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Harmonics in Photovoltaic Inverters & Mitigation Techniques

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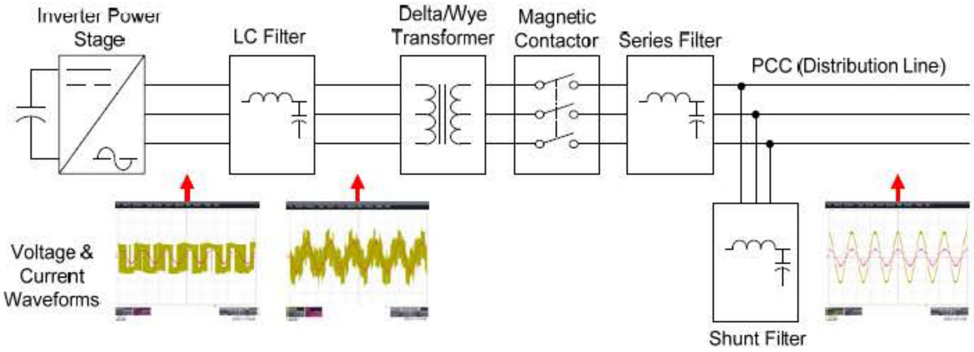
Introduction

Renewable sources of energy such as solar, wind, and BESS attracting many countries as conventional energy sources are depleting. In renewable energy sector, large-scale photovoltaic PV power plant has become one of the important development trends of PV industry. The generation and integration of photovoltaic power plants into the utility grid have shown remarkable growth over the past two decades. Increasing photovoltaic power plants has increased the use of power electronic devices, i.e., DC/AC converters. These power electronic devices are called inverters. Inverters are mainly used to convert direct current into alternating current & act as interface between renewable energy & grid. Inverter-based technologies and various non-linear loads are used in power plants which generate harmonics in system. Intensive efforts have been made to articulate the strategies of eliminating or reducing harmonics distortions generated due to output of this conversion. This study aims to investigate the causes of harmonics in PV Inverters, effects of harmonics, mitigation techniques & recent integration requirements for harmonics.

PV Inverter System Configuration:



Above fig shows the block diagram PV inverter system configuration. PV inverters convert DC to AC power using pulse width modulation technique. There are two main sources of high frequency noise generated by the inverters. One is PWM modulation frequency & second originates in the switching transients of the power electronics switching devices such IGBTs. This component is mainly attenuated by the LC filter and the transformer. An LC filter is used to attenuate the PWM modulation frequency and its harmonics in the inverter system.

Harmonic Generation & Effects:

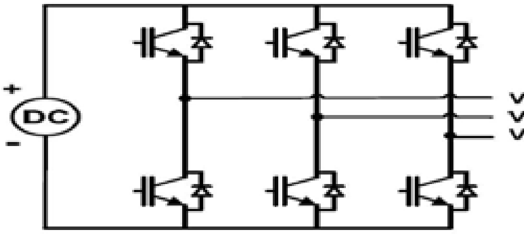
Before We understand reasons for harmonics in PV inverters and PV power plants, let us start with some basics of Harmonics.

"Harmonics are voltages and/or currents present in an electrical system at some multiple of the fundamental frequency." (IEEE Std 399, Brown Book).

Harmonics are any frequency that exists in the system except the fundamental frequency. In other words, harmonics appear as the distortion on the desirable sinusoidal waveform on power line.

An inverter is an electronic device that can transform a direct current (DC) into alternating current (AC) at a given voltage and frequency. PV inverters use semiconductor devices to transform the DC power into controlled AC power by using Pulse Width Modulation (PWM) switching.

Pulse Width Modulation, or PWM is the process of modifying the width of the pulses in pulse train in direct proportion to a small control signal; greater the control voltage, the wider the resulting pulses become. Pulse width modulation (PWM), which controls the switching status (turn on/off) of semi-conductors (such as IGBTs) supplied by a dc source, is the fundamental principle for synthesising an AC current. PWM works by comparing a 50 Hz voltage reference with a high frequency modulation signal known as a carrier.



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.

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. To generate more precise sinusoidal AC voltage waveforms and keeping the size of the LC filter small, high modulation frequencies are generally used. However, all PWM methods inherently generate harmonics and noise originating in semiconductor switching transients.

Rapid rise of current, either in positive or negative direction gives rise to harmonic generation. This results to non-sinusoidal nature of the waveform of the output of an inverter voltage source.

Harmonic currents produced by the PV or Wind plants depends on the type of inverter/converter technology used for DC/AC or AC/DC conversion and its control strategy. The output current is also linked to the harmonics of the voltage at the POC, which depends on the contribution of all the generations and loads connected to the network.

Also, non-linear loads which demands a current waveform different from the shape of applied voltage wave causes Harmonics in system. The non-linear load devices include solid state power switching devices such as diodes, thyristors, SCRs, or transistors etc. These nonlinear devices convert dc power by drawing the current in pulses. These semiconductor devices form the majority of electronic component used in electronic devices.

