Comparison of PSFB and FB-LLC for high power DC/DC conversion

High Voltage Controllers (HVC)
Created by: Colin Gillmor
Presented by: Michael O’Loughlin
Agenda

1/ Typical High Power DC/DC application

2/ The PSFB and FB-LLC
   – How the PSFB works
   – How the FB-LLC works

3/ Comparison: PSFB and FB-LLC

4/ Conclusions
   – Conclusions
   – Further Reading
   – TI Components
   – Reference Designs
Typical Battery Charger Specifications

Input: Universal Single Phase Line with PFC

Output Voltage:
- 1.75:1 range (Li-Ion), 400V/230V
- 1.25:1 range (Lead Acid), 14.1V/11.4V

Output Power
- Output Power: 3.3kW, increases during charging

Constant Current and Constant Voltage modes

Options:
- PSFB or FB-LLC – but which?
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The PSFB (and ZVS)

Buck Derived topology $V_{OUT} = D \cdot V_{IN} \cdot \frac{N_S}{N_P}$

QA, QB – reference pair
D controlled by phase shifting QC, QD

Energy transfer when diagonal pairs of switches are ON
QE, QF are SRs, Diode rectification is possible
ZVS allows efficient operation from high input voltages

ZVS = Zero Voltage Switching

Energy in $C_{STRAY}$ is $E = \frac{1}{2} C_{STRAY} \cdot V_{DS}^2$

• ZVS brings $V_{DS}$ to zero before MOSFET turned on.
• No energy in $C_{STRAY}$ therefore no switching losses.
Introduction to the FB-LLC

The FB-LLC:
A Full bridge variant of the ‘usual’ half bridge LLC

Reposition $C_R$ and add two switches, $A'$ and $B'$
Same drive signals can be used as on half bridge LLC
- Applied to Diagonal Pairs, $A$, $A'$ and $B,B'$

Increased complexity is justified
- Primary voltage doubled
- Primary current halved
- More power for same size
- The same arguments as for all Full Bridge vs Half Bridge topologies
PSFB and FB-LLC: Side by side

**PSFB**
- Constant Frequency
- Wide conversion range
- Can be easily Synchronised
- Easy to parallel for current sharing
- ZVS
- High Efficiency

**FB-LLC**
- Variable Frequency
- Limited conversion range
- Difficult to Synchronise
- Difficult to force current sharing
- ZVS
- Highest Efficiency

Component Count – similar
Component stresses – different
Method of operation - different

Which to choose
How to choose

---

Texas Instruments
# PSFB and FB-LLC: Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PSFB</th>
<th>FB-LLC</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching Frequency</td>
<td>Fixed</td>
<td>Variable</td>
<td>Fixed frequency has system level advantages (eg. synchronisation)</td>
</tr>
<tr>
<td>Primary switches</td>
<td>4</td>
<td>4</td>
<td>2 High Side, 2 Low Side</td>
</tr>
<tr>
<td>Rectifiers</td>
<td>2</td>
<td>2</td>
<td>Same rectifier circuits can be used</td>
</tr>
<tr>
<td>Isolation</td>
<td>Yes</td>
<td>Yes</td>
<td>Built into transformer</td>
</tr>
</tbody>
</table>

More Comparisons will be added later with a summary and conclusions at the end
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Phase Shifted Full Bridge

Buck Derived topology
$V_{OUT} = D \frac{V_{IN} N_S}{N_P}$
OUTA, OUTB – reference pair
D controlled by phase shifting OUTC & OUTD
QE, QF are SRs, Diode rectification is possible

Mouse over the waveforms to play the animation

PA Leg
Left Leg
QA, QB

AP Leg
Right Leg
QC, QD
PSFB: Other Features

Adaptive Delays: The time needed to achieve ZVS for both PA and AP legs is a function of the transformer current. Some controllers allow the user to change the delay times of the primary and secondary switches as a function of the current, UCC28950, UCC28951, UCC3895.

SR disable: The ability to disable the SRs and revert to diode rectification at light loads. This prevents reverse currents in the resonant tank and improves light load efficiency.

Bi-Directional operation:
The PSFB isn’t well suited to bi-directional operation but we do have some examples -

**PMP5726** This is a slow drain modulation power converter – not truly bi-directional but it allow SRs to operate right down to zero load for improved transient response.

