Application Report

Power Topology Considerations for Solar String Inverters and Energy Storage Systems

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ABSTRACT

As PV solar installations continues to grow rapidly over the last decade, the need for solar inverter with high efficiency, improved power density and higher power handling capabilities continues to scale up. In addition, more and more solar inverters are looking to integrate energy storage systems to reduce energy dependency on the central utility gird. This application report looks into topology considerations for designing power stages commonly used in Solar Inverters and Energy Storage Systems (ESS).

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1 Introduction

Solar string inverters are used to convert the DC power output from a string of solar panels to a usable AC power. String inverters are commonly used in residential and commercial installations. Recent improvements in semiconductor technology is allowing for string inverters with high power density (from 10s of kW to 100s of kW). Due to modularity and ease of serviceability of string inverters, they are becoming a popular alternative over central inverters.

The main limitation of solar installations is the supply and demand gap - solar energy is abundantly available during peak day hours when the demand for energy is not high. So electrical energy generated from solar power has low demand. This problem has spawned a new type of solar inverter with integrated energy storage. This application report identifies and examines the most popular power topologies used in solar string inverters as well as Power Conversion Systems (PCS) in Energy Storage Systems (ESS).

2 Solar String Inverters

Figure 2-1 shows the typical architecture of a solar string inverter.

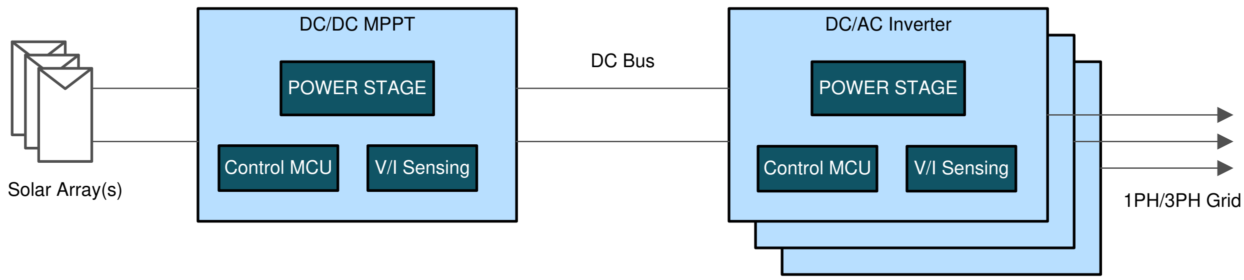

Figure 2-1. Block Diagram of Solar String Inverter

As Figure 2-1 illustrates, there are two major power blocks in the string inverter. The first is a DC/DC power stage that converts the variable string output to a stable high-voltage DC link suitable for DC/AC inverter stage. For a single phase power stage, it is typically 400 V and for three phase, around 800 V. This DC/DC stage also works as a Maximum Power Point Tracking (MPPT) converter. This DC link voltage is converted to AC voltage at the grid voltage level by the second block which is a DC/AC inverter power stage. A more detailed block diagram of Solar String inverter is available on TI's *String inverter* applications page.

2.1 Power Stages for DC/DC MPPT

The MPPT DC/DC power stage performs the functions of translating the string voltage to a level suitable for the inverter (typically 400 V for single phase and 800 V for three phase) and Maximum Power Point Tracking (MPPT). The current trend is towards increasing this DC link voltage to 1000 V or beyond to reduce power losses in the system and to allow more panels to be added in series. In certain cases, it will have two power stages – a boost converter stage working as MPPT and an isolated DC/DC power stage to have safety isolation between the grid and the solar panels and to reduce the DC link voltage variation. However, in most cases, all these functions are performed by a single power stage – a non-isolated one in case there is no safety isolation requirement or an isolated one if safety isolation is required.

The boost converter is the preferred non-isolated topology in string inverters. It will be more efficient to maintain the DC link voltage higher than the highest voltage expected from the panel. A buck or buck-boost stage will be less efficient due to the higher current to be supported with a lower DC link voltage. To increase power level and to reduce ripple currents, interleaving of multiple boost power stages is done.

The isolated power stages used can be PWM-controlled full-bridge topologies (hard-switched, phase-shifted, or dual active) or resonant topologies like LLC, CLLLC, and so forth. The trend is towards soft-switched topologies that can accept relatively wider input voltage range. The dual active bridge with multiple phase controls is an example.

2.2 DC/AC Inverter Stage

The inverter power stage performs the function of converting the DC link voltage to the grid AC voltage. This inverter stage can be of two types depending on grid connectivity – if it is used for powering only an isolated grid (like only a building) on its own, it is called an off-grid inverter and if it connects to a larger grid sharing the load from other sources, it is called a grid-tied inverter.

An off-grid inverter could be used as a back-up source or as a main power source, but while it is active, it is the only source in the micro grid it powers. Therefore, this type of inverter need not have to address the burden of synchronizing with other sources in the grid. They are used only in smaller capacity systems with lesser need to communicate with other systems.

A grid-tied inverter has the additional task of synchronizing in amplitude, frequency, and phase with the existing grid comprised of multiple sources and loads. It also needs to address the situation of detecting and isolating itself from the grid in the event of any faults in the grid like black-out, brown-out, overvoltage, and so forth. This is called anti-islanding protection. Grid-tied inverters tend to be of comparatively higher power than off-grid inverters. Since there could be multiple grid-tied inverters in a typical application, the need for communication is more important with them.

Various buck derived non-isolated topologies modulated with a sine PWM are used as inverters. These include two-level H-bridge, HERIC, three-level TNPC, three-level NPC, and three-level ANPC.

3 ESS Integration: Storage-ready Inverters

Solar energy is highly variable during the day and from day to day (throughout the year) as well. In a grid connected system, maximum power is delivered to the grid during noon, while in the morning and evening it is less. In many regions world-wide, the price of power is demand-dependent – the price (cost per watt) is higher when demand is high (like evenings and mornings), and it is lower when demand is low (noon, late night). So a consumer with solar installation gets a lower price for the power he produces during the noon time, while paying higher for the power he consumes off the grid in the evening. Also, if there is any fault in the grid, all the power produced goes to waste as the grid is not accessible. Due to such issues, the trend is to have some local energy storage so that energy can be stored and released to the grid when it is accessible and when demand is high. Figure 3-1 illustrates this type of system.

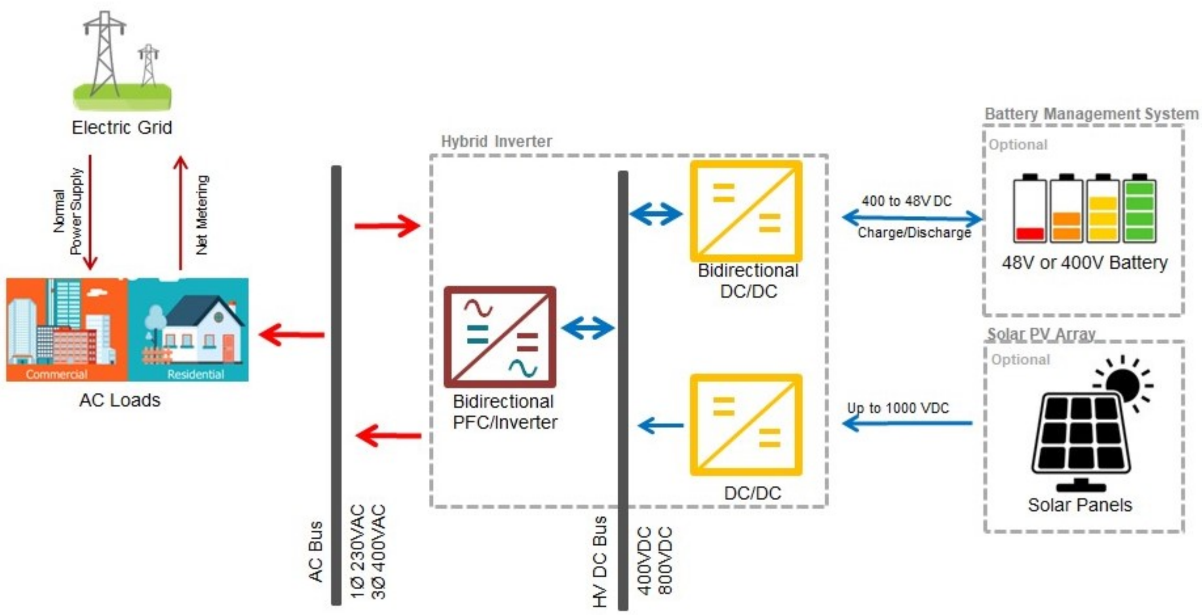

Figure 3-1. ESS Integrated Solar Inverter

The differences from a conventional grid-tied system are the addition of a battery, a bidirectional DC/DC power stage to charge and discharge the battery, and the conversion of the inverter stage to a bidirectional inverter and PFC stage. As far as power conversion is concerned, this trend towards local energy storage means an increased focus on bidirectional power conversion stages. The major blocks in such a storage ready solar string inverter is given in Figure 3-2.

