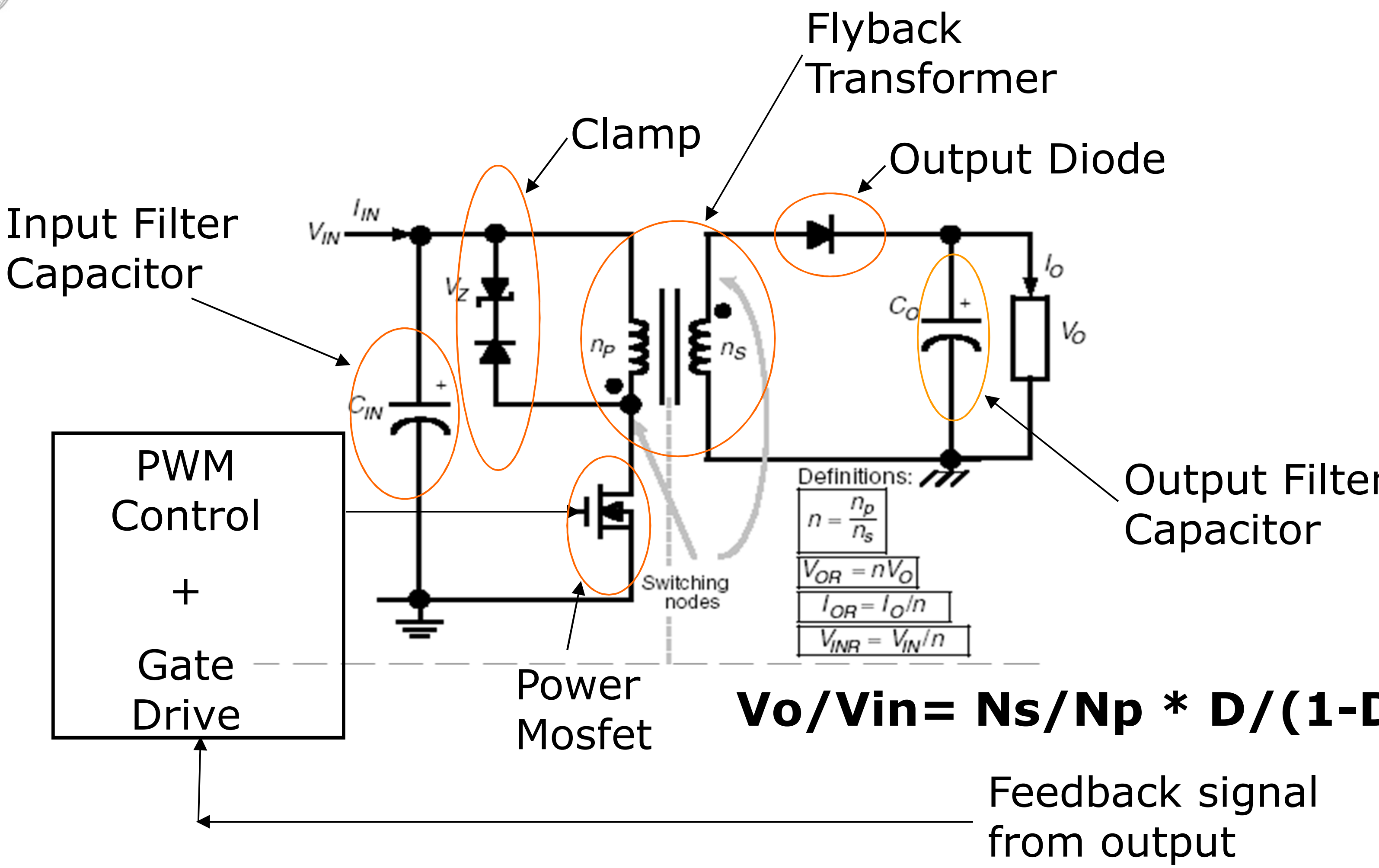
Steps to Exercise (Part 2)

Part 2 Basic Design

- Choose the topology
- Input the specs. parameter
  - Understand design specs. requirement
- Run your design and observe the waveforms
- Review the generated design of magnetic component

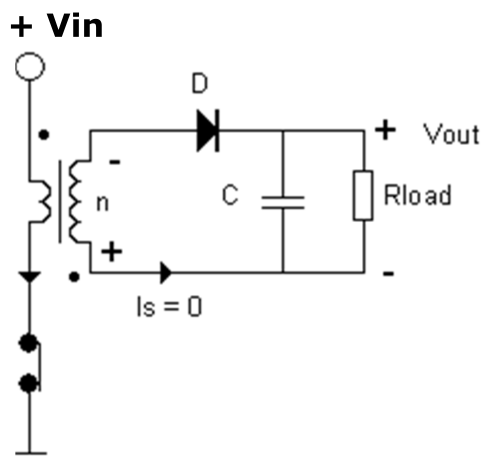


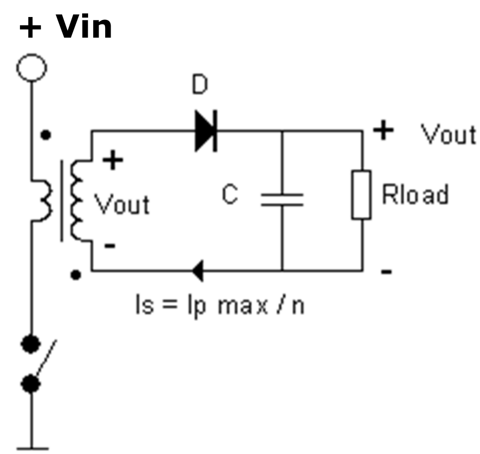
Flyback DC-DC Converter



Vo/Vin= Ns/Np * D/(1-D)

The Operation of the Flyback Converter





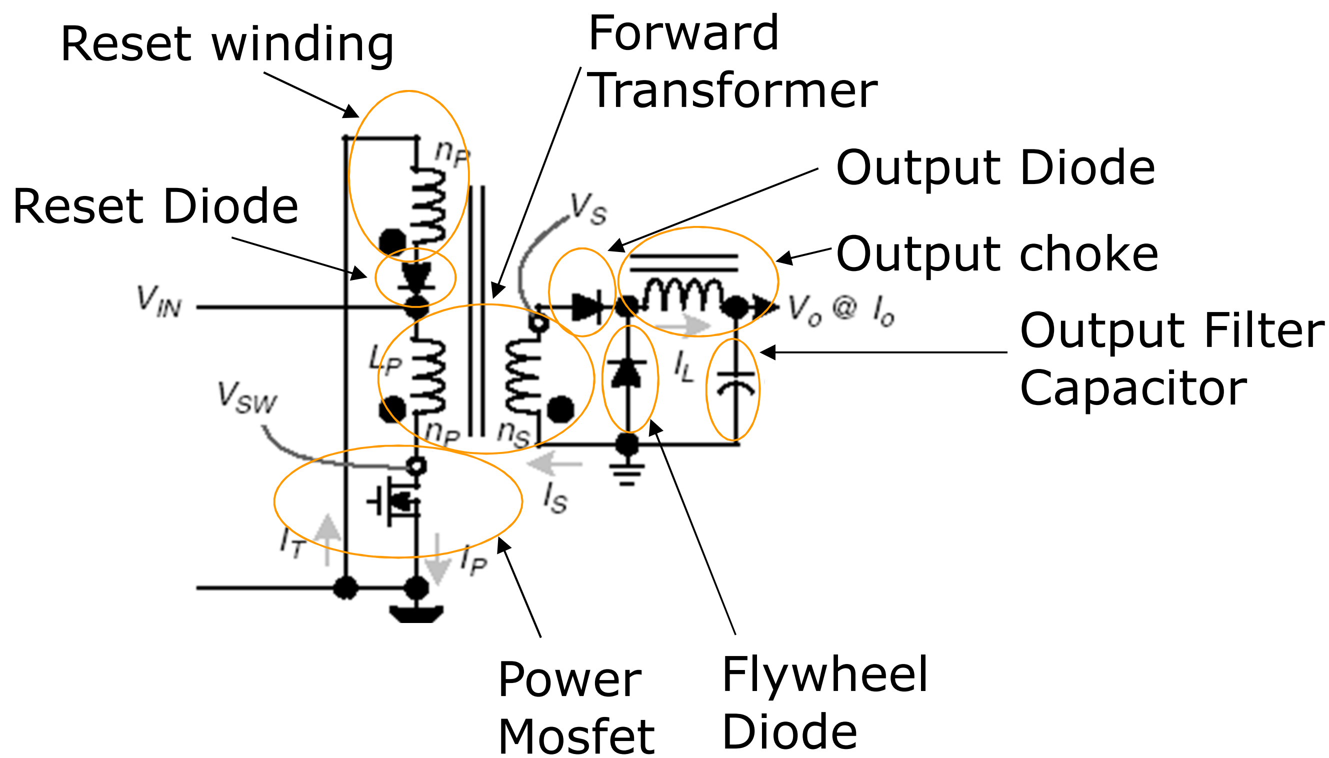
MOSFET Turned-On

- Diode D is off
- Cap. C discharges

MOSFET Turned-Off

- Diode D is on
- Cap. C is charged

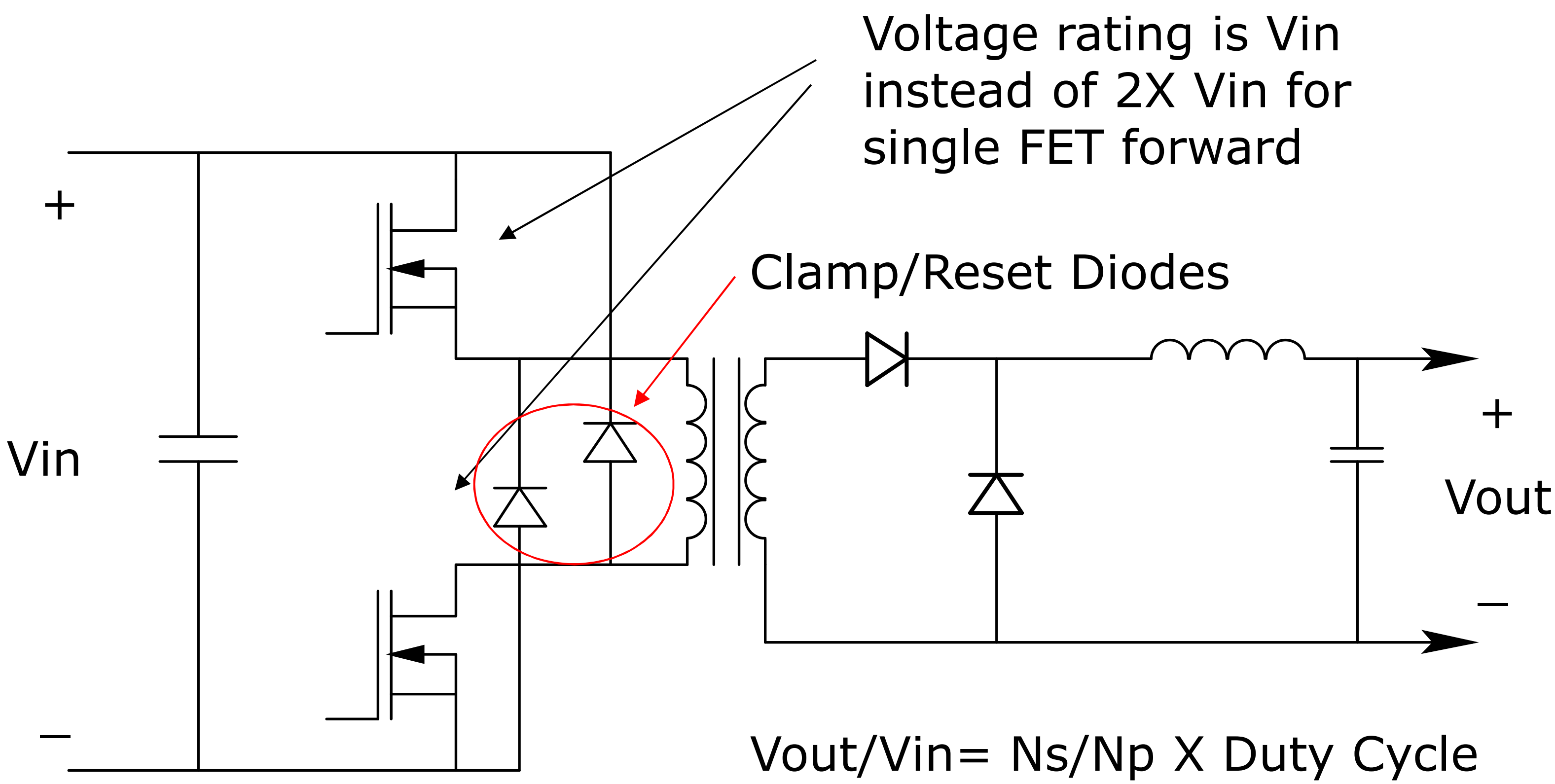
Forward DC-DC Converter



Comparing the Flyback and the Forward Converter

	Flyback	Forward
Higher Power Range		X
Lower input current		X
Lower output ripple		X
Higher Efficiency		X
Fewer Parts	X	
Lower CE & Input harmonic current	X	

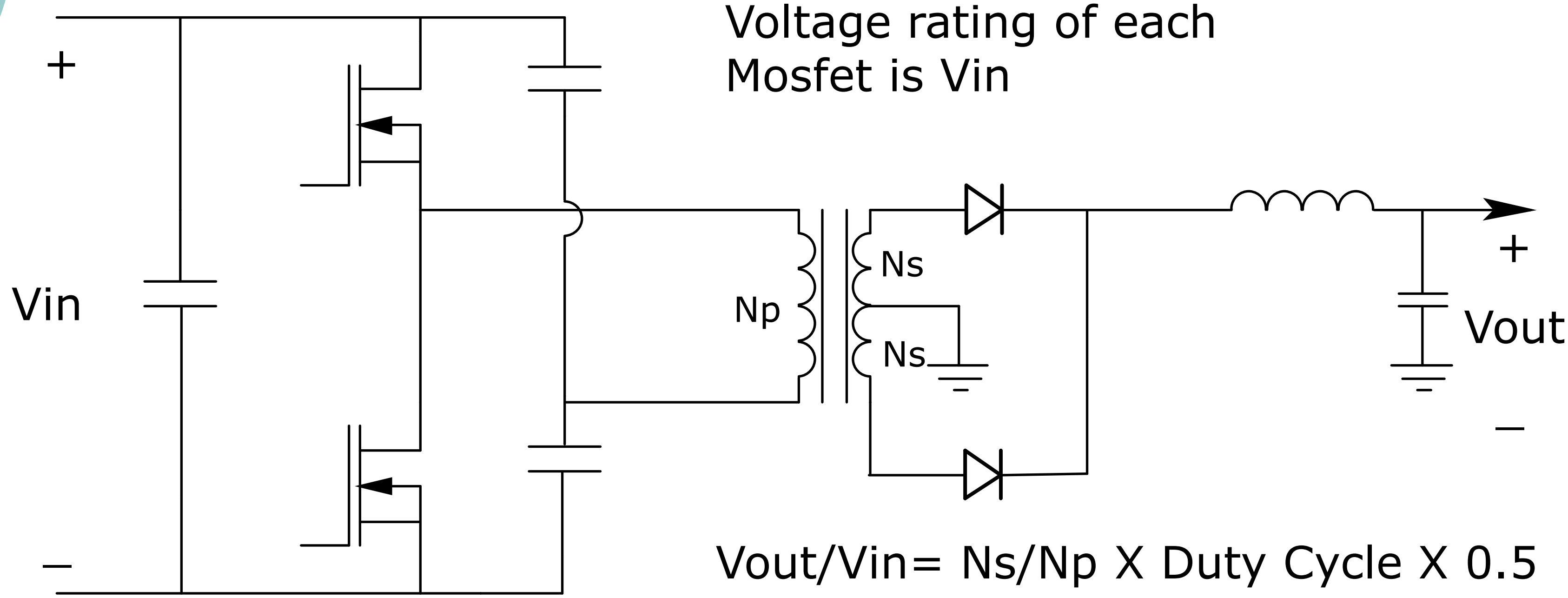
Two FET Forward DC-DC Converter



Vout/Vin= Ns/Np X Duty Cycle

Increases the power capability of Forward converter

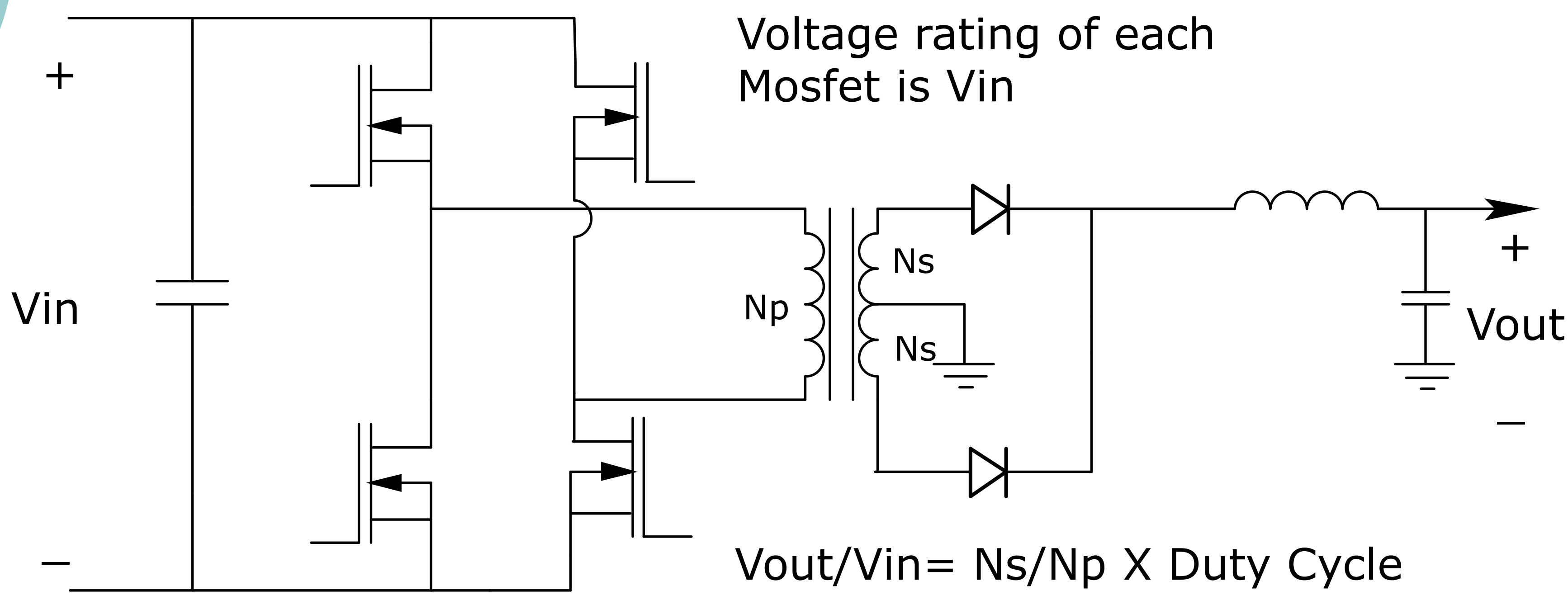
Half Bridge DC-DC Converter



Voltage rating of each Mosfet is Vin

Vout/Vin= Ns/Np X Duty Cycle X 0.5

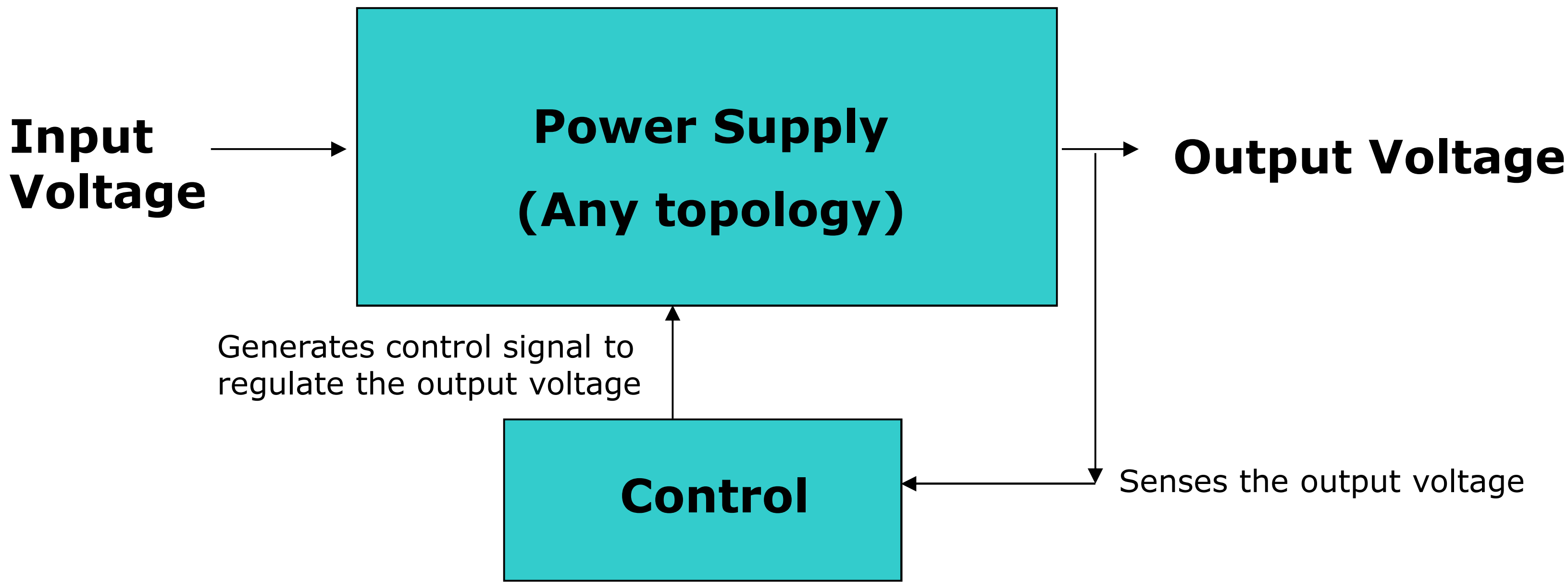
Full Bridge DC-DC Converter



Voltage rating of each Mosfet is Vin

Vout/Vin= Ns/Np X Duty Cycle

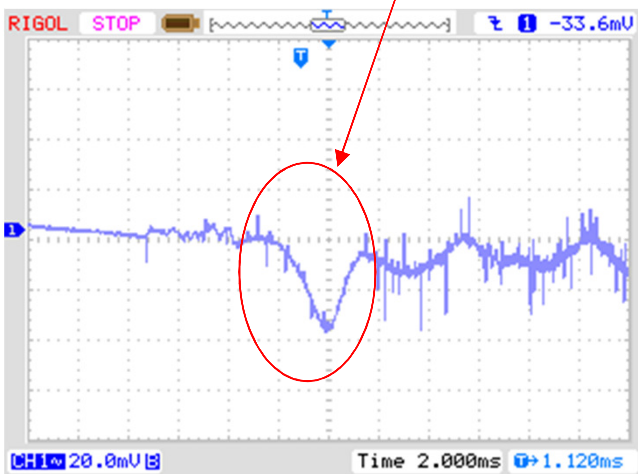
Basics in Feedback and Control Systems



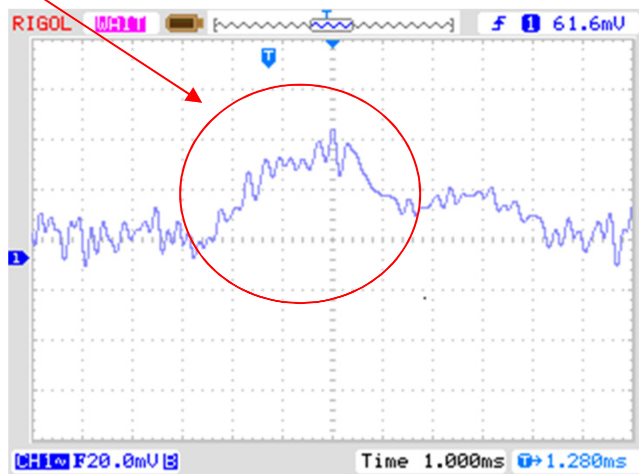
Design consideration: Speed of response & stability

Control System Response to Output Load Step Current

Vout drop or spike based on response time of controller



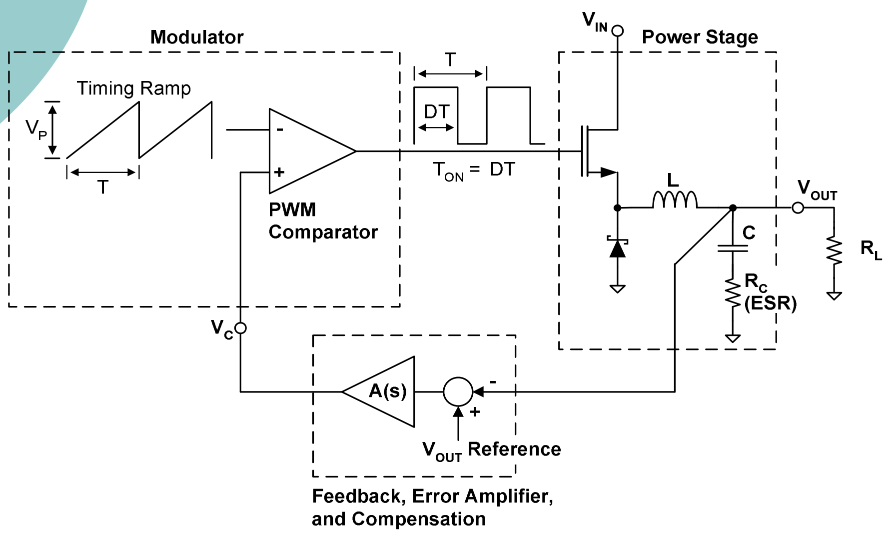
Vout with 0 to 2.5A load step



Vout with 2.5A to 0A load step

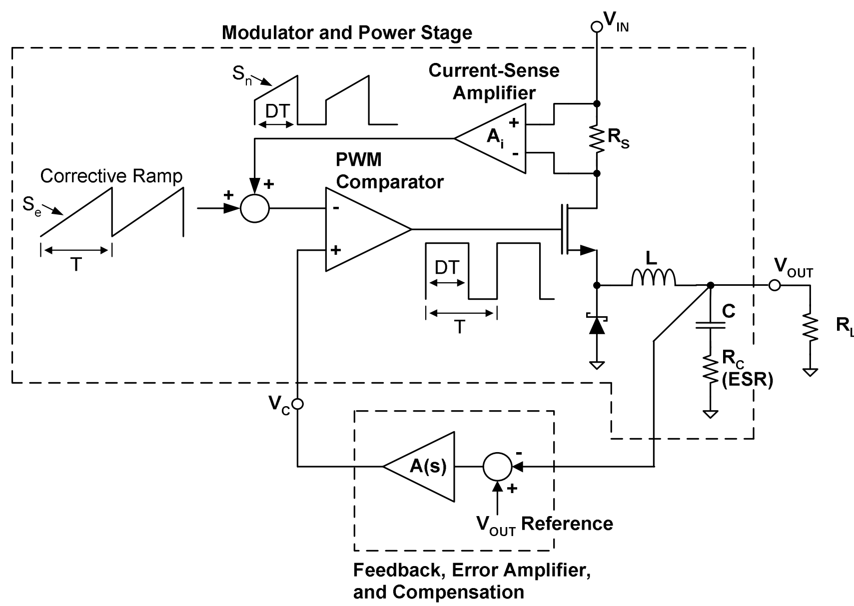
Types of Control Approaches

Voltage Mode Control



- Simpler
- More difficult to compensate for stability

Current Mode Control



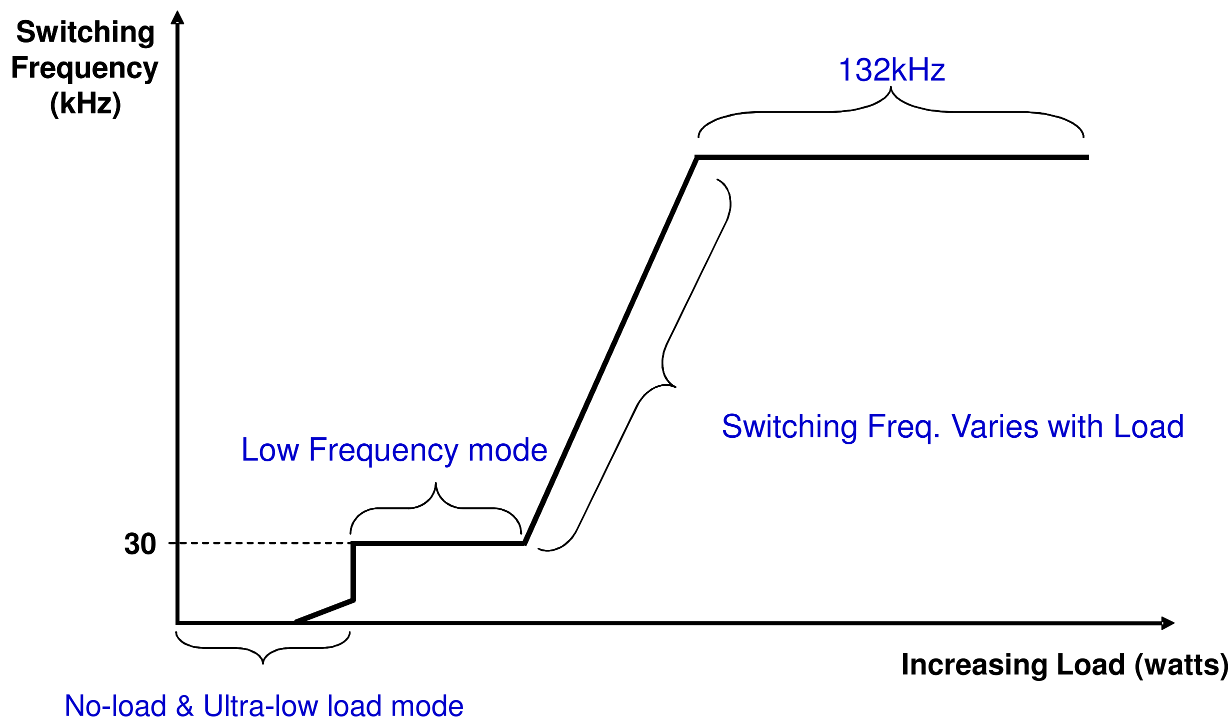
- More complex (multiple control loops)
- Easier to compensate for stability
- Provides faster response to drain current changes

Modern Control Approaches

Modern Controller Approaches

- Variable freq. with multiple modes
- On/Off control
- Burst Mode
- Digital control
- Primary Side Control

Modern Flyback Controller Offers Multiple Mode of Operation



List of References

Maniktala, S. (2005). *Switching Power Supply Design & Optimization.* New York: McGraw Hill.

Maniktala, S. (2006). *Switching Power Supplies A to Z.* Boston: Newnes.

Maniktala, S. (2008). *Troubleshooting Switching Power Converters.* Boston: Newnes.

Power Integrations (2010). TOPSwitch-JX Data Sheet. Retrieved on Dec. 19, 2011 at www.powerint.com.

High Efficiency Switch-mode Power Supply Design Overview

Module Three

Rectifiers &

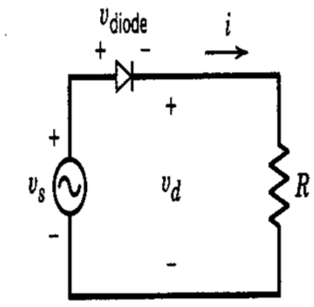
Active Power Factor Correction

Simplest Rectifier – resistive load

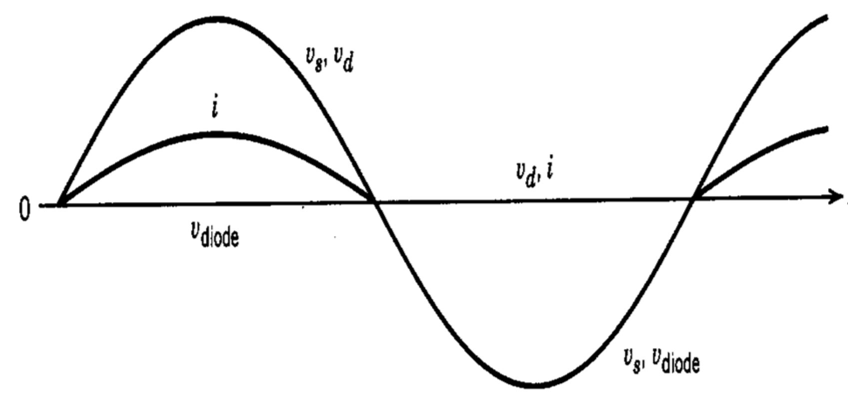
- Simplest case:
- AC source – Diode – Load

- Diode conducts while voltage across it is +ve

- Diode blocks while voltage across it is -ve

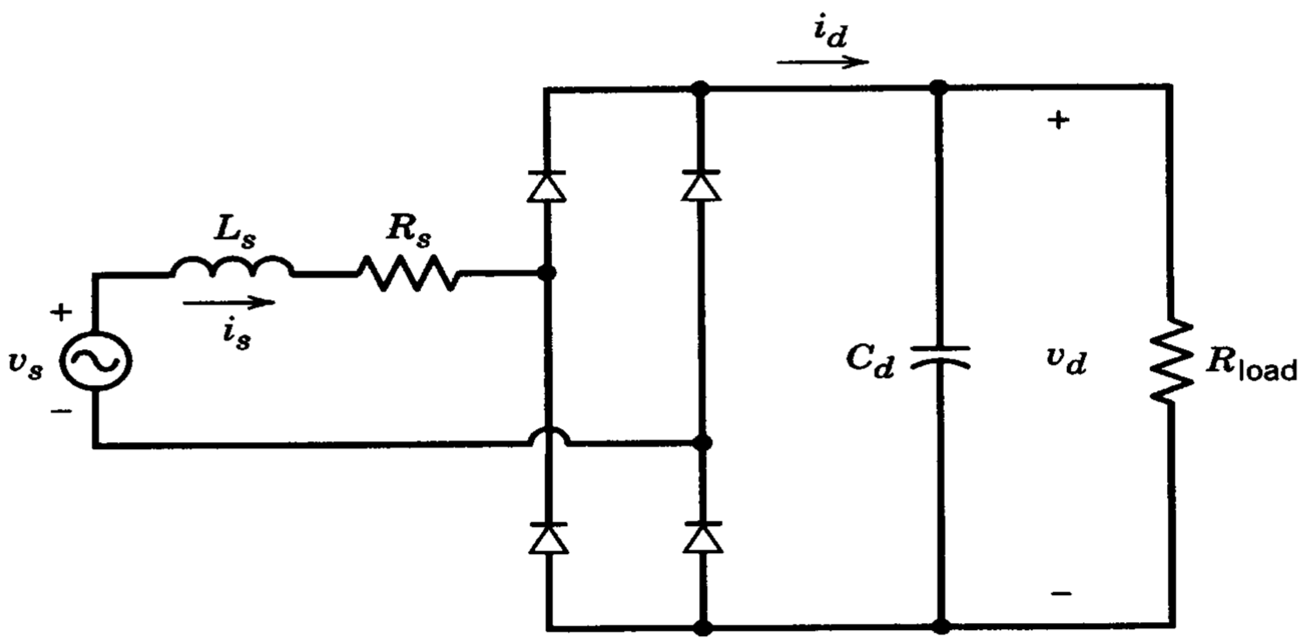


(a)



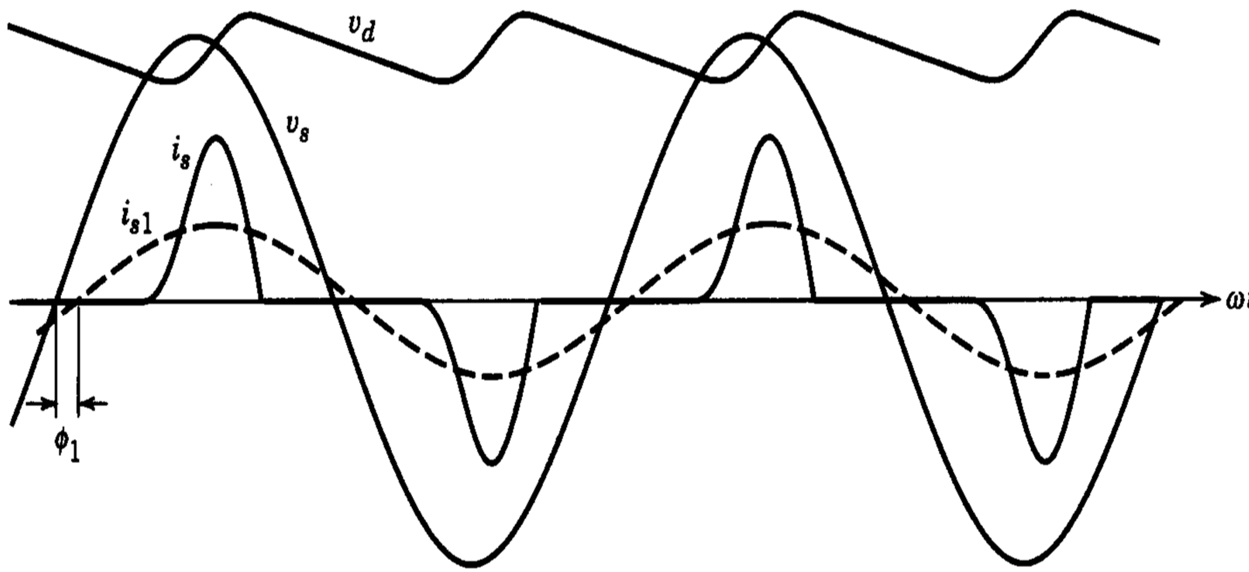
(b)

Diode-Rectifier with a Capacitor Filter



We can increase efficiency with synchronous rectifier by replacing the Diodes with Mosfets

Diode-Bridge Rectifier: Waveforms



- Analysis using PSpice

The Power Triangle

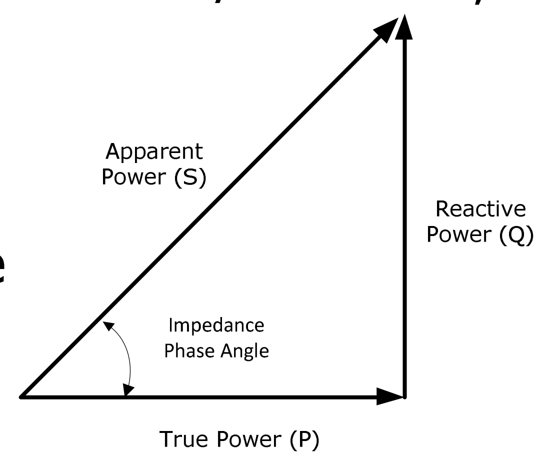
•True Power – it is the power dissipated by a load, P (watts). $P = I^2R = E^2/R$

•Reactive Power – it is the power merely absorbed and returned in load due to its reactive properties, Q (VAR). $Q = I^2X = E^2/X$

•Apparent Power – it is the total power in AC circuit, both dissipated and absorbed/returned, S (VA)

$S = I^2Z = E^2Z$

Power Triangle



The Power Factor Equation

•Power Factor – describes the input characteristics of an electrical appliances powered by alternating current

•Power Factor – is the ratio between Real Power and Apparent Power.

$$PF = \frac{P_{REAL}}{P_{APPARENT}} = \cos\phi$$

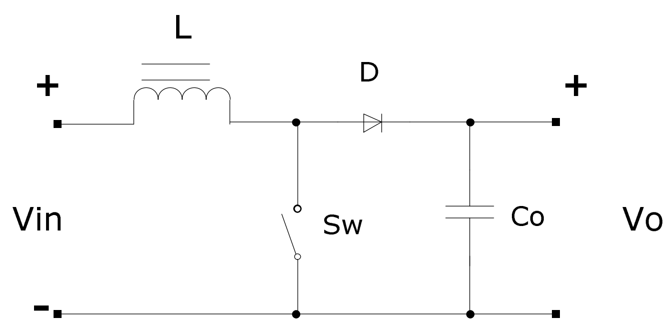
•If the Power Factor is lagging then the circuit is predominantly inductive. Impedance angle is positive.

•If the Power Factor is Leading then the circuit is predominantly capacitive. Impedance angle is negative.

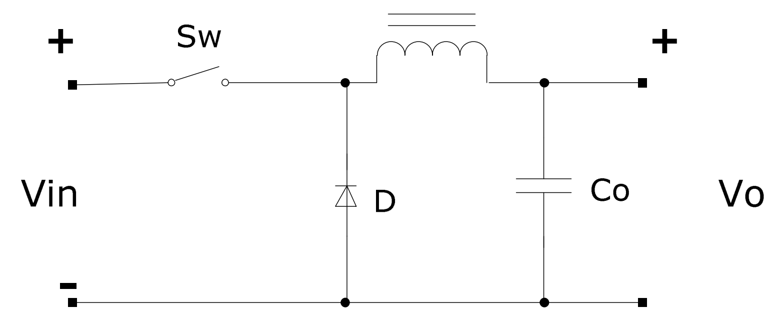
•Poor Power Factor of an Inductive load can be corrected by adding capacitor in parallel.

Active Power Factor Correction

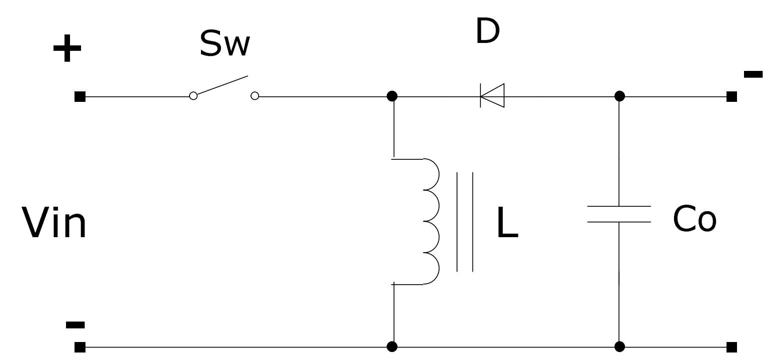
Basic Converter Topologies for Active PFC Circuit



Boost Converter



Buck Converter



Buck – Boost Converter

Comparing the Three Active Power Factor Correction Approach

Boost Converter	Buck Converter	Buck – Boost Converter
High PF Correction	Poor PF Correction	High PF Correction
Vout > Vin	Vout < Vin	Vout is free
Small Filter	Large Filter	Large Filter
Vds rating = Vout	Vds rating = Vin	Inrush Current Protection
	Short Circuit Protection	Short Circuit Protection
		Output Isolation

The Boost Converter Approach

Active Power Factor Correction using Boost Converter

Characteristic of Boost Converter:

•Output voltage is always higher than the input voltage, is the same polarity, and is not isolated from the input.

•The input current for a boost power stage is continuous, same as the inductor current.

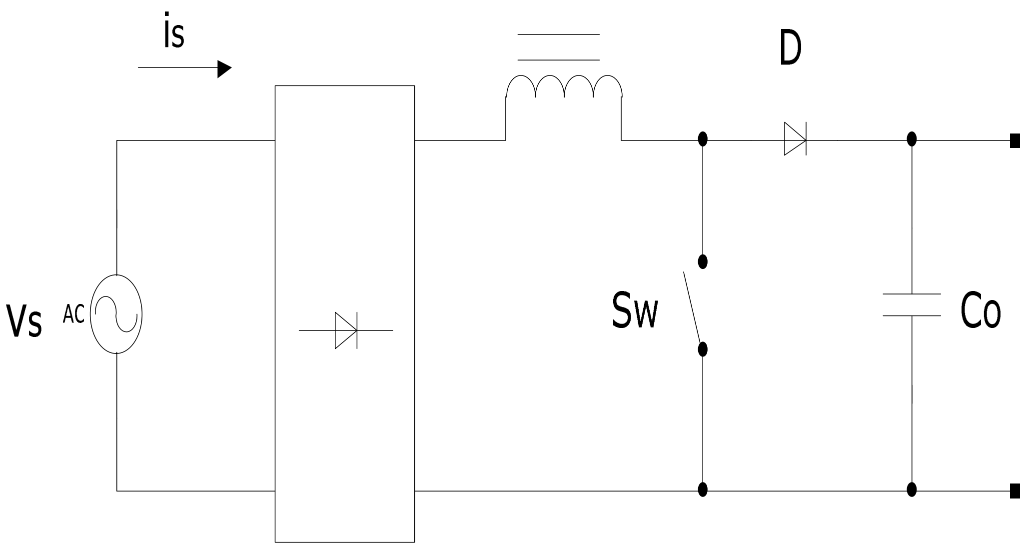
•The output current for a boost power stage is discontinuous, because the output diode conducts only during a portion of the switching cycle.

•The output capacitor supplies the entire load current for the rest of the switching cycle.

