Grid-Connected Solar Electronics

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I. INTRODUCTION

With rising fuel costs, increasing concerns for global climate change, and a growing worldwide demand for electricity, utilizing renewable energy sources such as solar power becomes a necessity rather than a luxury. The total solar energy absorbed by Earth's atmosphere, oceans and landmasses is approximately 3,850,000 exajoules (EJ) per year but only a fraction of that is captured for electrical power production. Solar powered systems can generate electricity using photovoltaic (PV) panels, or thermal collectors. The world solar PV market installation reached a record high of 5.95 gigawatts (GW) in 2008[1]. These PV systems can range from utility scale systems like the 14 MW solar array at Nellis Air Force Base to 4kW roof-top home systems to 15 W solar backpack for charging portable electronics.

For our project, we have chosen to explore solar PV systems for residential building. Specifically we will focus on the grid-connected electronics utilized in setups for typical households. We then present the various topologies used in grid-tied inverters with a special emphasis on multilevel inverters. Finally, we showcase a test setup we attempted using an Enphase Micro-inverter along a 250 W panel.

II. GRID-CONNECTED ELECTRONICS

The simplest PV system consists of multiple solar cells connected to form a PV module. Commercially available modules range in power from 10 watts to 300 watts. One or more of these modules are connected to an inverter which convert's direct-current (DC) output of other modules into alternating current (AC). Optionally, batteries may provide energy storage or backup power in case of a power interrupting or outage on the grid.

1. Grid-Tie Inverters

Most residential households will use a grid-connected PV system. In this scenario, as depicted in Fig. 1, a grid-tie inverter (GTI) is used to complement the generated solar power with grid power. In addition to regulating the voltage and current received from the solar panels, a GTI ensures that the power supplied to the distribution panel of the house will be in phase with the grid power. On the DC side, maximum power point tracking (MPPT) optimizes the power output by varying the closed loop system voltage. On the AC side, these inverters ensure that the sinusoidal output is synchronized to the grid frequency (nominally 60Hz). In addition, the voltage of the inverter output needs to be variable and slightly higher the grid voltage to enable current to supply the loads in the house or even have excess power flow *out* to the utility. In some areas, net metering allows the homeowner to sell energy back to the local energy supplier. In this scenario, the meter literally "runs backwards."

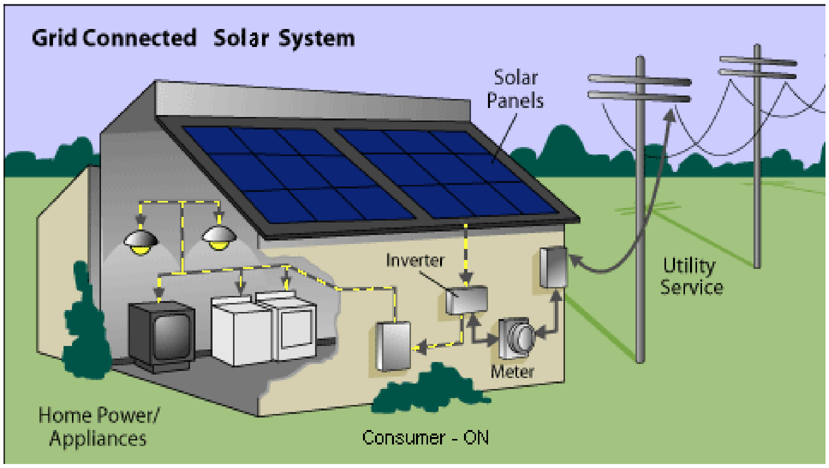


Fig. 1. Grid connected solar system

2. Commercial Products

Residential grid-tie inverters range in power capacity from 175W to as much as 10kW. A complete system will string several PV modules to a single inverter installed near the house distribution panel. Multi-kW systems may employ two or more inverter to meet the peak power demands. An entirely different approach is taken with micro-inverter based systems, like the Enphase M190, which employ a single roof mounted inverter per panel. As shown in the comparison of commercial inverters in Table 1, the cost per kW goes down substantially with higher power inverters.

