

Harmonics and Noise in Photovoltaic (PV) Inverter and the Mitigation Strategies

1. Introduction

PV inverters use semiconductor devices to transform the DC power into controlled AC power by using Pulse Width Modulation (PWM) switching. PWM switching is the most efficient way to generate AC power, allowing for flexible control of the output magnitude and frequency. However, all PWM methods inherently generate harmonics and noise originating in the high dv/dt and di/dt semiconductor switching transients. In order to reduce harmonics and switching noise, external filtering needs to be added. The following conceptual figure shows how the AC output voltage is generated at the inverter power stage output using PWM switching.

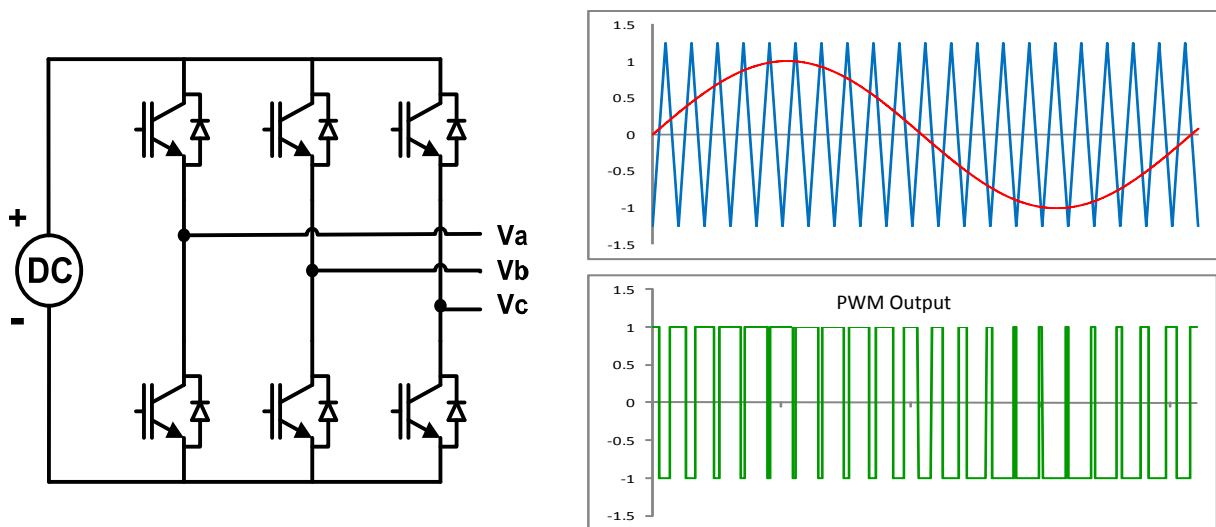


Figure 1. Three Phase Inverter PWM Generation

As shown in Figure 1, the PWM waveform is generated by comparing a reference signal (sinusoidal red trace) and a carrier waveform (triangular blue trace). The PWM waveform controls the Insulated Gate Bipolar Transistor (IGBT) switches to generate the AC output. When the reference signal is bigger than the carrier waveform, the upper IGBT is triggered on (lower IGBT being off) and positive DC voltage is applied to the inverter output phase (A). In the other case, when the reference signal is smaller than the triangular carrier waveform, the lower IGBT is turned on (upper IGBT being off) and negative DC voltage is applied to the inverter output. The reference signal magnitude and frequency determine the amplitude and the frequency of the output voltage. The frequency of the carrier waveform is called the modulation frequency. In order to generate more precise sinusoidal AC voltage waveforms and keeping the size of the LC filter small, high modulation frequencies are generally used.

There are many industrial standards that control the noise and harmonic contents in an inverter system, such as AC motor drives, Uninterrupted Power Supplies (UPS) or other AC power applications. In the case of grid-tied PV inverters, the Institute of Electrical and Electronics Engineers (IEEE) 1547, Underwriters Laboratories (UL) 1741 and FCC Part 15B standards specify the guidelines to control the harmonic contents of the output current and the Electro Magnetic Interference (EMI) generation in the inverter. The guidelines guarantee that:

- The inverters do not generate excessive noise and harmonics, which can contaminate the AC grid voltage.
- The inverters are immune to electrical and magnetic noise from other sources and provide reliable operation in an environment of high electromagnetic noise.
- The inverters do not generate unwanted radiated or conducted noise, which can disturb the stable operation of other equipment coupled either electrically or magnetically.