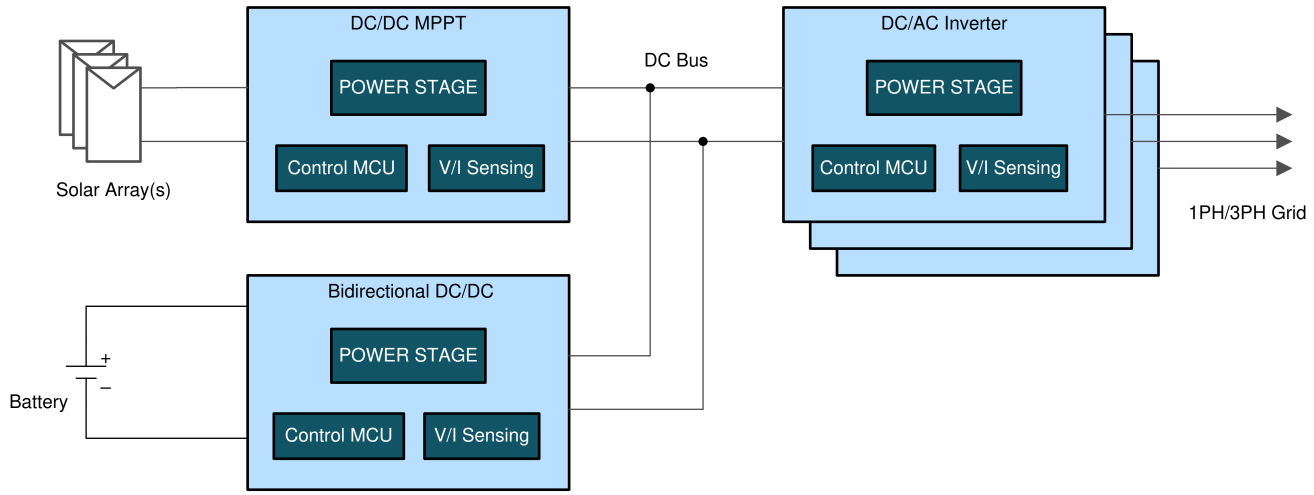

Figure 3-2. Block Diagram of Storage-ready Solar String Inverter

As Figure 3-2 illustrates, there are three major power blocks in this type of inverter. The first two stages do not differ from those used in a string inverter without storage. These are the DC/DC MPPT power stage and the DC/AC inverter. An additional DC/DC converter power stage charges a storage battery pack from this DC link. Unlike the MPPT converter power stage, this needs to be a bidirectional power stage to enable it to convert the stored energy in the battery pack to the DC link voltage. A more detailed block diagram of Energy Storage Power Conversion System is available on TI's *Energy storage power conversion system (PCS)* applications page.

3.1 DC/DC MPPT Power Stage

The DC/DC MPPT power stage in a storage ready inverter does not differ from the power stages used in normal string inverter. The boost converter (interleaved for higher power levels) is the preferred topology for non-isolated configuration, while the phase-shifted full bridge, dual active bridge , LLC and CLLLC are used in isolated configuration.

3.2 Bidirectional DC/DC Power Stage

This power stage is unique to the storage ready inverters. It works as a battery charger in one direction and as a constant voltage DC/DC converter to convert the variable battery voltage to the required constant bus voltage level in the other direction. Though Lead-acid type batteries are very popular in energy storage systems, newer systems are increasingly moving to various types of Lithium batteries. The battery voltage depends upon the system power level. Lower power single phase systems commonly use 48-V battery, while higher power three phase systems use 400-V battery. Intermediate battery voltages are used infrequently. Systems with higher power range of string inverters could use 800-V battery for storage.

The common topologies for the bidirectional DC/DC power stage are the CLLLC converter and the Dual Active Bridge (DAB) in isolated configuration. In non-isolated configurations, the synchronous boost converter can be used as a bidirectional power stage. In low cost single phase systems with lower battery voltages, current-fed push-pull topology (with or without active clamp) is also used.

3.3 Bidirectional Inverter/ PFC Power Stage

The power stages used in the inverter power stage needs to be bidirectional in the storage ready inverter as it should be able to charge the battery when the situation demands it. However, there is no need for any special power topology to achieve this, as the inverter power stages commonly used in standard string inverters like two-level H-bridge, HERIC, three-level TNPC, three-level NPC, and three-level ANPC are all capable of bidirectional operation. The only difference will be in the firmware used for controlling these power stages to enable bi-directional operation.

4 Power Converter Topologies for DC/DC Power Stages

This section explores five popular topologies used in the DC/DC power stage of solar string inverters.

4.1 Synchronous and Interleaved Boost Converter

The boost converter is one of the basic converter topologies and quite simple to implement. It needs only one controlled switch (MOSFET, IGBT, and so forth) and an uncontrolled switch (diode) along with an inductor to realize it. The efficiency also is quite high if it is designed well, due to fewer components. At higher power levels, the diode is replaced by another controlled switch (used as a synchronous switch) to reduce conduction losses. Thus it becomes the synchronous boost converter.

With even higher power levels (as encountered in string inverters), we end up paralleling the power devices so as to reduce conduction losses. However, paralleling the devices does not help with the increased ripple currents. So multiple stages of synchronous boost converters are used with phase-interleaved PWMs driving each converter. For 'n' number of interleaved stages, the phase difference between the individual PWMs is 360 º/n. This significantly reduces ripple currents and helps reduce the overall size. The efficiency as well as thermal loss distribution also gets improved compared to single- or paralleled-power stages. Figure 4-1 shows a two-phase interleaved boost topology. For more detailed analysis of this topology, see *Under the Hood of a Multiphase Synchronous Rectified Boost Converter White Paper.*

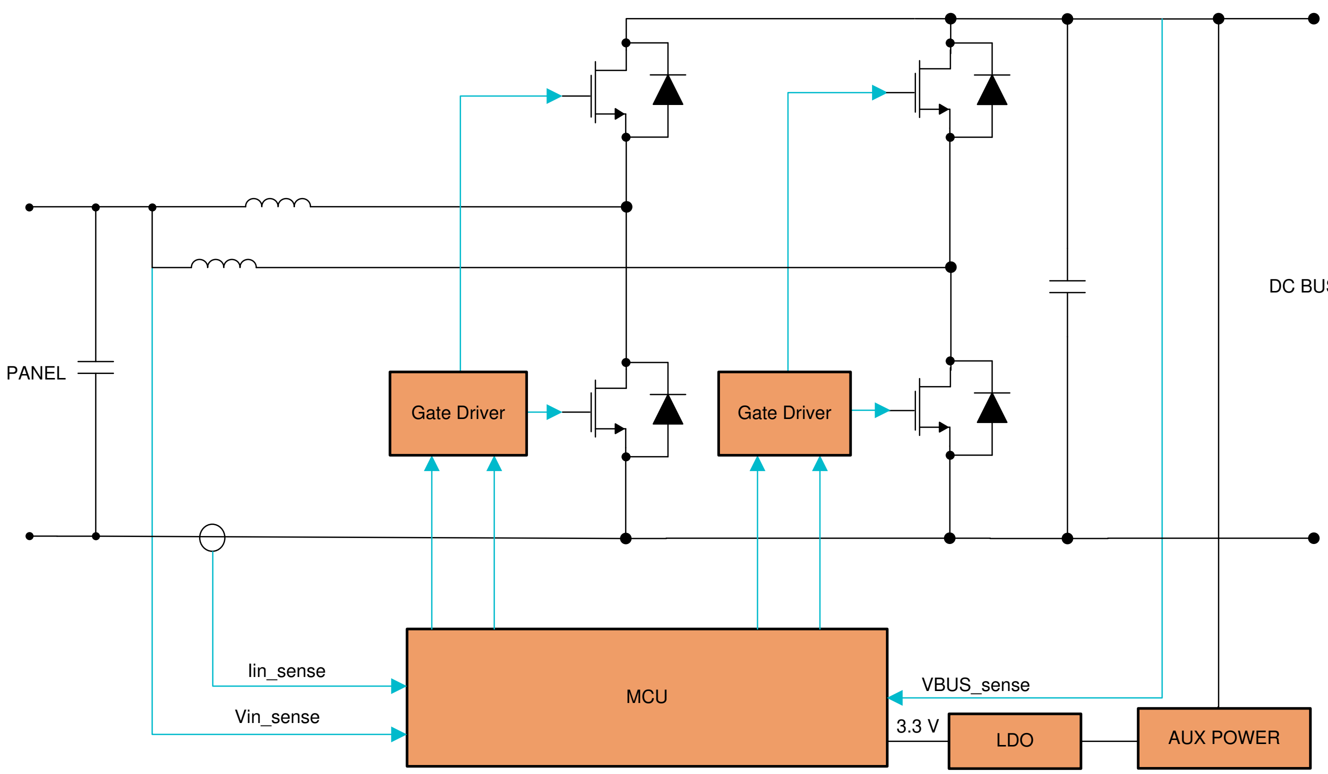

Figure 4-1. Two-phase Interleaved Boost Topology

A typical solar MPPT DC/DC power stage implementation using interleaved boost converter is discussed in the *Digitally Controlled HV Solar MPPT DC-DC Converter Using C2000™ Piccolo™ Microcontroller Application Report.* This topology being a unidirectional DC/DC topology is an option to consider for the DC/DC stage (see Figure 3-1) between the solar panels and HV DC Bus.