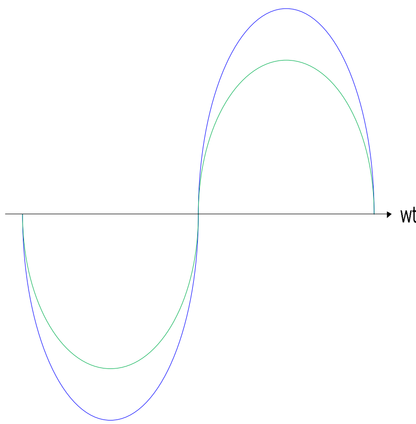
The Boost Converter Operation

Basic Principle of PFC Operation:

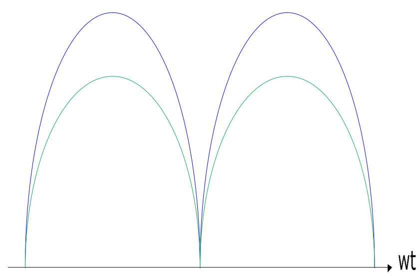
- Input current i_s should be sinusoidal and in phase with v_s.
- If phase between input voltage and current $\Phi = 0$, Hence, power factor = $\cos \Phi = 1$



PFC Boost Converter Circuit



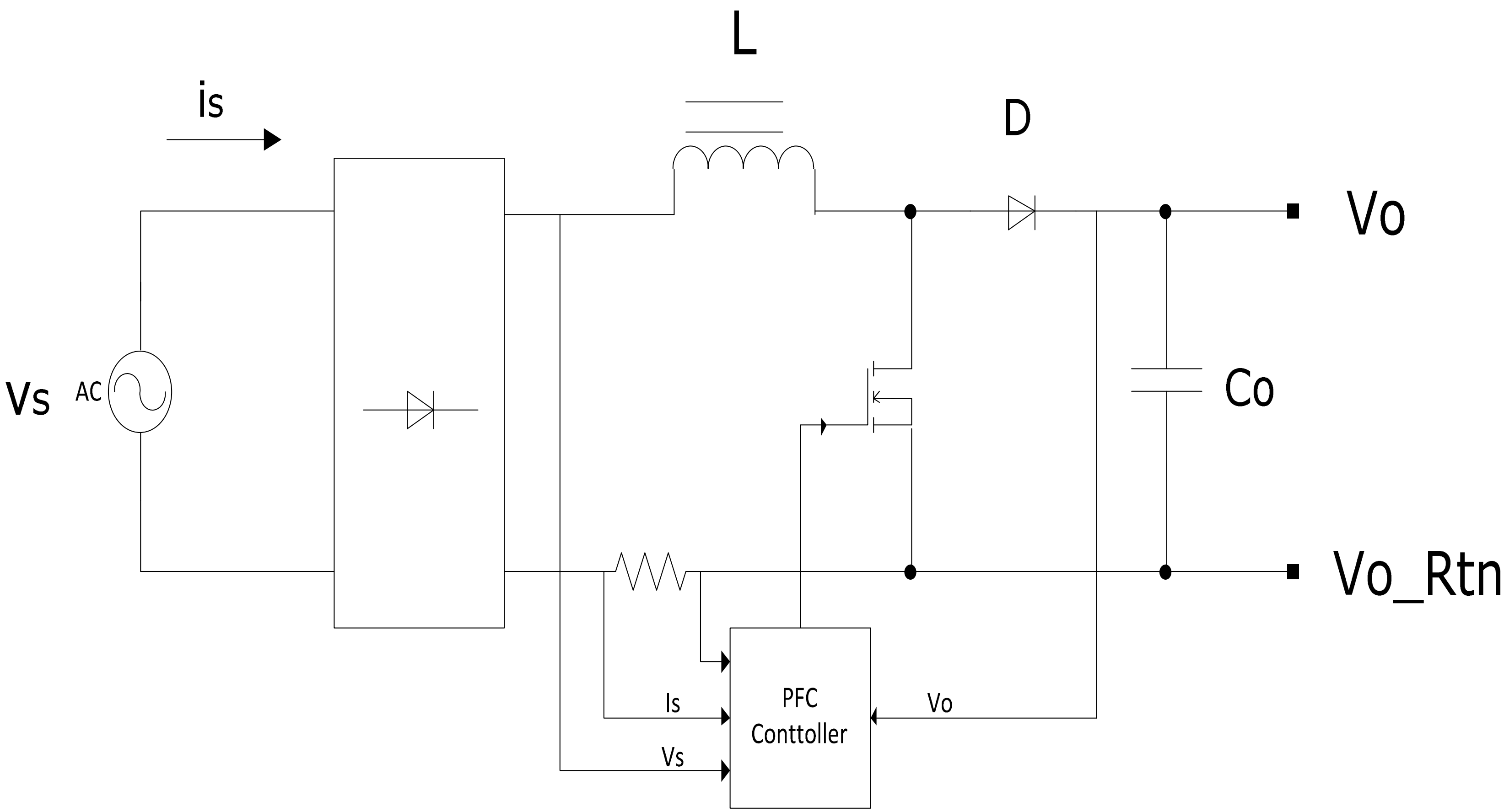
Input Voltage and Input Current



Rectified Vs and IL

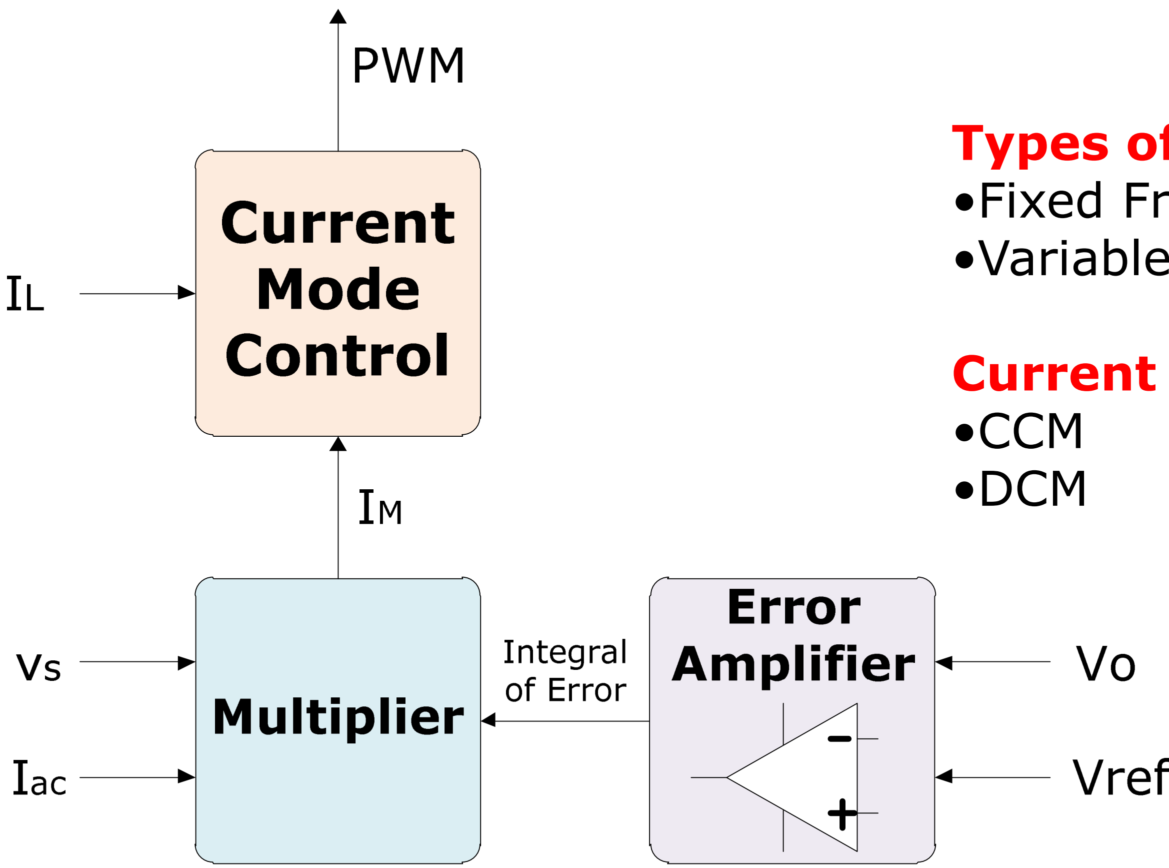
The Boost Converter Block Diagram

Block Diagram of Boost PFC



The PFC Controller

Block Diagram of PFC Controller

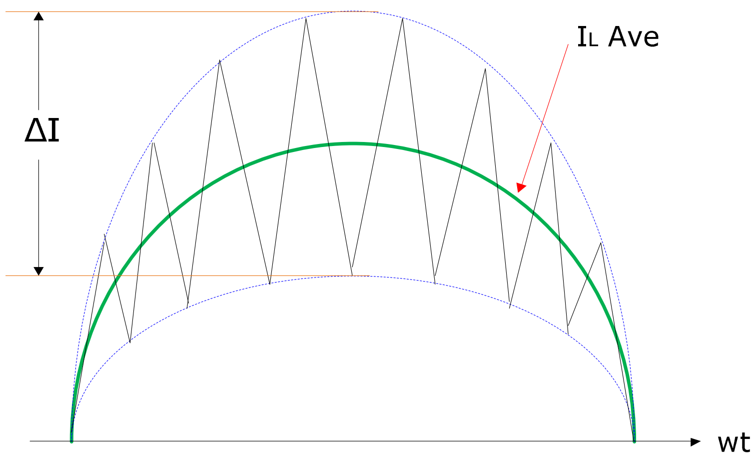


Types of PWM
- Fixed Frequency
- Variable Frequency

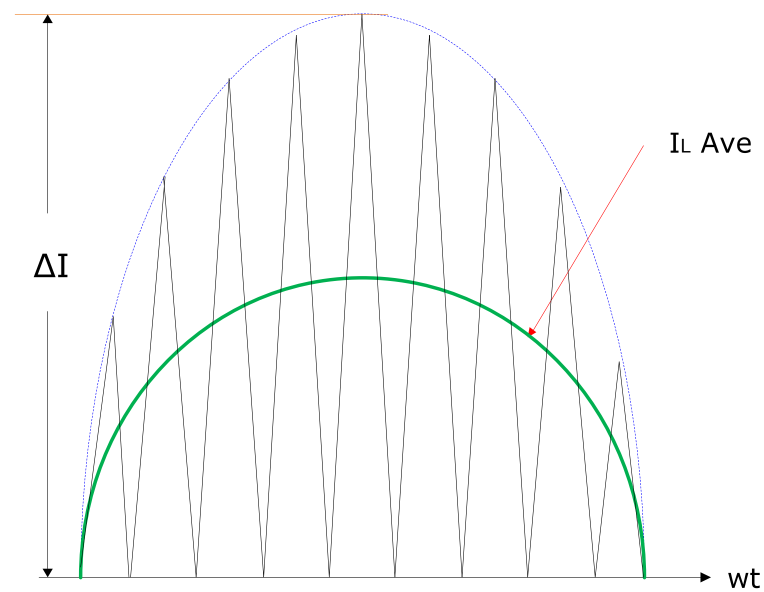
Current Mode Setting
- CCM
- DCM

The CCM and DCM Inductor Current

Inductor Current



Continuous Conduction Mode



Discontinuous Conduction Mode

Comparing CCM and DCM for Boost PFC

- Continuous Conduction Mode
  - Advantages:
    - Low EMI
    - Small Current Ripple
  - Disadvantages:
    - Large size of inductor
- Discontinuous Conduction Mode
  - Advantages:
    - Small size of inductor
  - Disadvantages:
    - High EMI

Design Consideration for PFC Choke

- Inductor Ripple Current
  ΔI = 20% to 40% of I_{Load}

- Size of the Inductor

- Shape of the Inductor
  - Toroid, EE

- Flux Saturation of the Inductor
  - Bmax

- Core Material
  - Molypermalloy (MPP), Iron Powder

- Core Losses
  - DCR Loss
  - Hystereris Loss

Output Capacitor Sizing for hold-up Time

Factors affecting the selection of output capacitor:

•Hold-up time capability, usually 20 ms for computer power supplies.

•Ripple current handling capability.

$$C_{out} = \frac{2 \bullet P_{out} \bullet t_{holdup}}{(V_{o\_\min}{}^2 - V_{o\_low}{}^2)}$$

C_{out} = Output Capacitance
P_{out} = Output Power
t_{holdup} = holdup time
V_{o_min} = minimum value of output regulated voltage
V_{o_low} = minimum voltage required by the load

Considerations in Selecting the PFC Diode

Important Parameters in selecting the Boost Diode:

•Size and Packaging

•Reverse Breakdown Voltage

•Forward Current Rating

•Reverse Recovery Time
- •Fast Recovery Diode - affect the switch mosfet
- •Silicon Carbide Diode
  - -No recovery Charge, hence can be used without the need of snubber.
  - -Improves Efficiency

Considerations in Selecting the PFC Mosfer

Important Parameters in selecting the Switch Mosfet:

- Size and Packaging
- Drain to Source Voltage, V_{DS}
- Drain Current Rating, I_{Drain}
- Turn On Resistance, R_{ds} ON
- Gate Charge, Q_G
- Output Capacitance, C_{OSS}
- Miller Capacitance, C

Simulating the Boost PFC

http://schmidt-walter.eit.h-da.de/smps_e/smps_e.html

Create simple boost PFC design based on specified parameter and simulate circuit performance

Select the Power Factor Pre-regulator

- Understand the waveforms displayed
- Determine the effect of the value of PFC choke

Evaluating the PFC Circuit

- Measurement of Input Power Factor Correction
  - PF > 0.97
  - Input Voltage and Input Current Waveform

- Harmonic Current Content
  - Limit as per EN 61000-3-2

- Efficiency of the PFC Circuit
  - Output Power
  - Input Power
    - -Apparent Power
    - -Real Power

- Equipment Needed
  - Power Meter
  - Oscilloscope
  - High Voltage Differential Probe

Measuring The PF (Class Exercise)

Measuring Power Factor

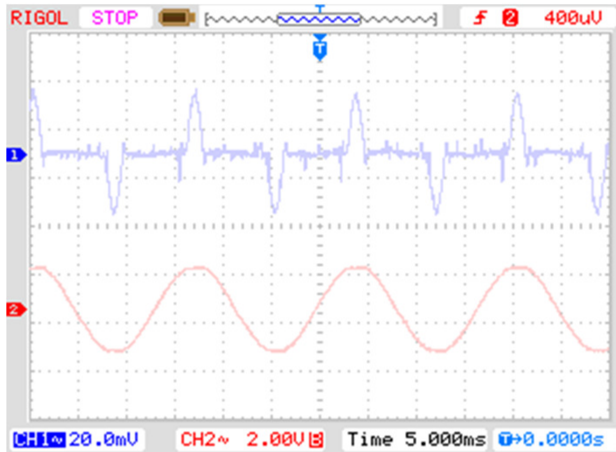
- Use power meter and set to measure PF
- Turn on the power supply
- Connect the meter to the AC input side
- Measure PF based on load & line input
- Do actual measurement in 30W flyback
- Do actual measurement in 180W boost PFC
- Measure PFC at different load conditions

Power Meter

Input Current Waveform with & without PF

Input current

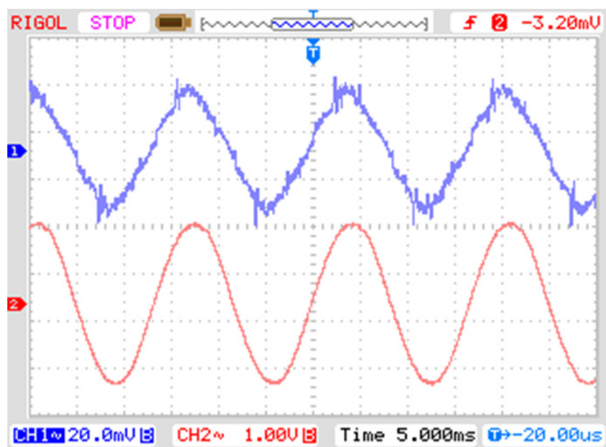
Input Voltage



Input current with 30W O/P & 238VAC I/P 30W f.back board (PF=0.57)

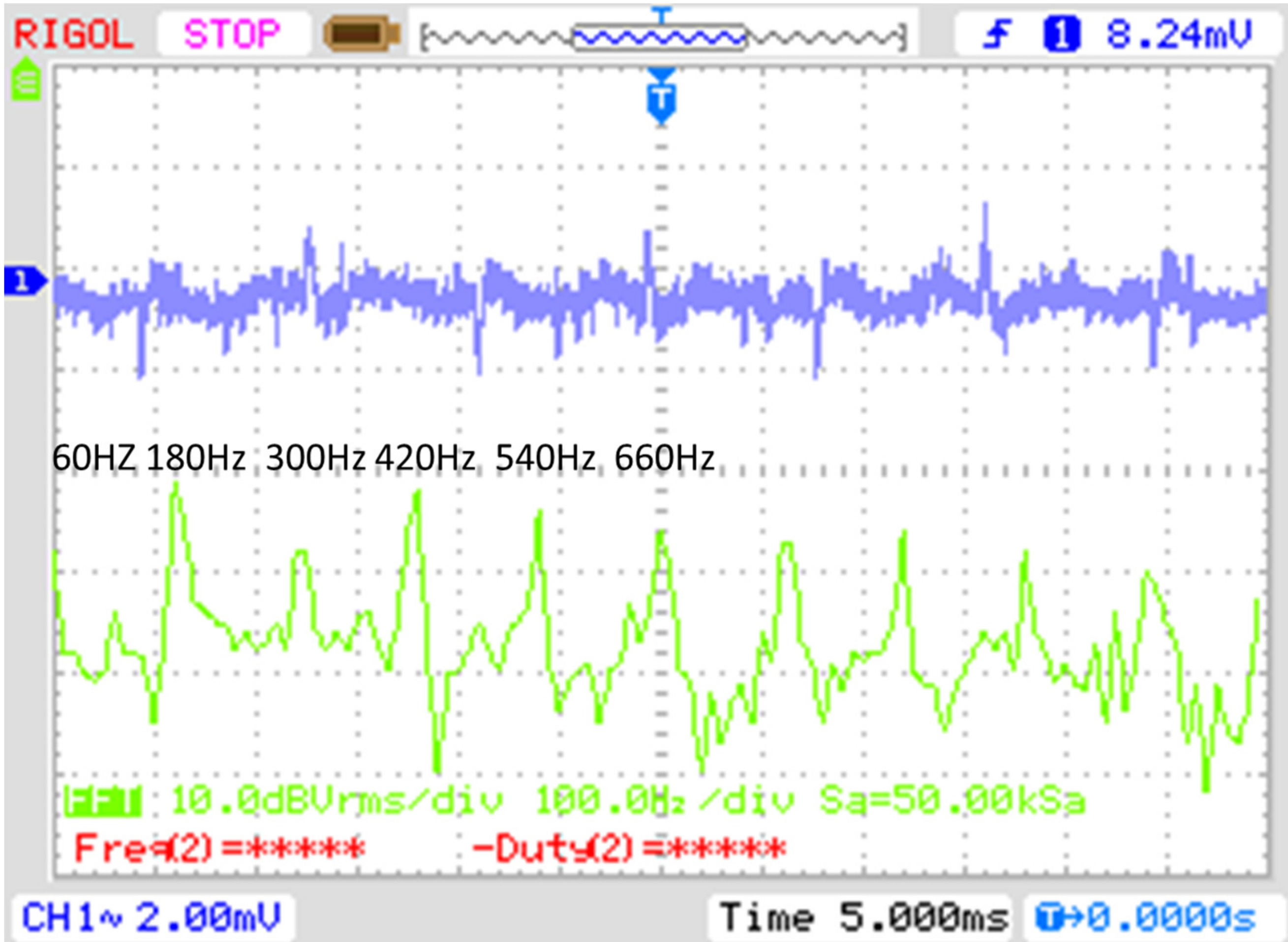
Input current

Input Voltage

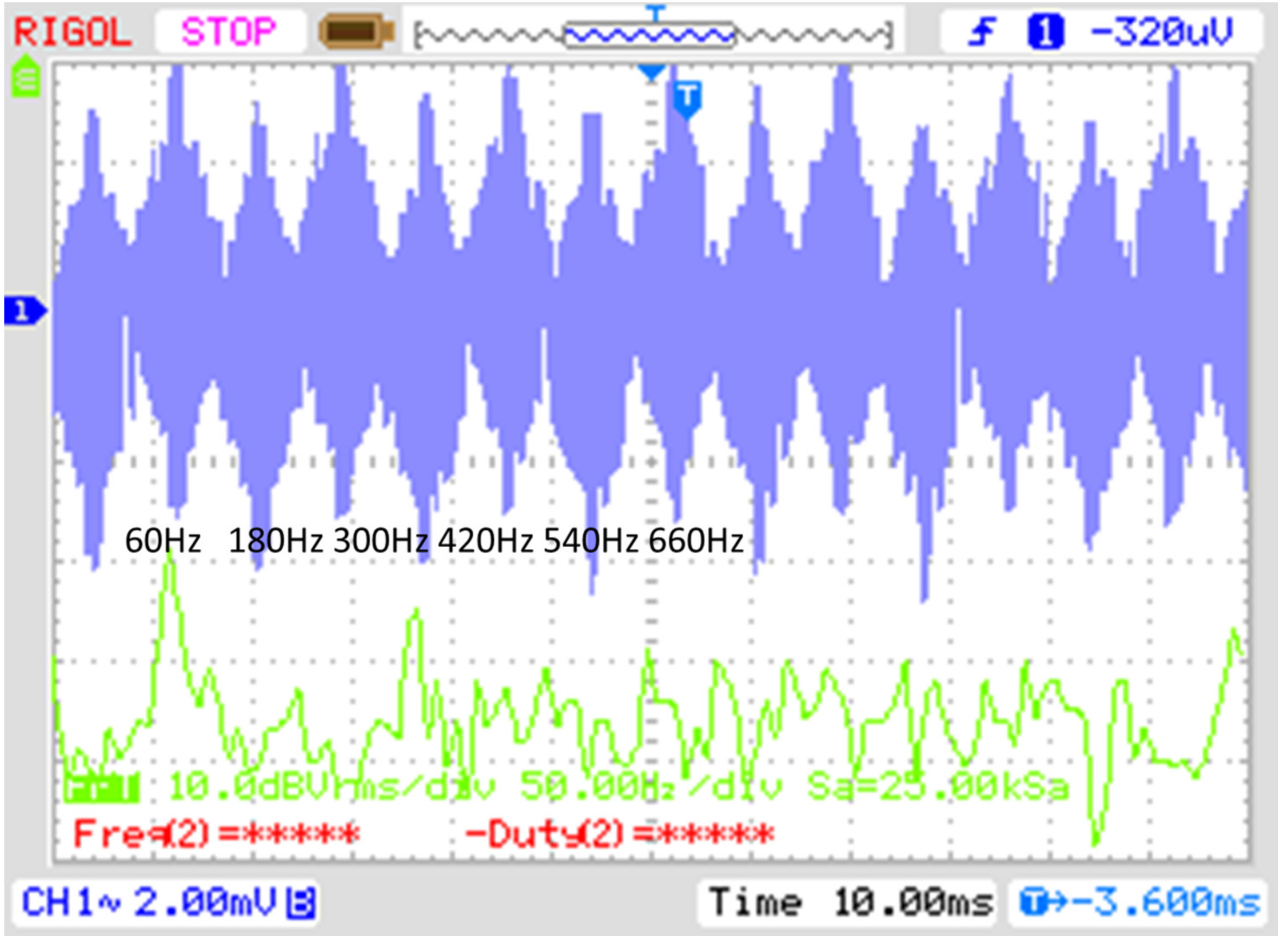


Input current with 120W O/P & 238VAC I/P 180W PFC board (PF=0.97)

Input Current Waveform & Freq. Spectrum without PFC



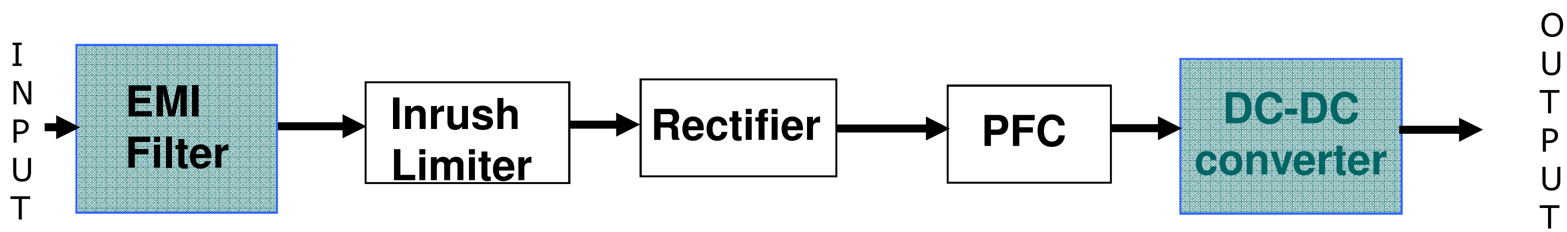
Input Current Waveform & Freq. Spectrum with PFC



Determine Impact of PFC Stage to Efficiency

Measuring Efficiency

- Measure efficiency of PFC + Rectifier + EMI Filter stage
- Measure efficiency of DC/DC stage
- Measure & computer overall efficiency



List of References

Erickson, R. (2001). *Fundamentals of Power Electronics.* New York: Springer.

Maniktala, S. (2005). *Switching Power Supply Design & Optimization.* New York: McGraw Hill.

Maniktala, S. (2006). *Switching Power Supplies A to Z.* Boston: Newnes.

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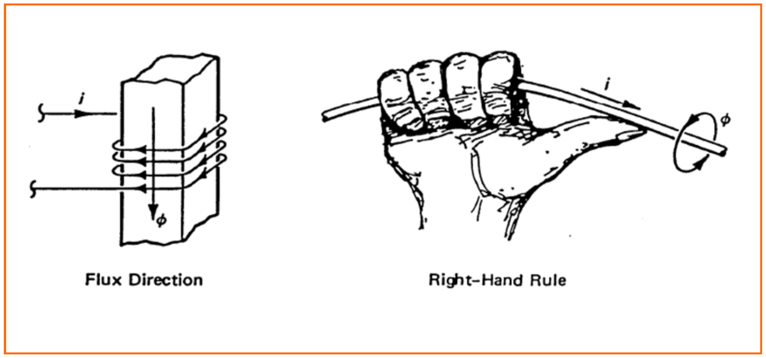
High Efficiency Switch-mode Power Supply Design Overview

Module Four

Design of Magnetic Components

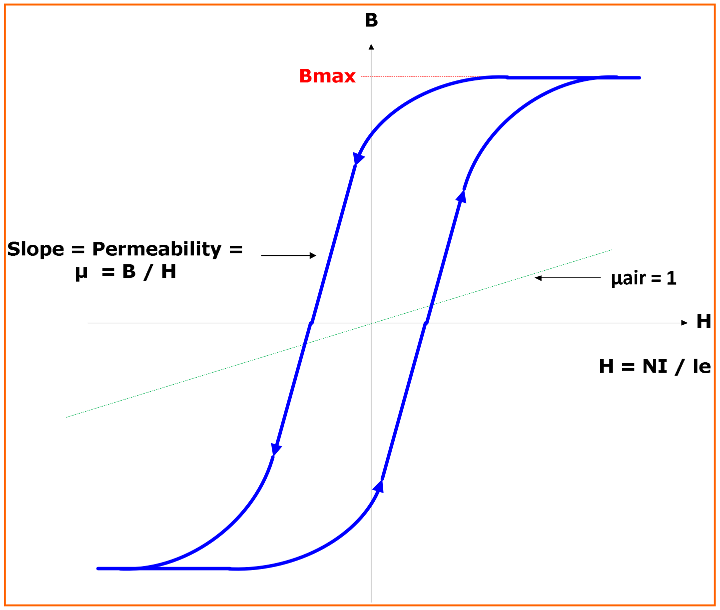
The Right Hand Rule



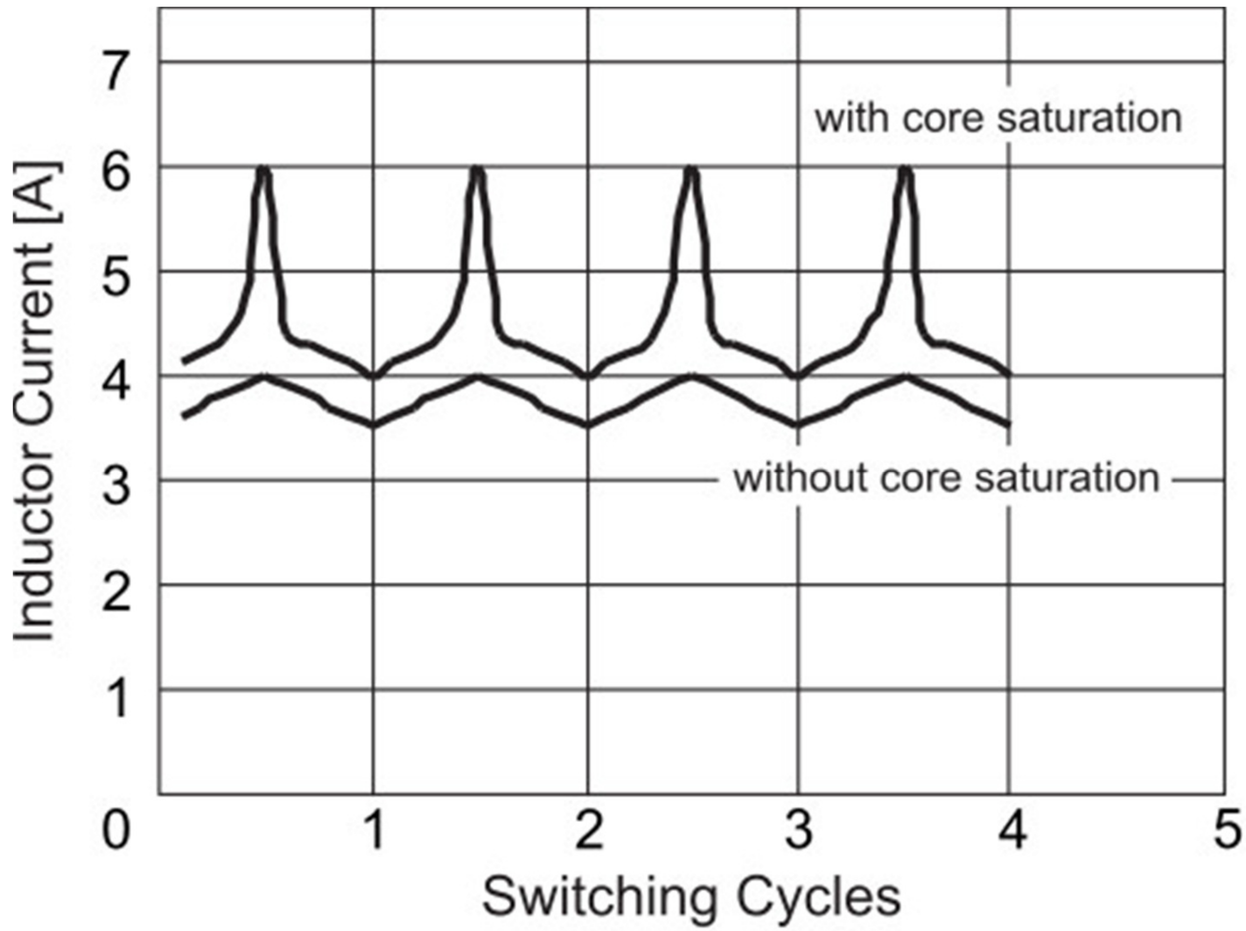
- Flux direction as result of current flow
- Wrap one's right hand around a conductor with thumb pointing in the direction of current flow
- Fingers point in the direction of flux lines

Characteristics of Magnetic Material

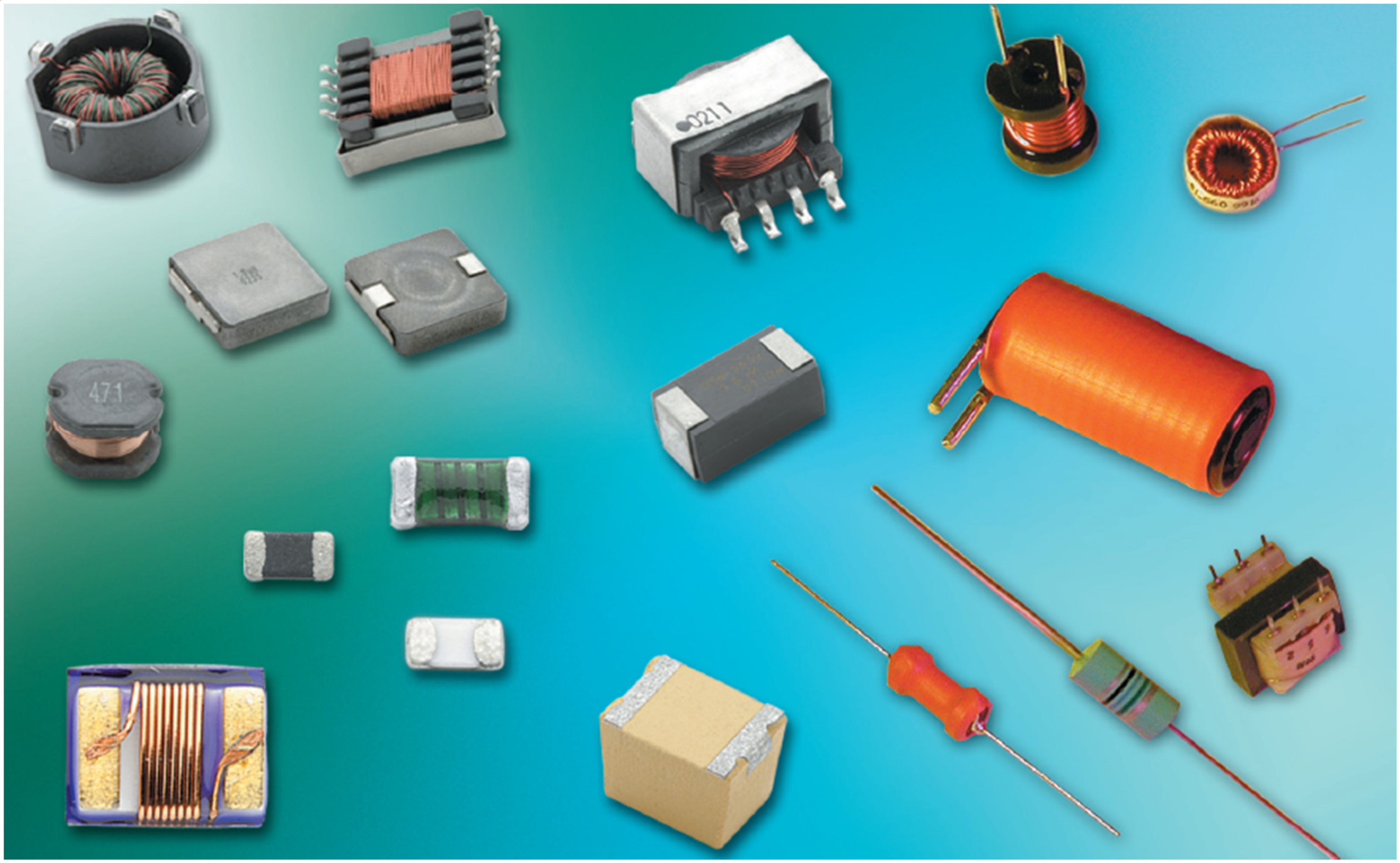
- B = Flux Density
  - 1Tesla = 10000 gauss
- H = Magnetic Field Strength
- H = NI/Le, Amp-turns /meter
- Le is the magnetic path length
- μr = relative permeability to air
  - $\mu_{air} = 4 \bullet p \bullet 10^{-7}$ H/m
  - μ Permeability = $\mu r \bullet \mu_{air}$
- L inductance = $(\mu \bullet N^2 \bullet Ae) / Le$
  - Ae is the magnetic path cross section area
  - Le is the magnetic path length



Inductor Current with & without core saturation



Different Shapes of Inductor



Basics of Inductor

Inductors

•A passive component designed to resist changes in current and store energy in its magnetic field.
•The voltage induced across an inductor by a change of current is defined as:
$V = L\,(di/dt)$

Magnetic Core Types

Toroidal Core
•Four Type of Toroidal Core: Ferrite, Powdered Iron, alloy and high flux, and tape wound.
•Characteristics of toroidal inductors include: self shielding (closed magnetic path), efficient energy transfer, high coupling between windings and early saturation.

E Core
•Closed magnetic path like a toroidal core when configured as ungapped.
•Gapped E cores have a partially open magnetic path.
•Advantage of gapping an E core is that you can obtain higher inductance values before reaching saturation.

Core Materials

Ceramic Core

Ceramic core inductors are often referred to as “air core” inductors.
Ceramic core inductors are most often used in high-frequency applications where low inductance values, very low core losses, and high Q values are required.

Ferrite Core

Ferrite is a magnetic material which consists of a mixed oxide of iron and other elements that are made to have crystalline molecular structure.
The most popular metal combinations are manganese and zinc (MnZn), and nickel and zinc (niZn).

Kool Mu Core

Kool Mu® is a magnetic material that has an inherent distributed air gap; it allows the core to store higher levels of magnetic flux.

MPP Core

MPP is an acronym for molypermalloy powder. The basic raw materials are nickel, iron, and molybdenum. MPP stores higher amounts of energy and has a higher permeability than Kool Mu.

Powdered Iron Core

Powdered iron cores are made of nearly 100 % iron. Powdered iron cores are typically the lowest cost alternative and their permeabilities typically have a more stable temperature coefficient than ferrites.

Common Magnetic Materials

Material	Permeability (Relative to Air)	Flux Saturation (Bsat in Gauss)	Loss at 1000 gauss, 100kHz (mW/cm^3)	Common Application
Ferrite Magnetic Inc. P	**3500**	**5000**	**80**	Power Transformer Filter Inductor (gapped) PFC Inductor (gapped)
Ferrite Magnetic Inc W	**10,000**	**4200**	**250**	EMI Filters (Common mode only)
Molypermalloy MagneticInc MPP	**60**	**7500**	**340**	Filter Inductors PFC Inductors
Sendust Mag. Inc Kool-Mu	**60**	**10,000**	**850**	Filter Inductors PFC Inductors
Powdered Iron Micrometals 52	**75**	**14,000**	**3200**	Filter Inductors PFC Inductor
80% Cobalt Tape Honeywell 2714A	**100,000**	**5500**	**90**	Magnetic Amplifier

Note: Low permeability material has higher core loss

Inductor Electrical Specifications

Inductance

The inductance for a given inductor is influenced by the core material, core shape and size, the turns count, and the shape of the coil.

DCR (DC Resistance)

The resistance of the inductor winding measured with no alternating current.

Saturation Current

The cause of the inductance to drop due to the DC bias current is related to the magnetic properties of the core. The core, and some of the space around the core, can only store a given amount of magnetic flux density. Beyond the maximum flux density point, the permeability of the core is reduced. Thus, the inductance is caused to drop.

Rated Current

The level of continuous DC current that can be passed through the inductor. It is also related to the inductor's ability to dissipate this power lost in the windings.

Permeability of Core

The permeability of a magnetic core is the characteristic that gives the core the ability to concentrate lines of magnetic flux. For a given core shape, size and material, and a given winding, higher permeability magnetic materials result in higher inductance.

Inductor Electrical Specifications

Self Resonant Frequency (SRF)

The frequency at which the inductor's distributed capacitance resonates with the inductance.

Distributed Capacitance

In the construction of an inductor, each turn of wire or conductor acts as a capacitor plate. The combined effects of each turn can be represented as a single capacitance known as the distributed capacitance. This capacitance is in parallel with the inductor.

Quality Factor Q

The Q value of an inductor is a measure of the relative losses in an inductor. The Q is also known as the "quality factor" and is technically defined as the ratio of inductive reactance to effective resistance, and is represented by: $Q = X_L/Re$

Impedance, X_L

The impedance of an inductor is the total resistance to the flow of current, including the AC and DC component. The DC component of the impedance is simply the DC resistance of the winding. The AC component of the impedance includes the inductor reactance.

Factors Affecting Performance

Copper Loss

The power lost by current fl owing through the winding. The power loss is equal to the square of the current multiplied by the resistance of the wire (I^2R). This power loss is transferred into heat.

Core Losses

Core losses are caused by an alternating magnetic field in the core material. The losses are a function of the operating frequency and the total magnetic flux swing.
The total core losses are made up of three main components: hysteresis, eddy current and residual losses.

Eddy Current Losses

Eddy current losses are present in both the magnetic core and winding of an inductor. Eddy currents in the winding (or conductor) contribute to two main types of losses:

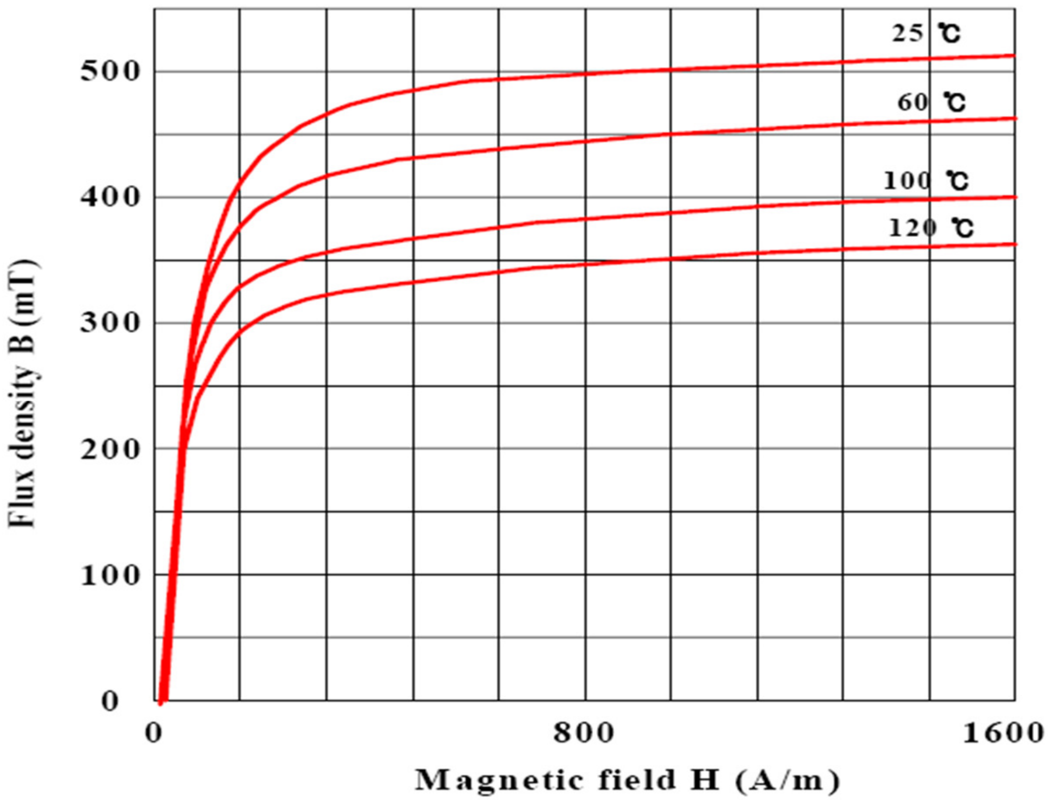
- losses due to proximity effects
- Skin effects - is the tendency for alternating current to flow near the surface of the conductor in lieu of flowing in a manner that utilizes the entire cross-sectional area of the conductor. This phenomenon causes the resistance of the conductor to increase.

Currie Temperature

Above this temperature, ferrite core loses it magnetic properties. The permeability will drop to near unity then inductance will drop dramatically.

Effect of Temperature on Magnetization Curve

- Typical Magnetization Curve at different ferrite core temperature



Design of Inductor

Determine the two important parameters:

- Inductance required with dc bias
- DC Current

Compute the product of LI^2 where:

L= inductance required with dc bias (mH)

I= maximum dc output current = Iomax + $\Delta I/2$

Locate the LI^2 value on the Core Selector charts

- Follow this coordinate in the intersection with the first core size curve.
- Read the maximum nominal inductance, AL, on the Y-axis.
  - -This represents the smallest core size and maximum AL at which saturation will be avoided.
  - - Bsat for Ferrite is around 0.35 Tesla , > (Imax * L)/(N * Ae)

Calculate the number of turns

$N = (L / AL)^{1/2}$ where L is in nH

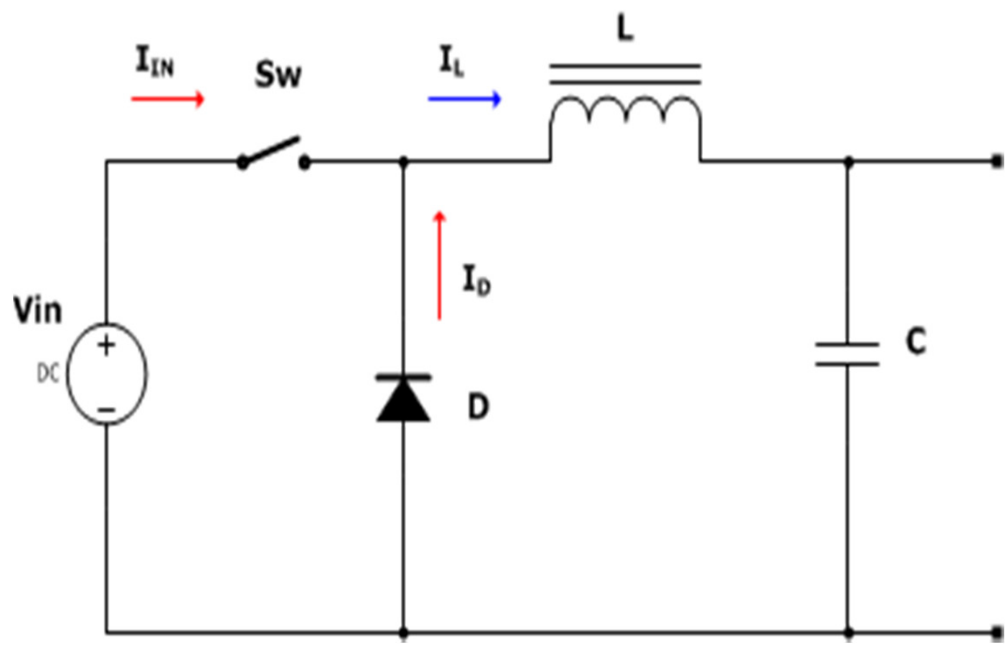
Choose the wire size

- Select from the wire table using 400 circular mil per amp.

Design Example

Select the core for the buck converter with the following requirements:

Vout = 5 V
Vout Ripple = 0.5 V
Io max = 6 A
Io min = 1 A
Vin(min)= 25 V
Vin(max)= 35 V
fsw = 100 kHz



Design Computation

Calculate the off time:

$$t_{off} = \frac{(1 - \frac{Vout}{Vin_{\max}})}{fsw} = \frac{(1 - \frac{5V}{35V})}{100kHz} = 8.57\mu\sec$$

Calculate the minimum current ripple:

$$\Delta I = 2 \bullet Iout_{\min} = 2 \bullet 1Amps = 2Amps$$

Calculate the minimum current ripple:

$$L = Vout \bullet \frac{toff}{\Delta I} = 5\text{V} \bullet \frac{8.57\mu\sec}{2A} = 21.4\mu H = 0.0214mH$$

Calculate the LI^2:

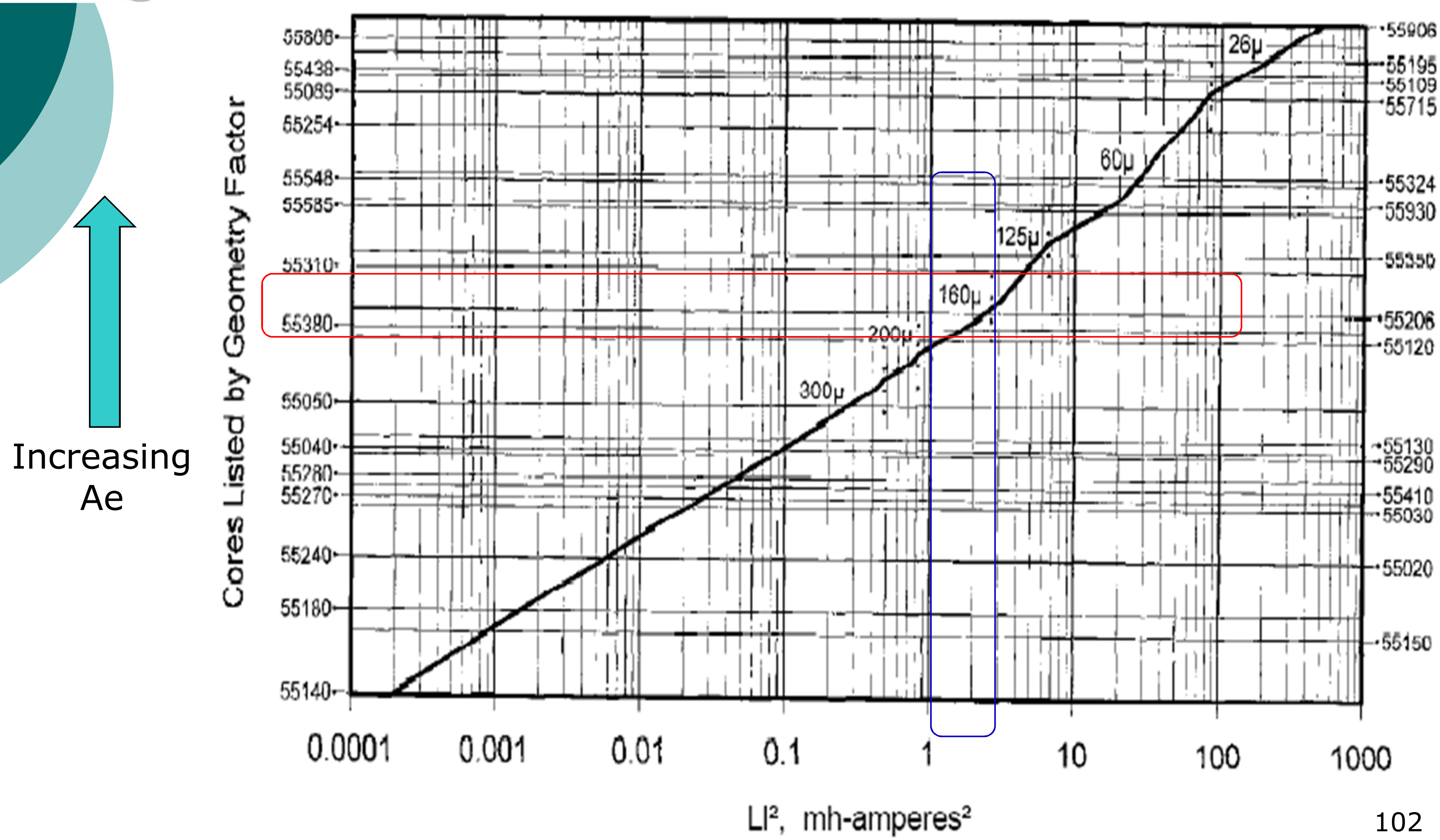
$$LI^2 = L(Iout_{\max})^2 = 0.0214mH \bullet (7A)^2 = 1.05mJ$$

Core Selection

Go to Magnetics Inc. website www.**mag-inc**.com

Check MPP Torooid cores for the practice exercise

Molypermalloy Powder Core DC Bias Core Selector Chart



Core Selection

Using the MPP Core:

•Locate the LI^2 value of 1.05 mJ on the Core Selector Chart.

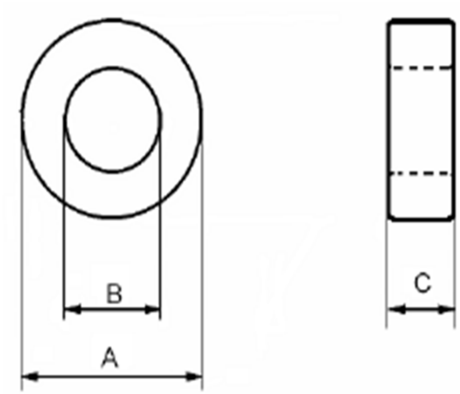
•The 1.05 mJ coordinate falls in the 160μ section. The 160μ core is the 55378-A2 core (see the Molypermalloy Powder Cores catalog MPP-400).

•The 55378-A2 core has a minimum inductance of A_L=114 nH/T^2.

