

Power Topology Considerations for Solar String Inverters and Energy Storage Systems



Vedatroyee Ghosh, Harald Parzhuber

ABSTRACT

As PV solar installations continue to grow rapidly over the last decade, the need for solar inverters with high efficiency, improved power density and higher power handling capabilities continue to increase. Today this is state of the art that these systems have a power conversion system (PCS) for battery storage integrated.

This application note outlines the most relevant power 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 an AC power. String inverters are commonly used in residential and smaller commercial installations. Wide bandgap semiconductors like Silicon carbide (SiC) and Gallium nitride (GaN) allow to operate converters at higher switching frequencies which allows use of smaller magnetic components and in turn drive power density of these systems up. To scale power levels up very often such systems are made in modular fashion to get from 10th of kW to 100th of kW.

To cope with the fact that Photovoltaic (PV)-systems stop generating energy when sun light goes down, these systems very often incorporate a power conversion port for a battery energy storage system (BESS). Excess energy generated during day time is stored into the battery and can be used during times the energy from the PV-string is not enough.

2 Solar String Inverters

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

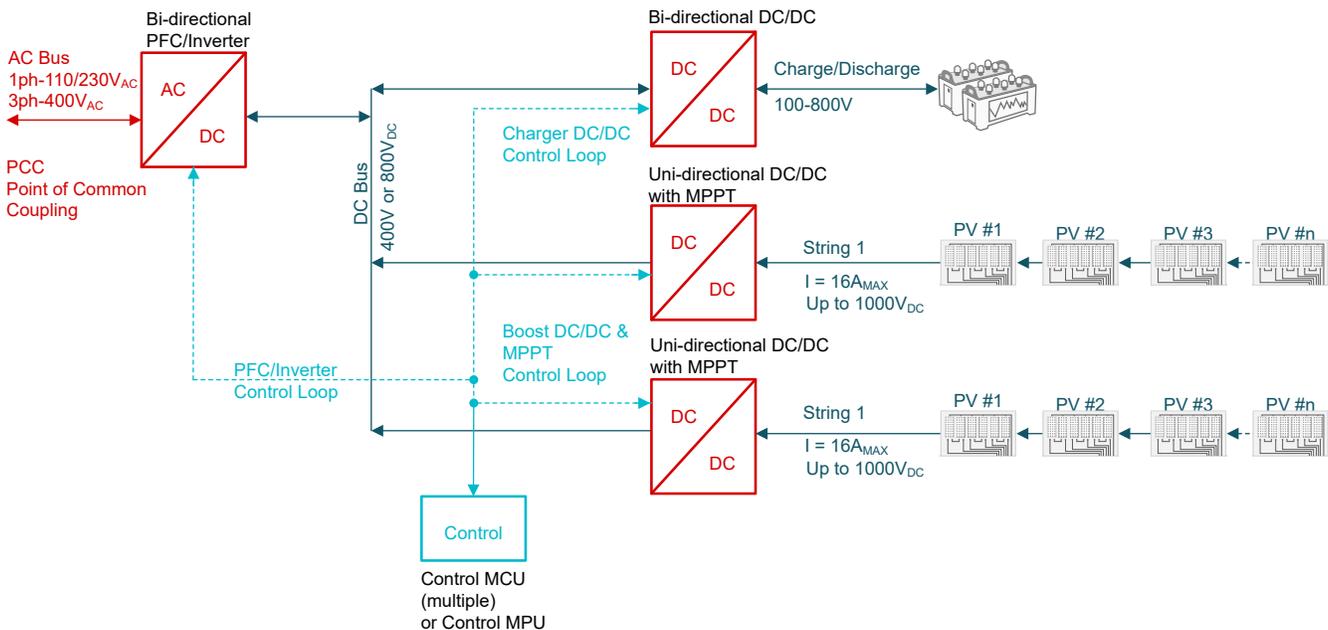


Figure 2-1. Solar String Inverter Block Diagram

As Figure 2-1 illustrates, there are three major power blocks in the string inverter. The first stage is a uni-directional DC/DC converter stage that converts the variable string output to a stable high-voltage DC link suitable for the next stages, the second is a bidirectional DC/DC power stage the third a bidirectional DC/AC inverter stage. For single-phase systems the DC Bus voltage is typically 400V_{DC}. For three-phase systems the DC-Bus voltage is around 800V_{DC} or even higher up to 1500V_{DC}. This first DC/DC stage is also able to perform the Maximum Power Point Tracking (MPPT) for a complete string. It simply searches for the maximum power by changing voltage and current across a complete string. This DC Bus voltage is then converted to an AC voltage at the grid voltage level by the DC/AC inverter power stage. In today's systems, the AC/DC is built as bidirectional PFC/Inverter to allow the operation of the DC/DC power stage that connects to a battery energy storage system, and allows to charge and discharge the ESS in both directions.

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 function of translating multiples of MPPT voltage of a panel (depending on the number of panels in a string) to a stable voltage level suitable for the inverter or DC/DC stage for battery input. The input voltage is regulated by MPPT which is either performed through software or through external add-ons like a power optimizer. A PV panel acts as a current source where the short circuit current is