4.2 Phase-shifted Full Bridge (PSFB)

Figure 4-2 illustrates the basic topology of the Phase-Shifted Full-Bridge converter. The PSFB topology is similar to a hard-switched full bridge except the way the active switches are driven – even though it is a PWM-controlled topology, all the switches are driven with 50% duty cycle PWMs. This topology allows only unidirectional power transfer. It is a modular topology and hence can be scaled to higher power levels.

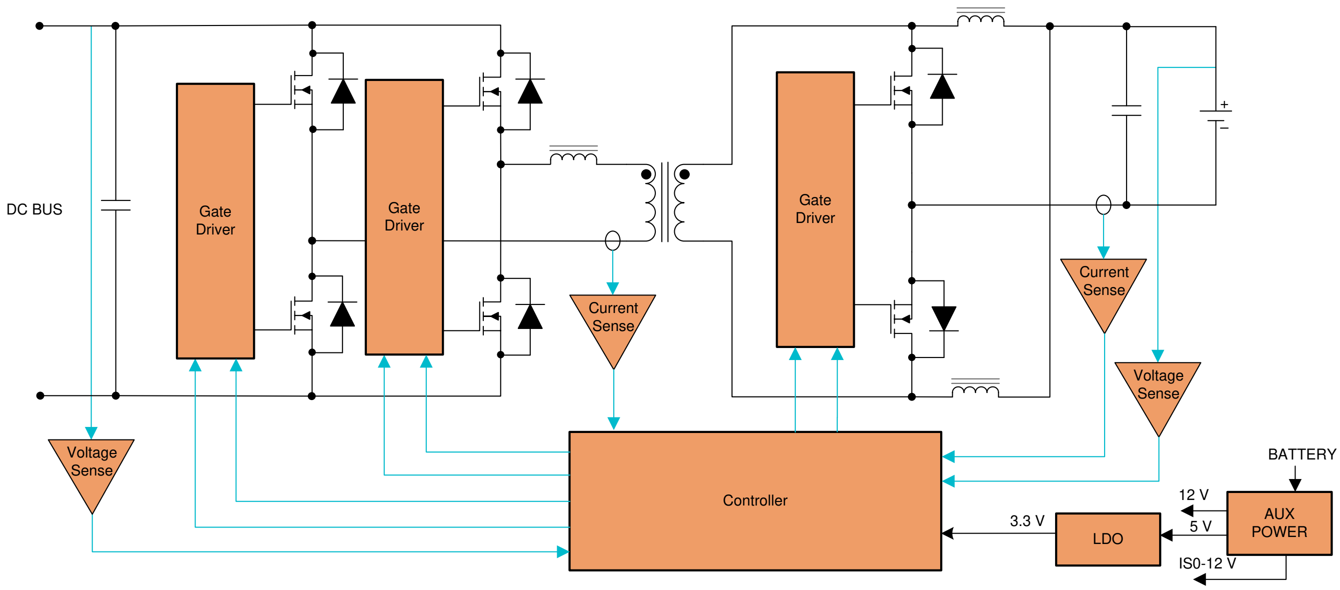

Figure 4-2. Phase-shifted Full-Bridge Topology

The power transfer between the primary and secondary is controlled by varying the phase between the switch legs of the primary side bridge. With proper control, it is possible to obtain ZVS turn on of one leg and low voltage turn on of the other leg, thus minimizing losses. The diodes on the secondary can experience hard switching, resulting in more losses which can reduce the efficiency of this converter. This converter suffers non-ZVS turn-on and turn-off at light load conditions. Because of this, burst mode operation is typically used to maintain ZVS at light load conditions. Frequency dithering can be easily implemented to reduce the conducted EMI signature in this topology. A DC blocking capacitor to block DC voltage offset saturating the transformer in voltage mode control and an additional shim inductor to tune ZVS operation are required, making the converter bulky.

For more detailed analysis of this topology, see the *Phase-Shifted Full Bridge DC/DC Power Converter Design Guide.* TI's Phase-Shifted Full Bridge DC/DC Power Converter reference design explains the implementation of this topology in a typical application. This topology being a unidirectional DC/DC topology is an option to consider for the DC/DC stage (see Figure 3-1) between the solar panels and HV DC Bus.

4.3 Resonant LLC Converter

The LLC converter being a resonant converter can have very low switching losses. The output voltage regulation is achieved by varying the switching frequency of operation. The gain of this converter is a function of switching bridge gain, resonant tank gain and transformer turns ratio. There are three modes/regions of operation for the resonant LLC converter – operation at resonant frequency, above resonant frequency and below resonant frequency. During below resonant frequency operation, the resonant tank current reaches zero within the switching cycle and hence leads to soft switching on secondary rectifier diodes. However, this leads to more conduction losses due to higher circulating energy. Above resonant frequency operation, leads to increased switching losses and hard commutation of secondary rectifier diodes, but results in lower conduction losses due to reduced circulating energy. Hence the best performance of these converters is obtained when operated close to resonance frequency where ZVS turn on and ZCS turn off is possible. This converter provides unidirectional power flow and is generally used in applications less than 5 kW. Figure 4-3 shows the topology of LLC resonant converter.

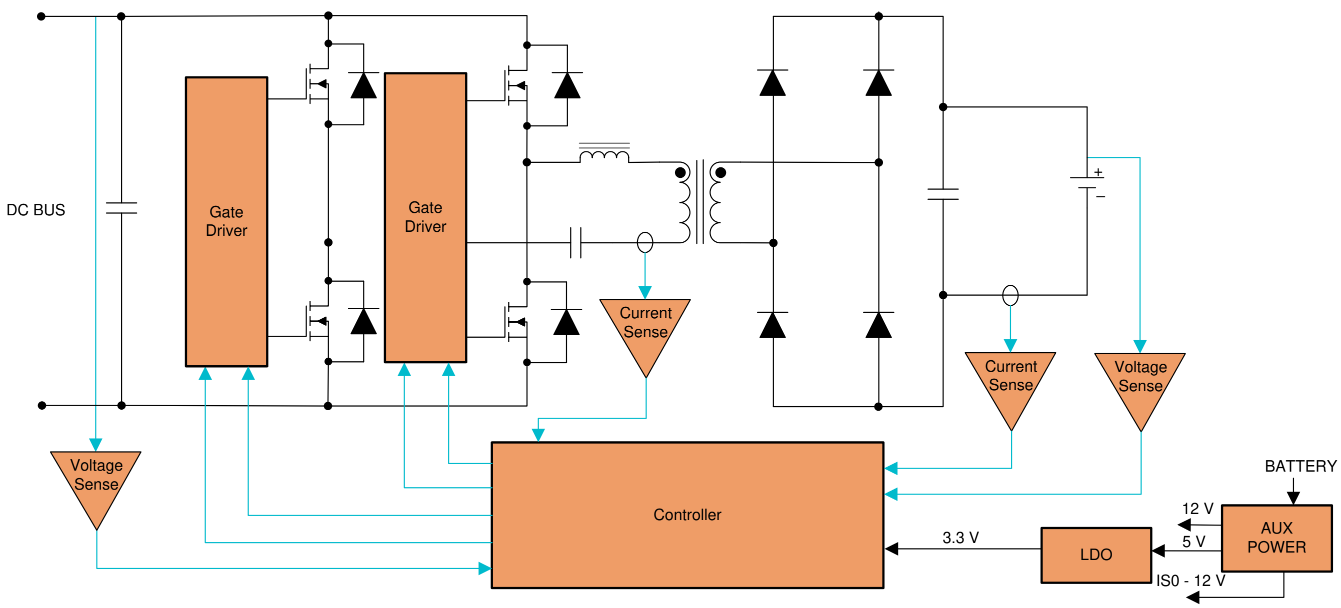

Figure 4-3. LLC Converter

Paralleling and synchronization of multiple LLC converter modules to increase the power output is difficult and often requires complex control logic for safe operation. Implementation of synchronous rectification in LLC converter quite tricky, especially in high output voltage designs (greater than 400 V). The ripple current and peak voltage stress across the active and passive switching devices are significantly high. Higher output capacitance is needed for handling high ripple current. Also the transformer of LLC converter is also comparatively higher in size. These passive components significantly reduce the power density of the converter. Since this converter soft switches during turn on and turn off, the EMI performance is comparatively better. The TI reference design Two Phase Interleaved LLC Resonant Converter Reference Design Using C2000™ MCUs contains details on the implementation of this converter. This DC/DC topology being unidirectional, is an option to consider for the DC/DC stage (see Figure 3-1) between the solar panels and HV DC Bus.

