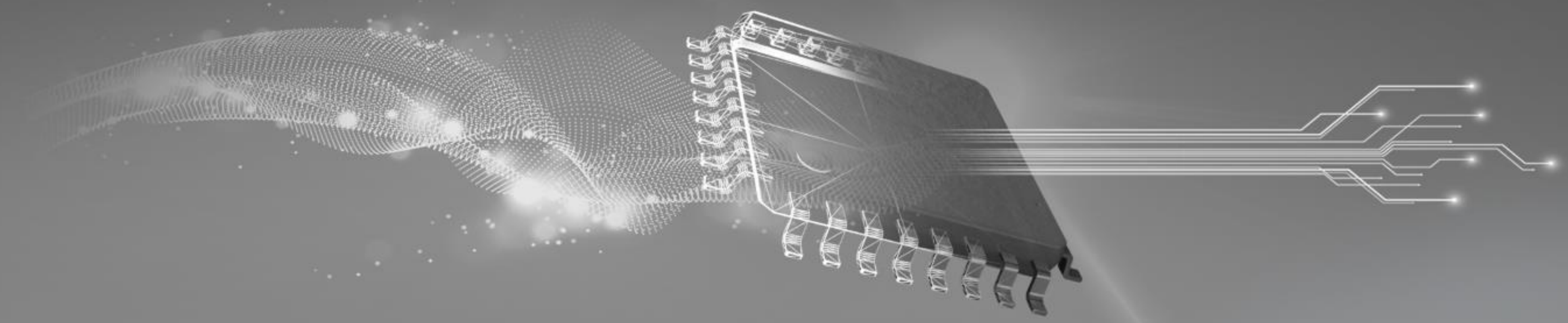
TI TECH DAYS



AC/DC, DC-DC bi-directional converters for energy storage and EV applications

Ramkumar S, Jayanth Rangaraju

Grid Infrastructure Systems

Detailed Agenda

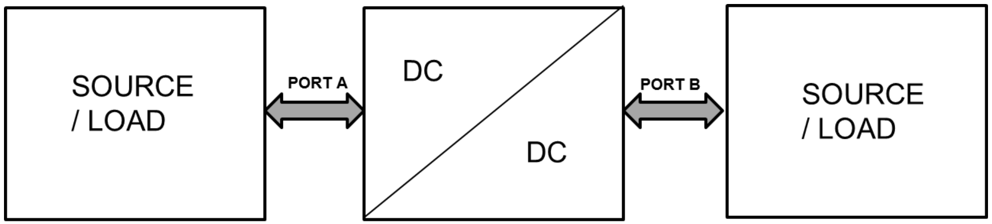
1. Applications of bi-directional converters
   1.1. Power storage applications
   1.2. EV charger applications

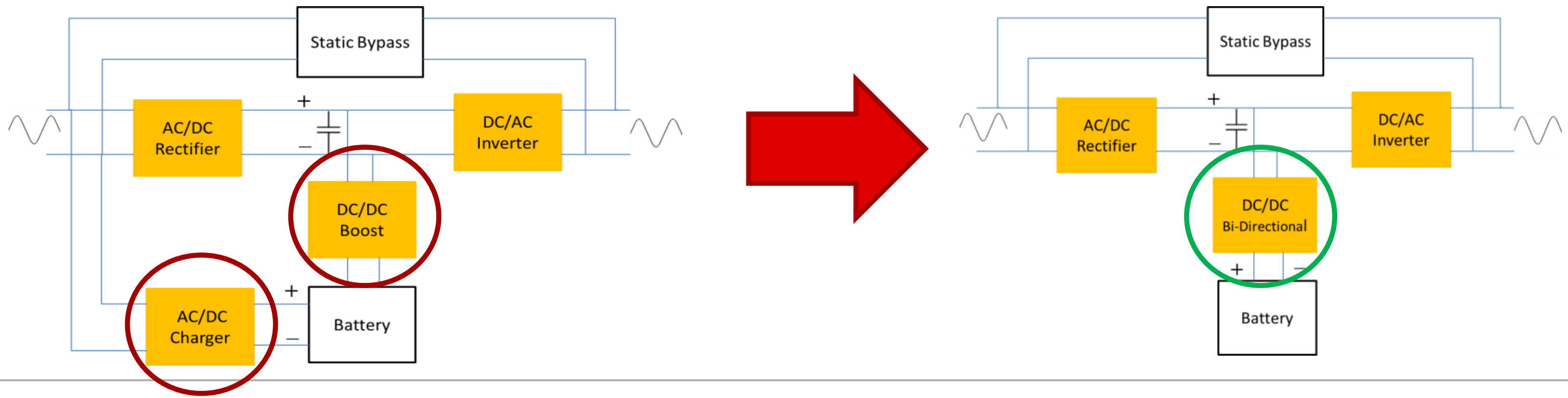
2. Bi-directional topologies and associated reference designs
   2.1. DC/DC topologies
      2.1.1. Active clamp current fed full-bridge
      2.1.2. DAB
      2.1.3. Fixed frequency LLC
      2.1.4. Phase shift LLC
   2.2. AC/DC topologies
      2.2.1. 3 Level T-type

Applications of Bi-Directional Converters

What is a Bi-Directional Converter

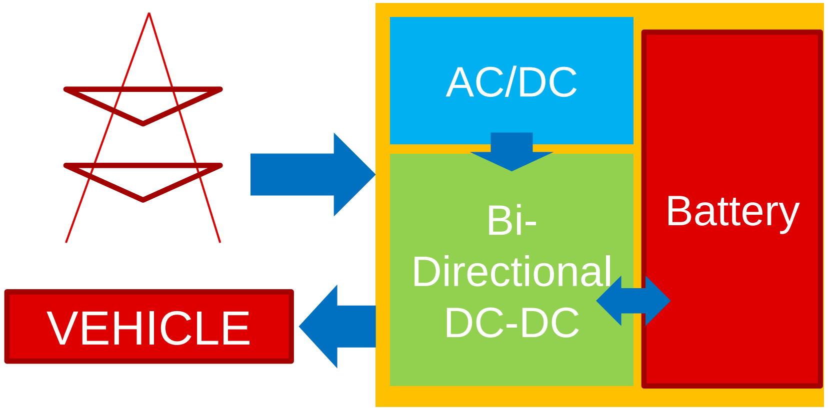
Bi-directional converters use the same power stage to transfer power in either directions in a power system.





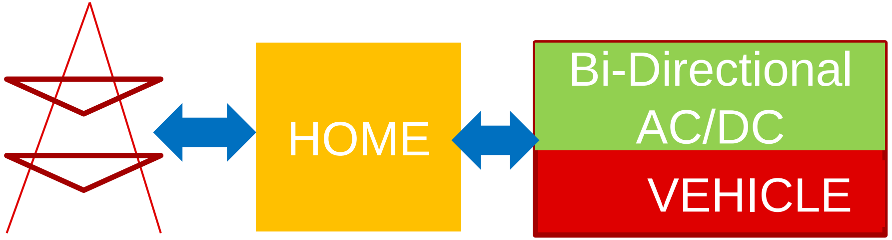
Use Case of Bi-Directional Converters

Super Chargers



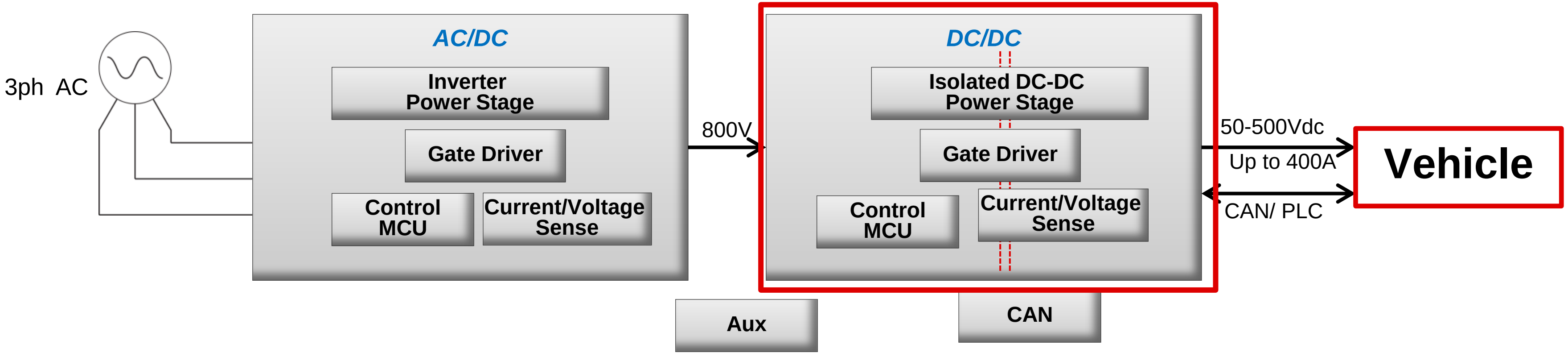
- Helps reduce peak demand tariff.
- Reduces load transients.
- Needs Bi-Directional DC-DC stage

Vehicle to Grid



- V2G needs “Bi-Directional” Power Flow.
- Ability to change direction of power transfer quickly.
- High efficiency >97% (End to End) at power levels up to 22KW.

EVSE/ESS Power Stage



Popular for ESS

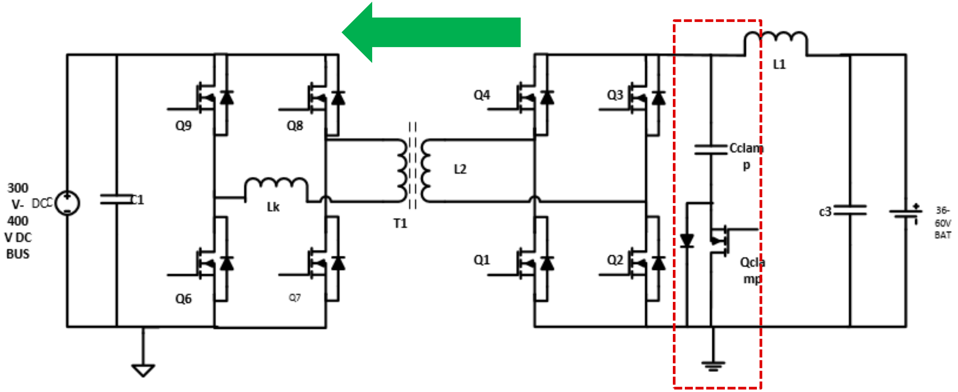
- Current fed push-pull
- Open loop fixed frequency LLC
- Active clamped Current fed push-pull