Most of the PV inverters manufactured in the United States are designed to meet UL 1741 and IEEE 1547 standards. As the capacity of PV generation in power distribution systems grows, utility companies become increasingly concerned that the noise and harmonics from the PV inverter systems will adversely impact the power quality or affect the operation of other equipment and cause it to malfunction or otherwise disrupt the stable operation of the power distribution system.

This article lists the possible sources of the harmonics and switching noise generated by the PV inverter and describes how they can be controlled to meet customer requirements and relevant industrial standards. To present the theoretical and experimental analysis of this phenomenon, a Solectria Renewables PVI 82kW - 480VAC PV inverter system is being used. However, since most PV inverters have similar types of component configurations, the information in this article can be used to understand the harmonics and EMI issues in a variety of inverter systems.

2. PV Inverter System Configuration

Figure 2 shows the block diagram of a Solectria PVI 82kW inverter, including the filters used for attenuating the high frequency noise on the inverter output voltages and currents. There are two main sources of high frequency noise generated by the PWM inverters. The first one is the PWM modulation frequency (2 ~ 20kHz). This component is mainly attenuated by the LC filter and the transformer. The second source originates in the switching transients of the power electronics switching devices (IGBTs). The frequency of the switching transients is dependent on the device switching characteristics, gate drive circuit and the snubber circuit in the inverter, and ranges from several hundred kHz to 100MHz. The series filter and the shunt filter are designed to attenuate the frequency components caused by these switching transients and also the harmonics from other subsystem components such as the switched mode power supply (SMPS) and other inverter control circuitry.

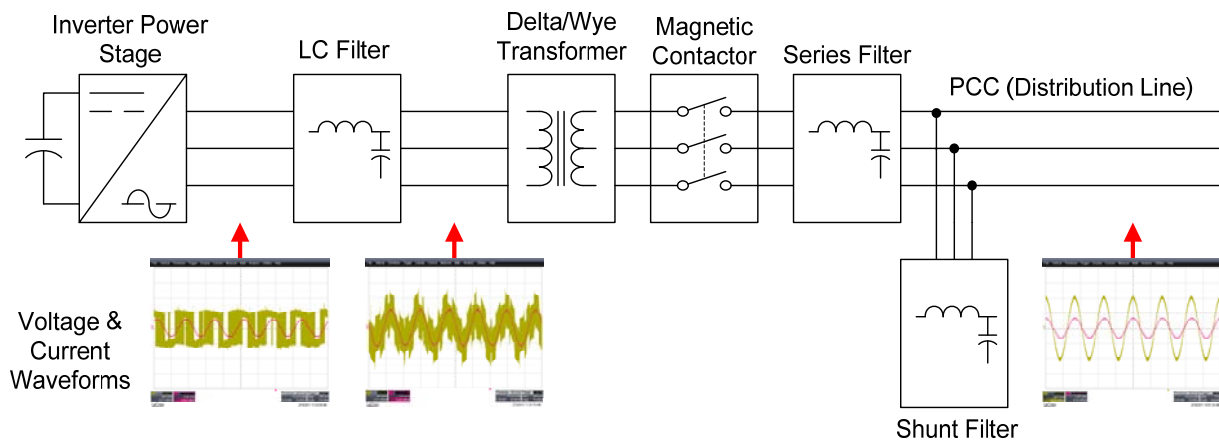


Figure 2. PVI 82kW Inverter Filtering Configuration and V/I Waveforms

Figure 2 also shows the voltage and current waveforms in each stage of the inverter. Most of the harmonic components in the voltage and current waveforms are filtered out by the LC, series and shunt filters. The inverter output current is in phase with the voltage (unity power factor) and the total harmonic distortion (THD) is less than 5% at rated operation, which is far better than the current THD of most industrial loads, and is comparable to the output current waveforms of an Uninterruptable Power Supply (UPS).

