Ensuring Efficiency and Reliability in Solar Power Inverters

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The market for solar power inverters, or photovoltaic inverters, is growing as the demand grows for renewable energy sources. These inverters need to be extremely efficient and reliable. This TechNote reviews the power circuits used in these inverters and recommends the best choices for switches and rectifiers in these systems.

Photovoltaic Inverters Need to be Highly Efficient

A photovoltaic system generates ac power from sunlight and consists of an array of modules. These modules are formed from a series connection of many solar cells. The solar cells convert the energy from the sunlight into electrical energy through the photovoltaic effect. The array of solar modules is connected to an inverter which converts this power into a form that can be connected directly to the ac power utility.

The energy conversion efficiency of the solar modules is in the range 15% - 18% for commercially-used photovoltaic systems. The efficiency of the solar inverters is in the range 93% - 95%. So there is a very large difference in the efficiency of the solar modules and inverters. A solar inverter with an efficiency of say 80% would be less expensive than one with an efficiency of 95%, and would use a different topology. However, designers of solar inverters have invested significant resources in developing solutions to achieve very high levels of efficiency, requiring power components with very low losses. It is interesting to understand why the efficiency of photovoltaic inverters is so important.

For this explanation we will assume that a 3 kW peak power installation generating 2550 kW-hr/year is a commercially and environmentally viable solution. The issue of electricity pricing and incentives, which widely varies from country to country, is needed for a full analysis of commercial viability, but will not be considered here.

In southern Germany, the current location of the largest installed base worldwide, a 3 kW peak power installation would generate 2550 kW-hr/year. We will assume that the efficiency of the inverter is 95%. If the inverter efficiency could be increased to 96%, this would generate 27 kW-hr/year more electricity:

$$\left(\frac{96\%}{95\%}-1\right)\times 2550\,kWh = 27\,kWh$$

The cost of the modules to generate 1 kW peak power is around $6000. So $18,000 is needed for 3 kW peak power. The investment in modules to get an additional 27 kW-hr is readily calculated:

$$\left(\frac{27}{2550}\right)\times \$18000 = \$190$$

By using higher efficiency power topologies and power semiconductors, it is possible to improve the efficiency. From analysis of the inverters on the market, it evidently makes economic sense for inverter manufacturers to improve the efficiency. For illustration, if the efficiency of the inverter were now only 86% instead of 96%, the extra investment in modules needed to compensate for the worse efficiency would be $1900. This is very close to the price of a 3 kW inverter on the market. So it would not make commercial sense to use such an inverter.

Increasing the efficiency of the system using more efficient solar modules is also possible, but at a higher cost. Significant research, development and production investment is being made to increase the efficiency of modules using new material and production concepts.

Boost Conversion Stage

The level of the dc voltage generated by the solar array is of the order of several hundred volts. The level will vary depending on several factors. First, a larger number of modules connected in series will result in a larger output voltage. This is predetermined during installation. The solar inverter must therefore be designed to function with different module combinations. Second, the output power will reduce with increasing cell temperature. Finally, the output power of the module array is dependent on how much light is falling on it -- the power output will be higher during a sunny day with cloudless skies than on an overcast day in winter. Further, both the daily and seasonal changes in the position of the sun will affect the power output.

In the calculation from the previous section, we noted that the annual output in kilowatt hours is an important quantity. We were taking the efficiency as an annual quantity over all input conditions, and noted that it needed to be maximized. The V-I curve of the solar module output will have an optimal point where there is maximum power. Operating at any other point on the V-I curve will result in lower power and therefore worse efficiency. So at all times, the inverter tracks this optimal point to maximize the overall system efficiency. This process is called *maximal power point tracking* (MPPT).