Popular for EV Charging

- CLLC
- Dual Active Bridge
- Phase Shift LLC

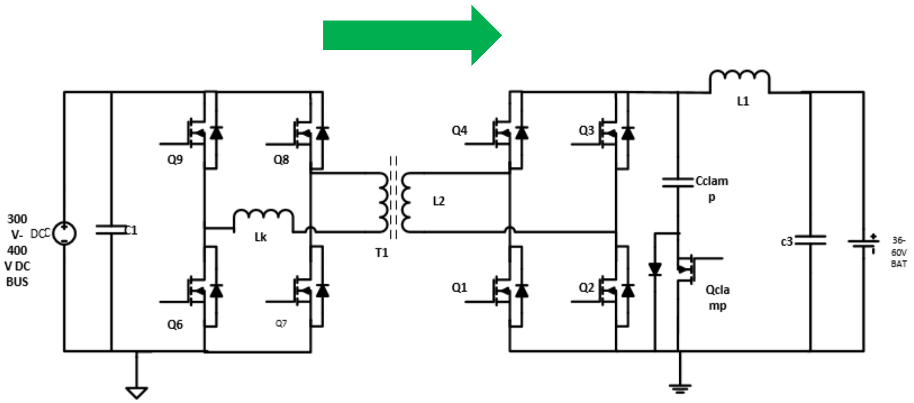
Active Clamp Current Fed Full Bridge

Backup Mode : Active Clamp Current Fed Full Bridge



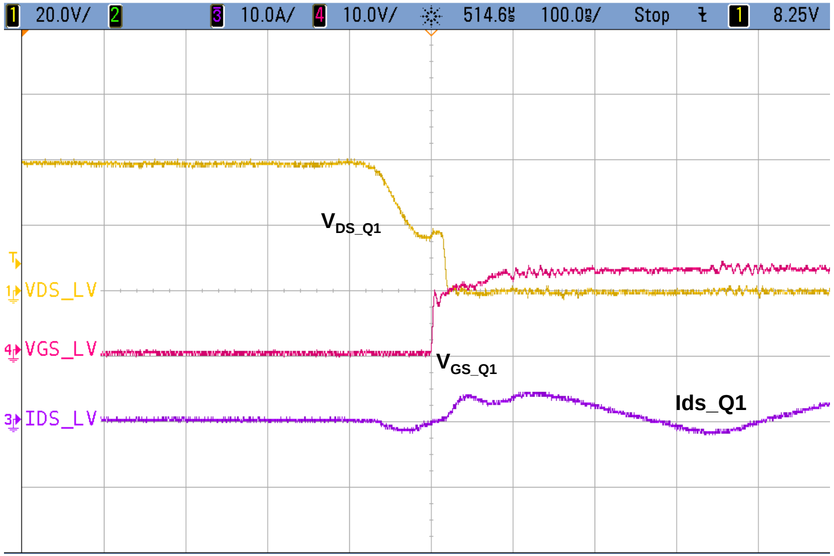
- Low Voltage Mosfet ZVS/ZCS at turn-on
- High Voltage Mosfet ZVS at turn-on and turn-off
- High Voltage Mosfet low di/dt at turn-off, low Qrr loss
- Reduced ripple current for the battery
- Peak voltage spike limited to < 5V without any snubber

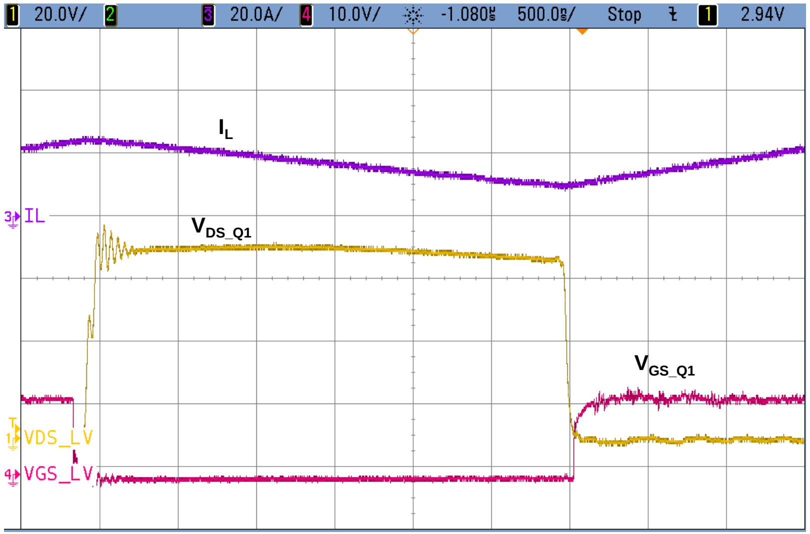
Battery Charging Mode : Phase Shift Full Bridge



- Low Voltage Mosfet Achieve ZVS turn-on and turn -off
- Reduced ripple current for the battery
- Peak voltage spike limited to < 15V without any snubber
- Soft-Switching of HV Mosfet possible if Phase-Shift control used

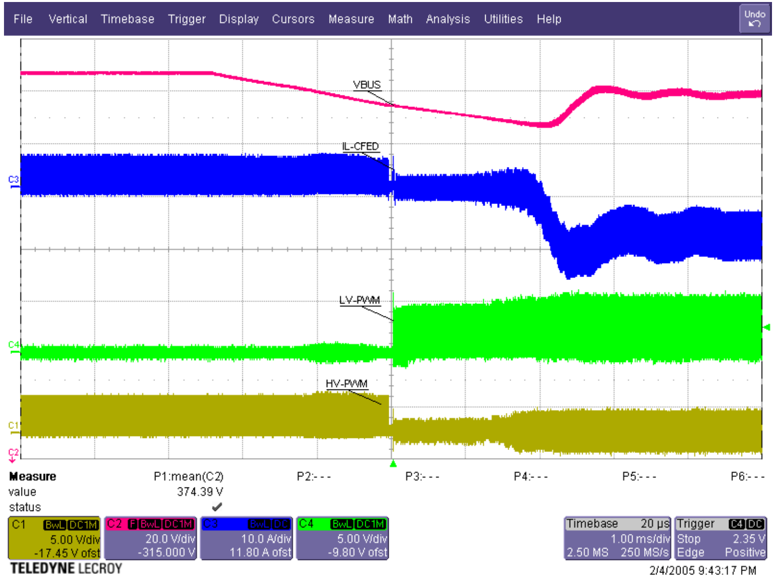
Boost Mode ZVS Waveform

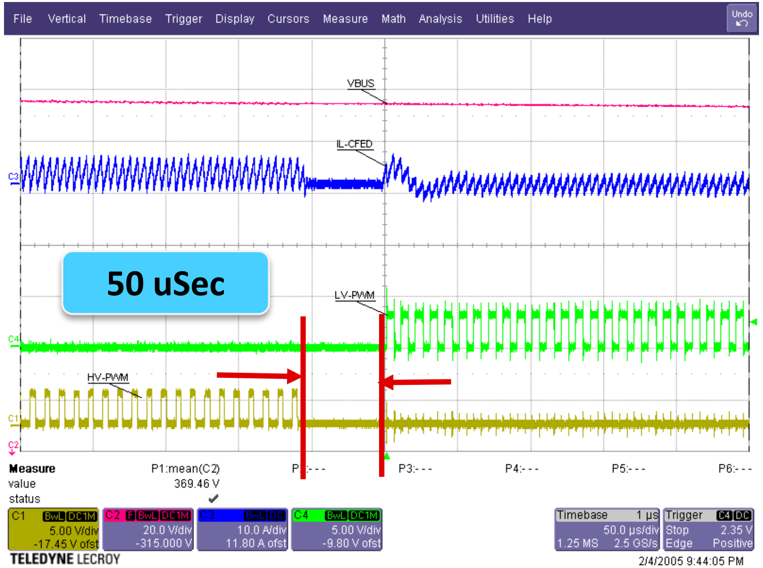




ZVS Turn on of LV Mosfet when Input Current > 15A, ZCS turn on at <15A

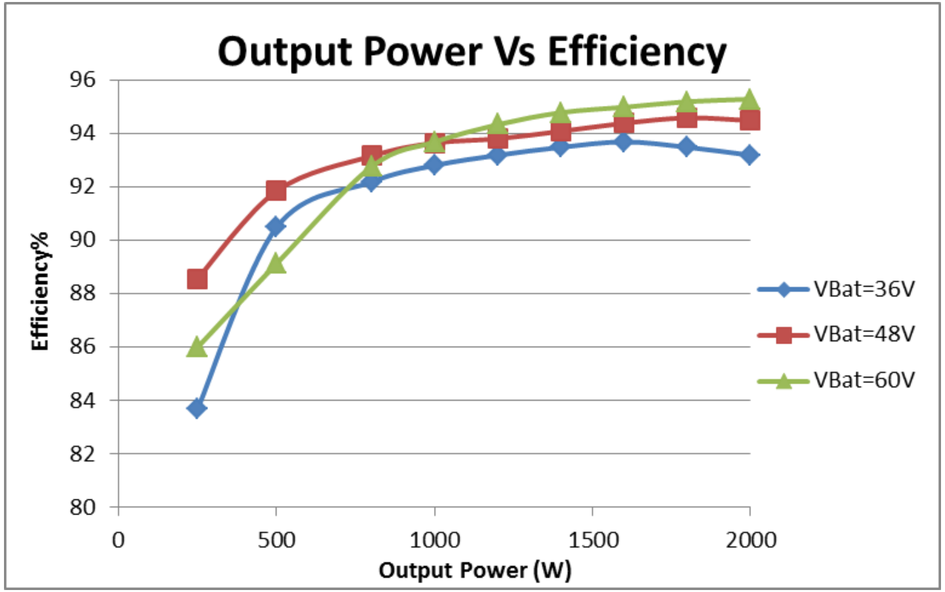
Mode Transition Waveform

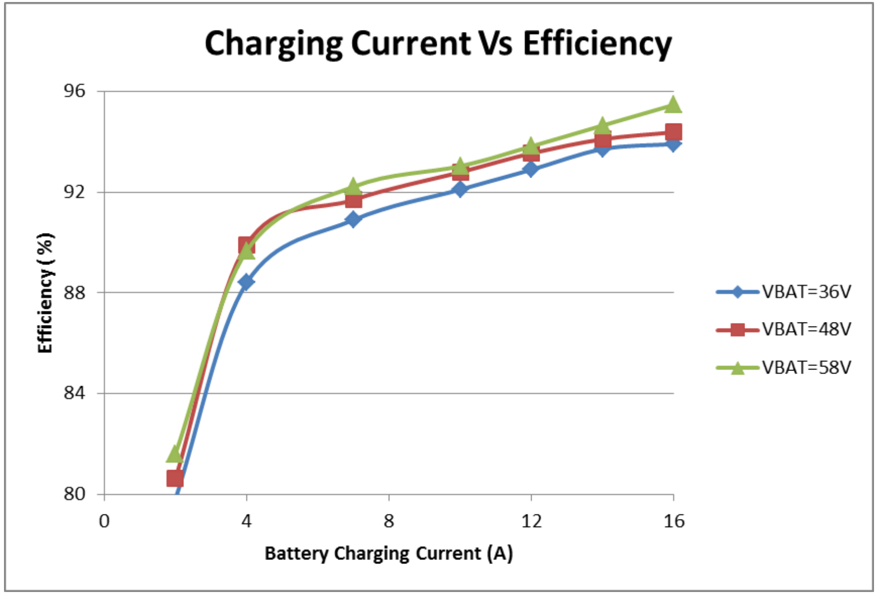




- ❑ When Bus voltage drops to 370V, Mode transition from charging to backup begins (soft start).
- ❑ When Bus voltage drops to 360V, full backup in boost mode starts

Backup Supply Efficiency





95.5% Efficiency at 60V Battery Voltage

96% Efficiency at 58V Battery Voltage

Key Points for Active Clamp Current Fed

ADVANTAGES

- simple topology for control.
- Presence of the current fed inductor:
  - Reduces battery ripple current.
  - Minimizes the filter capacitors required.
  - Prevents transformer hard saturation
  - Easy over current protection
- Achieve 96% efficiency in Backup Mode.
- Less than 15V voltage spike on mosfet helps use low voltage highly optimized mosfet.
- Battery Charging mode operation increase efficiency >96%
- Easy system paralleling possible.
- Low di/dt on high voltage mosfet, so reduced Qrr loses can use Si Mosfet for HV side

DIS-ADVANTAGES

- More Components, add to BOM cost
- Need additional low power winding at startup.
- Switching frequency limited to ~150KHz in most application.
- Additional conduction loss in clamp mosfet.