•Minimum Turns without considering the DC Bias.

$$N = \sqrt{\frac{L}{A_L}} = \sqrt{\frac{21400\, nH}{114\, nH / T^2}} = 14\, turns$$

Magnetics Core Specification



Permeability (μ)	A_L (nH/T^2)	Nominal DC Resistance (Ohms/mH)	B/NI Gauss per Amp. Turn
160	114 ± 8%	0.13	48.5 (<1500 gauss)

Dimensions (mm)		
	Uncoated	Coated
O.D. (A)	17.3 nom	18.03 max
I.D. (B)	9.65 nom	9.02 min
Ht. (C)	6.35 nom	7.11 max

Markings		
XXXXXX	55378A2	X
Lot Number	Part Number	Inductance Grade

Physical Characteristics					
W_A (mm^2) Window Area	A_e (mm^2) Cross Section	L_e (mm) Path Length	V_e (mm^3) Volume	Weight (grams)	Box Quantity (pieces)
57.6	23.2	41.4	960	8.3	2,000

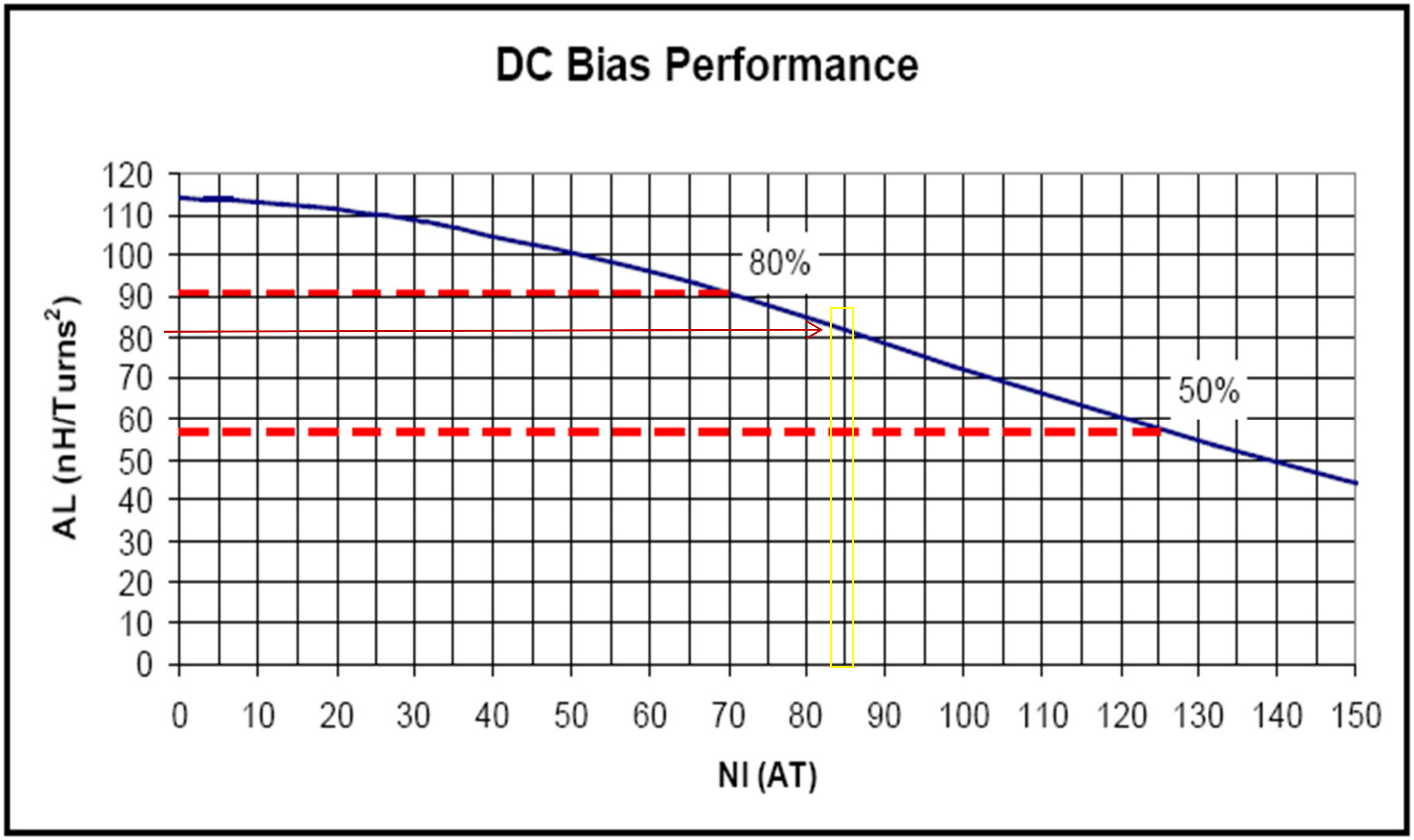
Winding Turn Length (mm)	
Winding Factor	Length/Turn
100% (Unity)	36.7
60%	31.5
40%	26.4
20%	24.1
0%	23.3

Wound Coil Dimensions (mm)	
Maximum O.D. (u.w.f.)*	24.9
Maximum HT. (u.w.f.)*	16.3

*u.w.f. – unity winding factor

Surface Area (mm^2)	
Unwound Core	990
40% Winding Factor	1,470

Magnetics Core Specification



Selected Core and Required Turns

- Powder cores have the property of soft saturation. This has the effect of gradually decreasing the permeability (inductance) with increased DC bias current. Therefore, to achieve the minimum inductance of 21.4 μH at the specified DC bias of 6 amperes, additional turns will be required.

- Considering the DC bias degradation performance, the final number of turns required is 17.

- Using 400 circular mils/amp, this gives a wire size of AWG 16.

$$H = NI = 14 \bullet 6A = 84 \text{ A - turns}$$

with change of permeability :

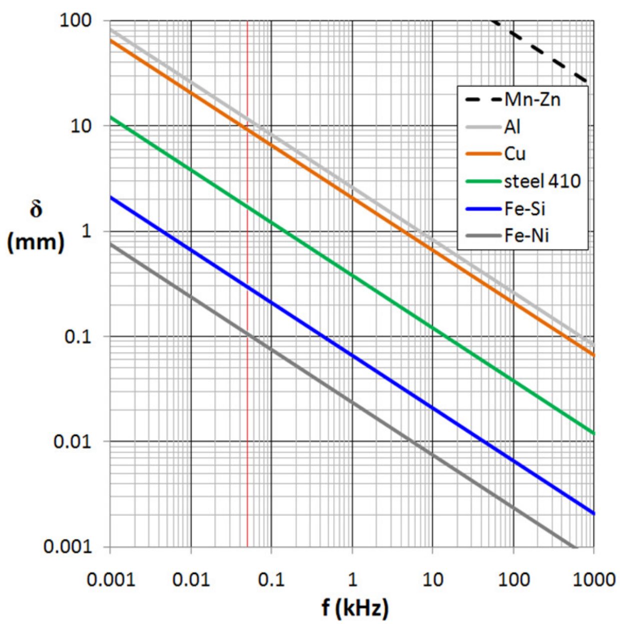
$$\mathrm{A_L} = 82nH / Turns^2$$

$$\mathrm{N} = \sqrt{\frac{21400nH}{82nH / Turns^2}} \approx 17 \text{ Turns}$$

A 55378-A2 core with 17 turns of AWG 16 wire meets the design requirement.

Determine the Size of Wire

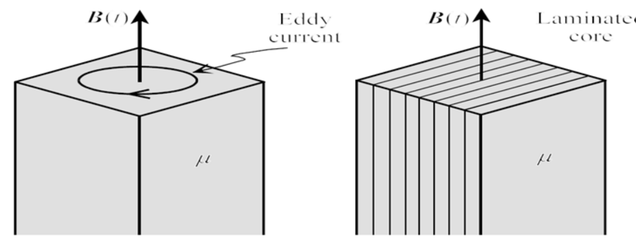
- Determine appropriate gauge of wire to be used
- Power loss through the copper wire is determined by its size
- Use the rule of thumb in sizing the wire, 400cir-mils/Amp
- Copper $\rho = 1.68 \times 10^{-8}\ \Omega \cdot m$

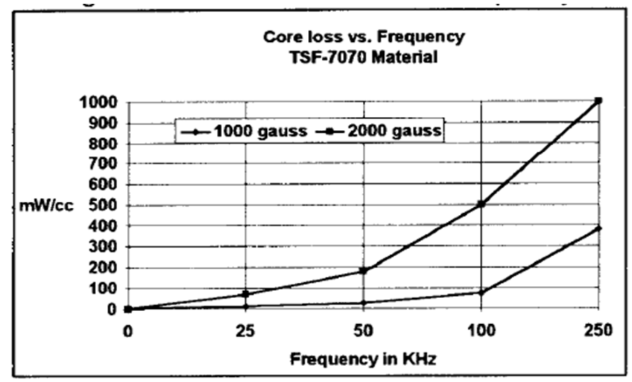


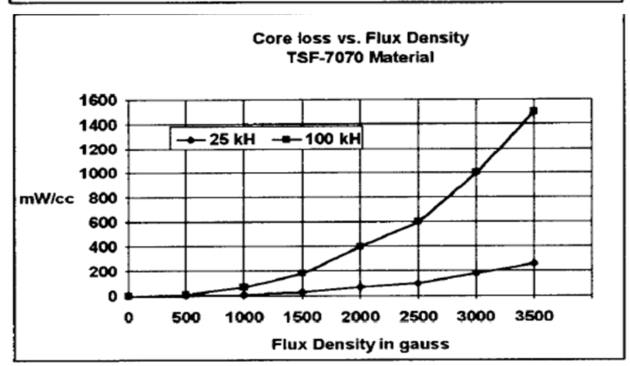
American Wire Gauge (AWG)	Diameter Mil	Circular Mil (CM)	Area (mm^2)	Diameter (mm)
0000	460	211,592	107	11.7
000	410	167,800	85.0	10.4
00	365	133,072	67.4	9.27
0	325	105,531	53.5	8.25
1	289	83,690	42.4	7.35
2	258	66,369	33.6	6.54
3	229	52,633	26.7	5.83
4	204	41,740	21.2	5.19
5	182	33,101	16.8	4.62
6	162	26,251	13.3	4.12
7	144	20,818	10.5	3.67
8	128	16,509	8.37	3.26
9	114	13,092	6.63	2.91
10	102	10,383	5.26	2.59
11	90.7	8,234	4.17	2.31
12	80.8	6,530	3.31	2.05
13	72.0	5,178	2.62	1.83
14	64.1	4,107	2.08	1.63
15	57.1	3,257	1.65	1.45
16	50.8	2,583	1.31	1.29
17	45.3	2,048	1.04	1.15
20	32.0	1,022	0.518	0.812
21	28.5	810.1	0.410	0.723
22	25.3	642.4	0.326	0.644
23	22.6	509.5	0.258	0.573
24	20.1	404.0	0.205	0.511
25	17.9	320.4	0.162	0.455

Losses

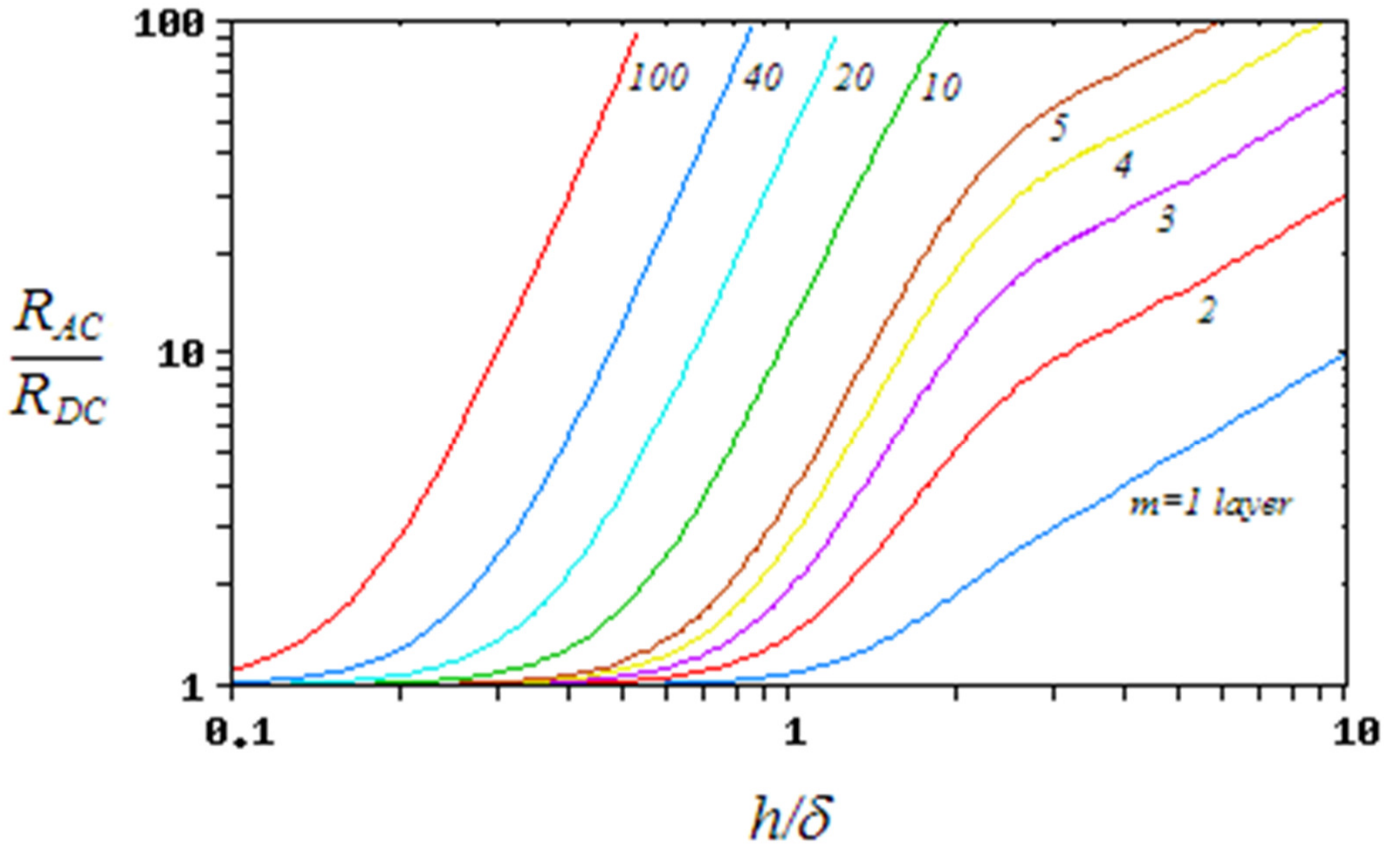
- **Winding Loss**
  - Current moving through copper causes the copper to heat up as it moves through the resistance of the wire.
  - $\mathbf{R_{LOSS} = (I_{(RMS)})^2 \times R_{WINDING}}$
- **Two major source of core loss**
  - **Eddy Current Loss**
    - The time-varying magnetic flux passing through the core induces circulating currents. Eddy current heat up the core and cause loss of energy.
  - **Hysteresis Loss**
    - It is the form of heat caused by the movement of the magnetic dipoles as the excitation field oscillates back and forth.
- Core loss is strongly related to frequency, increasing linearly as the frequency goes up.
- Core loss is also related to flux density.







Dowell's Curves (Considers skin & proximity effect)

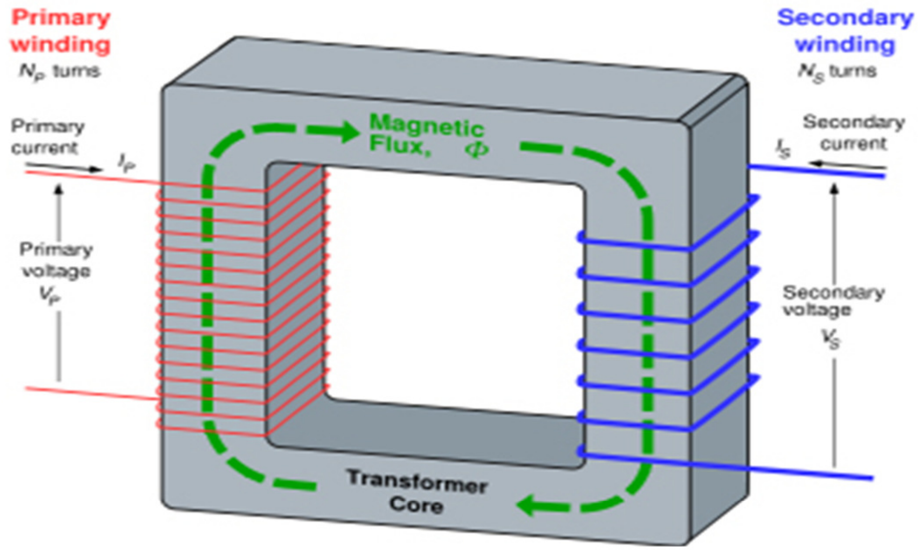


Where h is height of a square wire or 0.89*diameter of circular wire and δ is skin depth

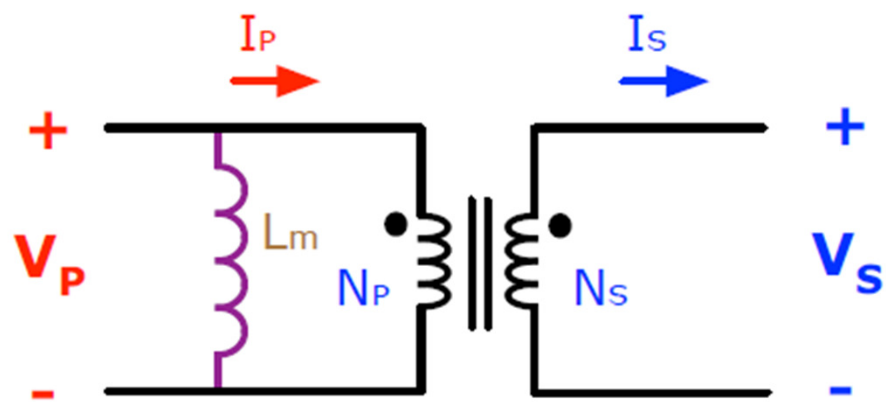
Basic Inductor Design

- Determine L needed from application
- Determine core size (far away from saturation)
- Determine air gap length, or if pre-gapped core, A_L
  - $1/\mu r(w/gap) = 1/\mu rc(w/o\ gap) + lg/le$
  - lg is the gap and le is the magnetic path length
- Determine number of turns (consider DC bias)
- Determine wire size
- Check DC resistance, losses and efficiency
- Review temperature rise based on estimated losses
- Test in the application and measure results

The Flyback Transformer



Basic model needs to include effect of leakage inductance and winding capacitance



Basic Model

Exercises

1. Determine total loss of the inductor in the practice exercise
   - Consider skin effect & then w/ proximity using Dowell's curve

   The effective resistance due to a current confined near the surface of a large conductor (much thicker than δ) can be solved as if the current flowed uniformly through a layer of thickness δ based on the DC resistivity of that material. We can therefore assume a cross-sectional area approximately equal to δ times the conductor's circumference. Thus a long cylindrical conductor such as a wire, having a diameter D large compared to δ, has a resistance *approximately* that of a hollow tube with wall thickness δ carrying direct current. Using a material of resistivity ρ we then find the AC resistance of a wire of length L to be:

   $$R \approx \frac{L\rho}{\pi(D-\delta)\delta} \approx \frac{L\rho}{\pi D\delta}$$

   The final approximation above assumes $D \gg \delta$.

2. Determine relative permeability of actual toroid inductor and compute A_L
3. Make an inductor with 440 uH range using Ferrite core
   - Use EFD25 core start winding at pin 1 and end in pin 3
   - Need to introduce gap

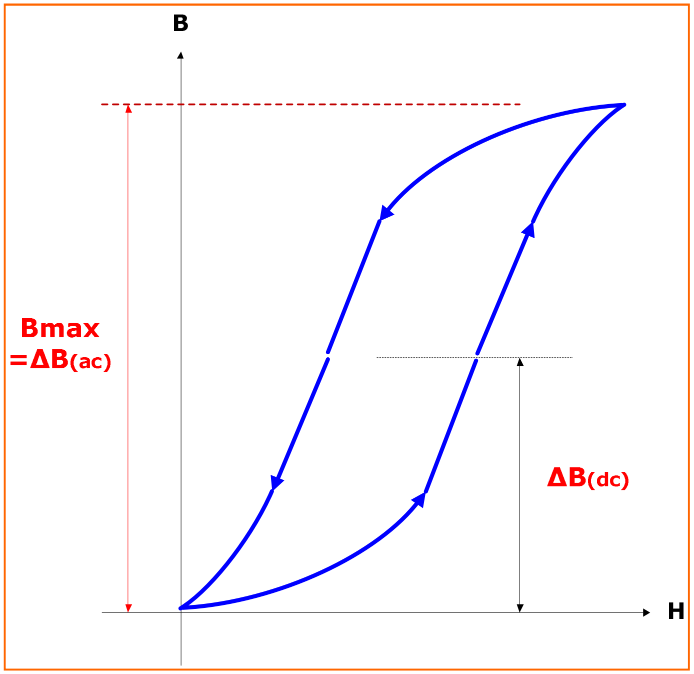
Exercises

4. Leakage inductance of Flyback transformer
   - Measure primary inductance
   - Measure ESR
   - Measure primary leakage inductance

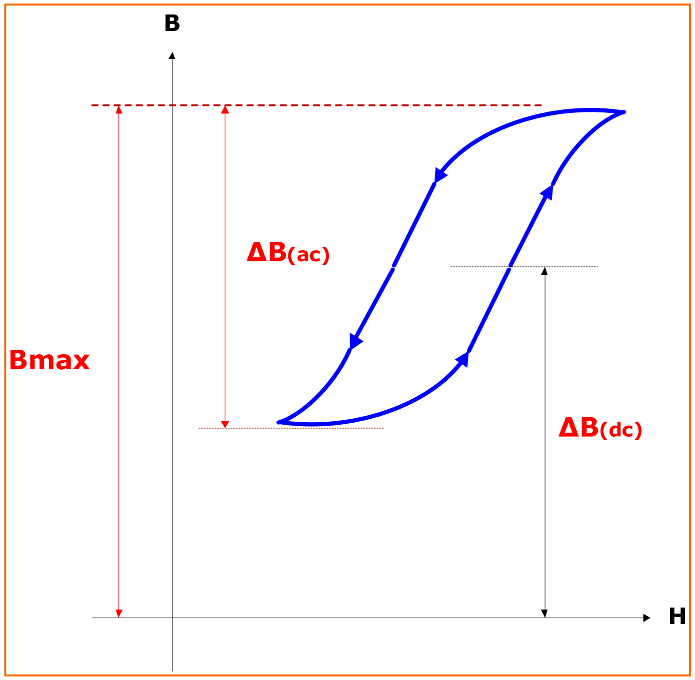
Flyback B-H Curve

- The flyback converter is operating in unidirectional hysteresis curve.
- Figures shown below are the modes of operation of the flyback converter.
- For the same flux density, the CCM could handle more power than DCM.

- DCM Mode



- CCM Mode

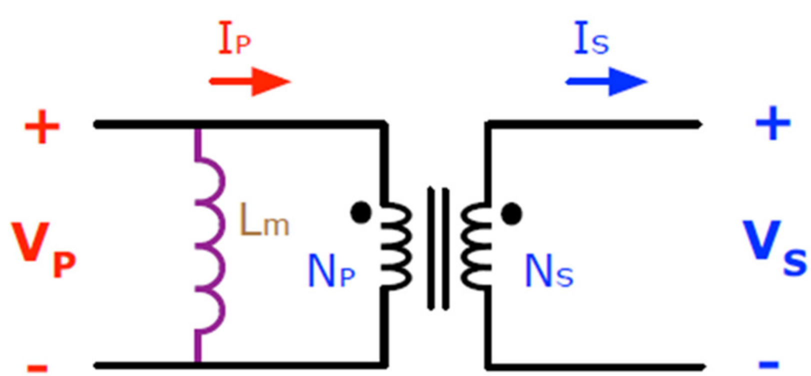


The Transformer Equation

- **Faraday's Law**

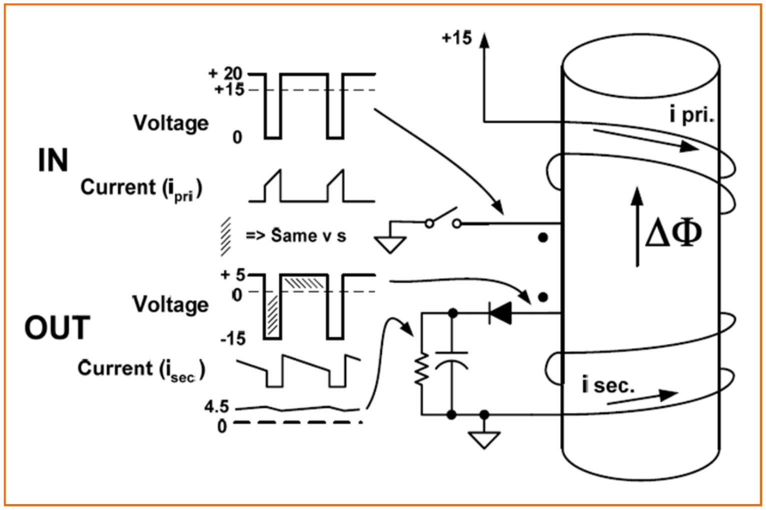
  Bsat> (Vmax * T)/(N * Ae)

- Vmax in Volt, B in tesla, Ae in m^2, T is time in seconds that Vmax is applied, N is number of turns
- The saturation density, Bsat, determines the maximum volt turns that can be applied to a given transformer or inductor winding at a given frequency

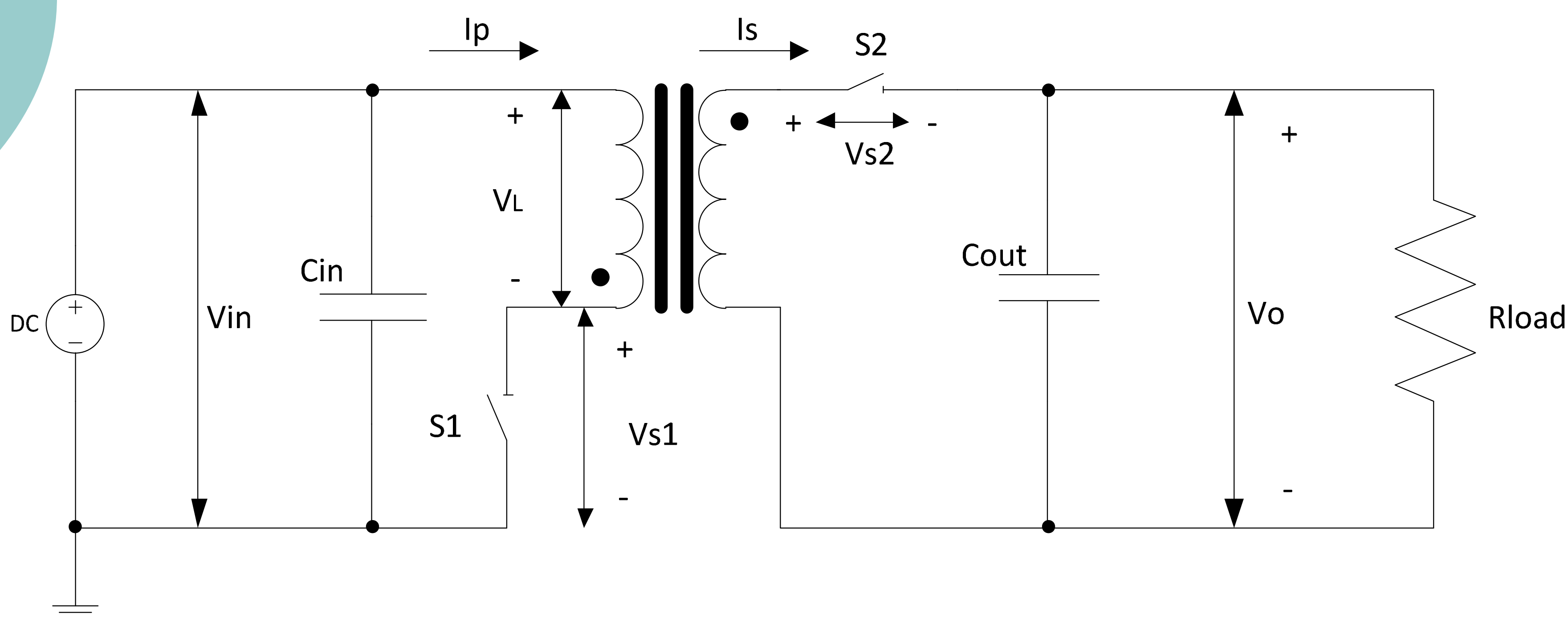


Flyback Transformer Operation

- Figure shown is a conventional Flyback transformer
- Energy is delivered to the magnetic core during the pulse applied to the primary
- Energy is transferred from the core to the load during the remaining portion of the cycle

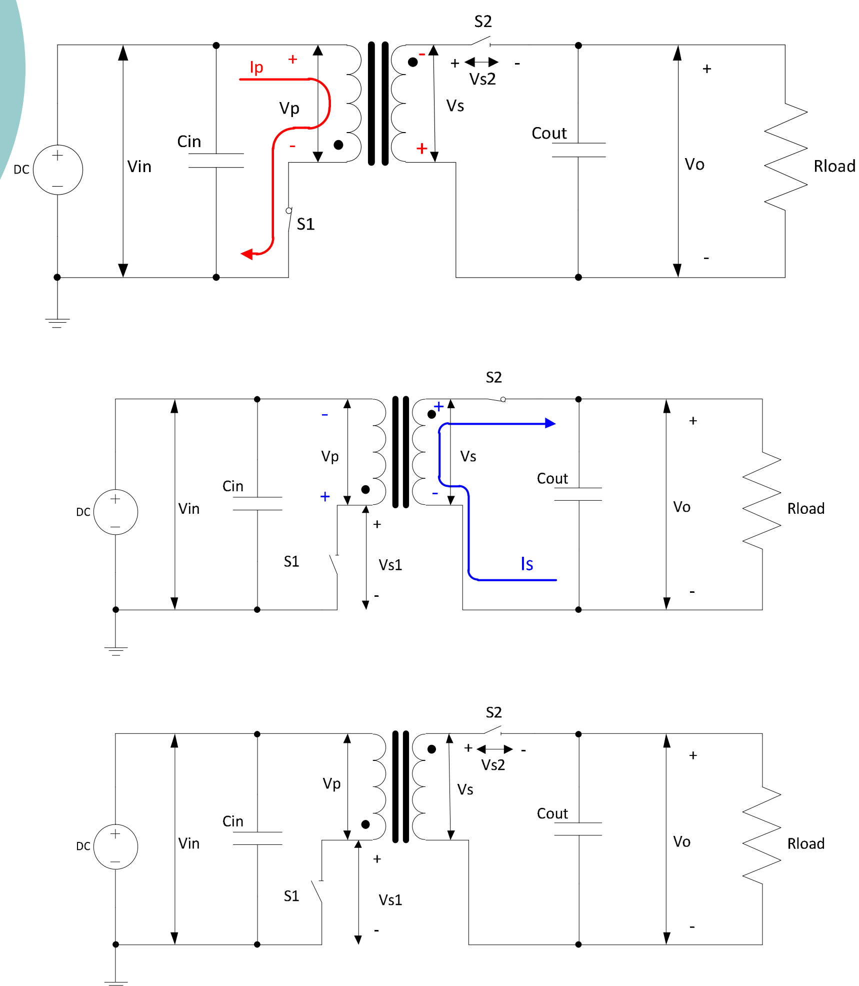


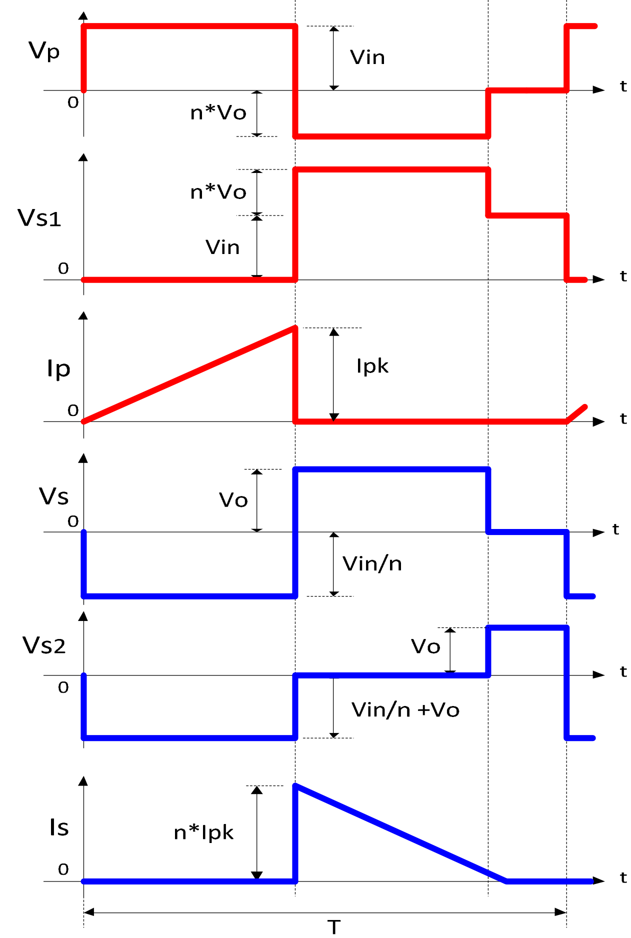
Simplified Flyback Circuit



Flyback Operation Details

Duration	D1 * T	D2 * T	D3 * T
S1	ON	OFF	OFF
S2	OFF	ON	OFF





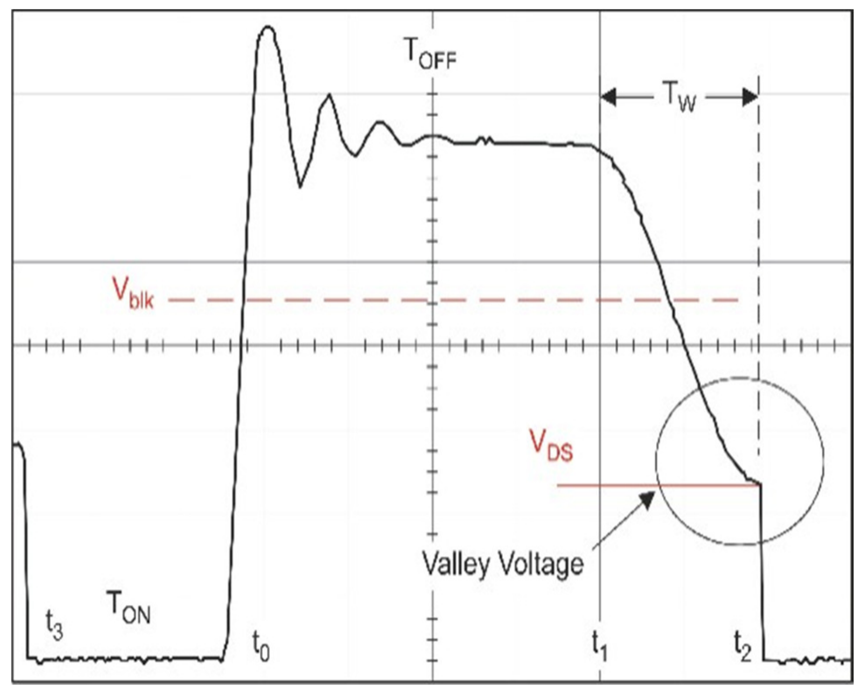
Reflected Voltage to the Primary (VOR)

- Voltage across the primary during turn OFF

$$V_{Poff} = -(V_O + V_d)(N_P/N_S)$$

- This is the same as the actual reflected voltage to the primary

- The reflected voltage is dependent on turns ratio (N_P/N_S) and output voltage



Modes of Flyback Operation

- Flyback converters are generally classified as either constant frequency or variable frequency flyback converters

- Two Modes of operation for constant frequency flyback converters
  - Continuous Conduction mode (CCM)
  - Discontinuous Conduction Mode (DCM)

- Variable frequency flyback converter
  - Critically Discontinuous Mode

Continuous Conduction Mode

- Current in the inductor does not go to zero at the end of transfer cycle.

- **Advantages:**
  - Better output voltage regulation with load
  - Lower output voltage ripple
  - Lower peak currents
    - Lower transistor rating required
  - Higher power capability
  - Lower transient output voltage at turn off

- **Disadvantage:**
  - Size of magnetic will be bigger
    - more turns needed for the desired inductance
  - Commutating the secondary diode can cause switching noise around the output diode and ringing in the transformer.
  - Can give worst EMI results

Discontinuous Conduction Mode

- The inductor current falls to zero at or before the end of transfer cycle.

- **Advantages:**
  - Design do not have a problem with zero current loads
  - Easy to stabilize the loop
    - No Right Half Plane Zero
  - More rapid response with dynamic load
  - The size of the magnetic will be smaller than CCM design
  - A slow recovery secondary diode can be used.

- **Disadvantages:**
  - Higher cost than CCM
  - High capacitor ripple current
  - Peak current in the inductor is higher,
    - thus the resulting output voltage ripple will be higher
    - High peak diode current
  - Peak current is high, hence mosfet current rating (Id) higher than CCM

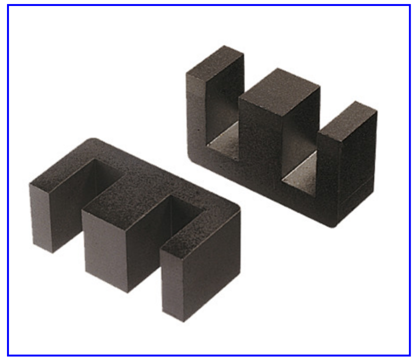
Core Material and Geometry

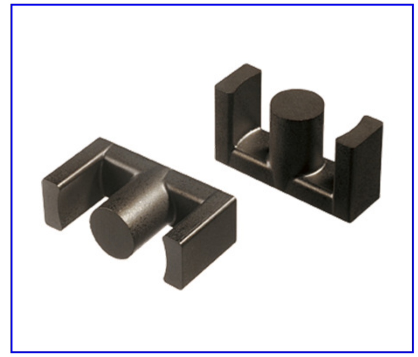
- Types of Cores
  - Materials Characteristics
    - Ferrite - high permeability but low flux saturation
    - Powder Iron - low permeability but high flux saturation
  - Shape of the core
    - EE
    - EI
    - EF
    - Pot core
  - Specifications
    - Ae - is the effective cross sectional area of the core
    - Ve - is the effective volume of the core
    - Le - is the magnetic path flux length
    - AL - is the inductance factor
    - μe - is the permeability of the core
    - Airgap - effective air gap of the core
    - Bmax - is the flux density, assume 3000 gauss for ferrite

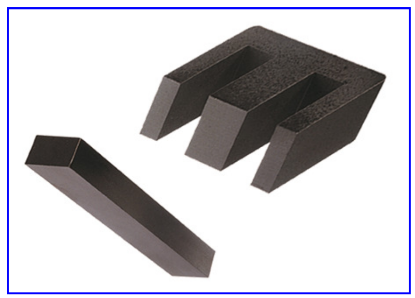
Various Cores and Bobbins

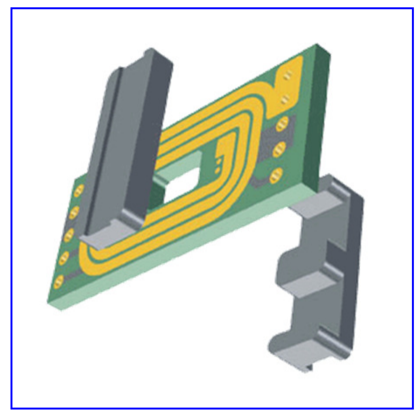
Core Selection (Power VS Size)

- **Output Power = 1 – 10W**
  - EL Core (EI12.5, EI16, EI19)
  - EE Core (EE8, EE10, EE13, EE16)
- **Output Power = 10 – 20W**
  - EL Core (EI22)
  - EE Core (EE22)
- **Output Power = 20 – 30W**
  - EL Core (EI25)
  - EE Core (EE22)
- **Output Power = 30 – 50W**
  - EL Core (EI28, EI30)
  - EE Core (EE25)
- **Output Power = 50 – 70W**
  - EL Core (EI35)
  - EE Core (EE40)
- **Output Power = 70 – 100W**
  - EL Core (EI40)
  - EE Core (EE35)







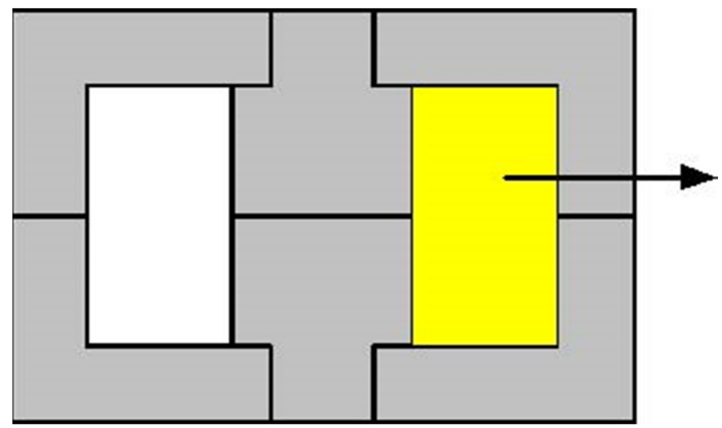


Winding Area and Cross Sectional Area

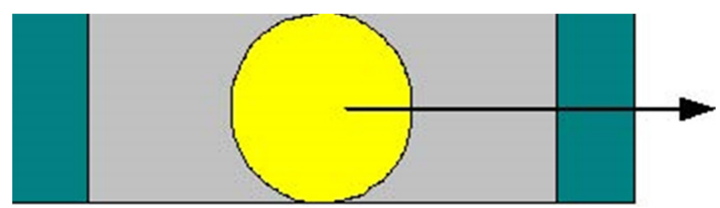
- Core Material - Ferrite
- Core Geometry - EE
- Winding Area
  - $Aw = mm^2$
- Cross Sectional Area
  - $Ae = mm^2$

Area product Ap =Aw X Ae
=(Pout*CD)/(Kt*Bmax*f)
Pout is output power
CD is current density of wires
Kt is constant depend on topology
Bmax is peak to peak flux density
f is switching freq.

- Winding Area (Aw)



- Cross Sectional Area (Ae)



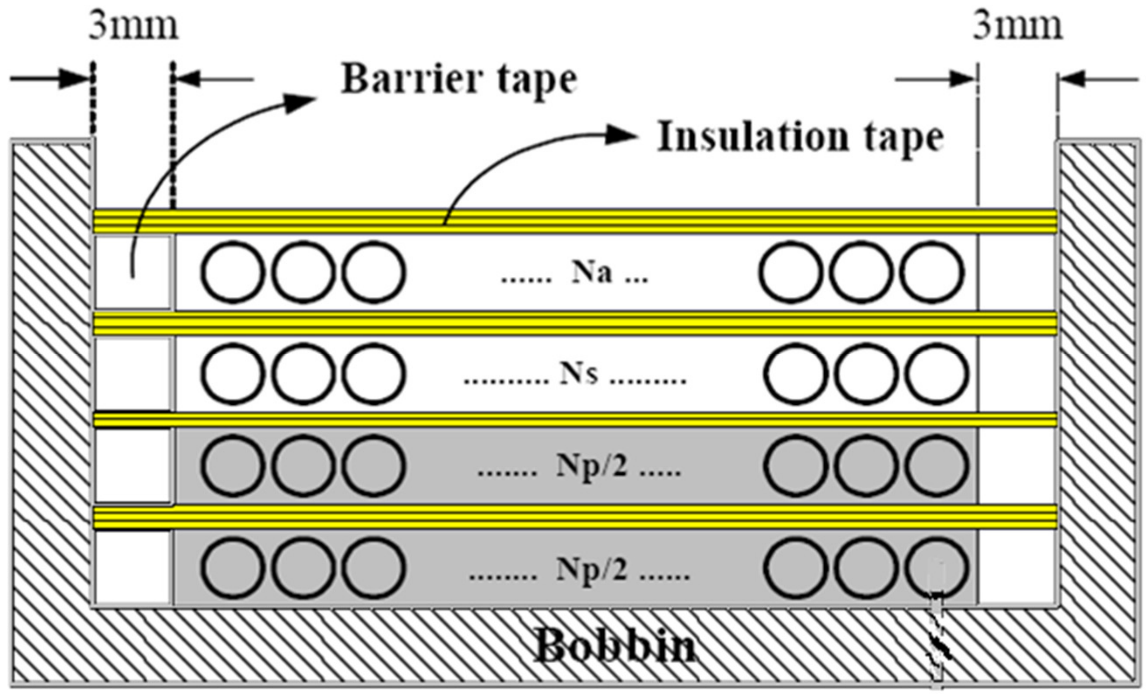
Leakage Inductance and Safety Requirements

- **Leakage inductance**
  - Leakage inductance
    - Is caused by the imperfect coupling between the primary and the secondary windings.
    - results from the parts of the primary's magnetic field that does not link the secondary.
  - Usually expressed as a percentage of winding inductance
    - e.g., 3% leakage
  - Leakage inductance can be measured by shorting the secondary winding and then measure the "primary" inductance.
  - This appears to be in series with the primary winding when considered in the transformer circuit.

- **Safety requirements**
  - Insulations
    - A thin layer insulating paper or plastic film will reinforce the insulation between the wires and mechanically helps form a neat solid coil.
  - Space Winding (Creepage and Clearance)
    - Space left at the end of a coil former where no copper windings are placed.
    - This keeps the copper wire from going out to the very edges of the coil former, and improves the voltage isolation between layers and windings.

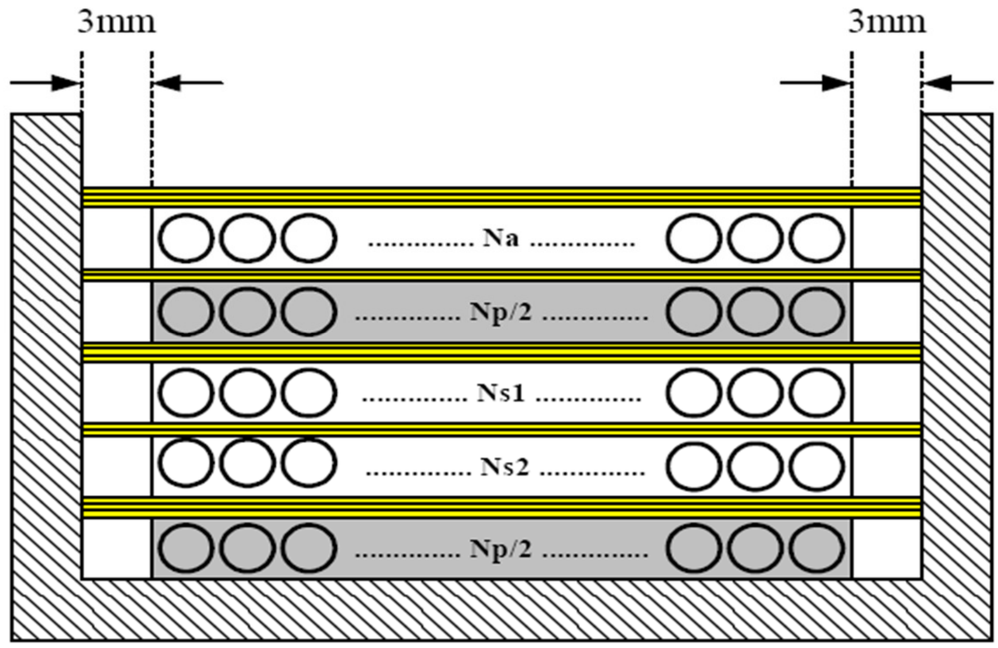
Transformer Construction

- Primary Winding is considered to minimize windings resistance and reduce conduction loss.



Transformer Construction

- Sandwich Winding is considered to improve coupling to minimize leakage inductance and reduce proximity effect
- Less turn-off ringing, better EMI performance



Steps to Transformer Design

- Specifications of the Flyback Converter
- Select Conduction Mode
- Compute for the Transformer Current
- Calculate Primary Inductance of the Transformer
- Determine Number of Turns
  - Optimize Windings – Winding Area VS Flux Saturation, Size of the Wire
- Compute Air Gap Length
- Select Core
  - Material, Geometry, Size and Power Capability, Winding Area, Cross Sectional Area, Maximum Flux Density
- Compute Transformer Losses
- Select Transformer Constructions Method
  - Leakage Inductance
  - Safety Requirements

Flyback Transformer Design Procedure

1. Power Supply Specification
   - Input: Input Voltage, Line Frequency
   - Output: Voltage and Current
2. Select Converter's Mode of Operation
   - CCM or DCM
3. Compute Transformer's Current
   - Primary Current and Secondary Current
4. Compute for Required Primary Inductance of the Transformer
5. Select Core
   - Material, Geometry, Size and Power Capability, Winding Area, Cross Sectional Area
6. Compute Number of Turns for Primary Winding
   - Consider Reflected Voltage, Maximum Flux Density, Minimum Input Voltage
   - Optimize Windings – Winding Area VS Flux Saturation, Size of the Wire
7. Compute Number of Turns for Secondary Winding
8. Determine the required Air Gap Length
9. Determine Wire Size
10. Compute Transformer Losses
11. Select Transformer Constructions Method
    - Minimum Leakage Inductance and Safety Requirements

List of References

Brown, M. (1994). *Power Supply Cookbook.* Boston: Butterworth-Heinemann

Dixon, L. (2000). *Magnetics Design Handbook.* Texas Instruments. McGraw Hill.

Erickson, R. (2001). *Fundamentals of Power Electronics.* New York: Springer.

Lancaster, K. (2010). Inductor 101. *Vishay.* retrieved on December 29, 2011 at www.vishay.com/inductors.

Maniktala, S. (2006). *Switching Power Supplies A to Z.* Boston: Newnes.

Maniktala, S. (2008). *Troubleshooting Switching Power Converters.* Boston: Newnes.

Pressman, A. (1991). *Switching Power Supply Design.* New York: McGraw-Hill.

