The Power to Amaze.

POWER CONVERTER TOPOLOGY TRENDS

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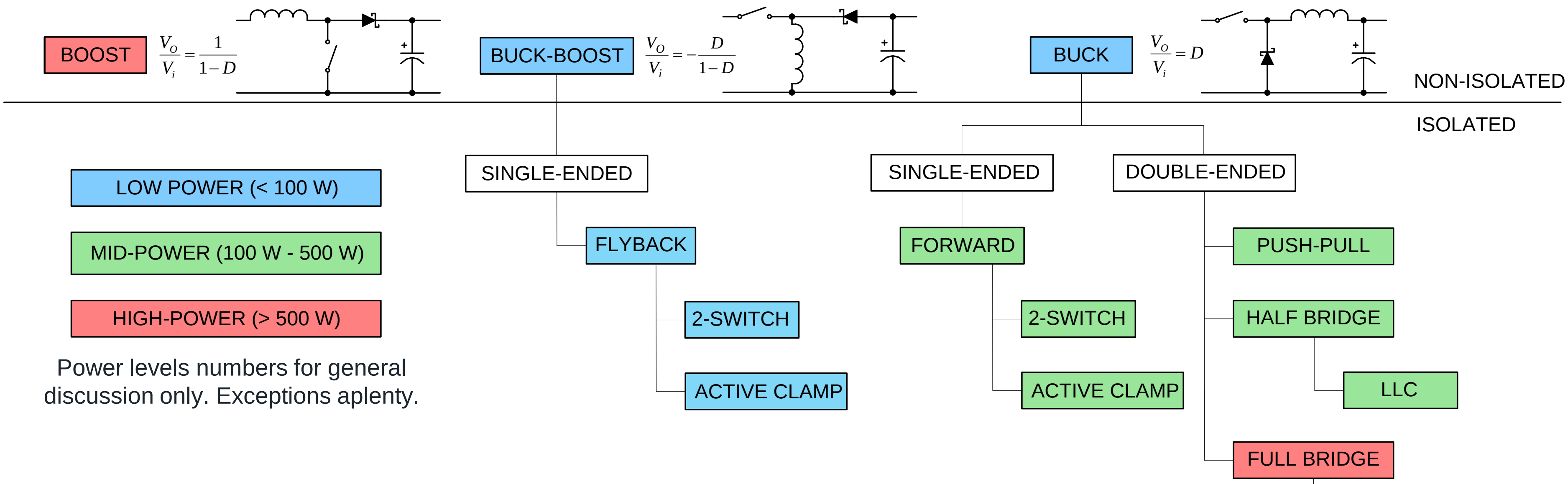
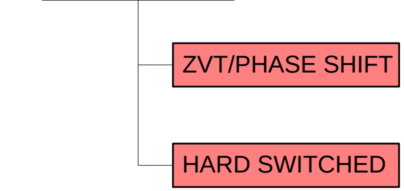
Agenda

- Topology Overview
- Non Isolated Topologies
- Isolated DC-DC Derivatives
- Single Ended Topologies
  - Transformer Reset Techniques
  - Flyback Converter
  - Forward Converter
- Double Ended Topologies
  - Push Pull
  - Half Bridge
  - Full Bridge
- Summary

Isolated Power Topology Derivatives





8 “Mainstream” Converter Topologies

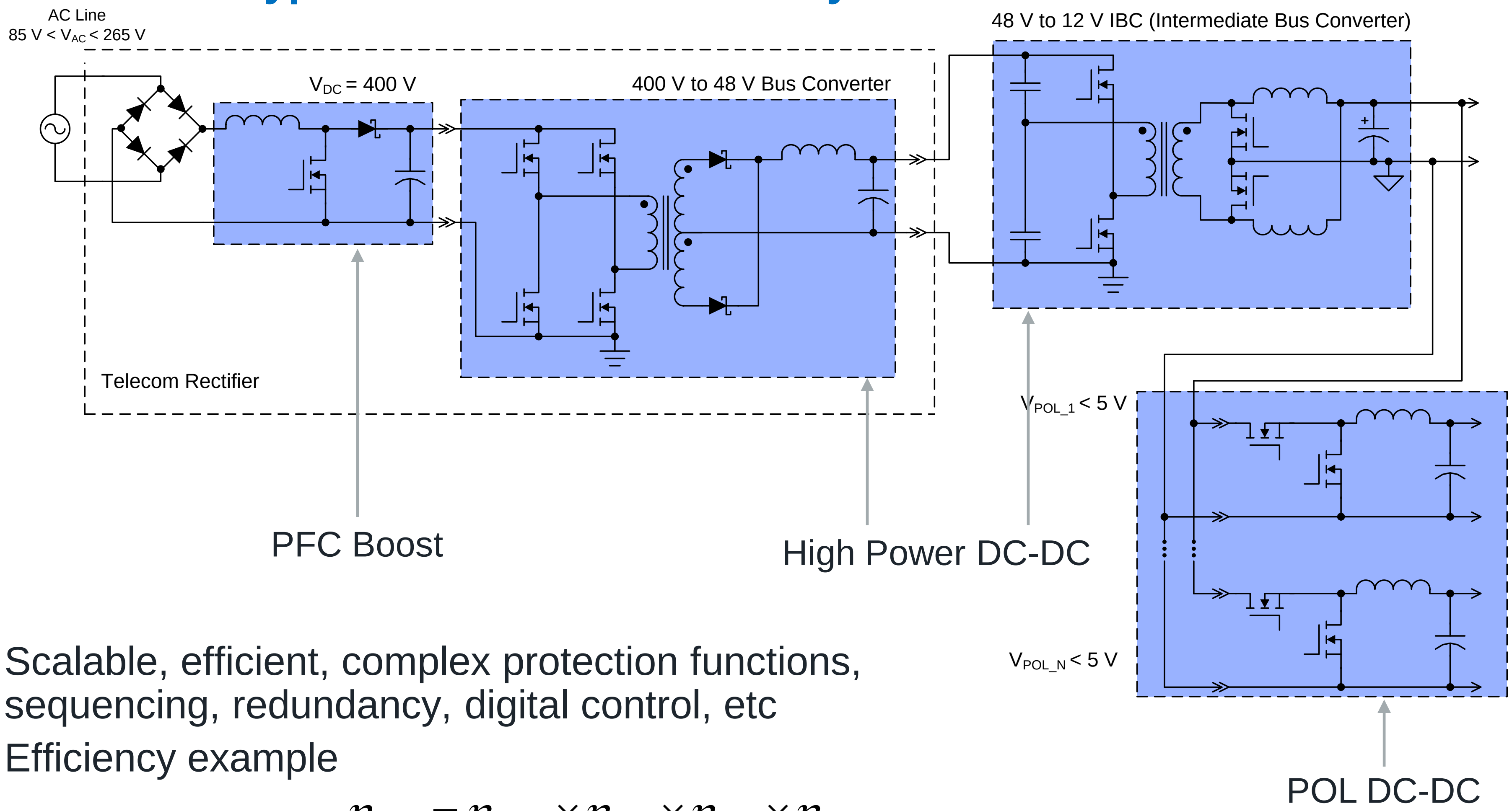
- Non-Isolated
  1. Boost
  2. Buck-Boost
  3. Buck
- Isolated
  4. Flyback
  5. Forward
  6. Push-Pull
  7. Half Bridge
  8. Full Bridge

Other Topologies?

- Numerous Variations Exist
  - Sepic
  - Cuk
  - Current Fed Buck
  - Tapped Inductors
  - Multiple Outputs
  - Interleaving
  - More?
- Different Ways to Operate Them
  - Voltage Mode Control
  - Current Mode Control
  - Digital Control
  - Variable Frequency
  - CCM, DCM, BCM
  - ZVS
  - ZCS
  - Synchronous Rectification
- Some Practical Converter Topology Advice
  - *Most* power conversion requirements can be met using one or more of the 8 mainstream topologies
  - Save more difficult topologies for unique application requirements
  - Beware of publications proclaiming the “best” topology

Multi-Stage Topology

Typical Distributed Power System

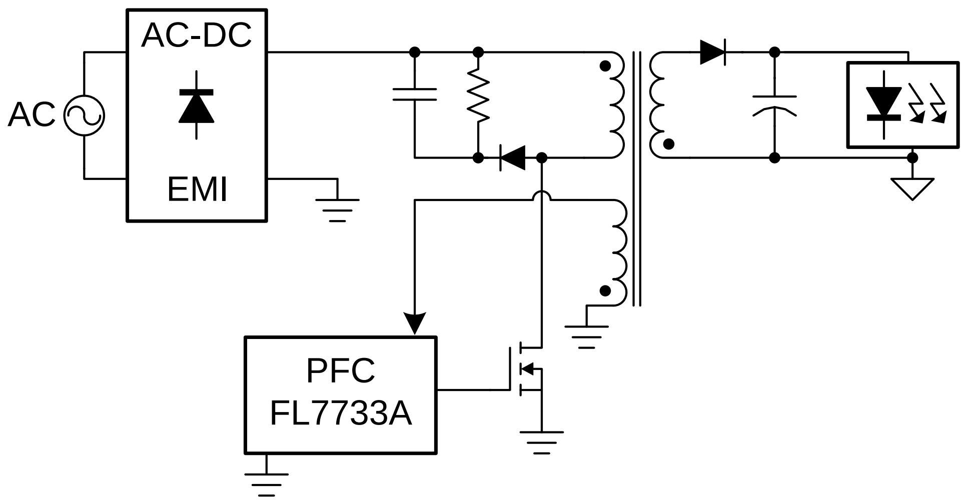


- Scalable, efficient, complex protection functions, sequencing, redundancy, digital control, etc
- Efficiency example

$$\eta_{SYS} = \eta_{PFC} \times \eta_{DC} \times \eta_{DC} \times \eta_{POL}$$

$$\eta_{SYS} = 98\% \times 95\% \times 95\% \times 96\% = 84.9\%$$

Single-Stage Topology
PFC Flyback

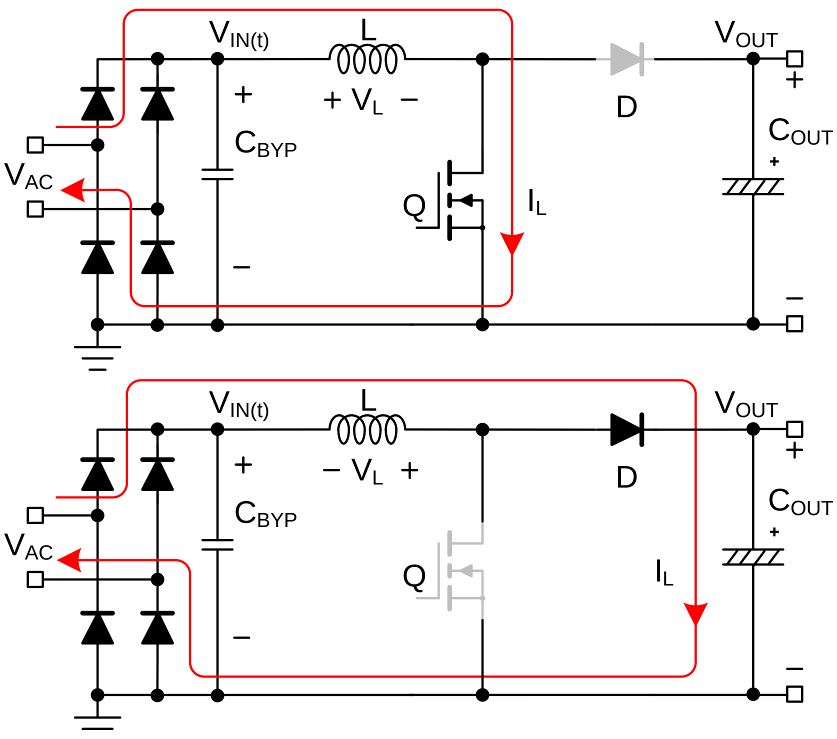


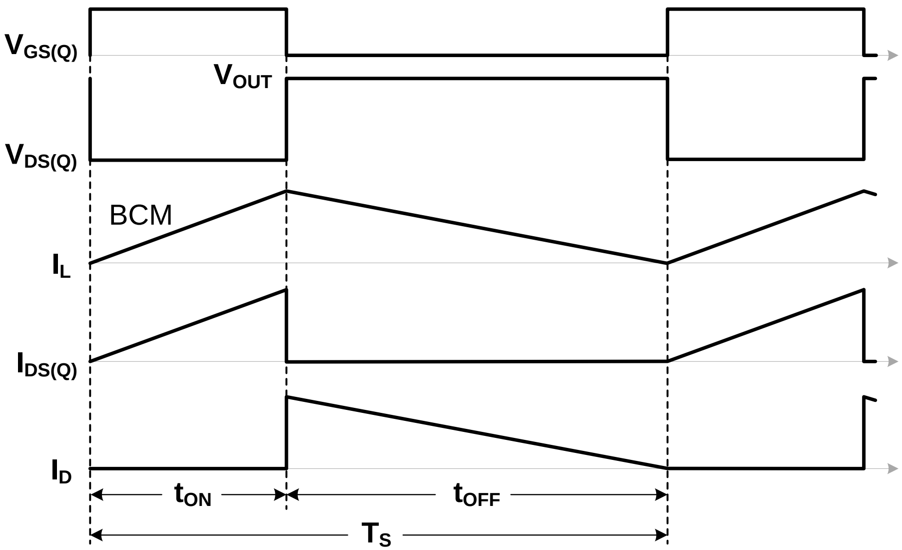
- Difficult to meet: Low cost, high PF, low THD, high efficiency, wide V_{IN} with single-stage

$$\eta = 84.9\%$$

Non-Isolated Converter Topologies

Boost Converter (Step Up)





Boost CCM transfer function:

$$\frac{V_{OUT}}{V_{IN(t)}} = \frac{T_S}{t_{OFF}} = \frac{1}{1-D}$$

- $V_{IN} < V_{OUT}$
- Most efficient at lower D
- Continuous input current
- CCM, BCM, DCM modes

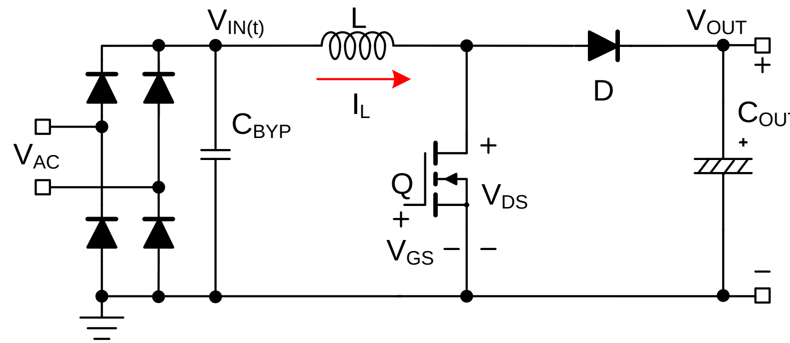
Inductor volt-second balance:

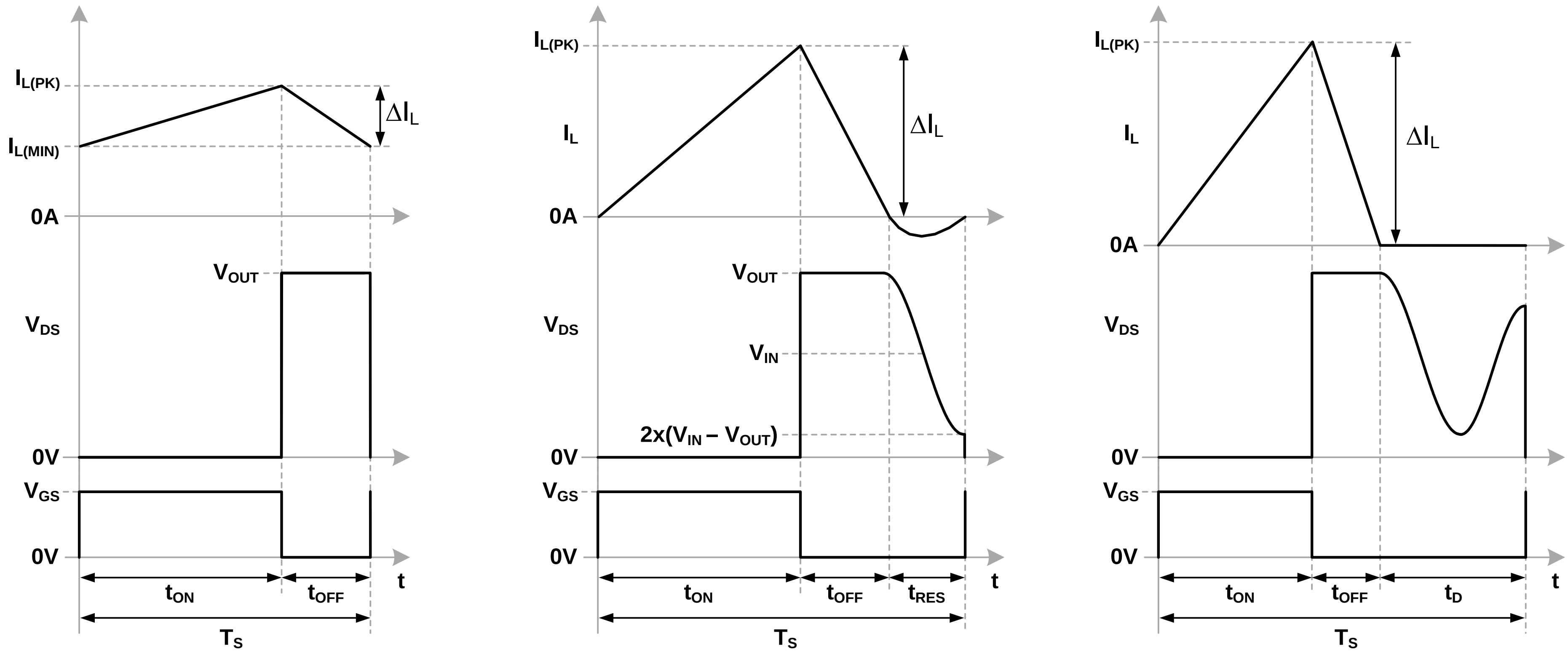
$$\langle V_L \rangle_{T_S} = V_{IN(t)} \times t_{ON} + \left[\left(V_{IN(t)} - V_{OUT}\right) \times t_{OFF}\right] = 0$$