4.4 CLLLC Converter

The CLLLC converter shown in Figure 4-4 incorporates all the functionalities of the LLC described before, but a major advantage of this topology is that with the use of active switches across the secondary, we can obtain bidirectional power transfer. The ZVS/ZCS operation of this converter over a large load range results in increased efficiency.

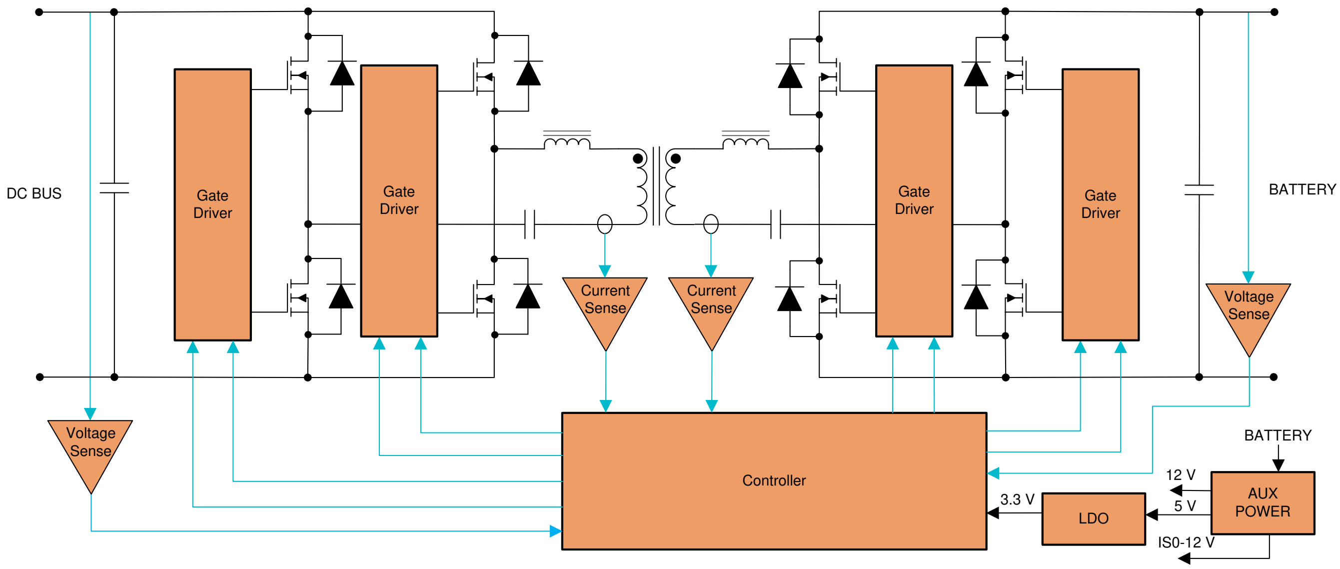

Figure 4-4. CLLLC Converter

This converter can be used at higher power levels up to 10 kW. But scaling to higher power levels and paralleling can be difficult, as it requires a highly symmetrical tank structure and synchronization of multiple modules can be quite difficult. Also this converter, with capacitors in the primary and secondary side of the transformer, naturally prevents saturation over time of the core of the transformer. Similar to the LLC converter, this topology also gives superior EMI performance due to its soft switching characteristics.

The TI reference design Bidirectional CLLLC resonant dual active bridge (DAB) reference design for HEV/EV onboard charger contains details on the implementation of this converter. This topology being a bidirectional DC/DC topology is an option to consider for the bidirectional DC/DC stage (see Figure 3-1) between the Battery Management System and HV DC Bus.

4.5 Dual Active Bridge (DAB)

Figure 4-5 shows the basic topology of the Dual Active Bridge converter. It consists of full bridge with active switches on both the primary and secondary sides connected together by a high frequency transformer. Because of the inherent lagging current in one of the bridges, the current discharges the output capacitance of switches of one bridge (say, the secondary side) and some switches of the primary side thereby enabling ZVS turn on. In addition to this lossless capacitive snubbers can be used across the switches to reduce turn off losses. The main advantages of this converter are its inherent bidirectional capability which is achieved by controlling the phase angle between the two bridges and its modularity that allows it to be scaled to higher power levels.

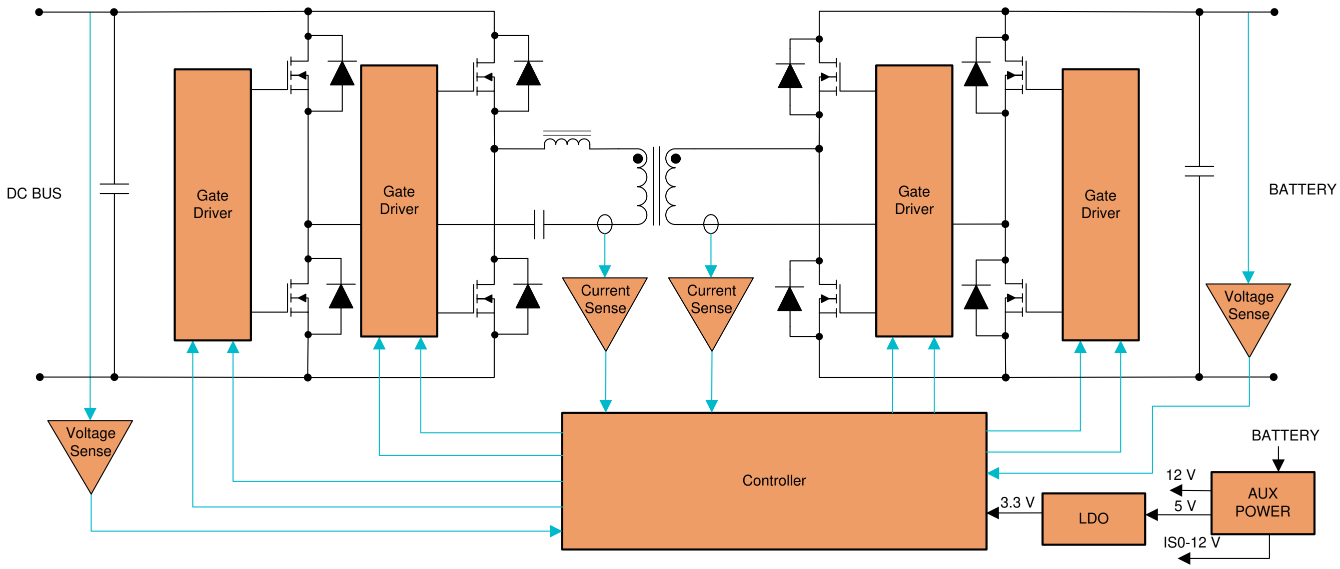

Figure 4-5. Dual-active Bridge Converter

The control scheme of the DAB ranges from simple (or single phase shift modulation) to complex (for extended, dual and triple phase shift modulation). This topology can be used to cover wide variation of battery voltages with single phase shift modulation but circulating currents in the transformer increase which drastically reduces efficiency. But with advanced modulation schemes like triple phase shift, the converter can theoretically achieve ZVS efficiently over the entire operating range. Since transformer utilization is high for this topology, the size of transformer required to deliver same amount of output power is relatively smaller. The output capacitor needed to handle the ripple current is also low for this converter. This converter with relatively fewer number of devices, soft-switching commutations, low cost, and high efficiency is used in applications where the power density, cost, weight, isolation and reliability are critical factors. One limiting feature is that the converter often requires an additional shim inductor which is needed for tuning ZVS operation that can make the converter bulky.

The TI reference design Bi-directional, dual active bridge reference design for level 3 electric vehicle charging stations contains details on the implementation of this converter. This topology being a bidirectional DC/DC topology, can be used for the bidirectional DC/DC stage (see Figure 3-1) between the Battery Management System and HV DC Bus.

4.6 Active Clamped Current-fed Bridge

The Active clamped current-fed bridge converter shown in Figure 4-6 is another bidirectional power conversion topology commonly used in low voltage (48 V and lower) battery storage systems. Some lower power systems use a push-pull power stage on the battery side instead of the full bridge. This power stage works as a phase shifted full bridge while charging the battery from the DC bus and as an isolated boost converter (with active clamp) while discharging the battery to the DC bus.