High Efficiency Switch-mode Power Supply Design Overview

Module Five

Designing for High Efficiency and High Power Density

Resonant Converters

Introduction to Resonant Conversion

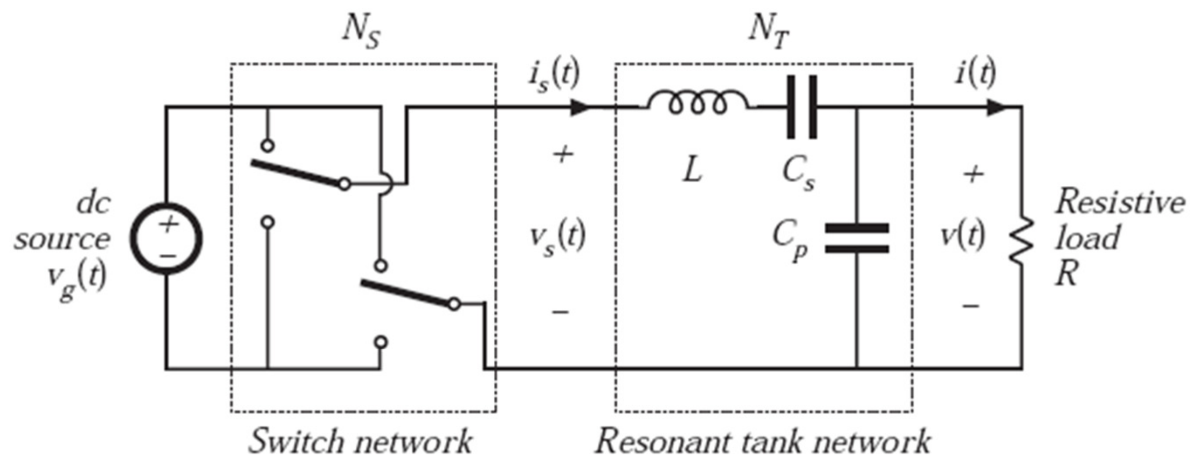
Resonant power converters contain resonant L-C networks whose voltage and current waveforms vary sinusoidally during one or more subintervals of each switching period. These sinusoidal variations are large in magnitude, and the small ripple approximation does not apply.

Some types of resonant converters:

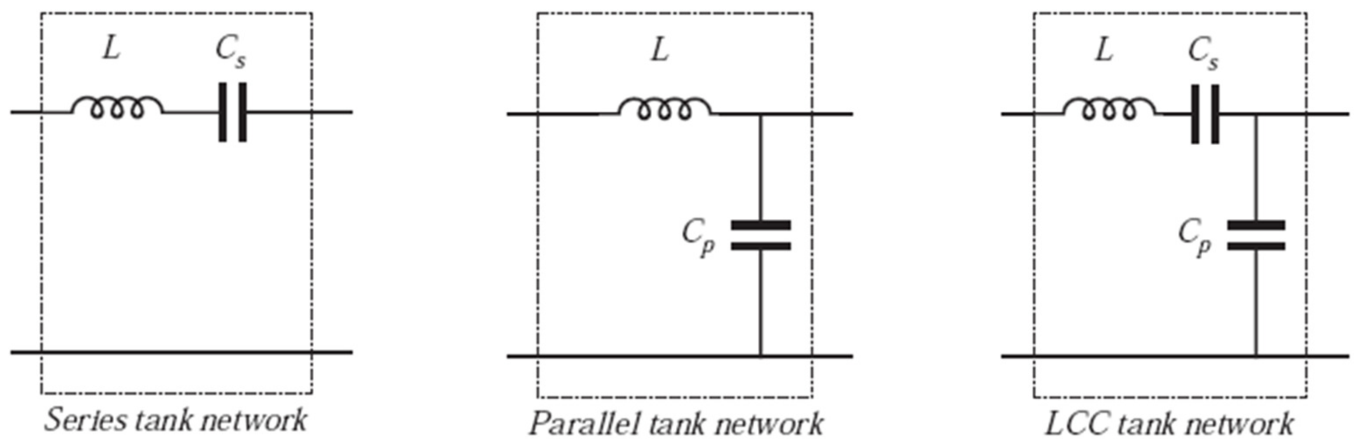
- Dc-to-high-frequency-ac inverters
- Resonant dc-dc converters
- Resonant inverters or rectifiers producing line-frequency ac

Variety of Resonant Converter Approach

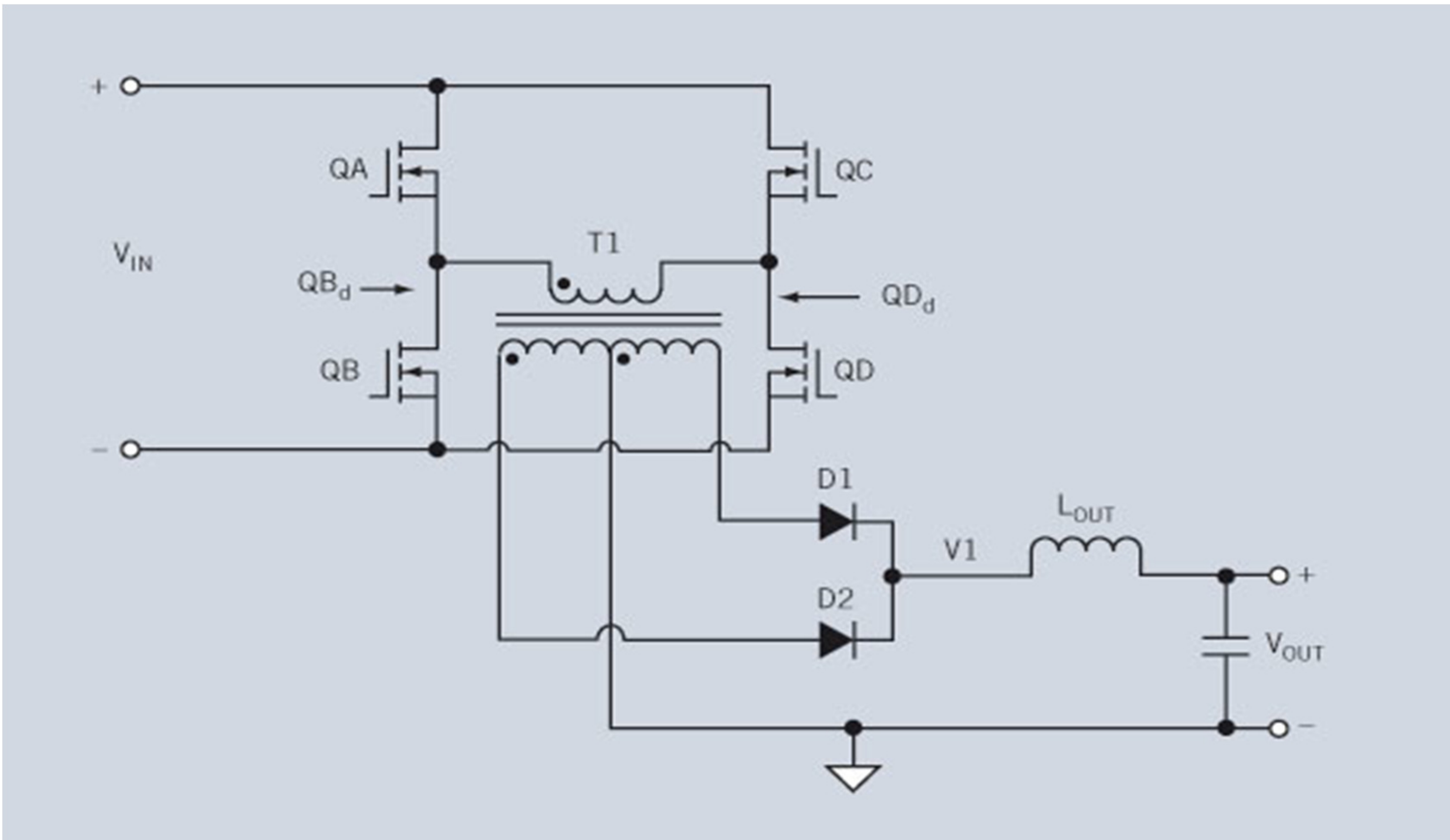
Basic circuit



Several resonant tank networks



Full Bridge Converter

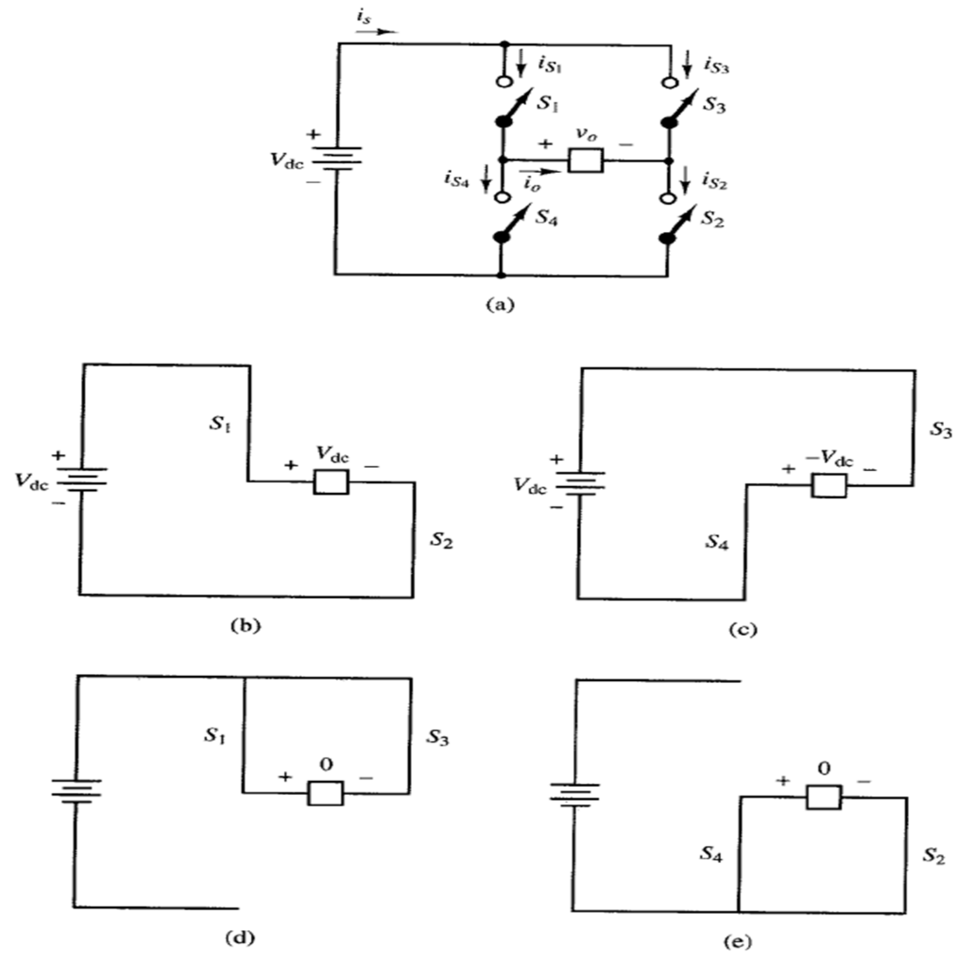


Ref: Power Electronics, Texas Instrument

Full Bridge Converter Switch State

Valid Switch States

- Each half bridge can be in one of two states
  - Upper on, lower off
  - Lower on, upper off
- Four allowed states in total (assuming CCM).
- Usually operated in CCM to ensure that output voltage is defined by $V_o = D\, V_{in}$



Ref: Power Electronics, Texas Instrument

ZVS Full Bridge Converter

ZVS Benefits

•Zero power "Lossless" switching transitions

•Reduced EMI / RFI at transitions

•No power loss due to discharging Coss

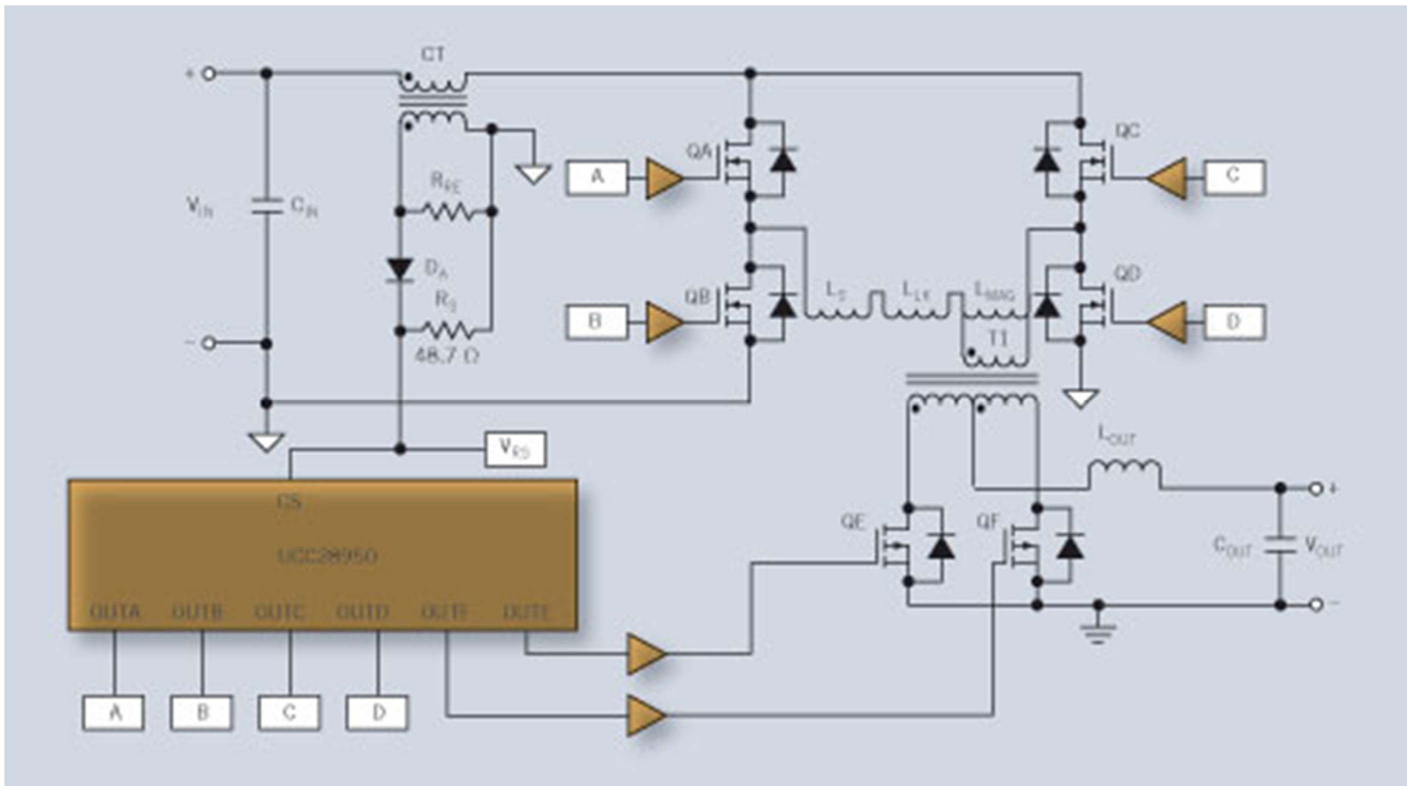
•No higher peak currents, (ie. ZCS) same as square wave systems

•High efficiency with high voltage inputs at any frequency

•Can incorporate parasitic circuit and component *L & C*

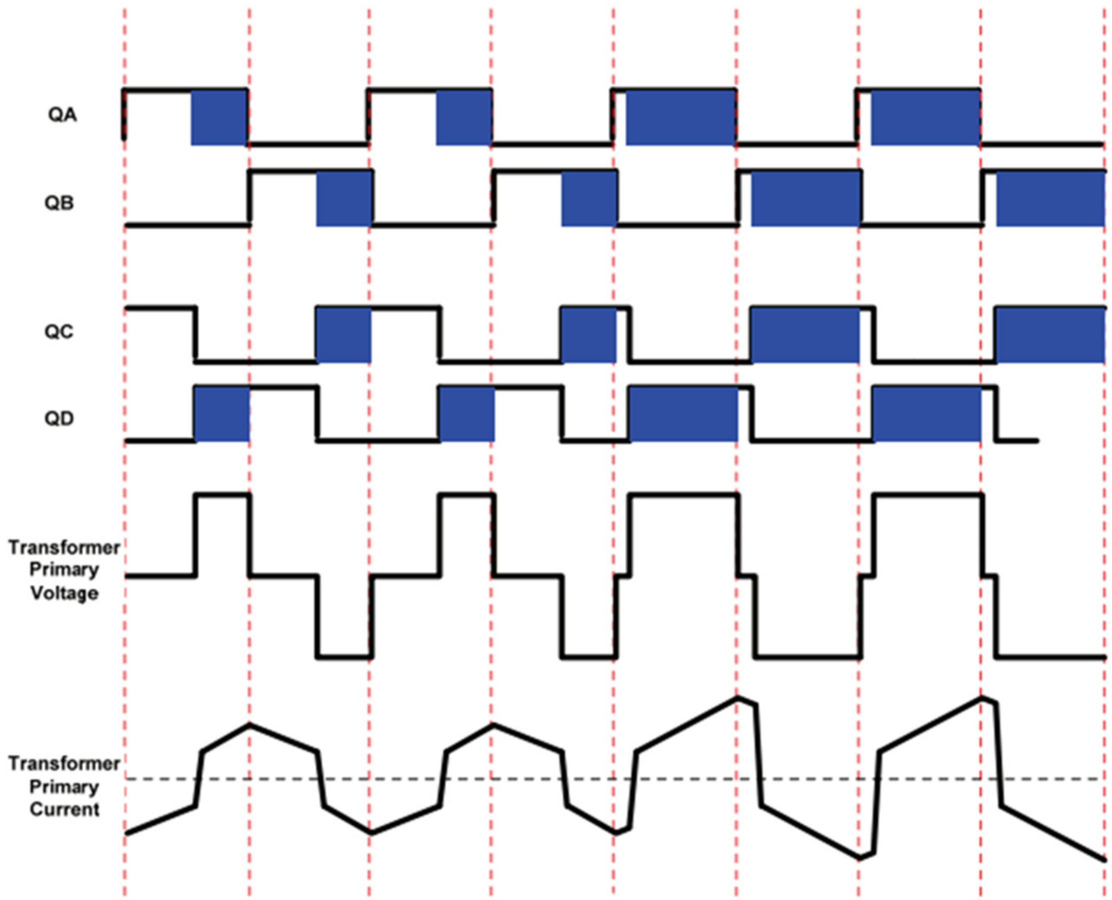
•Reduced gate drive requirements (no "Miller" effects)

ZVS Full Bridge Circuit



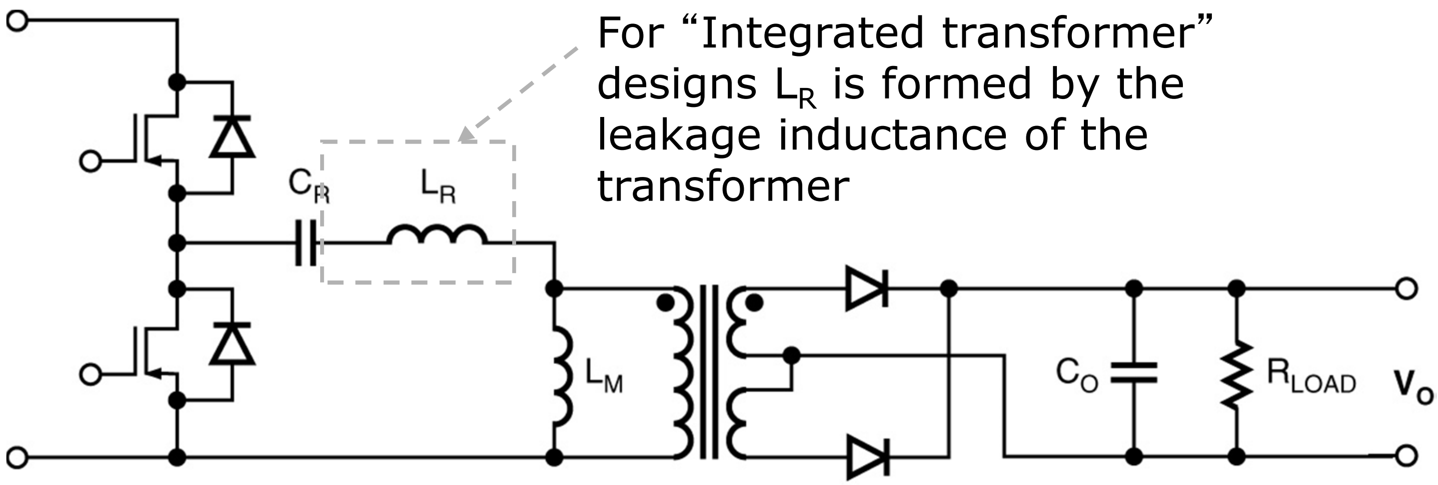
Ref: Power Electronics, Texas Instrument

ZVS Full Bridge Timing Diagram



Ref: Power Electronics, Texas Instrument

LLC Converter



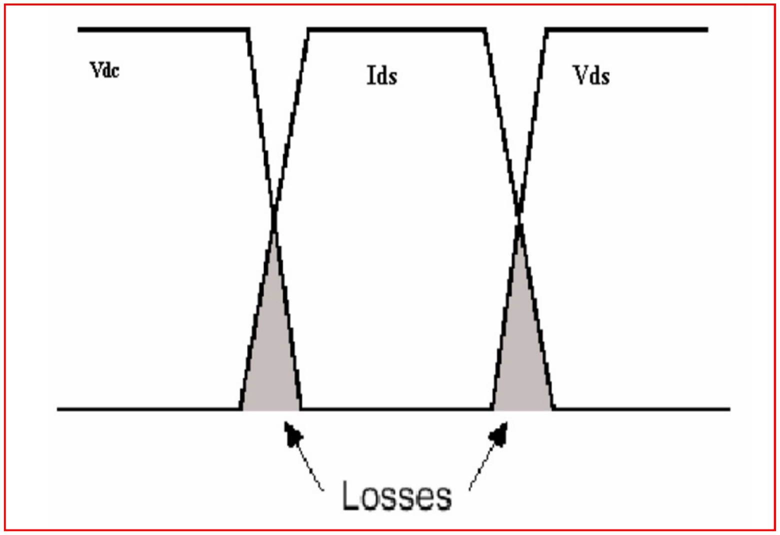
For "Integrated transformer" designs L_R is formed by the leakage inductance of the transformer

- LLC resembles a half-bridge, but there are differences
  - No output choke
  - Transformer core is gapped to set L_M
  - Symmetric, almost 50% duty-cycle at all times, on the MOSFETs
    - There is a short "dead-time": MOSFETs are both off for a short period every cycle
      - During this dead-time Zero Voltage Switching occurs
  - Output voltage is controlled with *switching frequency* and not by duty cycle

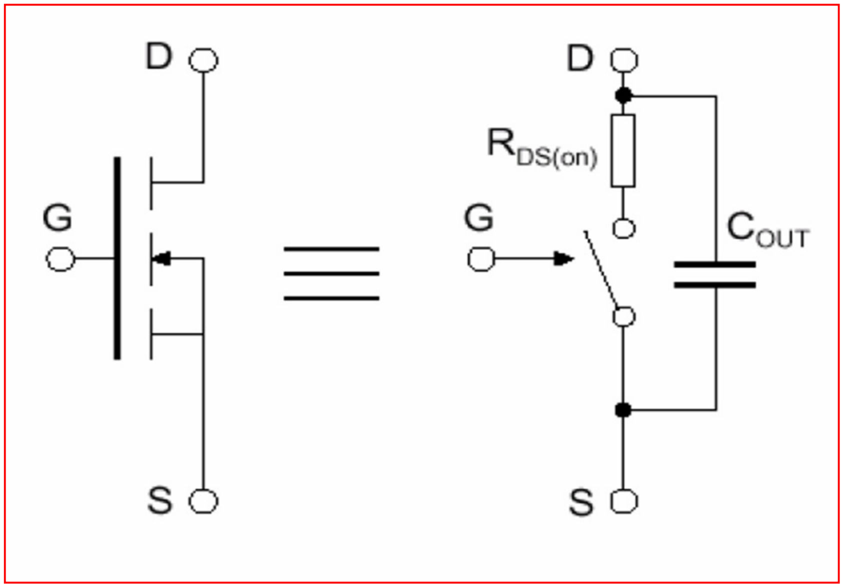
How Does LLC Converter Gets High Efficiency?

•Improved Efficiency – It reduces switching loss through zero voltage switching.
•ZVS - Voltage across the switch drops to zero before switch turns on.
•It processes power in a sinusoidal manner and the switching devices are softly commutated.

- ➢Remove overlap area between V and I when turning on
- ➢Capacitive loss is eliminated



Switching Losses

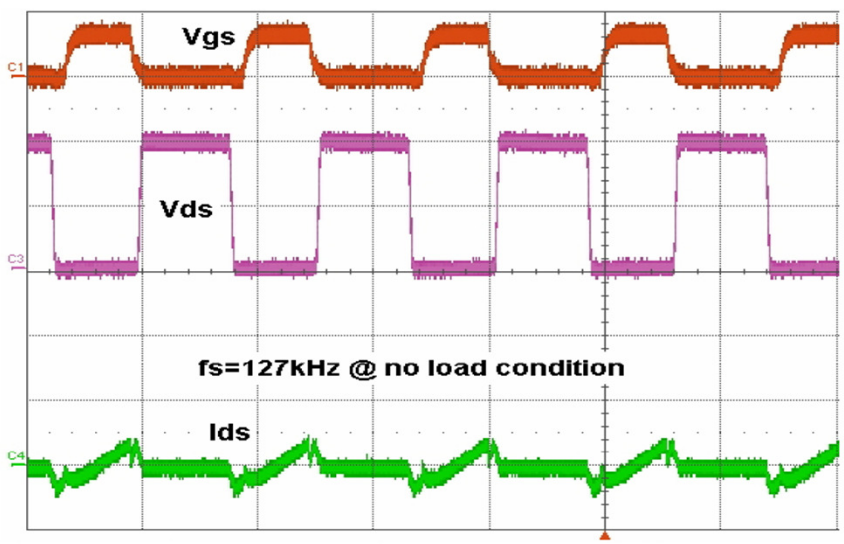


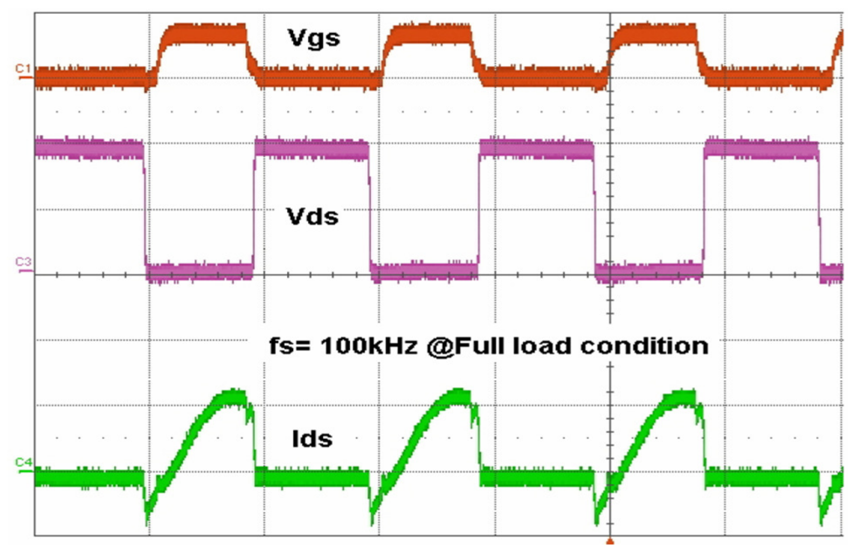
Capacitive Loss

Features of LLC Converter

- Narrow frequency variation over wide range of load.
- Resonant frequency change with the load.
- Attained zero voltage switching even at light load.

$$F_{max} = F_s = \frac{1}{2\pi\sqrt{L_s C_s}} \qquad F_{min} = \frac{1}{2\pi\sqrt{(L_s + L_m)C_s}}$$





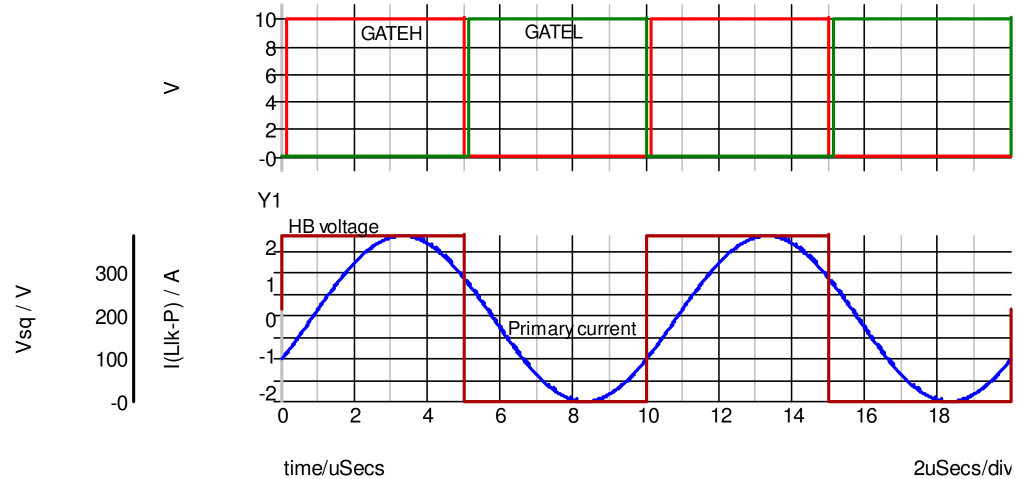
LLC as Compared to PWM

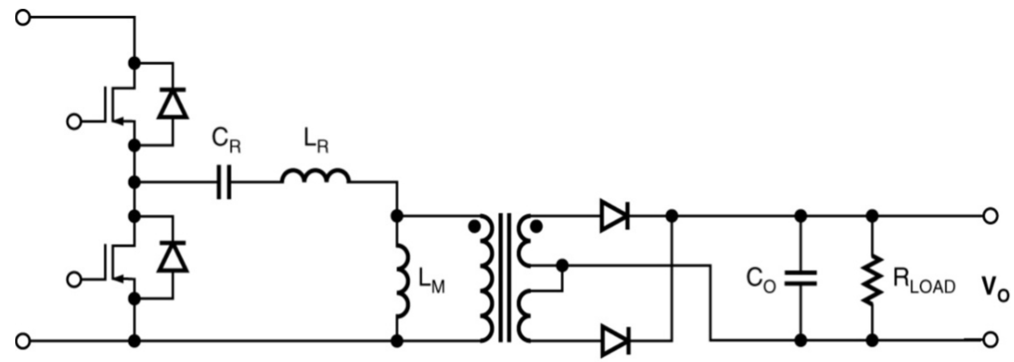
- At turn-on the PWM converter dissipates the energy stored in the Coss as heat
    - Faster turn-on doesn't reduce this loss

- In an LLC the current in the Drain reverses (flows in the body diode), before turn-on, so there is almost no voltage and no energy in the Coss at turn-on.
    - During this reversal of current the voltage on the Drain goes to zero and the energy in the Coss is recycled and not dissipated

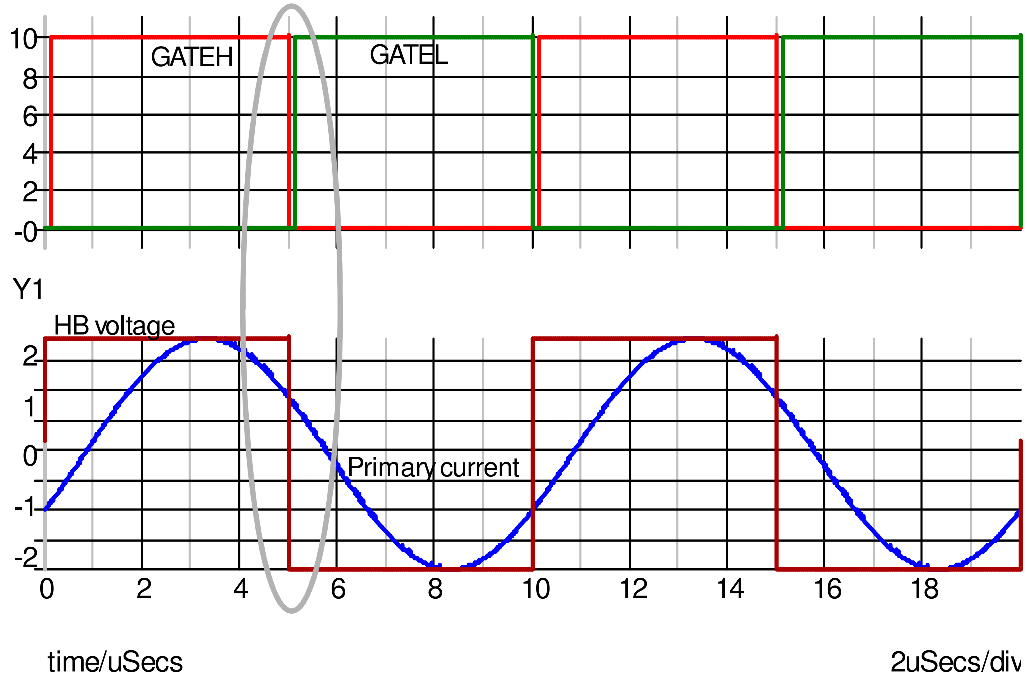
LLC Waveforms

- GATEH and GATEL (gate drive signals, for high and low side MOSFETs) are out-of-phase, always slightly less than 50% duty cycle, and always symmetric
- Dead-time typically constant even as switching frequency changes due to line and load changes
- Primary current is sinusoidal and lags the voltage
- Because primary current lags voltage, ZVS is possible





ZVS Waveform



- During the dead-time, ZVS occurs
- The series inductance stays at a roughly constant current during the dead-time

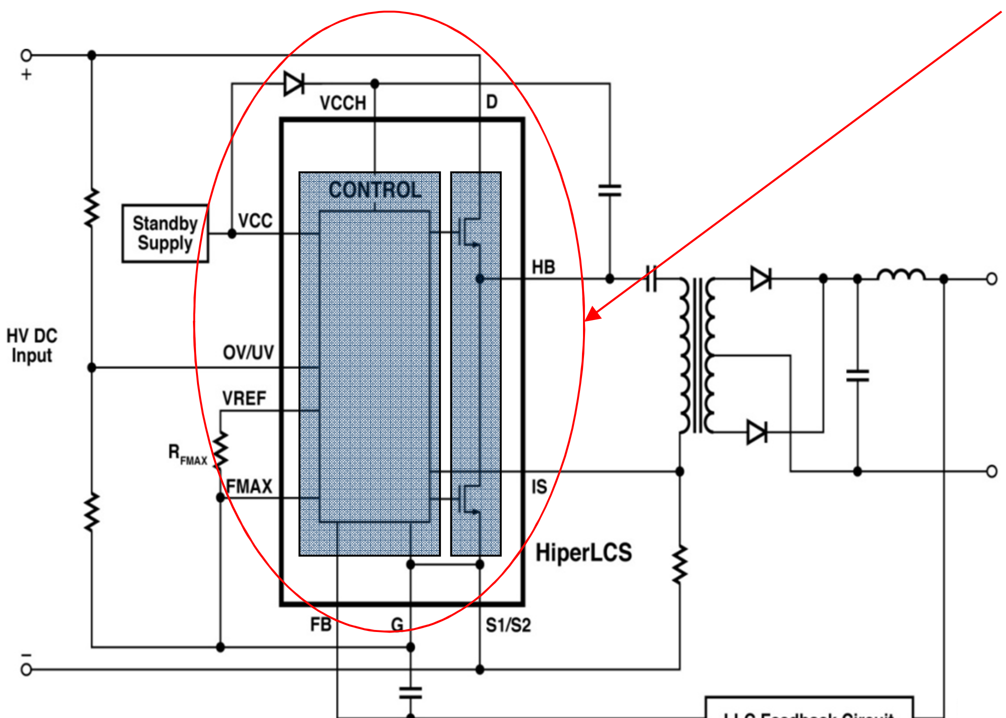
LLC Advantages

- High efficiency due to lossless switching from ZVS
  - E.g. 96% @24V with Schottkys
- Single magnetic component (with integrated magnetics)
  - No losses associated with output choke
  - Reduced cost
- Excellent output cross regulation due to no output choke
- Leakage inductance in primary limits rate of rise of current, increasing reliability
- Integrated magnetics: separated primary and secondary yields low common mode EMI
- Can run high frequency (>=300 kHz)
  - Smaller transformer and ceramic output capacitors

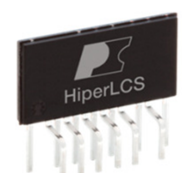
Practical Implementation

High freq. resonant converter for high power density & high efficiency

- Highly integrated solution for high efficiency ZVS half bridge topology
- 1MHz max. switching freq. (Set at high resonant freq. & advantage during start-up)



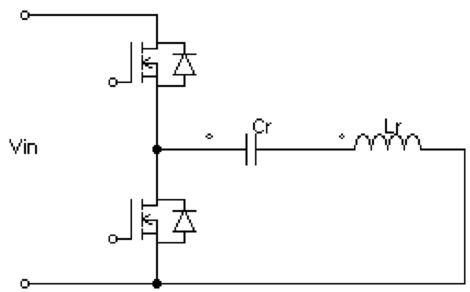
Integrates the LLC controller (variable freq.), drivers, protections, low side & high side power Mosfets into a single package



Advantage of High Freq. at Start-up

Start-up at high freq. to reduce peak start current

During power-up output capacitors are empty and present a short circuit. The current from the LLC bridge is limited by the impedance of the resonant tank

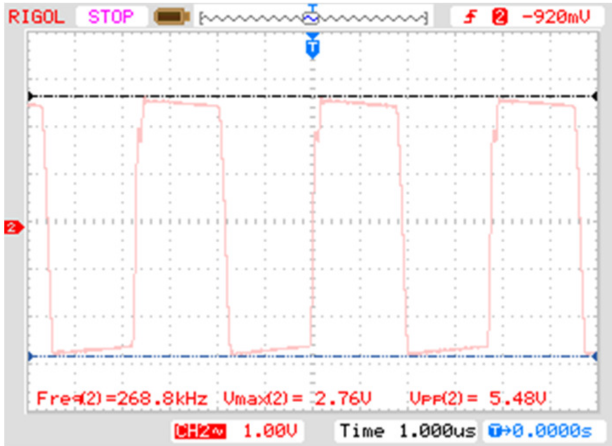


Equivalent circuit for the first switching cycle at start-up (Diode voltage drop neglected)

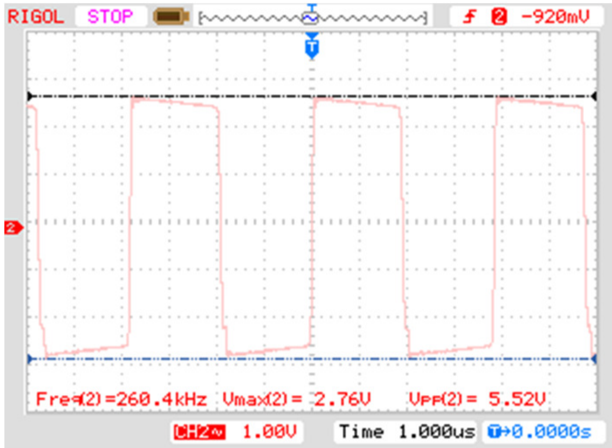
To limit this current, the switching frequency must be set to high value. At high value, the impedance of the resonant tank is greater and the current taken from the source is smaller

The start-up frequency should be greater than 2 x the resonant frequency (operating frequency)

Output Voltage Waveform of LLC Transformer

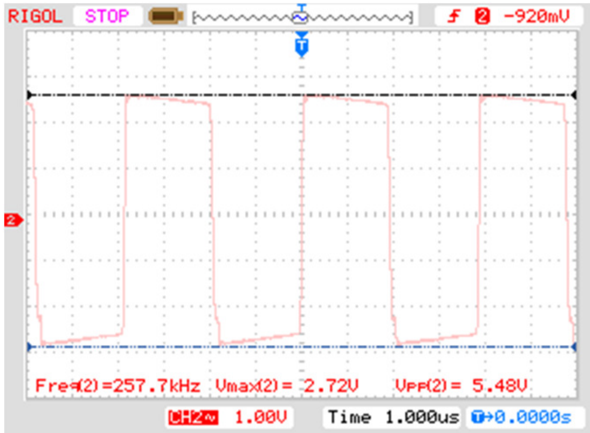


24V at 1A Load



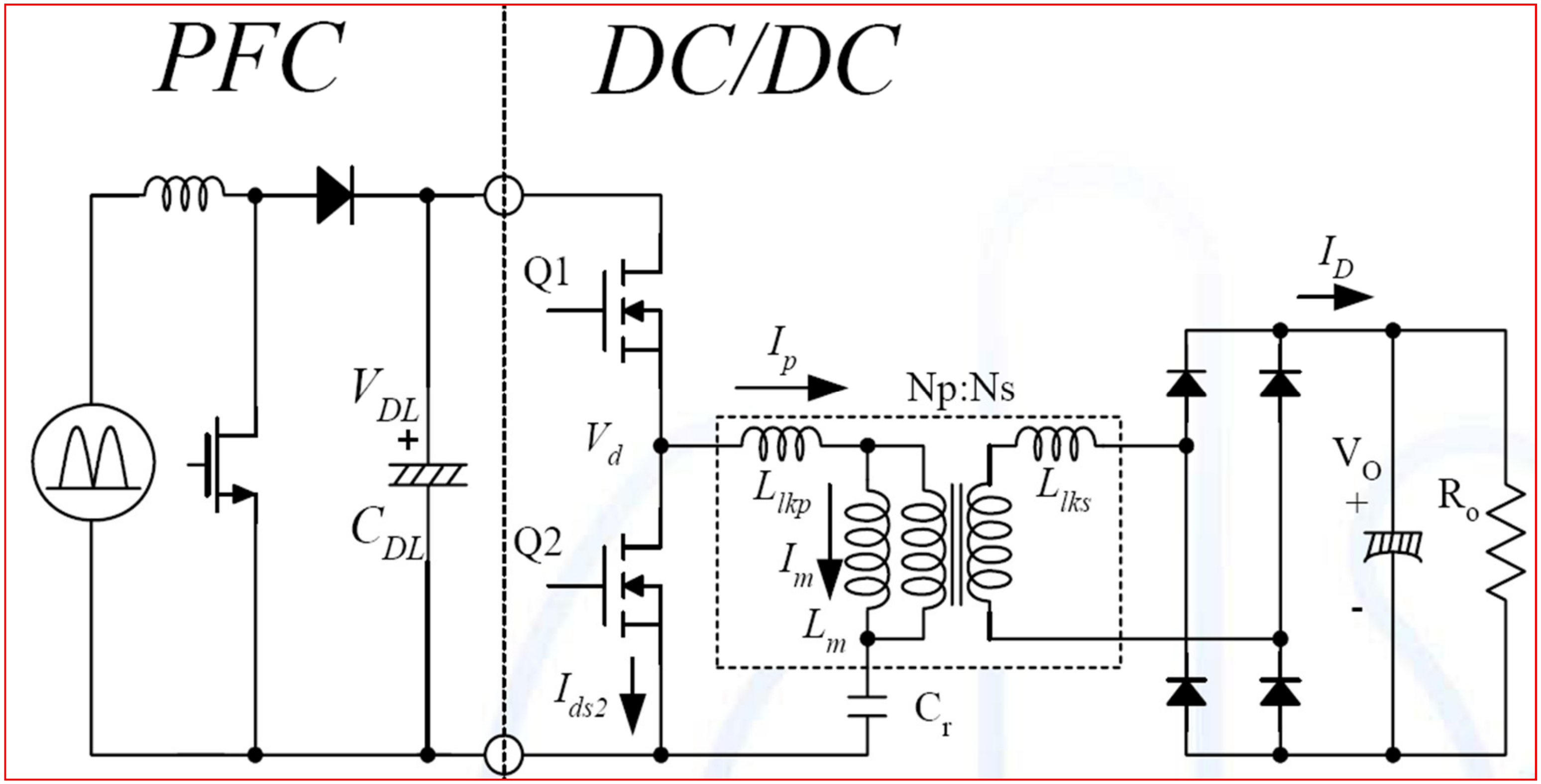
24V at 3A Load

Note: Freq. varies with output load



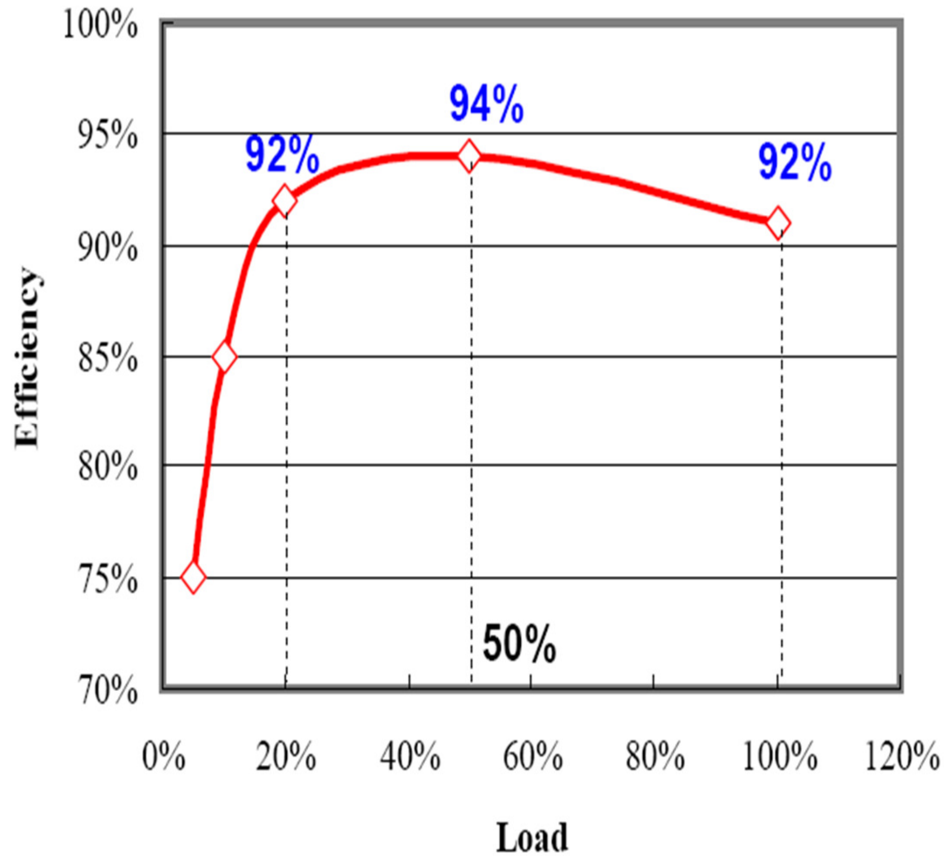
24V at 5A Load

PFC and LLC Converter



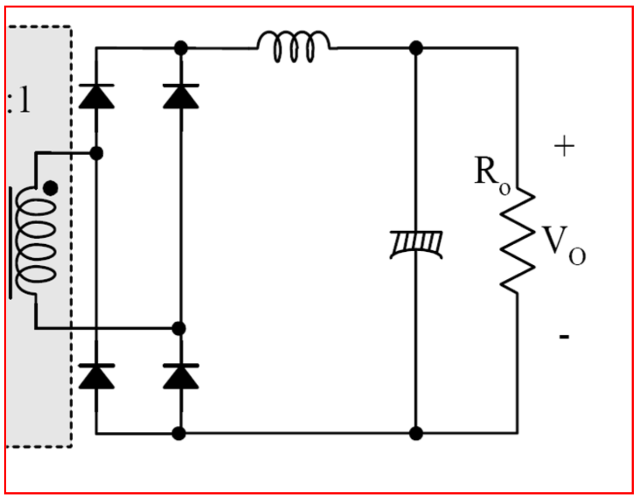
Further Improvement of Efficiency

- Output rectifier diode dissipates power.
- Optimized the LLC converter using SR.
- Synchronous rectification will realized the increase of efficiency.

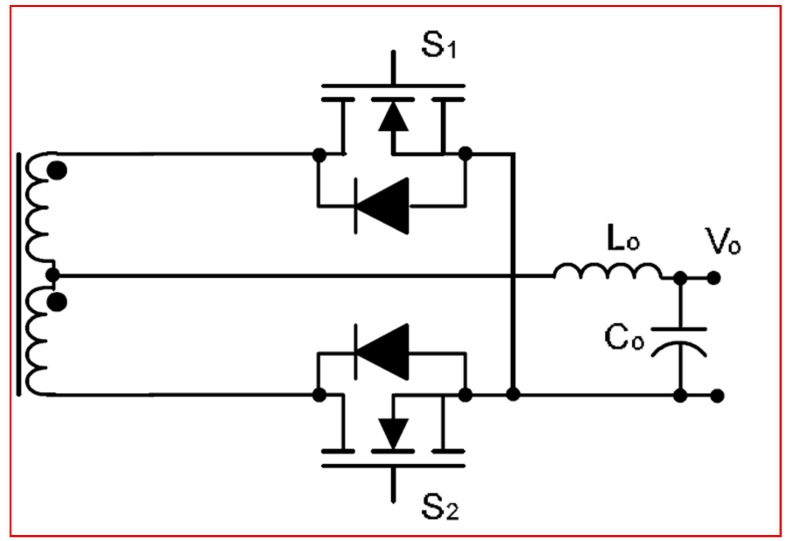


LLC Converter Output Rectifier

Bridge Output Rectifier



Synchronous Output Rectifier



Class Exercise with 150W LLC Converter with Boost PFC

- Monitor the voltage waveforms of LLC Mosfets (high & low side)
- Determine the resonant freq. at full-load
- Monitor effect of output load to the switching freq. & duty cycle
- Measure overall efficiency (PFC + LLC) across the load range

List of References

Andreycak, B. (1999). Zero Voltage Switching Resonant Power Conversion. *U-138.* Retrieved on Dec. 29, 2011 at http://www.ti.com/lit/an/slua159/slua159.pdf

Erickson, R. (2001). *Fundamentals of Power Electronics.* New York: Springer.