$$V_{IN(t)} \times (t_{ON} + t_{OFF}) = V_{OUT} \times t_{OFF}$$

$$V_{IN(t)} \times T_S = V_{OUT} \times t_{OFF}$$

Operating Mode
CCM, BCM or DCM



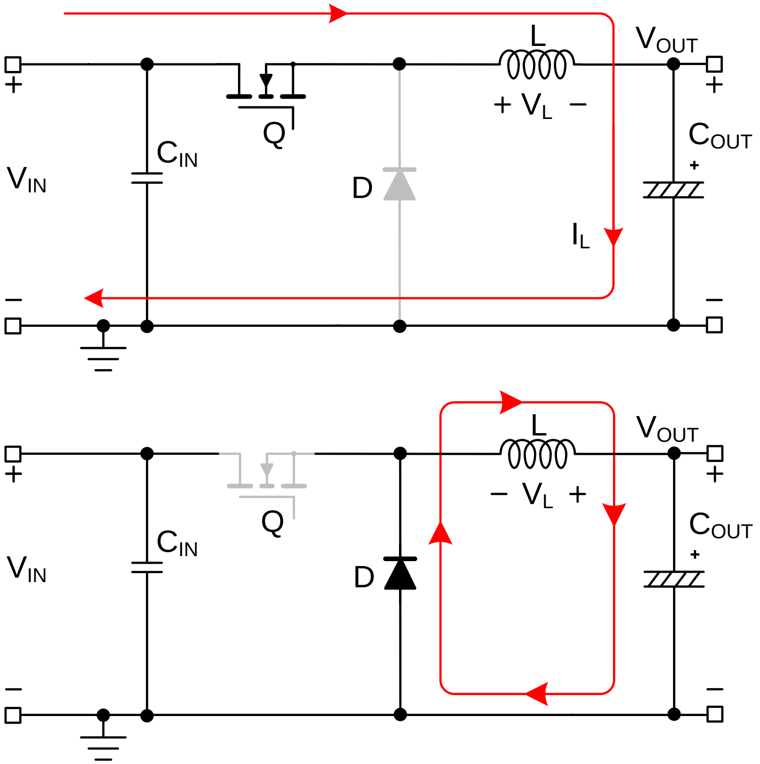


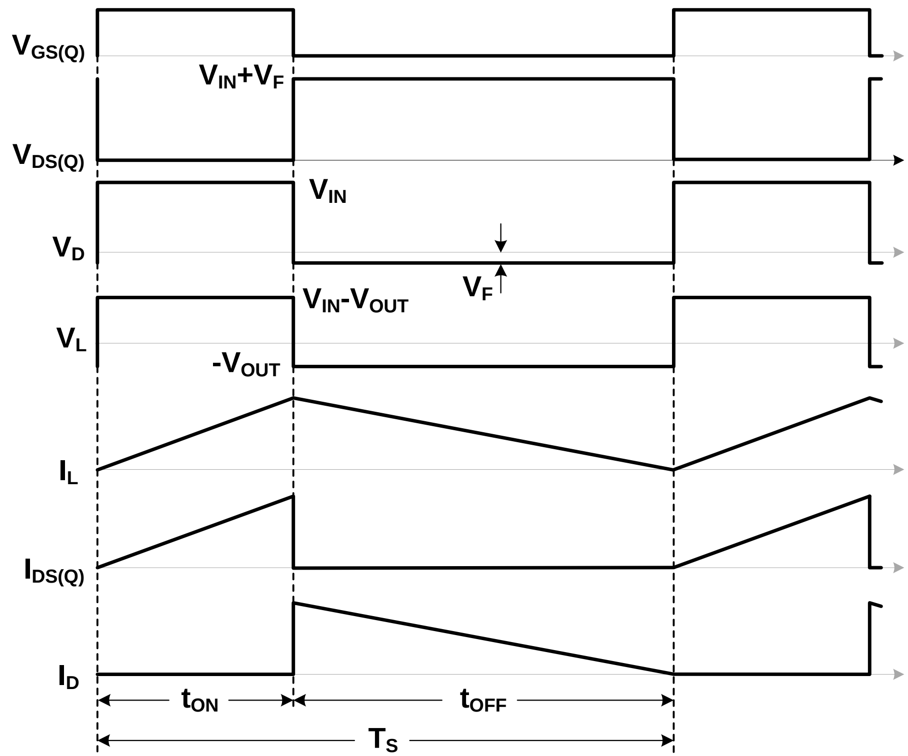
CCM
(Fixed Freq)

BCM
(Variable Freq)

DCM
(Fixed Freq)

Buck Converter (Step Down)





Inductor volt-second balance:

$$\langle V_L \rangle_{T_S} = [(V_{IN} - V_{OUT}) \times t_{ON}] - V_{OUT} \times t_{OFF} = 0$$

$$V_{IN} \times t_{ON} = V_{OUT} \times (t_{ON} + t_{OFF})$$

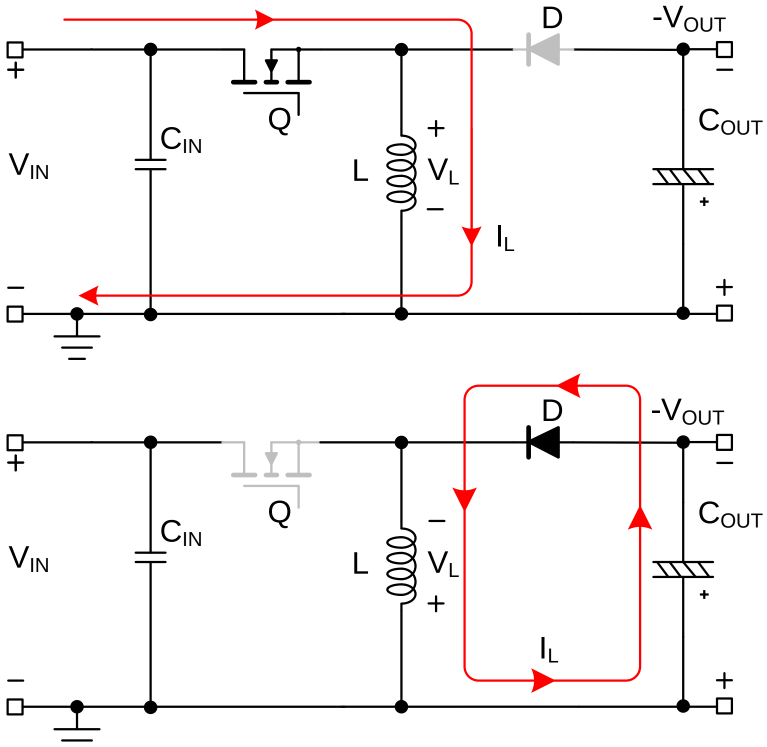
$$V_{IN} \times t_{ON} = V_{OUT} \times T_S$$

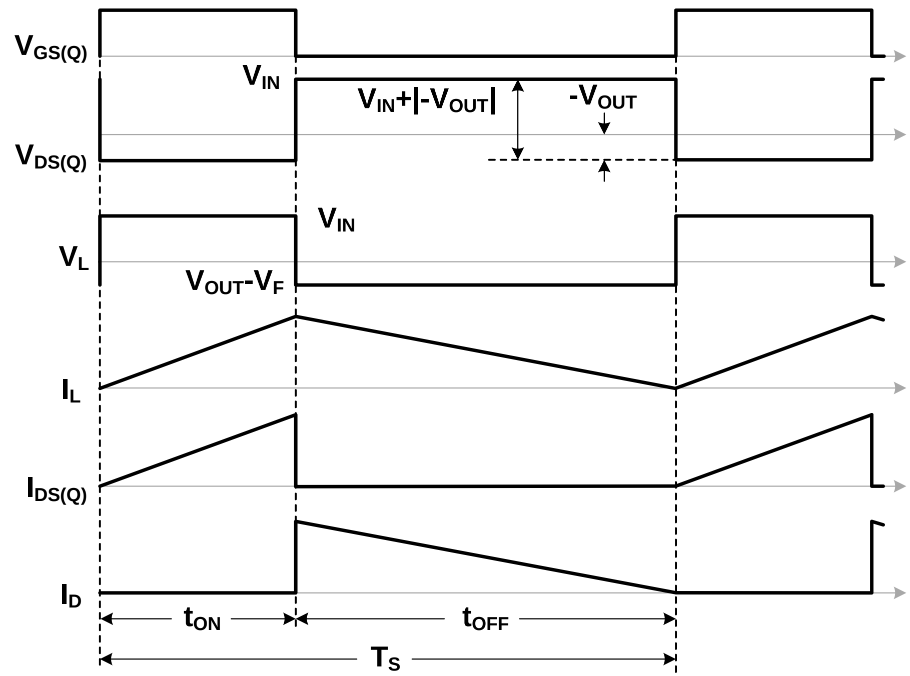
Buck CCM transfer function:

$$\frac{V_{OUT}}{V_{IN}} = \frac{t_{ON}}{T_S} = D$$

- $V_{IN} > V_{OUT}$
- Most efficient at higher D

Buck-Boost Converter (Inverting)





Inductor volt-second balance:

$$\langle V_L \rangle_{T_S} = V_{IN} \times t_{ON} + V_{OUT} \times t_{OFF} = 0$$

$$V_{IN} \times t_{ON} = -(V_{OUT} \times t_{OFF})$$

$$\frac{V_{OUT}}{V_{IN}} = -\left(\frac{t_{ON}/T_S}{t_{OFF}/T_S}\right) = -\left[\frac{t_{ON}/T_S}{(T_S - t_{ON})/T_S}\right]$$

Buck-Boost CCM transfer function:

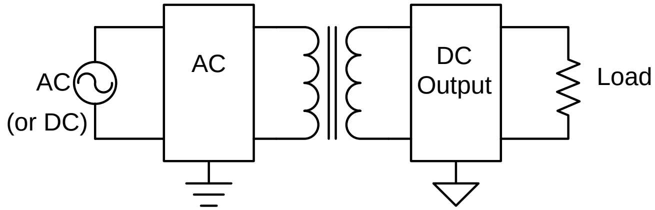
$$\frac{V_{OUT}}{V_{IN}} = -\left(\frac{D}{1-D}\right)$$

- $V_{IN} < V_{OUT}$ or $V_{IN} > V_{OUT}$
- Used for negative V_{OUT}

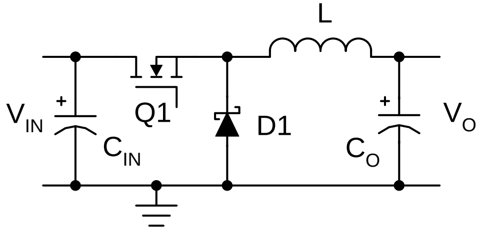
Single Ended Converter Topologies

Benefits of a Transformer

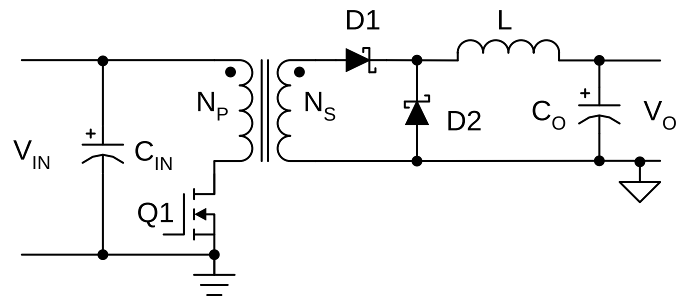
1. Provides primary to secondary safety isolation – subject to regulatory standards



2. Voltage conversion resolution



$$\frac{V_O}{V_{IN}} = D$$



$$\frac{V_O}{V_{IN}} = \frac{N_S}{N_P} D$$

Ex: For F_{SW}=300kHz (T_{SW}=3.33µs), N_P:N_S=4:1, 36V<V_{IN}<75 and V_O=5V

Buck Converter

6% < D < 14%
200 ns < t_{ON} < 467 ns

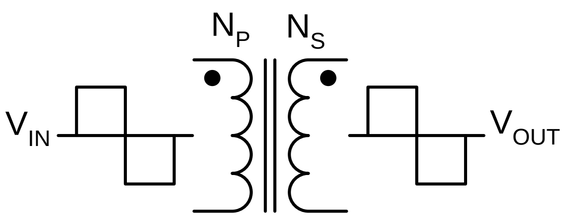
Isolated Buck (Forward) Converter

27% < D < 55%
900 ns < t_{ON} < 1.8 µs

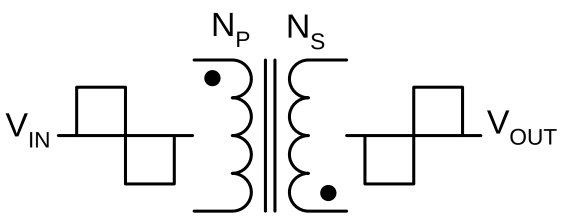
3. Potential ground differences between primary and secondary

4. Multiple outputs can be regulated/quasi-regulated

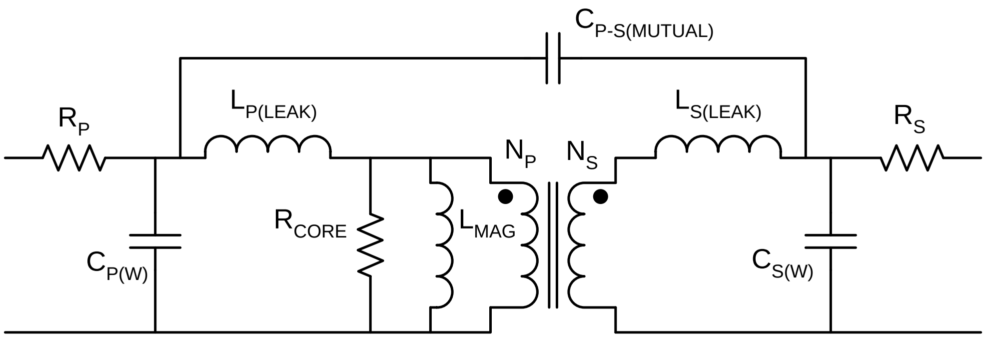
Transformer Characteristics



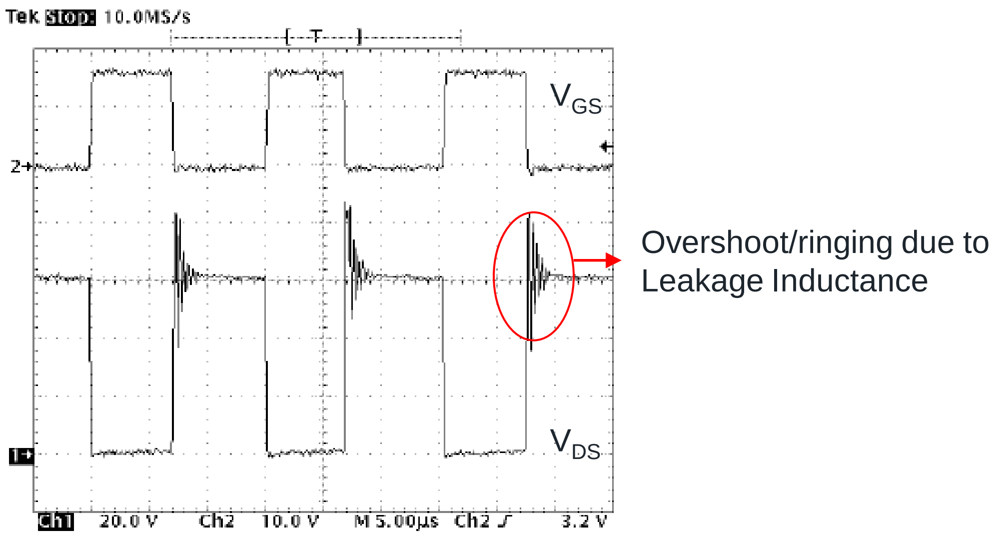
- Ideal transformer
  - Perfect coupling between N_p:N_s
  - No energy storage



- Flyback “transformer”
  - Really a coupled inductor
  - Primary energy stored during t_{ON}
  - Power transferred during t_{OFF}