- **Power Storage**
- **EV/HEV 12– 400V Aux System**

2-kW, 48V to 400V, >94% Efficiency, Bi-Directional Converter

Features

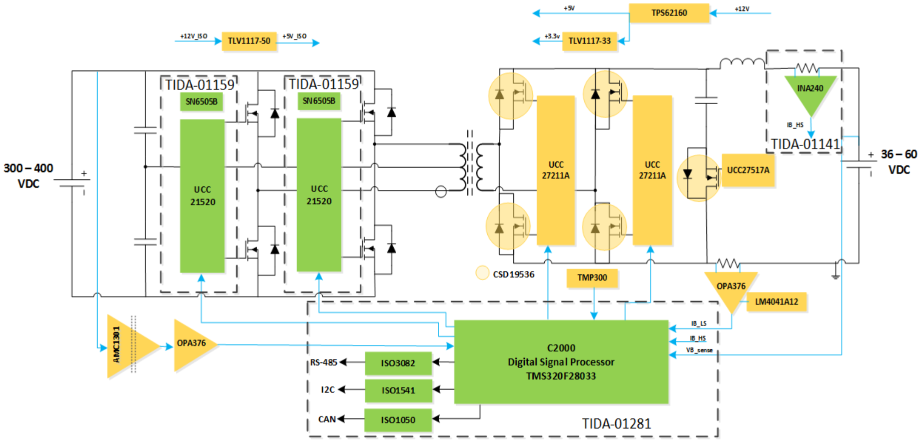
- Digitally-controlled bi-directional power stage operating as half-bridge battery charger and current fed full-bridge boost converter
- 2kW rated operation for discharge and 1kW rated for charging
- High efficiency **>95.8% as charger & >95.5% as boost converter**
- Seamless (**50uS**) transitions between charge and boost modes
- ZVS at high loads and synchronous rectification switching schemes for high efficiency
- Protections for Over current, Short circuit, OV and UV
- Communication for V & I set, direction control, & status monitoring

Benefits

- Wide operating voltage range of 300V-400VDC HV bus range and 36V to 60V LV bus range
- High efficiency boost operation at light loads with flyback mode
- Configurable for high wattages through power stage modifications
- Power limiting for high temperature operation, aids in increased product lifetime
- Form factor 1U rack mountable: 180 mm x 170 mm (approximate)

Target Applications

- Energy storage systems
- Automotive



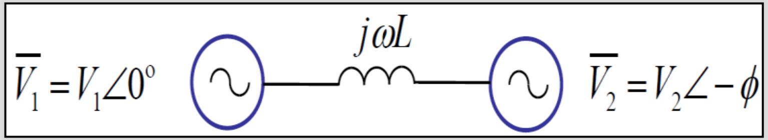
Tools & Resources

- **TIDA-0095x Tools Folder**
- **Design Guide**
- **Design Files:** Schematics, BOM, Gerbers, Software, and more
- **Device Datasheets:**
  - TMS320F28033,UCC21520,UCC27211A, CSD19536, INA240, AMC1301, TLV70422

Dual Active Bridge

DAB - Theory of Operation

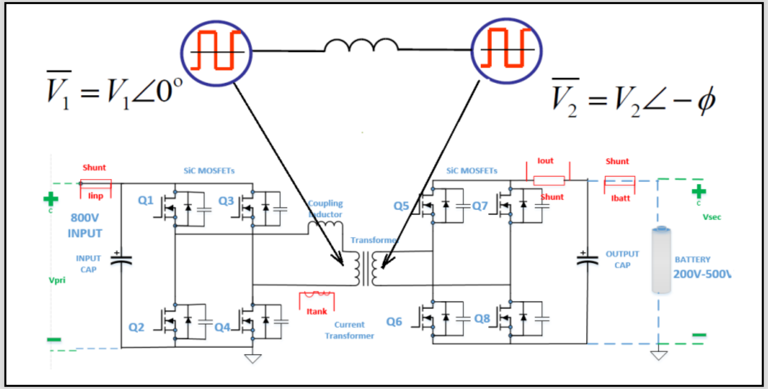
- Power transfer analogy
  - Two sinusoidal voltage sources
  - Power transfer from leading bus to lagging bus
  - The magnitude and direction controlled by varying the phase angle difference.
- High frequency square wave across the primary and secondary modulated at switching frequency
- The high frequency signals are phase shifted with respect to each other leading to power transfer.
- Lagging current discharges parasitic capacitance prior to turn on and results in ZVS.



$$P = \frac{V_1 V_2 \sin\phi}{\omega L}$$

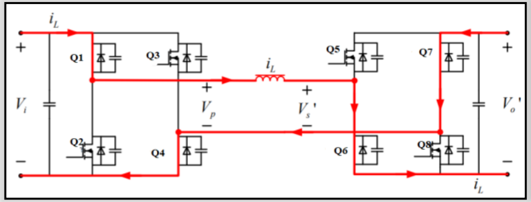
$\phi > 0$

$\phi < 0$

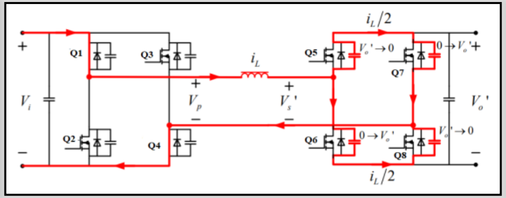


DAB - Zero Voltage Switching

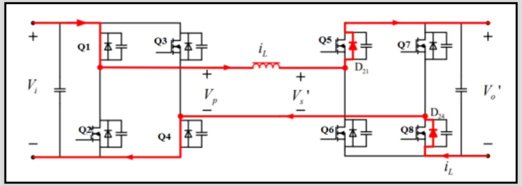
Switching transition from interval 1 to 2:



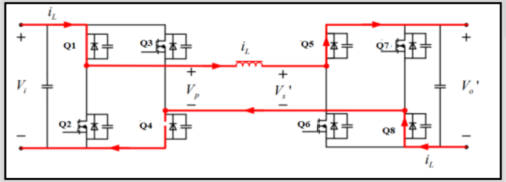
Interval 1



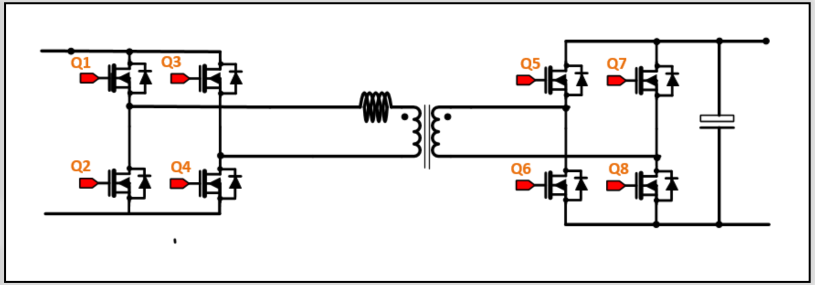
Interval 2 (capacitor)

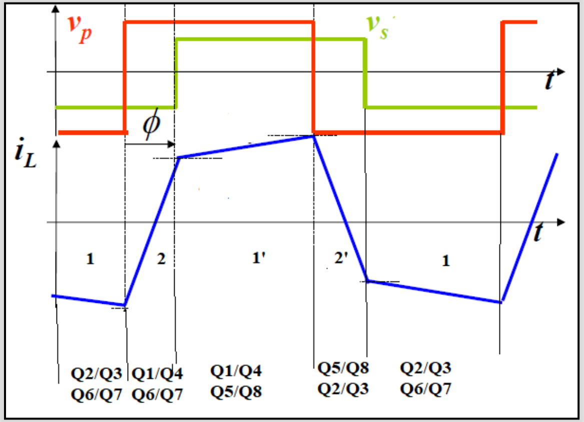


Interval 2 (diode)



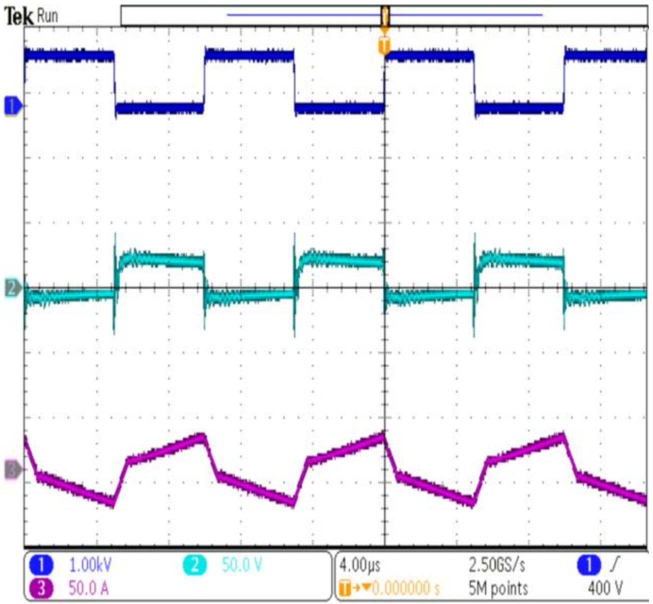
Interval 2



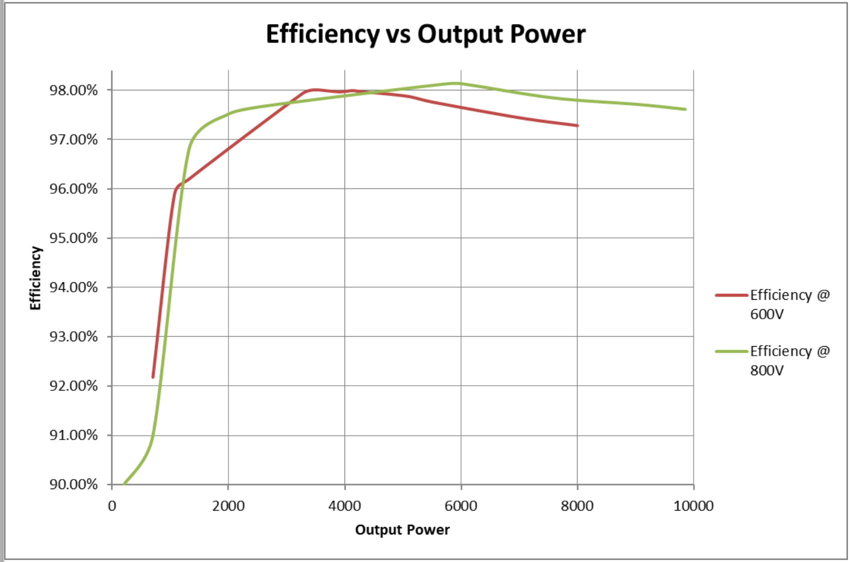


ZVS transition on secondary side			
Cap Q5	Discharges to zero	D5	Off to On
Cap Q6	Charges to Vo	D6	Off
Cap Q7	Charges to Vo	D7	Off
Cap Q8	Discharges to zero	D8	Off to On

Test Results



Steady stage switching waveforms



Peak Efficiency of 98.2% at Vout 700V

Key Points for Dual Active Bridge

ADVANTAGES

- Topology capable of achieving high efficiency.
- High switching frequency possible to increase power density.
- Capable of operating in wide input and output voltage variation condition (with reduced efficiency)
- Backup mode efficiency ~97% possible.
- Basic Single Phase Shift is easy to control.
- Easy to parallel multiple modules.