Table 1. Comparisons of commercial products

Model	Enphase M190	Solectria PVI 1800	XantrexGT 3.3	SMA Sunnyboy	Solectria PVI 15kW
Power	190	1800	3300	7000	15000
Price	$225	$1599	$2154	$4005	$11500
Price/W	**$1.18**	**$0.88**	**$0.65**	**$0.57**	**$0.76**
CEC Efficiency	95	94.5	95.5	94.5	94.5
Size (in)	8 x 5.25 x 1.25	5.6 x13 x 18	29 x 16 x 6	18 x 13.8 x 9.3	35 x 25 x 14
Weight	4	34	49	94	376
Vol/Watt (in^3/W)	**0.27**	**0.75**	**0.79**	**0.33**	**0.81**

3. System Economics

A complete grid-tied solar system consists roof mounted solar modules, wiring, and grid tie inverter. Installation costs vary depending on the region, roof size and type, and difficulty level of installation. However, California residents can achieve substantial cost savings through government-sponsored initiatives. The Federal Government currently offers a tax credit that gives back 30% of the cost of your residential solar system. [7] In addition, the California state government – through the California Solar Initiative (CSI) – is offering significant cash rebates to reduce the cost of solar by another 10%. The CSI rebate is scheduled to decrease over time but the current rebate for PG&E customers is $1.55/W. A few cities even have additional incentives on top of the 45% you'll get from the federal government and state. Berkeley has launched a new program called BerkeleyFIRST (Financing Initiative for Renewable and Solar Technology) to help property owner s 'go solar'. Property owners install solar now and pay for it over 20 years on their property tax bill [6]. Table 2 shows a number of residential systems at various rated power.

Table 2. Typical hardware cost for residential solar systems

System Size	2.5 kW	4.2kW	4.2kW	15.4kW
Inverter Model	Enphase Micro-Inverter	Enphase Micro-Inverter	SMA SunnyBoy	SMA SunnyBoy
PV Array (sq ft)	202	345	342	1370
Average Daily KWH**	10.2	17.5	17.2	64.9
Inverter Size (watts peak)	2600	4200	4000	14000
List Price	$19085	$32492	$29177	$104757
PG&E Rebate*	-$3199	-$5484	-$5382	-$20322
Federal Tax Credit*	-$5725	-$9747	-$8753	-$31427
Net Hardware Price	-$10160	-$17620	-$15041	-$53007
Price/Daily kWh	$996	-$986	-$874	-$816
Price/kW	$4147	-$4110	-$3581	-$3442

III. EVOLUTION OF PV INVERTERS

1. Centralized Inverters

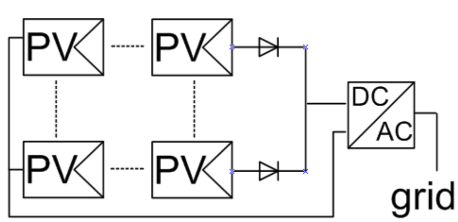


Fig. 2. Centralized Inverters

Initially, the interface between Photovoltaic power supply and the grid rely on the centralized inverter technology, as shown on Fig. 2. Inverters are connected in into series, called strings, generating a sufficient high voltage to avoid amplification. All strings are then connected in parallel to support high power to output. Only one inverter is utilized to interface the grid. This technology suffers from disadvantageous issues, including high voltage DC cable from a big number of strings to the inverter and losses in string diodes. This structure is also limited from Maximum Power Point (MPP) Tracking and controlling mismatch between strings so individual PVs, resulting in low efficiency and reliability. The nonflexible design makes it less appealing in mass production. With all these issues, this technology is not used in new solar systems installation.

2. String Inverters

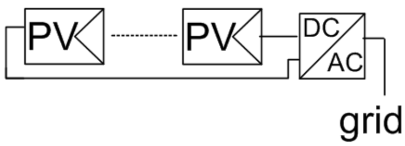


Fig. 3. String inverters

This technology, shown in Fig. 3, illustrates effort to solve problems of the previous design. It has a string of inverters connected in series with an AC module. While still avoiding high voltage amplification, this structure has improved performance with no diode loss in series, separate MPP tracking for each string and lower cost with mass productions. The inverter can be implemented with high voltage MOSFET/IGBT. It is possible to have less PVs in string with voltage amplification by DC-DC converter or a line frequency transformer, which increases total area. Although having been introduced to the market for about 10 years, this structure remains a favorite structure in new installation. However, in a common scenario of partial shading, MPP tracking may still not be sufficient to achieve a certain efficiency requirement.