**TIDA-00653** A 48V/12V bidirectional battery charger. PSFB in forward direction. Push-Pull in reverse direction.
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How the FB-LLC works

- LLC is popular because -
  - ZVS reduces switching losses
  - It can achieve good efficiency
  - Low EMI

- The gain of the LLC stage is $V_{out}/V_{in}$
- Regulate $V_{out}$ by changing $f_{sw}$
- $C_R$, $L_R$ and $L_M$ form a resonant tank.

Basically the LLC is a Potential Divider

$Z_1 = C_R L_R$

$Z_2 = L_M$

$L_M$ = Magnetizing Inductance, $L_R$ = Resonant Inductance, $C_R$ = Resonant Capacitance
LLC: First Harmonic Approximation

- LLC Stage Analysis is difficult
  - No easy analytical solution
- Approach used here is FHA
  - Assumes that only the first harmonic of the switching waveform is significant
  - Reasonably accurate close to resonance
  - Increasingly inaccurate as system operates away from resonance
- Most efficient close to resonance.

An Alternative LLC Design Process is described in slua733
LLC: Gain vs Frequency Characteristic

First Harmonic Approximation Calculation
Gives an APPROXIMATE value for Gain

\[
\text{Gain}(f, Q) = \frac{L_N f^2}{L_N f^2 + (f^2 - 1)(1 + jf L_N Q)}
\]

\[
L_N = \frac{L_M}{L_R}
\]

\[
L_N = \frac{L_M}{L_R}
\]

\[
R_E = \frac{8N^2 R_L}{\pi^2}
\]

\[
N_T = \text{Turns Ratio}, \quad R_L = \text{Load}, \quad L_M = \text{Magnetizing Inductance}, \quad L_R = \text{Resonant Inductance}, \quad C_R = \text{Resonant Capacitance}
\]

\[
f_0 = \frac{1}{2 \pi \sqrt{L_R C_R}}
\]
LLC: Gain range

- Can get the same gain range across different frequencies – A or B have the same gain range (Vertical bars) but different frequency spans. Complex tradeoffs to choose best operating range.
- Increased core losses at higher frequency
- Above resonance: Loss of rectifier ZCS
  ZCS = Zero Current Switching
- Possible loss of ZVS at higher frequency
- Summary:
  Design optimisation is very difficult
LLC – Below, At and Above Resonance

- Above Resonance, ZVS achieved, CCM* on sec, Rectifiers not soft switched. Lower RMS currents for given power

- At Resonance, ZVS achieved, CCM on sec, Rectifiers are soft switched (ZCS), Optimum efficiency

- Below Resonance, ZVS achieved, DCM on sec, Rectifiers are soft switched (ZCS), RMS currents higher for given power.

CCM = Continuous Conduction Mode, DCM = Discontinuous Conduction Mode
FB-LLC: Other Features

The time needed to achieve ZVS is a function of the magnetizing current. Some controllers change the delay times as a function of the current.

SR disable – the ability to disable the SRs and revert to diode rectification at light loads. This prevents reverse currents in the resonant tank and improves light load efficiency.

Bi-Directional operation
The FB-LLC (like the normal LLC) isn’t well suited to bi-directional operation but some examples have been published in the literature, I’m not aware of any production ready design

- Seamless Operation of Bi-Directional LLC Resonant Converter for PV System
  Abe et al, APEC 2014
- Bidirectional LLC Resonant Converter for Energy Storage Applications
  Jiang et al, Apec 2013
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## Comparison: PSFB and LLC

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<th>FB-LLC</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversion Ratio</td>
<td>Vo = D Vin, PWM</td>
<td>Complex, approximate expression, FM*</td>
<td>Easier to calculate on PSFB</td>
</tr>
<tr>
<td>ZVS</td>
<td>Yes but difficult at light loads</td>
<td>Yes, more difficult as frequency increased</td>
<td>ZVS on PA leg more difficult than AP leg (PSFB) and more difficult at higher frequency (FB-LLC)</td>
</tr>
<tr>
<td>Rectifier ZCS turn off</td>
<td>No, high di/dt at turn-off</td>
<td>Yes – ZCS - at or below resonance (f₀)</td>
<td>ZCS reduces reverse recovery switching losses n/a if SiC or Schottky Diodes used.</td>
</tr>
<tr>
<td>Light Load Operation</td>
<td>Use Burst Mode to maintain ZVS</td>
<td>Use Burst Mode to prevent f&lt;sub&gt;sw&lt;/sub&gt; increasing unreasonably</td>
<td>FB_LLCC losses will be higher in this condition</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Good</td>
<td>Good, best at Resonance</td>
<td>FB-LLC best at ‘Sweet Spot’</td>
</tr>
</tbody>
</table>
Synchronisation
Easy on the PSFB, difficult on the FB-LLC

So why Synchronise?
• With two sources and some non-linearity you get mixing which gives energy at the sum and difference frequencies – \((f_1 + f_2)\) and \((f_1 - f_2)\). The difference frequency can appear in the audible range.