Fairchild Applications Engineering (2007). AN4151. *Fairchild Semiconductor.* Retrieved on December 29, 2011 at www.fairchildsemi.com/an/AN/AN-4151.pdf

Maniktala, S. (2005). *Switching Power Supply Design & Optimization.* New York: McGraw Hill.

Maniktala, S. (2006). *Switching Power Supplies A to Z.* Boston: Newnes.

Power Integrations (2010). HiperLCS Data Sheet. Retrieved on Dec. 19, 2011 at www.powerint.com.

High Efficiency Switch-mode Power Supply Design Overview

Module Six

Practical Design Considerations

Safety Considerations

PCB Design

EMI Considerations

Snubber Design

Considerations for Product Safety

- End Objective is that product is designed for safe operation
  - Protection against electric hazard by:
    - Limiting the current <0.5mA and voltage (SELV-safe extra low voltage <43V/50Vrms, 60VDC)
    - Earthing
    - Automatic disconnect in the event of fault
    - Inaccesibility of live parts
    - Following creepage & clearance requirements
    - Use layer of insulation (e.g. 2121V DC withstand)
  - Protection against fire hazard by:
    - Use current limiting devices (e.g. fuse, breaker)
    - Use of flame retardant materials (e.g. PCB 94V0)

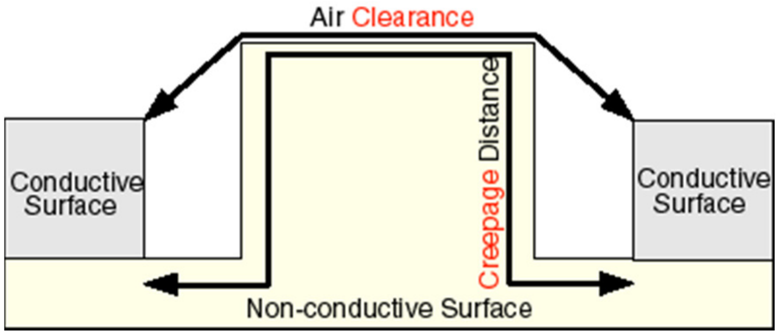
Safety Classes & Insulation Types

- Safety Classes
  - Class 0-functional insulation only
  - Class I -designed to be earthed with protection by basic insulation
  - Class II-no provision for earthing (e.g. two wire cord), but uses double or reinforced insulation
  - Class III-operate at SELV
- Insulation types
  - Basic-one level of protection, failure protected by earthing
  - Double-two levels of protection through redundant insulation
    - (Dielectric withstand of 4242V DC or 3000V AC rms)
  - Reinforced-single layer of greater strength, replacing 2 layers

Double insulation symbol

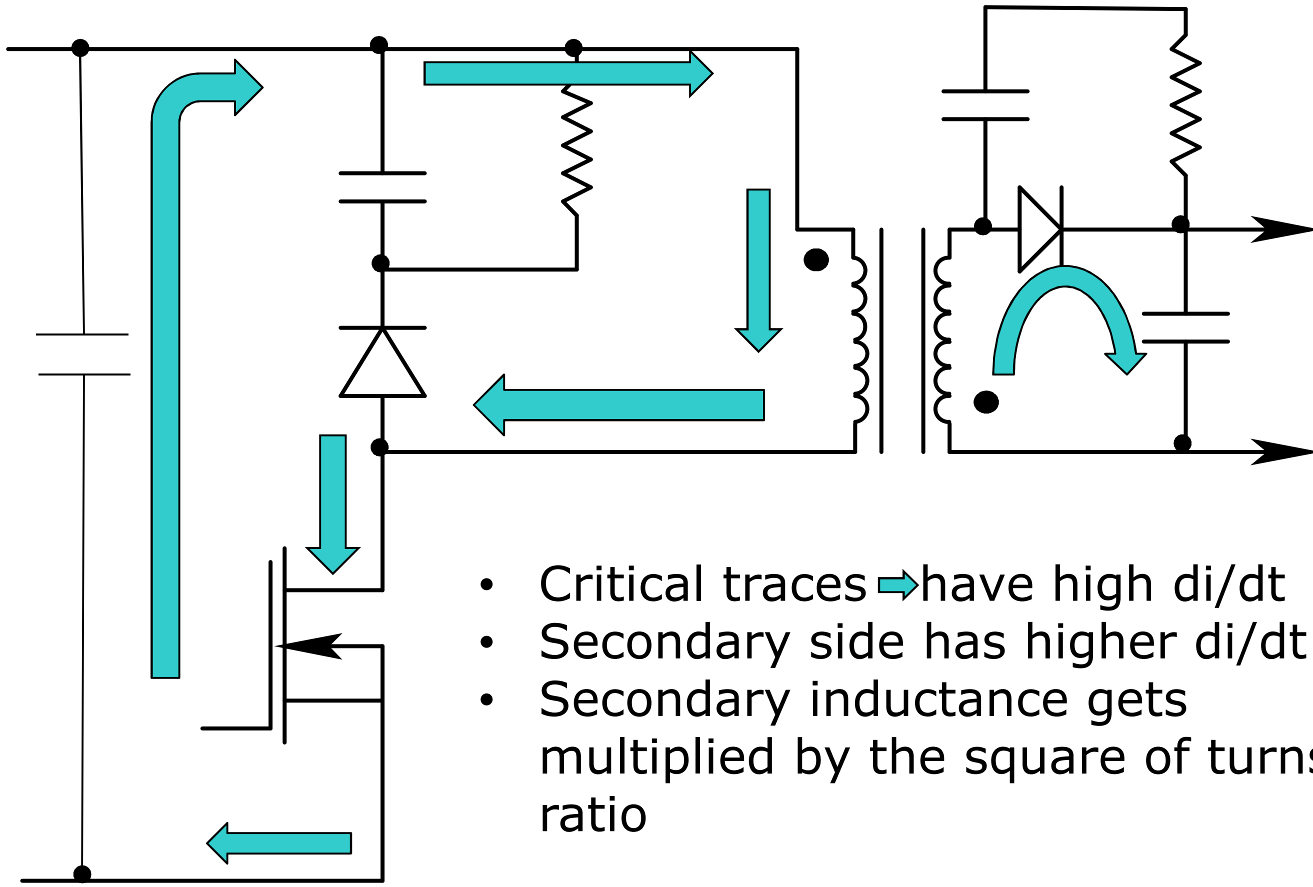
Difference Between Creepage and Clearance

- Physical separation provides protection from hazardous voltage
  - Creepage is the shortest distance between conducting paths along the surface of the insulating material
  - Clearance is the shortest distance between conducting paths through air



Maximum Input Voltage		I.T.E.		Medical Equipment	
		Basic	**Reinforce**	**Basic**	**Reinforce**
125V	Air Clearance	1.3mm	2.6mm	1.6mm	3.2mm
	Creepage Distance	1.5mm	3.0mm	3.0mm	6.0mm
250V	Air Clearance	2.0mm	4.0mm	2.5mm	5.0mm
	Creepage Distance	2.5mm	5.0mm	4.0mm	8.0mm

Identify Paths with Critical Traces



- Critical traces ⇨ have high di/dt
- Secondary side has higher di/dt
- Secondary inductance gets multiplied by the square of turns ratio

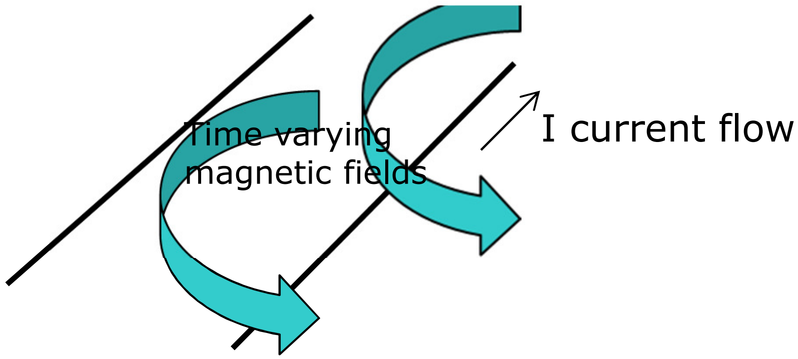
Parasitics
The Unwritten Schematics

- Parasitics
  - Trace resistance (AC & DC), contact resistance, solder/via
  - Trace inductance (quick estimate: 20nH/inch., 1.2nH /via)
  - Inter-trace capacitance

- Capacitive coupling

(a) (b)

- Magnetic coupling

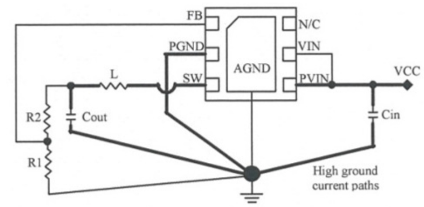


PCB Design Considerations

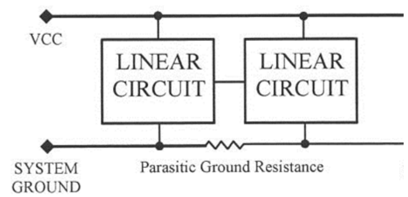
- Pay special attention to location of decoupling capacitors
- Locate the feedback circuit components away from switching noise sources (noise can cause offset, instability, or device failure)
- Careful design is required to comply with creepage and clearance requirements while simultaneously achieving good thermal performance
- VCC return and feedback signal return should be kept separate
- Avoid long length of traces carrying switching currents
- Consult relevant data sheet and application notes

Grounding Techniques

- Grounding Techniques
  - Single point (star)
    - Used to connect different (signal, power, digital) ground points



  - Multi-point
    - Used to connect similar ground points



  - Mixed of single & multi-point
    - Mixing similar & different ground points

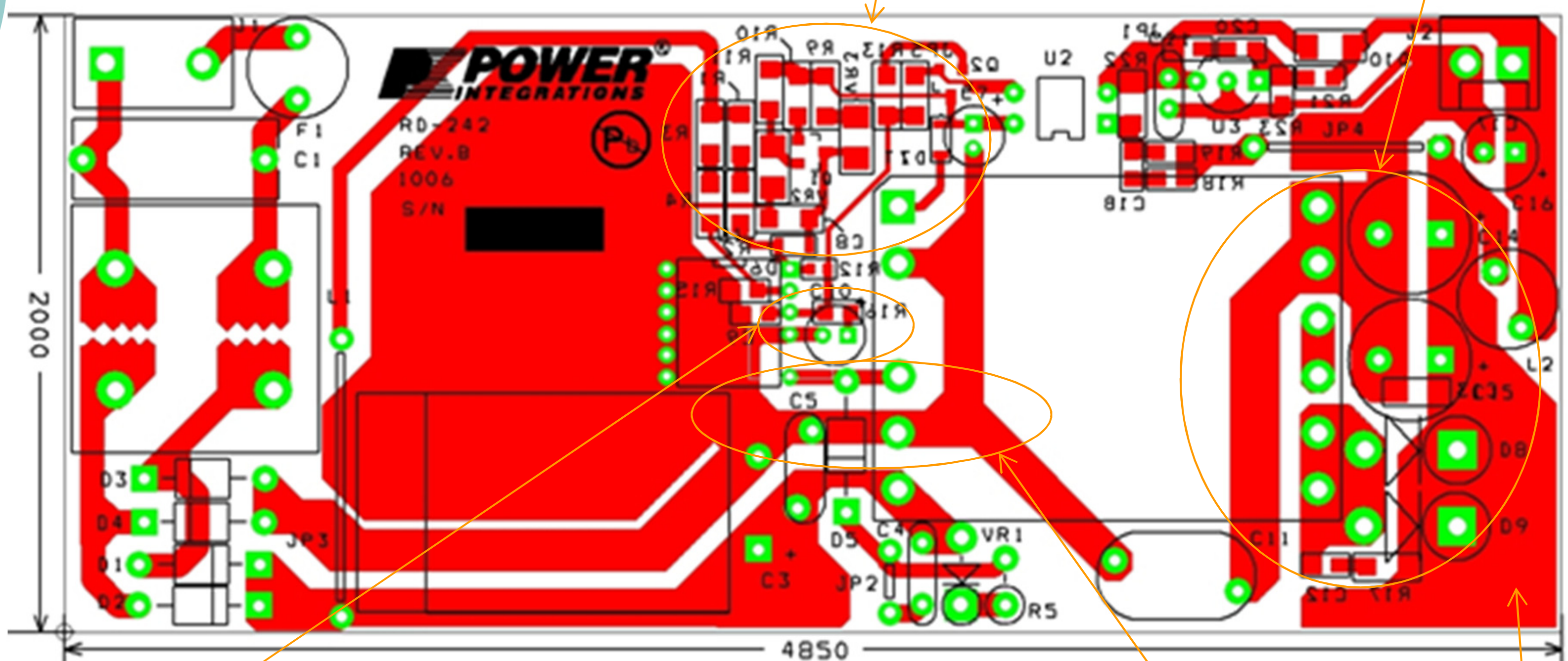
Design Procedure

1. Place/lay-out location of critical components/stages
2. Carefully design critical traces
3. Properly design appropriate grounding technique
4. Minimize current loops (More effective to reduce inductance by decreasing length than increasing width)
5. Carefully review traces sensitive to parasitic
6. Consider thermal design consideration

Flyback Evaluation Board Layout Design

Note: Locate feedback circuit away from noise & field sources

Keep the loop area small to reduce parasitic inductance and lower EMI



Note: Location of decoupling capacitor

Top View

Note: Grounding use Star (single pt.)

Increase area for thermals without emitting noise

PCB Copper Foil as Heat Sink

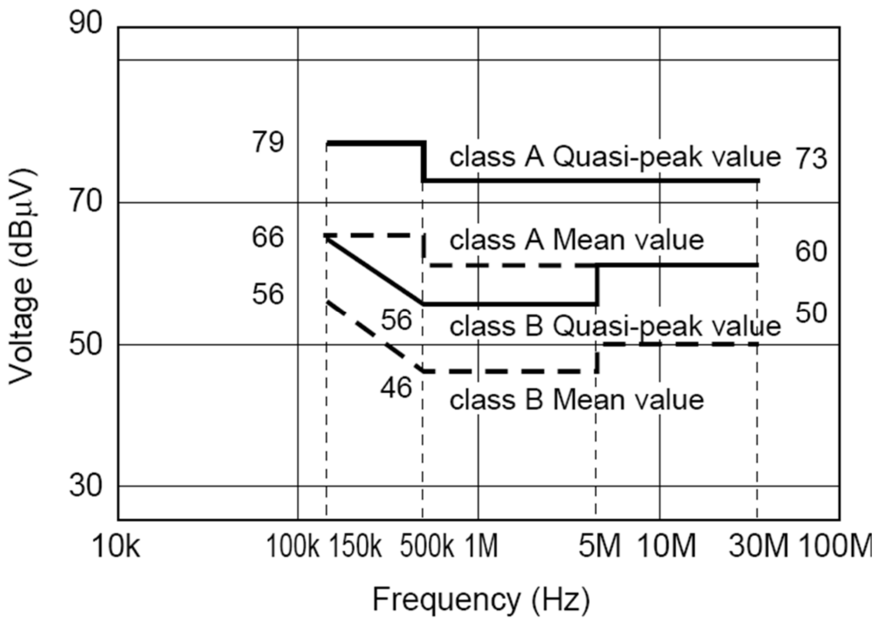
- Be careful that this will not cause increase in EMI
  - OK if metal tab connects to quiet node (e.g. ground)
- Practical for up to 3 inch. side (either side) with 2oz. Cu
  - $A=985 \times Rth^{-1.43} \times P^{-0.28}$
    - A is area of Cu foil in square inches
    - Rth is thermal resistance case to ambient
    - P is the power dissipation of the device
- Rth= ΔT/P
  - ΔT is difference in case and ambient temperature
- Example, ΔT= 110-40= 70 deg. C, P=1.35W
  - Rth= 52 deg. C/ W
  - Solving for A= 3.1 sq. inch.,
    or 1.76 inch. per side (square)

EMC Standards

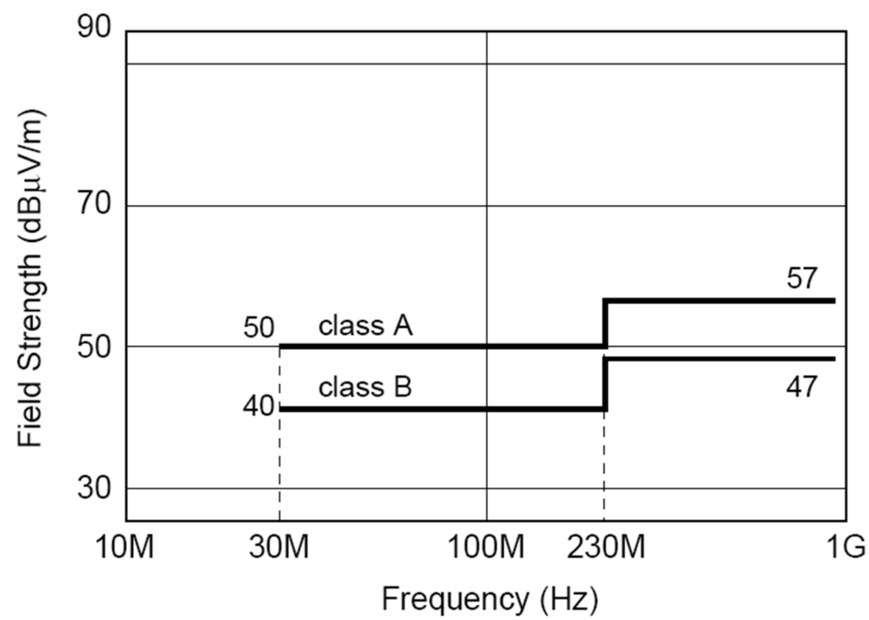
Limits of CISPR 22/EN55022

Class A Equipment: The equipment which is used in light industrial commercial areas.
Class B Equipment: The equipment which is used in residential areas.

Conducted Emission Limits



Radiated Emission Limits

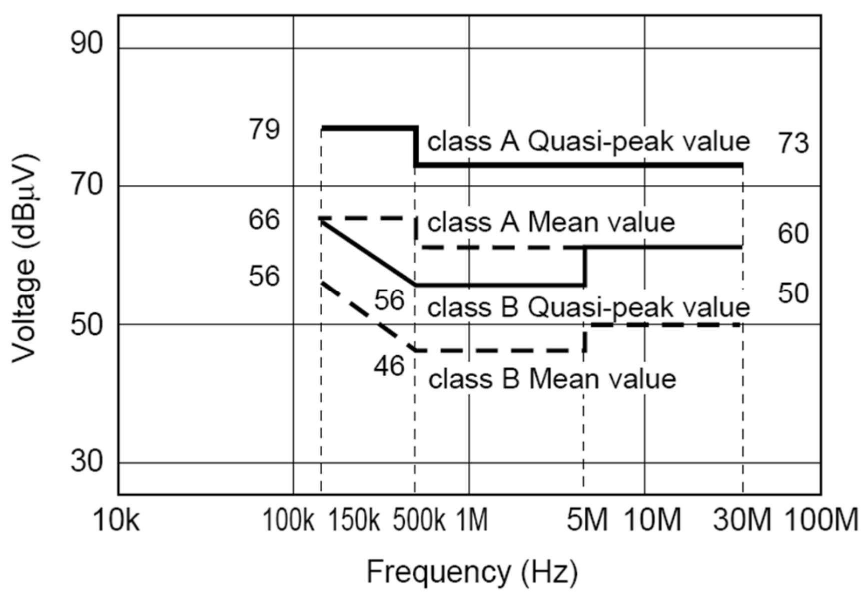


EMC Standards

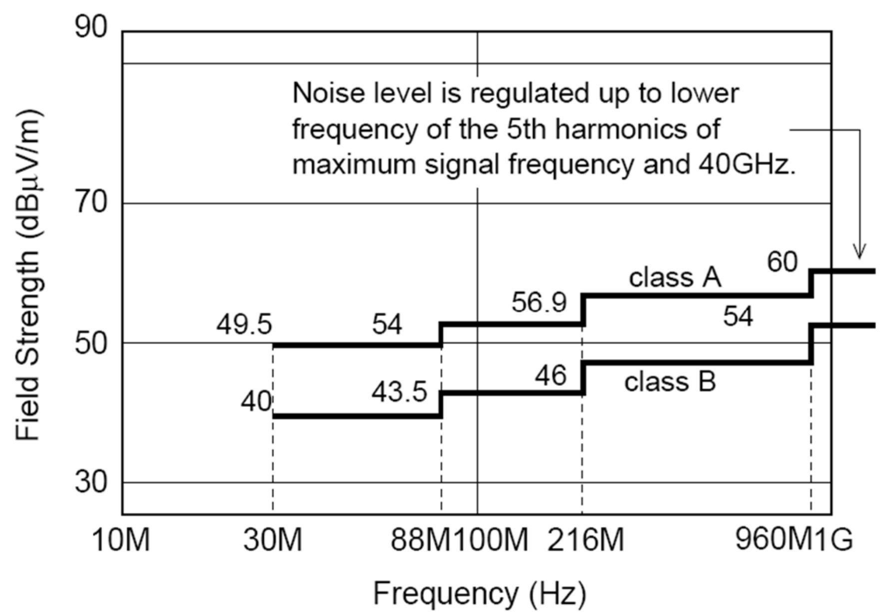
Limits of FCC Part 15 Subpart B

Class A Equipment: The digital equipment that is sold for commercial, industrial and office use.
Class B Equipment: The digital equipment that is sold to be used in residential areas.

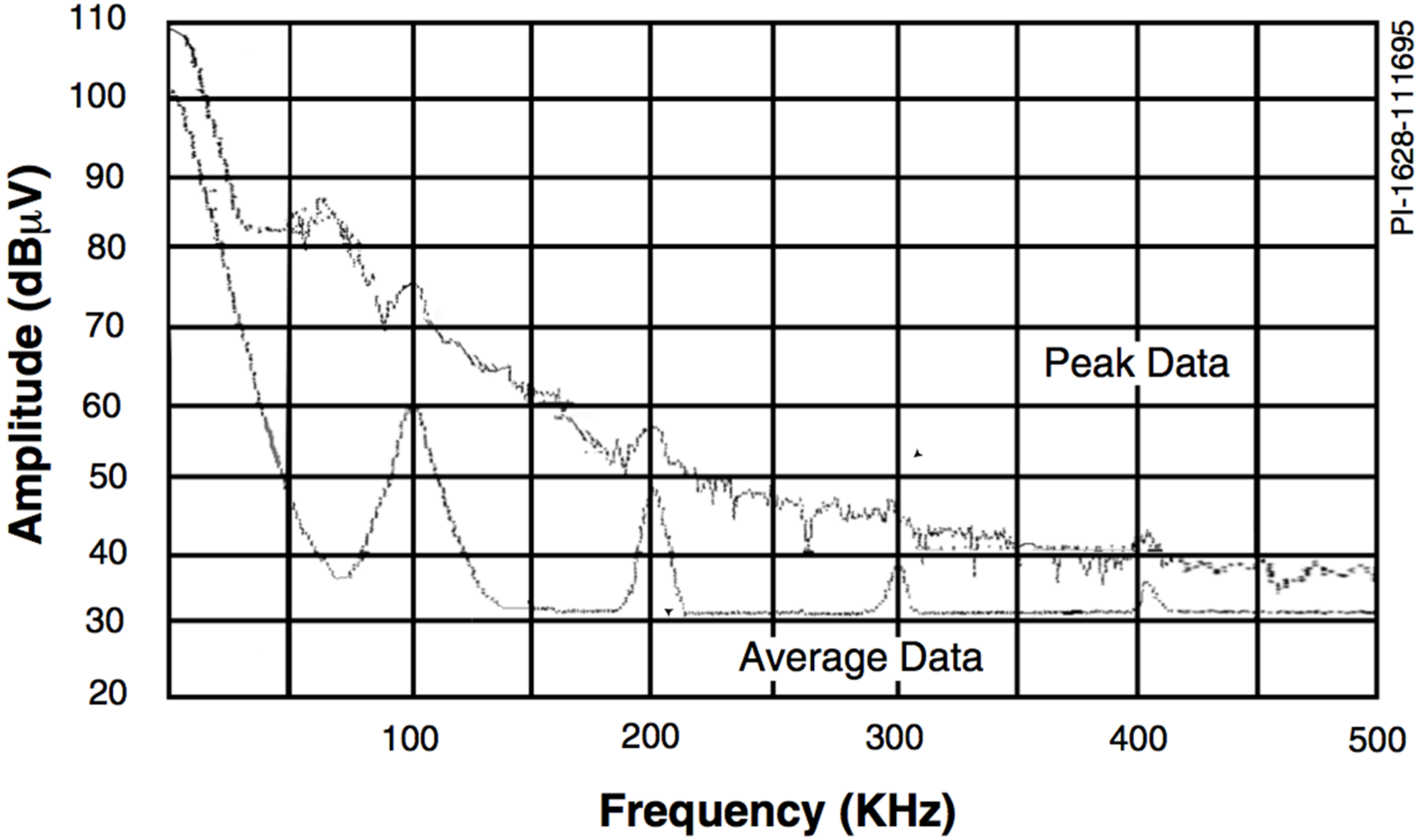
Conducted Interference Limits



Radiated Interference Limits

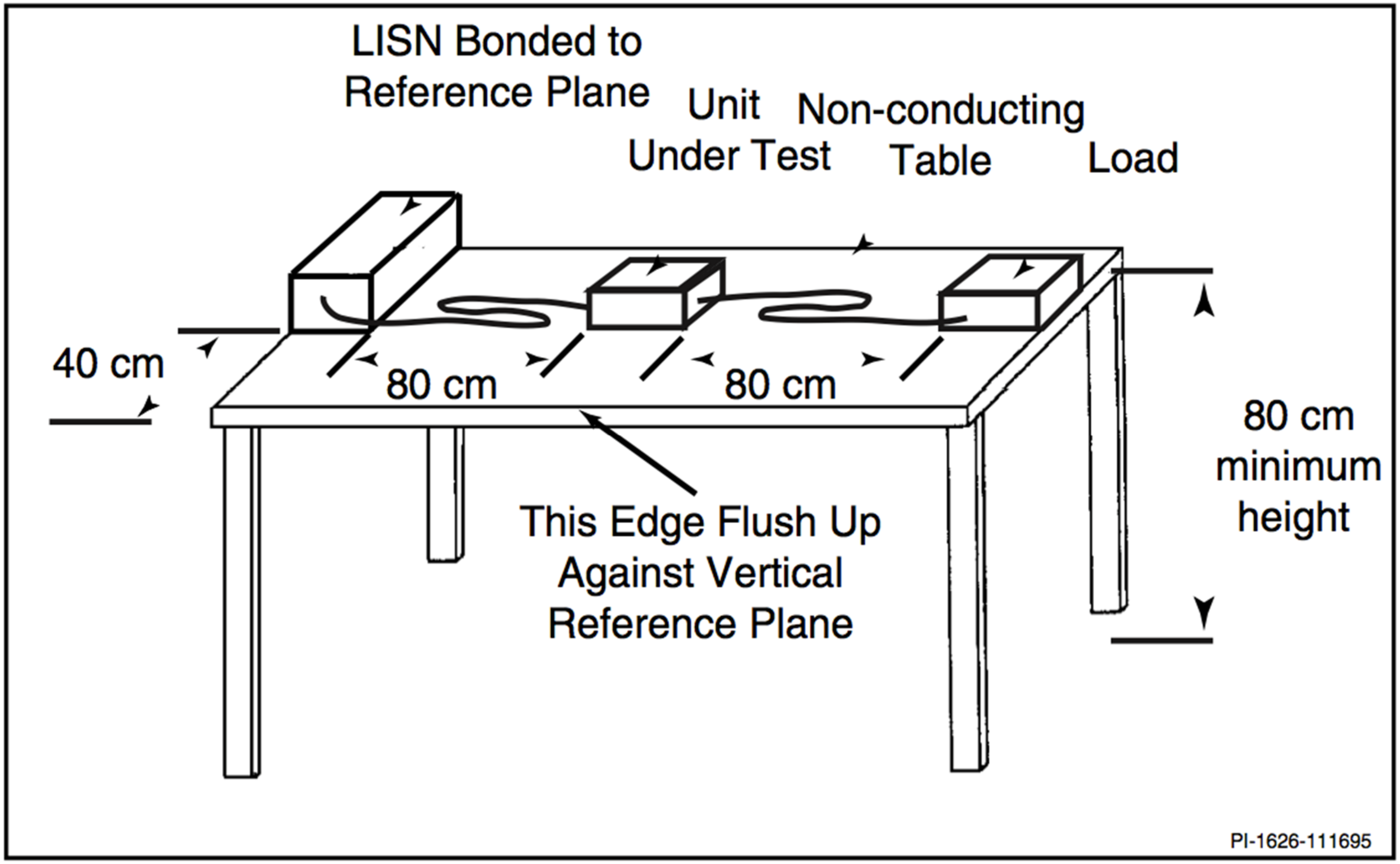


EMI Peak Data vs Average Data



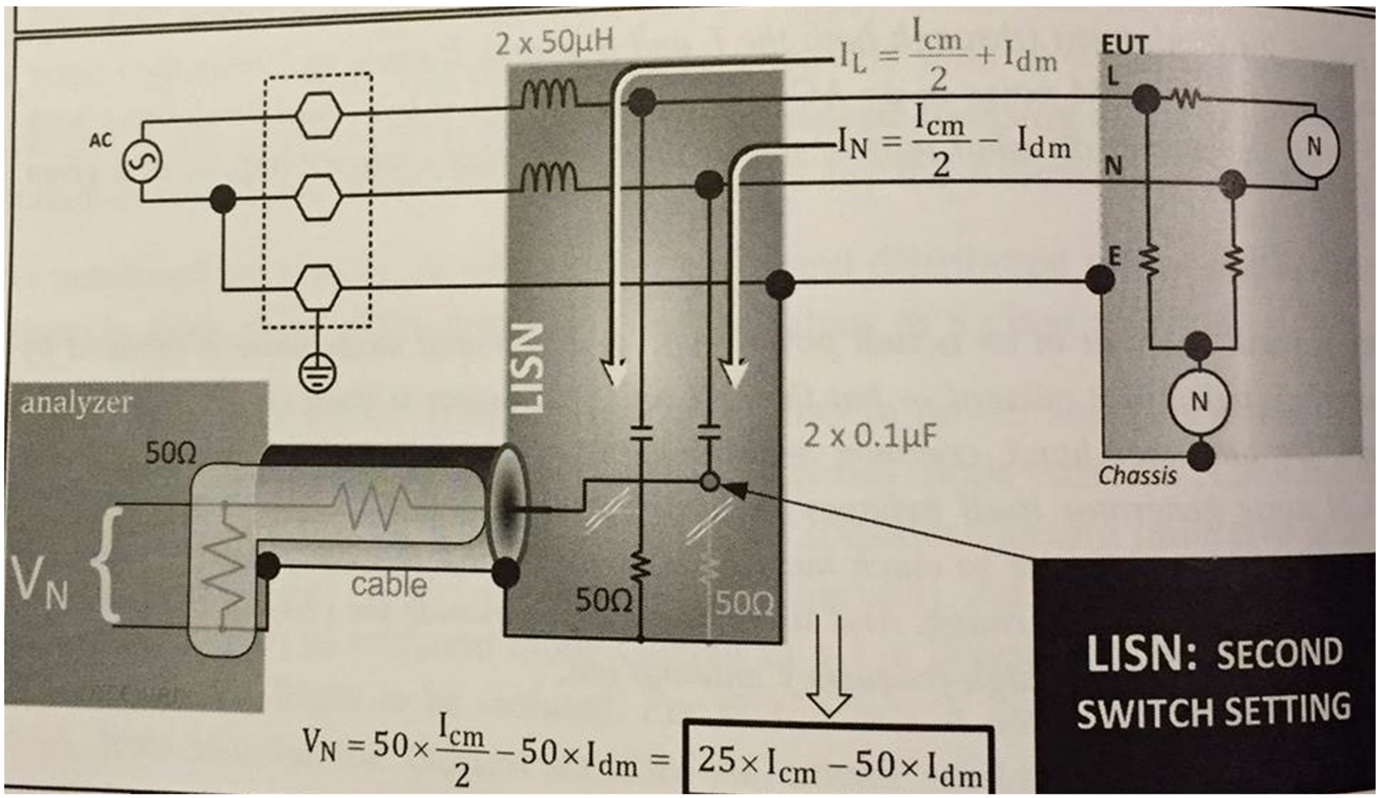
Ref: PI, App Note 15

EMI Compliance Test Setup



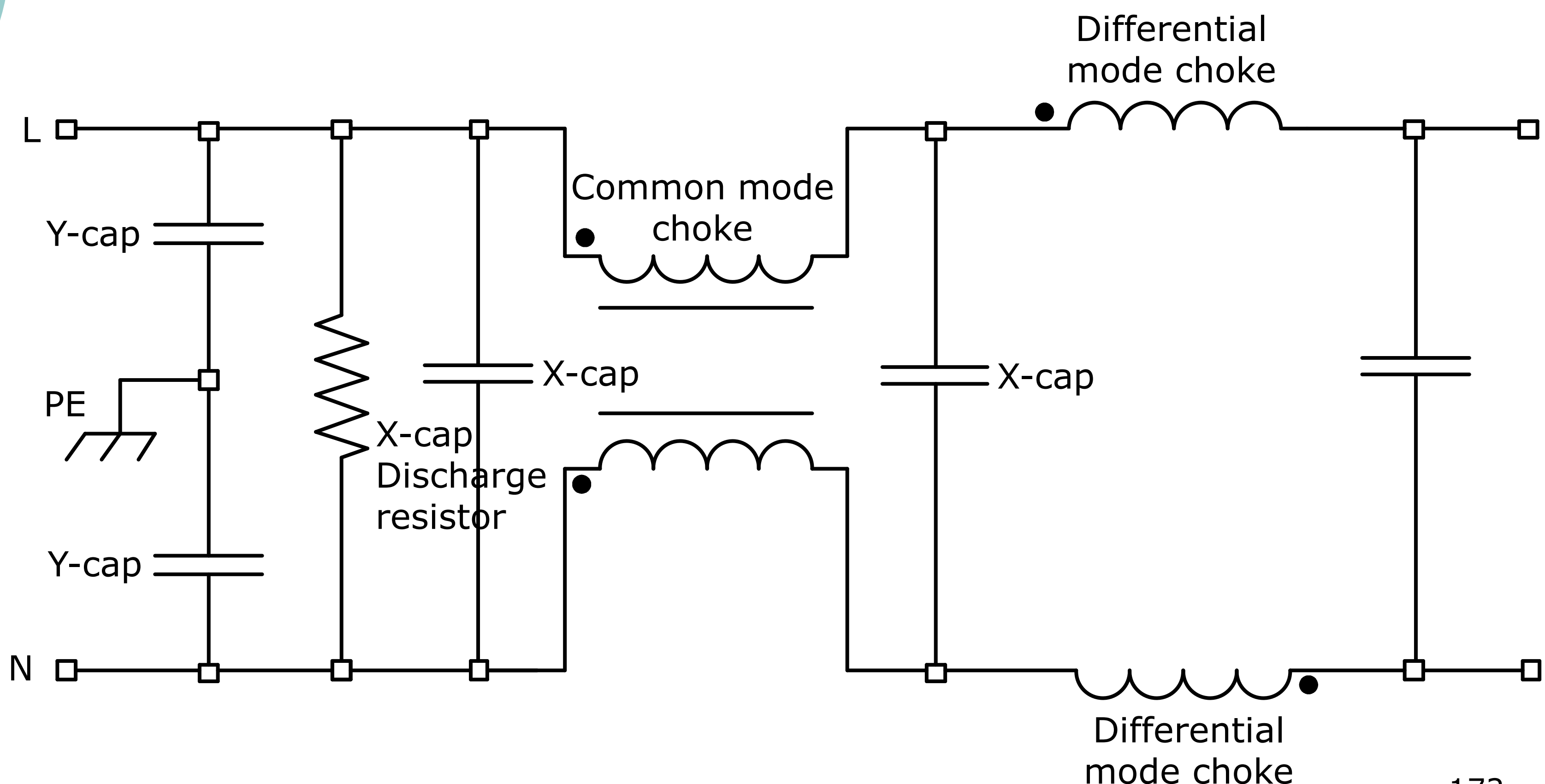
Ref: PI, App Note AN -15

Testing Conducted EMI

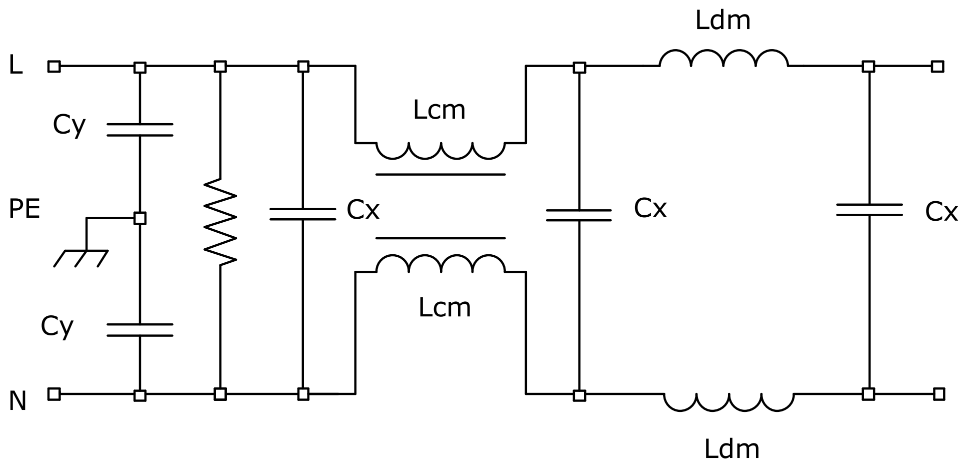


EMI Filter Components

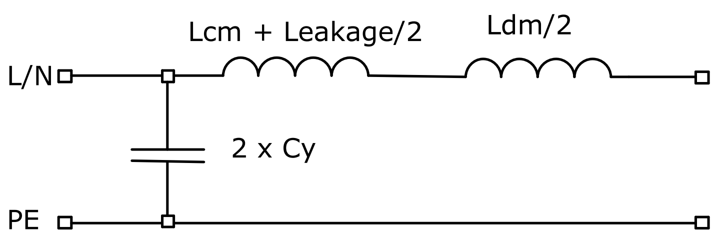
- Y-cap & common mode choke filters HF common mode noise
- X-cap & differential mode choke filters HF differential mode noise



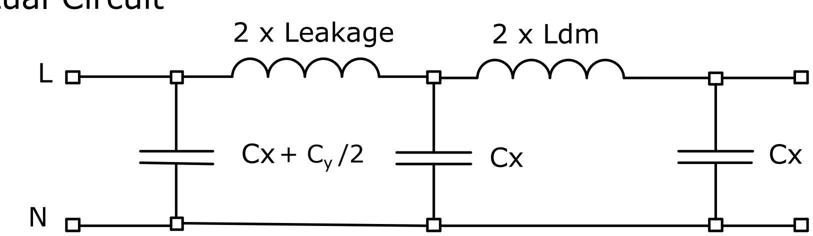
CM & DM Equivalent Circuit



Actual Circuit

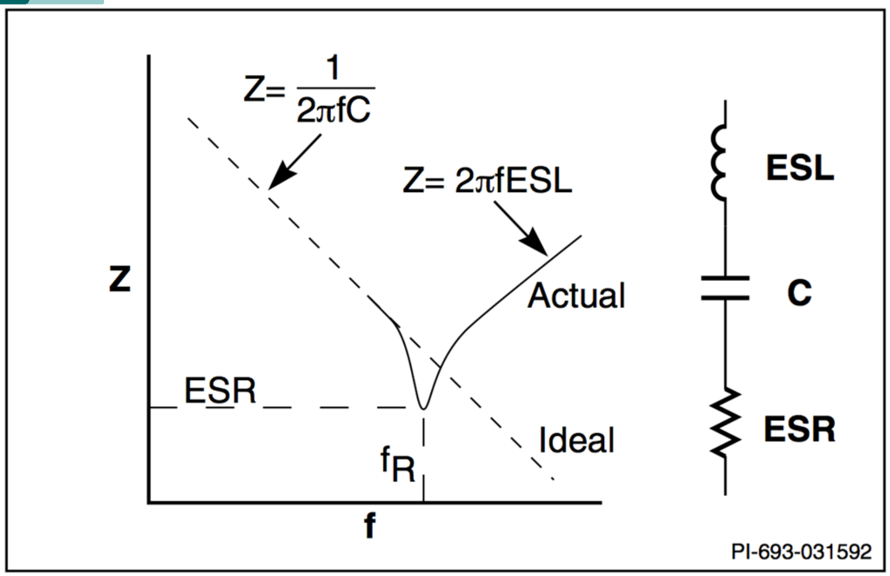


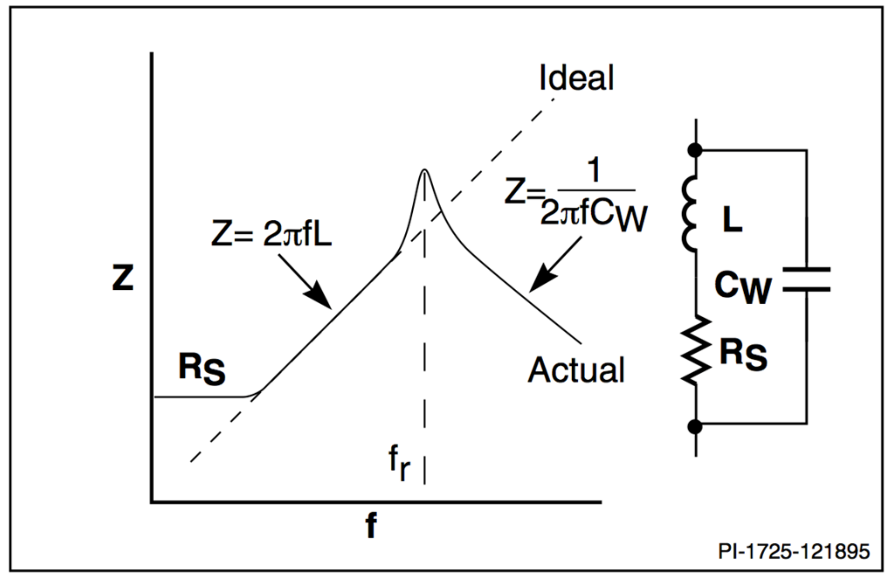
Equivalent Circuit in CM



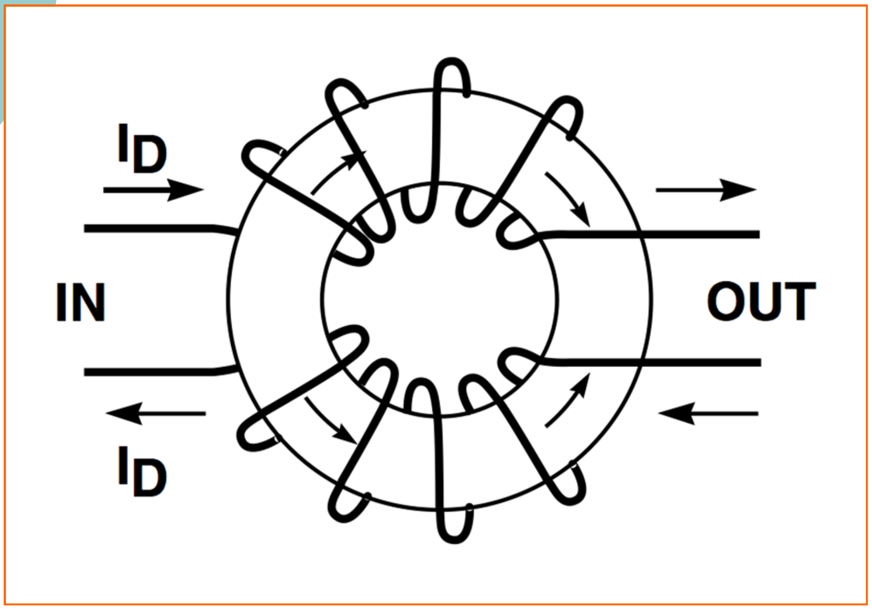
Equivalent Circuit in DM

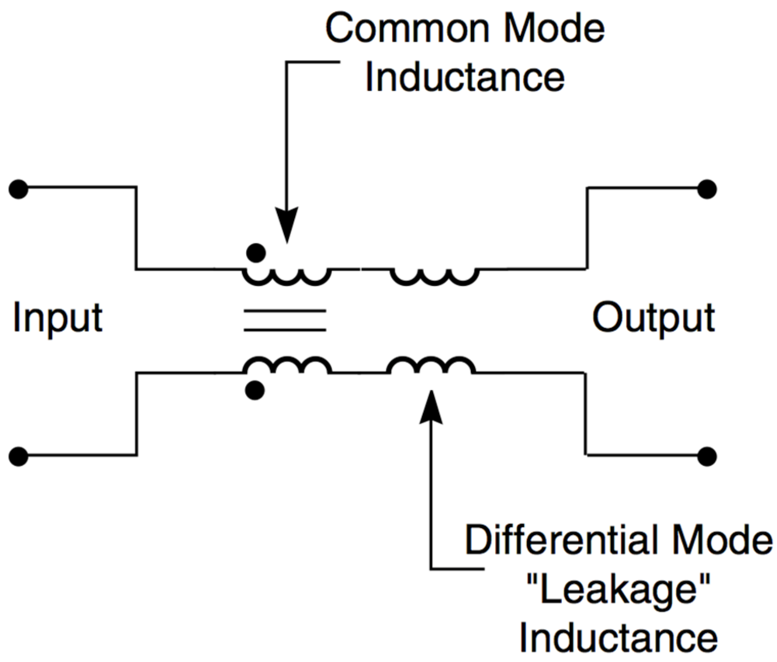
EMI Components Characteristics Impedance





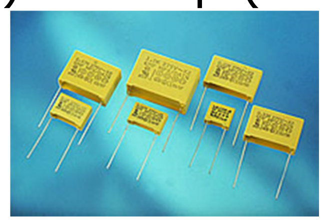
Common Mode Choke



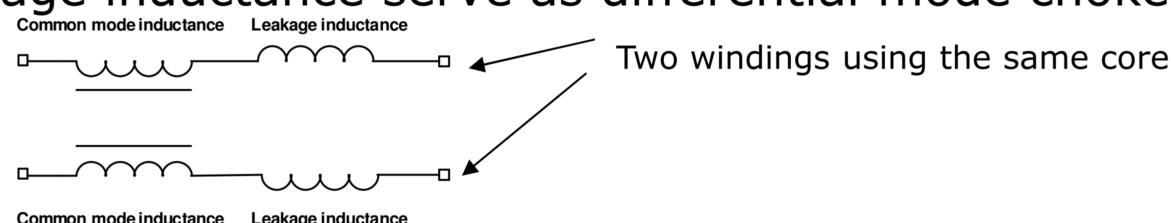


Safety Considerations on Line EMI Filter

- Value of Y-cap is limited by the max. allowable leakage current
  - Class I cannot exceed 3.5mA, others 0.25mA to 0.75mA
  - 79uA per nF at 250VAC/50HZ, 6.3nF for 0.5mA
- X-cap (X2) & Y-cap (Y2) need to be safety rated (pass 2.5KV, 5KV)



- Common mode winding (each line) must meet spacing requirement
  - Leakage inductance serve as differential mode choke