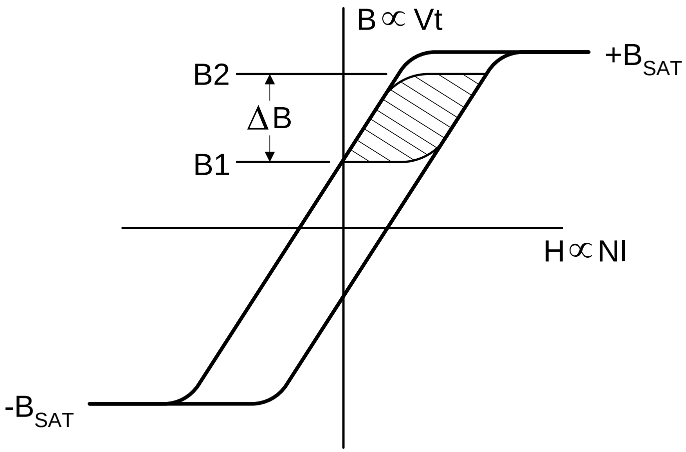
Parasitic Transformer Model



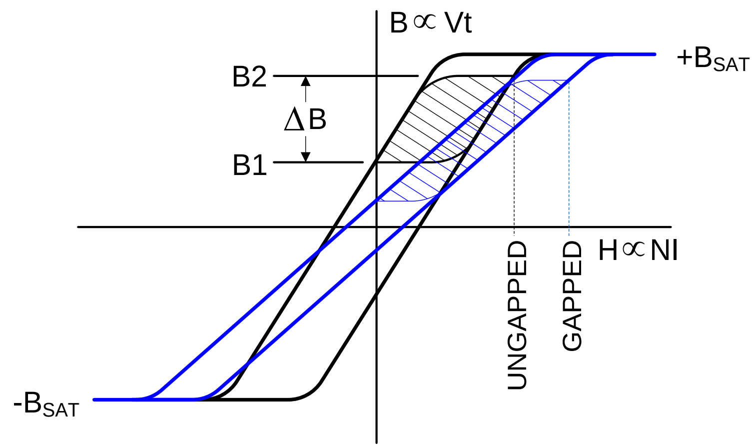
CCM Flyback (V_{DS} = 32 V, V_{LK} = 12 V)

Single Ended Topologies Defined

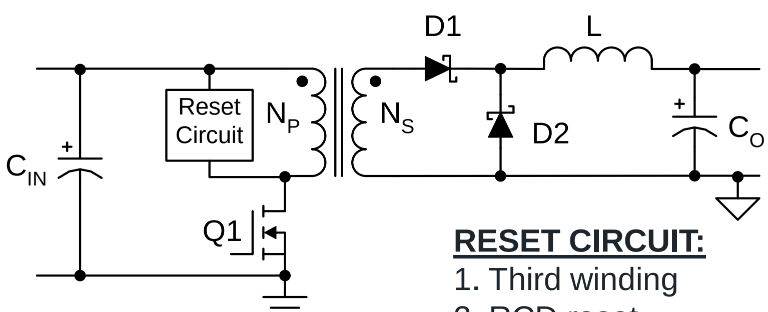
Single Ended – Transformer operation limited to first quadrant



(a) Forward Converter Transformer Hysteresis



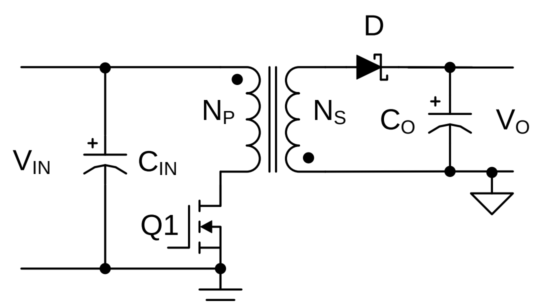
(c) Gapped Flyback "Transformer"



(b) Forward Converter

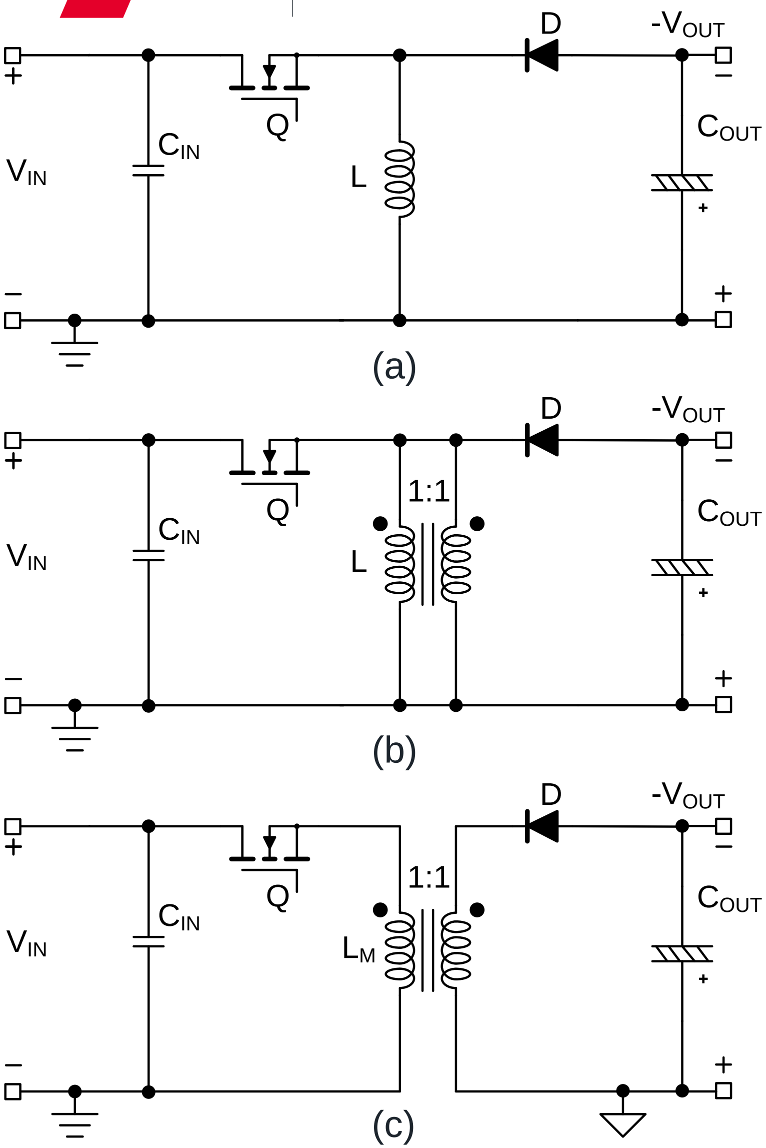
<u>RESET CIRCUIT:</u>

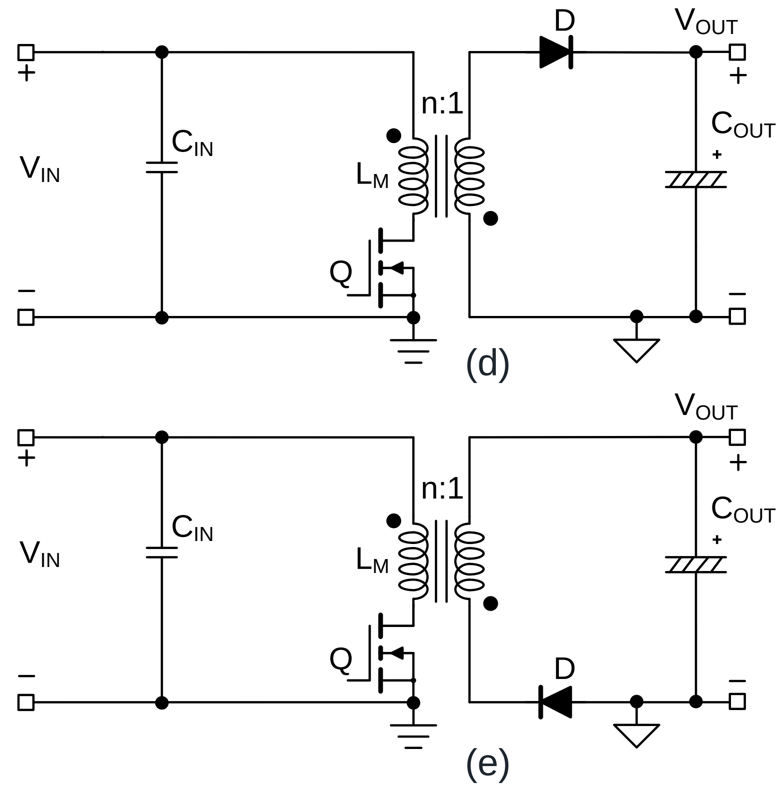
1. Third winding
2. RCD reset
3. Resonant reset
4. Active clamp reset



(b) Flyback Converter

Flyback Converter Derivation

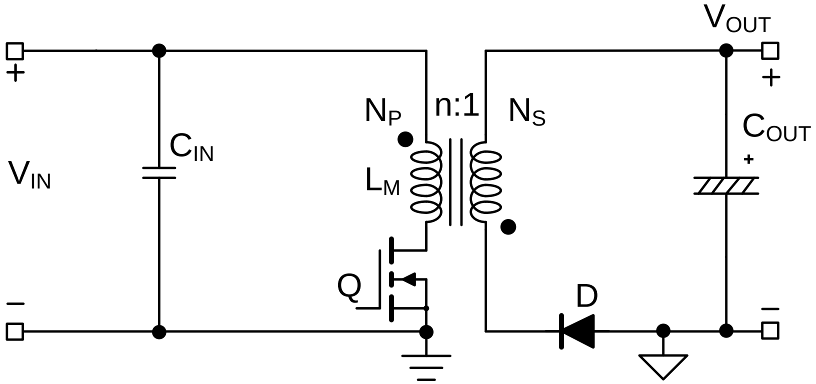




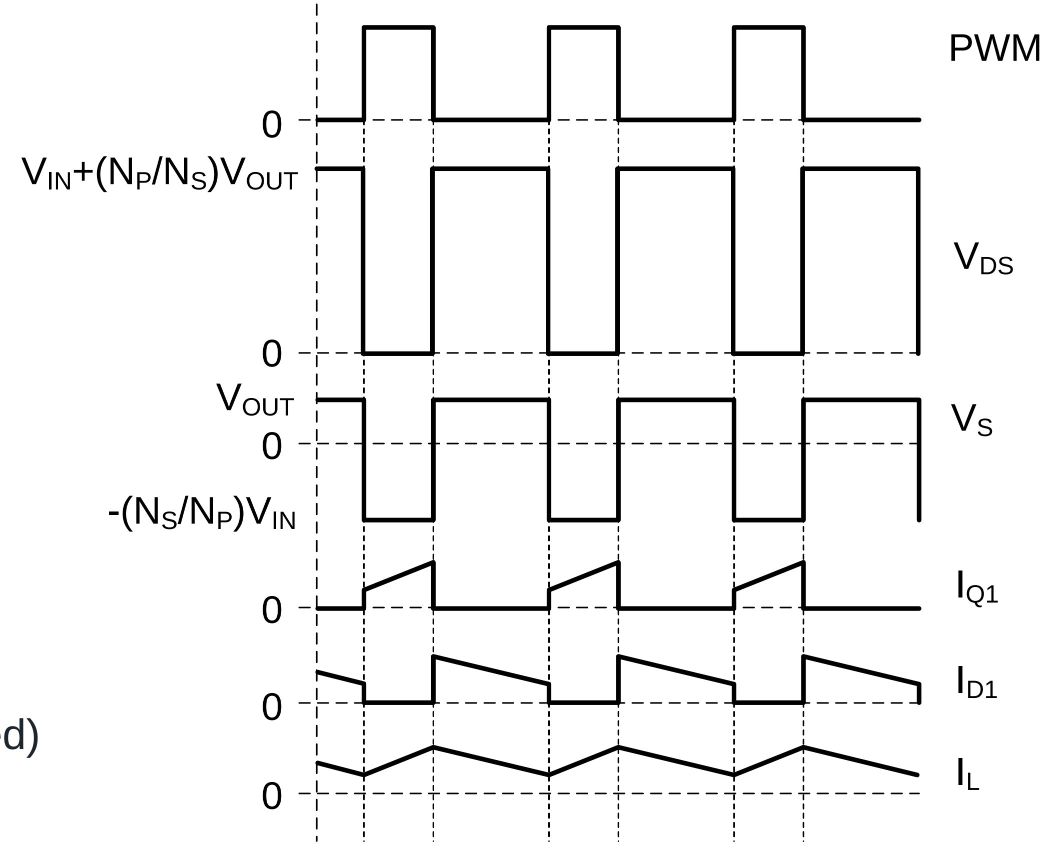
a) Non-isolated buck-boost
b) Coupled inductor buck-boost
c) Isolated buck-boost
d) Isolated flyback converter
e) D can be in return path

Flyback Converter

CCM Operation



(a) Flyback Converter



(b) CCM Waveforms

- CCM Transfer Function

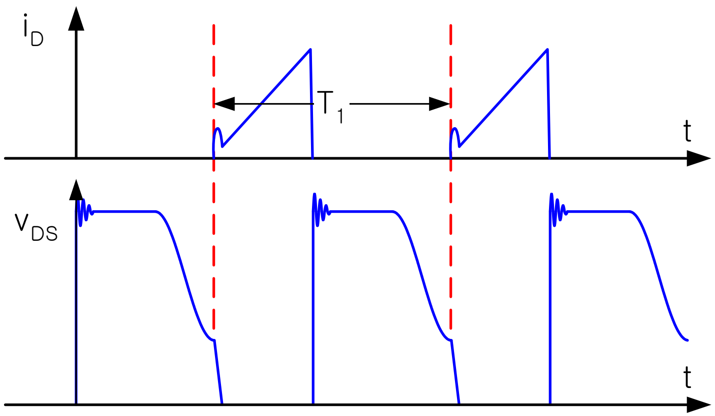
$$\frac{V_O}{V_{IN}} = \frac{N_S}{N_P} \times \frac{D}{1-D}$$

- Limitations
  - Q1 switching loss (hard switched)
  - D2 conduction loss
  - Q1(V_{DS}) > V_{IN}
  - 50% duty cycle limit
  - Right half plane zero in CCM
  - Output rectifier reverse recovery

Quasi-Resonant Flyback

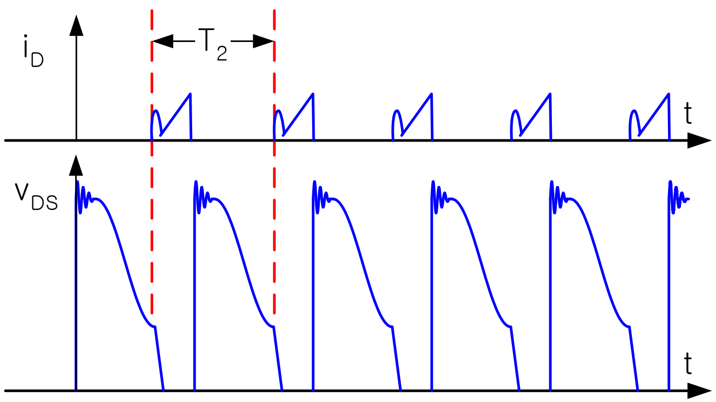
Conventional Valley Switching

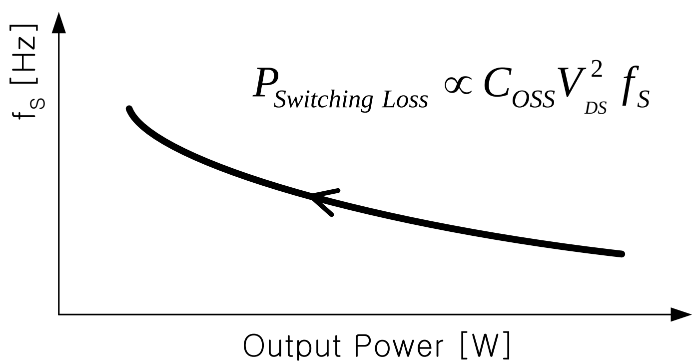
Wide frequency variation depends on output load condition