approximately proportional to the irradiation available. The open circuit voltage across a PV panel is dependent on the ambient temperature conditions. For residential use cases, PV panels usually depict an output MPPT voltage of 33V for a 400W panel and 40V or higher for 500W or 600W rated panels.

Since a string inverter is a cost-sensitive application, a non-isolated boost converter is the preferred topology for conversion of the input string voltage to a stable DC link voltage. Figure 2-2 depicts such an example present in TIDA-010938. This input voltage exists as multiples of 33V or 40V depending on the type and wattage of panels used. The DC link voltage can vary depending on whether it is a single-phase application or a three-phase application. For single-phase, the bus can be rated up to 500-550V and for three-phase usually up to 1200V. 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 of this stage, multiple strings can be added as independent inputs. Each input can be designed independently and symmetrically. Usually a CLLLC stage or synchronous boost is not employed here since it will not be cost effective.

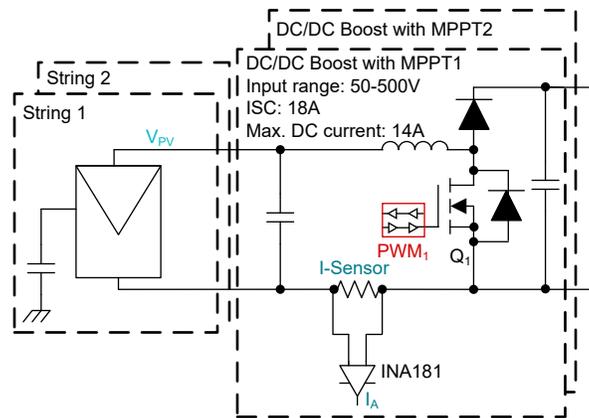


Figure 2-2. DC/DC MPPT Stage Block Diagram

A boost converter needs one controlled switch (MOSFET, IGBT, etc) in combination with an uncontrolled switch (diode) and an inductor to realize it. This topology has several benefits such as lower number of components, high efficiency, simple implementation, etc. 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. 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 $360^\circ / n$. This significantly reduces ripple currents and helps reduce the overall size.

It is important to keep in mind that the switching transistors need to be appropriately rated depending on the type of application. This translates to 650V drain-source voltage rating for single-phase and up to 1200V rating for three-phase applications (higher drain-source voltage rating required for systems with higher DC bus voltage). Going higher with DC link voltage to beyond 1000V will reduce power losses in system and allow more panels to be added in series. However, the devices need to be chosen with appropriate ratings.

2.2 Power Stages for Battery Port DC/DC

For non-isolated applications, a bidirectional DC/DC converter can be used to have the possibility of battery energy storage system (BESS). Bi-directionality is important for the DC/DC converter to act like a battery charger (in buck mode) and discharging the battery (in boost mode) to provide a higher and stable output voltage at the DC link. This can then be transferred into AC power towards the grid by means of a DC/AC converter in conditions like low irradiance scenarios or night-time conditions.

