POWER CONVERTER TOPOLOGY TRENDS
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
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

Power levels numbers for general discussion only. Exceptions aplenty.
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
Scalable, efficient, complex protection functions, sequencing, redundancy, digital control, etc

Efficiency example

\[ \eta_{SYS} = \eta_{PFC} \times \eta_{DC} \times \eta_{DC} \times \eta_{POL} \]

\[ \eta_{SYS} = 98\% \times 95\% \times 95\% \times 96\% = 84.9\% \]
Difficult to meet: Low cost, high PF, low THD, high efficiency, wide $V_{\text{IN}}$ with single-stage

$$\eta = 84.9\%$$
Non-Isolated Converter Topologies
Boost Converter (Step Up)

Inductor volt-second balance:

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

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

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

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
Operating Mode
CCM, BCM or DCM

CCM (Fixed Freq)

BCM (Variable Freq)

DCM (Fixed Freq)
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

![Transformer Diagram]

2. Voltage conversion resolution

\[
\frac{V_O}{V_{IN}} = D
\]

Ex: For \(F_{SW}=300kHz\) (\(T_{SW}=3.33\mu s\)), \(N_P:N_S=4:1\), 36\(V\)<\(V_{IN}\)<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 \(\mu s\)

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

Overshoot/ringing due to Leakage Inductance

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

(b) Forward Converter

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

(b) Flyback Converter

(c) Gapped Flyback “Transformer”
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

- CCM Transfer Function
  \[
  \frac{V_Q}{V_{IN}} = \frac{N_S}{N_P} \times \frac{D}{1-D}
  \]

- 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

(b) CCM Waveforms
Quasi-Resonant Flyback
Conventional Valley Switching

Wide frequency variation depends on output load condition

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

Output load decreases
Operating frequency increases
- Frequency variation depends on output load conditions
- Operating frequency is within narrow variation (127.5 kHz ~ 92.6 kHz)
Two-Switch, Quasi-Resonant Flyback

VIN (FROM PFC)

FAN7382

1. VCC
2. HIN
3. LIN
4. COM
5. LO
6. VS
7. HO
8. VB

C3

Q1

Q2

D1

D2

D3

VLED

C1

VCC

PBIAS

VIN (FROM PFC)

RDY

PBIAS

(DCIN)

R4

ACIN

Q1

D1

D3

D4

VHS

VA

D4

VIN (FROM PFC)

R1

R2

R3

FAN6300H

1. DET
2. FB
3. CS
4. GND
5. GATE
6. VDD
7. NC
8. HV

RDY

(The Power to Amaze)
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 $\rightarrow V_{OUT} > 2 \times V_{IN}$
  - Valley switch $\rightarrow$ otherwise
  - Window valley switching
Two-Switch Quasi-Resonant Flyback

Measured Waveforms

- **V_{DS} Valley Switching on First Valley**
  - \( V_{OUT} < \frac{1}{2} V_{IN} \)
  - \( D = 42\% \)
  - \( F_S = 63 \text{ kHz} \)
  - \( P_{OUT} = 85 \text{ W} \)

- **Extended Window Valley Switching**
  - \( V_{OUT} < \frac{1}{2} V_{IN} \)
  - \( D = 11\% \)
  - \( F_S = 68 \text{ kHz} \)
  - \( P_{OUT} = 24 \text{ W} \)
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)

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

\[ P_{SW} = V_{DS} \times I_D \times F_{SW} \]

(a) Hard Switching

(b) “Ideal” 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

Normal
Flux Imbalance
Saturation
Primary Current
### Double Ended (<500 W)

**Half Bridge Converter (Symmetrical)**

#### Advantages
- Better transformer utilization
- MOSFET voltage stress limited to $V_{\text{IN}}$
- Best for high $V_{\text{IN}}$ off line applications up to 500W
- Single winding primary
- Transformer balanced by $C_1$ and $C_2$
- 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

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

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 \( V_{\text{IN(MAX)}} \)
Asymmetrical Half Bridge Converter

- Secondary rectifier voltage stress:
  \[ V_{D1} = D \times V_O \quad V_{D2} = V_O \times (1 - D) \]

- Reverse recovery and parasitic ringing

- Wide $\Delta D$ 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

\[ f_p = \frac{1}{2\pi \sqrt{(L_M + L_r)C_r}} \quad f_o = \frac{1}{2\pi \sqrt{L_r C_r}} \]

\[ Q = \sqrt{\frac{L_r}{C_r R_{ac}}} \]

\[ M = \frac{2nV_o}{V_{in}} \]
LLC Topology Variations

**Primary Side Variation**
- Transformer across the high 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
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 ($2V_{IN}$) 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

(a) (b) (c) (d)

(e) (f) (g)
Phase Shifted Full Bridge with Current Doubler

- 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

Current Doubler Timing Diagram (PSFB Application)
# High Power Topology Summary

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