DIS-ADVANTAGES

- Preferable to use SiC or GaN
- Reduced efficiency compared to CLLC in a narrow range.

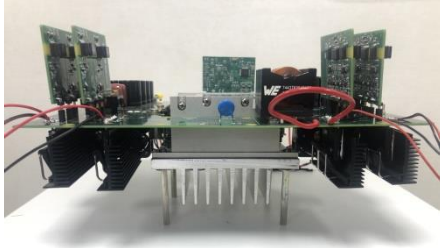
- **EV/HEV OBC /Off Board (SiC)**
- **ESS (Higher End)**

Bi-Directional Dual Active Bridge (DAB) DC:DC Design

Features

- Input Voltage: 700-800-V DC (HV-Bus voltage/Vienna output)
- Output Voltage: 380-500 V (Battery)
- Output power level: 10 kW
- Single phase DAB capable of bi-directional operation
- Soft switching operation of switches over a wide range
- Achieves peak efficiency – 98.2%, full load efficiency – 97.5%
- Less than 3% ripple target for output voltage
- Dual channel reinforced isolated gate driver
- Snubber less devices reduce parasitic device volume
- Single phase shift modulation
- Switching frequency -100 kHz, Power density – 2.25 KW/L

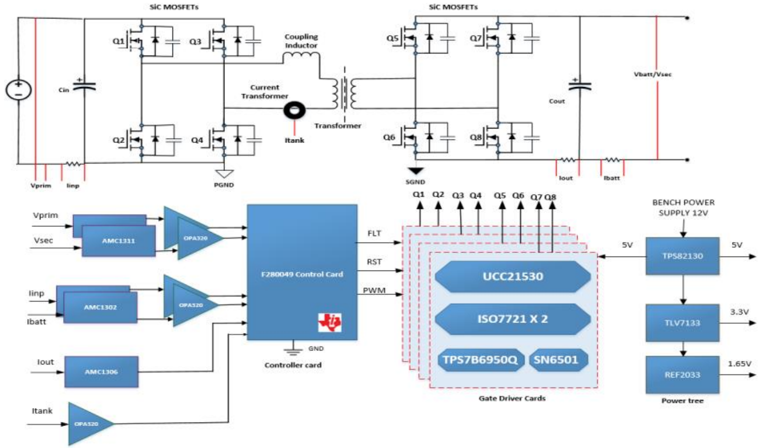
Applications



- EV charging stations, On board chargers
- Power conversion systems (PCS) in energy storage

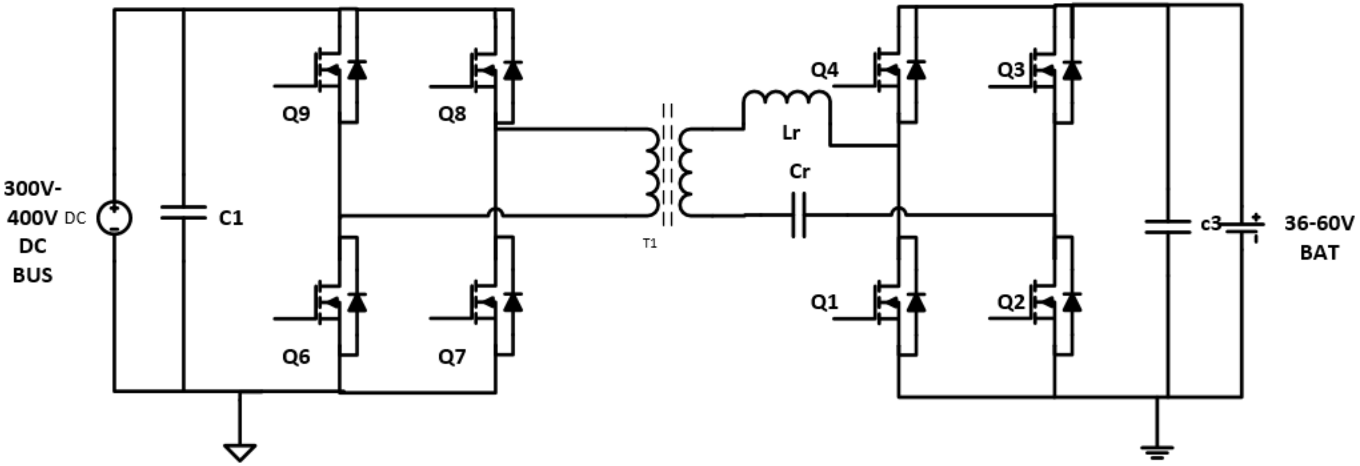
Benefits

- Single phase shift modulation provides easy control loop implementation. Can be extended to dual phase shift modulation for better range of ZVS and efficiency.
- SiC devices offer best in class power density and efficiency
- Dual channel reinforced gate driver UCC21530 reduces the total component count for driving SiC MOSFETS
- Provides modularity and ease of bidirectional operation



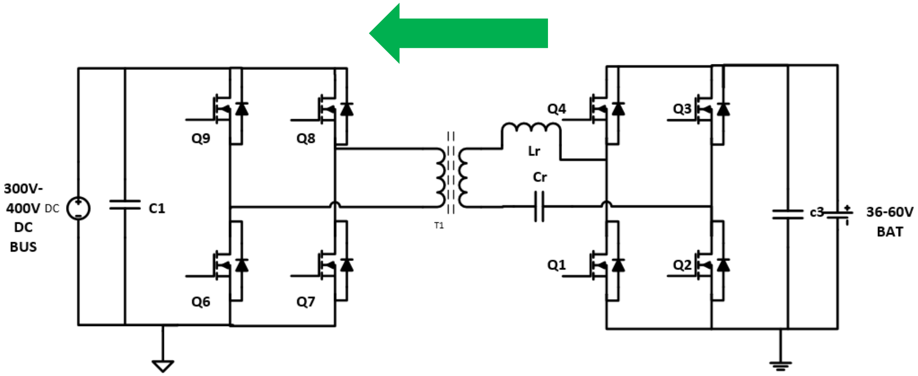
Bi-Direction Resonant Converters

Bi-Directional LLC



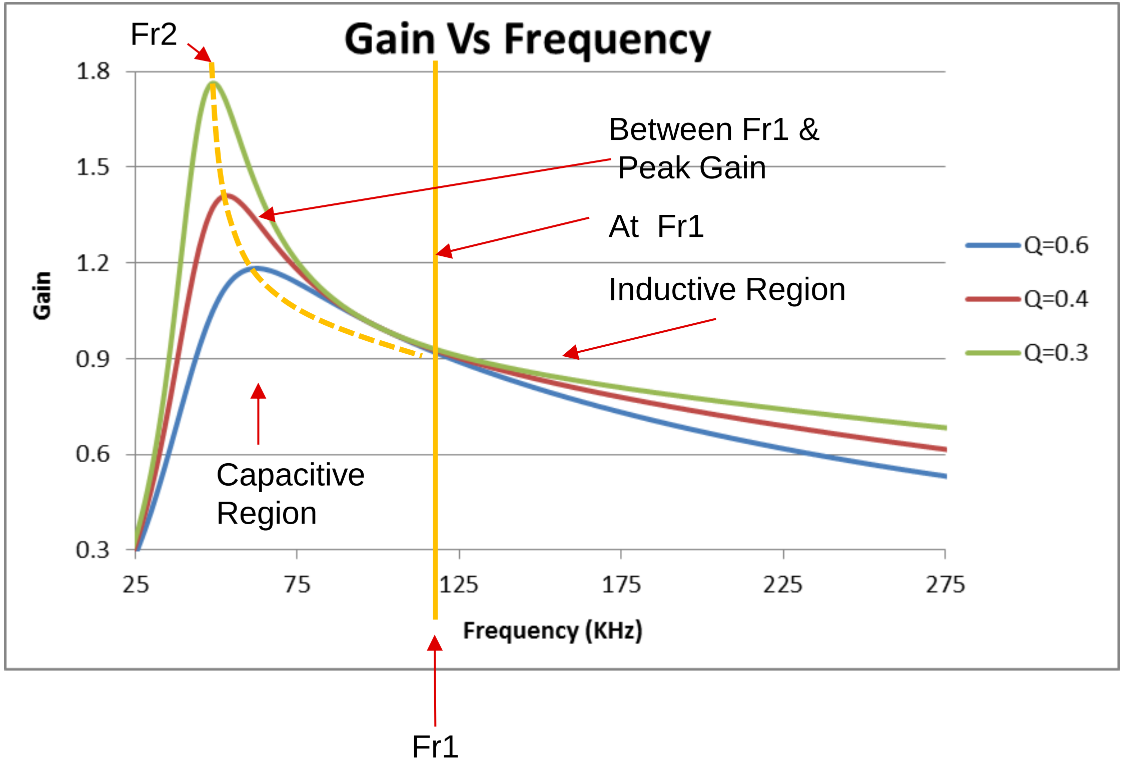
- Capable of delivering high efficiency and high power density.
- In Cost sensitive applications more suitable for narrow voltage range operation.
- For wide input/output voltage range operation, need to use GaN or SiC switches.