Solar energy has daily, seasonal and yearly fluctuations, so it is not the most reliable source. 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.

To increase the power level of this stage and to reduce the current ripple, interleaving of branches can be carried out. Interleaving helps in reducing output current ripple, output noise, decrease of the size of the EMI filter, and increase power density. It is relatively simple to implement and control, however for optimum performance it is recommended to have the interleaved half-bridges as symmetrical as possible, to have balanced current flow between the them. Such multiphase designs also enable multiples of switching frequency across the output EMI filter, thus making the design smaller. A typical application of such a non-isolated topology can be seen in [TIDA-010938](#) in [Figure 2-3](#). Here, we can see two interleaved stages with an applied phase difference of 180° between each other.

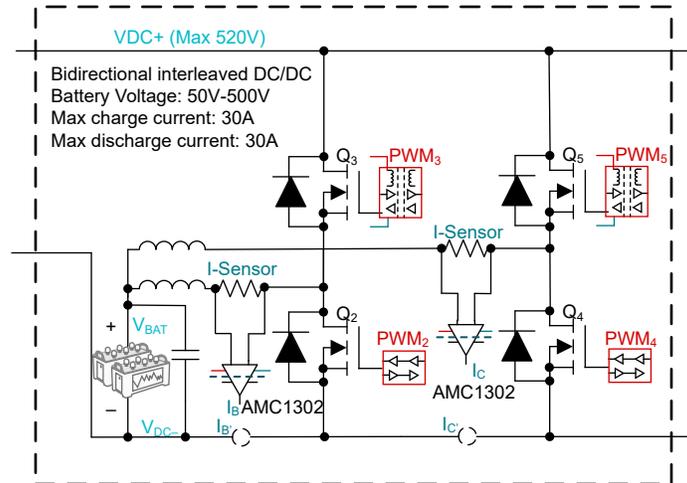


Figure 2-3. DC/DC Stage for Battery Block Diagram

Isolation comes into play when we talk about systems relating to automotive applications or battery with lower voltage ratings. Most popular topologies in this regard include the Dual Active Bridge with Extended Phase Shift (for example in [TIDA-010054](#)) which deals with a primary voltage of 700V to 800V DC, and secondary voltage of 350V to 500V DC (single-phase-shift SPS) or 250V to 500V (extended-phase-shift EPS) for power levels up to 10 kW, Phase-shifted Full-Bridge (for example in [PMP22951](#)) which deals with a voltage of 400V down to 54V and a power level of 3kW or CLLLC Dual-Active Bridge (for example in [TIDM-02002](#)) which deals with a primary voltage range of 380–600V to a secondary voltage range of 280–450V and power levels up to 6.6kW. Depending on whether it is a three-phase or a single-phase application, the drain-source voltage rating of the devices would change. This translates to 650V drain-source voltage rating for single-phase and up to 1200V rating for three-phase application (higher drain-source voltage rating required for systems with higher DC bus voltage).

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 48V battery, while higher power three phase systems use 400V battery. Systems with even higher power range of string inverters could use 800V battery for storage. This may vary depending on the application and use case.

A more detailed block diagram of Energy Storage Power Conversion System is available on TI's [Energy storage power conversion system \(PCS\)](#) applications page.

2.3 Power Stages for Single-Phase DC/AC

The inverter power stage is kept bidirectional to enable power conversion from DC link into grid compatible AC power and vice versa. State of the art string inverters tend to be grid-tied and synchronized to the grid at all times via Phase-Locked Loop (PLL). The inverter or PFC stage can be divided into two broad categories namely whether the grid is single-phase or three-phase. Single-phase further dictates the rating of the devices on whether it is split-phase ($110V_{RMS}$ in Japan, the USA etc) or $230V_{RMS}$ (in Europe, ROA, and so on).