3. Micro-Inverters

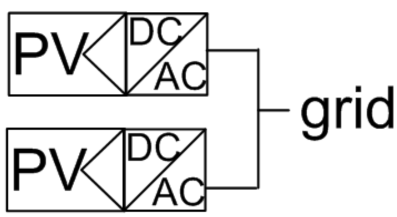


Fig. 4. Micro-inverters

The micro-inverter solution, also called AC module, shown in Fig. 4, is the integration of PV and inverter into one electrical device. With only one PV to control, there is no PV mismatch. MPP tracking can be done at individual PV level, maximizing possible efficiency. As it is modularized, the micro-inverter is good for mass production, which potentially leads to low manufacturing cost and low retail prices. This technology is also very appropriate for residential applications with low power requirements and where partial shading is a critical issue. This type of inverter is also designed with a "plug and play" feature so that it can be installed without a deep electrical knowledge. However, if implemented by a big number for industrial applications, due to the distributed installation, the maintenance requirements can increase the cost and discourage wide usage. To keep inverter boxes watertight and use components that have large temperature ambient is major concerns. It will be necessary to develop a system that can detect failure of any micro-inverter and isolate it immediately. This type of inverter has recently become emerging product and promised a remarkable market share in future.

4. Multi-string Inverters

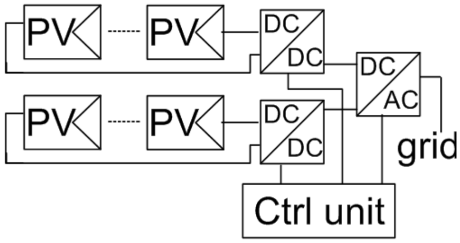


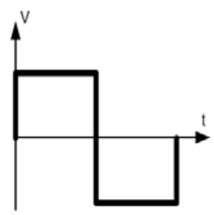
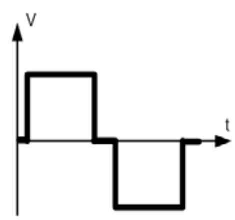
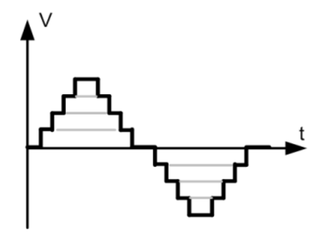
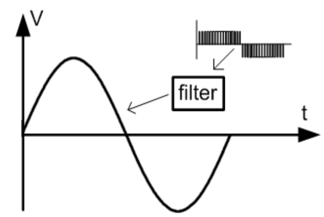
Fig. 5. Multi-string inverters

Multi-string inverter, shown in Fig. 5, features the optimal MPP tracking for a single string of PVs. In this structure, DC-DC converter is implemented for each string for MPP tracking and power combination of different string to a DC bus. A big power stage works as a grid connected half bridge inverter without transformer. The multi-string inverter is useful when PV strings of different rated power, different orientation are combined. The DC-DC part can be implemented with high-frequency pulse width modulation (PWM) converter to reduce implementation area.

IV. INVERTER TOPOLOGY

Inverters can be classified by their output waveform in four categories: square wave, modified square wave, also called quasi-square wave, multilevel and sine wave (synthesized from a high frequency PWM), as shown in Table 3. Although the square and quasi-square wave inverters can be accepted in some applications, and are available in the market, they are not recommended due to their poor quality waveform. Multilevel and sine wave inverters are considered the state of the art technology. The main difference between the two topologies is the switching frequency, the former based on low frequency while the later based on high switching frequency.