Output load decreases

Operating frequency increases



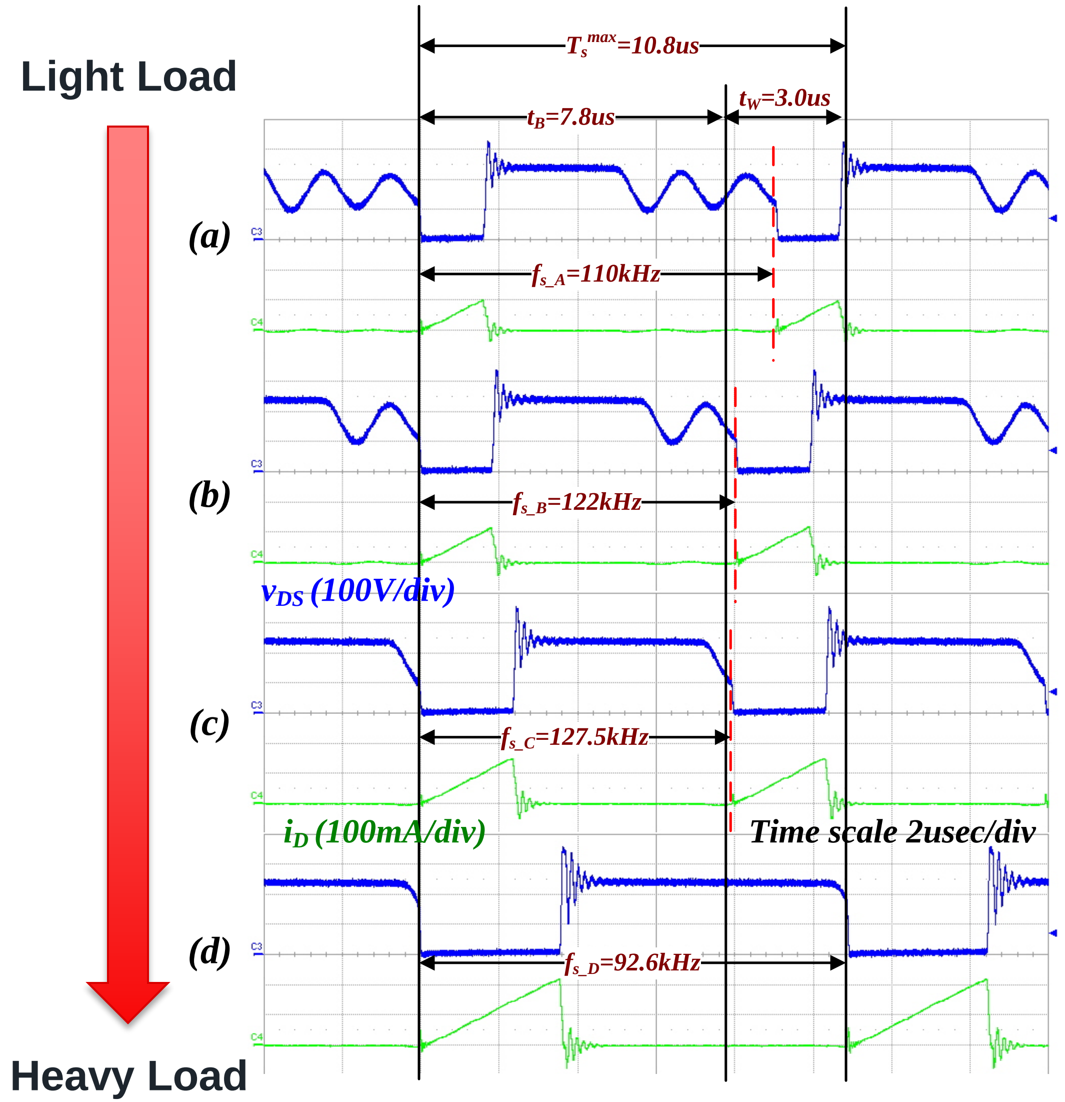


$$P_{Switching\ Loss} \propto C_{OSS} V_{DS}^2 f_S$$

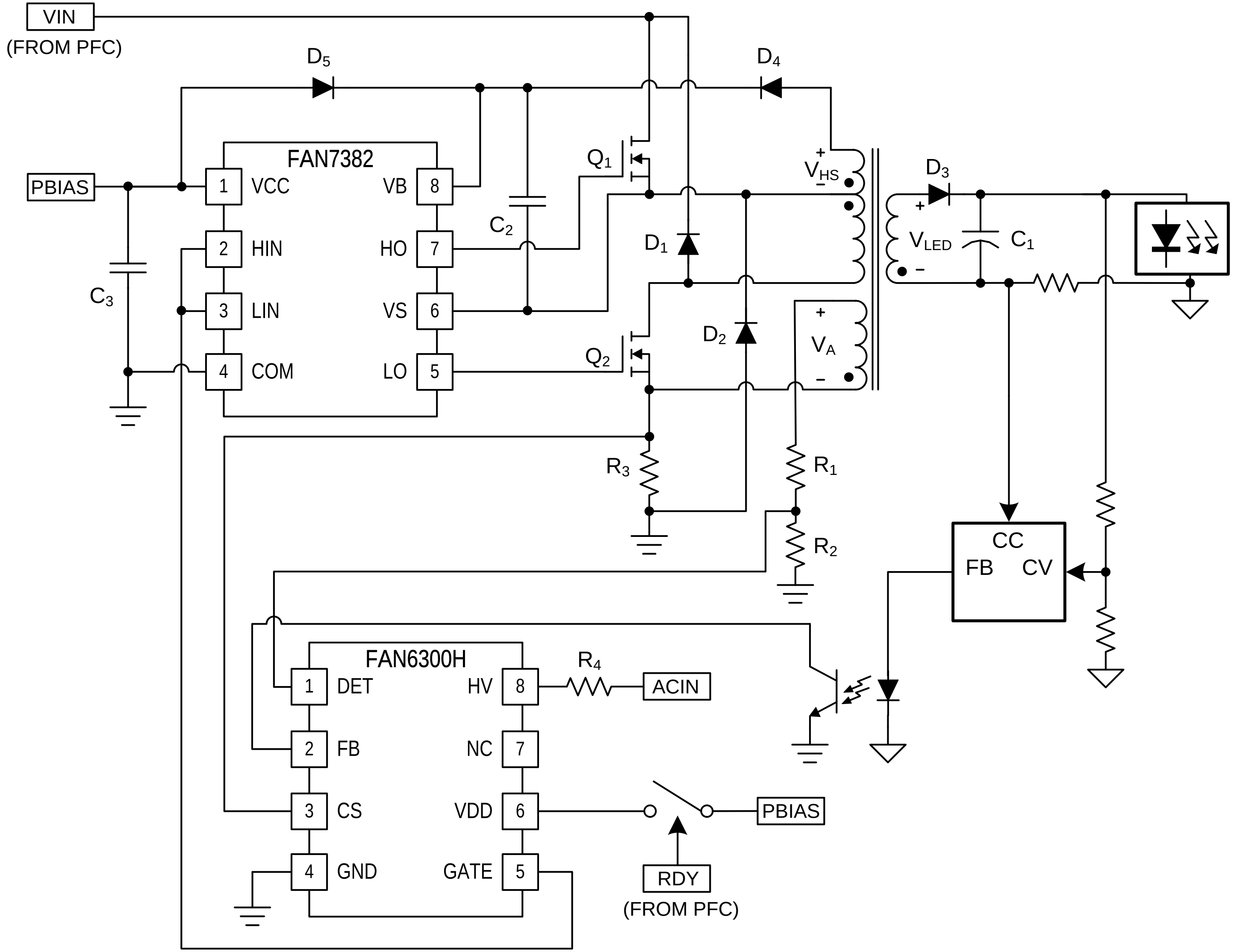
Quasi-Resonant Flyback

Window Valley Switching

- Frequency variation depends on output load conditions
- Operating frequency is within narrow variation (127.5 kHz ~ 92.6 kHz)

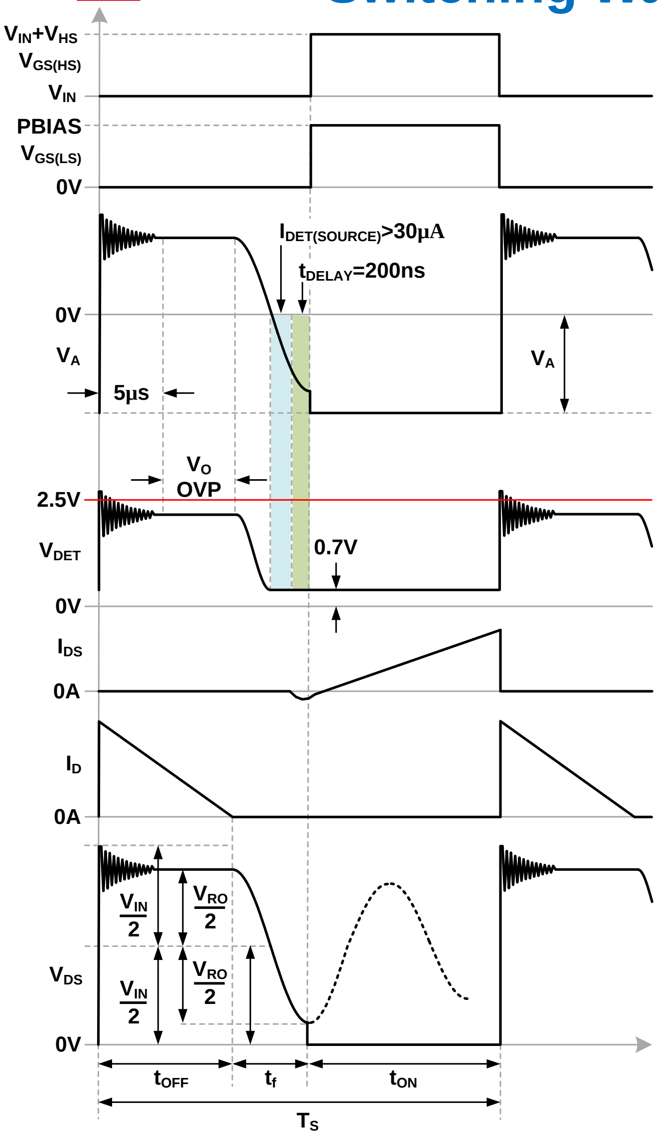


Two-Switch, Quasi-Resonant Flyback



Two-Switch Quasi-Resonant Flyback

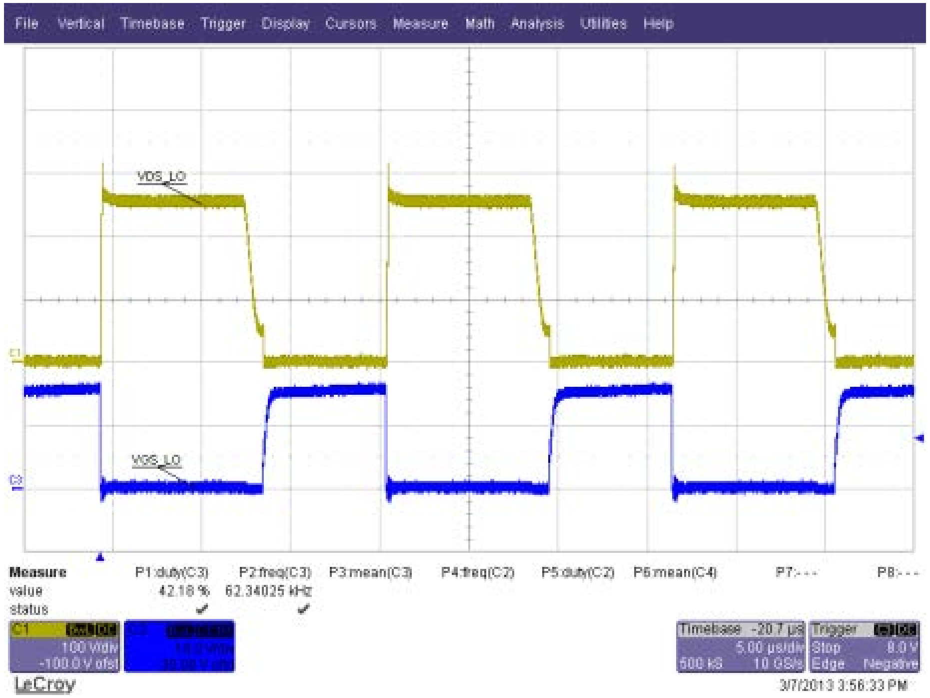
Switching Waveforms

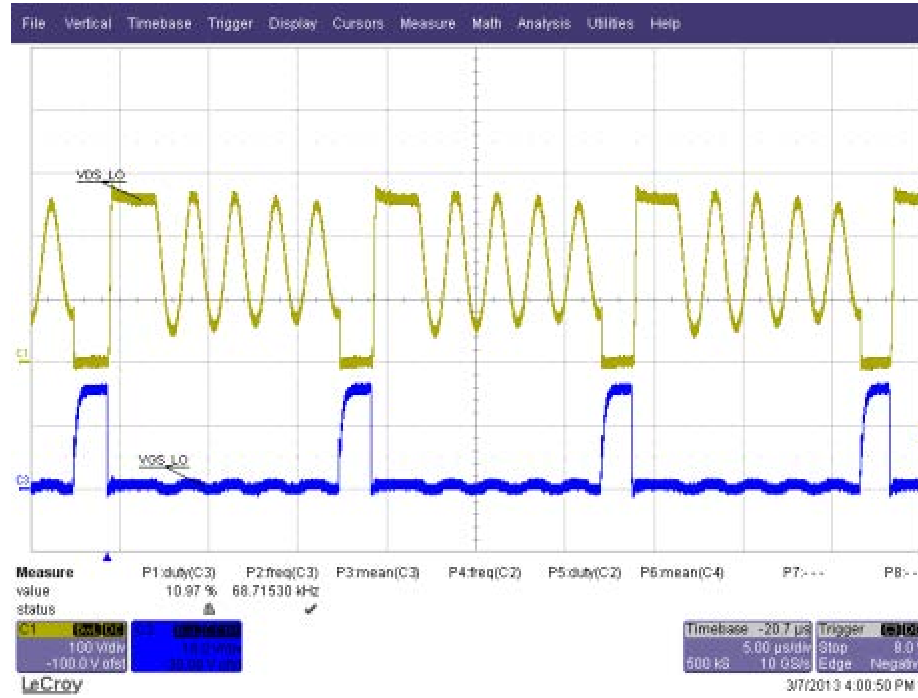


- Quasi-resonant, variable frequency
- HS and LS MOSFETs switch synchronously
- Switching period, $T_S = t_{OFF} + t_f + t_{ON}$
- Inductor current switches from 0 A (ZCS) every switching cycle
- VDS
  - ZVS → $V_{OUT} > 2 \times V_{IN}$
  - Valley switch → otherwise
  - Window valley switching

Two-Switch Quasi-Resonant Flyback

Measured Waveforms

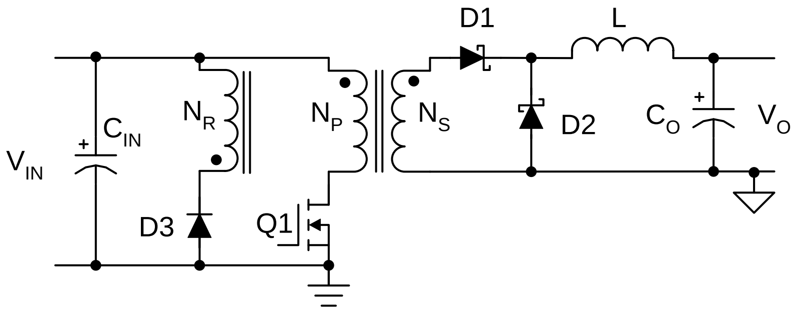




- V_{DS} Valley Switching on First Valley
  - $V_{OUT} < ½ V_{IN}$
  - D = 42%
  - F_S = 63 kHz
  - P_{OUT} = 85 W

- Extended Window Valley Switching
  - $V_{OUT} < ½ V_{IN}$
  - D = 11%
  - F_S = 68 kHz
  - P_{OUT} = 24 W

Forward Converter Basics

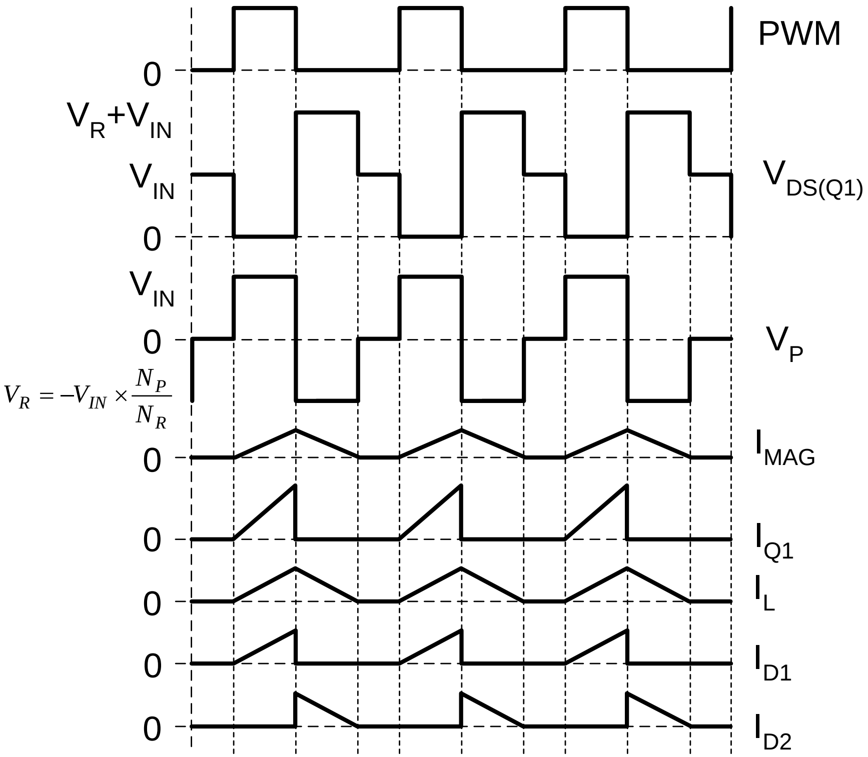


(a) Forward Converter with Reset Winding

- Really a Transformer Coupled Buck
- CCM Transfer Function

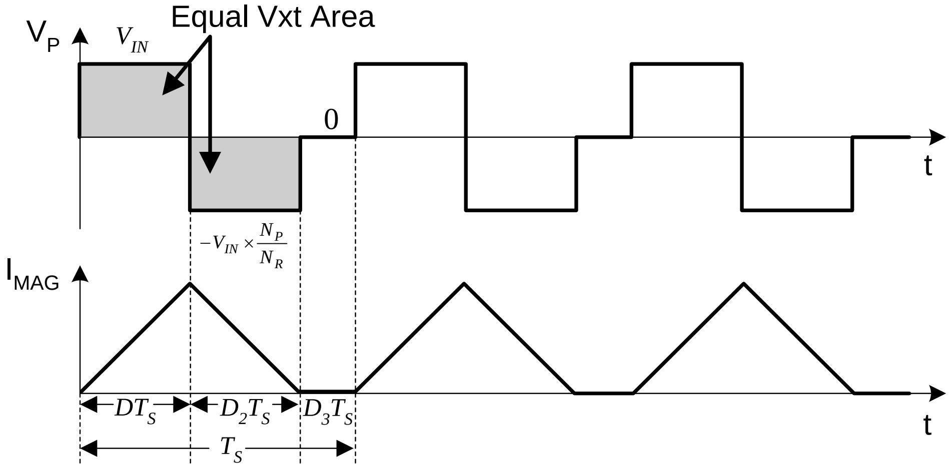
$$\frac{V_O}{V_{IN}} = \frac{N_S}{N_P} \times D$$