• Audio systems especially want to avoid any beat frequencies.

• Reduces aperiodic system noise.– spikes on the CS waveforms causing unwanted PWM jitter for example.
## PSFB and FB-LLC: Comparison

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<tr>
<th></th>
<th>PSFB</th>
<th>FB-LLC</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronisation</td>
<td>Simple</td>
<td>Difficult</td>
<td>FB-LLC uses Fsw as the Vout control variable.</td>
</tr>
</tbody>
</table>
Paralleling and Current Sharing: PSFB

Easy on the PSFB, difficult on the FB-LLC

Paralleling is used to increase system level power in manageable steps. A 10kW system may be built from three 3.3kW systems in parallel.

Redundancy, n+1  eg  10kW = 4 x 3.3kW

Expansion to meet future expected load growth

We also want the three sub-systems to share the load equally.
Paralleling and Current Sharing: FB-LLC

Easy on the PSFB, difficult on the FB-LLC

Reference design tiduct9 is a current sharing, paralleled, synchronised HB-LLC. It uses a C2000 processor to control the system and modulate the duty cycle.

FM and PWM modulation of PH2 for Synchronisation and current sharing.

Figure 11. Correct PWM Waveforms for Two Phases Regardless of Individual Duty Cycles
## PSFB and FB-LLC: Comparison

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<th></th>
<th>PSFB</th>
<th>FB-LLC</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paralleling and Current Share</td>
<td>Simple</td>
<td>Difficult – especially if SYNC needed</td>
<td>FB-LLC needs Microcontroller</td>
</tr>
</tbody>
</table>
Synchronous Rectification

Easy on the PSFB, less so on the FB-LLC

The SR signals for the PSFB are synchronous with the primary signals.

A timing based approach to SR control won’t work in the FB-LLC, especially when it is operating below resonance. Vds sensing must be used on the FB-LLC.

SR gives significant efficiency improvement for low output voltages – 12V, 24V, 48V
SR is marginally useful for medium output voltages – 130V
SR is not worth while for high output voltages – 400V

SRs are controlled rectifiers, if you don’t turn them off they will conduct current in either direction.
# PSFB and FB-LLC: Comparison

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<thead>
<tr>
<th></th>
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<th>FB-LLC</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronous Rectification</td>
<td>Easy</td>
<td>Needs Care</td>
<td>Diode rectification used on high Vo designs. Low di/dt rates in FB-LLC makes SR drive tricky.</td>
</tr>
</tbody>
</table>

**UCC27424 SR Driver**

**SR Controller**

**UCC24612**

**UCC24610**
Dithering

Dithering is the deliberate changing the switching frequency and is sometimes used as a method to reduce the conducted EMI signature of a product.

In a PWM system changing the switching frequency does not change the on time so the duty cycle changes and so does Vout. The duty cycle has to be corrected by the operation of the control loop otherwise it will cause Vout variations. Depends on relative speeds of dithering and loop bandwidth.

In the LLC the switching frequency is the control variable. Dithering is not possible without changing Vout – the control loop cannot correct for this.
- True for both DFC (Direct Frequency) and HHC (Hybrid Hysteretic) control methods.

Dithering is a complex subject. [slup269 Understanding Noise-Spreading Techniques and their Effects in Switch-Mode Power Applications](#) gives some insight.
# Dithering

<table>
<thead>
<tr>
<th>Dithering</th>
<th>PSFB</th>
<th>FB-LLC</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dithering</td>
<td>Simple</td>
<td>Very Difficult</td>
<td>Dithering is of marginal benefit.</td>
</tr>
</tbody>
</table>

![Graph showing comparison of Jitter and No Jitter](image-url)

**Jitter**

**No Jitter**
Component Stresses: General

- The component stresses in the following slides are all based on simulations of 3kW PSFB and FB-LLC designs operating at constant 250A output.
- The FB-LLC resonant frequency was set to 100kHz
- The PSFB was switching at 100kHz
Input Current

Input current in FB-LLC is about 5% higher than the PSFB. This isn’t really significant. Input current wave shapes are different. PSFB has more HF harmonics than FB-LLC. (PSFB current has sharper edges!)