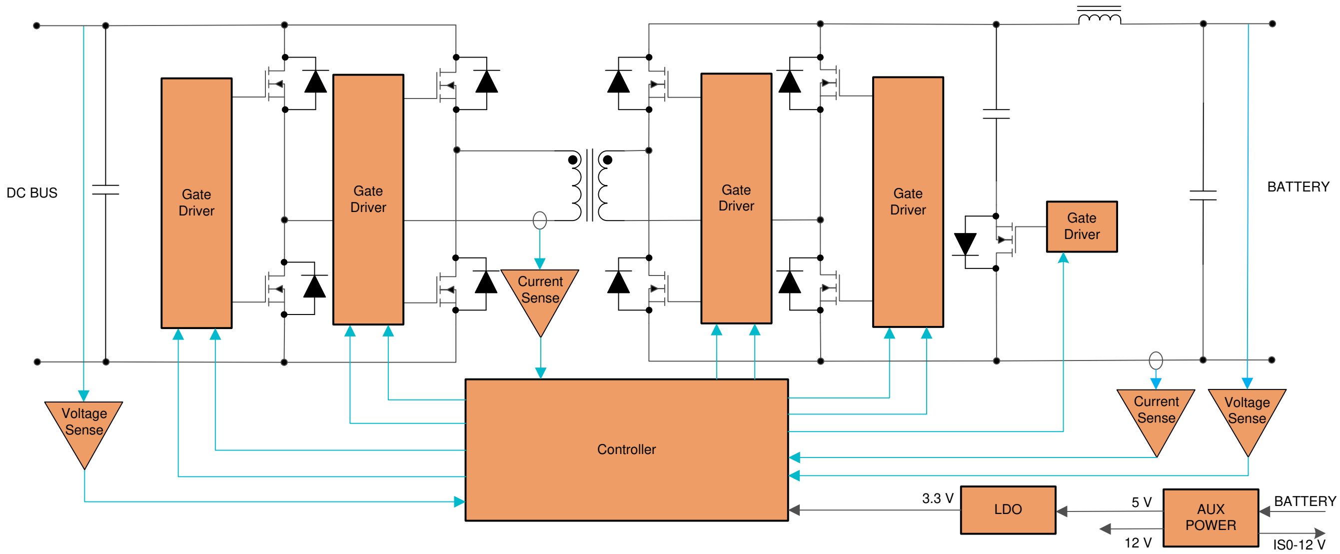

Figure 4-6. Active Clamped Current-fed Bridge Converter

While charging the battery, phase shift control is used similar to the PSFB circuit discussed earlier. With sufficient leakage inductance in the transformer, the circuit can achieve ZVS on the HV and LV side MOSFETs. While discharging battery, the circuit transforms to a current-fed bridge topology, which is nothing but an isolated boost converter. To achieve ZVS, an active clamp circuit consisting of a capacitor and a MOSFET is used. Simple fixed frequency duty cycle control is used in this mode. The simple control method is the biggest advantage of this topology - fixed frequency phase shift control while charging and fixed frequency duty cycle control while discharging. Soft switching is achieved without much effort in either direction. Low di/dt on the HV side MOSFETs allows the use of Silicon devices (with relatively faster body diodes), reducing system cost. However, the conduction losses are higher due to the relatively large clamp circuit current, reducing the efficiency somewhat. It will also need low power start-up winding on the boost inductor for safe start-up. Still, it is considered to be a lower cost option for the bidirectional DC/DC stage (see Figure 3-1) between the Battery Management System and HV DC Bus.

The TI reference design 2kW, 48V to 400V, >93% Efficiency, Isolated Bidirectional DC-DC Converter Reference Design for UPS contains details on the implementation of this converter.

4.7 Comparison of Topologies

Table 4-1 shows the summary of the DC/DC topologies discussed.

Table 4-1. Summary of DC/DC Topologies

	Interleaved Synchronous Boost	Phase-shifted Full Bridge (PSFB)	LLC	CLLC	Dual-active Bridge (DAB)	Active clamped current-fed bridge
Device stress	Low	Low	High	High	Lowest	High
Transformer rating	Non-isolated	Medium	High	High	Low	Medium
Power output to transformer rating	Non-isolated	Medium	Low	Medium	High	Medium
Capacitor RMS currents	Low (Input) Medium (output)	Medium	High	High	Low	High
Polarity	Bidirectional	Unidirectional	Unidirectional	Bidirectional	Bidirectional	Bidirectional
Conduction losses	Low	Medium	High	Medium	Lowest	Medium
Turn ON switching loss	High (Hard Switching)	ZVS	ZVS	ZVS	ZVS	ZVS
Turn OFF switching loss	High (Hard Switching)	High	Low on primary side; secondary side turn off is ZCS	Low on primary side; secondary side turn off is ZCS	High (device turn off at high current)	High on primary side; low on secondary side
Total losses	High	High	Low	Low	Medium	High
Control complexity	Simple	Simple	Moderate	Moderate	Simple to complex	Simple
Wide panel Voltage, Fixed Bus Voltage	Yes	Yes (with reduced efficiency)	No, needs additional DC/DC stage	Limited range	Yes (with reduced efficiency)	Yes
Paralleling Modules	Easy	Easy	Intensive	Intensive	Easy	Easy
Switching Frequency	Fixed/ Medium	Fixed/High	Variable/ High (Si /SiC)	Variable/Very High (SiC/ GaN)	Fixed/High	Fixed/Medium

5 Power Converter Topologies for DC/AC Stages

This section examines five popular topologies used in the DC/AC power stage of solar string inverters.

5.1 Two-level H-bridge Inverter

Figure 5-1 shows the two-level H-bridge inverter topology which is a conventional bridge inverter in which one half of the bridge uses fast switching devices S1 and S2, and the other half (S3 and S4) uses slow (100 Hz and 120 Hz) switching devices (unipolar mode). All four devices can be made to switch at high frequency (bipolar mode) to improve waveform shape; but it results in more switching losses.

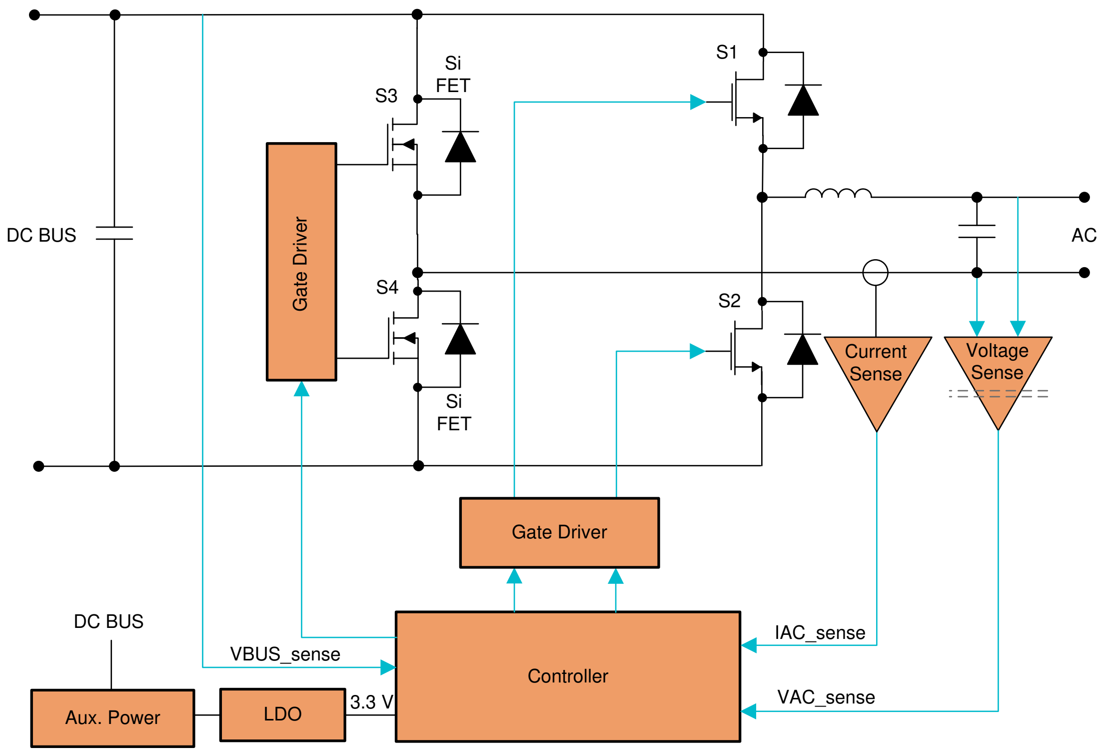

Figure 5-1. Two-level H-bridge Inverter

The current flows only through two switches at a time. S1/S2 are driven synchronously with complimentary PWM signals and the S3/S4 on the slow line frequency legs can be low $R_{DS(on)}$ Si MOSFETs to further reduce conduction loss. The two level H-bridge is inherently capable of bidirectional operation (in opposite direction, it works as a totem-pole PFC), which is ideal for ESS integrated string inverters. Since switching is only between two levels (either VDC or zero), the harmonic distortion of the generated voltage waveform can be relatively higher. Another disadvantage is that with silicon MOSFETs, the totem-pole arrangement allows operating in only discontinuous-conduction mode (DCM) or critical-conduction mode (CrM) because if continuous-conduction mode (CCM) is allowed, the reverse recovery of the MOSFET body diodes (which is much higher than that of standard fast-recovery diodes) can cause excessive losses. So typically IGBTs are used with only moderately high switching frequencies (below 25 kHz) when CCM operation is required. However, with the advent of silicon carbide (SiC) and gallium nitride (GaN) switching devices with zero-recovery reverse conduction has made it possible to operate in CCM operation even at high switching frequencies.