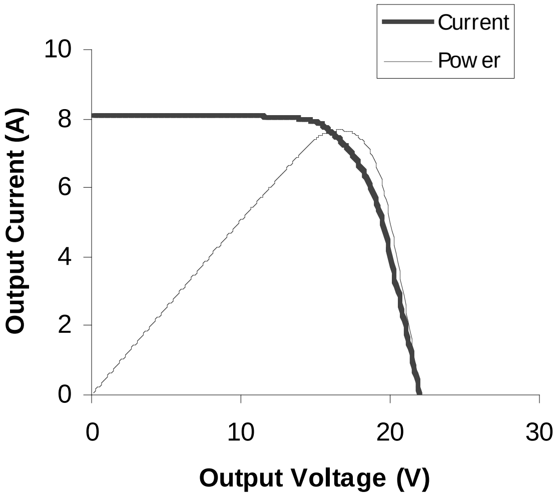

Fig. 1: V-I Curve For Solar Module

Fig. 1 shows the form of a V-I curve for a solar module. These curves are measured under standard conditions of 1000 W/m^2 irradiation at 25°C. The bold curve shows how the output current changes with the output voltage. The thinner curve shows a scaled version of the power curve, which is calculated by multiplying the voltage and the current for any given voltage. The peak power is seen to occur somewhat below 20 V. As discussed earlier, modules are connected in series to form a module array which has the same output current, but much higher output voltages. Inverters for mains power are designed to have a wide input voltage range, for example 200 V – 500 V.

The V-I curve will change with temperature and illumination conditions. For MPPT, the solar module current and voltage are measured with an ADC. This information is fed into a digital signal processor (DSP). The impedance of the inverter input circuit is then modified until the optimum power point is found.

The inverter power input circuit needs to have an adjustable input impedance. The most efficient standard topology to do this is a boost converter stage, as is almost universally used in power factor correction (PFC) stages on ac input power supplies.

The dc output of the boost stage is then converted into a sinusoidal waveform in phase with the voltage of the power utility signal. Three configurations are in common use (see Fig. 2).

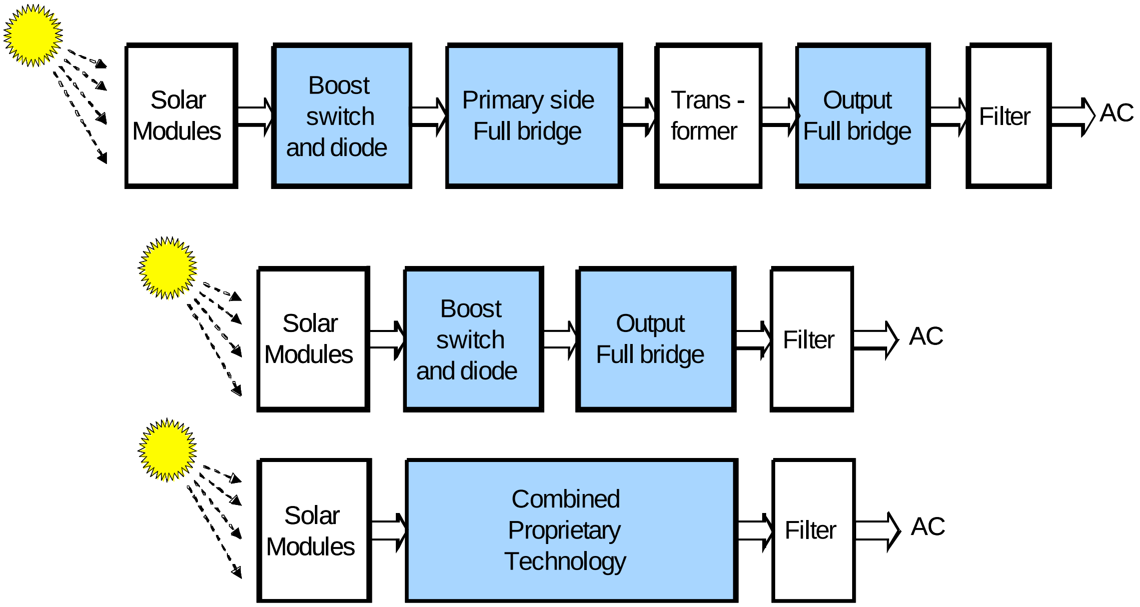

Fig. 2: Solar Inverter Topologies

The first topology shows a boost stage followed by an isolated full bridge converter. The full bridge transformer provides isolation. A second full bridge stage on the output generates the ac voltage waveform from the dc output of the full bridge stage. This is filtered before being connected to the ac power supply network via an additional two pole relay switch used for safety isolation in the event of a fault and for isolation from the network during the night.