*above Resonance, **At Resonance, ***below Resonance

<table>
<thead>
<tr>
<th>400Vin, 250A</th>
<th>PSFB A RMS</th>
<th>FB-LLC A RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.8V</td>
<td>8.8A</td>
<td>9.2A*</td>
</tr>
<tr>
<td>12V</td>
<td>9.2A</td>
<td>9.3A**</td>
</tr>
<tr>
<td>14V</td>
<td>10A</td>
<td>10.7A***</td>
</tr>
</tbody>
</table>

*above Resonance, **At Resonance, ***below Resonance
Primary Switches

At a constant 250A output current

Currents in 4 LLC switches are equal
Currents in 4 PSFB switches are equal

RMS current about 12% higher in PSFB

Difference reduces as Vout and Pout increase
This assumes constant output current

Estimate a 40% higher dissipation in PSFB for a given Rds_on

Use lower Rds_on switches to reduce losses.

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Power</th>
<th>PSFB A RMS</th>
<th>FB-LLC A RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.8V, 2.7kW</td>
<td>7.87A</td>
<td>6.52A *</td>
<td></td>
</tr>
<tr>
<td>12V, 3kW</td>
<td>7.69A</td>
<td>6.59A **</td>
<td></td>
</tr>
<tr>
<td>14V, 3.4kW</td>
<td>7.72A</td>
<td>7.52A ***</td>
<td></td>
</tr>
</tbody>
</table>

*above Resonance, **At Resonance, ***below Resonance
Resonant and Blocking Caps

C\textsubscript{R} is required in the LLC topology. Current is output reflected current, \( I_{OE} \) plus magnetizing current, \( I_{mag} \). Current is about 17\% higher in the PSFB.

A DC blocking capacitor is needed for Voltage Mode Control in the PSFB – \( C_{BLK} \) 7.5\mu F at 3kW. Not needed in Peak Current Mode Control.

Capacitors perform different functions. Both are non-polarised. \( C_{BLK} \) larger and more expensive than \( C_{R} \).

<table>
<thead>
<tr>
<th>400Vin, 12Vo, 3kW</th>
<th>PSFB (Blocking)</th>
<th>FB-LLC (C\textsubscript{R})</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-P Voltage</td>
<td>±2.8V</td>
<td>±300V</td>
</tr>
<tr>
<td>RMS current</td>
<td>11A</td>
<td>9.4A</td>
</tr>
<tr>
<td>Part Rating</td>
<td>600V</td>
<td>600V</td>
</tr>
<tr>
<td>C</td>
<td>7.5\mu F</td>
<td>75nF</td>
</tr>
</tbody>
</table>

Sinusoidal Current in \( C_{R} \) - At resonance:

\[ I_{Pri\_LLC} = I_{Cres} \]

\[ V_{Cres\_LLC} \]
Resonant and Shim Inductors

$L_R$ is required in the LLC topology. Current is output reflected current, $I_{OE}$ plus magnetizing current, $I_{mag}$, Same as in the resonant capacitor.

A Shim inductor may be needed to store energy for ZVS in the PSFB – $L_{SHIM} 5uH$ at 3kW. – depends on $L_{Leak}$

Possibility to use transformer leakage inductance in both circuits

FB-LLC inductor is likely to be bigger than the PSFB Shim Inductor.

<table>
<thead>
<tr>
<th>400Vin, 12Vo, 3kW</th>
<th>PSFB ($L_{SHIM}$)</th>
<th>FB-LLC ($L_R$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS Current</td>
<td>11A</td>
<td>9.4A</td>
</tr>
<tr>
<td>$L$</td>
<td>5uH ($L_{shim}+L_{leak}$)</td>
<td>34uH</td>
</tr>
</tbody>
</table>

Sinusoidal Current in $L_R$, At resonance
Trapezoidal current in $L_{SHIM}$

Current is about 17% higher in the PSFB
Transformer – Primary

Primary currents are about 17% higher in PSFB
• Copper losses will be greater

Generally, a FB-LLC transformer will be larger than an equivalent PSFB transformer.
• Must operate at lower frequencies – below resonance.