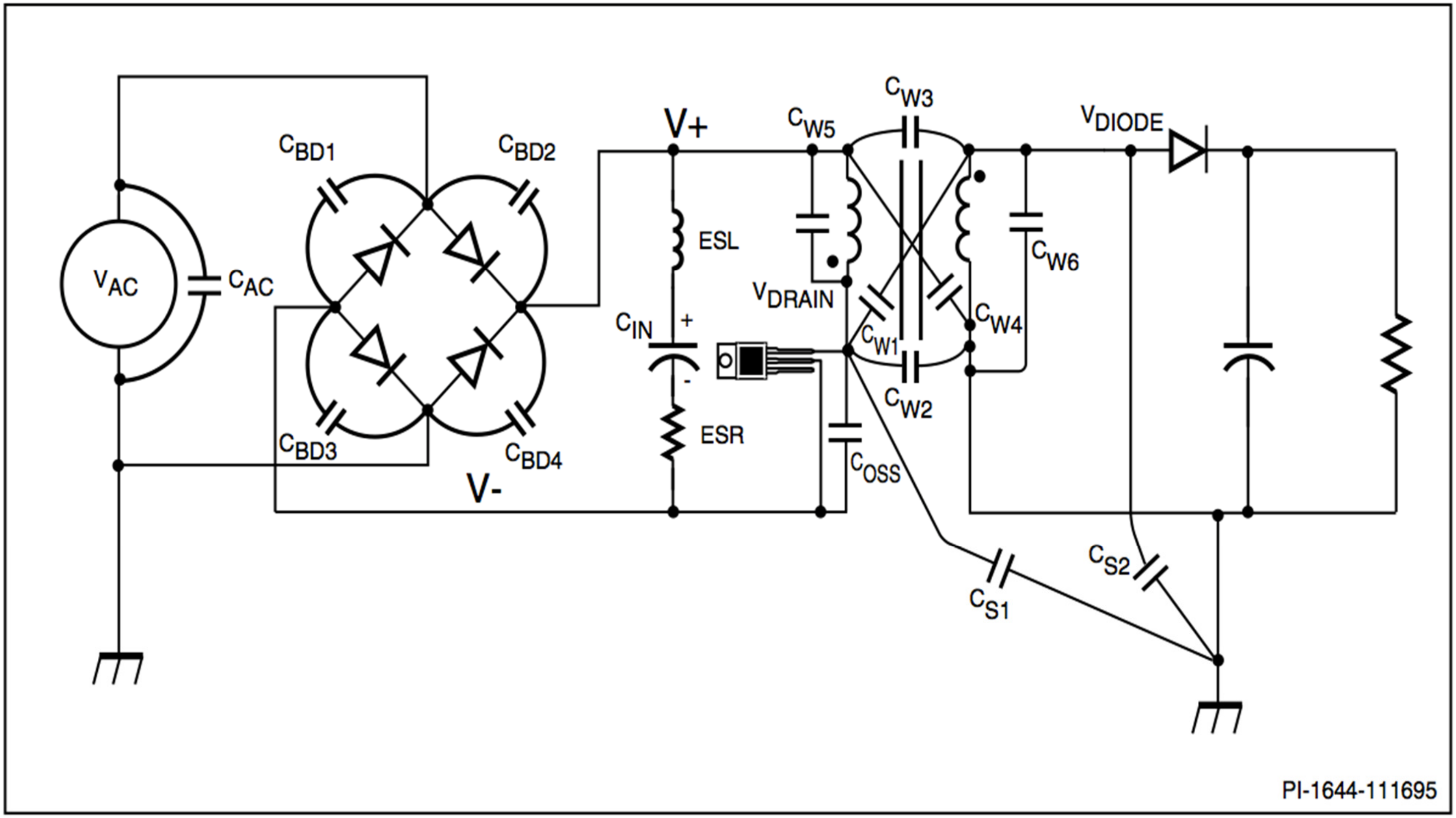


- X cap. discharge resistor needed for >0.1uF total capacitance

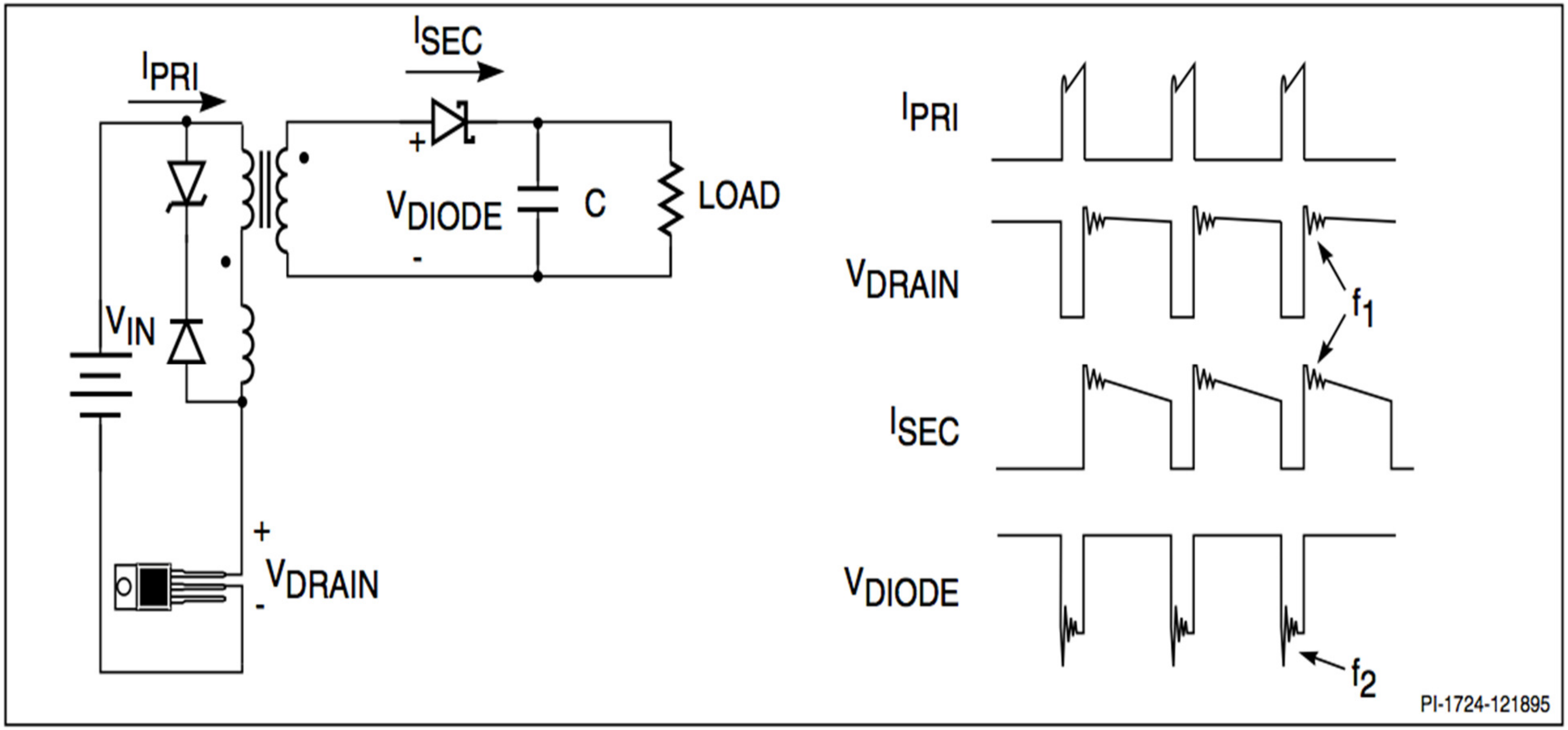
Design Considerations of Line EMI Filter

- Core size (Area)is sufficient to avoid saturation
  - Saturation reduces filtering effect
  - DM choke tends to saturate more than CM
- Reduce interwinding capacitance (single layer, split in winding)
- Add more stages in cascade to increase attenuation
- Properly select capacitor material
  - Metallized film more stable over temp., voltage, and time
  - Self-healing feature of metallized film cap.
  - Ceramic maybe less expensive and fails open
- Compensate Y-cap. value limitation with higher CM choke inductance
- Understand the equivalent circuit for CM and DM
- Check the scans for actual freq.peaks (CM noise 10 to 30MHZ)

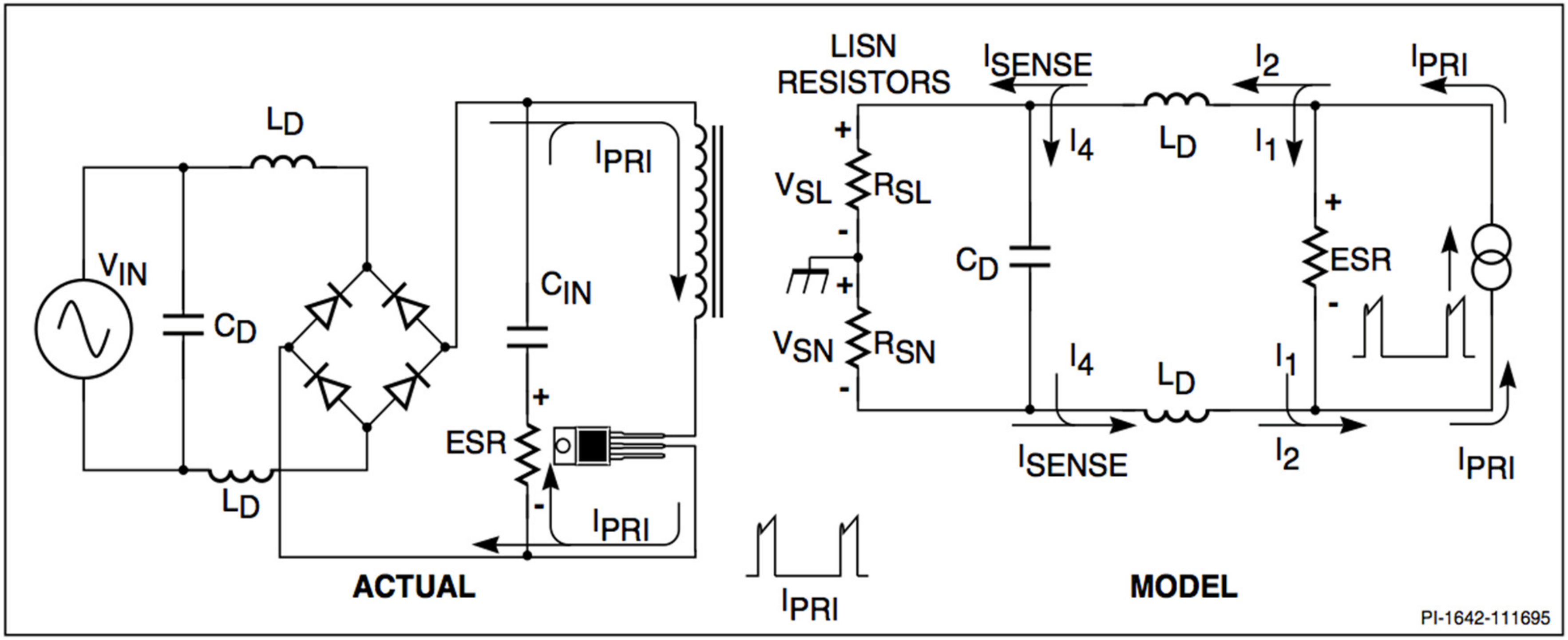
Source of EMI



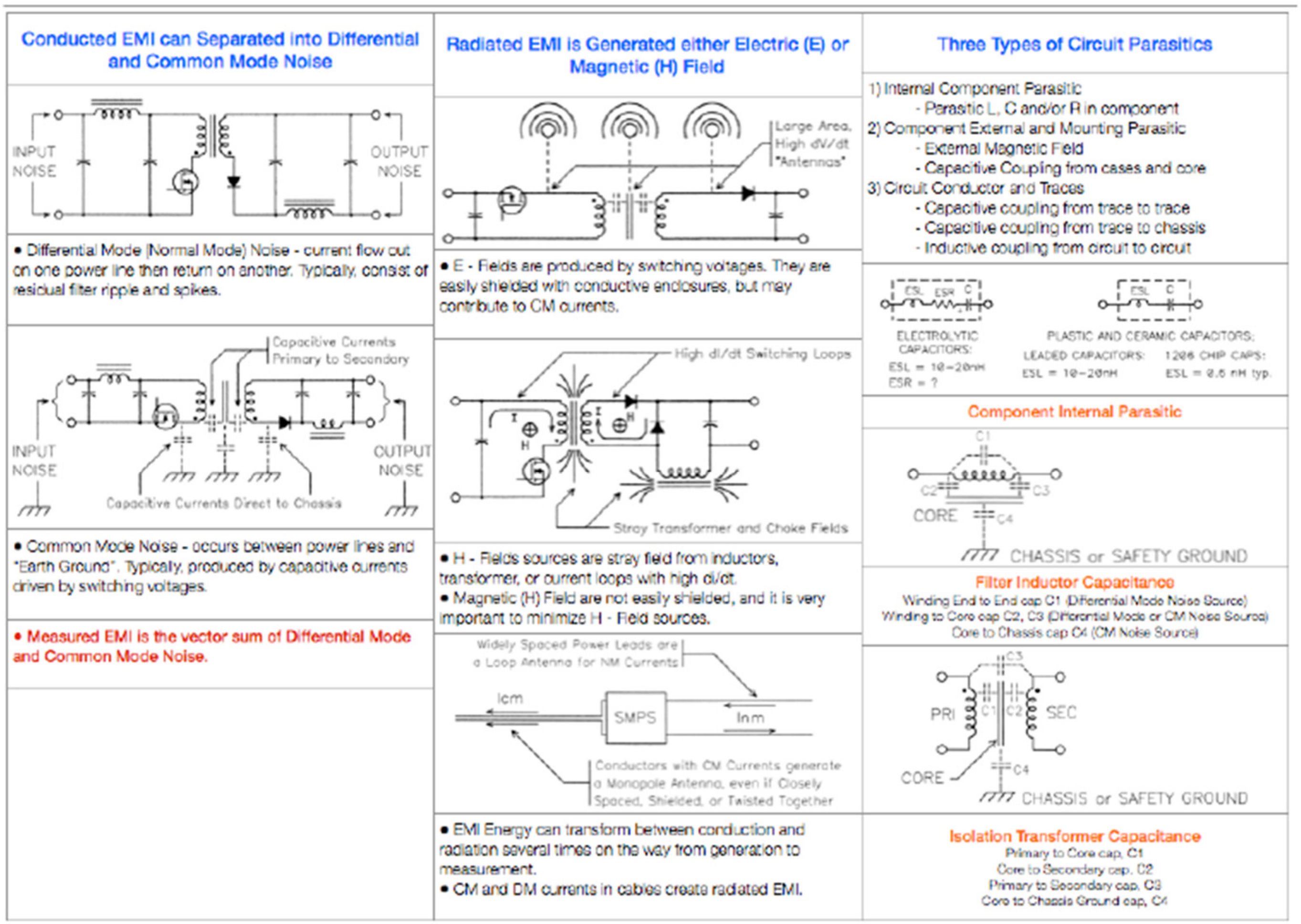
Source of EMI



Source of EMI



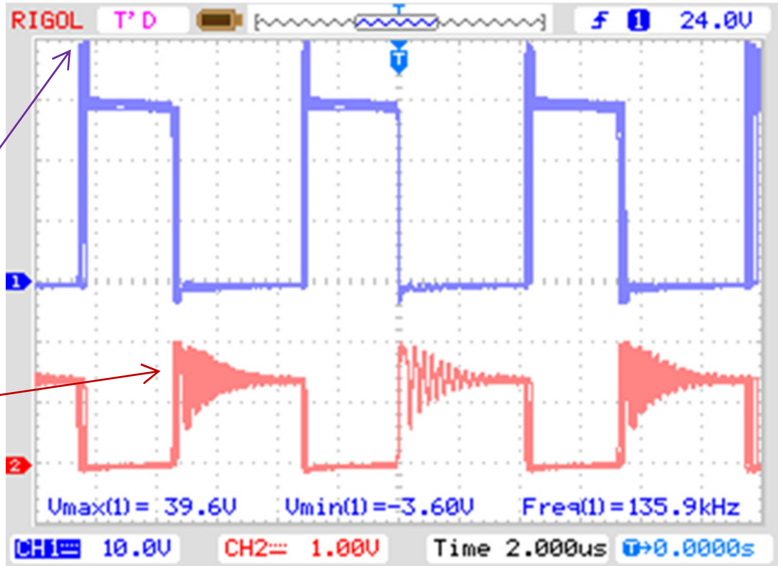
EMI
Summary Chart



Comparing the RCD Clamp and the RC Snubber

Circuit	Advantages	Disadvantages
RC Snubber	Effective in damping the ringing	No clamping action
RCD Clamp	Effective in clamping the peak but ringing is sustained	EMI concern due to continuous ringing

Using them together offer best solution in combining all their advantages but at reduced efficiency and increased cost

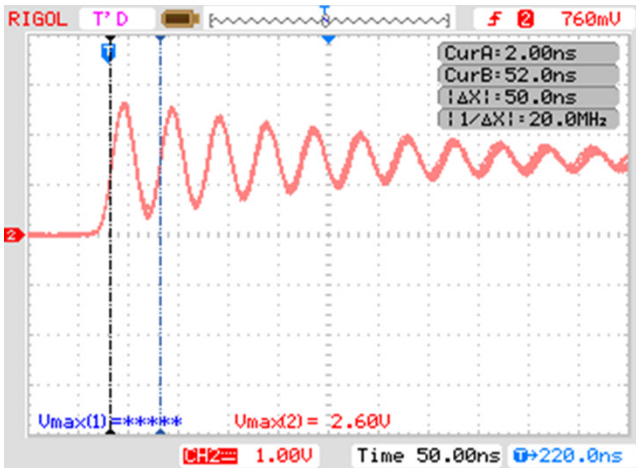


120VAC Input & 2A Output Load

Output Diode Voltage Channel 1

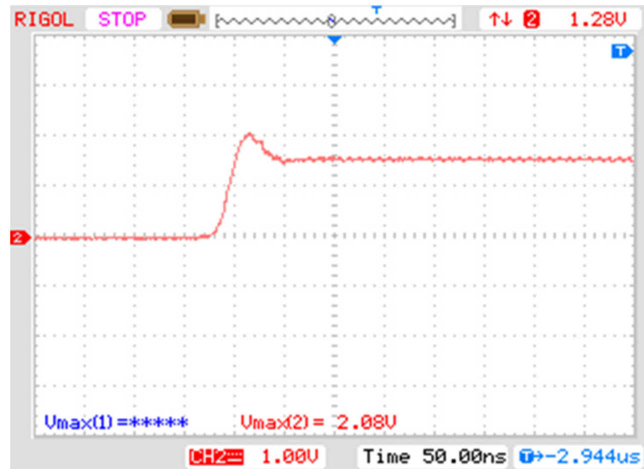
MOSFET Vds Channel 2

Secondary Side Ringing Without and With RC Snubber



Output diode voltage without snubber (voltage probe setting at X 20)

Vpeak= 52V



Output diode voltage with snubber (voltage probe setting at X 20)

Vpeak= 42V

Snubber Design

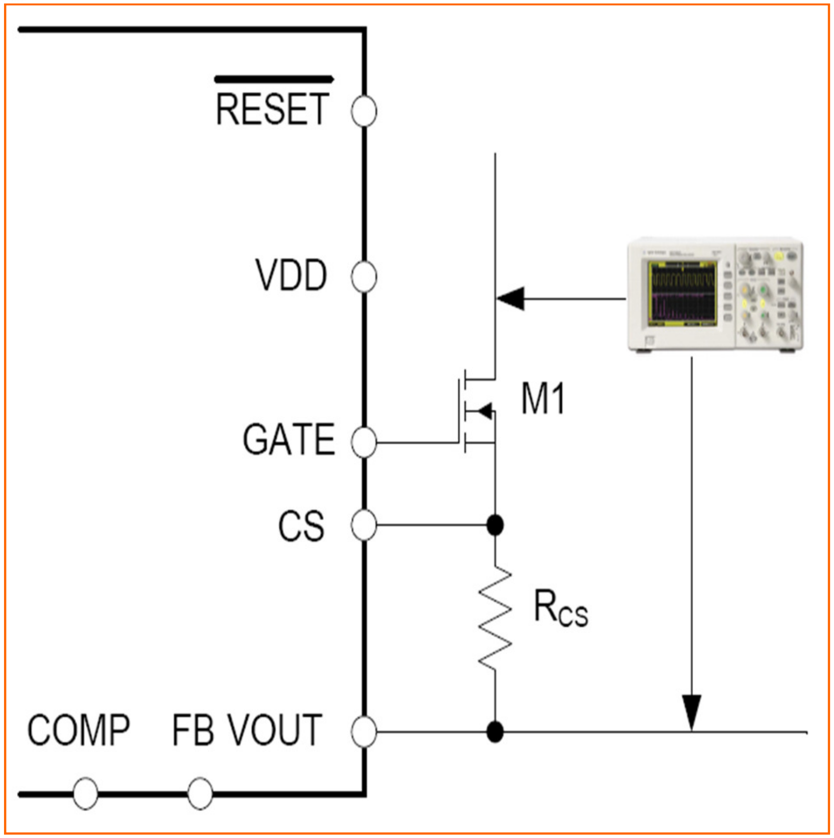
Snubber Circuit – is a voltage transient spike suppressor on both the primary and secondary sides of the converter.

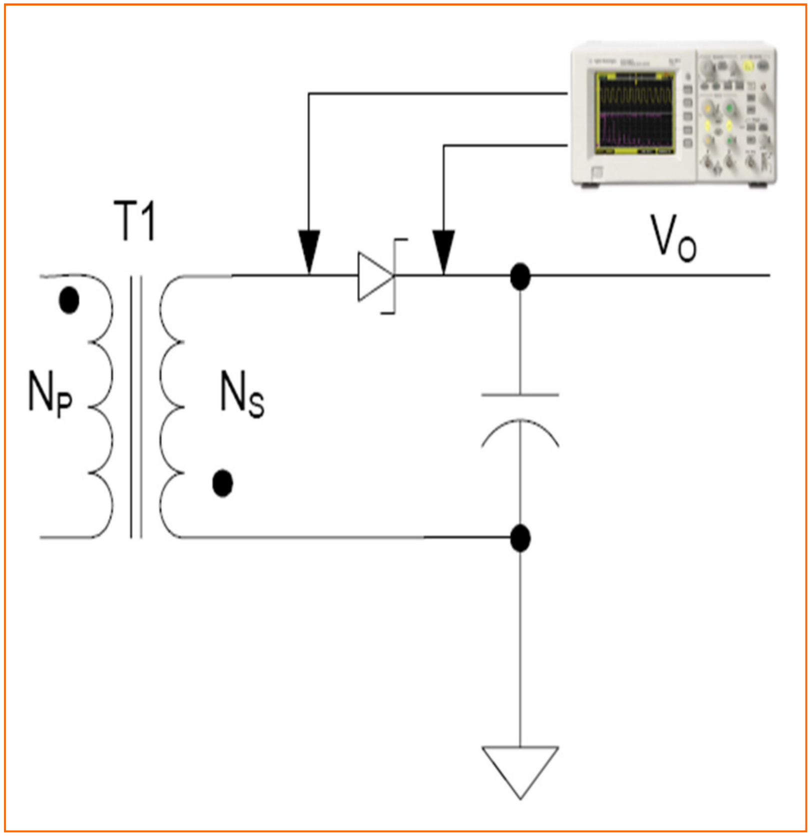
Voltage Transient Spikes are functions of transformer leakage inductance and parasitic inductance of the PWB.

Benefit of the Snubber Circuit:
- •Improve Efficiency
- •Increase Reliability

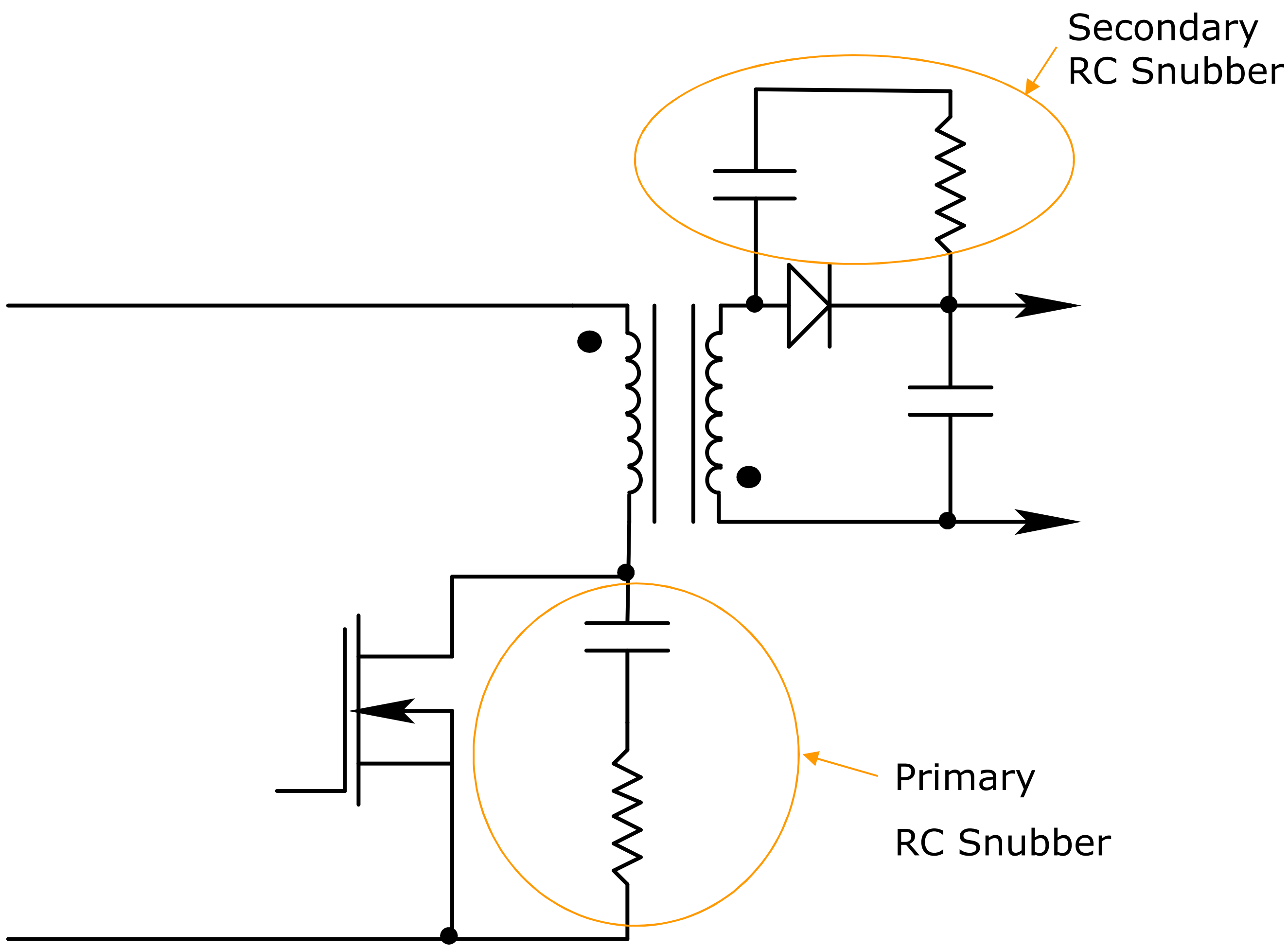
Types of Snubber Circuit:
- •Active Snubber
- •Passive Snubber
  - •Dissipative Snubber – energy in snubber circuit is dissipated in the resistive element
  - •Non-Dissipative Snubber – energy in the snubber circuit is returned to the input or moved ahead in the output

Measurement of V_{DS} and V_{AK} Waveforms





Flyback with Snubber Networks



RC Snubber Design

Peak Voltage (Vpeak) across the Output Rectifier

Elements that form a parasitic LC network

•Secondary leakage inductance, L_{LS}

•Capacitance of the output rectifier, C_D

Reverse Current Recovery, I_{rec}

$$V_{peak} = I_{rec}\sqrt{\frac{L_{LS}}{C_D}} + V_{in} \bullet \frac{N_P}{N_S}$$

RC Snubber Design Procedure

- Need for snubber & clamper
  - Damp the ringing between parasitic inductance & capacitance
- Design Procedure
  1. Determine the L_L leakage inductance (measured inductance value with other windings shorted)
  2. Measure the ringing freq. F_R
  3. Compute R to damp the ringing, $R = 2 \times \pi \times F_R \times L_L$
  4. Compute C to protect R, $C = 1/(2 \times \pi \times F_R \times R)$
  5. Estimate (conservative) power dissipation at switching freq. $P_{diss} = C \times V^2 \times F_{switch}$, V is voltage across device
  6. Test snubber design to verify performance

Computing the R & C Values

- Design Procedure
  1. Measured L_L leakage inductance (measured inductance value with other windings shorted)=0.2 uH
  2. Measured ringing freq. F_R=20 MHz
  3. Computed R= 25 ohms
  4. Computed C= 0.32nF
  5. Estimated power dissipation at switching freq. = 53 mW
     Use C= 1nF, V= 20V, Switch Freq. of 132KHz
  6. Test snubber design with practical values to verify performance (use 22 ohms & 1nF)

RCD Snubber Design

Peak Voltage (Vds) across the Switch Mosfet

Elements that form a parasitic LC network
- Primary leakage inductance, L_{LP}
- Primary winding capacitance in the transformer, C_P
- Mosfet output capacitance, Coss
- Number of primary turns, Np
- Number of secondary turns, Ns

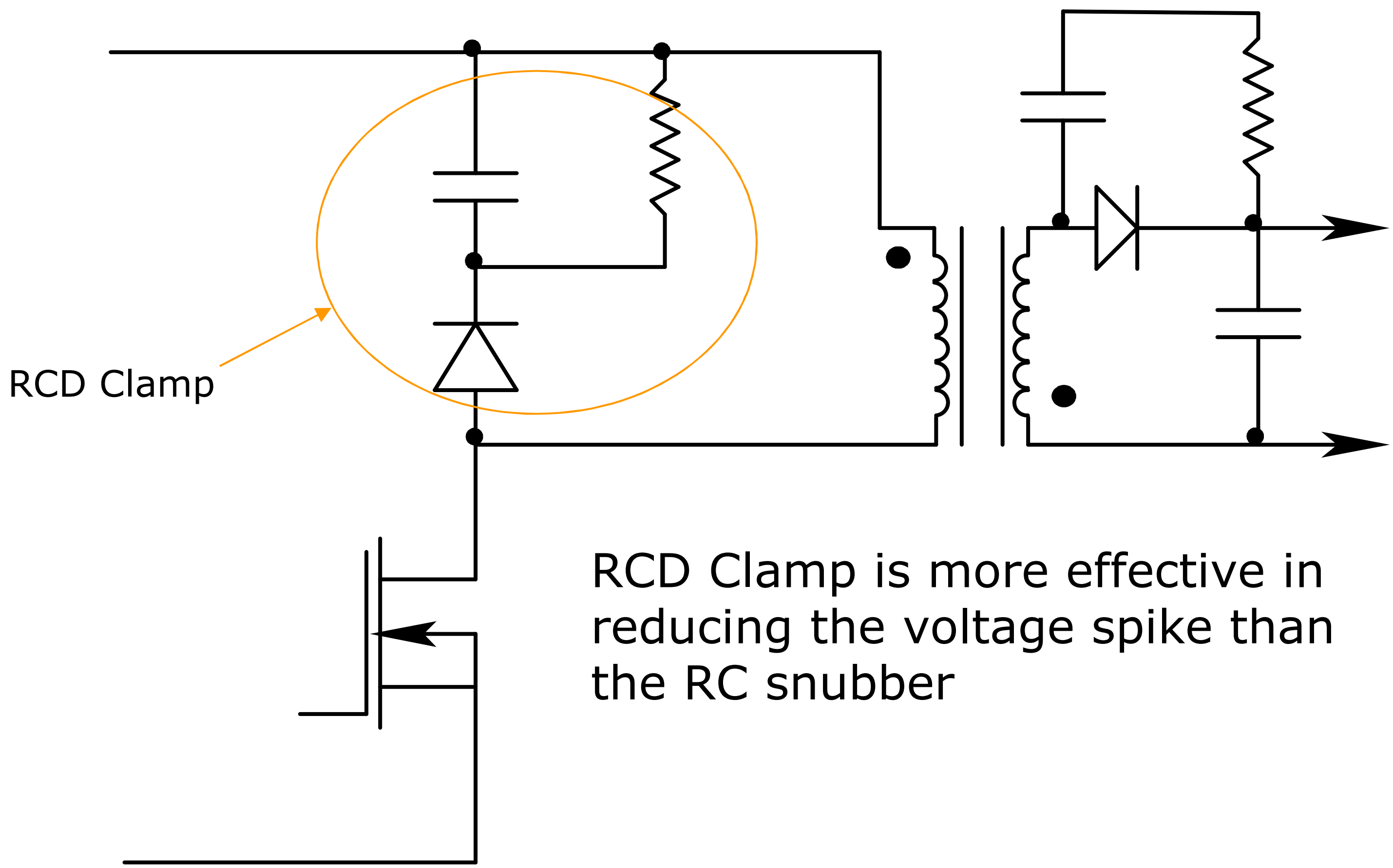
$$V_{ds(peak)} = I_{pri}\sqrt{\frac{L_{LP}}{C_p + Coss}} + V_{in} + \left(Vout * \frac{N_p}{N_s} \right)$$

RCD Snubber Design

A snubber could therefore be used to clamp the voltage spike or damp the ringing to reduce noise in the system or both.

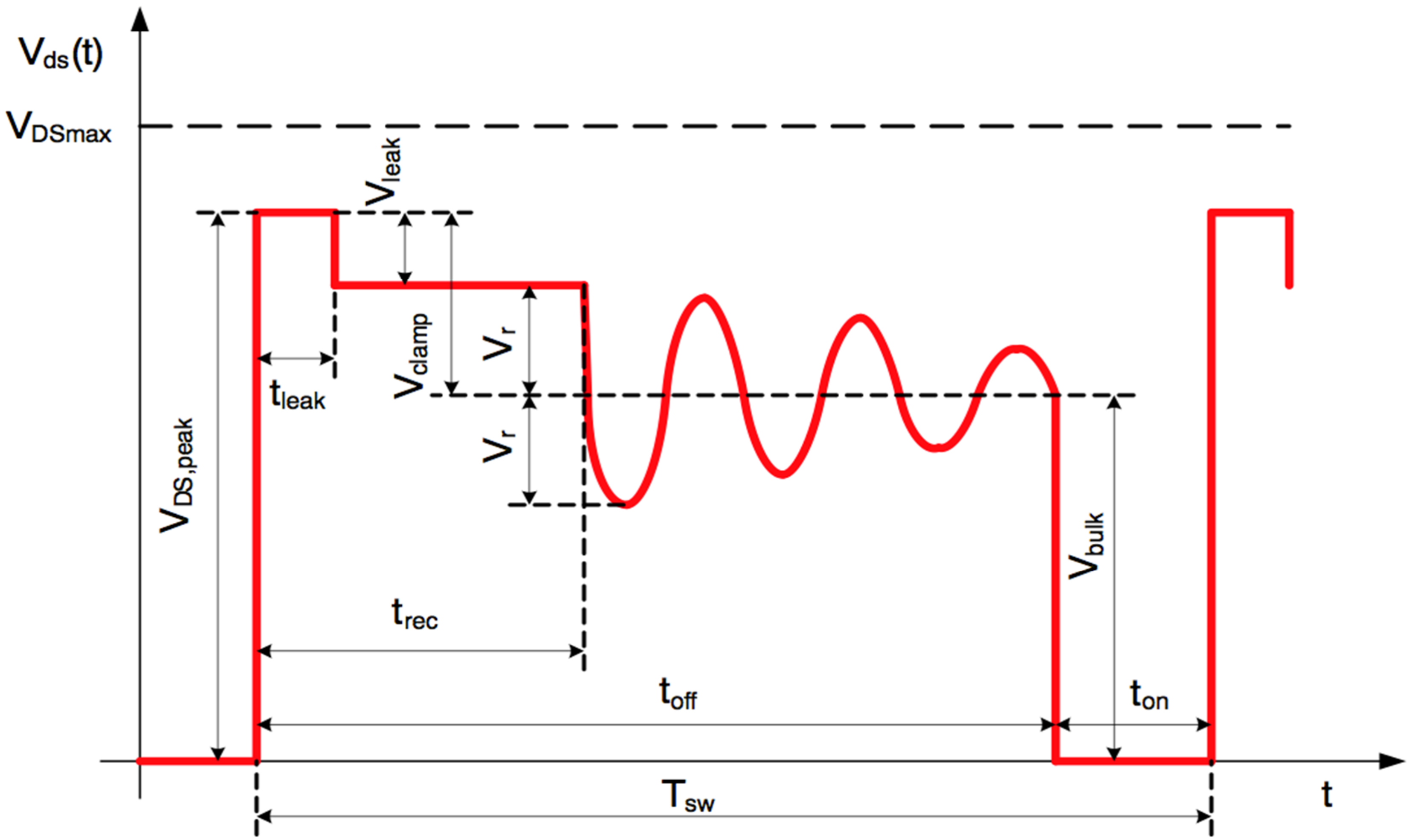
Three categories:
- Rate-of-rise control snubber
- Voltage clamp snubber
- Damping snubber

Flyback with Primary RCD Clamp and Secondary Snubber



RCD Clamp is more effective in reducing the voltage spike than the RC snubber

RCD Snubber Network Design



Ref: Onsemi, AND8461-D

Class Exercises

- Case study on 30W Flyback board design
  - Trace the grounding pattern/connection
  - Identify the different ground connections
  - Identify proper placement locations (noise consideration)
  - Design to minimize EMI

- Measure the 30W Flyback board output diode voltage
  - With RC snubber
  - Adjust RC snubber values
  - Compare the two measurements (including efficiency)

List of References

Williams, T. (2005). *The Circuit Designer's Companion.* Boston: Newnes.

Schmitt, R. (2002). *Electromagnetics Explained.* Boston: Newnes.

Maniktala, S. (2008). *Troubleshooting Switching Power Converters.* Boston: Newnes.

High Efficiency Switch-mode Power Supply Design Overview

Module Seven

Power System Architecture & Digital Power Supply

Power Systems Architecture

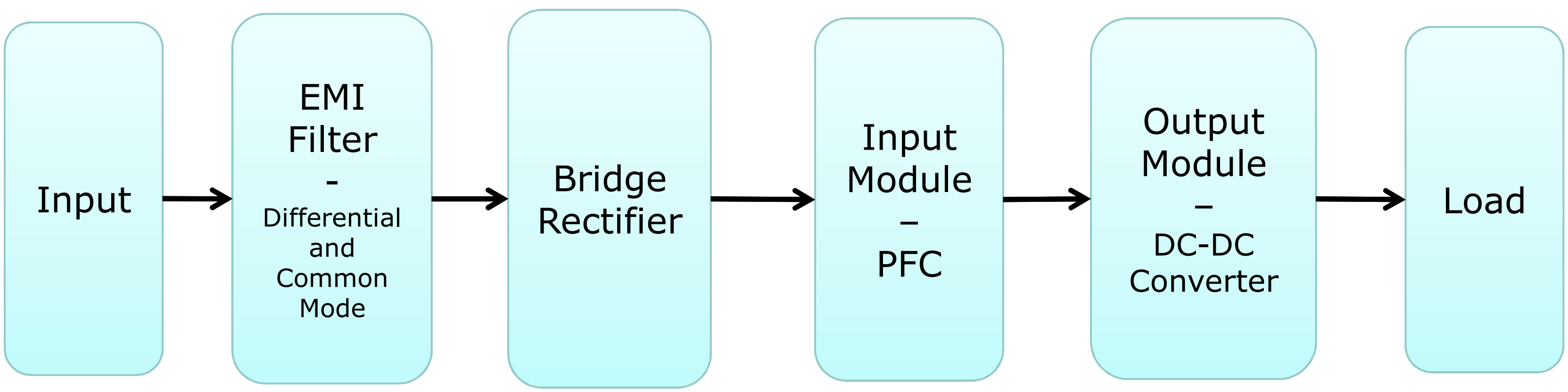
Ultra-Low Stdby/No-load Systems

Digital Control Systems

Introduction to Power Supply System

What is the Power Supply System?

Overall Block Diagram of the AC – DC Power System.

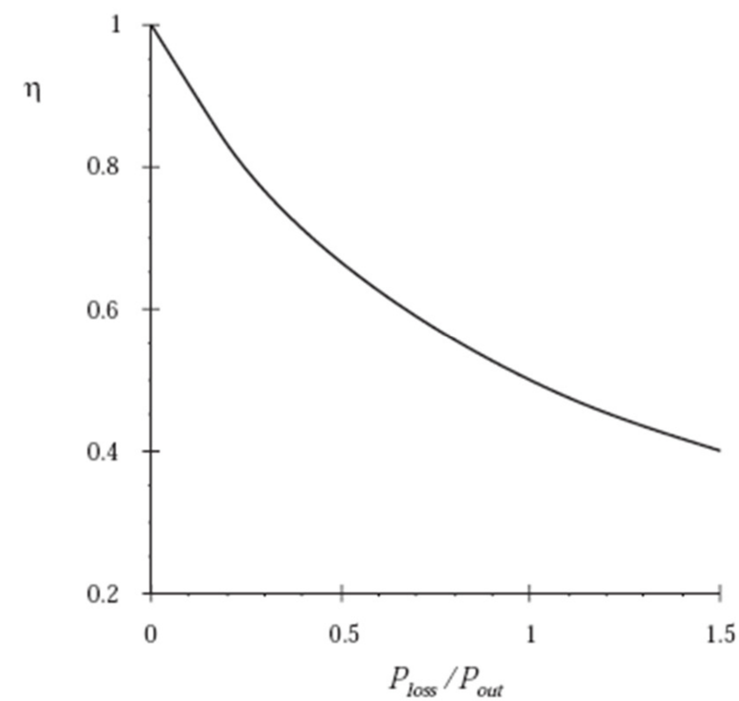


High Efficiency is Important

$$\eta = \frac{P_{out}}{P_{in}}$$

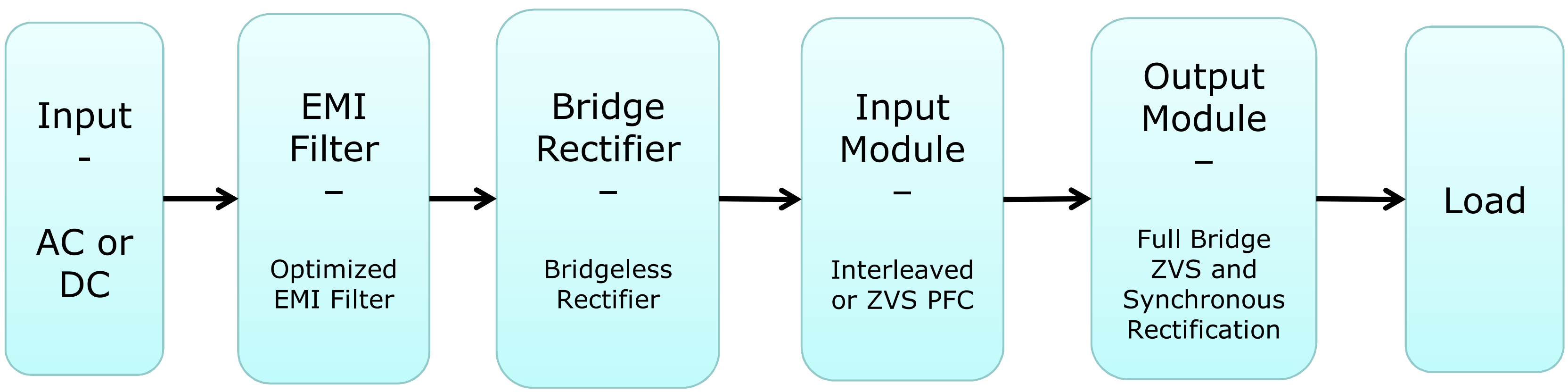
$$P_{loss} = P_{in} - P_{out} = P_{out}\left(\frac{1}{\eta} - 1\right)$$

- High efficiency leads to low power loss within converter
- Small size and reliable operation is then feasible
- Efficiency is a good measure of converter performance



Introduction to Power System

Components of High Efficiency Power System:



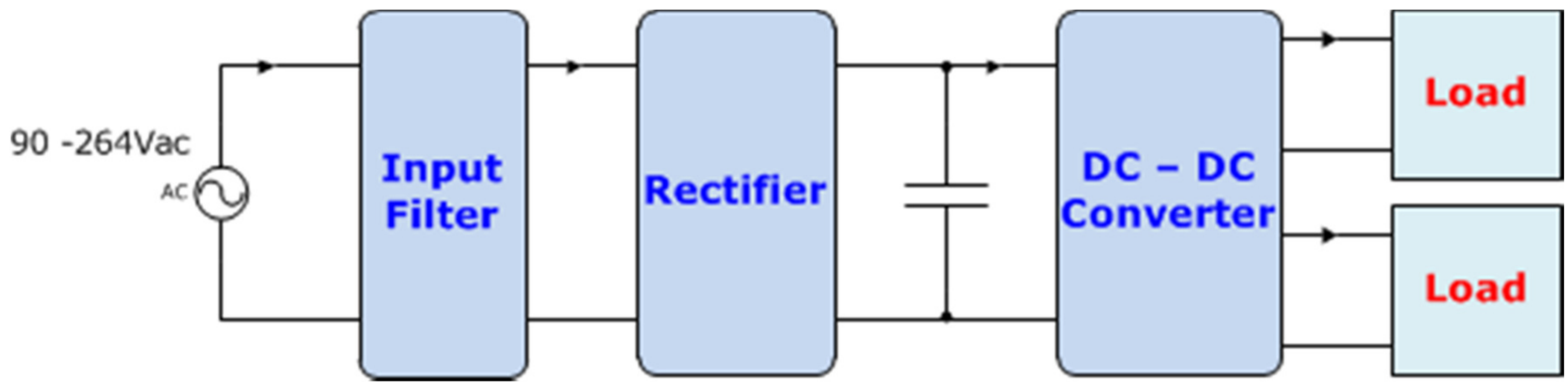
Use power loss analysis in each stage to understand areas for efficiency improvement

Types of Power Supply System

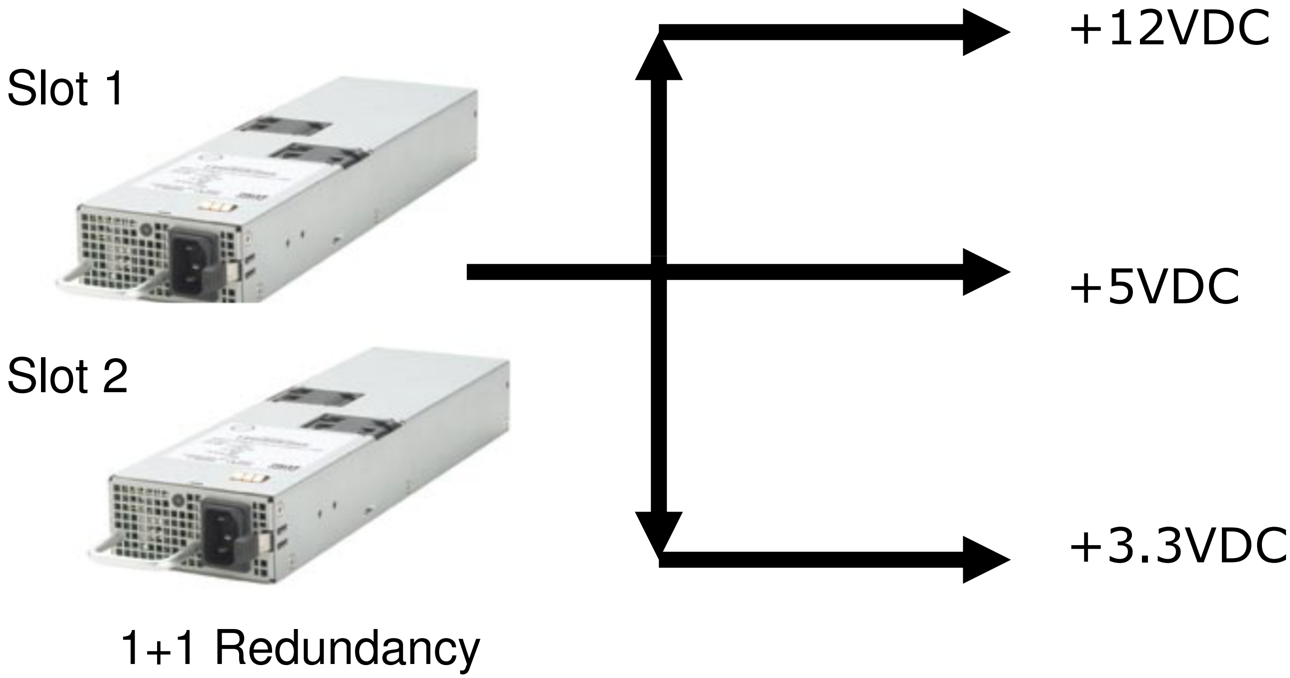
- Centralized Power Supply System
- Distributed Power supply System
- Differences between the two power system
  - Application
  - Efficiency

Centralized Power Supply System

Computer Power Supply System



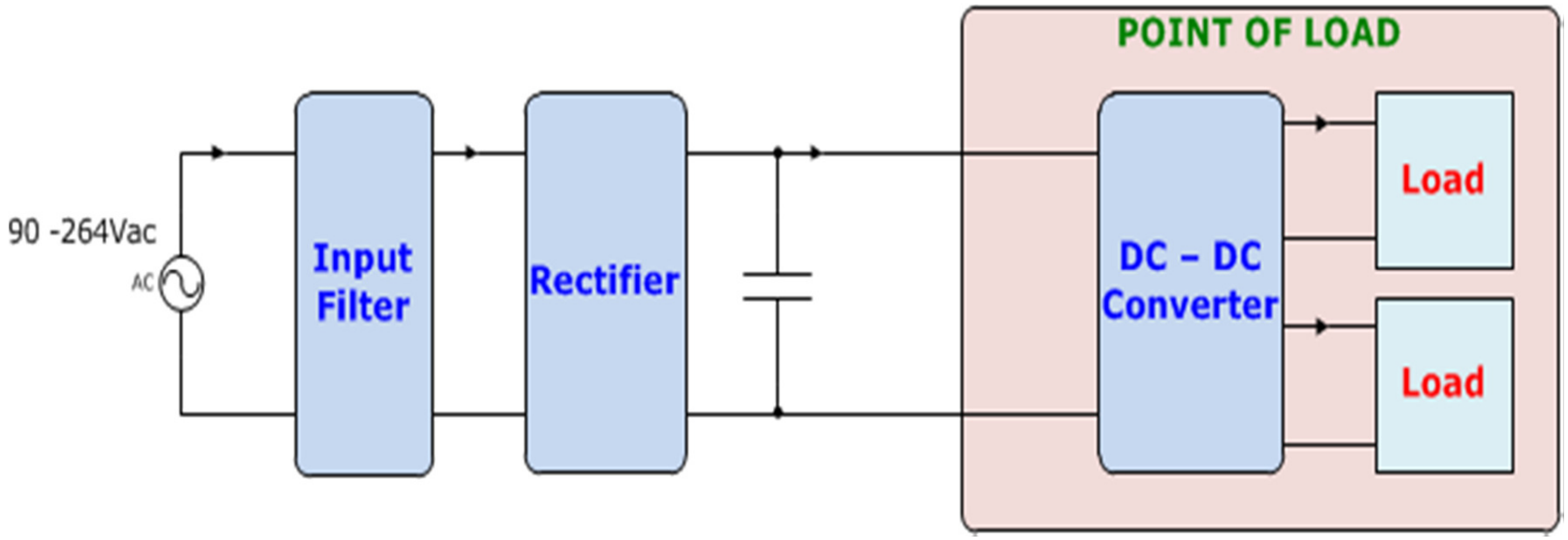
Centralized Power Architecture with Redundancy