The second system shows a non-isolated approach. Here the ac voltage waveform is generated directly from the dc voltage coming from the boost stage.

The third approach shows that the boost and ac waveform generation elements can be combined into a proprietary topology, which combines these functions using innovative interconnection of power switch and power diode elements to achieve this.

Component Selection for the Power Stages

Fig. 3 shows the power components used in a topology having a boost converter followed by a full bridge output stage.

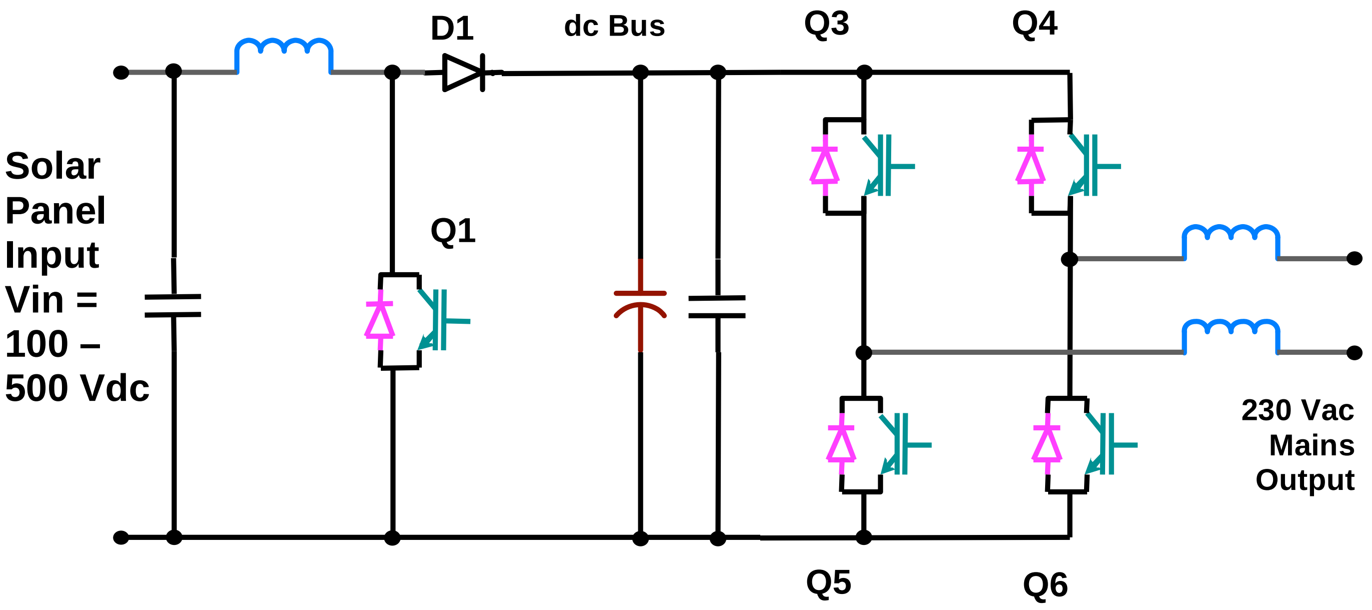

Fig. 3: Photovoltaic Inverter Power Stage (Boost + Output Bridge)

One of the most important design decisions is the choice of the voltage rating for the switches and diodes in the boost converter. Two options are generally open: 600 V or 1200 V. Choosing 600 V permits the use of MOSFETs for the input power stage. Increasing this to 800 V with MOSFETs widens the input voltage range further but will reduce efficiency, or increase expense, compared with a 600 V solution.