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.

Present-day string inverters which tend to be cost and power density competitive are generally transformer-less in nature. Transformer-less string inverters present low impedance paths for return currents. This leakage current is a well-known challenge in PV applications due to PV surfaces exposed over grounded roof or other surfaces in the proximity. The large surface areas can lead to high values of stray capacitance between the PV panel and ground, which can go as high as $200nF/kWp$ in damp environments or on rainy days. This parasitic capacitance can cause high common-mode current flowing into the system when common-mode voltage of the converters is not well mitigated and can lead to EMI and issues such as grid current distortion. Issues with safety and Residual Current Detection (RCD) can be found that needs to be addressed by the topology that is being used. Hence the corresponding topology that is selected, needs to work around this problem.

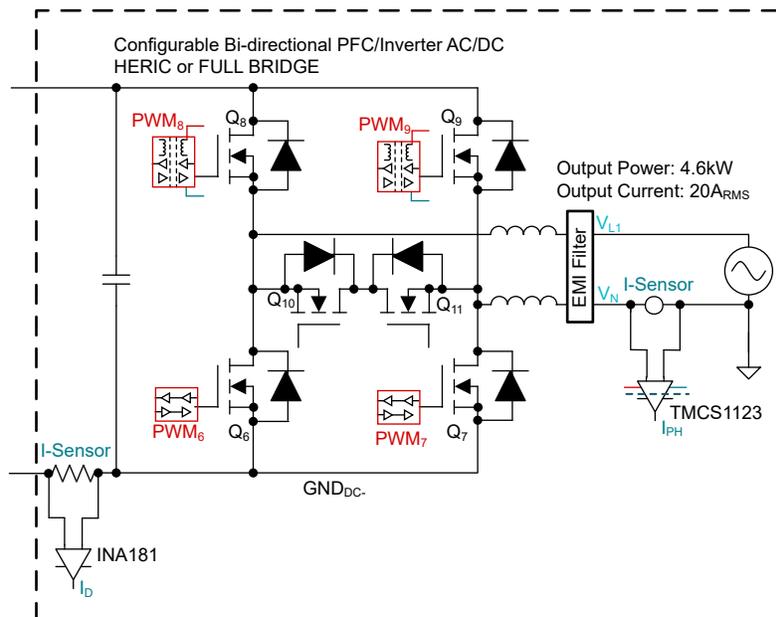


Figure 2-4. Single-Phase DC/AC Stage Block Diagram

Figure 2-4 represents a HERIC-based DC/AC converter topology present in [TIDA-010938](#). This can also be configured into H-Bridge mode when only FETs Q6, Q7, Q8, Q9 operate and Q10 and Q11 are not used. Various buck derived non-isolated topologies modulated with a sine PWM are used for the inverter stage. These include topologies for single-phase such as two-level H-Bridge with bipolar modulation, three-level H-bridge with unipolar modulation, HERIC and totem-pole ([TIDA-010933](#) which is a 1.6kW rated for inverter stage). TIDA-010938 depicts an inverter stage rated up to 4.6kW and can be configured into unipolar, bipolar and HERIC based converters. [Table 2-1](#) lists the benefits and challenges with each of these systems.

Table 2-1. Benefits and Challenges of Single-Phase DC/AC Topologies

	3L H-Bridge Unipolar	2L H-Bridge Bipolar	3L Totem-Pole	3L HERIC
Benefits	<ul style="list-style-type: none"> • Simple control scheme • 4 switches • 2 PWM • Smaller passives • Low THD • Uniform loss distribution • $f_{\text{ripple}} = 2xf_{\text{pwm}}$ 	<ul style="list-style-type: none"> • Simple control scheme • 4 switches • 1 PWM • Uniform loss distribution • Low common-mode noise • $f_{\text{ripple}} = f_{\text{pwm}}$ 	<ul style="list-style-type: none"> • 4 switches • Could be achieved with 1 PWM • $f_{\text{ripple}} = f_{\text{pwm}}$ 	<ul style="list-style-type: none"> • Low THD • Low EMI • Small passives • Low common-mode noise • $f_{\text{ripple}} = f_{\text{pwm}}$
Challenges	<ul style="list-style-type: none"> • High EMI • High common-mode noise 	<ul style="list-style-type: none"> • Biggest passives • Lower efficiency 	<ul style="list-style-type: none"> • Complex control at zero-crossing • High THD • High common-mode noise • Non-uniform loss distribution 	<ul style="list-style-type: none"> • Complex control scheme • 6 switches • Non-uniform loss distribution • 3 PWM