Fewer parts, but need to distribute low voltage high current to remotely located loads

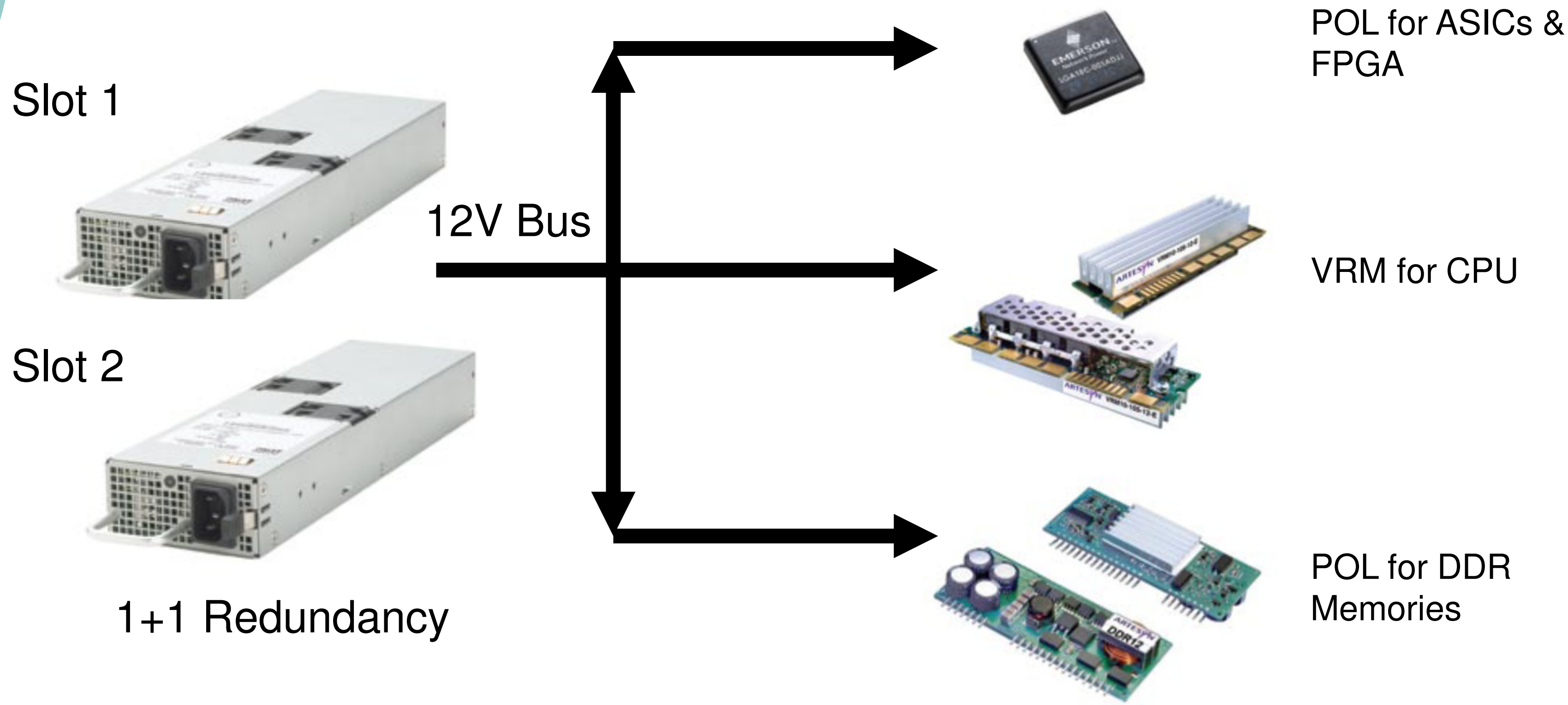
Distributed Power Supply System

Server Power Supply System



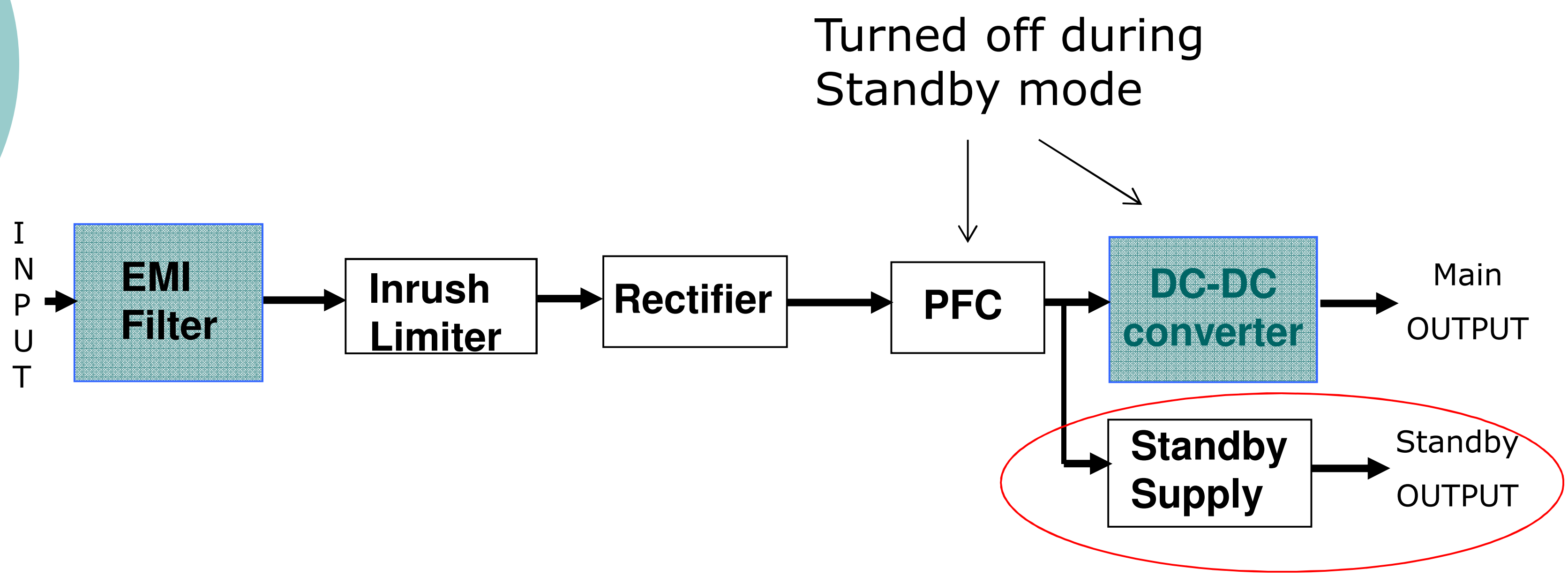
Distributed Bus Configuration with Redundancy

Application Example for a 12V Bus Architecture



Simpler AC/DC front-end with single O/P, distribute low voltage high current at point of load, more parts

The Standby Mode



Added aux./standby supply

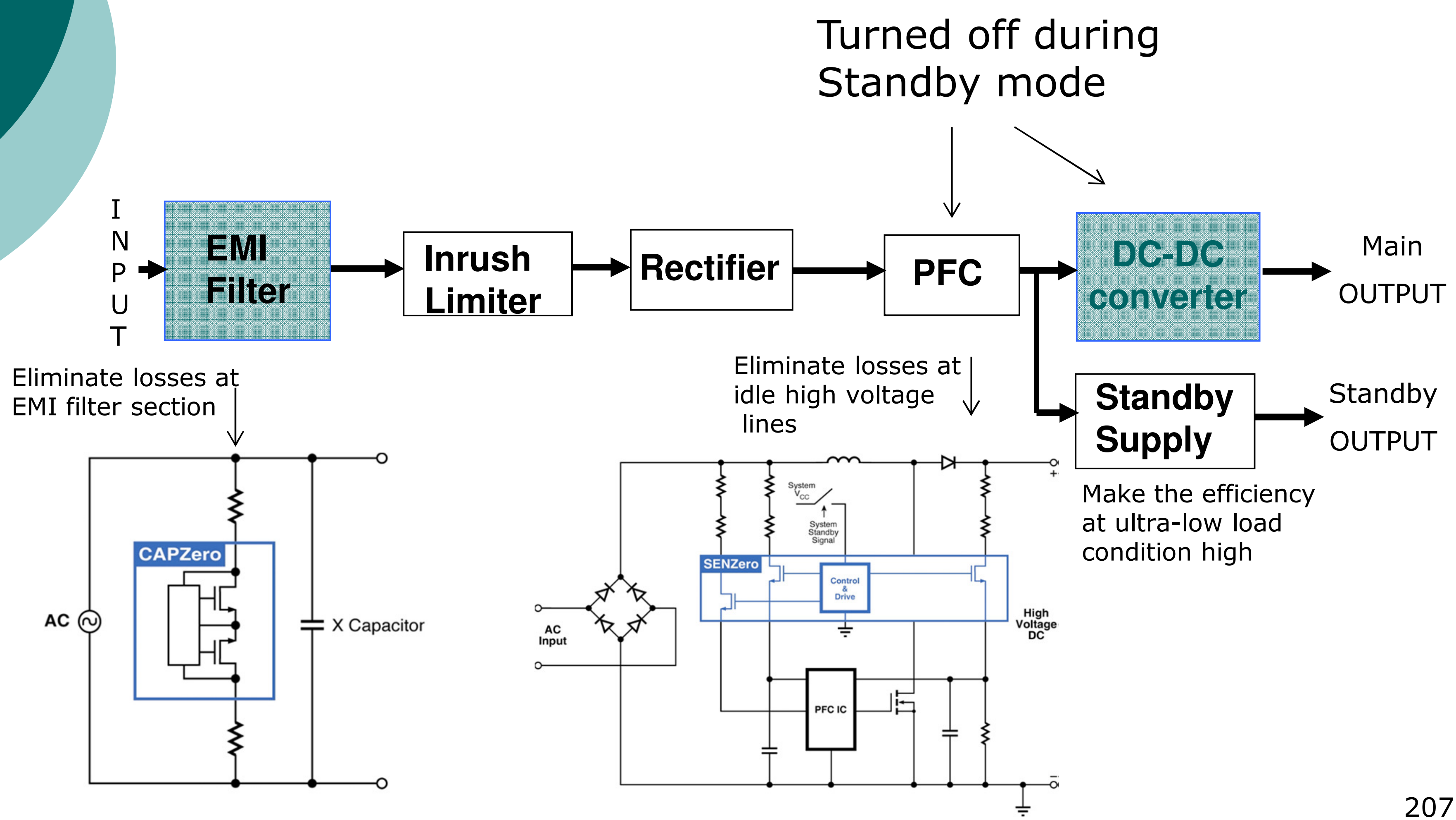
No-Load/Standby Power Requirements

1. Strict energy saving deadlines are coming for appliances, IT equipments, TV & audio systems, toys, and leisure equipments

   - April 2011! ErP Lot 7 (external power supplies) requires ≤ 300 mW or ≤ 500 mW of no-load power
   - Jan. 2012! China flat panel TV standard requires ≤ 500 mW of standby power
   - Jan. 2013! ErP Lot 6 (internal power supplies) requires ≤500 mW of standby/no-load power

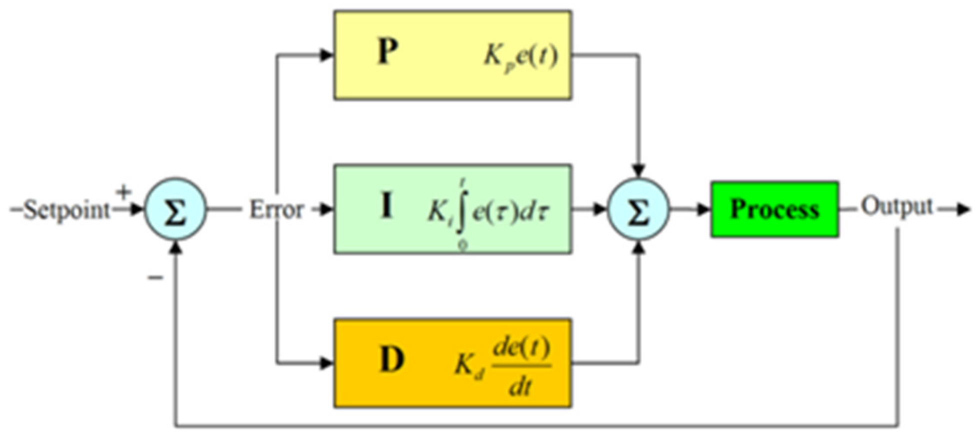
2. Market leaders are moving to stringent standby/no-load power requirements as part of their "Green" marketing initiative (e.g. HP, Apple, LG,…..)

Ways to Lower No-Load and Standby Power



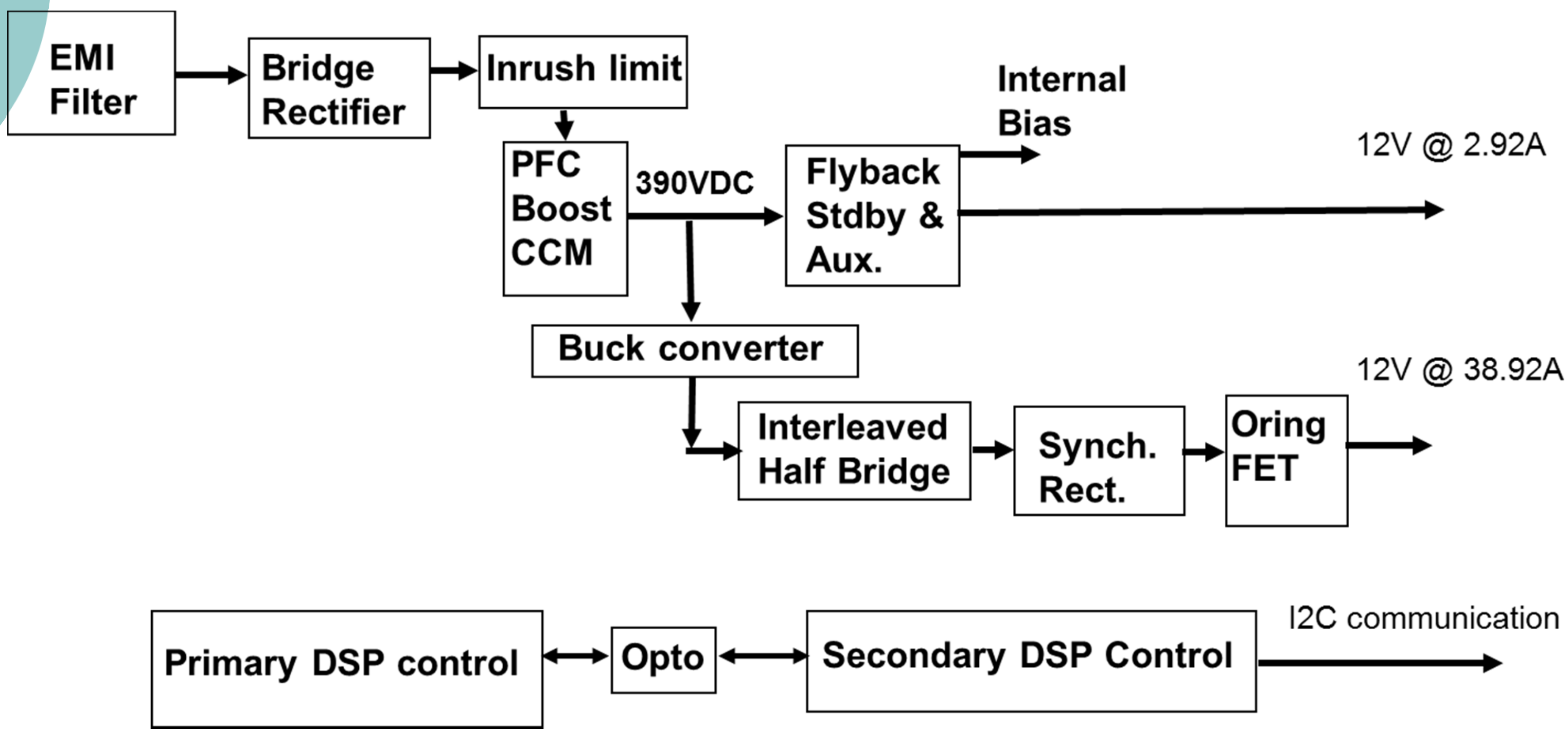
Digital Content in a Power Supply

- Digital controller for housekeeping (Microchip)
- Digital control system for feedback loop (TI)



- Digital Communication (system & power supply)
  - I2C communication (serial communication)
  - PMBus Standard

Block Diagram of Digital Power Supply



Circuit Description

Aux./Stdby Flyback: Single FET flyback topology operating at continuous conduction mode and switching at around 100khz.

PFC Boost Converter: Boost converter operating at continuous conduction mode and switching at around 80khz. Usually implemented using Infineon CoolMos FETs and Silicon Carbide Schottky diode (as boost diode).

DC/DC Converter: Two stage approach of Buck converter + Interleaved half bridge

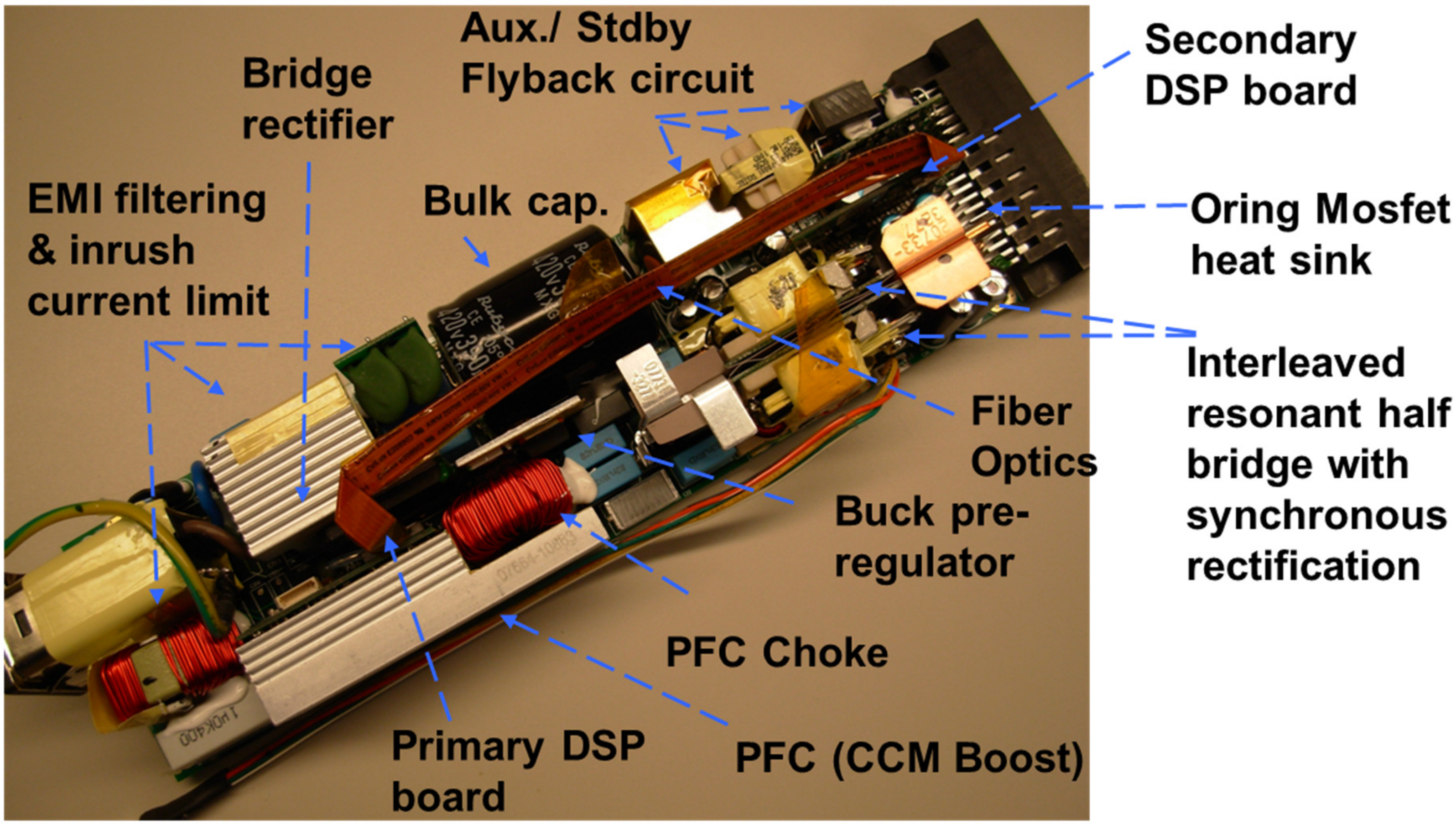
Buck converter: Steps down the 390VDC from the PFC to a lower level, which is then inputted to the half bridge converter. The stepped down voltage can be in the range of 200V. This output is regulated based on the actual load conditions. Operating freq. estimated at around 120khz.

Interleaved half bridge: Converter operating at resonant mode and open loop with duty cycle set just below 50%. Switching freq. is around 120khz, causing the output ripple frequency to be at 240khz.

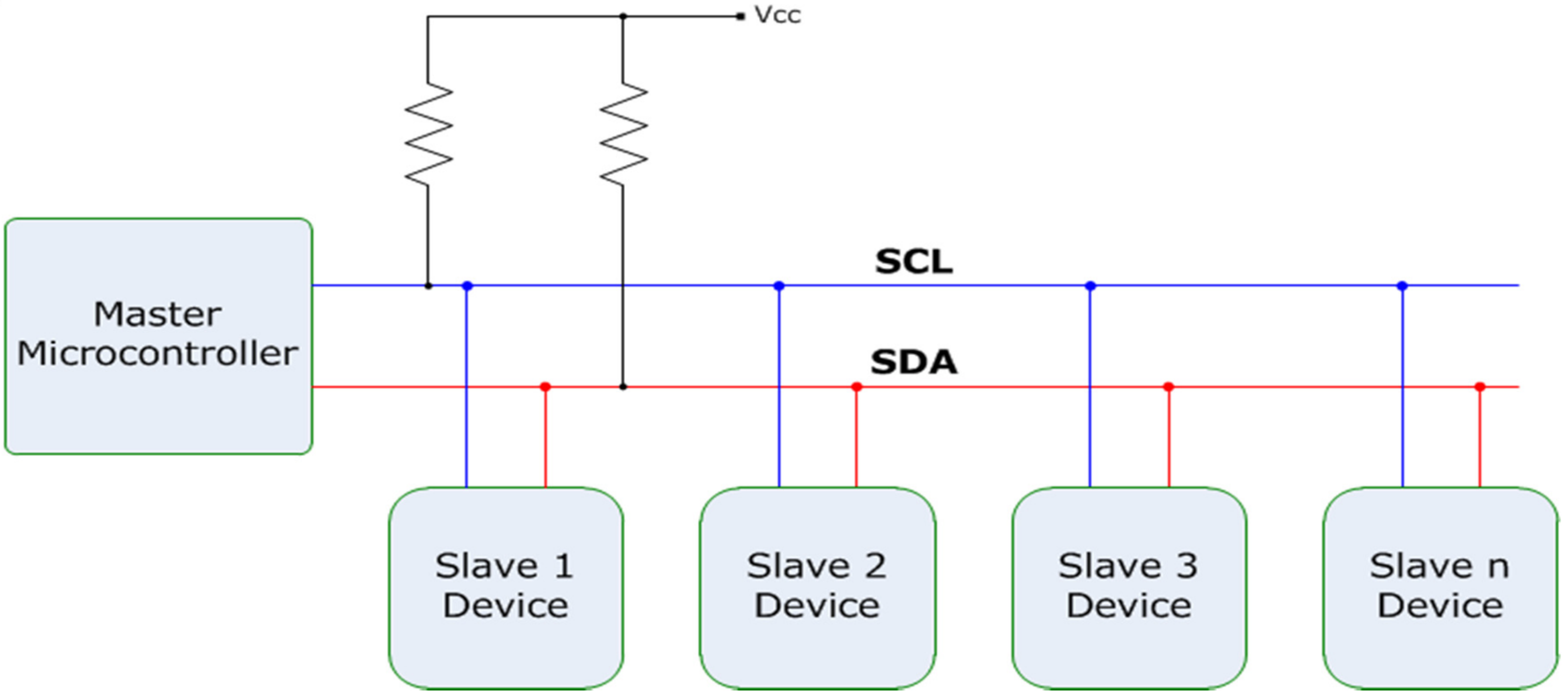
Primary DSP: PFC controller, primary reporting & monitoring, primary house keeping.

Secondary DSP: DC/DC controller, secondary reporting & monitoring, secondary house keeping.

Board Layout of Digital Power Supply

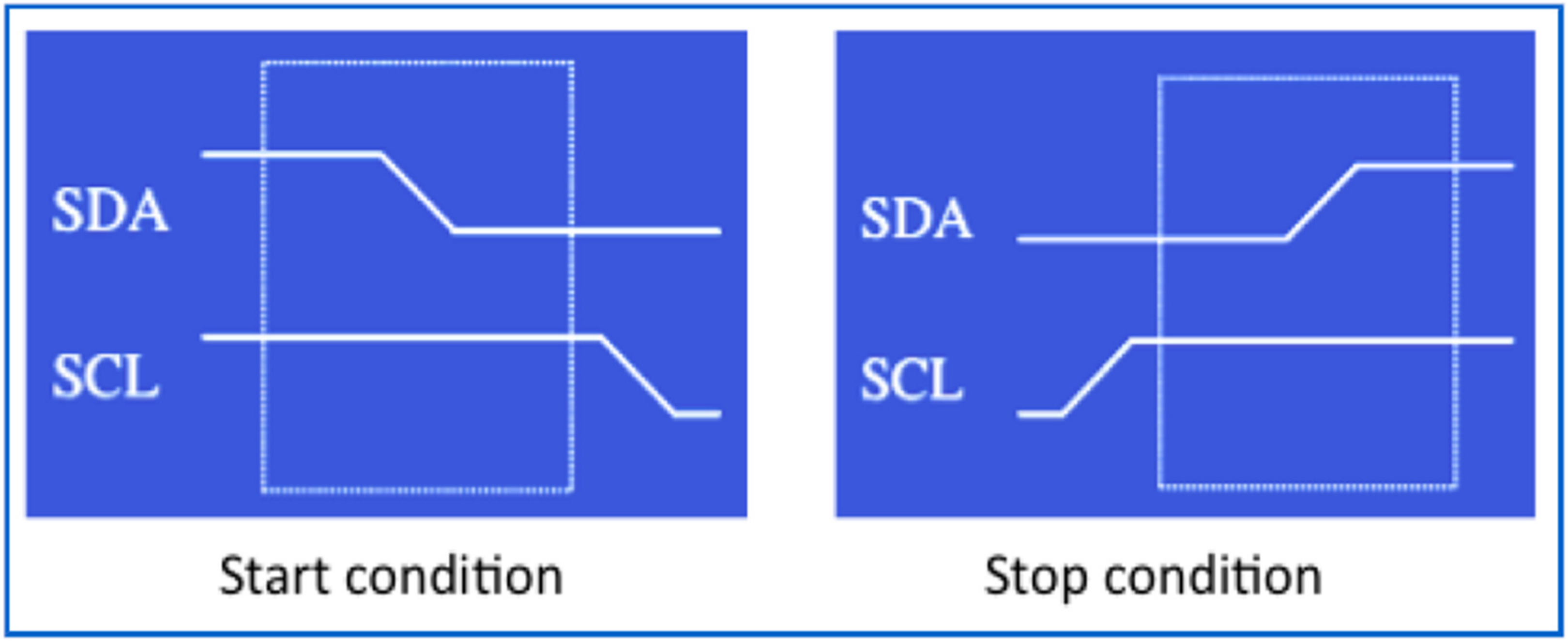


I2C BUS Communication



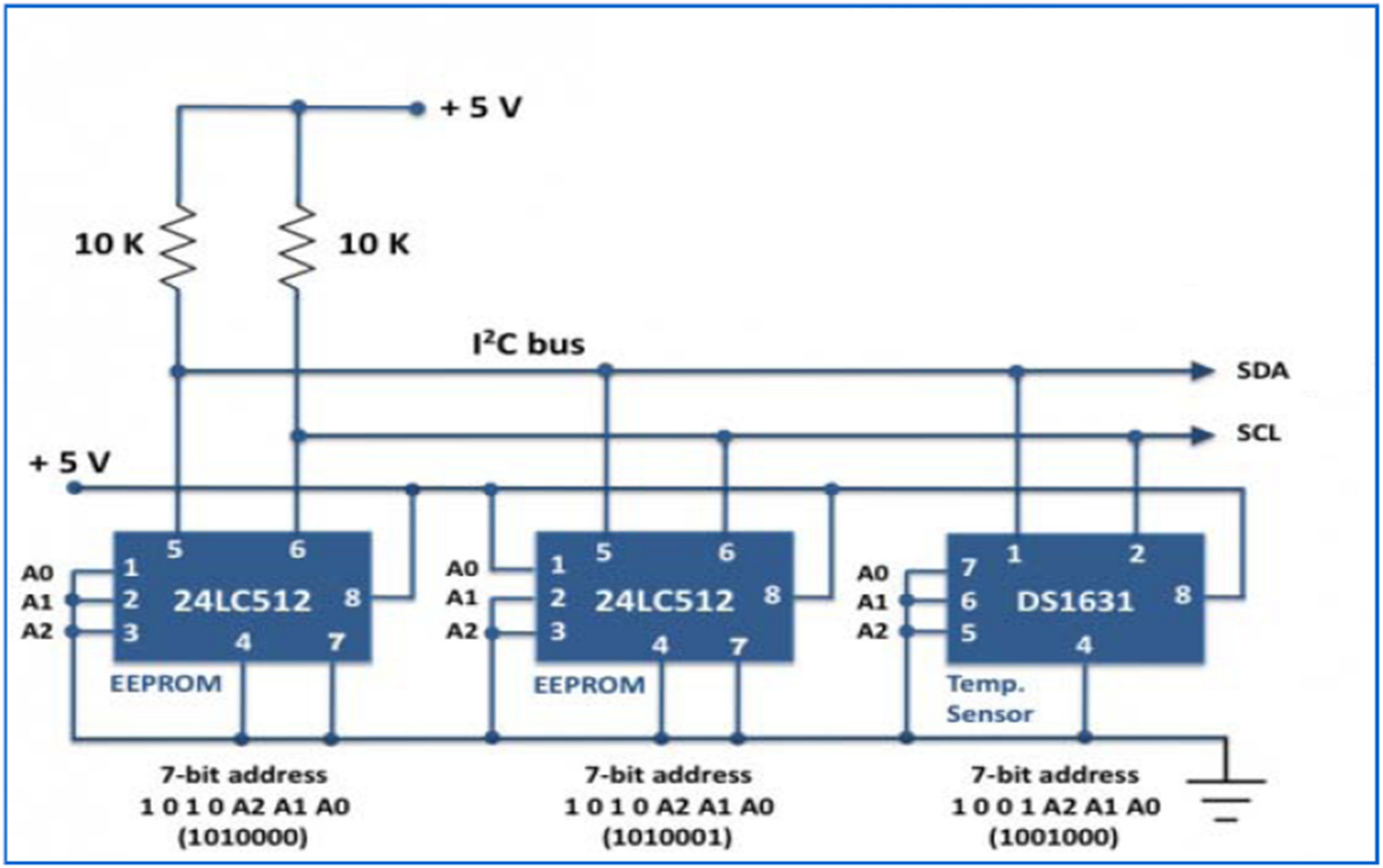
- I2C bus has two lines: a serial data line (SDA) and a serial clock line (SCL).
- Data sent from one device to another goes through the SDA line
- SCL line provides the necessary synchronization clock for the data transfer. SCL clock is always driven by the master.
- Devices on an I2C bus are either Masters or Slaves.
- Master can initiate a data transfer and Slaves respond to the Master.
- Multiple masters on a common bus, but only one could be active at a time.

Start and Stop Conditions



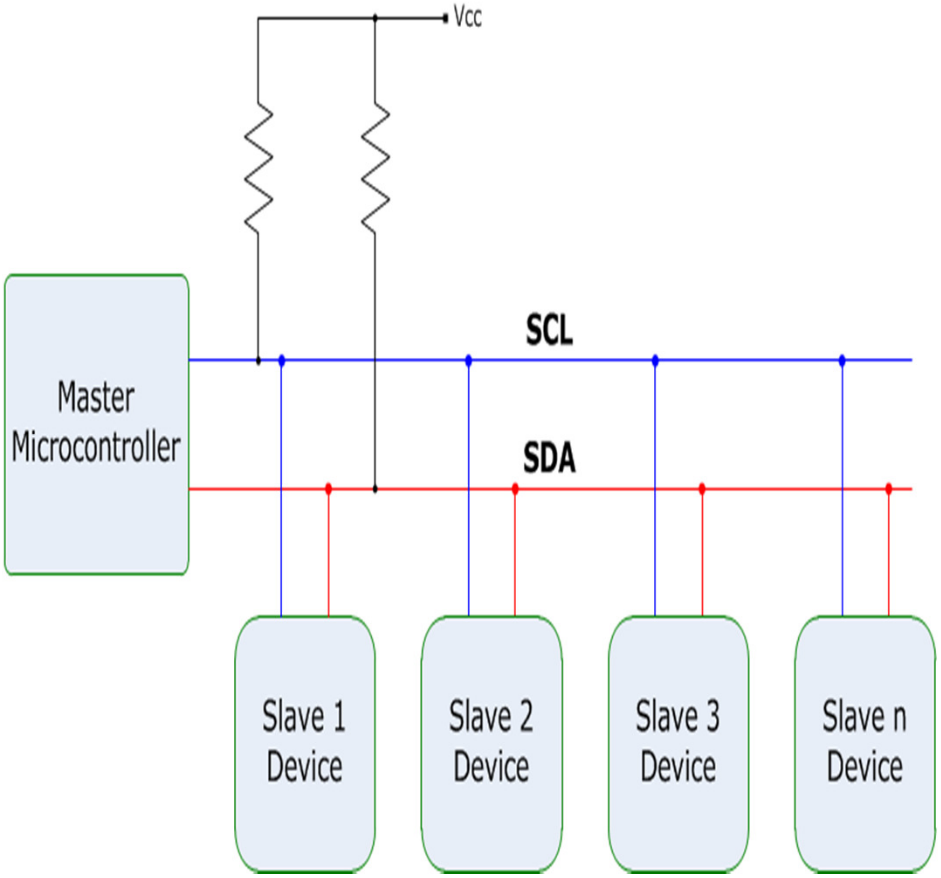
- Master will start condition and inform all the slave devices.
- Start and stop sequence mark the beginning and the end of transaction.

I2C Circuit Diagram



I2C BUS Hardware

- Pull Up Resistor in SCL and SDA Lines
- Number of Devices connected in the bus
- Capacitance in the BUS
- Signal Integrity in the BUS



Defining PMBus

What Is PMBus?

A Standard Way
To Communicate
With Power Converters
Over A Digital
Communications Bus

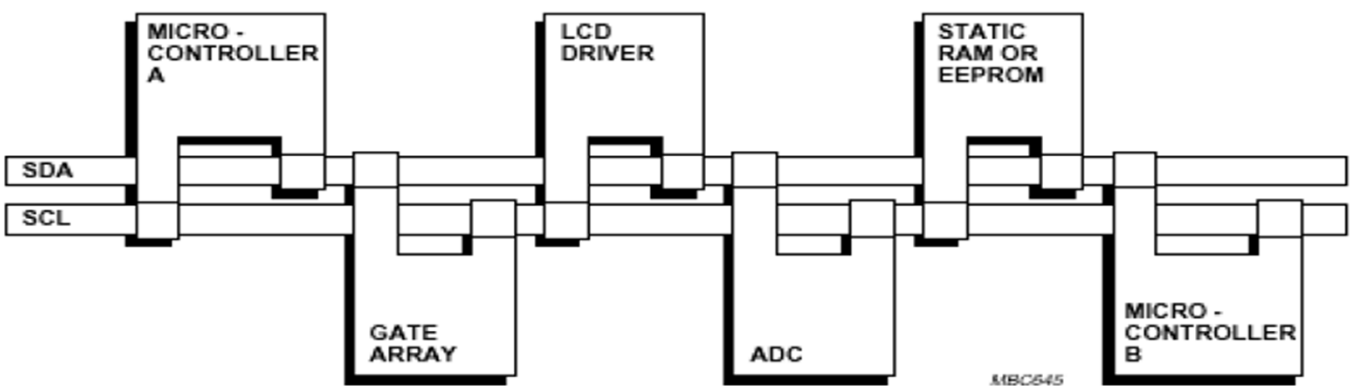
PMBUS as a Standard

PMBus Is An Open Standard

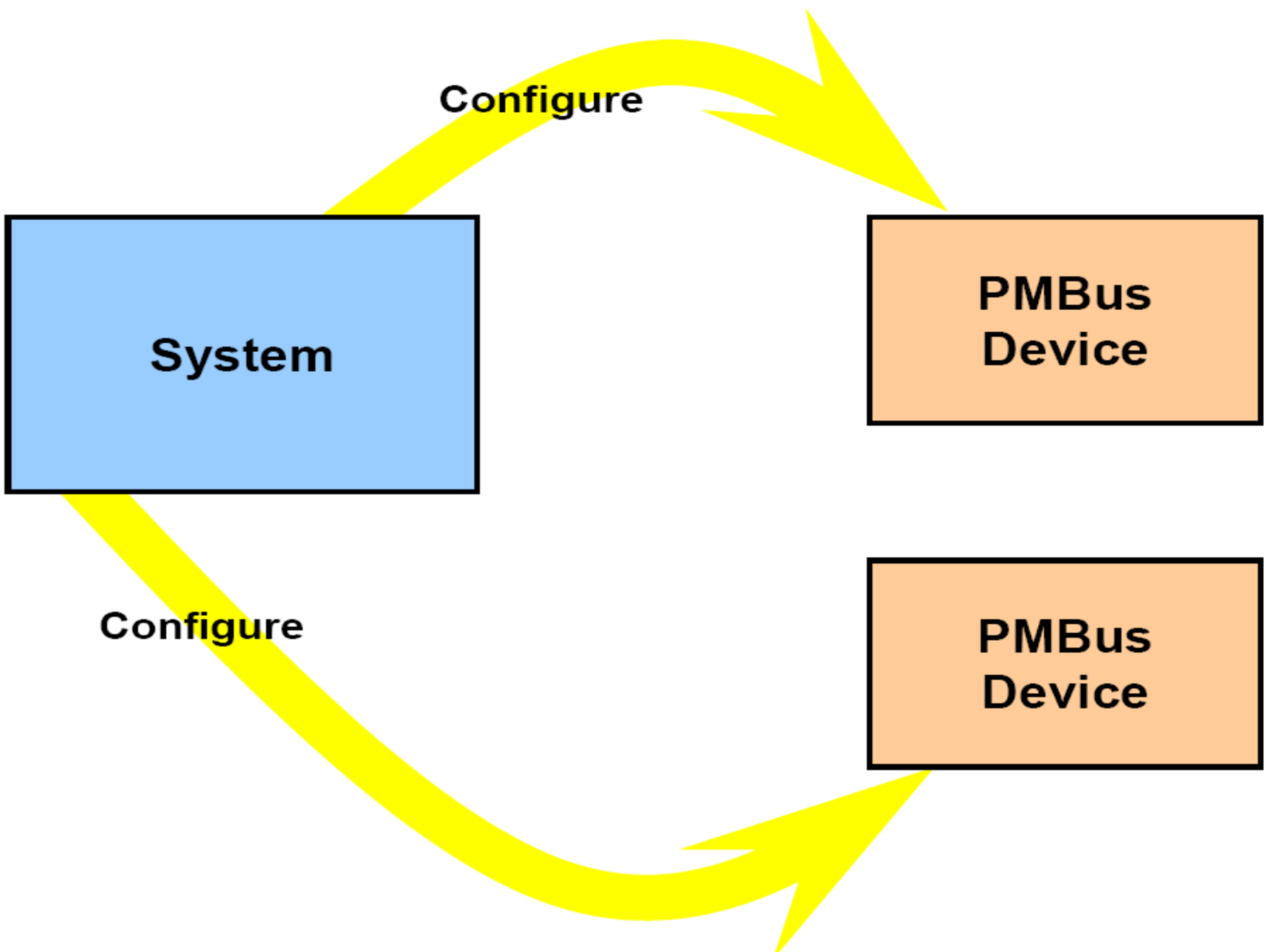
- Owned By The System Management Interface Forum (SM-IF)
  - SM-IF Membership Is Open To All
- Royalty Free
- Released Specifications Freely Available
- Works With All Types Of Power Converters
  - AC-DC Power Supplies
  - Isolated DC-DC And Bus Converters
  - Non-Isolated Point-Of-Load Converters
  - Microprocessor Power Converters

PMBUS Set-up

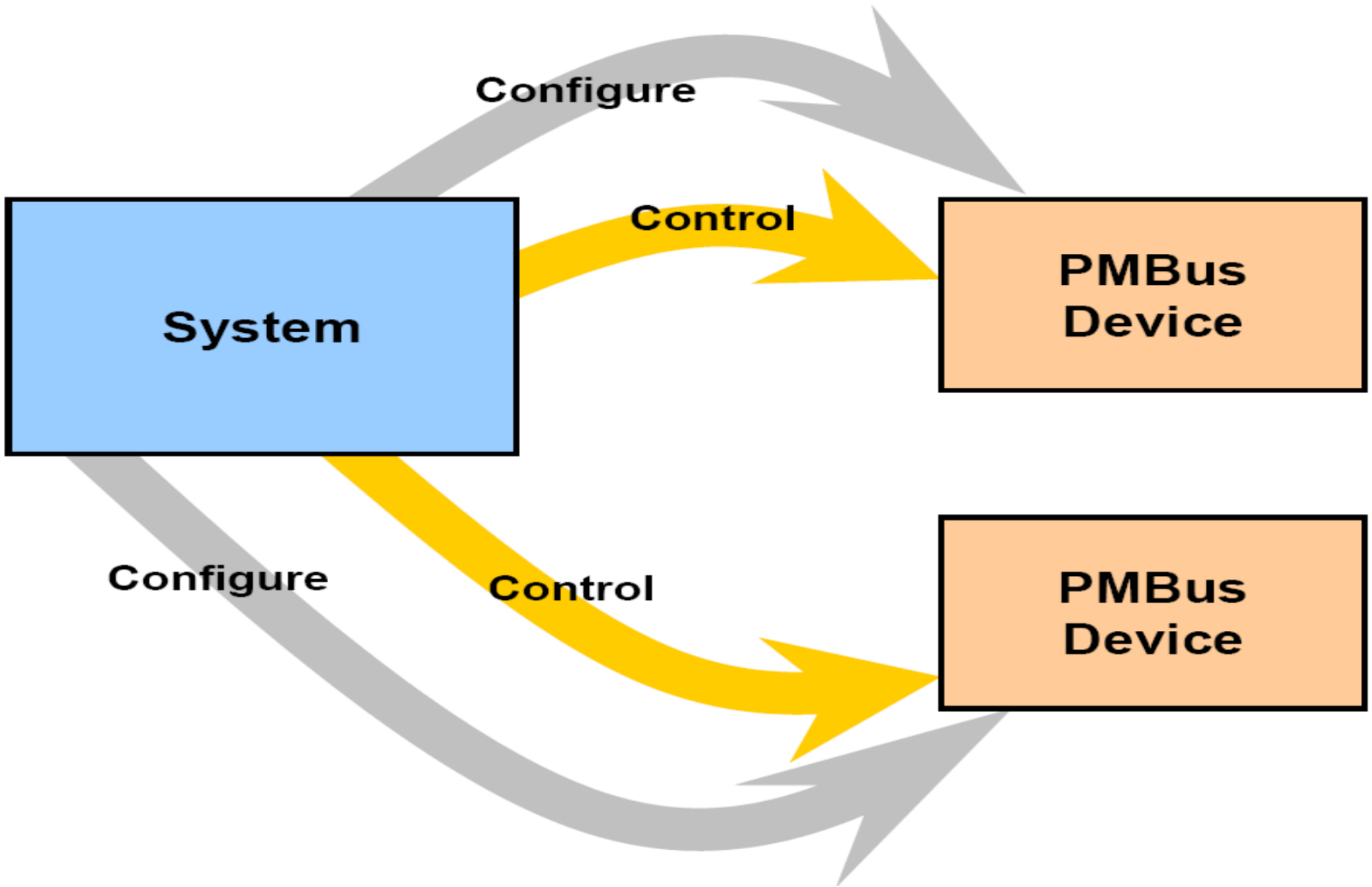
- PMBus is based on SMBus (System Management Bus)
- SMBus is an existing standard developed initially for Smart Battery Management
- SMBus is based on I2C
- I2C (Inter-Integrated Circuit) Protocol
- Low-bandwidth, short-distance, two-wire interface for communication amongst ICs and peripherals. Two Bus lines required: SDA(for data) and SCL(for clock)
- Originally developed by Philips for TV circuits.
- Many devices are available that have hardware interfaces compatible with this protocol.