Table 3. Inverter topologies by waveforms

<table>
<tr><th>Square wave</th><th>Quasi-Square</th><th>Multilevel</th><th>Sine wave (HF – PWM)</th></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2" rowspan="2">Poor quality waveform</td><td colspan="2">Good quality waveform</td></tr>
<tr><td>- Low switching frequency
- Efficient and robust</td><td>- High switching frequency
- Compact & low cost</td></tr>
</table>

Multilevel inverters are the best available solution for high power applications. However, for medium and low power applications, there is not a clear tradeoff to make it more appealing than sine wave inverters, or vice versa. High frequency inverters favor compactness and reduced cost, while low frequency ones are claimed to have the best efficiency and robustness.

The final choice of one inverter instead of the other better depends on the application. In our application of stand-alone renewable energy systems (SARES), multilevel inverters have great potential with its reliability, surge power capacity and efficiency.

V. MULTILEVEL INVERTERS

Fig. 6 shows one multilevel inverter topology example, implemented by cascade H-bridge. The timing diagram depicts how it works. The operation of a multilevel inverter can be described as an optional stacking of a number of DC voltage source stages. Dependent on a certain time of operation that one stage is stacked (forward or reverse) or bypassed.

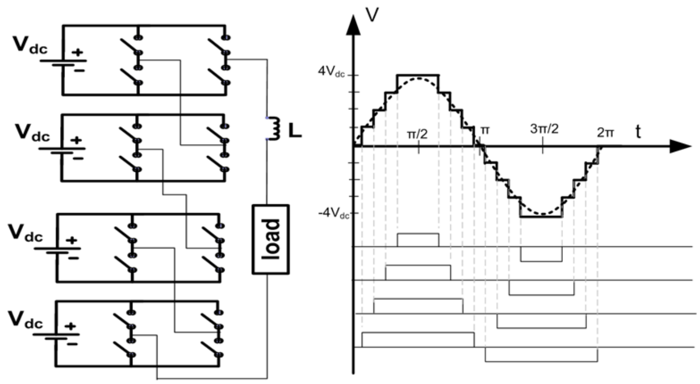


Fig. 6. Cascade H-bridge multilevel inverter and operation

With multi-steps, multilevel inverters have low output distortion and EMI. Voltage stress on devices of each stage is a fraction of overall voltage rating, allowing high performance devices with low voltage rating, improving efficiency. Voltage and current harmonics are also significantly reduced. Multilevel PWM and step modulation can be used to synthesize voltages with high spectral quality even at low switching frequency. Small-step feature means low dv/dt stress, thus, relaxing electro-magnetic compatibility (EMC) requirements.

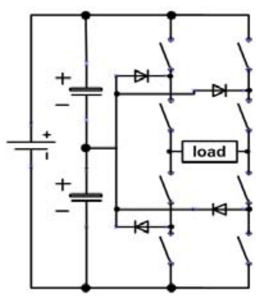
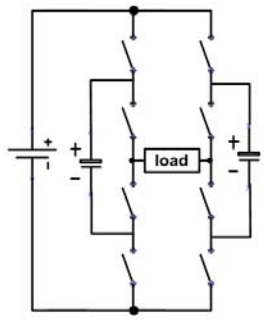
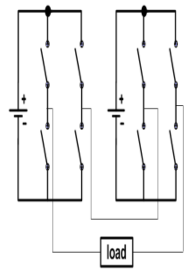
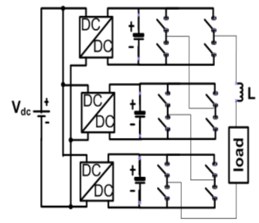
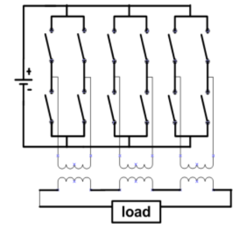
Beside the advantages, multilevel inverters also have some issues, such as requiring a big number of semiconductor switches, which increased as the number of steps/levels increases, and complex design for synchronous gate drivers for different levels.

Multilevel Inverter Topology

There are many types of multilevel inverter topologies in its history, starting from the series H-bridge design, followed by the diode-clamped, which utilizes a bank of capacitors to split the DC bus voltage, and then the switched flying capacitor (or capacitor-clamped) topology. An inverter design can also cascade these fundamental topologies to make hybrid topologies to improve power quality.