This topology is demonstrated in the TI reference designs C2000™ Solar DC/AC Single Phase Inverter and Single-Phase Inverter Reference Design with Voltage Source and Grid Connected Modes. Even though a two level H-bridge can give only a single phase output, a full three arm bridge can give three phase output as demonstrated in the TI reference design Three-Phase Inverter Reference Design Using Gate Driver With Built-in Dead Time Insertion. This bidirectional DC/AC topology is an option to consider for the bidirectional DC/AC stage (see Figure 3-1) between the HV DC Bus and the AC Bus in a storage ready solar inverter.

5.2 Highly Efficient and Reliable Inverter Concept (HERIC)

The HERIC inverter is an improvement over the two level H-bridge topology by adding two more switches as Figure 5-2.

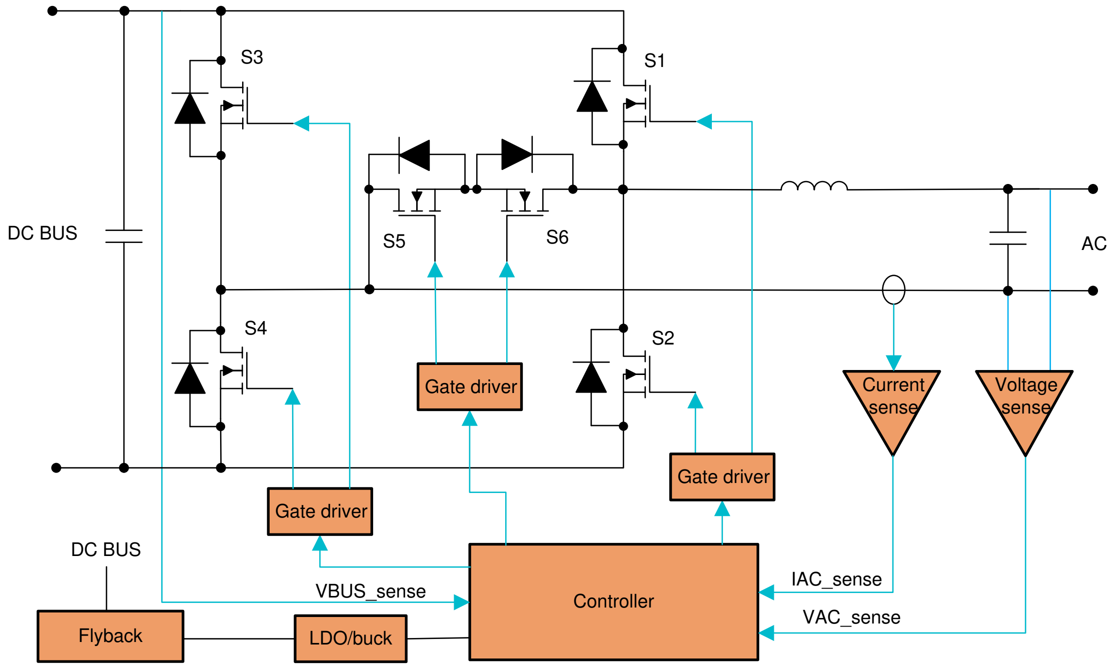

Figure 5-2. HERIC Converter

The converter operates as follows: During the positive half-cycle of the grid voltage S5 is kept ON, S1 and S4 are switched simultaneously at the switching frequency, supplying a positive voltage to the load, while S2, S3 and S6 are OFF. During this time (positive active vector) current flows from the DC input to the grid. When zero vector (freewheeling period) occurs, S1 and S4 also are switched OFF and the current flows through S5 and anti-parallel diode of S6. During the negative half-cycle of the grid voltage, S6 is kept ON, while S2 and S3 are switched together at the switching frequency, while S1, S4 and S5 are OFF. During this period (negative active vector) the current flows from the DC input to the grid in opposite direction. When zero vector (freewheeling period) occurs, S2 and S3 also turn OFF, and current freewheels through S6 and anti-parallel diode of S5. As can be seen from this operation, the body diodes of S1 to S4 do not come into operation at all and hence we can use Si MOSFETs for these and switch them at relatively higher frequency. Since the switches S5 and S6 are switching only at line frequency, we can use IGBTs (their anti-parallel diodes need to be ultra-fast though).

Since we are able to achieve three level switching (positive vector, zero vector and negative vector) low distortion can be achieved on the output. The TNPC inverter is an extension of the HERIC topology. This DC/AC topology being bidirectional, is an option to consider for the bidirectional DC/AC stage (see Figure 3-1) between the HV DC Bus and the AC Bus in a storage ready solar inverters.

5.3 Three-level TNPC Inverter

Figure 5-3 shows the basic topology of the three level T-Type Neutral Point Clamped (TNPC) inverter is depicted in . The TNPC inverter is an extension of the HERIC topology to suit three phase output. For 800-V DC link voltages, the high side and the low-side switch on each phase would usually be implemented with 1200-V IGBTs/MOSFETs as the full voltage has to be blocked by them. However, the bidirectional switches to the dc-link midpoint need to block only half of the voltage. It can be implemented with devices having a lower voltage rating like two 600-V IGBTs including anti-parallel diodes. Due to the reduced blocking voltage, the middle switch shows very low switching losses and acceptable conduction loss. If bipolar devices are used for the single 1200-V device, we can get reduced conduction losses, as the forward voltage drop of only one device occurs. This is in contrast to the NPC topology in which always two devices are conducting in series. The reduced conduction loss makes the TNPC an interesting choice even for low switching frequencies. As it is a three level topology, it has a good THD performance; and hence the inductor at the output can be smaller.

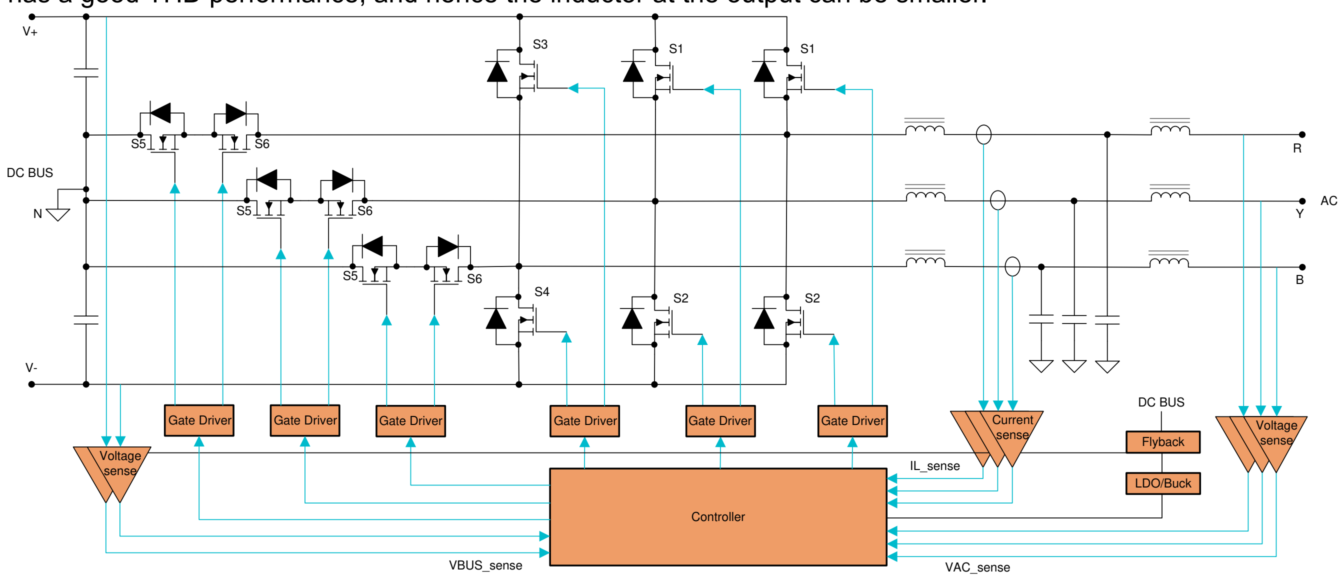

Figure 5-3. Three-level TNPC Inverter

While the conduction losses are significantly lower when compared with NPC, the switching losses are high due to the devices blocking full dc link voltage. Due to limited component count and better conduction losses compared to NPC topology, the TNPC topology is best suited for applications up to 40-kHz switching frequency; beyond which the NPC topology performs better. One of the drawbacks of this topology is the high peak voltage stress across the high voltage blocking FETs. The TI reference design 10kW 3-phase 3-level T-type inverter reference design for solar string inverter demonstrates the implementation of an inverter and the TI reference design Three-level, three-phase SiC AC-to-DC converter reference design demonstrates the implementation of a PFC stage of this type of power stage. This DC/AC topology being bidirectional, is an option to consider for the bidirectional DC/AC stage (see Figure 3-1) between the HV DC Bus and the AC Bus in a storage ready solar inverters.