Harmonics limits in grid connected PV systems:

The voltage and current supplied by a power system is not a pure sine wave. It contains some amount of distortion, which has a fundamental frequency and harmonics at that frequency. Total Harmonic Distortion (THD), also known as Harmonic Distortion Factor (HDF), is the most popular index to measure the level of harmonic distortion to voltage and current. THD is defined as ratio of the RMS of all harmonic components to the RMS value of fundamental component. And usually it is expressed in percentage (%).

These distortions in voltage and current waveforms cause them change from its normal characteristics or shape. It is generally classified as a serious power quality problem. As discussed above, In the PV system, the harmonics can be produced due to the use of inverter, converter, and other power electronic devices. In this context, the Photo voltaic power plants contain several power-electronic devices that produce distortion. In addition to this, the amplitudes of high current and voltage harmonic make additional losses in the power grid and malfunctioning of grid-side protection devices. Therefore, strict regulation is imposed to ensure a less level of harmonic distortion at the Point of common coupling (PCC). The harmonic distortion can be characterized and measured by total harmonic distortion (THD) of either voltage or current.

During the advancement of the PV system integration requirements into the grid, different harmonic distortion standards are imposed; however, they are similar, excluding EREC G83 and VDE-AR-N4105, which are notably strict in which imposed a THD for PV integration should be less than 3%. Tables 1-a and 1-b provide the harmonic limits that should be achieved at PCC for current and voltage, respectively.

Table 1-a. Current harmonics distortion limits of the PV systems.

The Standards	Type	Harmonic Order (h)	Distortion Limit	THD (%)
IEEE 1547 AS 4777.2 (Australia). GB/T (China), and ECM (Malaysia)	Odd	33 < h	<0.3%	<5%
		23≤h≤33	<0.6%	
		17≤h≤21	<1.5%	
		11 ≤ h 15	<2%	
		3≤h≤9	<4%	
	Even	10≤h≤32	<O5%	
		2 ≤h ≤8	<1%	
UK (EREC G83 Stds.)	Odd	h = 3, 5, and 7	<(2% 1.14, and 0.77)%	<3%
		h =9,11, and 13	<(24033, and 0.21)%	
		11≤h≤15	<0.15%	
	Even	h= 2, 4, and 6	<0.03,033, and OM%	
		8 ≤ h ≤ 40	<0.23%	
IEC 61000-3-2	Odd	h=3,5, and 7	<(3.45,171, and 1.15)%	<5%
		h = 9,11, and 13	<0.6,0.5, and 0.3)%	
		15 ≤ h≤ 39	<0.225%	
	Even	h = 2,4 and 6	<(1.6,065, and 0.45)%	
		8≤ h ≤ 40	<0.345%	

Table 1-b. Voltage harmonics distortion limits of the PV systems

The Standards	Voltage Bus	Max. Individual Harmonics	THf)(%)
IEEE 519	(V≤ 1)kV	5%	8%
	(15≤V≤69)kV	3%	5%
	(69≤V≤ 161)kV	1.5%	2.5%
	(V> 161)kV	1%	1.5%
IEC 61000-3-2	(13≤V≤69)kV	3%	5%
	(69≤ V ≤ 161)kV	1.5%	2.5%
	(V >161)kV	1%	1.5%

IEEE Std 519- Recommended Practices and Requirements for Harmonic Control in Electric Power Systems, provides a basis for limiting harmonics. As per IEEE-519 standard, following points are important:

1. Harmonic Current Limit:

- ✓ The harmonic current limits specify the maximum amount of harmonic current that the customer can inject into the utility system, i.e., Customer is responsible for maintaining current harmonic components as per acceptable limits.
- ✓ Current limits vary by the ratio of short circuit current at PCC divided by load current (I_{sc}/I_L).

Table 2,3 & 4 shows Harmonic current limits for utility customers.

2. Voltage Limit:

- ✓ Power Supplier is responsible for maintaining the quality of voltage on power system.
- ✓ Voltage limits are based on bus voltage level at PCC.

Table 2—Current distortion limits for systems rated 120 V through 69 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics) [a, b]						
$I_{se}(/I_L)$	3≤h<11	It≤h < 17	17≤ h< 23	23≤h<35	35≤h≤50	TTD
<20[e]	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	84
50<100	10.0	4.5	4.0	13	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

[a] Even harmonics are limited to 25% of the odd harmonic limits above

[b] Current distortions that result in a dc offset, e g . half wave conveners, are not allowed.