If the input voltage range needs to be increased further, fast switching IGBTs are ideal for the application. For a boost converter stage having a dc input, the losses can be estimated by the following equations, which ignore switching node capacitance losses, and assume that the input current ripple is zero [1], [2]:

$$Power\ Loss\ IGBT = D \times I_{IN} \times V_{CE(SAT)} + f_{SW} \times (E_{ON} + E_{OFF})$$

$$Power\ Loss\ MOSFET = D \times I_{IN}^{2} \times R_{DS(ON)} + f_{SW} \times (\frac{Q_{GS2} + Q_{GD}}{I_G}) \times V_{DCBUS} \times I_{IN}$$

$$Power\ Loss\ Diode = (1 - D) \times I_{IN} \times V_F + \frac{1}{6} t_B \times V_{DCBUS} \times I_{RRM}$$

$$Extra\ Loss\ In\ Switch\ Due\ To\ Diode = f_{SW} \times \left(V_{DCBUS}(I_{IN} + \frac{1}{2} I_{RRM})t_A + V_{DCBUS}(\frac{1}{3} I_{RRM})t_B \right)$$

$$D = \frac{V_{DCBUS} - V_{IN}}{V_{DCBUS}}$$

Here I_{IN} is the input current, f_{SW} is the switching frequency, D is the duty cycle determined by V_{DCBUS}, the intermediate bus voltage and V_{IN}, the input voltage. For the IGBT, $V_{CE(SAT)}$ is the IGBT saturation voltage, E_{OFF} is the switching off energy and E_{ON} is the switching on energy. For the MOSFET, $R_{DS(ON)}$ is the on-state resistance, Q_{GS2} and Q_{GD} gate charge values and I_G the gate drive current. For the diode, V_F is the forward voltage, I_{RRM} the reverse recovery time and t_A and t_B the two components of the reverse recovery time. The additional loss in the switch caused by the reverse recovery of the diode is shown separately as this applies to both the IGBT and the MOSFET.

Some important points should be noted in the equations. The conduction loss of an IGBT is proportional to current, whereas the conduction losses of a MOSFET are proportional to the square of the current. Other things being equal, this would put a MOSFET at a disadvantage over an IGBT for higher currents. The switching losses of both IGBTs and MOSFETs are both proportional to the switching frequency. The IGBT switching losses are dominated by the device E_{OFF} parameter, which is usually much higher than the MOSFET switching energy, determined by a combination of switching and device conditions.

For example the HGTG30N60A4D 30A 600V IGBT has an E_{OFF} of 750 µJ, despite being one of the fastest 600V IGBTs on the market. In comparison, a 45 mΩ 600 V MOSFET has a combined switch on and switch off energy of only 92 µJ, here assuming 3 A gate drive current, 400 V bus voltage and 10 A input current:

$$\left(\frac{Q_{GS2}+Q_{GD}}{I_G}\right)\times V_{DCBUS}\times I_{IN}=\frac{34/2+51}{3}\times 400\times 10=92000nJ=92\mu J$$

As a result of this, for 600 V or 800 V rated boost switches, superjunction MOSFETs are used. This technology has the best conduction losses for high-frequency switching applications. 600 V MOSFETs with $R_{DS(ON)}$ values below 100 mΩ in TO-220 package and 50 mΩ in TO-247 are available on the market today.

For solar power inverters requiring 1200 V power switches, IGBTs are the technology of choice. Newer IGBT technologies such as NPT trench and NPT field stop have been optimized to reduce the conduction losses at the cost of higher switching losses, making them less suitable for boost applications running at high frequencies. On the other hand, older NPT planar technology has better switching losses but worse conduction losses.

The FGH40N120AN 40 A 1200 V IGBT based on older NPT planar technology has excellent E_{OFF} of 43 µJ /A in comparison with devices from newer technologies, where it is very difficult to achieve such levels. The disadvantage from the FGH40N120AN device's higher $V_{CE(SAT)}$ is more than outweighed by the benefit of low switching losses at the high boost switching frequencies.

The FGL40N120AND part has a co-packed anti-parallel diode. In normal boost operation the diode will never conduct. However, during start up, or transient conditions, a boost circuit can be forced into a mode of operation where the anti-parallel diode would conduct. As IGBTs have no inherent body diode, this co-packed diode is needed to guarantee reliable operation.