LLC transformers in general can be low profile – increased leakage inductance is not a problem

One reason LLC is very popular in DTV

<table>
<thead>
<tr>
<th>400Vin, 12Vo, 3kW</th>
<th>PSFB</th>
<th>FB-LLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>I_PRI</td>
<td>11A RMS</td>
<td>9.4A RMS</td>
</tr>
<tr>
<td>L_MAG</td>
<td>550uH</td>
<td>172uH</td>
</tr>
</tbody>
</table>
Transformer – Secondary

RMS currents are about 13% lower in PSFB – lower Cu and SR\textsubscript{RDSON} losses

Average currents are the same – Diode Vf losses are the same.

Ripple current is much higher in FB-LLC

For the Centre Tapped Secondary
LLC V\textsubscript{SEC} is 2 x V\textsubscript{OUT}
PSFB Vsec is Vin/N\textsubscript{T} Stress is higher in PSFB

<table>
<thead>
<tr>
<th>400Vin</th>
<th>PSFB (A RMS)</th>
<th>FB-LLC (A RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.8Vo, 2.7kW</td>
<td>251</td>
<td>276*</td>
</tr>
<tr>
<td>12Vo, 3kW</td>
<td>248</td>
<td>278**</td>
</tr>
<tr>
<td>14Vo, 3.4kW</td>
<td>252</td>
<td>315***</td>
</tr>
</tbody>
</table>

*above Resonance, **At Resonance, ***below Resonance
Output Rectifiers

This is a comparison of the currents in the center tapped secondary.

To a first approximation
RMS current determines \( I^2R \) losses in SRs
Average current determines \( Vf*If \) losses in Diodes

FB-LLC has higher secondary currents than the PSFB, expect higher conduction losses

Voltage stresses (Centre Tapped Secondary)
2xVout (FB-LLC)
2 xVin Ns/NP (PSFB)

\*above Resonance, **At Resonance, ***below Resonance
Output Capacitors

Ripple current is about 9 times higher in the FB-LLC FB-LLC: Capacitor Ripple rating usually sets C needed*
Less of a problem at high Vout (400V)

FB-LLC requires significantly more output capacitance than the PSFB

The FB-LLC will deliver much higher peak currents into an output short than the PSFB.

*It’s not possible to use battery to absorb the ripple currents at the output of the power stage

<table>
<thead>
<tr>
<th>400Vin, 12Vo, 3kW</th>
<th>PSFB</th>
<th>FB-LLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>I_{COUT} (200kHz)</td>
<td>14A (RMS)</td>
<td>125A (RMS)</td>
</tr>
<tr>
<td>Example</td>
<td>41000uF, 16V 4.2A</td>
<td>250000uF, 16V 4.2A</td>
</tr>
<tr>
<td>Parts used</td>
<td>5 x 8200uF</td>
<td>32 x 8200uF</td>
</tr>
</tbody>
</table>
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<tbody>
<tr>
<td>Output Capacitor</td>
<td>Small, Low Ripple</td>
<td>Large C, Very High Ripple</td>
<td>Ripple current in Cout is about 9 times greater in the FB-LLC than the PSFB Low ESR high quality capacitors needed in the LLC.</td>
</tr>
<tr>
<td>Primary Switches</td>
<td>Same voltage stresses but ....</td>
<td></td>
<td>RMS primary switch currents are higher in the PSFB.</td>
</tr>
<tr>
<td>Transformer</td>
<td>Fixed frequency operation</td>
<td>Operates over a wide frequency range</td>
<td>Generally, a FB-LLC transformer will be larger than an equivalent PSFB transformer</td>
</tr>
</tbody>
</table>
Comparison - EMI

dv/dt rates are similar – pri/sec voltage changes drive CM currents through transformer.
di/dt rates on PSFB are higher than on the LLC – these draw DM currents from the input

LLC transformer will have lower pri/sec cap because it can tolerate more leakage inductance – should be lower CM currents

LLC converters manage “almost” sinusoidal current waveforms
Variable switching frequency on the LLC complicates EMI filter design

PSFB operates at a fixed switching frequency makes EMI filter design easier

• PSFB is inherently a higher noise topology than the FB-LLC
• BUT: no SMPS topology is noise free