2.1. PWM frequency and LC filter

An LC filter is used to attenuate the PWM modulation frequency and its harmonics in the inverter system. The leakage inductance of the integrated isolation transformer further attenuates the high frequency component so that the output current will be sinusoidal and meet the desired THD limit. A symmetrical PWM scheme is generally preferred to reduce the ripple in the inverter output current. A symmetrical PWM scheme compared to an asymmetrical PWM reduces the effective peak-to-peak ripple current by half when using the same switching frequency.

As shown in Figure 2, the inverter’s power stage output voltage waveform is composed of a series of square waveforms and includes high frequency components. The current waveform is relatively smooth and sinusoidal as the inverter output current flows into the inductor in which it cannot change instantaneously.

Figure 3 compares the power stage output to the inverter output current. In the time domain, the waveforms do not look very different. However, the Fast Fourier Transformation (FFT) results show that the inverter current after the LC filter has much less high frequency components than the unfiltered power stage output current.

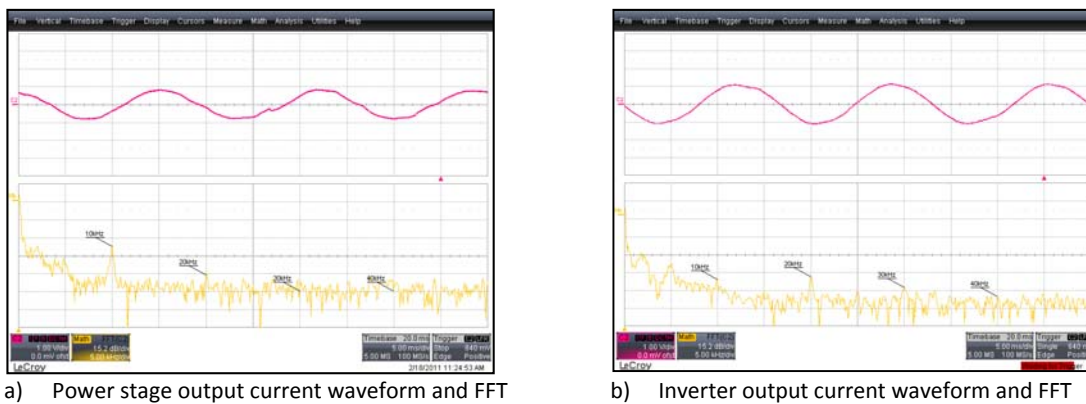
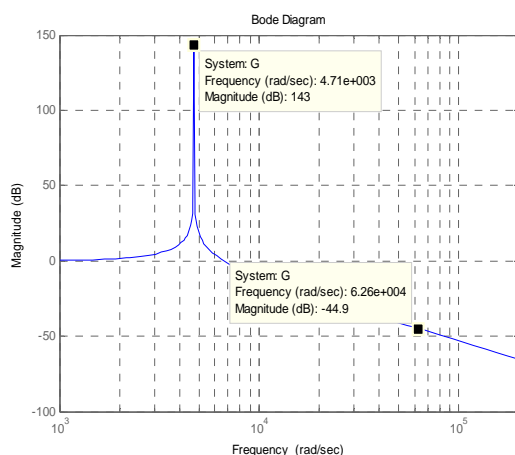


Figure 3. PVI 82kW Current Harmonic Analysis

This filtering effect can be illustrated in a Bode Plot. Figure 4 (a) shows the LC filter frequency characteristics using the theoretical frequency analysis and the measured harmonic components with a frequency analyzer when the inverter operates at full power. In the example the LC filter resonant frequency is tuned to 750Hz. Assuming a PWM modulation frequency of 10 kHz it would be attenuated to 45dB below the fundamental current component. The actual inverter output current FFT result shows that the 10 kHz ripple component is further attenuated to 60dB below the fundamental component by the shunt filter, which is about 0.1% of the fundamental 60Hz current. Figure 4 (b) shows that all the harmonic component frequencies are well controlled and the overall THD is 2.31%.



a) LC Filter Bode Plot (Theoretical Result)

THD	2.31%	12 th	0.08%
		13 th	0.16%
2 nd	0.71%	14 th	0.25%
3 rd	1.85%	15 th	0.05%
4 th	0.57%	16 th	0.05%
5 th	0.52%	17 th	0.06%
6 th	0.10%	18 th	0.04%
7 th	0.61%	19 th	0.05%
8 th	0.07%	20 th	0.04%
9 th	0.08%	21 st	0.05%
10 th	0.12%	22 nd	0.03%
11 th	0.24%	23 rd	0.07%

b) Inverter output current FFT (Test Result)

Figure 4. PVI 82kW System Output Current Harmonics Analysis

2.2. High frequency noise generated by switching transients

When the switching devices are turned on and off, high dv/dt and di/dt cause oscillations during the transients, which contain high frequency noise in the range of 100kHz or higher. Figure 5 shows the switching transients of the IGBT voltage and current with two different gate drive circuit designs.