The main multilevel inverter topologies with their advantages and disadvantages are summarized in the Table 4.

Table 4. Main multilevel inverter topology comparisons

Diode-clamped	**Switched capacitor**	**Cascade H-bridge**		
		Transformer-less	Bi-direct. DC-DC	Multiple transf.
				
- Common node → less cap - Easy pre-charge cap - Single source	- Cap voltage balanced - Power flow well ctrl. - High power density - Efficient - Single source	- m = 2s + 1 (m: level, s: source) - Modularized → good for mass production	-Enable high efficiency DC-DC conversion -Possible I/O isolation -Single source	- Single DC source - Robust and reliable
- Hard intermediate node stabilization in single inverter - Diodes quadratically proportional to level - No I/O isolation	- Complicated control and start-up - Rely on switch performance - Large number of caps	-Multiple sources. -No I/O isolation	- High frequency	- Several Low freq. transformer → bulky - I/O isolation

VI. MULTILEVEL INVERTER MOTIVATION AND OPERATION

Multilevel inverters, compared with typical H-bridge inductors, use multiple switches and capacitors to create several DC voltages from the DC input. The inverter switches between these DC voltages to synthesize the desired waveform, using an inductor to filter the output. For example, Fig. 7 shows a 5-step diode-clamped inverter topology [14].

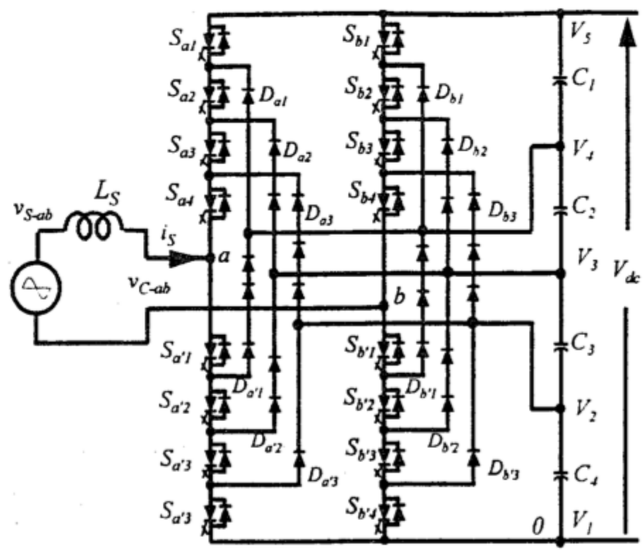


Fig. 7. 5-step diode-clamped inverter topology

The capacitors C1 through C4 each hold a DC voltage equal to the bus voltage divided by four. If the output waveform is symmetric around zero, the capacitors do not need explicit equalization circuit (i.e. for line-connected applications). The many diodes in the circuit allow current to flow correctly during switching transitions. Fig. 8 shows a typical waveform produced by this 5-step diode-clamped inverter [14].