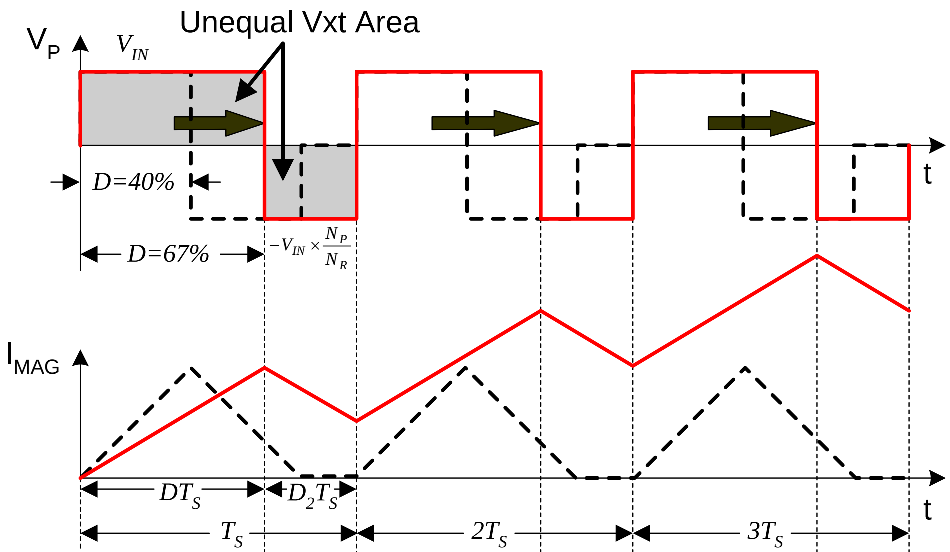
- Limitations
  - Q1 switching loss (hard switched)
  - D2 conduction loss
  - Q1(V_{DS}) > 2 V_{IN}
  - 50% duty cycle limit (N_P:N_R = 1:1)



(b) DCM Waveforms (D<0.5)

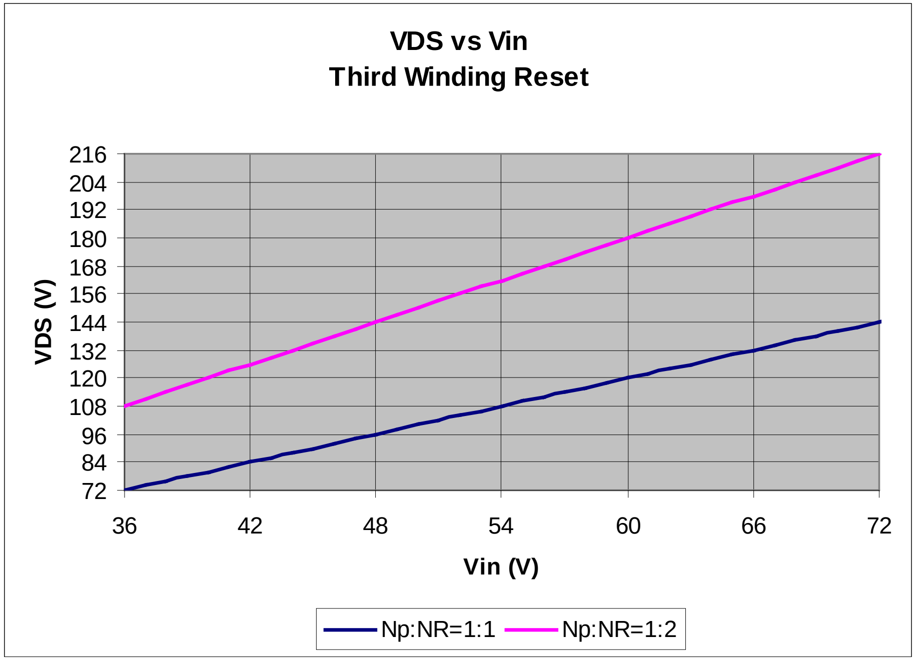
Problems with Duty Cycle > 50%



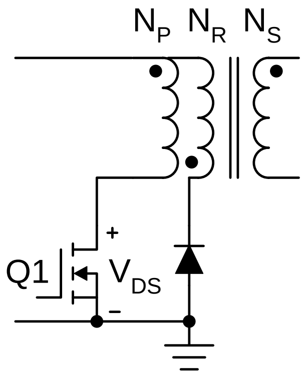


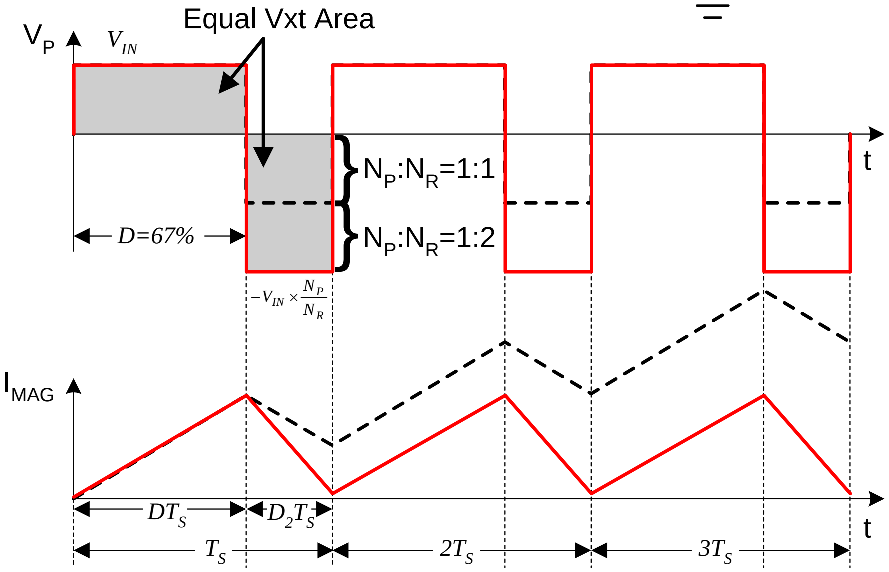
- Common practice is to use 1:1 bifilar transformer winding for N_P:N_R
- D = 40%
  - Converter operates in DCM
  - Transformer is completely reset on every switching cycle
- D = 67%
  - Converter wants to operate in CCM
  - Transformer can NOT reset on every switching cycle
  - I_{MAG} increases due to volt second product imbalance
  - Transformer saturation will result
  - Operation beyond D = 50% requires additional reset voltage

Duty Cycle Greater Than 50%



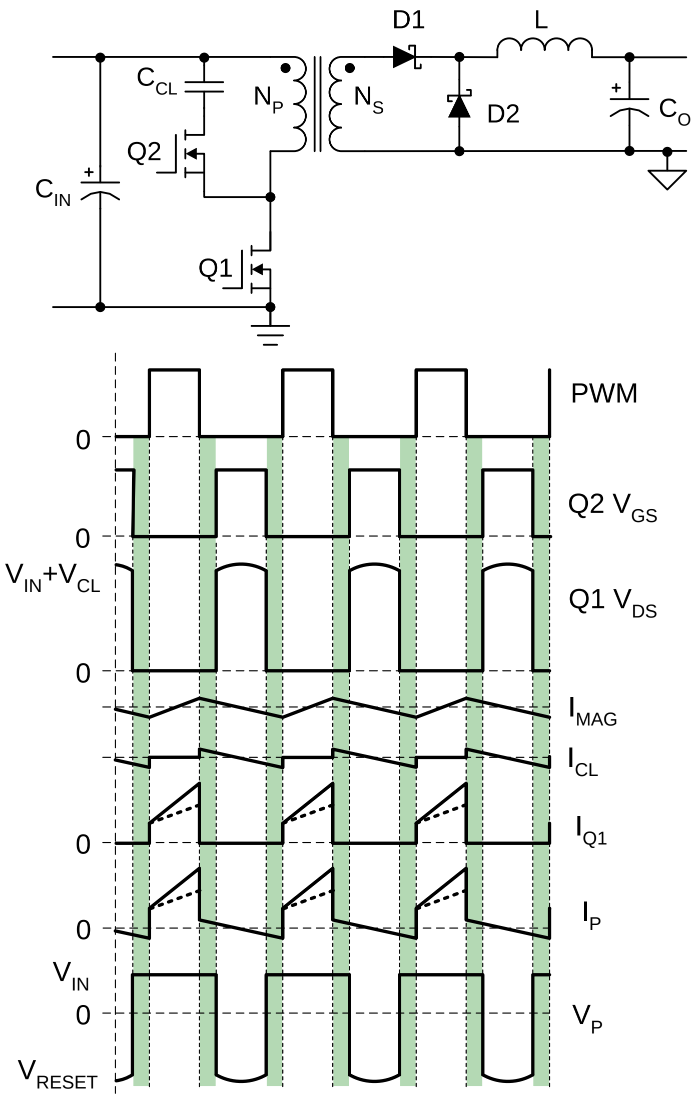
- For $N_P:N_R = 1:2$
  - **$V_{DS}=3V_{IN}$**





Conclusion: Reset winding technique, D > 50% not practical for high V_{IN} applications due to additional MOSFET V_{DS} stress

Active Clamp Forward Converter

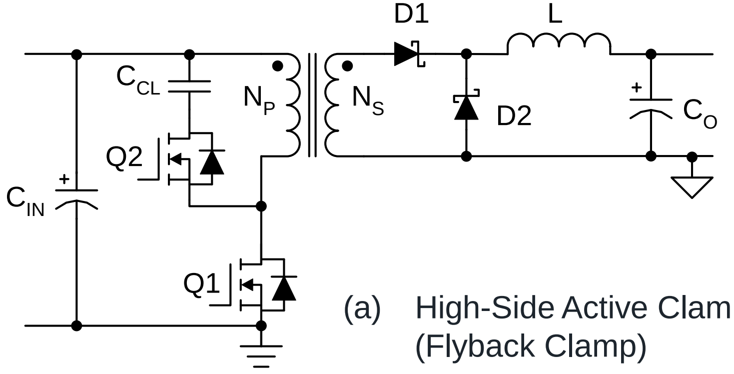


- Advantages
  - Reduced MOSFET V_{DS} voltage stress
  - Higher efficiency through ZVS
  - Use of parasitic elements
  - Higher frequency operation
  - Suitable for off-line (HS clamp) or DC-DC (LS clamp)
- Disadvantages
  - Conditional ZVS only
  - Dual primary side gate drive with accurate dead-time control and max duty cycle clamp required
  - Poor transient response due to C_{CL}
- Transfer Function

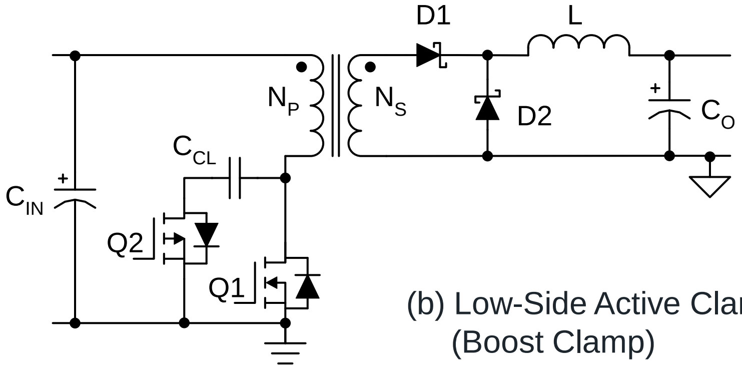
$$\frac{V_O}{V_{IN}} = \frac{N_S}{N_P} \times D$$

Active Clamp Forward Converter

Two Versions



(a) High-Side Active Clamp (Flyback Clamp)

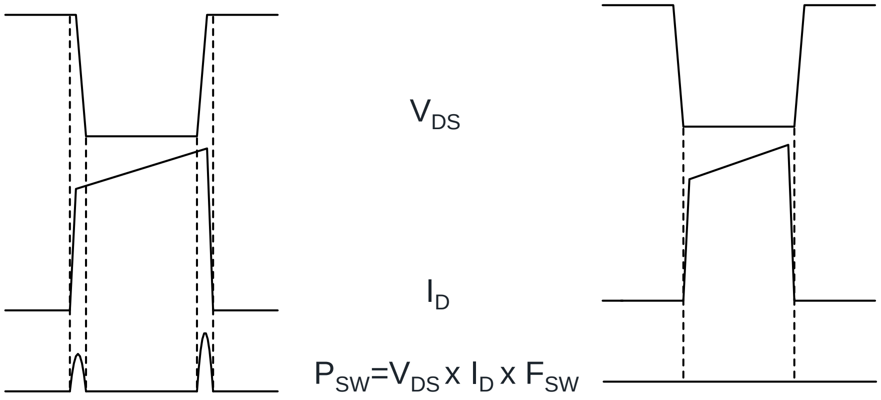


(b) Low-Side Active Clamp (Boost Clamp)

PARAMETER	HIGH-SIDE ACTIVE CLAMP (off-line)	LOW-SIDE ACTIVE CLAMP (telecom)
V_{DS}	$\left(\frac{1}{1-D}\right)\times V_{IN}$	$\left(\frac{1}{1-D}\right)\times V_{IN}$
V_{RESET}	$\left(\frac{D}{1-D}\right)\times V_{IN}$	$\left(\frac{D}{1-D}\right)\times V_{IN}$
V_{CL}	$\left(\frac{D}{1-D}\right)\times V_{IN}$	$\left(\frac{1}{1-D}\right)\times V_{IN}$
C_{CL} (applied voltage)	Lower voltage by V_{IN} volts Highest V_{CL} occurs at D_{MAX}	Higher voltage by V_{IN} volts Not practical for off-line
C_{CL} (cap value)	Same value as low-side for given ripple voltage	Same value as high-side for given ripple voltage
Clamp MOSFET (Q2)	N-Channel Can be used for > 500 V	P-Channel Can be used up to 500 V
Gate Drive	Gate drive transformer required	Level shifting gate drive required

Active Clamp Forward Converter
Zero Voltage Switching (ZVS)

- ZVS occurs when the voltage across the MOSFET, V_{DS}, is positioned to "zero volts" prior to the start of the next switching cycle.
- Benefits of ZVS
  - Reduced switching losses
  - Higher operating frequency possible (smaller passive component size)
  - Higher converter efficiency
  - Increased reliability
  - Reduced radiated emissions (EMI)

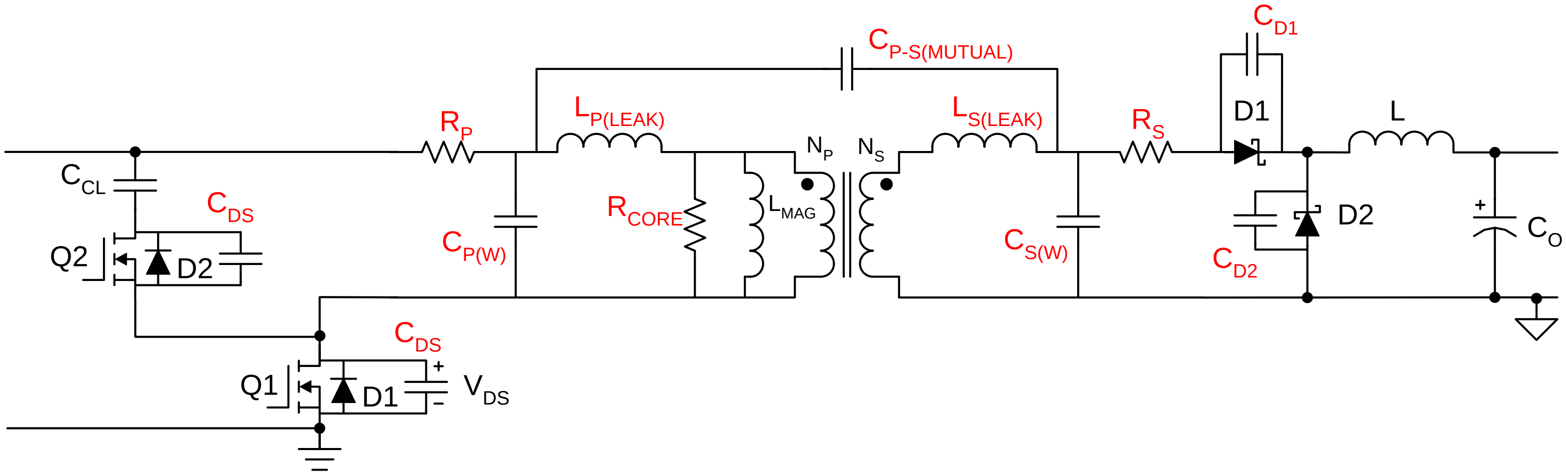


(a) Hard Switching

(b) "Ideal" ZVS

Active Clamp Forward Converter
Zero Voltage Switching (ZVS)

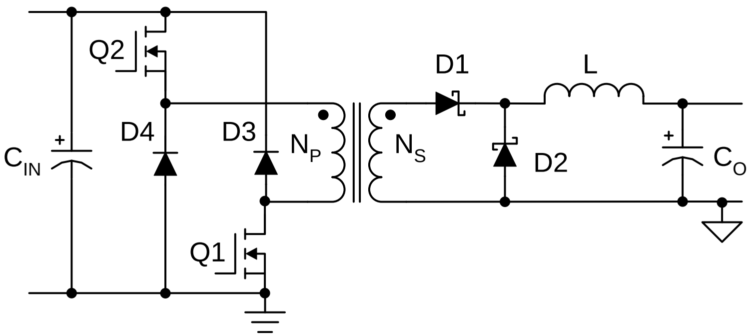
- Parasitic elements can be used to benefit ZVS