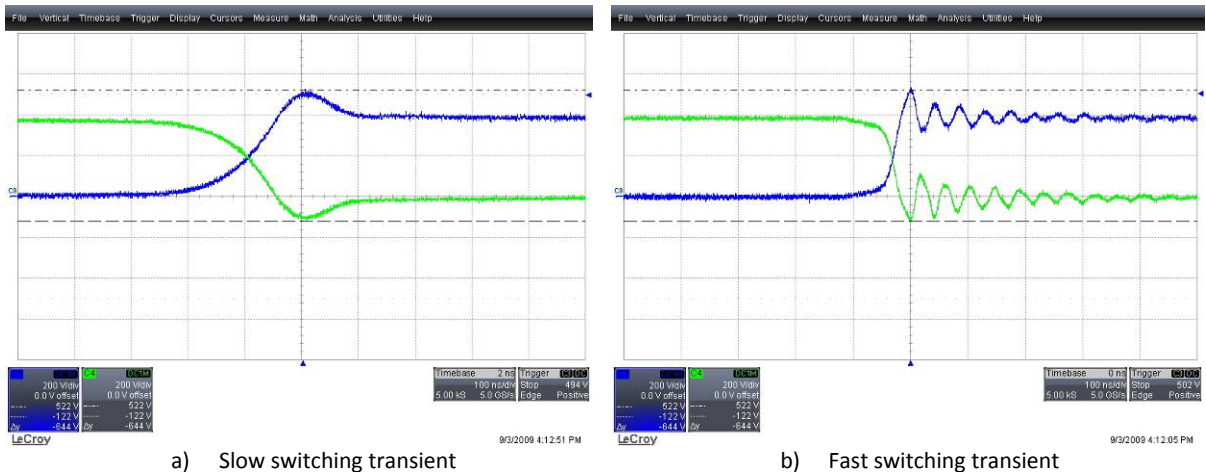


Figure 5. High Frequency Noise Generated by IGBT Switching Transients

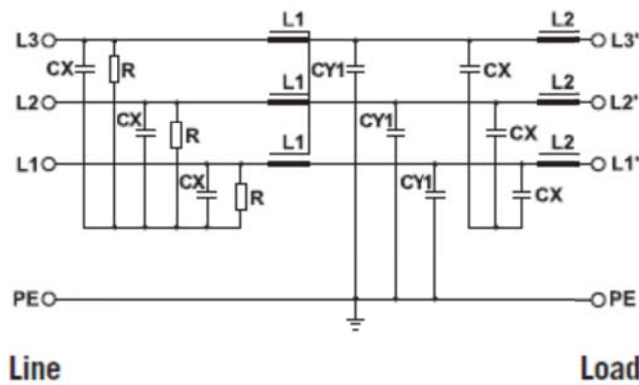
By using a slow switching transient (a), the oscillation can be minimized but switching losses are increasing due to longer operation of IGBTs in the active region. With a faster switching speed, the switching losses can be kept lower but oscillations in voltage and current are being generated due to the parasitic inductance and capacitance in the inverter stack. This high frequency oscillation falls into the frequency band regulated by FCC. In order to increase the overall efficiency of the inverter and at the same time to minimize EMI, the IGBT switching speed and noise filter design must be carefully coordinated.

There are other sources of switching noise in the inverter system caused by the Switch Mode Power Supplies SMPS and the digital control logic circuits. The noise from these components can reduce the system performance by contaminating internal analog feedback signals, resulting in logic level or communication errors and could also cause EMI interference with the outside world.