2.4 Power Stages for Three-Phase DC/AC

Three-phase topologies include two-level converter, three-level NPC, and three-level ANPC (TIDA-010210), T-type (TIDA-01606) and Flying cap. For three-phase systems, an elaborate comparison can be found in [Comparison of AC/DC Power-Conversion Topologies for Three-Phase Industrial Systems](#). Table 2-2 lists the benefits and challenges with each of these systems.

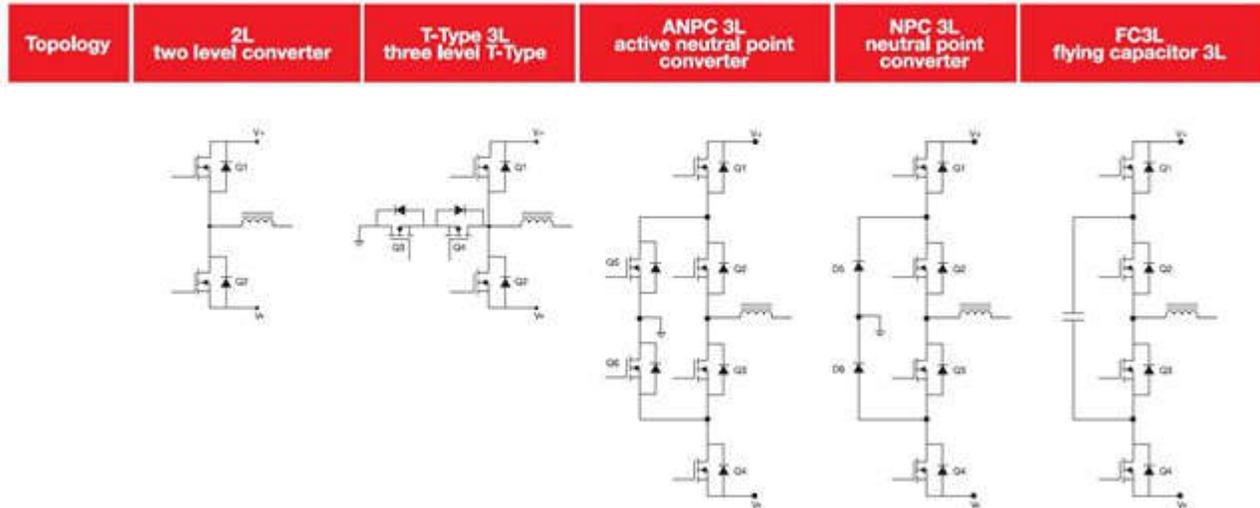


Figure 2-5. Schematic Representation of Three-phase DC/AC Topologies

Table 2-2. Benefits and Challenges of Three-phase DC/AC Topologies

	2L	T-Type 3L	ANPC	NPC 3L Derived From ANPC	Flying Capacitor 3L
Benefits	<ul style="list-style-type: none"> Simple control scheme 2 switches only 2 PWM 	<ul style="list-style-type: none"> Simple control scheme Q3/Q4 see 1/2 VDC Better EMI than 2L $f_{\text{ripple}} = f_{\text{pwm}}$ 	<ul style="list-style-type: none"> Good efficiency All switches see 1/2 VDC Better EMI than 2L 	<ul style="list-style-type: none"> Lower cost than ANPC All switches see 1/2 VDC Better EMI than 2L $f_{\text{ripple}} = f_{\text{pwm}}$ 4 PWM 	<ul style="list-style-type: none"> Highest efficiency Only 4 HF FETs and 1 cap $f_{\text{ripple}} = 2 \times f_{\text{pwm}}$ Smallest magnetics Lowest EMI
Challenges	<ul style="list-style-type: none"> Q1/Q2 see full VDC High EMI for bigger f_{pwm} Biggest passives 	<ul style="list-style-type: none"> Q1/Q2 see full VDC 4 PWM 	<ul style="list-style-type: none"> More complex control scheme Shutdown sequencing critical 6 PWM 	<ul style="list-style-type: none"> Lower efficiency than ANPC More complex control Shutdown sequencing critical 	<ul style="list-style-type: none"> Initial charging of flying capacitor Shutdown sequencing critical

3 Future Technology and Trends

String inverters and power conversion systems for Energy Storage are driving the process of decarbonization. Cost, design size and efficiency are the most important metric to drive these end equipments to the next level. Introduction of Wide bandgap technologies like SiC and GaN allows operation at higher switching frequencies, which improves the power densities and form factor, and enables size reduction of passive components, thus bringing the cost of the system down. With a large portfolio of GaN devices, TI is prepared to support this trend with leading edge products. More information is available on TI's [Gallium nitride \(GaN\) power stages](#) application page.

Another trend that can be observed is to increase DC bus rating towards 1500V-2000V. By doing this higher power levels can be achieved with lower current levels, thus influencing the losses in the system. This however, drives the isolation requirements and the device ratings of system components which need to be selected appropriately.