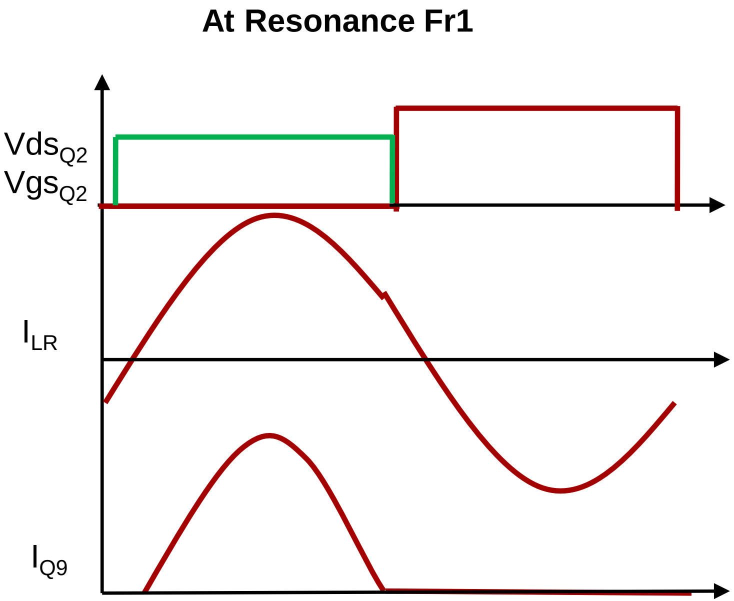
Backup Mode: Full Bridge LLC



- In this mode power transfer from battery to high voltage DC Bus.
- Power stage work as LLC Converter
- The Low voltage mosfet achieve ZVS turn-on.
- The body diode of the high voltage mosfet have ZCS turn/on and ZCS turn/off in a narrow operating region resulting in very low Qrr losses.
- If application designed to operate in this narrow range, then capable of achieving >97-97.5% efficiency

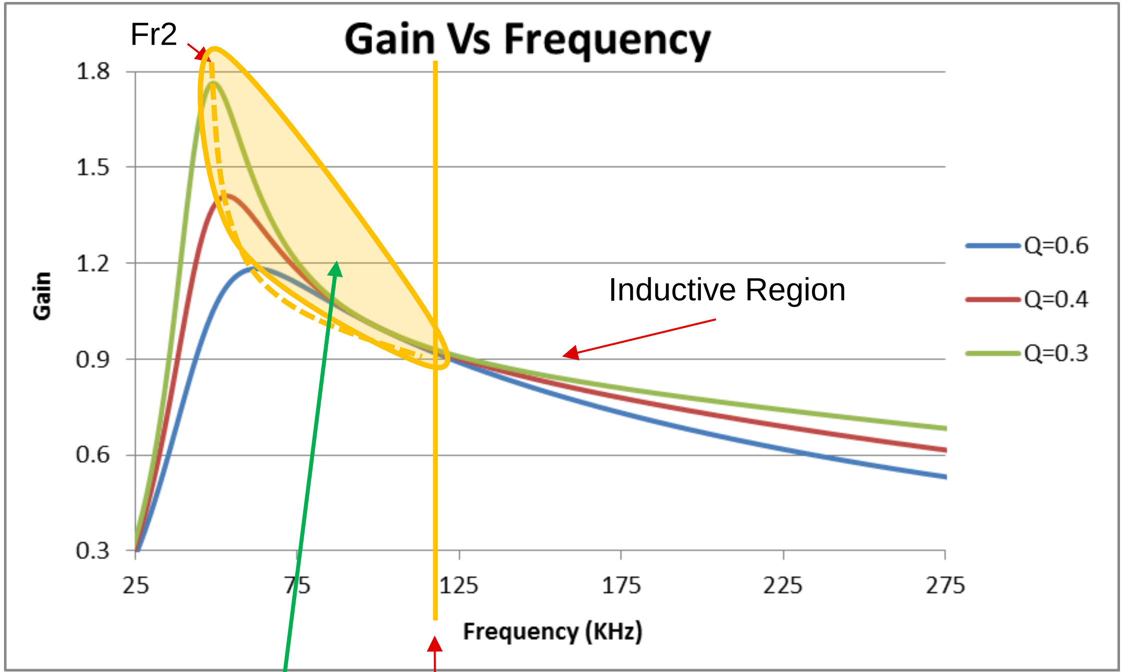
The Gain Curve





– Lowest RMS Currents
– Unity gain point
– ZVS for HV mosfet & ZCS for LV mosfet

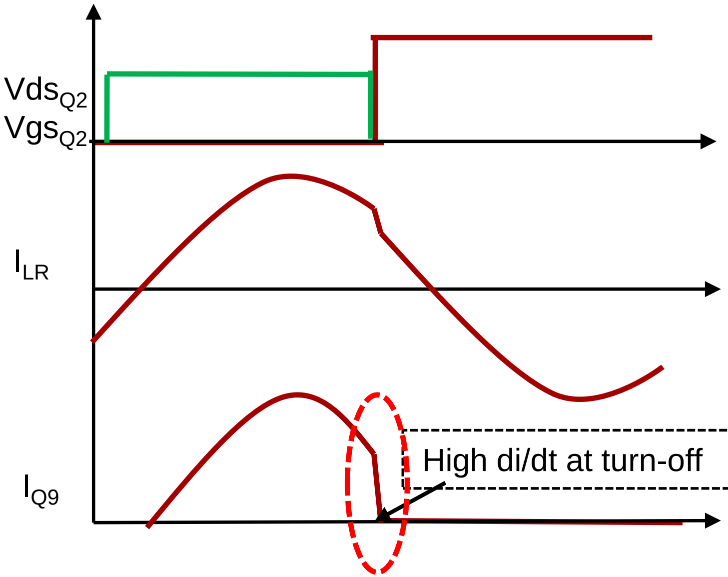
The Gain Curve



Fr1

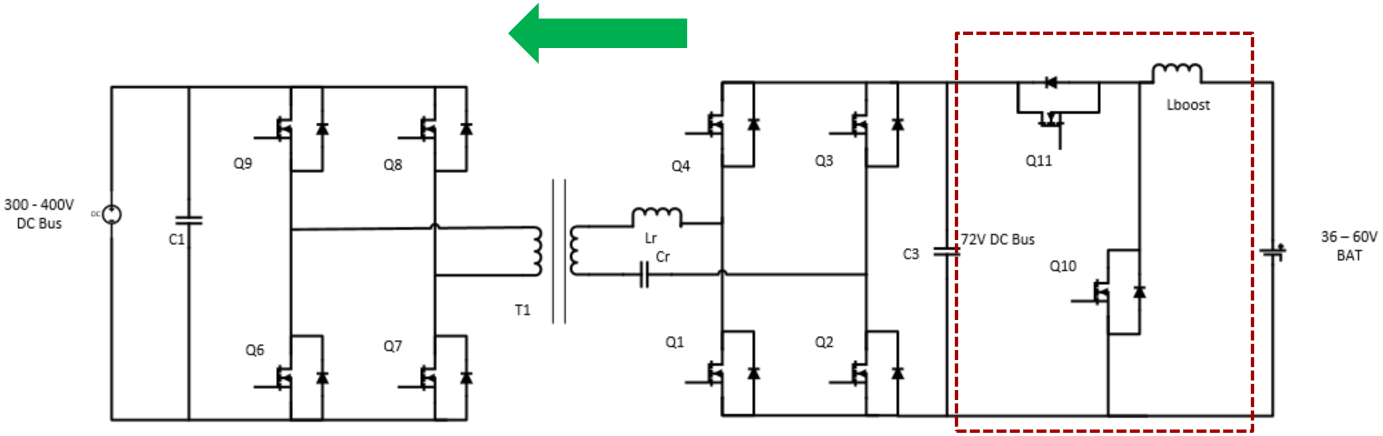
Safe operating region when using High Voltage Mosfet.
For SiC or GaN, can operate even in inductive region

Inductive Region >FR1



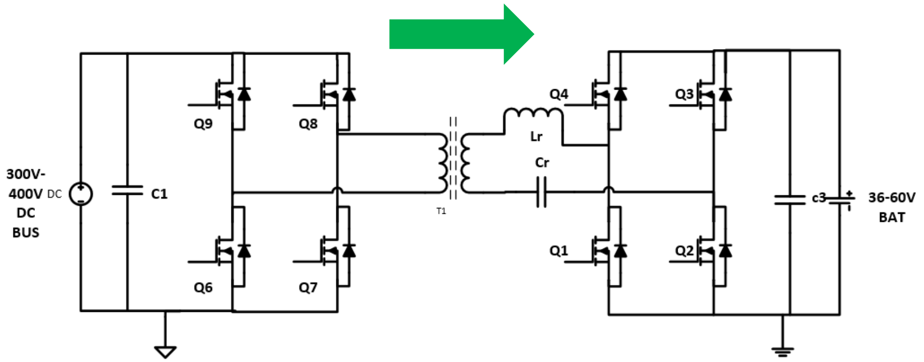
- Frequency Increases to operate at light load
- ZVS for HV mosfet
- High di/dt on LV mosfet results in Qrr losses

Need for 2nd Stage for Wide Operating Region



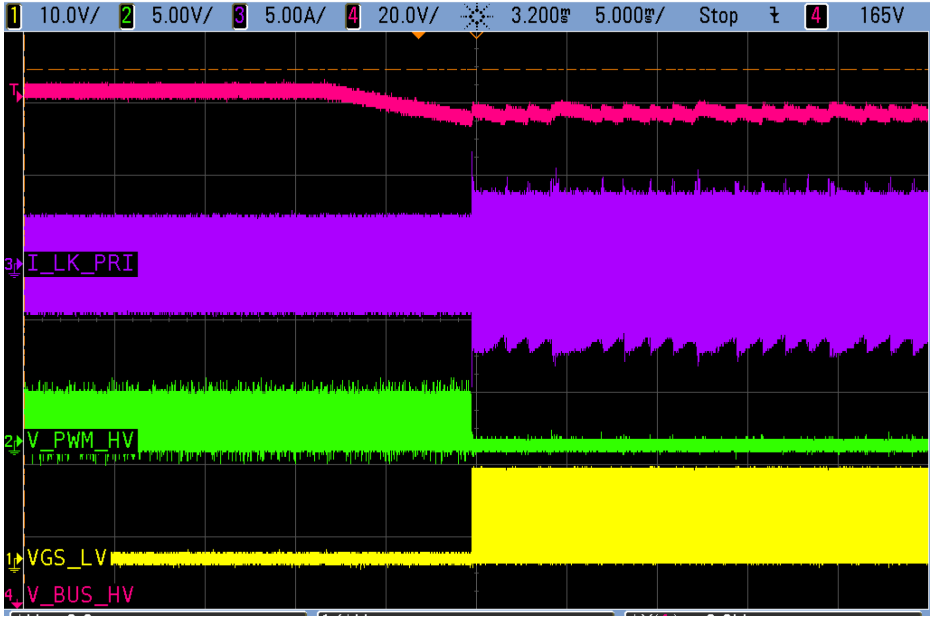
- The second conditioner stage boosts the batter voltage to a fixed 72V (an example).
- This can help operate the LLC converter operate at fixed frequency.
- This enables use of HV Si Mosfets for cost optimized applications.

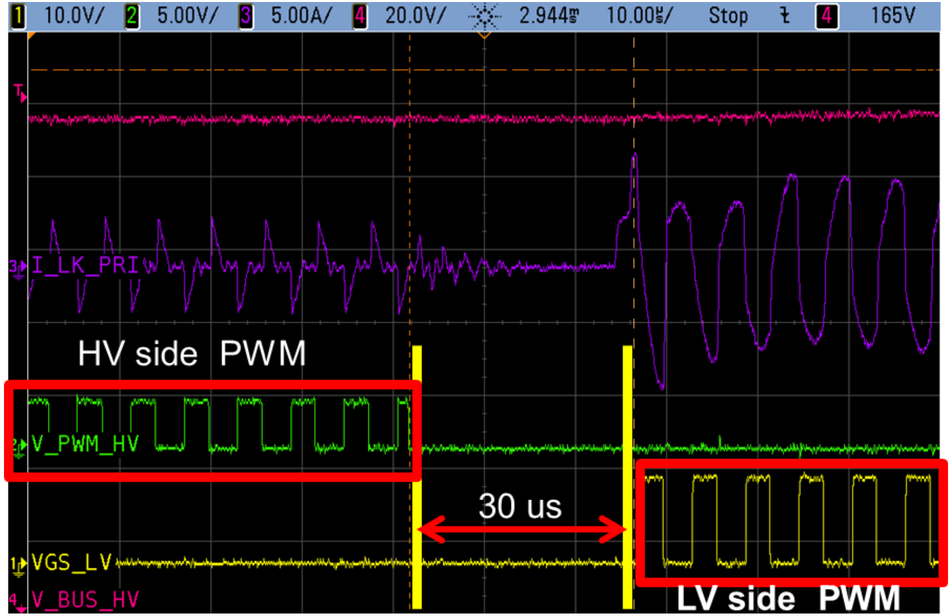
Battery Charging Mode: Full Bridge LC



- In this mode power transfer from high voltage DC Bus to battery.
- Power stage work as ‘LC Converter’
- The High voltage mosfet achieve ZVS turn-on.
- The body diode of the low voltage mosfet have high di/dt at turn-off. Some have some Qrr loss.
- At light load, need to operate in burst mode.
- Efficiency upto 95% possible when the Low voltage mosfet is operated as synchronous rectifier.