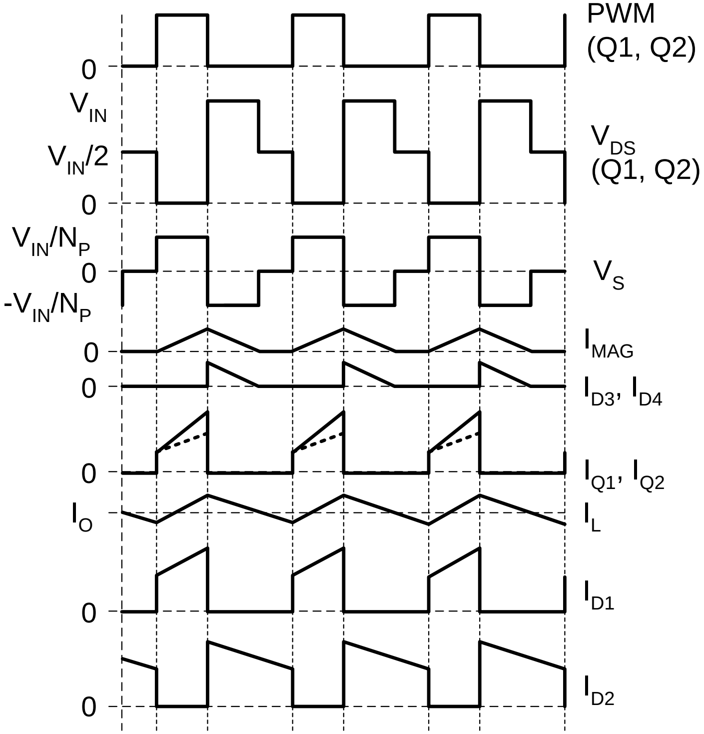


- Active Clamp Forward converter uses fixed frequency resonant transitions to achieve ZVS when specific operating conditions are met

Single Ended (<500W)

2 Switch Forward Converter





- Advantages
  - Ruggedness
  - MOSFET voltage stress limited to V_{IN}
  - Magnetizing energy recycled by D3, D4
  - Universal input, 150 W < P < 500 W
- Disadvantages
  - Limited to less than 50% duty cycle
  - High side gate drive required for Q2
  - Hard switching
- Transfer Function

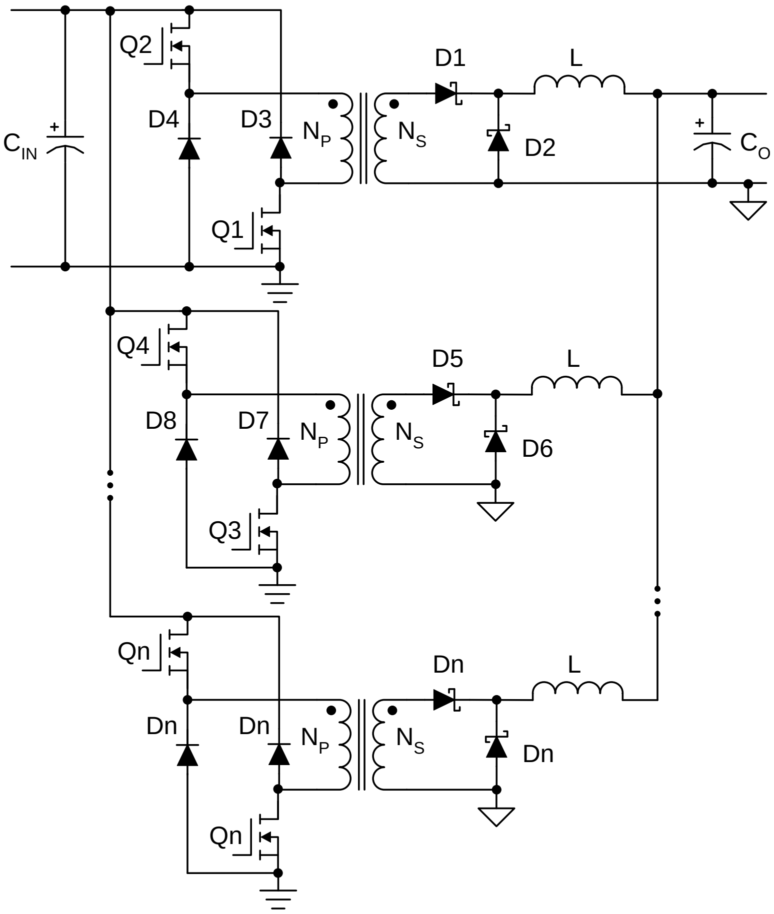
$$\frac{V_O}{V_{IN}} = \frac{N_S}{N_P} \times D$$

Single Ended (>1kW)

Interleaved 2 Switch Forward Converter

- Advantages
  - Can operate multiple power stages out of phase
  - Ripple current cancellation at output capacitor
  - Reduced RMS current at input capacitor
  - Multiple stages can add up to kW of power
  - Smaller output inductors can improve transient response

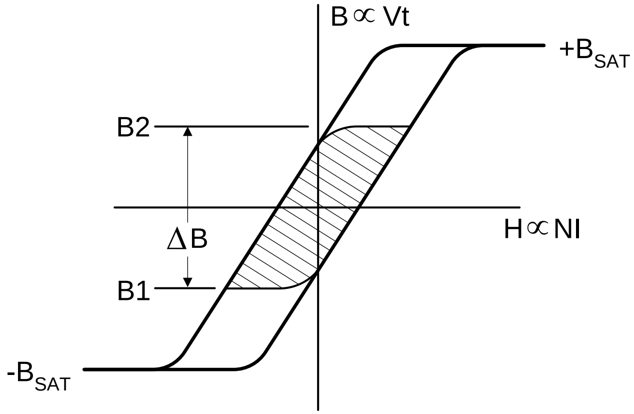
- Disadvantages
  - Design complexity
  - PCB layout can be challenging

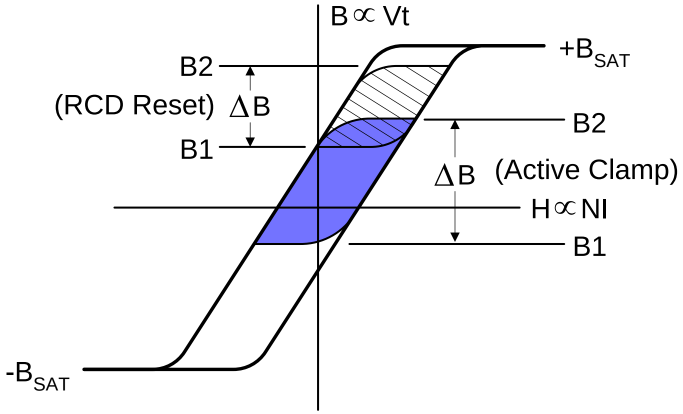


Double Ended Converter Topologies

Double Ended Topologies Defined

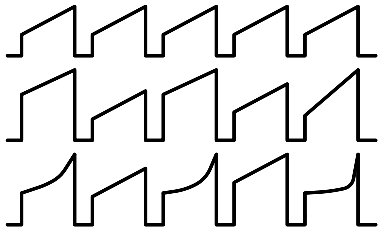
Double Ended – Transformer operation occurs in first and third quadrants





Half-Bridge, Full-Bridge

- Symmetrical operation between first and third quadrants
- No transformer reset circuitry required

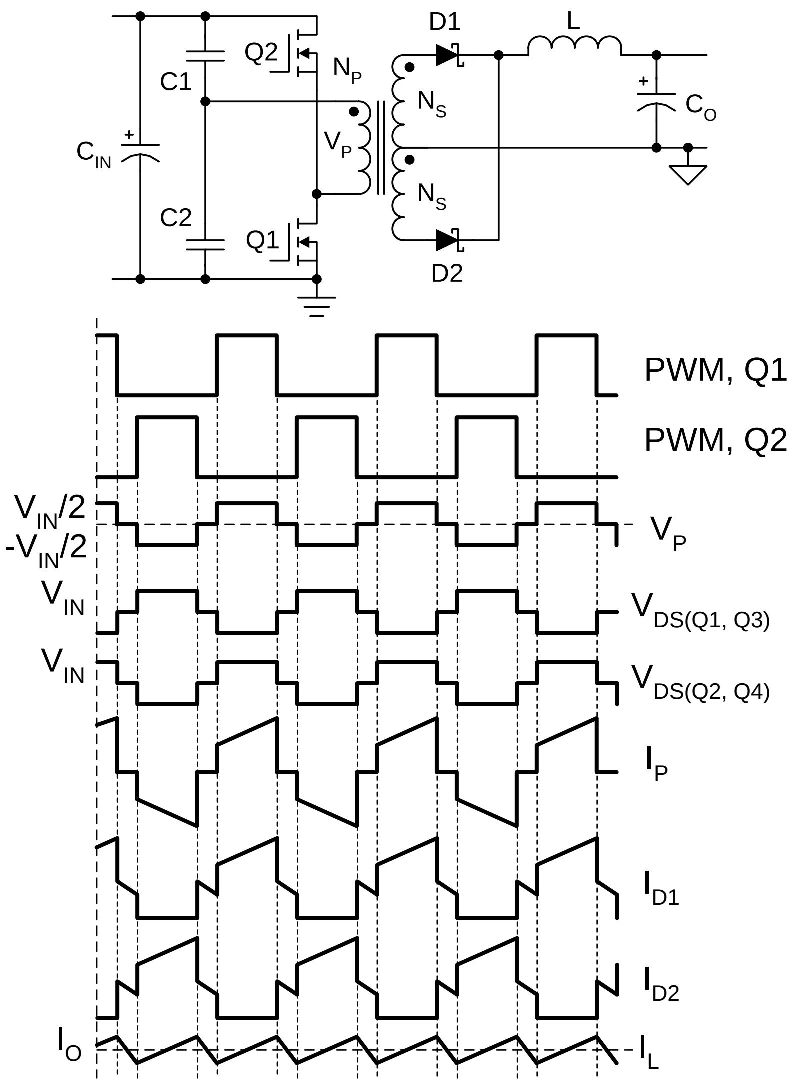


Active Clamp Forward

- "Single ended" *but* operates slightly into the third quadrant

Double Ended (<500 W)

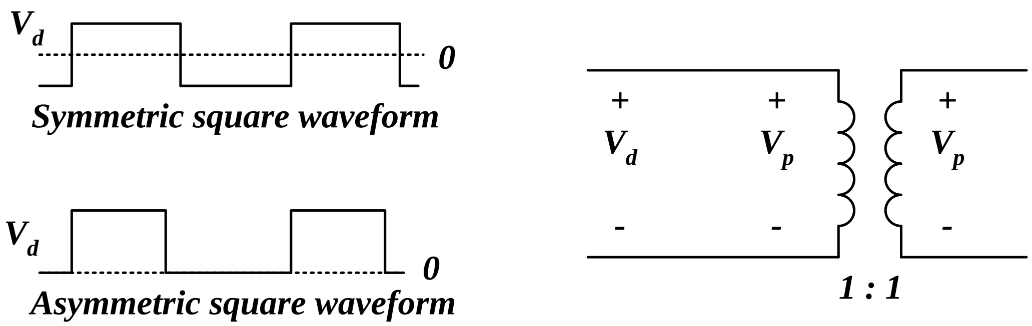
Half Bridge Converter (Symmetrical)



- Advantages
  - Better transformer utilization
  - MOSFET voltage stress limited to V_{IN}
  - Best for high V_{IN} off line applications up to 500W
  - Single winding primary
  - Transformer balanced by C1 and C2
  - Asymmetric and resonant versions can ZVS
- Disadvantages
  - Totem pole primary gate drive
  - High primary current
  - Possible cross conduction between Q1 and Q2
  - Hard switching
- Transfer Function

$$\frac{V_O}{V_{IN}} = 2 \times \frac{N_S}{N_P} \times D$$

Asymmetrical Half Bridge Converter

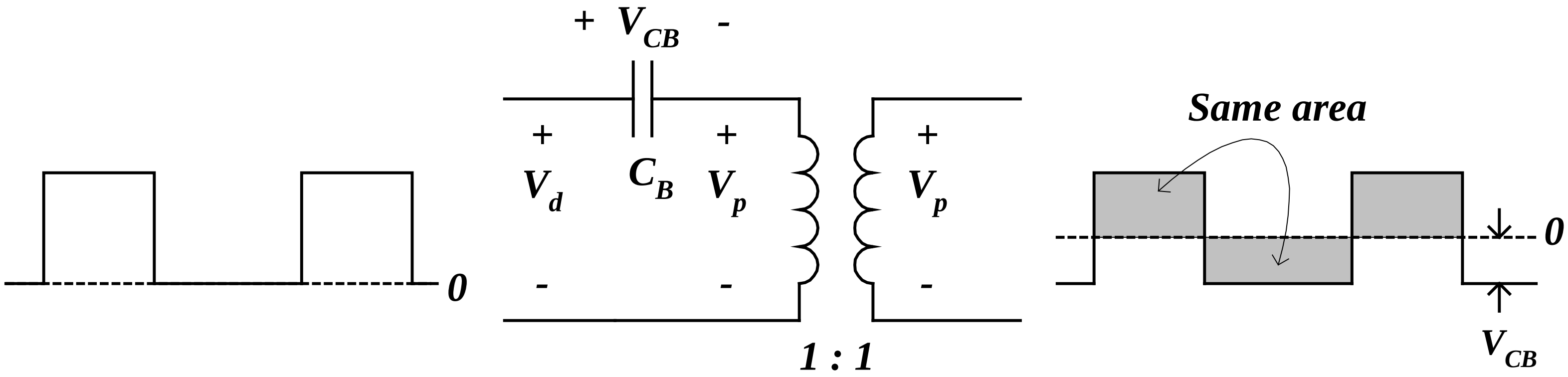


What if an asymmetric square wave is introduced to the transformer?

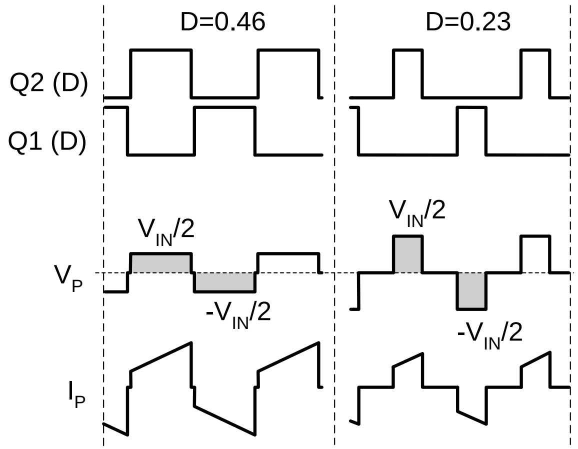
→ Transformer will be saturated

What if an asymmetric square wave is introduced to the transformer in series with a DC blocking capacitor?

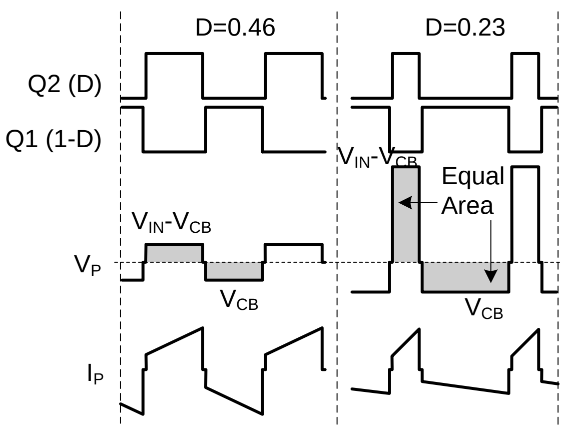
→ Not saturated due to the voltage of the blocking capacitor, C_B



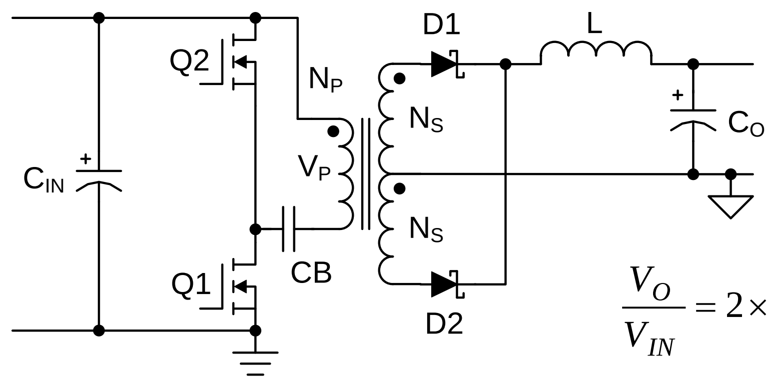
Asymmetrical Half Bridge Converter



(a) Symmetrical HB waveforms



(b) Asymmetrical HB waveforms



$$\frac{V_O}{V_{IN}} = 2 \times \frac{N_S}{N_P} \times D \times (1 - D)$$

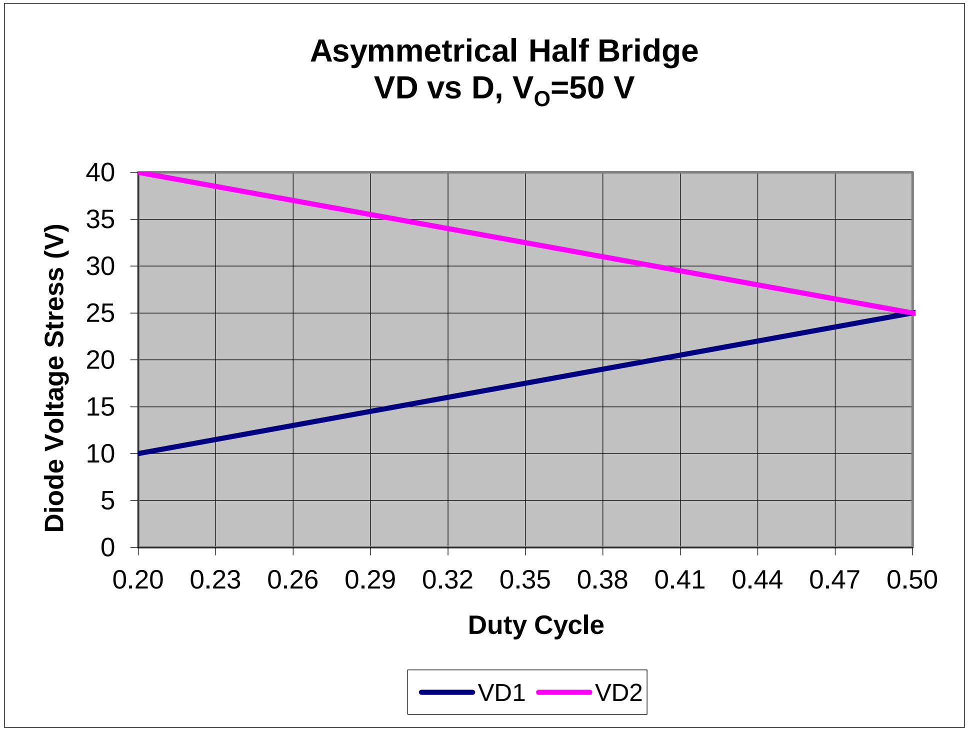
- Asymmetrical Gate Drive
  - Q2 modulated by D
  - Q1 driven by 1-D
  - Fixed dead time between Q1 and Q2
  - Dead time optimized for ZVS and anti cross conduction
  - Fixed frequency ZVS PWM operation
  - Near D=0.5, operation is same as symmetrical HB
- BUT, excessive voltage stress is applied to secondary rectifier at $V_{IN(MAX)}$