5.4 Three-level NPC Inverter

Figure 5-4 illustrates the basic topology of the Neutral Point Clamped inverter. This is also a multilevel topology like the TNPC inverter except that all switches of this topology are rated to half the bus voltage. The voltage stress on the devices is the lowest among all the topologies discussed so far.

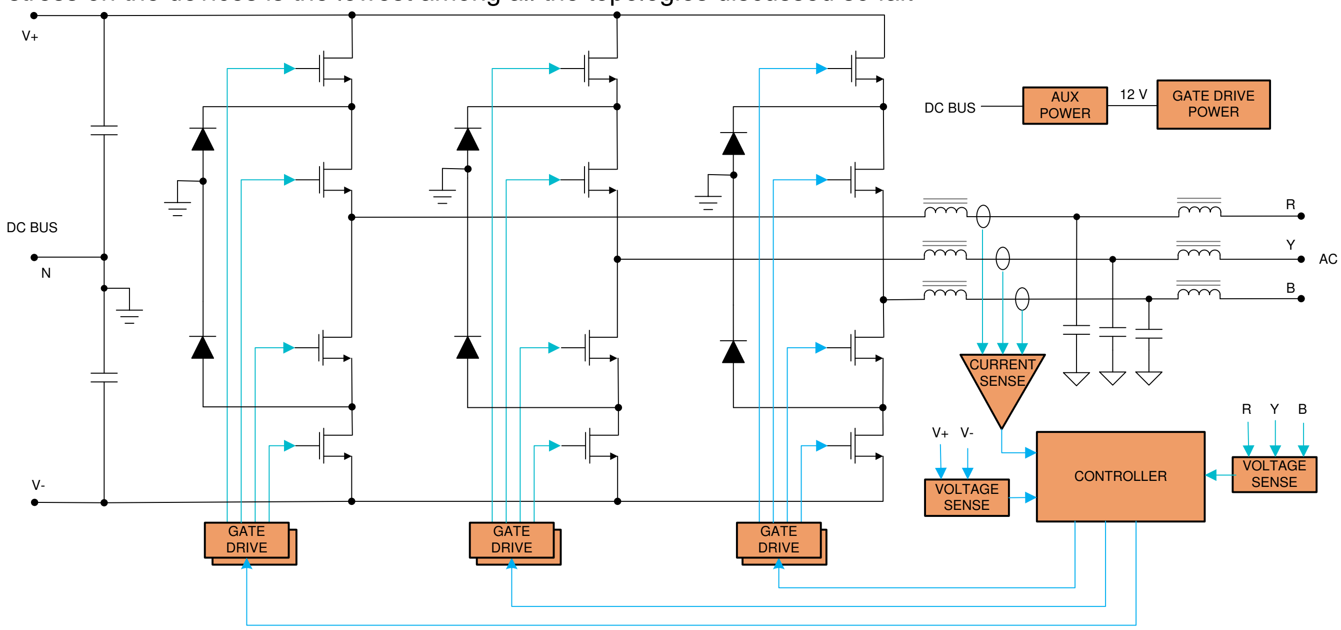

Figure 5-4. Neutral Point Clamped Inverter

Since only half of the voltage has to be switched, the switching losses in the transistor get reduced by half. In the NPC topology shown, it is possible to use 600-V components instead of 1200-V types. The 600-V technology has much faster components than are available in 1200-V technology. This will lead to further reduction in switching losses. This topology has lower ripple in the output current and only half of the output voltage transient. This will reduce the effort for filtering and isolation in the filter inductor. Hence we can achieve high power density with less inductance needed to maintain harmonic distortion in output. Multilevel inverters not only generate the output voltages with very low distortion, but also can minimize the dv/dt stresses across devices thereby reducing electromagnetic interference (EMI). This topology also offers bidirectional transfer of power and is the preferred choice for switching frequencies higher than 50 kHz due to lower switching losses and better efficiency. One drawback of the NPC topology is the high number of power semiconductor switches needed. Even though lower voltage rated devices can be used in a multilevel converter, each of the switches needs a gate drive circuit. This topology makes up for the complexity in its implementation by improved power density, higher efficiency as well as overall reduced system cost that comes from design of smaller size magnetics/ passive components and fewer cooling needs. As this topology uses both controlled switches and diodes, the loss distribution is unsymmetrical and hence thermal management can be quite challenging. This topology being a bidirectional DC/AC topology is an option to consider for the bidirectional DC/AC stage (see Figure 3-1) between the HV DC Bus and the AC Bus in a storage ready solar inverters.

5.5 Three-level ANPC Inverter

The Active Neutral Point Clamped (ANPC) inverter is an improved version of the NPC inverter, in which the diodes of the NPC topology are replaced with active switches as shown in Figure 5-5. We get a more uniform loss distribution because of this, making thermal management a lot easier. Also with reduced blocking voltage across all switches, Gallium Nitride (GaN) switches can be used in this topology which improves efficiency and power density of the converter. It is the most suitable topology for high-frequency switching because of the comparatively lower switching losses.

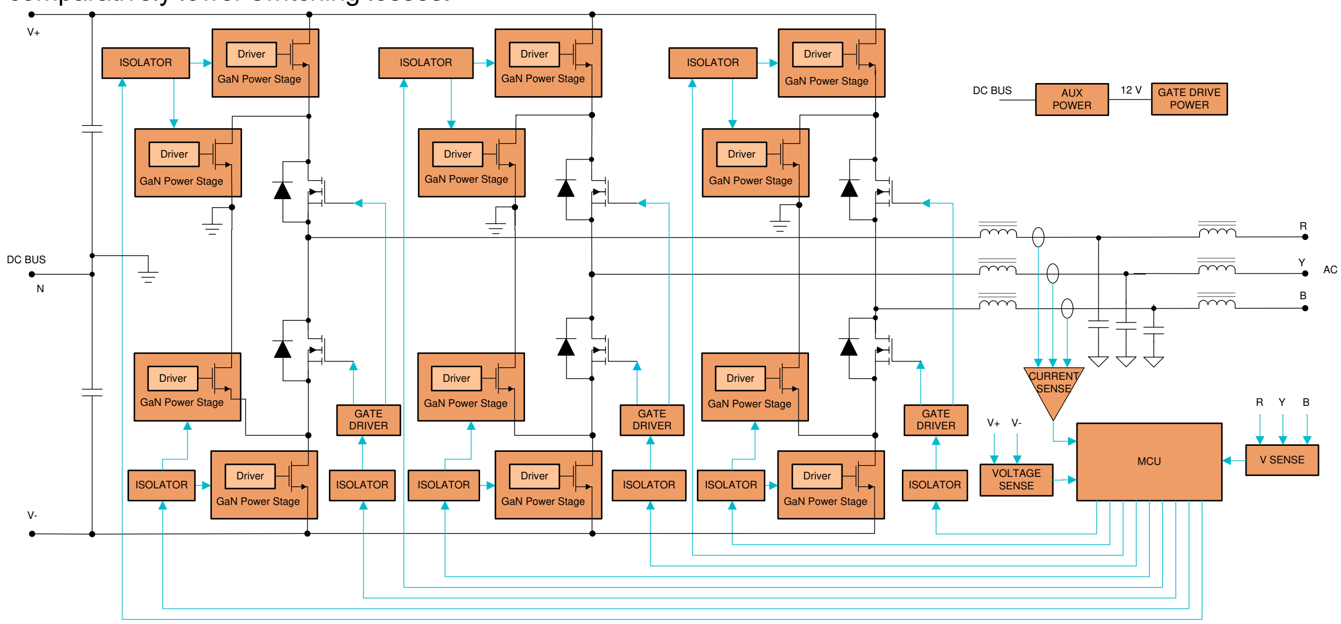

Figure 5-5. Active Neutral Point Clamped (ANPC) Inverter

The major drawback of this topology is the number of controlled switches to be addressed. In a three phase application, a total of 18 switches are required to be controlled by individual PWMs. Use of advanced smart switching schemes can help reduce the number of PWMs to a third, if implemented wisely. Each of the 18 switches would also need a gate driver, and that could also be cut to half by use of dual-channel gate drivers. This topology makes up for the complexity in its implementation by improved power density, higher efficiency as well as overall reduced system cost that comes from design of smaller size magnetics/passive components and fewer cooling needs. This bidirectional DC/AC topology is an option to consider for the bidirectional DC/AC stage (see Figure 3-1) between the HV DC Bus and the AC Bus in a storage ready solar inverters.

5.6 Summary of DC/AC Topologies

Table 5-1 compares and summarizes the previously-discussed inverter topologies.