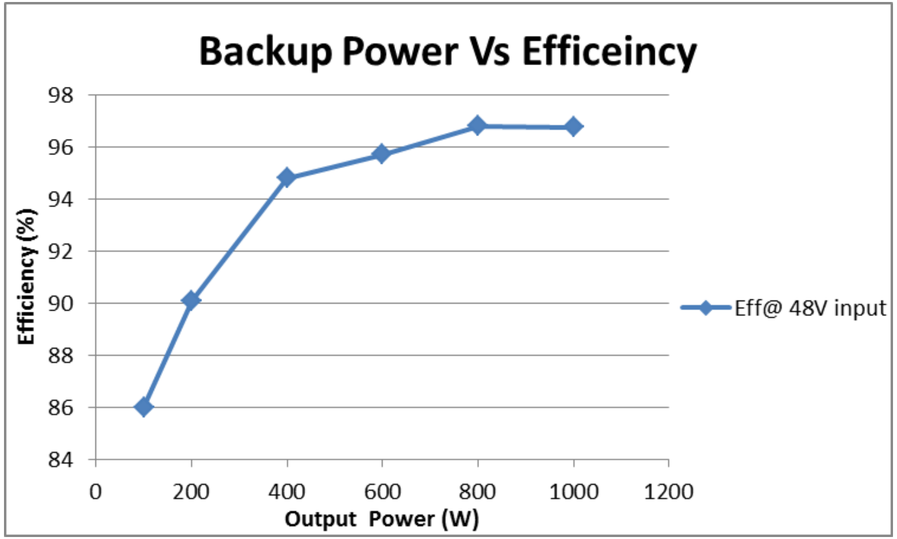
Mode Transition Waveform: Charging to Backup

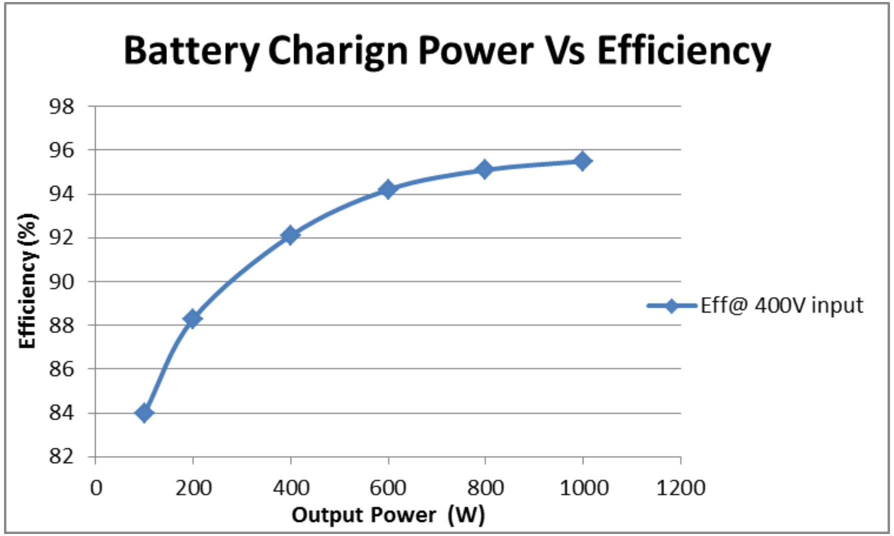




<30uS Mode transition from Charging to Backup

Efficiency Results





Peak Efficiency 96.9% in prototype Board

Peak Efficiency 95.2% in prototype Board

Key Points for Fix Frequency Resonant Converters

ADVANTAGES

- Topology capable of achieving high efficiency.
- High switching frequency possible to increase power density.
- Backup mode efficiency ~97.5% possible.
- Using C-LLC, battery charging mode efficiency also can be further increased.

DIS-ADVANTAGES

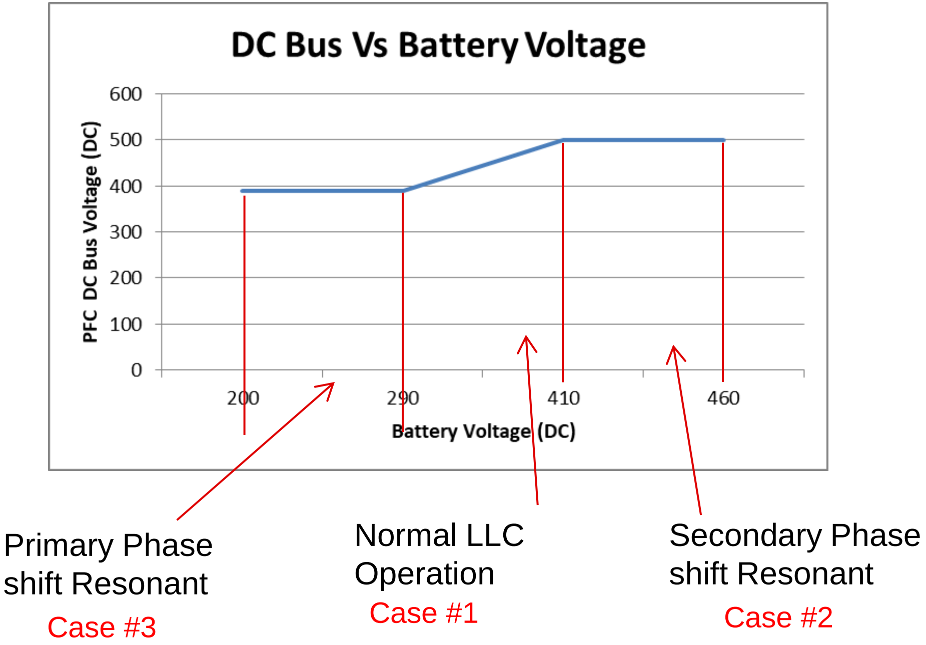
- Slightly Complex topology for control
- Using high voltage mosfet limit operating range.
- Preferable to use SiC or GaN
- Topology suitable for limited input/output voltage range region.

- **ESS**
- **EV/HEV OBC /Off Board (SiC)**

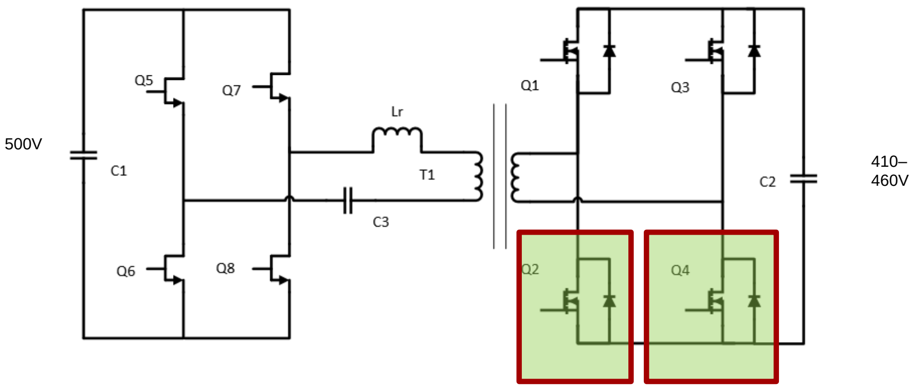
Phase Shift Resonant Converters

Hybrid Control Strategy for Wide Input and Output Voltage Range Applications

- Addition of Phase shift Control, allows us to vary the resonant tank gain without changing the switching frequency.
- Primary phase shift to reduce the gain.
- Secondary phase shift to increase the gain.

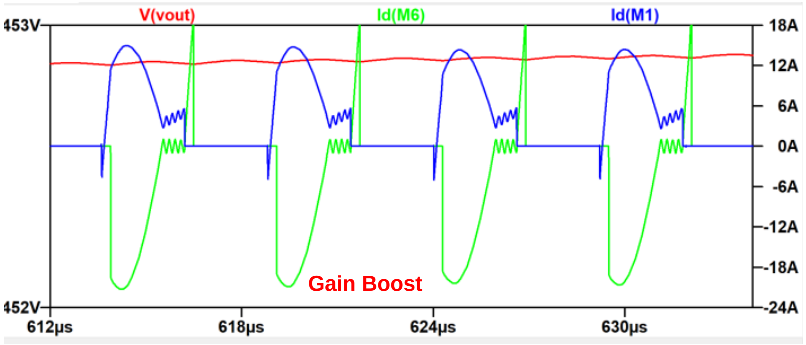


Case #2 Battery Voltage Between 410 – 450V



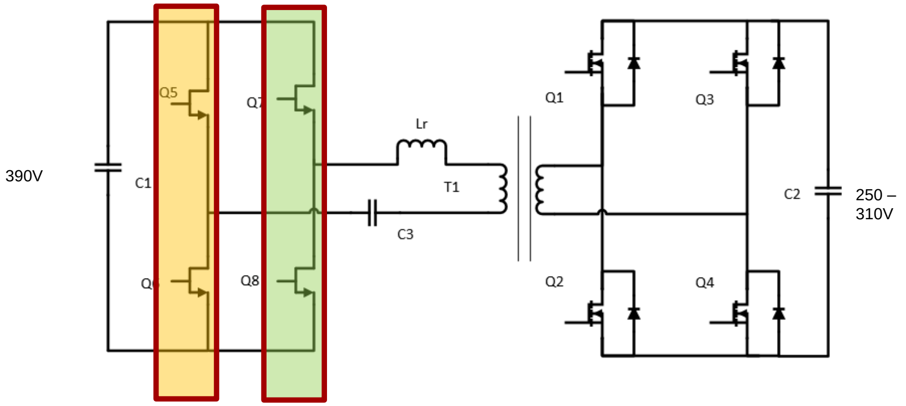
- Secondary side phase shift + Resonant LLC operation.
- Very little reduction switching frequency. This results in reduced increase in RMS current
- Achieves high efficiency.
- ZVS for primary mosfet. Slight turn-off loss for secondary mosfet.

Key operating waveform



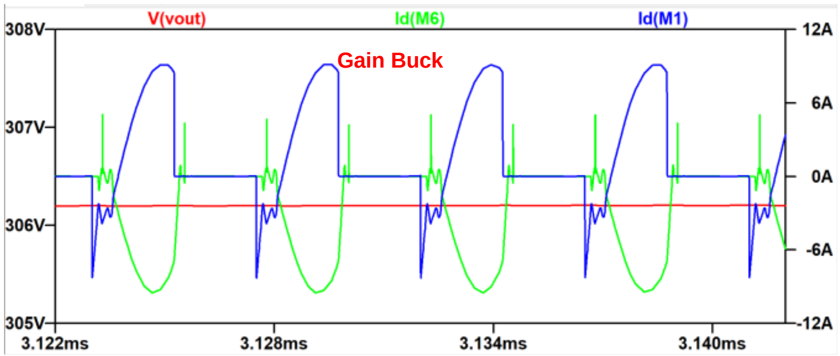
- Green waveform shows the secondary SiC current. Can clearly see the non ZCS operation at turn off, resulting in slight increase in switching loss.
- Blue waveform shows the GaN switch current indicated ZVS.