Asymmetrical Half Bridge Converter

- Secondary rectifier voltage stress:

$$V_{D1} = D \times V_O \qquad V_{D2} = V_O \times (1 - D)$$

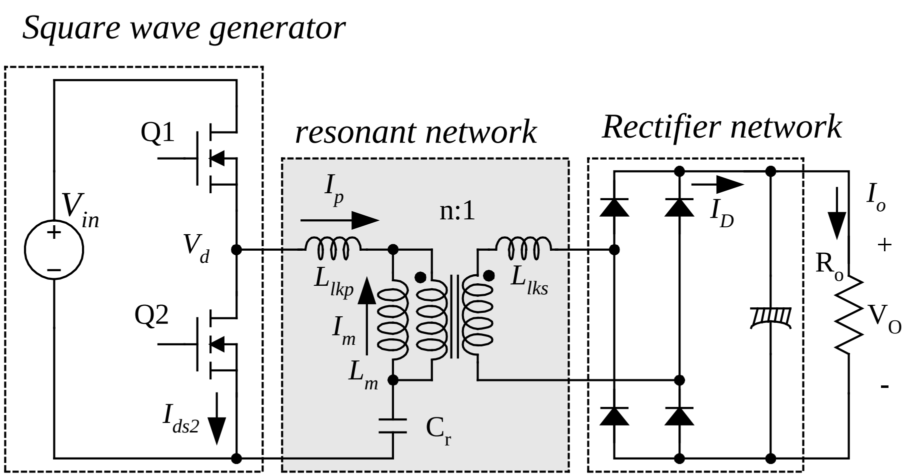
- Reverse recovery and parasitic ringing
- Wide ΔD range requires use of high voltage rectifiers
- Converter operates best near D = 0.5

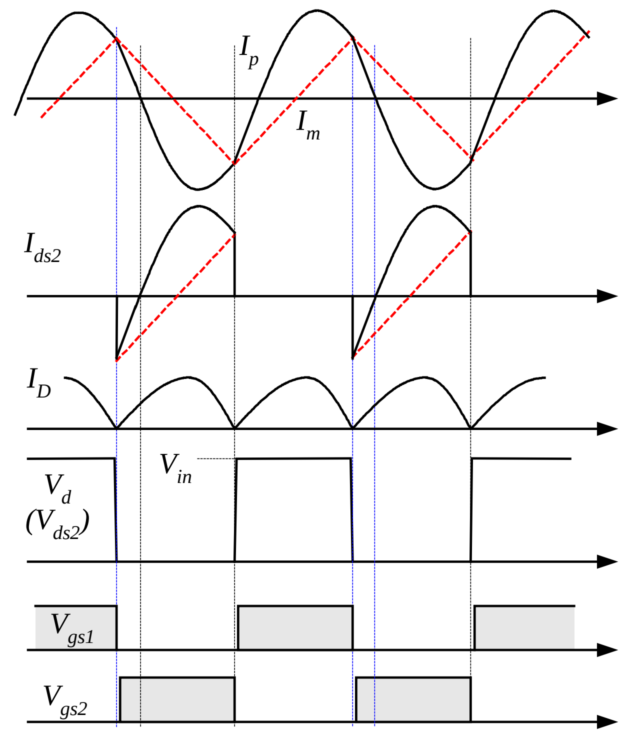


- Advantages
  - Fixed frequency ZVS
  - Constant power transfer (D and 1-D) reduces output ripple
  - Power stage can be controlled using any active clamp PWM controller
- Disadvantages
  - High voltage stress on secondary rectifier
  - Poor transient response due to blocking capacitor, C_B

LLC Resonant Half Bridge Converter

- Square wave generator: produces a square wave voltage, V_d by driving switches, Q1 and Q2 with alternating 50% duty cycle for each switch.
- Resonant network: consists of L_{lkp}, L_{lks}, L_m and C_r. The current lags the voltage (inductive) applied to the resonant network which allows the MOSFET’s to be turned on with zero voltage.
- Rectifier network: produces DC voltage by rectifying AC current





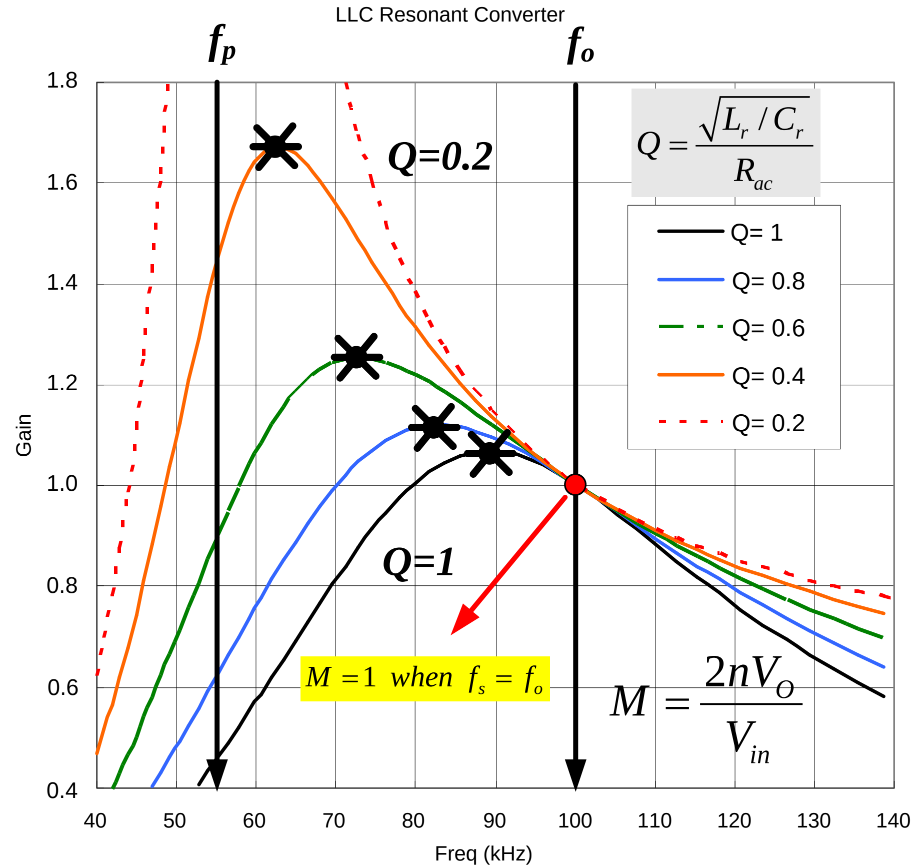
LLC Converter Characteristics

- Two resonant frequencies (f_o and f_p) exist
- The gain is fixed at resonant frequency (f_o) regardless of the load variation

$$M_{@\, f=f_o} = 1$$

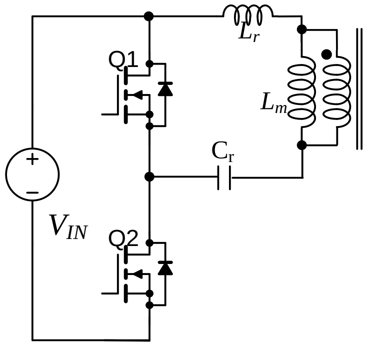
- Peak gain frequency exists between f_o and f_p
- As Q decreases (load current decreases), the peak gain frequency moves to f_p and higher peak gain is obtained
- As Q increases (load current increases), peak gain frequency moves to f_o and the peak gain drops

$$f_P = \frac{1}{2\pi\sqrt{(L_M + L_r)C_r}} \qquad f_O = \frac{1}{2\pi\sqrt{L_r C_r}}$$

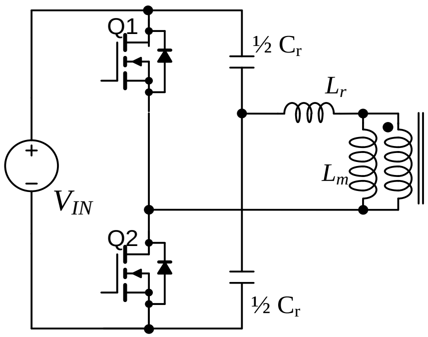


LLC Topology Variations

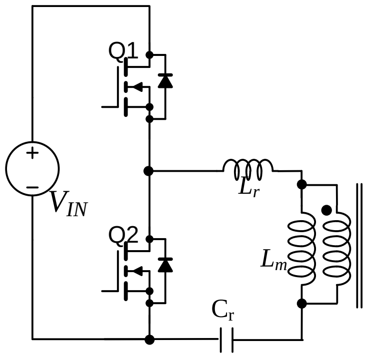
Primary Side Variation



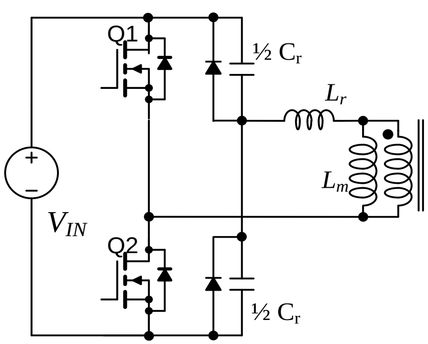
Transformer across the high side MOSFET



Split resonant capacitor

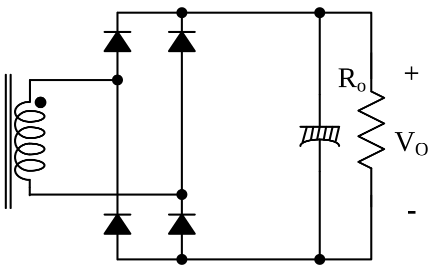


Transformer across the low side MOSFET

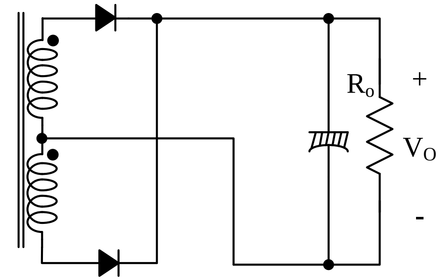


Split resonant capacitor with clamping diode

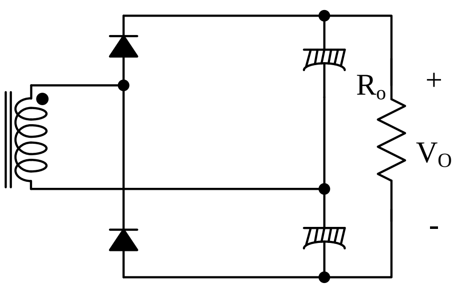
Secondary Side Variation



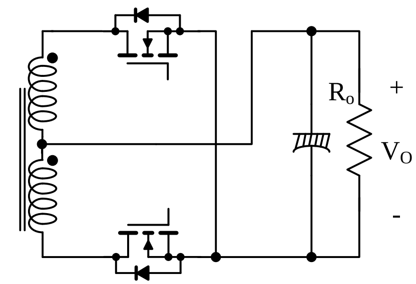
Full bridge rectifier with single winding



2 Rectifier diode with center tab winding



Voltage doubler rectifier with single winding



Synchronous rectifier with center tab winding

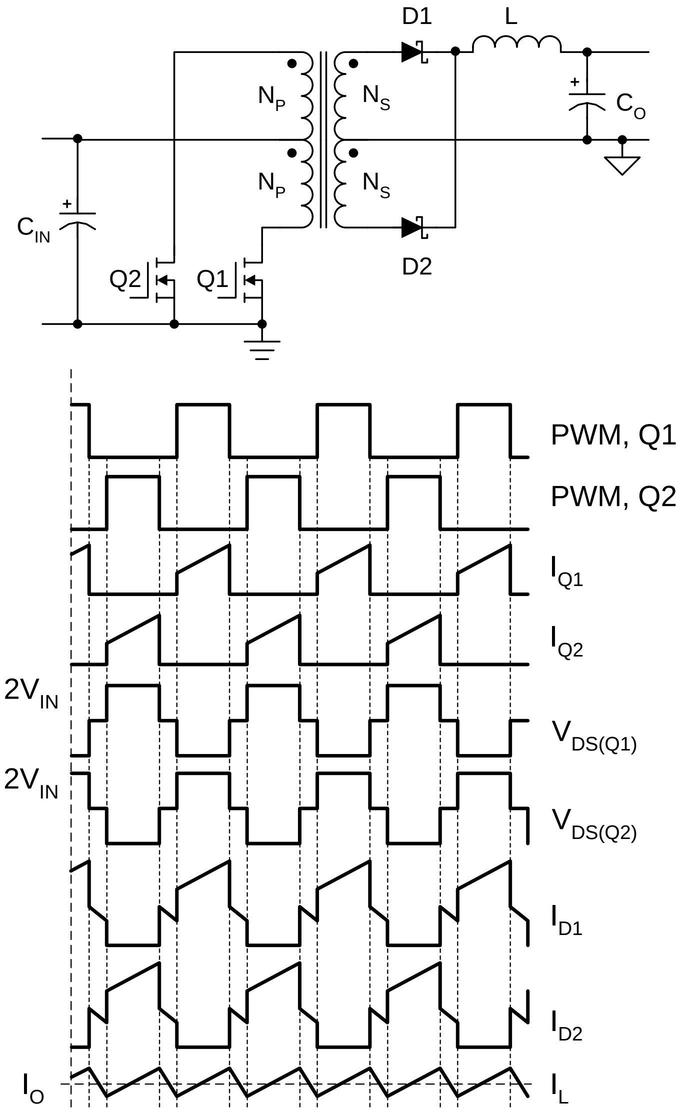
LLC Resonant Half Bridge Converter

- Advantages of the LLC resonant converter
  - Narrow frequency variation range over wide load range
  - Zero voltage switching even at no load condition
  - Reduced switching loss through ZVS → Improved efficiency and EMI
  - When the two magnetic components are implemented with a single core (use the leakage inductance as the resonant inductor), one component can be saved

- Disadvantages of the LLC resonant converter
  - Can optimize performance at one operating point, but not with wide range of input voltage and load variations (too wide frequency range)
  - Difficult to regulate the output at no load condition
  - Significant current may circulate through the resonant network, even at the no load condition
  - Quasi-sinusoidal waveforms exhibit higher peak values than equivalent rectangular waveforms
  - High output current ripple

Double Ended (<500W)

Push Pull Converter

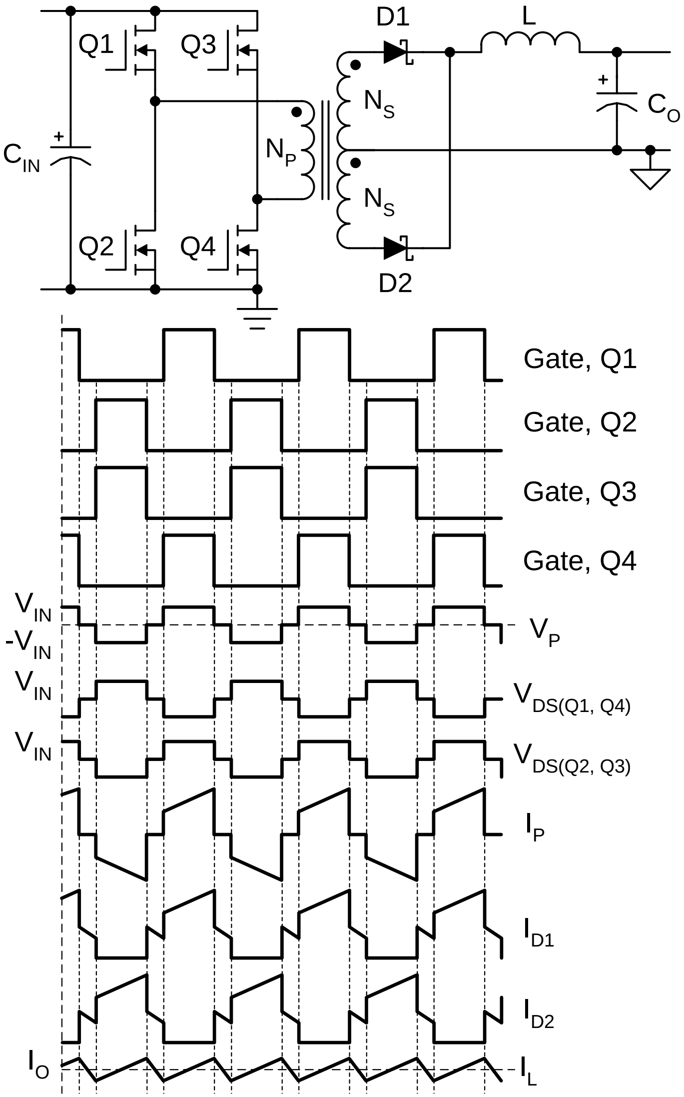


- Advantages
  - Lower primary current compared to HB
  - Best for lower V_{IN}, such as telecom DC-DC of US Line Voltage
  - Simple low-side gate drive
  - Low output current ripple
- Disadvantages
  - High voltage ($2xV_{IN}$) on primary MOSFETs
  - Transformer flux walking (VMC only)
  - Center tapped transformer structure
  - Hard switching
- Transfer Function

$$\frac{V_O}{V_{IN}} = 2 \times \frac{N_S}{N_P} \times D$$

Double Ended (>500W)