CM = Common Mode, DM = Differential Mode
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<tr>
<td>Switching Frequency</td>
<td>Fixed</td>
<td>Variable</td>
<td>Fixed frequency is nice to have</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Good, minimise Body Diode Conduction.</td>
<td>Good, best at Resonance</td>
<td>FB-LLC best at ‘Sweet Spot’</td>
</tr>
<tr>
<td>System level features</td>
<td>Good</td>
<td>Poor</td>
<td>Synchronisation, current share</td>
</tr>
<tr>
<td>Transformer</td>
<td>Fixed frequency operation</td>
<td>Operates over a wider frequency range</td>
<td>Generally, a FB-LLC transformer will be larger than an equivalent PSFB transformer</td>
</tr>
<tr>
<td>EMI</td>
<td>Medium level of noise generation</td>
<td>Low level of noise generation</td>
<td>FB-LLC: is inherently lower noise.</td>
</tr>
<tr>
<td>Vo range</td>
<td>Wide</td>
<td>Medium</td>
<td>A limiting factor for FB-LLC</td>
</tr>
</tbody>
</table>
## Conclusions

### Which to choose

- **PSFB**
  - Design is easier
  - Flexible all rounder
  - ‘Systems Friendly’ features – parallelability, current sharing, synchronisation are all easy
  - Suited to high power low and high output voltage

- **FB-LLC**
  - Design is difficult
  - Best efficiency at ‘sweet spot’
  - Better EMI performance than PSFB.
  - Less ‘Systems Friendly’.
  - Not suited to high power low Vout applications – Cout Ripple
  - Good for fixed Vo/Vin (High Voltages)

### How to choose

![Circuit Diagram](image)

*Texas Instruments*
Further Reading

1. Design and Optimization of a High-Performance LLC Converter; B McDonald, J Freeman: slup306
2. Designing an LLC Resonant Half-Bridge Power Converter; H. Huang: slup263
3. LLC Design for UCC29950: J Leisten: (note: despite the title this covers LLC design in general.) slua733
10. Seamless Operation of Bi-Directional LLC Resonant Converter for PV System: Abe et al. APEC 2014
12. Understanding Noise-Spreading Techniques and their Effects in Switch-Mode Power Applications, Rice et al. slup269

Note_1: A Google search for ‘slup306‘ for example should find these TI papers
Texas Instruments Components

- **UCC27714**: High-Speed, 4-A, 600-V High-Side Low-Side Gate Driver
- **UCC24610**: Secondary Side Synchronous Rectifier Controller
- **UCC24612**: High-Frequency Multi-Mode Synchronous Rectifier Controller
- **UCC256301**: Wide Vin LLC Resonant Controller With High-Voltage Start Up Enabling Ultra-Low Standby Power (one of a family of UCC25630x HHC controllers)
- **UCC28950**: Green Phase-Shifted Full-Bridge Controller with Synchronous Rectification. Automotive qual version is available (-Q1)
- **UCC28951-Q1**: Phase-Shifted Full-Bridge Controller for Wide Input Voltage Range
- **UCC28955**: BiCMOS Advanced Phase Shift Resonant Controller. Automotive version is available (-Q1)
- **UCC25600**: 8-Pin High-Performance Resonant Mode LLC Controller
- **UCC21520**: 4A/6A, 5.7 kVrms Isolated Dual Channel Gate Driver
- **UCC27424**: Dual, Low side, 4A MOSFET Driver
Reference Designs

*(EVSE) Reference Design, tidub87* is a reference design for Level 1 and Level 2 Electric Vehicle Service Equipment

**PMP20657B** This is is a compact, efficient unidirectional 48V to 12V @ 400W power converter.

**PMP6712** is a 1600W DCDC converter using the UCC28950 controller in a dual phase master-slave configuration

Existing Reference Design **PMP8880, 12V, 460W with SRs**

**PMP5726** This is a slow drain modulation power converter – not truly bi-directional but it allows SRs to operate right down to zero load for improved transient response.

**TIDA-00653** A 48V/12V bidirectional battery charger. PSFB in forward direction. Push-Pull in reverse direction

**TIDA-00705** 480-W, 97% $\eta$, Ultra-Compact (480W/in3), Bi-Directional DC-DC (Low voltage, half bridge)

**Reference Design Library** The full TI reference design library
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