The datasheet E_{ON} losses specified in IGBT datasheets generally include the extra losses caused by a diode identical to the anti-parallel diode packaged with the IGBT.

Let us estimate the power loss in this IGBT for a solar module input voltage of 300 V, a current of 10 A and a boost voltage of 600 V when using a boost switching frequency of 15 kHz. From the datasheet, E_{ON} is 2.5 mJ, E_{OFF} is 1.8 mJ and $V_{CE(SAT)}$ is 2.9 V at 125ºC. As the energies are specified at 40 A, and as the energies are approximately proportional to input current, the energies are scaled by a factor of 10/40:

$$Power\ Loss\ IGBT=50\%\times 10\times 2.9+15000\times(2.5+1.8)\times 10/40=31W$$

Different devices can be compared with this equation, also under different operating conditions.

For the boost diodes, fast recovery diodes such silicon carbide diodes (such as the Hyperfast or Stealth families) are needed. Silicon carbide diodes have a low forward voltage and low losses and are often used despite their high cost.

When selecting the boost diode, it is important to consider the effect of the reverse recovery current (or diode capacitance for silicon carbide diodes) on the boost switch as this results in additional losses.

For example consider the diode used in the FGL40N120AND datasheet. The total t_{RR} is 130 ns at 125ºC. The parameters t_A and t_B are estimated to be 36 ns and 78 ns respectively: this is not a soft switching diode, but not a very hard switching diode. I_{RRM} is 13 A and $V_F = 2.7$ V at 125ºC. The test conditions are 600 V and 40 A. The losses are lower at 10 A than at 40 A, but it is difficult to predict this accurately:

$$Power\ Loss\ Diode = 50\% \times 10 \times 2.7 + \frac{1}{6} \cdot 78ns \times 600 \times 13 \approx 13.5W$$

$$Extra\ Loss\ In\ Switch\ Due\ To\ Diode = 15000 \times \left(600(10 + \frac{1}{2} \cdot 13) \cdot 36ns + 600(\frac{1}{3} \cdot 13) \cdot 78ns \right) \approx 13W$$

It is interesting to note that the extra power loss caused by the diode in the IGBT is of the same order of magnitude as the loss in the diode itself.

With reference to the overall efficiency of a 3 kW system, it has just been shown that the losses in the boost stage amount to nearly 2% points of efficiency loss, using the components shown with a fixed bus voltage of 600 V. By moving the boost voltage to track the input voltage as closely as possible, while still maintaining a sufficiently high bus voltage for the following stage, it is possible to make the system much more efficient.

Switches and Diodes for Bridge Output Stages

After filtering, the output bridge generates a 50 Hz sinusoidal voltage output. One common implementation is a standard full bridge structure (Fig. 3, again). Q3 and Q6 are turned on to apply a positive voltage between the left and right terminals. Q4 and Q5 switch are turned on to apply a negative voltage between them.

600 V power switches are used in this application so 600 V superjunction MOSFETs are ideal for the fast switching devices. As these switching devices see the full reverse recovery current from the other device’s diode when switched on, fast recovery superjunction devices such as the 600 V FCH47N60F are ideal here. With 73 mΩ $R_{DS(ON)}$ this has low conduction losses compared with fast recovery competition devices. For the device which is switched at 50 Hz, there is no need to use the fast recovery version. These parts have superior diode dv/dt and diode di/dt characteristics in comparison with standard superjunction MOSFETs, increasing system reliability. An alternative solution is to use IGBTs in the output stage as shown in the figure. For 1200 V full bridges, the FGL40N120AND mentioned earlier is an ideal switch for new high frequency solar inverters.

As the output waveforms are sinusoidal, more complex formulae than the ones used for the boost stage are used to predict the losses. The effect of reverse recovery is difficult to simulate using modeling tools like PSPICE, so an accurate assessment and measurement of losses is possible only when there is an experimental setup in place.

References

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2. J P Harper, *Understanding Modern Power MOSFETs* Fairchild Semiconductor Power Seminar 2006, http://www.fairchildsemi.com

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