Full Bridge Converter (PWM)

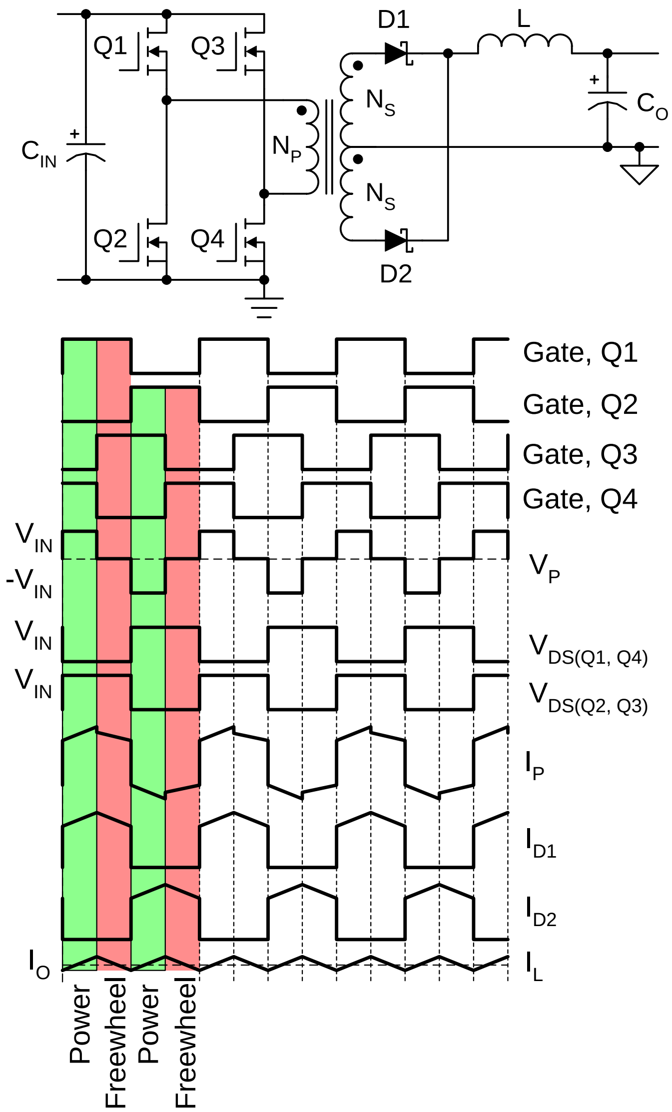


- Advantages
  - MOSFET voltage stress limited to V_{IN}
  - Twice the power compared to half bridge
  - Single winding primary
- Disadvantages
  - Dual, totem pole primary gate drive
  - Hard switching (Non-ZVT)
  - Parasitics degrade circuit performance
  - Circuit complexity
- Transfer Function

$$\frac{V_O}{V_{IN}} = 2 \times \frac{N_S}{N_P} \times D$$

Double Ended (>500W)

Phase Shifted Full Bridge Converter

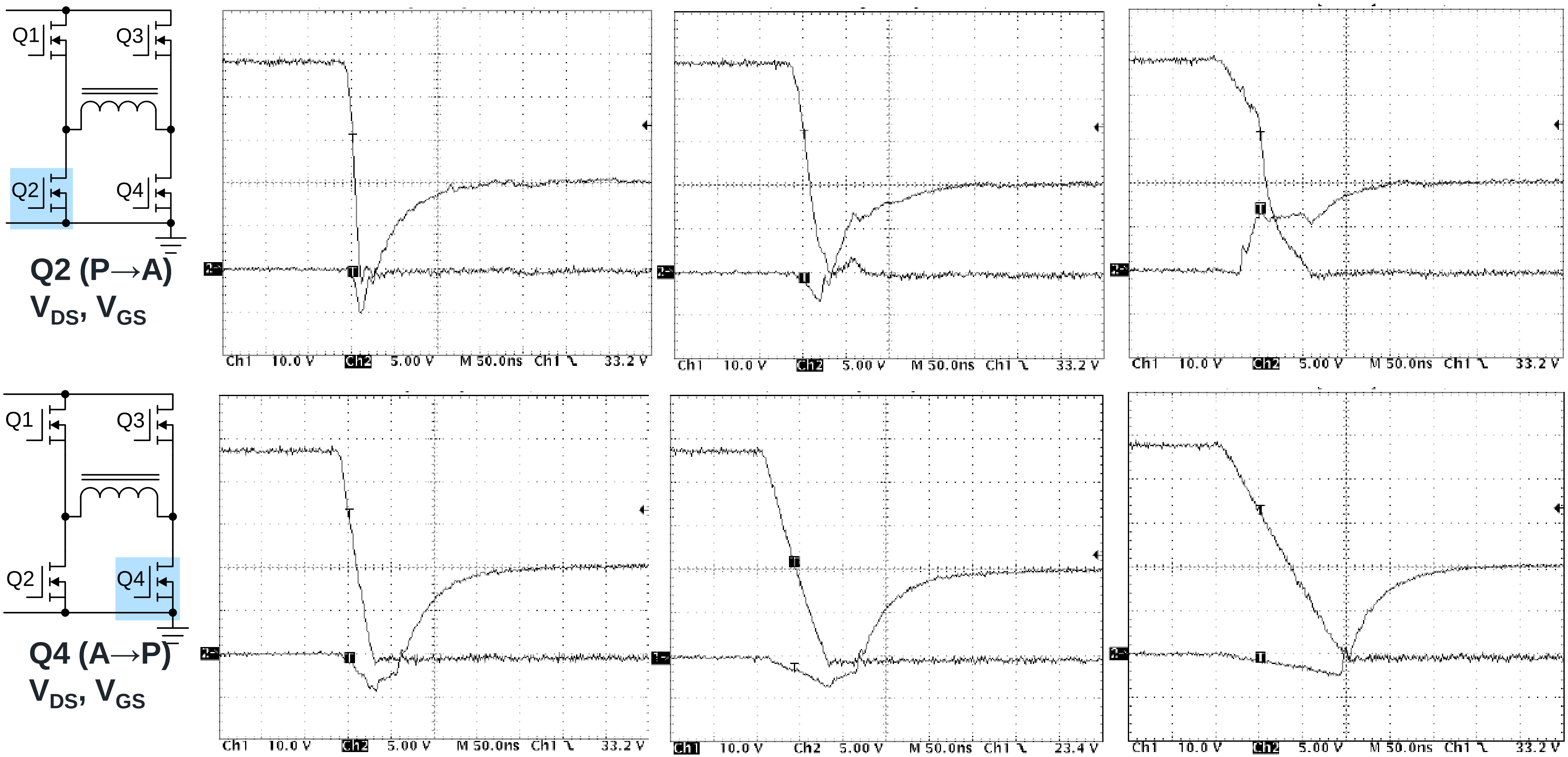


- Advantages
  - High Efficiency ZVS
  - Highest single stage processing power
  - MOSFET voltage stress limited to V_{IN}
  - Twice the power compared to half bridge
  - Full wave rectified secondary
  - Single winding primary
  - Excellent choice for EU line voltage (PFC pre-regulator) with output power >1kW
- Disadvantages
  - Dual, high side primary gate drive
  - Circuit complexity
  - High circulating primary current for ZVS
  - Loss of ZVS at light load current
- Transfer Function

$$\frac{V_O}{V_{IN}} = 2 \times \frac{N_S}{N_P} \times D$$

Phase Shifted Full Bridge Converter

ZVS Waveforms



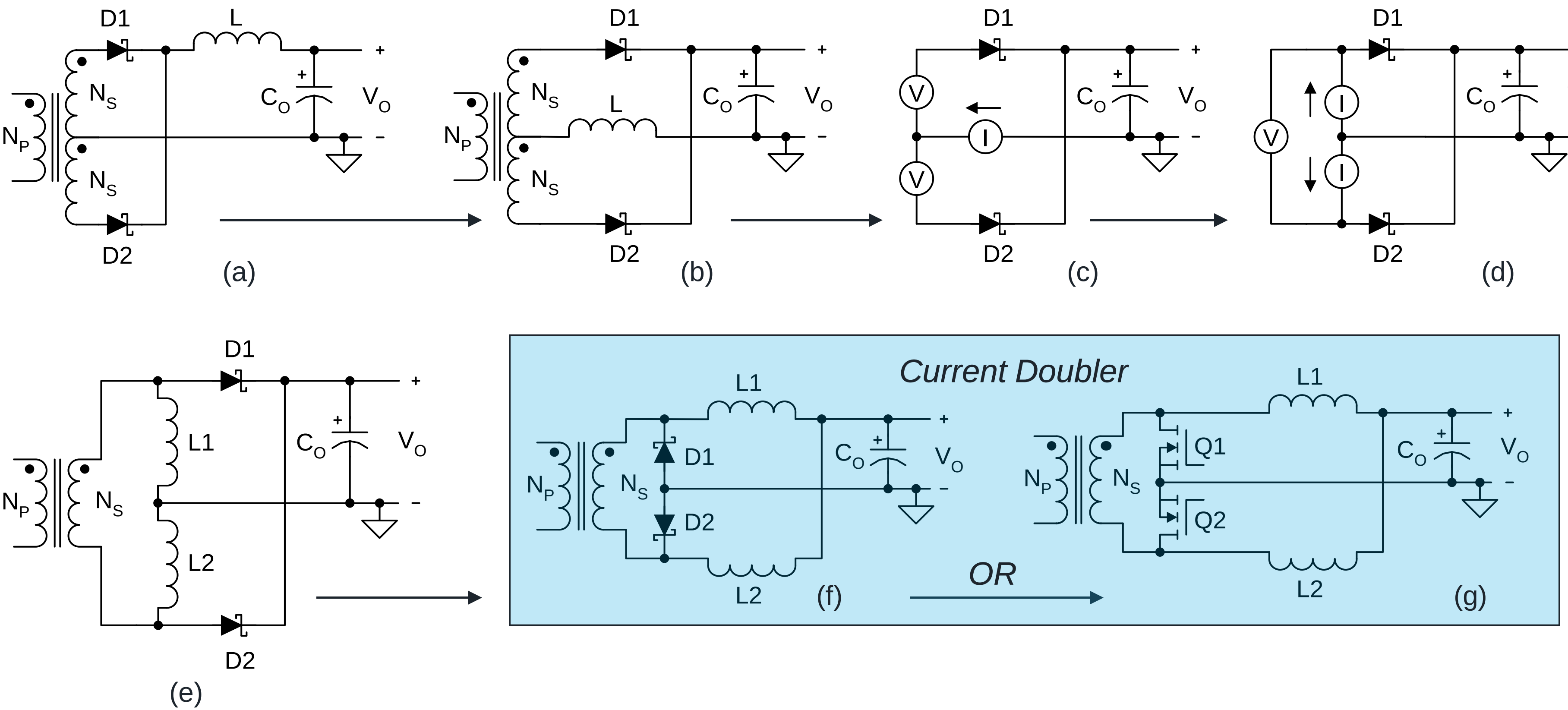
(a) $I_O = 100\%$ (b) $I_O = 35\%$ (c) $I_O = 0\%$

A="Active" or power phase
P="Passive" or freewheel phase

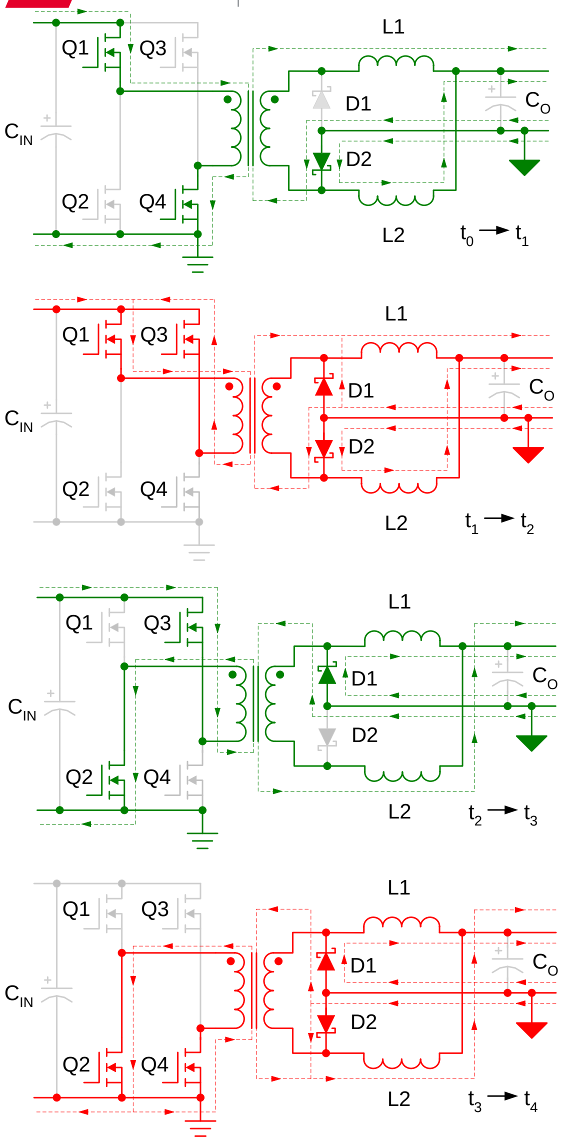
Current Doubler Rectifier

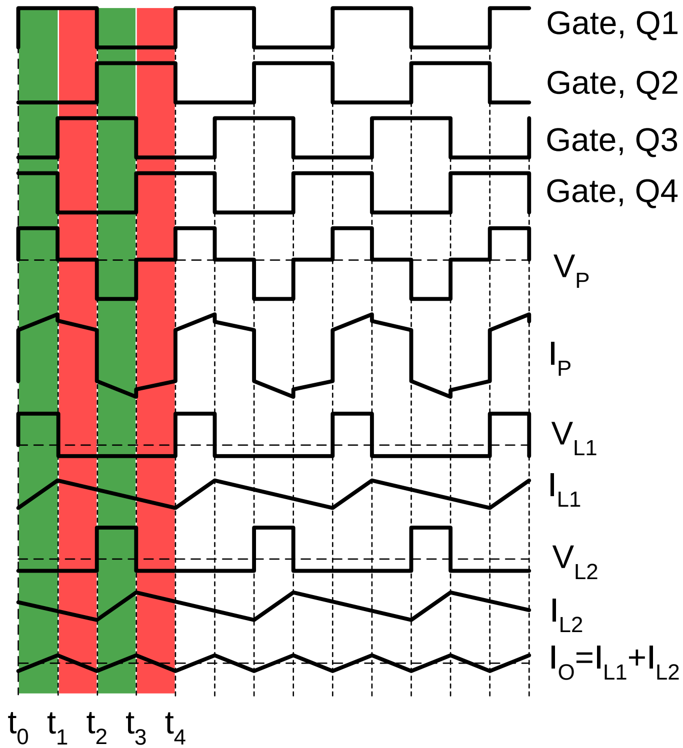
What is it? - *A full wave alternative rectification technique compatible with all double ended converter topologies*

Derivation of Current Doubler



Phase Shifted Full Bridge with Current Doubler





Current Doubler Timing Diagram (PSFB Application)

- Better thermal distribution for higher current outputs
- Each inductor carries half the load current at half the switching frequency
- Ripple currents cancel as a function of D
- Single winding secondary

High Power Topology Summary

Topology	Transformer	Primary Switches	V_{DS}	"Ideal" Application
CCM Boost	Inductor (non-isolated)	1	V_{OUT}	High power PFC > 300 W Interleaved PFC > Several kW
BCM Boost	Inductor (non-isolated)	1	V_{OUT}	PFC < 300 W Interleaved PFC < 1 kW
Forward	Single-end	1	$2xV_{IN}$	< 200 W, universal off-line or telecom
Active Clamp	Single-end	2	$V_{IN} \times \frac{1}{1-D}$	< 500 W, universal off-line or telecom, highest efficiency required
2-Switch Forward	Single-end	2	V_{IN}	< 500 W, universal off-line, PFC pre-regulator
Half Bridge	Double-end	2	V_{IN}	< 500 W, EU off-line, Intermediate Bus Converters
Push Pull	Double-end	2	$2xV_{IN}$	< 500 W, telecom or low V_{IN} (< 200 V)
Full Bridge	Double-end	4	V_{IN}	> 500 W, universal off-line
Phase Shifted FB	Double-end	4	V_{IN}	> 1 kW, universal off-line or telecom, highest efficiency required
Current Doubler	Double-end	NA	NA	Any double-ended topology, low V_{OUT}, high I_{OUT} most benefit

Summary

- Power Converter Topology Trends:
  - Advanced control algorithms breathing new life into classic topologies…
    - Buck → multiphase buck
    - Boost → BCM boost
    - Flyback → QR flyback
    - Forward → active clamp forward
    - Half bridge → LLC resonant
    - Full bridge → PSFB
  - The innovation trends are in new control methods that are pushing the limits of power processing, converter size, and operating frequencies.
    - Better uses of zero-voltage switching and zero-current switching for lower stresses
    - Better use of parasitic elements
    - Digital techniques including non-linear and multi-variant control
    - Better synchronous rectification timing control