Case #3 Battery Voltage between 250-310V



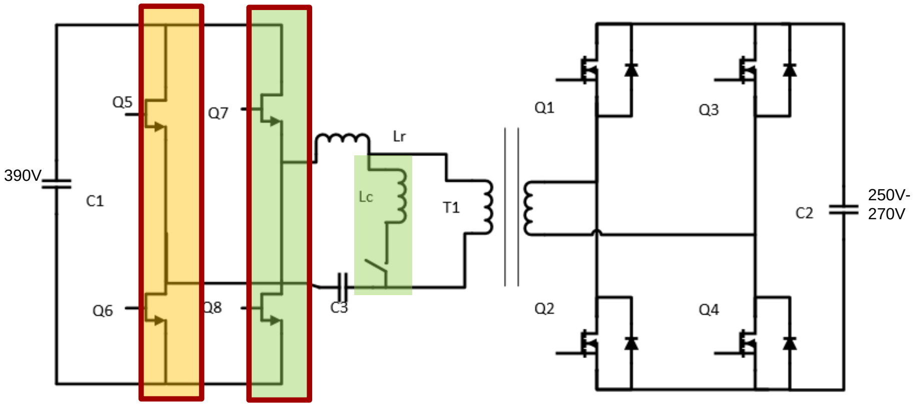
- Primary side phase shift + Resonant LLC operation.
- The added phase shift helps in clamping the max switching frequency of the converter.
- This can help in both reducing switching loss and above resonant frequency operation.
- ZVS for primary mosfet. ZCS for the secondary SiC

Key operating waveform



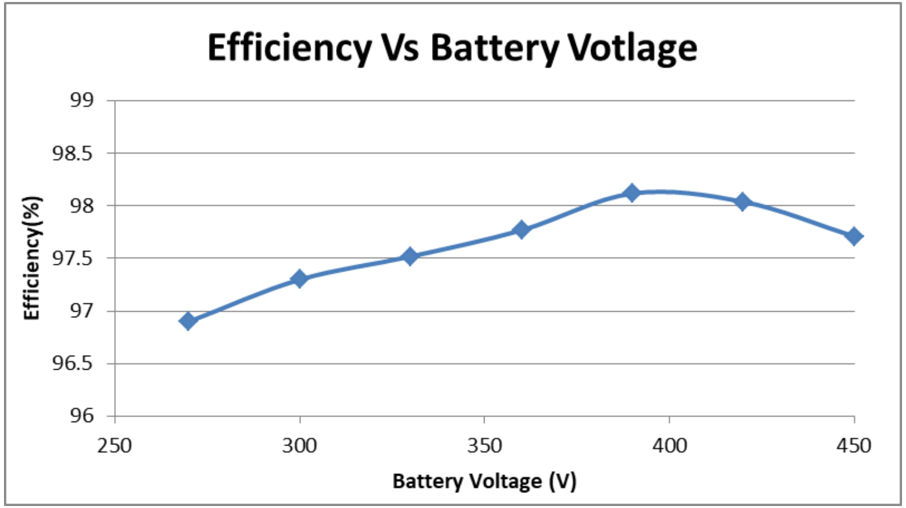
- Green waveform shows the secondary high voltage SiC current.
- Blue waveform shows the GaN switch current indicated ZVS.

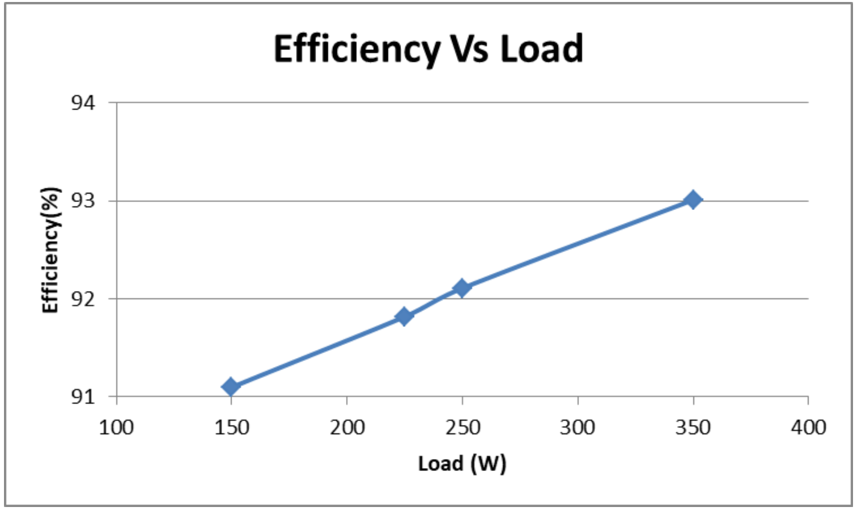
Case #4 Enhanced Case #3 with Range Extension



- At very light loads and lower voltage range, primary phase shift cannot gaurantee ZVS turn-on of the GaN switches.
- This lowers the efficiency, as well as can lead to huge temperature rise on the GaN switches.
- An additional inductance is switched into the system to increase the primary circulating current, thus ensuring ZVS across full load and line ranges.
- This inductance is switched in and out using a snubbed bi-directional low switches.

Hybrid Efficiency Result





Load Fixed at 1.1KW
while Output Battery Voltage varies

Light load efficiency
Battery Voltage fixed at 250V

Key Points for Phase Shift LLC

ADVANTAGES

- Topology capable of achieving wide range input and output voltage variation with high efficiency.
- High switching frequency possible to increase power density.
- In some applications, can eliminate a second stage DC/DC .
- Backup mode efficiency ~97.5% possible.
- Enables single stage LLC operation using Si Mosfet for wide line and load ranges.

DIS-ADVANTAGES

- Complex topology for control
- Needs high bandwidth isolated current sensing

- **ESS**
- **EV/HEV OBC /Off Board (SiC)**

97.5% Efficient, 3.3KW Off Board EV Charger with GaN

In Design

Features

- Dual Phase shift FB LLC topology
- Full load efficiency >97% with peak efficiency >97.5%
- Extended battery voltage support from 250V to 450V DC
- Compact form factor 179x100x45mm
- Using GaN for LLC primary stage, SiC for LLC secondary
- Output OCP, OVP, Short-circuit Protection, OTP
- Meets Norms: EN–55022 class A (CE)

Benefits

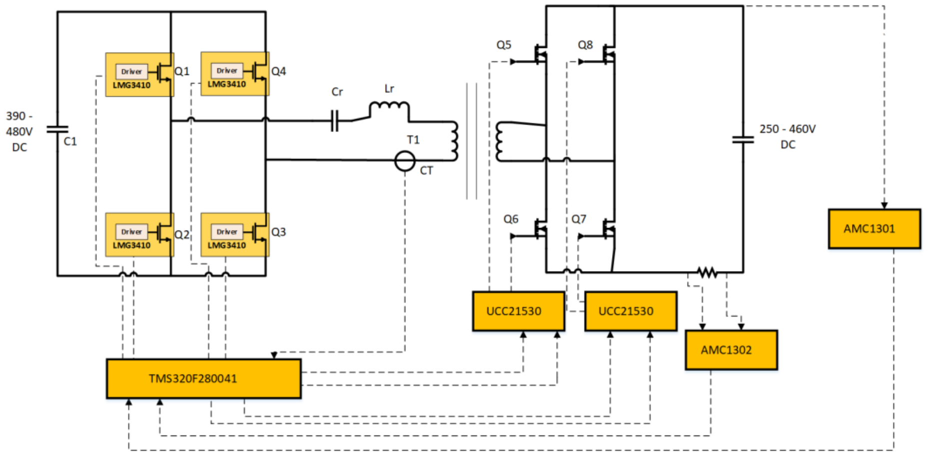
- Dual phase shift resonant control enables wide output battery voltage range.
- Minimal DC Bus voltage variation limited to 390-480V DC.
- LLC stage switching between 200KHz to 500KHz enabling a compact power stage while optimizing efficiency.

Target Applications

- Off Board EV Charger

Tools & Resources

- **TIDA-0xxx and Tools Folder**
- **Design Guide**
- **Design Files:** Schematics, BOM, Gerbers
- **Device Datasheets:**
  - UCC256403, UCC28064A



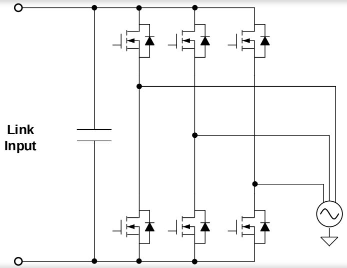
Topology Summary : Bi-Directional DC/DC

Param	ACTIVE Clamp	LLC	CLLC	DAB	PS-LLC
Suitable Application	ESS	ESS	EV	EV	EV/ESS
Wide Battery Voltage, Fixed Bus Voltage	Yes	No, needs additional DC/DC stage	Limited range	Yes (with reduced efficiency)	Yes (if a 10% bus voltage variation is acceptable)
Efficiency in Backup Mode (nominal voltage)	Medium	High	High	High	High
Efficiency in Charging Mode (nominal voltage)	High	High	High	High	High
Mode change from Buck to Boost (50uS)	Easy	Easy	Easy	Easy	Easy
Startup procedure (in cold start condition)	Needs a low power startup winding	No need for startup winding	No need for startup winding	No need for startup winding	No need for startup winding
Paralleling Modules	Easy	Intensive	Intensive	Easy	Intensive
Switching Frequency	Low	Fixed/ High (Si /SiC)	High	High	High (advantage clamp frequency range)

AC/DC Topologies

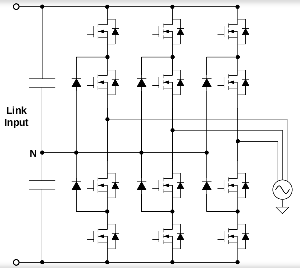
Inverter Topologies

Two level h-bridge



- Simple, well known architecture.
- Low component cost.
- Simple control structure.
- Losses are concentrated in few devices.
- Link voltage limited to component voltage rating.

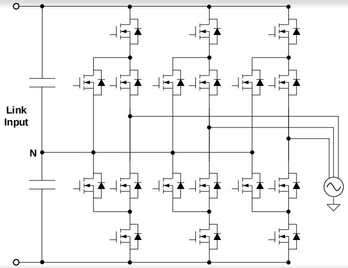
Three level NPC



- Stacks multiple switching devices to “double” link voltage limit.
- Able to use lower voltage/cost devices.
- Neutral point clamp centers switching devices.
- Unequal component loss distribution.
- Increased conduction loss.
- More complex control structure.