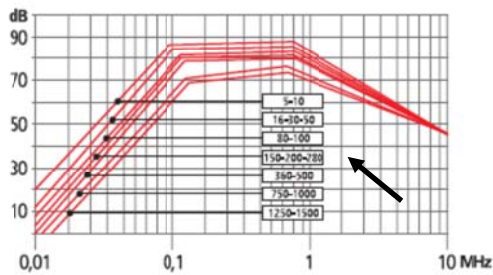
The high frequency noise can be further classified into radiated noise and conducted noise. The radiated noise can be controlled in many ways at the board level and at the system level such as shielding, component layout, wiring routing, and signal grouping. The conducted noise can be controlled by grounding or the use of proper filters, carefully designed to eliminate specific frequency components. In Solectria's PVI 82kW inverter, excellent noise levels were achieved by implementing a robust printed circuit board (PCB) layout in combination with hardware and software filters. Noise in signal circuits is solely controlled by ferrite beads and proper grounding. The PVI 82kW inverter also features series and shunt filters in the final output stage of the system. These filters are frequency band limiting and designed to filter out switching frequency transients.

Series Filter

The IGBT switching transients normally last 0.1 ~ 10usec, therefore, the filter should be tuned to between 100kHz and several MHz. Also, the controller uses a SMPS switched at 150kHz. The series filter in the PVI 82kW attenuates both common mode and differential mode noise. It provides 80dB common mode attenuation for the frequencies between 100kHz and 1MHz, and 70dB differential mode attenuation for the frequencies between 200kHz and 3MHz. The filter is selected to eliminate the system specific dominant frequency components, and is not active in the lower PWM modulation frequency range.



COMMON MODE ATTENUATION



DIFFERENTIAL MODE ATTENUATION

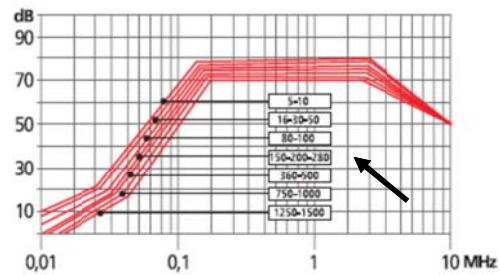
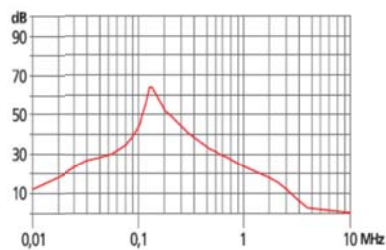


Figure 6. Series Filter Characteristics

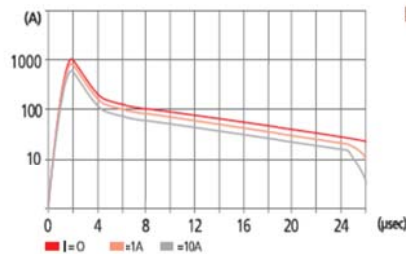
Shunt Filter

The selected shunt filter for the PVI 82kW inverter has a resonance point around 150kHz and provides a reduction of noise interference particularly in the frequency range between 50kHz and 5MHz. This filter is added to further reduce the switching noise from the power stage as well as from the switch mode power supply in the inverter control system. The shunt filter also provides a protection circuit against surges of atmospheric origin to the grid, typically caused by lightning and characterized by high current levels of short duration. The filter reacts in a few microseconds to current spikes of a few kA, and protects the system against impulse surges of up to 1000 volts.

RESONANCE CIRCUIT RESPONSE



RESPONSE TO CURRENT PULSE



ELECTRIC DIAGRAM

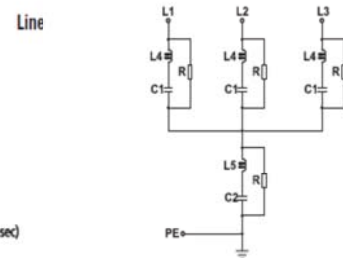


Figure 7. Shunt Filter Characteristics

3. System wide EMI Control

The following pictures show some of the EMI reduction strategies that are used in a PVI 82KW inverter.