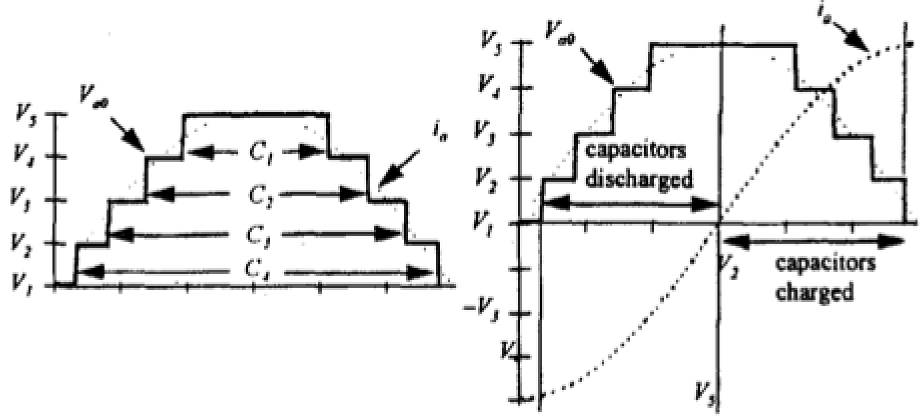


Fig. 8. Operation waveform of the 5-step diode-clamped inverter

To synthesize a waveform, the correct taps from the capacitor ladder are selected to obtain the closest voltage to the command voltage. With more stages, the inherent error in the waveform synthesis is reduced at the expense of additional complexity. These waveforms show an inverter that switches at approximately the frequency of the line. Additional strategies use PWM to dither between the voltage stages, increasing the frequency of the current ripple in the inverter.

The size of the filter inductor of an inverter is related to the maximum integrated voltage error over time. With line-frequency switching inverters, as shown above, the maximum volt-second product applied to the inductor is roughly proportional to the square of the step voltage. Thus, as the number of voltage steps is increased, the size (and likely cost) of the inductor can decrease quadratically.

If a constant-frequency PWM control method is used, the inductor size can only decrease linearly with the number of voltage steps. If switching frequency increases as the voltage steps become smaller, the inductor can decrease in size almost quadratically. For low-voltage applications (< 1kV), multilevel inverters are primarily used to reduce the size of the bulky filter inductors. With high-voltage applications, multilevel inverters are necessary to reduce the blocking voltage of the semiconductors in the converter.

VII. PANEL MISMATCH

The power produced by each PV panel or module in a solar array can vary for numerous reasons. The manufacturing process of the cells introduces variance, which may introduce a variation of 5% in the power produced by each cell. In installations, the direction of each panel may vary, yielding a difference in production varying with the time of day. Finally, dirt and other debris, plus shading from unrelated obstacles, can reduce the power produced by certain cells or panels.

In large installations, panels are often placed in series to create high-voltage strings. As the current through each string is constant, shaded or inferior panels are bypassed via panel-wide diodes when the string current exceeds their short-circuit currents. In this case, that panel produces no power. Methods of recovering this power are now under investigation by several groups and companies.

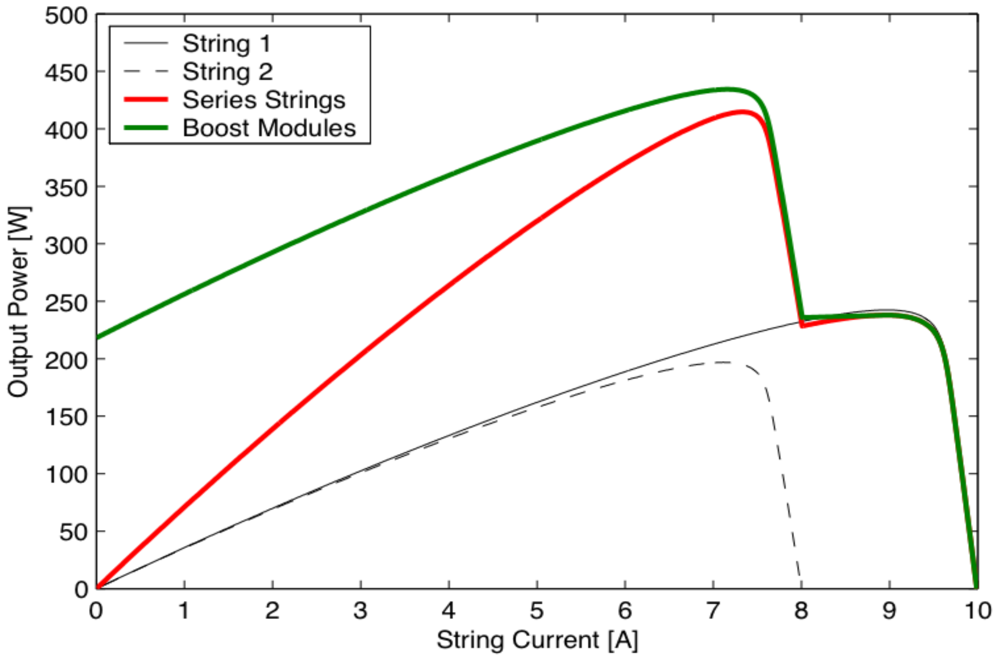


Fig. 9. Panel output power

Fig. 9 shows the output power of two panels placed in series. The red curve shows the power if no additional measures are used, where one panel has a short-circuit current of 10 A and the other has a short-circuit current of 8 A. The maximum power current is limited by the weaker panel, preventing the stronger panel from operating at its maximum power point.