Moving from two level converters to multi-level converters supports the increase in DC bus voltage and effectively improves common mode rejection which results in smaller EMI filter design. Implementing flying cap topologies multiplies with each level the ripple frequency seen by the boost inductors which can be in turn dimensioned with smaller values.

All of the above drives design size and cost down at same or even better efficiency for power converters in solar and battery storage systems.

4 Summary

All the topologies have their respective pros and cons when it comes to particular applications and use cases. 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 three-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 simpler non-isolated topologies. With storage ready inverters being state-of-the-art, bidirectionality becomes essential of both DC/DC converter for the battery port and converter towards the grid. Use of wide band-gap devices and high-performance MCUs add to the list of advantages by enabling smaller component sizing, high power density, high efficiencies and high functionality.

5 References

1. Texas Instruments, [110-kW, GaN-Based Single-Phase String Inverter With Battery Energy Storage System Reference Design](#), design guide.
2. Texas Instruments, [1.6-kW, Bidirectional Micro Inverter Based on GaN Reference Design](#), design guide.
3. Texas Instruments, [Bidirectional, Dual Active Bridge Reference Design for Level 3 Electric Vehicle Charging Stations](#), design guide.
4. Texas Instruments, [54-V, 3-kW Phase-Shifted Full-Bridge With Active Clamp Reference Design](#), design guide.
5. Texas Instruments, [Bidirectional CLLLC Resonant Dual Active Bridge \(DAB\) Reference Design for HEV/EV Onboard Charger](#), design guide.
6. Texas Instruments, [10-kW, Bidirectional Three-Phase Three-Level \(T-type\) Inverter and PFC Reference Design](#)
7. Texas Instruments, [11-kW, Bidirectional, Three-Phase ANPC Based on GaN Reference Design](#)
8. Texas Instruments, [Comparison of AC/DC Power Conversion Topologies for Three Phase Industrial Systems](#)

6 Revision History

Changes from Revision * (October 2018) to Revision A (December 2024)	Page
• Updated the numbering format for tables, figures, and cross-references throughout the document	1
• Added <i>Solar String Inverters</i> section.....	2
• Updated to include most commonly used topology of boost converter and added block diagram.....	2
• Updated to include most commonly used topologies in this application, added hyperlink to design guide, and added block diagram.....	3
• Updated to include topologies mostly seen in this power conversion stage, added hyperlink to design guide, and added block diagram.....	5

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