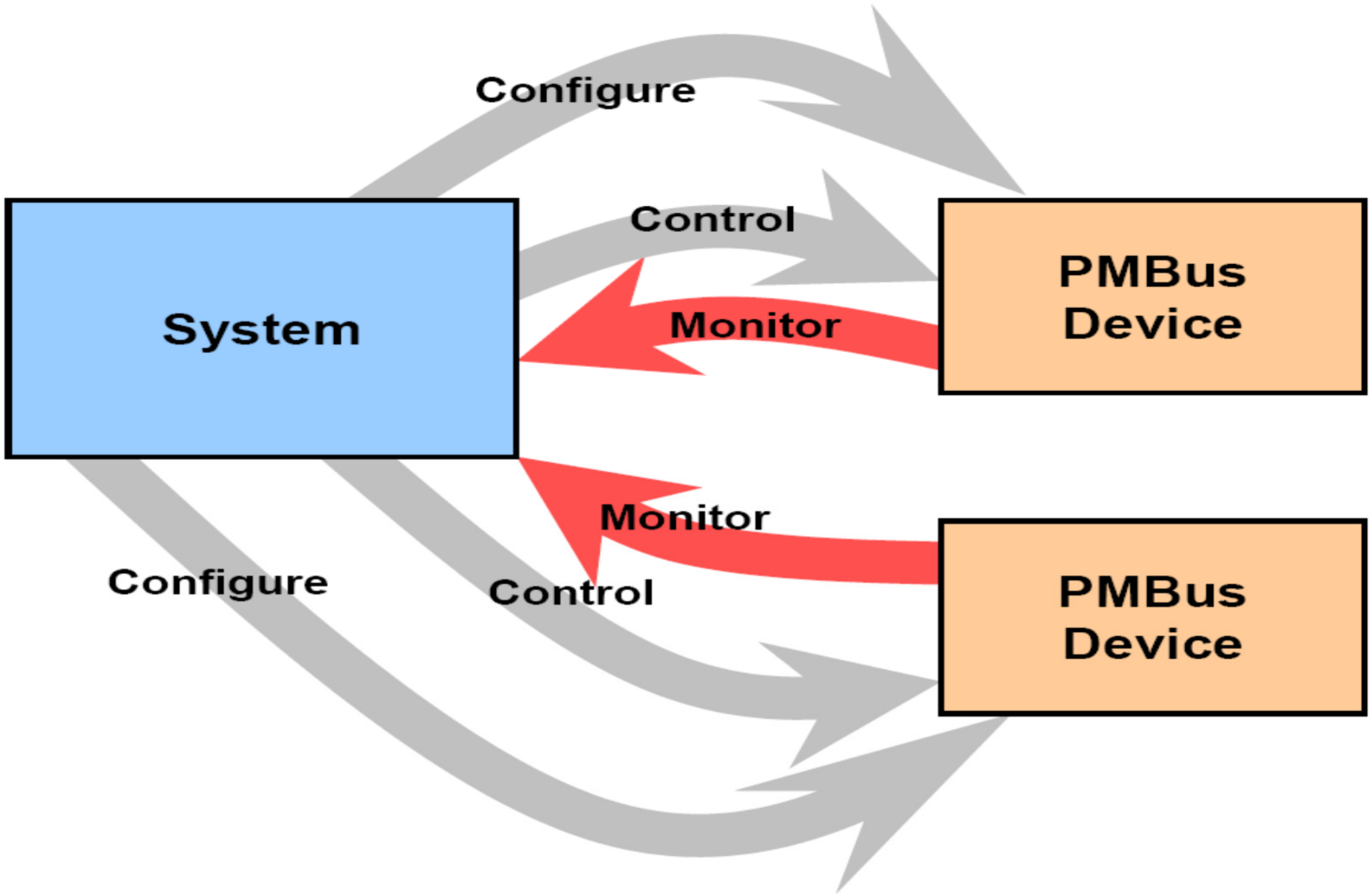
PMBUS for Communications with the System



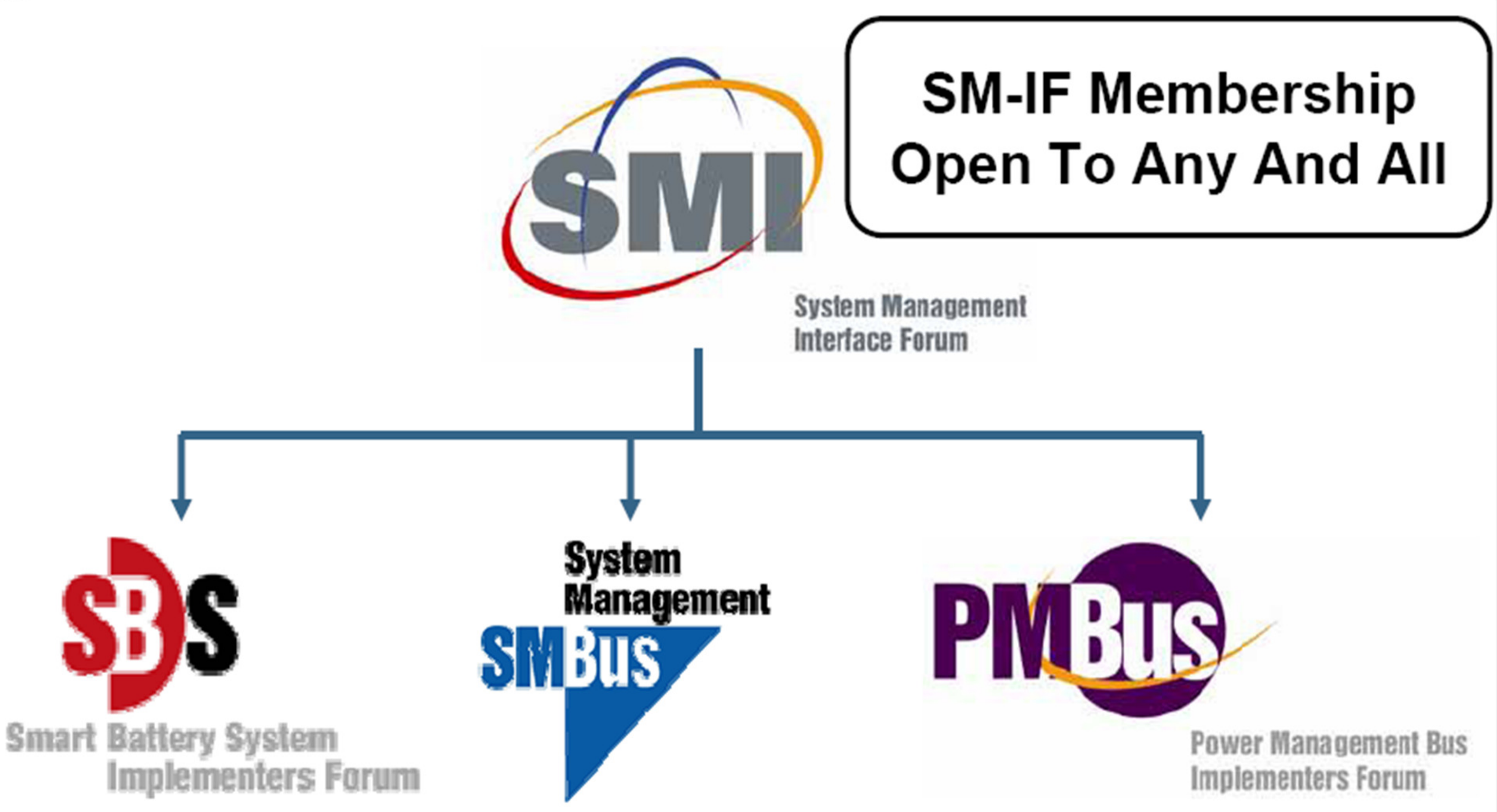
PMBUS for Communications with the System



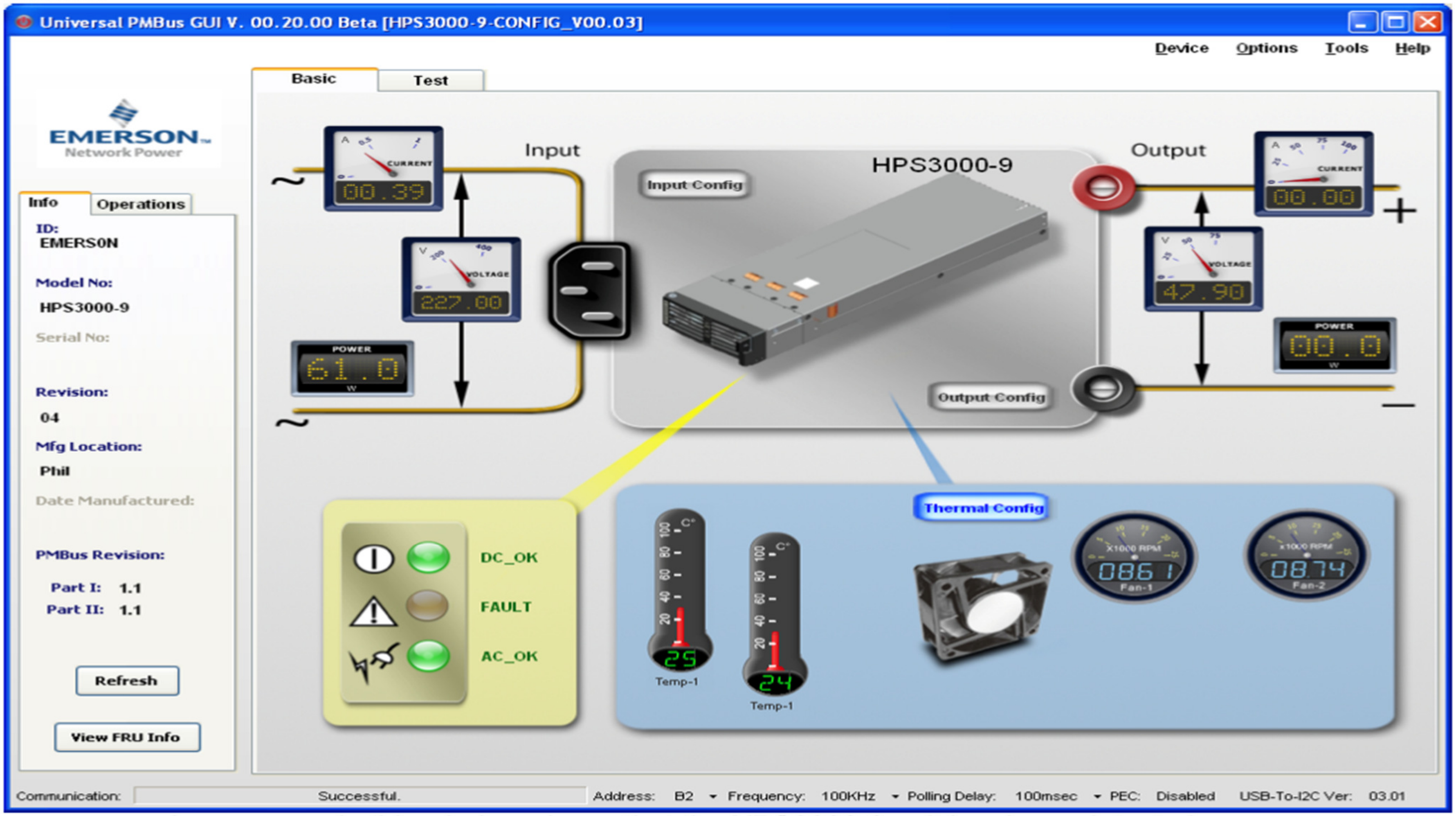
PMBUS for Communications with the System



Other Standards



Graphical User Interface (GUI)

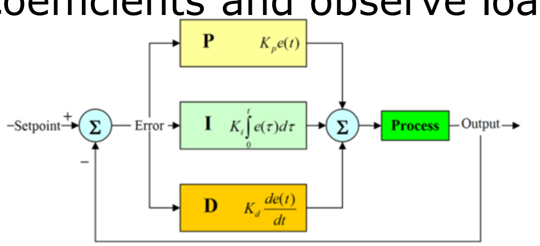


Class Exercises

- Eight (8) Bit Micro-controller for Programmable Buck Converter
  - Uses Microchip PIC16F684 to program O/P voltages & sequencing
  - Program and test dual buck converter (20A each) using switches

- Experiment with 250W Full Digital power supply
  - Communicate through Pmbus
  - Experiment in sending and executing commands

- Thirty Two (32) Bit Digital Signal Controller (DSC)
  - Uses TI TMS320F280 (DSC) with graphical user interface
  - DSC is used as digital control (PID controller) for buck converter
  - Interact with PC GUI to program dual buck converter
  - Set different controller coefficients and observe load step response
  - Perform manual tuning



List of References

Erickson, R. (2001). *Fundamentals of Power Electronics.* New York: Springer.

Maniktala, S. (2005). *Switching Power Supply Design & Optimization.* New York: McGraw Hill.

Maniktala, S. (2006). *Switching Power Supplies A to Z.* Boston: Newnes.

Maniktala, S. (2008). *Troubleshooting Switching Power Converters.* Boston: Newnes.

White, R. (2005). PMBus Introduction. *PMBus* retrieved on December 29, 2011 at www.pmbus.org/specs

High Efficiency Switch-mode Power Supply Design Overview

Module Eight

Practical Design of 30W Flyback Converter

Designing 30W Flyback Converter Design Flow

- Power Supply Specifications
- Draw the Schematic Diagram
- Design the Transformer
- Parts Selection
  - Compute for component's value
  - Select power devices
- Considerations to improve low load efficiency and no-load input power

Power Supply Specification

Power Supply Specifications

- Input Voltage = 90 – 265Vrms, minimum DC input = 90Vdc
- Output Voltage (VO) = 12V
- Output Current (IOUT) = 2.48A
- Auxiliary Voltage (VAUX) = 14V
- Auxiliary Current (IAUX)= 0.02A
- Efficiency (Eff)= 80%
- VSW = 1.0V
- VD = 1.0V

Minimum Input Voltage, VIN(MIN)

- **V_{IN}(MIN) = 90V**

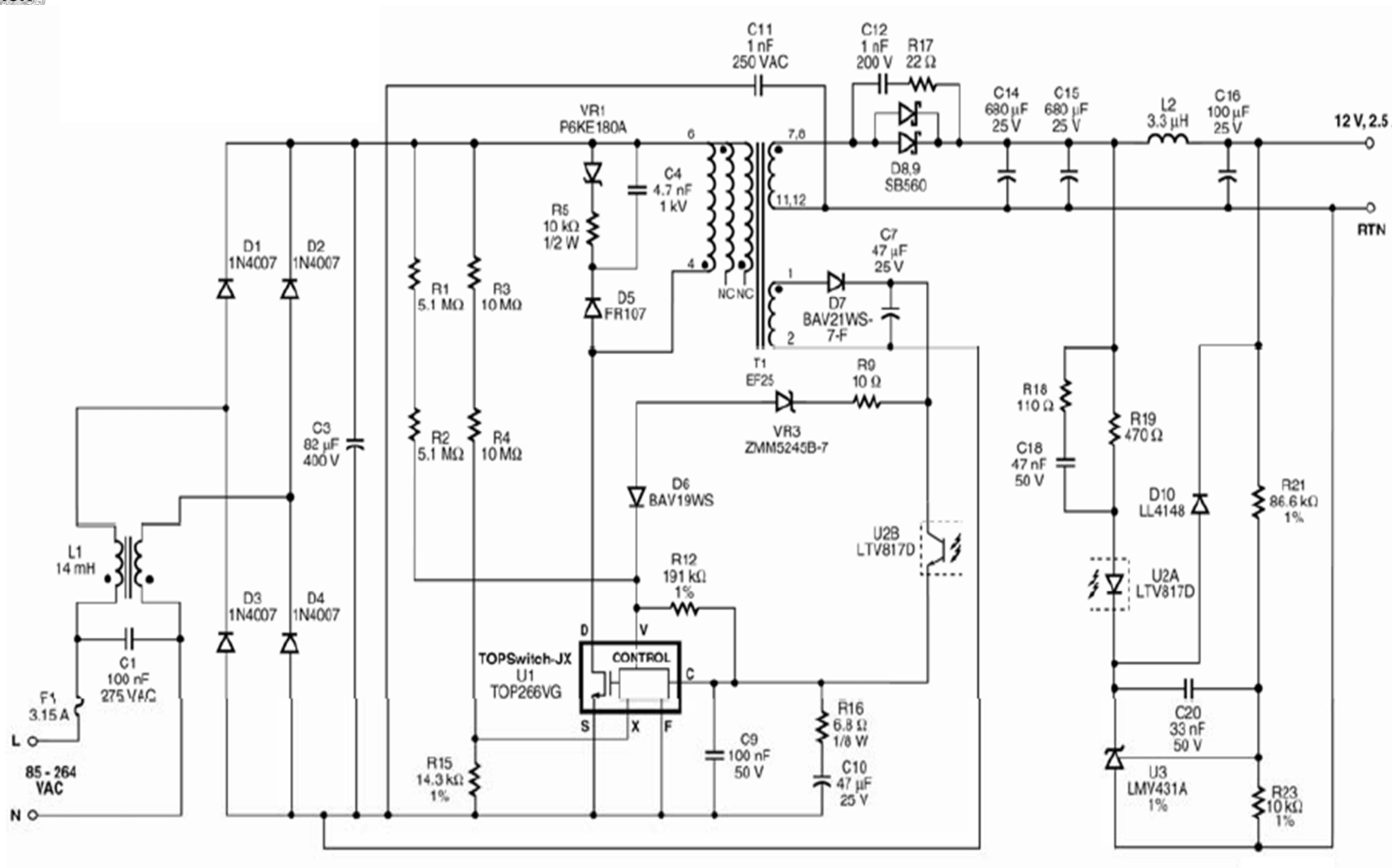
Total Output Power, POUT

- $P_{OUT} = (V_O \times I_{OUT}) + (V_{AUX} \times I_{AUX}) = (12V \times 2.48A) + (14V \times 0.02A)$
- **P_{OUT} = 30W**

Input Power (PIN)

- $P_{IN} = P_{OUT}$ / Eff = 30W / 0.796
- **P_{IN} = 37.68W**

Schematic Diagram



Flyback Transformer Design Procedure

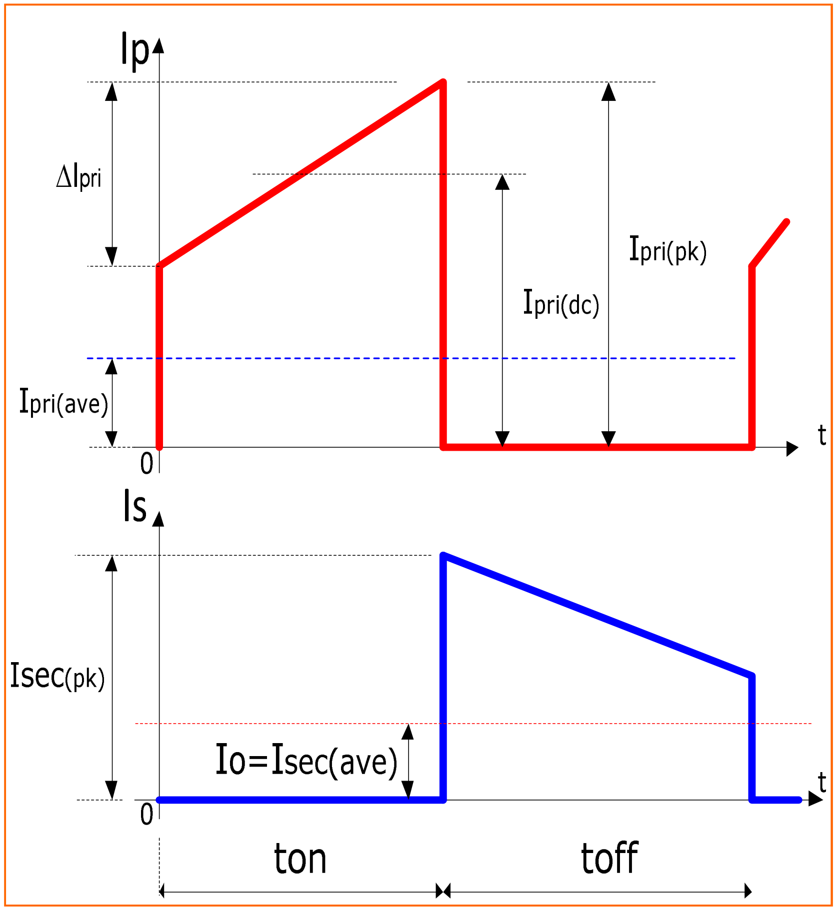
1. Power Supply Specification
   - Input: Input Voltage, Line Frequency
   - Output: Voltage and Current
2. Select Converter's Mode of Operation
   - CCM or DCM
3. Compute Transformer's Current
   - Primary Current and Secondary Current
4. Compute for Required Primary Inductance of the Transformer
5. Select Core
   - Material, Geometry, Size and Power Capability, Winding Area, Cross Sectional Area
6. Compute Number of Turns for Primary Winding
   - Consider Reflected Voltage, Maximum Flux Density, Minimum Input Voltage
   - Optimize Windings – Winding Area VS Flux Saturation, Size of the Wire
7. Compute Number of Turns for Secondary Winding
8. Determine the required Air Gap Length
9. Determine Wire Size
10. Compute Transformer Losses
11. Select Transformer Constructions Method
    - Minimum Leakage Inductance and Safety Requirements

Primary Winding Current

- **Mode of Operation is CCM, with variable frequency at light load**
- **Switching Frequency, f_{sw} = 120 kHz**
- **Maximum Duty Cycle, D_{max} = 0.60**

Assumptions in Computation:

- ΔI_{pri} = 20% to 80% of $I_{pri(pk)}$ to guarantee CCM operation at minimum load
- Use K_f=0.6 for CCM operation
- Compute the Inductance using minimum input voltage



Primary Winding Current

Primary Average Current, $I_{PRI(AVE)}$

$$I_{PRI(AVE)} = \frac{P_{IN}}{V_{IN(MIN)} - V_{SW}} = \frac{37.68\,W}{90\,V - 1\,V} = 0.42\,Amp$$

Primary DC Current, $I_{PRI(DC)}$

$$I_{PRI(DC)} = \frac{I_{PRI(AVE)}}{D_{MAX}} = \frac{0.42}{0.60} = 0.7\,Amp$$

Magnetizing Current, $I_{PRI(pk)}$

$$I_{PRI(PK)} = \frac{I_{PRI(DC)}}{(1 - \frac{k_f}{2})} = \frac{0.7}{\left(1 - \frac{0.6}{2}\right)} = 1.01\,Amp$$

Primary Winding Current

Primary Peak Current, ΔI_{PRI}

$$\Delta I_{PRI} = I_{PRI(PK)} \bullet kf = 1.01\,A \bullet 0.6 = 0.624\ \text{Amp}$$

CCM Primary RMS Current, $I_{PRI(RMS)}$

$$I_{PRI(RMS)} = (I_{PRI(DC)} \bullet \sqrt{D_{MAX}})\sqrt{\left(1 + \frac{1}{3}\left(\frac{\frac{\Delta I_{PRI}}{2}}{I_{PRI(DC)}}\right)^2\right)}$$

$$I_{PRI(RMS)} = 0.558\ \text{Amp}$$

Primary Inductance and Storage Energy

Primary Magnetizing Inductance Calculation

$$L_{PRI} = \frac{V_{IN(MIN)} \bullet D_{MAX}}{\Delta I_{PRI} \bullet f_{SW}} = \frac{90\,V \bullet 0.6}{0.624\,A \bullet 120\,kHz} = 721\,\mu H$$

Storage Energy

$$E = \frac{L_{PRI} \bullet I_{PRI(PK)}^{\ \ 2}}{2} = \frac{721\,\mu H \bullet (1.01\,A)^2}{2} = 0.0037\,J$$

Select Core Material

Core Shape: **EE**

Core Manufacturer: **TDK or Ferroxcube**

Core Part Number: **E25/10/6 use (PC40EF25-Z)**

Core material: **Ferrite**

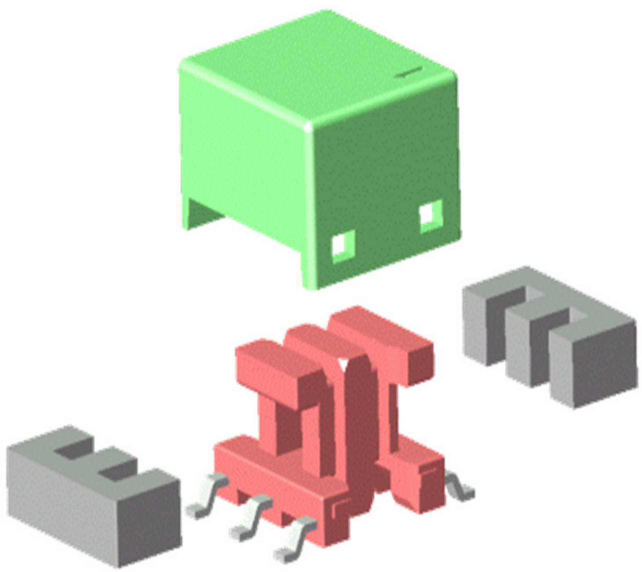
Bsat @ 100 = **380 mT**

Effective cross sectional area, $\mathbf{A_e = 51.8\ mm^2}$

Effective volume, $\mathbf{V_e = 2990\ mm^3}$

Magnetic path flux length, $\mathbf{L_e = 57.8\ mm}$

Inductance factor, $\mathbf{A_L = 2000\ nH/turn^2}$ **(ungapped)**



Select Bobbin (Coil Former)

Manufacturer: **TDK or Equivalent**

Part Number:

Winding Height:

Maximum winding area, $\mathbf{W_a = 15.1\ mm^2}$

Nominal winding width, $\mathbf{W_{width} = 5.2\ mm}$

Average length per turn, **MLT = 49.1 mm**

Area Product, $\mathbf{A_e W_a = 864\ mm^4}$

Calculate Number of Turns

$$N_S = 6 \text{ Turns}$$

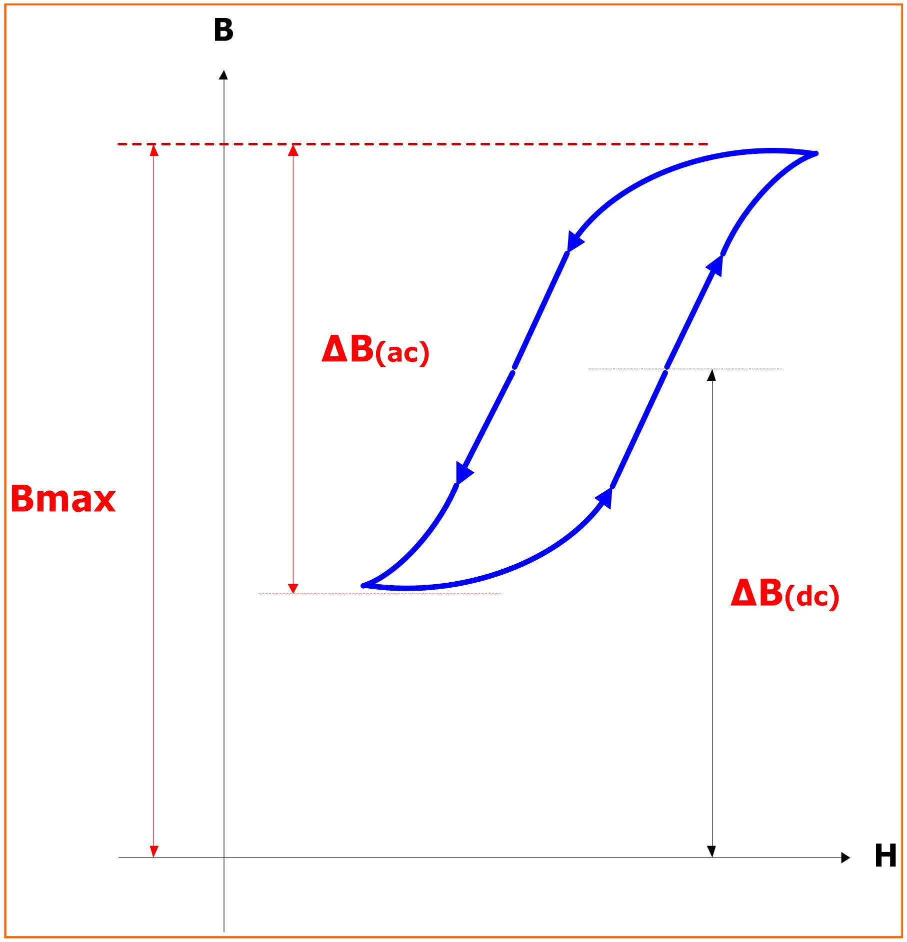
$$N_p = \frac{N_s (V_{IN(MIN)} - V_{SW})}{(V_O + V_D)} \bullet \frac{D_{MAX}}{(1 - D_{MAX})}$$

$$N_P = 62 \text{ Turns}$$

$$N_{AUX} = \frac{V_{AUX} + V_D}{V_O + V_D} \bullet N_S = 7 \text{ Turns}$$

Hysteresis, B-H Curve

- The flyback converter is operating in unidirectional hysteresis curve
- Figure shown is the mode of operation of the flyback converter
- For the same flux density, the CCM could handle more power than DCM



Calculate Maximum Flux Density, B_{MAX}

$$\Delta B_{DC} = \frac{L_{PRI} \bullet \Delta I_{PRI}}{N_P \bullet A_e} = \frac{721\ \mu H \bullet 0.624\ A}{62 \bullet 51.8\ mm^2} = 0.140\ T$$

$$\Delta B_{AC} = \frac{L_{PRI} \bullet I_{PRI(DC)}}{N_P \bullet A_e} = \frac{721\ \mu H \bullet 0.7\ A}{62 \bullet 51.8\ mm^2} = 0.157\ T$$

$$B_{MAX} = \Delta B_{DC} + \frac{\Delta B_{AC}}{2} = 0.22\ T = 2200\ gauss$$

L_{pri} – is in µH
$I_{pri(pk)}$ – in ampere
Np – in turn
Ae – in cm^2
ΔBac – in gauss

Calculate Air Gap Length

$$L_{gap} = \frac{\left(4\pi \bullet 10^{-7}\ \frac{H}{m}\right) \bullet N_P^{\ 2} \bullet A_e}{L_{PRI}}$$

$$L_{gap} = \frac{4\pi \bullet 10^{-7} \bullet 62^2 \bullet 51.8\ mm^2}{721\ \mu H}$$

$$L_{gap} = 0.347\ mm$$

- Airgap in mm^2
- Lpri in µH
- Ae in mm^2
- Bmax in gauss

- Note: this equation is approximation only (assumes very high un-gapped relative permeability)

Winding Loss

- **Select Wire Size and Compute for the Copper loss, 500cir-mils / amp**
- **Primary Winding**
  - Use AWG # 26: 254 cir-mils, 0.129 mm^2, 133.9 ohms/km
  - Average Length = No. of Turns x MLT = 62 x 49.1mm = 3.04m
  - R_{pri} = 133.9 ohms/km x 3.04 ohms = 0.408ohm
- **Secondary Winding**
  - Use AWG # 20: 1020 cir-mils, 0.518 mm^2, 33.31 ohms/km
  - Average Length = No. of Turns x MLT = 6 x 49.1mm = 0.2946m
  - R_{sec} = 33.31 ohms/km x 0.2946 m) = 0.00981 ohm
- **Auxiliary Winding**
  - Use AWG # 36: 25 cir-mils, 0.0127 mm^2, 1361 ohms/km
  - Average Length = No. of Turns x MLT = 7 x 49.1mm = 0.3437m
  - R_{aux} = 1361 ohms/km x 0.3437m = 0.4678

Transformer Winding Area

The winding area determines if selected bobbin is capable to accommodate the windings of the transformer based on the size of wire needed. Wa(bobbin) = 15.1mm^2

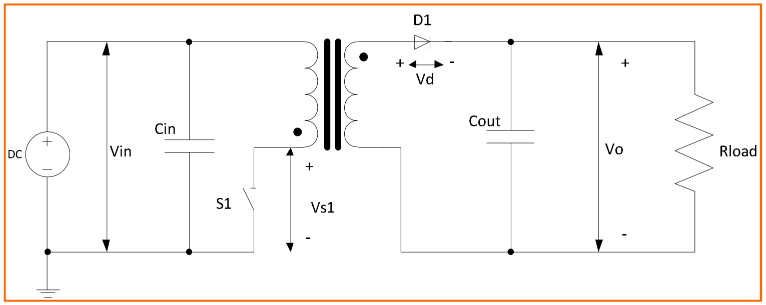
$$W_a = k(N_p \bullet N_{p(Aw)} + N_S \bullet N_{S(Aw)} + N_{aux} \bullet N_{aux(Aw)})$$

$$W_a = 1.2(62 \bullet 0.129\text{mm}^2 + 6 \bullet 0.518\text{mm}^2 + 7 \bullet 0.0127\text{mm}^2)$$

$$W_a = 13.4\text{mm}^2 \quad \leq \quad W_{a(bobbin)} = 15.1\text{mm}^2$$

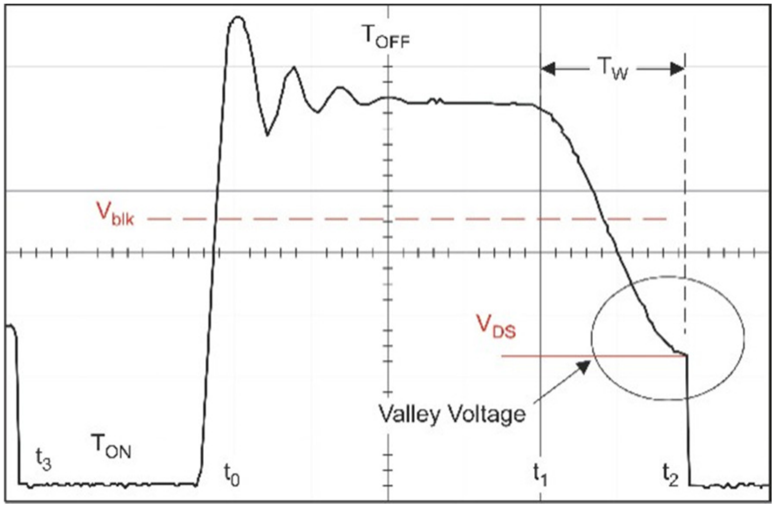
Computation of Reflected Voltage

- Vin= 375V, Vo= 12V
- Vd= 1V, Np= 62, Ns= 7
- Determine the peak voltage seen by the switch. (Neglect leakage inductance)



Answer:

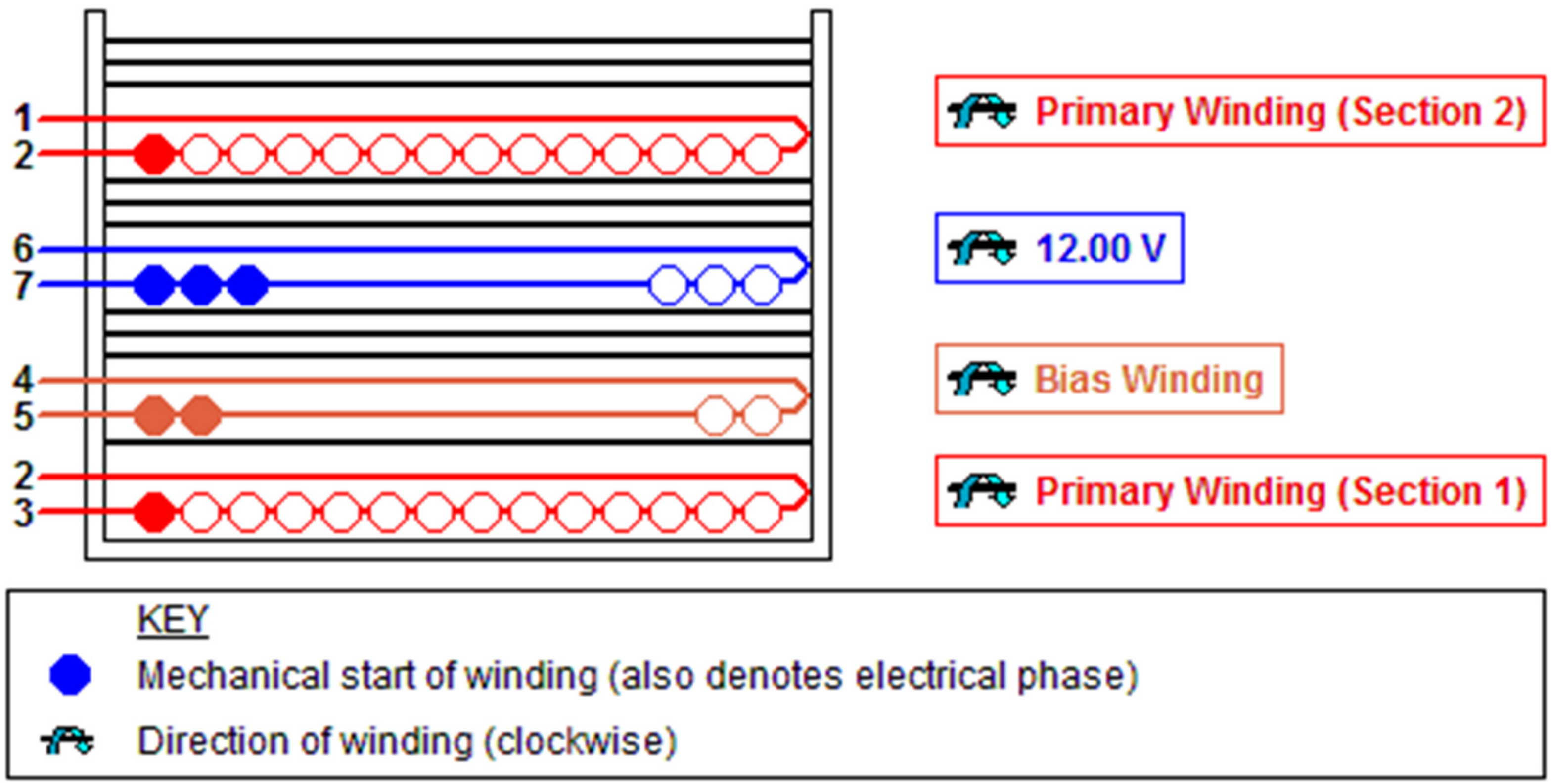
- Vsw_{off} = Vin + (Vo + Vd)(Np/Ns)
- Vsw^{off} = 375V + (13)(62/6)
- Vsw_{off} = 509V



Transformer Construction

Transformer Construction

Split or Interleaved Construction
- Improved coupling
- Reduce leakage inductance



Transformer Specification

Core

•Core type/size	: E25/13/7 (EF25)
•Manufacturer	: Ferroxcube
•Part number	: E25/13/7-3C90
•A_e	: 51.8 mm²
•A_{min}	: 51.8 mm²
•Airgap	: 297µm (custom airgap)
•A_L	: 216 nH/turn²
•Effective core volume	: 2990 mm³
•Core material	: 3C90
•Bsat @ 100ºC	: 380 mT

Bobbin

•Manufacturer	: Ferroxcube
•Part number	: CPH-E25/13/7-1S-10P
•Winding width	: 15.1 mm
•Winding height	: 4.1 mm
•Average winding length	: 49.1 mm/turn

Turns

•Primary	: 62 turns
•Secondary	: 6 turns
•Auxiliary	: 7 turns

Inductance

•Primary inductance	: 721 µH

Worst case current and flux density at minimum mains and peak output power

•Primary peak current	: 1.01 A
•Peak flux density	: 244 mT

Estimated losses at nominal mains and maximum continuous output power

•Copper losses	: 310 mW
•Core losses	: 150 mW
•Total losses	: 460 mW

Testing of Transformer

Electrical Test Specifications

- Electrical Strength
  - Apply 3000Vac, 60Hz for 1 second between primary and secondary windings.
- Measure Primary Inductance
  - Measured at 1Vpp, 1kHz between the primary winding.
- Measure Primary Leakage Inductance, should be <5% of Lpri.
  - Measure between the primary winding, with all other windings are shorted.

Select Switch Mosfet

- Determine the peak voltage seen by the switch mosfet, Vds.

- Formula shown does not consider the ringing caused by the primary leakage inductance and switch mosfet output capacitance.

- Determine the current rating of the switch, Id.

$$\mathrm{Vds} = \mathrm{Vmax} + \frac{\mathrm{Np}}{\mathrm{Ns}}(\mathrm{Vo} + \mathrm{Vd}) = 375 + \frac{62}{6}(12+1)$$

$$\mathrm{Vds} = 509$$

$$\mathrm{I}_{\mathrm{D\,(rating)}} = 1.5 \bullet \mathrm{I}_{\mathrm{PRI(pk)}} = 1.5 \bullet 1.01$$

$$\mathrm{I}_{\mathrm{D(rating)}} = 1.5\mathrm{A}$$

Primary Mosfet: Effect of Leakage Inductance, Coss and PWB Parasitics

•The parasitic inductance and capacitance form a parasitic LC network that resonates at turn off.

•Leakage inductance will increase the peak voltage, while capacitance will reduce the peak voltage as seen by the mosfet.

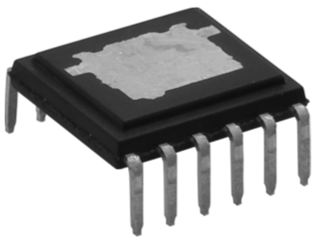
•Peak Voltage (Vds) across the Switch Mosfet
•Primary leakage inductance, L_{LP}
•Primary winding capacitance in the transformer, C_P
•Mosfet output capacitance, Coss
•Number of primary turns, Np
•Number of secondary turns, Ns

$$V_{ds(peak)} = I_{pri}\sqrt{\frac{L_{LP}}{C_p + Coss}} + V_{in} + \left(Vout \bullet \frac{N_p}{N_s}\right)$$

Mosfet Controller Specification

Selected Mosfet + Controller: TOP266VG

Electrical Characteristics:



- Reverse Voltage Breakdown, V_{DSS} = 725V
- Max. absolute Peak Drain Current, I_D = 4.08A
- Current limit (self protection) of 2.5A
- Drain-Source ON Resistance, $R_{DS(on)}$ = 2.8 Ω
- Output Power with PCB copper of 30W

Output Rectifier: Effect of Leakage Inductance, Coss and PWB Parasitics

Peak Voltage (Vpeak) across the Output Rectifier

Elements that form a parasitic LC network

•Secondary leakage inductance, L_{LS}

•Capacitance of the output rectifier, C_D

Reverse Current Recovery, I_{rec}

$$V_{peak} = I_{rec}\sqrt{\frac{L_{LS}}{C_D}} + V_{in} \bullet \frac{N_P}{N_S}$$

Output Rectifier

•Determine the voltage rating and current rating of the rectifier diode.

•Vreverse - is the maximum reverse voltage seen across the output rectifier and should be at least 150% of Vreverse.

•Current Rating - is the forward current rating of the output rectifier and should be at least 300% of the output current.

Diode Rating=1.5PIV

$$Diode_{DC\_current\_rating} := 3 \cdot Io = 7.5\,A$$

60 V, 5 A, Schottky, DO-201AD

Output LC Post Filter

•A post filter (LPF and CPF) is typically added to reduce high frequency switching noise and ripple.

•Inductor LPF should be in the range of 1 µH – 3.3 µH with a current rating above the peak output current.

•Capacitor CPF should be in the range of 100 µF to 330 µF with a voltage rating ≥1.25 x VOUT.

Input Bridge Rectifier

•Determine the voltage rating and current rating of the Input rectifier diode.

•Vreverse - is the maximum reverse voltage seen across the input rectifier and should be at least 150% of Vreverse.

•Current Rating - is the forward current rating of the input rectifier and should be at least 200% of the output current.

Selected Diode: **1N4007**

$$\mathrm{Bridge}_{\mathrm{reverse\_voltage\_rating}} := 1.5 \cdot V_{max} = 562.15\ \mathrm{V}$$

$$\mathrm{Bridge}_{\mathrm{current\_rating}} := 2 \cdot \left(\frac{\mathrm{Pin}}{V_{min}}\right) = 0.837\ \mathrm{A}$$

Transfer Function and Bode Plot

- Closed loop input to output transfer function of the converter.

- Bode Plot

- Open loop input to output transfer function

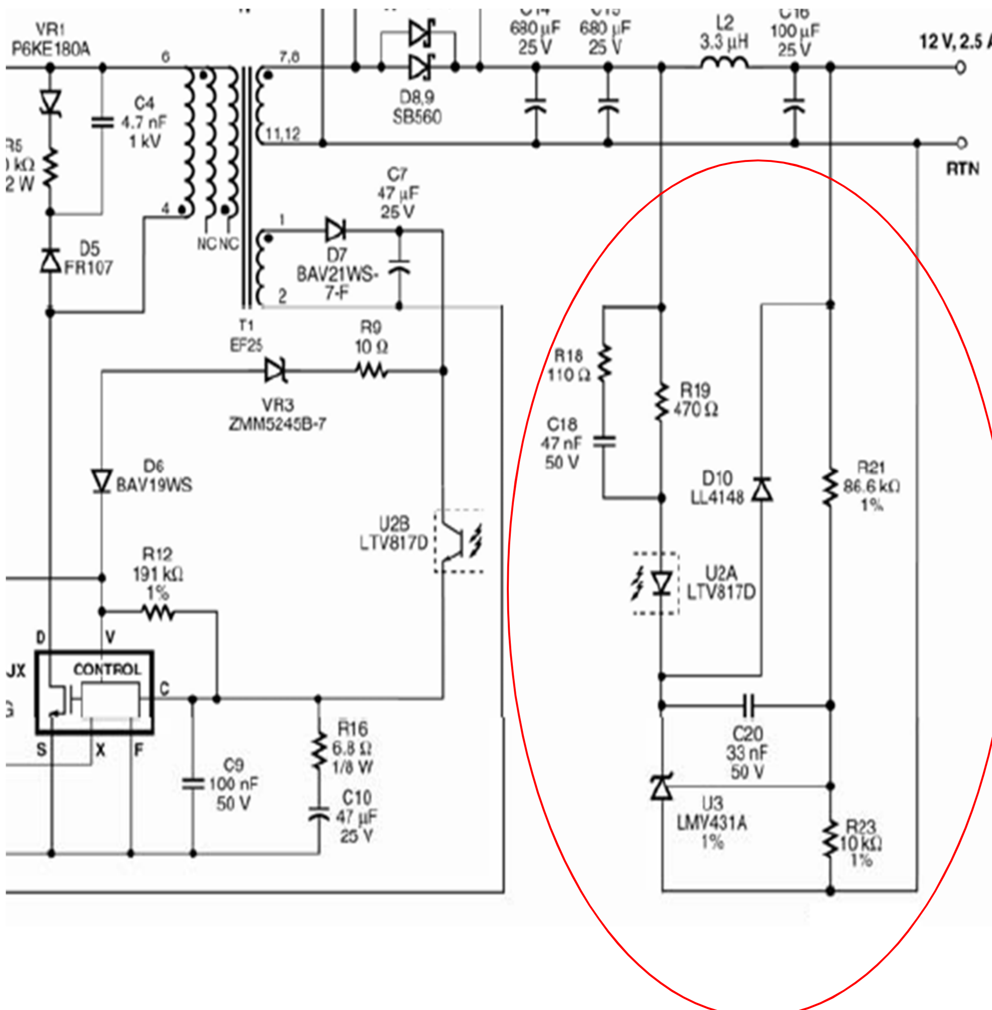
- Feedback loop compensation

Loop Gain Crossover Frequency

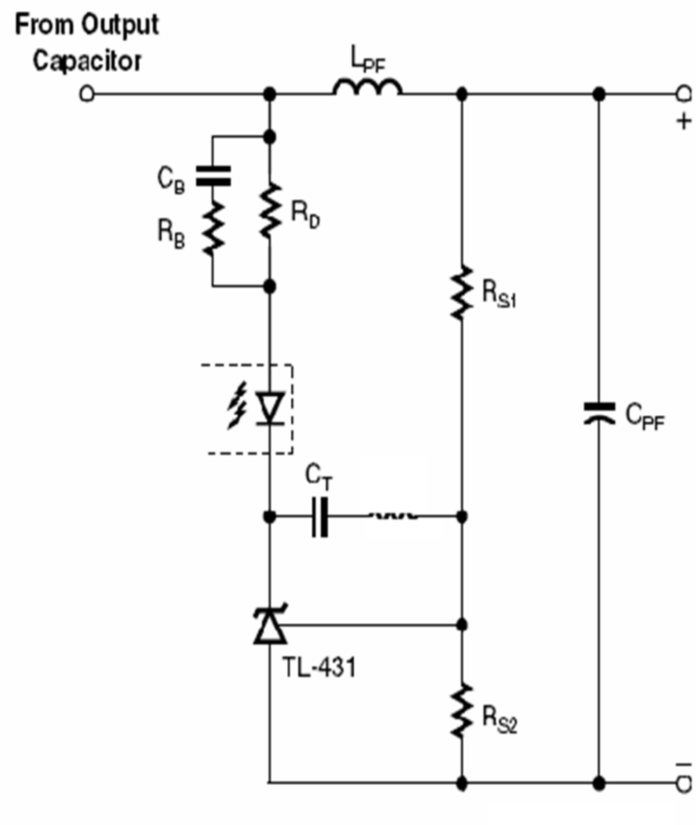
Selection on the loop gain crossover frequency depends on:

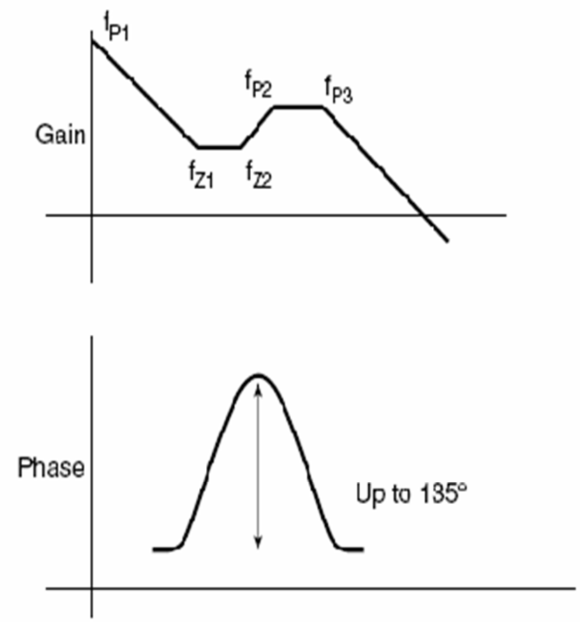
- Power supply topology
- Switching frequency
- Voltage mode or current mode control
- Output capacitor
- Power stage components (variations)
- Higher crossover frequency can reduce output overshoot but can increase noise.

Optocoupler and Shunt Regulator as Feedback Network



Feedback Loop Compensation





Pole/Zero	Formed by	Approximate Location
f_{P1}	C_T	0 Hz
f_{Z1}	C_T, R_{S1}	100 Hz
f_{Z2}	R_B, C_B, R_D	f_C
f_{P2}	TOPSwitch	7 kHz
f_{P3}	R_B, C_B, R_D	10 f_C

Loop Stability

•If the Flyback converter works in CCM and DCM, design the feedback loop for CCM. This guarantees stability in CCM and DCM.

•After calculation of the components for the compensation network it is good practice to plot the closed loop transfer function in worst case conditions, e.g. at high input line and light load and at low input line and full load.

•Utilize PI Power Expert software to simulate closed loop transfer function and determine stability margin.

Ways to Reduce Standby Power and Improve Efficiency

Remove power LED

•A LED current of 2.5 mA supplied from a 12V output voltage already adds 30 mW to the no-load power.
•A (high efficiency) LED in series with the LED of the optocoupler.
•Another option is to supply the LED from a separate low voltage winding.

Change the primary RCD clamp to a Zener clamp

•The advantage of the Zener clamp is that it only conducts when it is really needed and is independent of the switching frequency.
•Compared to a Resistor-Capacitor-Diode (RCD) clamp, it reduces no-load power but increases costs and EMI.

Ways to Reduce Standby Power and Improve Efficiency

Active X-cap discharge – CAP SENSE

•Replace a passive X-cap discharge (resistor) by an active discharge circuit.

Active start-up circuit

•Replace a passive start-up circuit (resistors) by an active charge circuit that is only active during start-up.

Increasing the impedance of the voltage divider on $V_{INSENSE}$

Increase the impedance of the output voltage divider

Replacing the integrated shunt regulator (TL431) by a discrete shunt regulator

•The widely available integrated TL431 shunt regulator versions usually require 1mA for proper regulation.

Class Exercise

Utilize PI Expert software as a tool in designing Flyback converter

- Input specs.
- Generate the design: schematic, BOM, & transformer design
- Estimate the performance
- Determine feedback loop stability
- Power components rating

List of References

Erickson, R. (2001). *Fundamentals of Power Electronics.* New York: Springer.

Maniktala, S. (2005). *Switching Power Supply Design & Optimization.* New York: McGraw Hill.

Maniktala, S. (2006). *Switching Power Supplies A to Z.* Boston: Newnes.

Maniktala, S. (2008). *Troubleshooting Switching Power Converters.* Boston: Newnes.

Power Integrations (2010). RDR-242 Reference Design for a 30W Power Supply. Retrieved on Dec. 19, 2011 at www.powerint.com.

Pressman, A. (1991). *Switching Power Supply Design.* New York: McGraw-Hill.