If a boost converter was added to the stronger panel to reduce its current while stepping up its voltage, both panels can be operated at their maximum power point. The green curve shows the power produced by the two panels when the stronger one has a maximum power-point tracking boost converter installed. An improvement of 20 W can be achieved from this scenario.

Two approaches to this solution can be used. First, the Enphase micro-inverter provides maximum power-point tracking on a panel basis, such that each panel is optimized, and then inverts the DC power to supply the grid directly. The National Semiconductor spinoff, SolarMagic, uses local DC-DC converters to allow each panel to match the series string current, as shown above. In this case, a central inverter is still used. This system has the advantage that only one (expensive) inverter circuit and controller is necessary, reducing total system cost. However, the Enphase system is simpler to install for residential applications, and provides remote data monitoring.

VIII. THE ENPHASE MICROINVERTER

The Enphase Micro-inverter combines a maximum power-point tracker and grid-connected inverter in a relatively compact package for use with a single PV panel, depicted in Fig. 10. It uses power-line communication to alert a base station with faults and transfer operation data. This data is then transferred to the web such that the performance of the PV installation can be monitored in detail.

Fig. 10. Enphase inverter and a 250W panel

The inverter uses a single-stage two-phase isolated fly-back topology as shown in Fig. 11. Five large electrolytic capacitors are connected across the PV array to filter the ripple current from the converter and ensure efficient power tracking. Using a two-phase topology also helps in reducing current ripple. Finally, an SCR bridge connecting the AC side allows the appropriate switching of phases as the line voltage inverts twice a period.

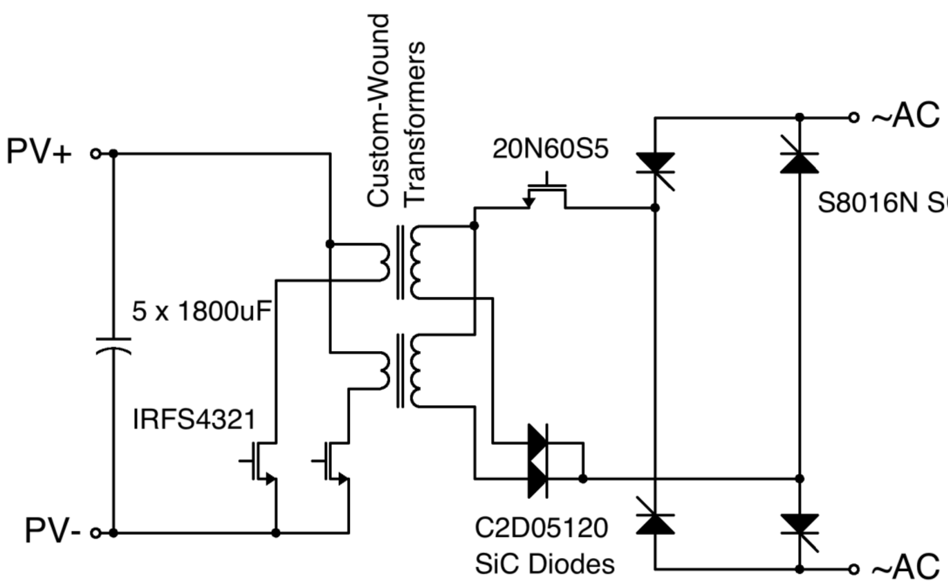


Fig. 11. Enphase micro-inverter fly-back topology

The converter achieves an efficiency of approximately 95% and a maximum power-point tracking accuracy of 98%. Due to the complexity of the system, and use of an FPGA for control purposes, the system is quite expensive at a list price of approximately $200 per 190W module.

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