Table 5-1. Summary of Inverter Topologies

	2-Level H-Bridge	HERIC	3-Level TNPC	3-Level NPC	3-Level ANPC
THD of output	High	Low	Low	Low	Low
Peak stress on devices	High	Low /(High Blocking)	Low /(High Blocking)	Low	Low
Power density	Low	Medium	High	High	Highest
Bidirectional	Yes	Yes	Yes	Yes	Yes
Conduction loss	Low	Medium	Medium	High	Medium
Switching loss	High	Medium	Medium	Low	Low
Efficiency	Low	High	High	High (at high frequency)	High (at high frequency)
Switching Frequency	Low	Medium	Medium	High	High
Cost	Low	Medium	Medium	High	Highest
Control	Easy	Medium	Medium	Medium	Complex
Inductor size	Large	Medium	Medium	Small	Small
EMI	High	Medium (high dv/dt)	Medium (high dv/dt)	Low	Low
Thermal management	Easy	Easy	Easy	Difficult	Easy

6 Future Technology and Trends

A lot of research and development is occurring in power conversion associated with solar string inverters. The aim is towards preserving the energy harvested by increasing the efficiency of power conversion stages and by storing the energy in distributed storage batteries. Increasing reliability of the system also has been another area of continued focus. In this context, some emerging technologies like usage of new Wider Band Gap (WBG) semiconductors for power conversion and Differential Power Processing (DPP) in panel power optimization are some of the new trends discussed in this section.

6.1 WBG Semiconductors

There has been a continuous effort in increasing the switching frequency of power converters so as to reduce their size and cost and to increase efficiency. While increasing switching frequency can help in reducing losses in passive components (due to the reduced bulk), it has the opposite effect on losses in active components. The limitation of conventional switching devices based on Silicon as base material (such as IGBTs and MOSFETs) to operate efficiently at higher switching frequencies prompted the development of switching devices based on wider bandgap materials like SiC and GaN. These devices now allow operation of power conversion topologies at multiple hundreds of kHz compared to Si devices that were limited to operation at a few tens of kHz. Also, these devices are capable of operating at higher temperatures than Si devices, increasing the reliability in solar inverters that typically need to operate at higher ambient temperatures.

Nowadays, SiC MOSFET devices are available at comparable voltage withstand capability as Si IGBTs, allowing them to directly replace IGBTs in topologies like HERIC, TNPC and so forth, at the same time increasing switching frequencies tenfold. While GaN devices are currently not available in higher withstand voltage levels as IGBTs, multiple sources are available for 600-V to 700-V rated devices. As they are capable of switching at even higher frequencies than SiC devices, there is keen interest in multi-level topologies like NPC, ANPC, and so forth, that can accommodate these devices efficiently. Also, isolated DC/DC topologies like CLLLC and DAB can operate much more efficiently with GaN devices allowing operation at multiple hundreds of kHz.

While WBG semiconductor devices help in reducing the size and increasing efficiency of power converters, their fast switching operation introduces newer challenges like more critical layout, higher EMI (due to increased dv/dt), and more complex thermal management. The layout and package parasitics become more prominent with higher speed switching. This leads to higher integration as in the case on TI’s gate driver integrated GaN power device. To reduce parasitics, GaN switches are packaged as SMD devices, making their thermal management more difficult. More insights into addressing these challenges are available in TI’s *Design considerations of GaN devices for improving power converter efficiency and density white paper.*

6.2 Differential Power Processing

In solar string inverters, individual solar panels are connected in series to get a voltage high enough to do efficient power processing. However, series strings of PV cells often experience severe power decrease when there is mismatch in the electrical characteristics of the PV cells, often caused by partial shading, panels at different tilt angles, dust accumulation, or cell degradation. Even after implementing a string-level MPPT converter, the power available may not be completely extracted. While individual power optimizers for each panel can solve this issue effectively, it has to process the entire power from the panel to which it is connected; hence called the Full Power Processing (FPP) method. This results in higher losses in conversion, and also increases cost. An alternate to this is called the Differential Power Processing (DPP) method, one type of implementation of which is shown in Figure 6-1.

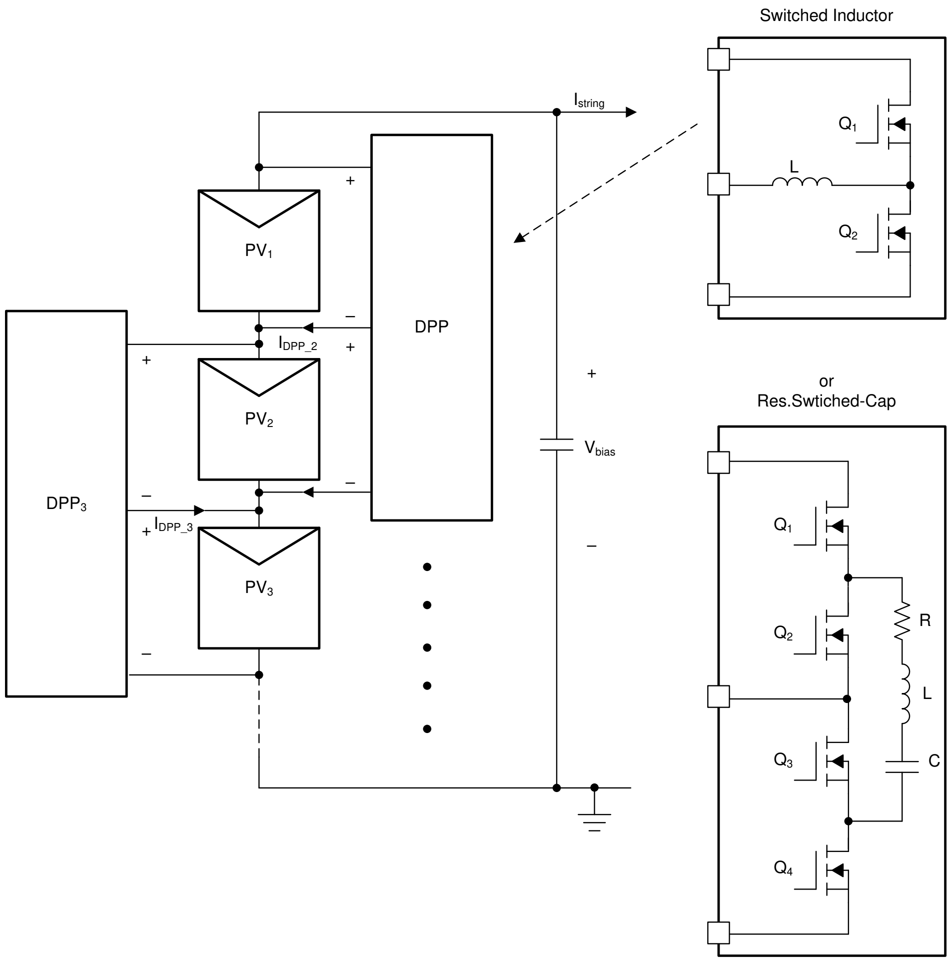

Figure 6-1. PV-PV DPP Architecture

In DPP converters, only the difference in power between adjacent panels needs to be processed by it. This reduces power conversion losses compared to the FPP method and also results in reduced cost of the system. There are multiple ways of implementing a DPP architecture like PV connected to bus (PV-bus), PV connected to PV (PV-PV), and PV connected to an isolated port (PV-IP). These architectures are those commonly used with active cell balancing in battery packs. PV-bus architecture is commonly used with lower string voltages. The PV-PV DPP converters have more potential for scalability than the PV-bus architecture, and hence are more suited for higher string voltages. Figure 6-1 shows the PV-PV architecture. It has the additional advantage of using only non-isolated topologies and hence are of comparatively lower cost.

The main stumbling block for acceptance of DPP is its higher cost compared to the unoptimized series string due to the increased number of components. However, The cost of DPP is lower than FPP and hence is preferable when individual panel power optimization is a requirement. Compared to FPP, the control of DPP is complex, as the MPPT algorithm needs to be a distributed one. Though it provides more watts per dollar over its lifetime compared to other architectures, the upfront cost and system complexity currently limits the use of DPP architecture in string inverters. As semiconductor technology continues to reduce the overall system cost year-over-year, there is a good chance that DPP could start becoming economically viable in the years to come.

7 Summary

The ultimate choice of a power topology boils down to the intended use case of that specific power converter block, namely the input and output parameters, the targeted power levels, efficiency and power density targets to name a few. While high power 3-phase commercial inverters would look at complex multilevel three-phase PFC stage and DC-DC stage to pack more-and-more power into them, the single phase residential inverters could be addressed by a simple 2-level H-bridge type PFC stage followed by a LLC DC/DC stage. With storage ready inverters becoming more commonplace, engineers may have to limit their Inverter and DC/DC topology choices to those that support bidirectional power transfer (such as TNPC, ANPC, DAB, and CLLLC between the local battery pack and the Grid.

No matter your choice of use case, the advancement in the field of power electronics in tandem with semiconductor technology is ready to offer everything you need to build your next generation storage ready solar inverter or a stand-alone energy storage system.

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