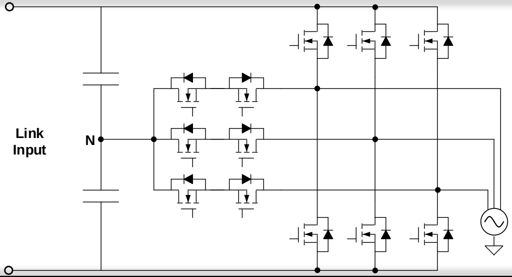
Inverter Topologies

Three level ANPC inverter



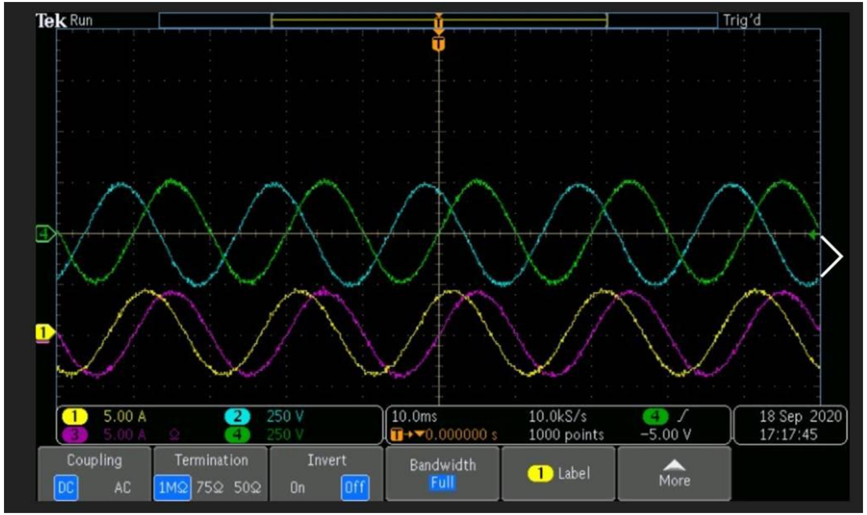
- Clamping diode replaces with active device.
- Similar benefits of NPC.
- More complex control structure.
- Similar losses to NPC, but balanced across devices.
- Increased conduction loss.

Three level TNPC inverter



- Reduced switching device count.
- Lower conduction loss.
- Simplified driver bias supply vs NPC and ANPC.
- Simplified control structure vs NPC and ANPC.
- Primary switches still experience full DC link voltage (blocking).
- Reduced switching voltage – half DC link voltage

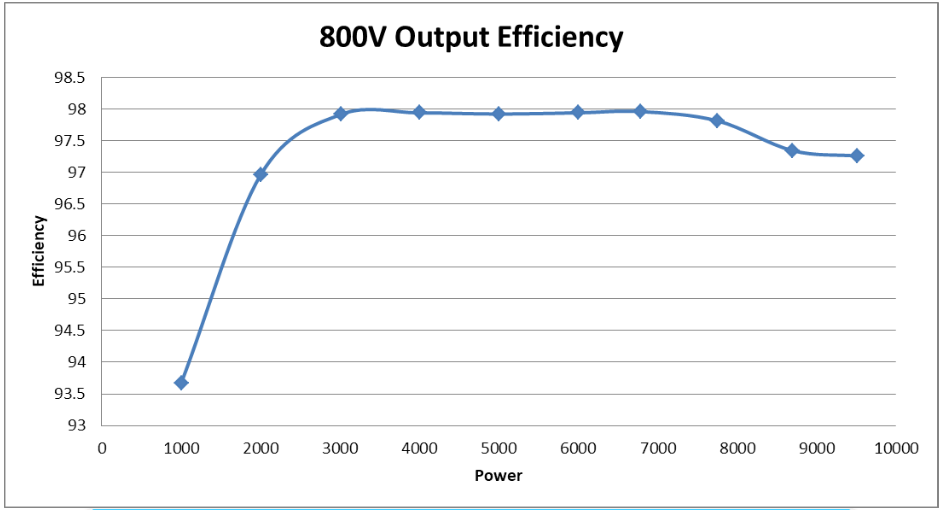
Test Results – Inverter



3 phase output voltages with resistive load

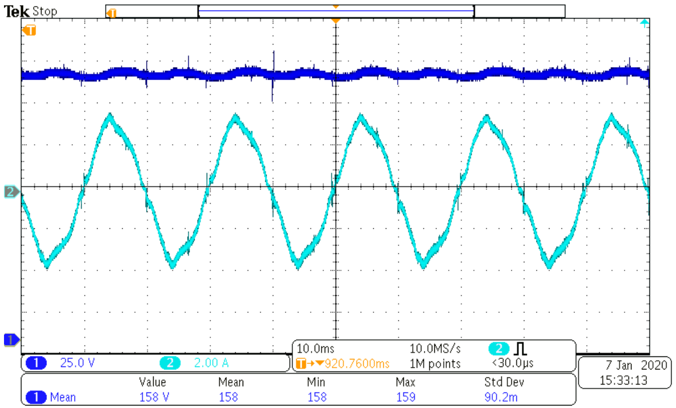
Peak Efficiency ~99% in the Inverter operation at 800V DC input

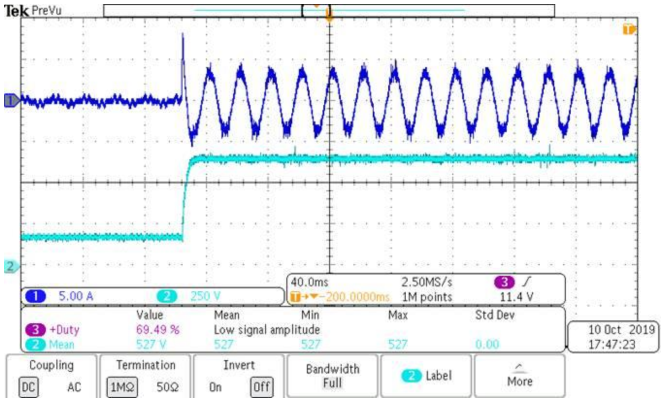
Test Results – PFC



Peak Efficiency 97.9% at 400VAC input

PFC Operating Waveforms





Key Points for Three Phase T-type

ADVANTAGES

- T-type topology offers the best compromise between conduction and switching losses at this voltage level.
- High power density due to SiC & reduced inductor sizing.
- Simple control for both PFC and Inverter Operation

DIS-ADVANTAGES

- Lower efficiency than ANPC at higher power densities and power level.

- **EV/HEV OBC /Off Board (SiC)**
- **ESS**

10KW, 3Ph T-Type PFC/Inverter

Features

- Rated nominal/Max DC voltage at 800V/1000V DC
- 3-Ph 3-Level PFC/inverter topology
- Max 10kW/10KVA power at 400VAC
- High Voltage (1200V) SiC MosFET based full bridge PFC/inverter for Peak efficiency of 98.5%
- PWM Frequency 50KHz, THD<2% at full load.
- Isolated current sensing using AMC1301 for load current monitoring
- **TMS320F28379D** Control card for digital control.
- Platform for testing both 2-level and 3-level inverter by enabling or disabling middle devices through digital control.

Applications

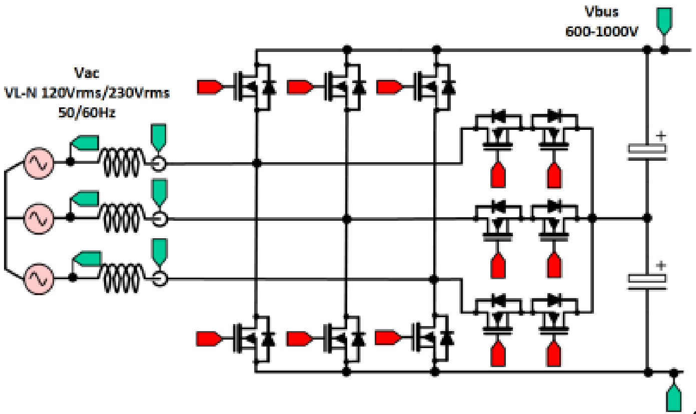
- Energy storage systems, solar inverters

Tools & Resources

•**Design Files:** Schematics, BOM and BOM Analysis, Design Files
•**Key TI Devices:** ISO5852S, UCC5320, SN6505, AMC1306, TMS320F28379D, OPA4350, PTH08080WAZT

Benefits

- 3-Level T-type inverter topology for reduced ground current in transformer-less grid-tie inverter applications
- Reduced size at higher efficiency using low R_{DS_ON} SiC MOSFETs and higher switching frequency (50kHz) at higher power (10kW)
- Platform for testing both 2-level and 3-level inverter by enabling or disabling middle devices through digital control



6.6kW, 3 Phase, Bi-Directional ANPC Power Stage Design for ESS

In Design

Features

- Power stage for **three phase inverters and PFCs using SiC**
- Up to 15A current (on AC side) capable
- Bidirectional operation with less than 1ms direction changeover
- High efficiency (98% at 400V output)
- High frequency operation (100KHz)
- Non-unity power factor capable
- Isolated current sensing for excellent noise immunity

Benefits

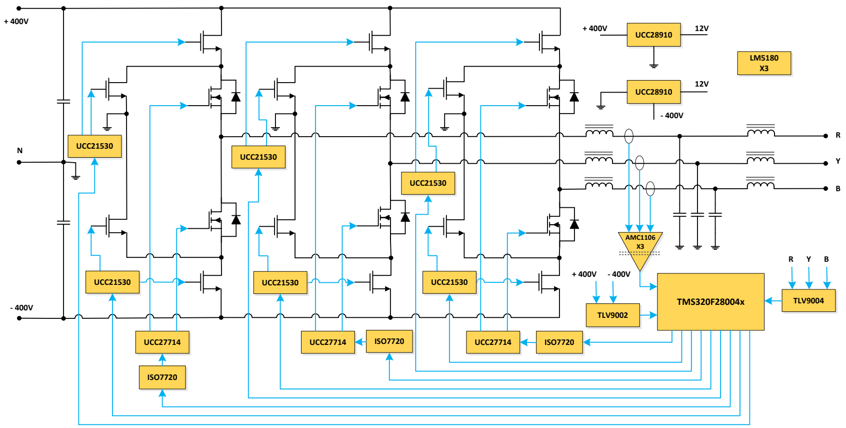
- Reduced size of power stage due to high switching frequency and high efficiency (less heat sinking)
- Switching devices are lower voltage rated (650V)
- Low component stresses help to improve system reliability
- Only 9 PWMs needed from MCU – simple control scheme
- Only four high frequency switching devices per arm – lower cost

Target Applications

- Energy Storage Systems (Three phase)

Tools & Resources

- TIDA-0xxxx and Tools Folder
- Design Guide
- **Design Files:** Schematics, BOM, Gerbers, and more
- **Device Datasheets:**
  - UCC21220, AMC1106, ISO7721, UCC28910, TMS320F28004x



Topology Summary: Bi-Directional AC/DC

	2-Level	3-Level NPC	3-Level ANPC	3-Level TNPC
THD of output current	High	Very low	Very low	
Peak voltage stress on active and passive devices	High	Low	Low	Low /(High Blocking)
Power density	Low	High	Higher	High
Bidirectional	Yes	Yes	Yes	Yes
Conduction loss	Low	high	Mid	Mid
Switching loss	High	Low	Low	Mid
Efficiency	Low	Mid	Highest (at high frequency)	High
Cost	Low	Mid	High	Mid
Control	Easy	Mid	Complex	Mid
Input inductor size	Large	Low	Low	Low