Solid Grounding



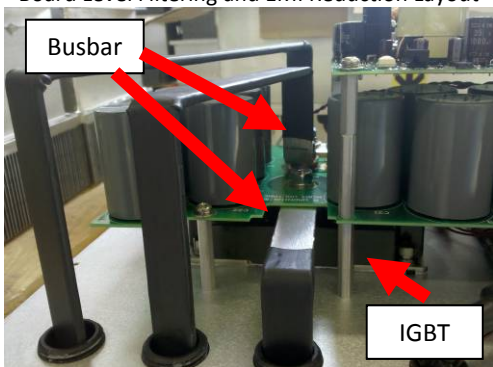
Controlled Wire Routing



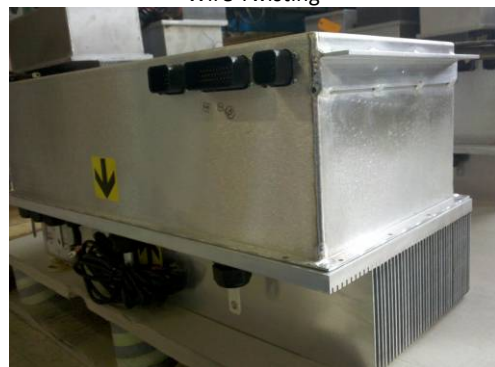
Board Level Filtering and EMI Reduction Layout



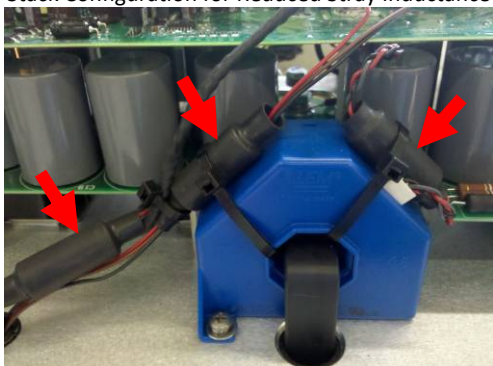
Wire Twisting



Stack Configuration for Reduced Stray Inductance



Power Electronics Enclosure for EMI Shielding



Analog Signal Conditioning using Ferrite Beads



DC side High Power Wiring for EMI shielding

4. Harmonics Generated by Firmware Control

Conventional PV inverters firmware runs at least two nested control loops. One is the AC current control loop to control the inverter output current, purely sinusoidal and in phase with the grid voltage, generating active power. The other is the DC voltage control loop in conjunction with a Maximum Power Point Tracking (MPPT) algorithm to most efficiently harvest the DC power generated by the solar panels.

When grid conditions change due to power grid transients, power line faults or load based voltage fluctuations in the distribution line, the inverter output current is controlled to balance the power transfer from the PV array to the grid. If the current control loop gains are tuned properly, the dynamic response due to the transients can be controlled at the bandwidth usually less than 1kHz. The DC voltage control loop is around the current control loop and is usually controlled at a lower sampling rate. If the DC voltage fluctuates due to sudden changes in weather conditions, the DC voltage control loop has a certain bandwidth to react and stabilize the system output. During sunlight transients, the system might generate even slower oscillations in the DC bus voltage and output AC currents control. Since the DC voltage control loop bandwidth is low, it does not cause any harmonics or EMI issues. However, if the voltage control loop were not tuned properly, the generation efficiency would decrease due to failure to track the maximum power point of the PV panels.

Solectria Renewables' inverters have been fully tested at different load conditions to have excellent dynamic characteristics for both the AC current and DC voltage control loops. The AC current control bandwidth is about 2kHz and the DC voltage control bandwidth is more than 100Hz.

5. Conclusion

This article described how the current harmonics and EMI are controlled in PV inverters. IEEE 1547, UL 1741 and FCC Part 15B standards impose strong guidelines for grid-tied PV inverters to reduce current harmonics and eliminate electromagnetic noise. Extra attention is given by the PV inverter manufacturer to design inverters that are immune to EMI problems and guarantee reliable operation of the inverter in all worst case operating conditions.

Different types of practical harmonics and noise reduction strategies for a commercial three-phase PV inverter were introduced in this article. The filtering of harmonics and EMI needs to be carefully designed to maintain the control bandwidth of the inverter and to provide clean and reliable control signals in both analog and digital electronic circuits. The PVI 82kW inverter system is equipped with several levels of harmonics and EMI filtering and its effectiveness and reliability have been proven in the harshest commercial and utility scale applications.



Controlled Workmanship



8 Hour HASS Burn-in Test and Final Verification