[e] All power generation equipment is limited to these values of current distortions, regardless of actual $I_{se}(/I_L)$

Where

I_{se} - maximum short circuit current at PCC

I_L - maximum demand load current (Fundamental frequency components) at the PCC under normal load operating conditions

Table 3-Current distortion limits for systems rated above 69 kV through 161 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics) [a, b]						
$I_{se}(/I_L)$	3≤h<11	It≤h < 17	17≤ h< 23	23≤h<35	35≤h≤50	TTD
<20[e]	2.0	1.0	0.75	0.3	0.15	2.5
20<50	3.5	1.75	1.25	0.5	0.25	4.0
50<100	5.0	2.25	2.0	0.75	0.35	6.0
100 < 1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0

Table 4—Current distortion limits for systems rated > 161 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics) [a, b]						
$I_{se}(/I_L)$	3≤h<11	It≤h < 17	17≤ h< 23	23≤h<35	35≤h≤50	TTD
<25[e]	1.0	0.5	0.38	0.15	0.1	1.5
25<50	2.0	1.0	0.75	0.3	0.15	2.5
≥50	3.0	1.5	1.15	0.45	0.22	3.75

Effect of harmonics:

Harmonics in systems can cause the following effects:

1 Heating Effect: Harmonics current causes heating of equipment's like power transformers, switchgears, cables, motors, generators etc.

2 Overvoltage: Harmonic voltage generated by harmonic current flowing against impedance led to significant over voltages. This causes the equipment failure. These over voltages can be enhanced by system resonance whereby a given harmonic current may generate a large harmonic voltage.

3 Resonance: When a harmonic current flow in an inductive-capacitive-resistive circuit, it can give rise to series & parallel resonance. This result to a high harmonic current of the appropriate frequency and this can cause increased harmonic voltage.

4 Interference: Harmonics cause interference with communication, signalling, metering control and protection system either by electromagnetic induction or by the flow of ground current.

5 Other adverse effect of harmonics includes overstressing and heating of insulation, machine vibration, destruction by heating of small auxiliary components of capacitor and motors and malfunctioning of electronics devices.

6 It also creates possibilities of fuse blowing actions, relay misoperation & tripping in circuit breakers.

7 Third harmonic, which causes a sharp increase in the zero-sequence current, and therefore increases the current in the neutral conductor.

Mitigation Techniques:

So far, we have covered reasons for harmonics generations and effects of Harmonics. Various harmonic mitigation methods are available and following are some of the techniques:

1 **Harmonic Elimination by Attenuation method:**

To attenuate harmonics, passive filters, inductive reactors, phase-shifting transformers, active filters, or multi-pulse converter sections can be used.

2 **K-rated transformers:**

K-Factor determines the total harmonic current which a transformer can withstand without going beyond its specified temperature threshold limits. Under normal circumstances the value of K-Factor ranges from 1-50. It is the load that determines the K-Factor of the specific transformer. For example, in the case of linear loads K-Factor of 1 is used whereas in worst harmonic conditions K-Factor of 50 is advisable. K-Factor rating indicates the tendency of a transformer to supply rated KVA output to a load of specified harmonic content.

There are some specific rules set by IEEE which must be followed before choosing a specific K-Factor value for a specific load. These include:

- ✓ For loads with Harmonic Currents less than 15% a standard non K-rated transformer could be used
- ✓ For loads with Harmonic Currents up to 35% a K-4 rated transformer should be used
- ✓ For loads with Harmonic Currents up to 75% a K-13 rated transformer should be used
- ✓ For loads with Harmonic Currents greater than 75% a K-20 rated transformer should be used

3 **Conductor spacing and over sizing.**

4 **Keeping Harmonic Load at relatively low percentage of total load:**

In designing or expanding a system, care should be taken that the total harmonic load is kept at a relatively low percentage of the total plant load (e.g., 30% would be a good maximum target). If the measured or calculated distortion levels are high, consideration should be given to location of harmonic loads, number of buses, size of the transformers, choice of transformer connections, etc., besides the addition of harmonic filters.

5 **Multiple Pulse bridge rectifiers:**

6 **Filters:**

The most common remedial measure for harmonic mitigation is to provide selected harmonic filters tuned to appropriate frequencies. Either existing capacitor banks could be modified to tuned filters by adding tuning reactors, provided the capacitors are adequately rated, or new filter banks could be added.

Passive filters have the drawbacks of fixed compensation, resonance problem of L-C filters and are bulky. APF (Active Power Filters) offers number of advantages over passive filter like no harmful resonance, can suppress supply current harmonics as well as reactive currents and voltage sags.

Following Types of APF are available:

a. Series APF: Connected in series with Transmission line and act as controlled voltage source. They are used to compensate harmonics in supply voltage.

b. Shunt APF: Connected in parallel with Transmission line and act as controlled current source used to compensate harmonics in supply current.

c. Hybrid APF: The active power filters are better solution for power quality improvement, but they require high converter ratings. So, to overcome the above drawback, hybrid power filters are designed. The hybrid power filters are the combination of both active and passive power filters. They have the advantage of both active and passive filters. Following are different hybrid filters based on the circuit combination and arrangement.

- ✓ Shunt Active Power Filter and Series Active Power Filter
- ✓ Shunt Active Power Filter and Shunt Passive Filter
- ✓ Active Power Filter in series with Shunt Passive Filter
- ✓ Series Active Power Filter with Shunt Passive Filter

Besides the harmonic requirements, the following additional design factors may need to be considered:

- ✓ The system power factor (displacement power factor) may be corrected to required or desirable value (usually above 0.9).
- ✓ The total kVA demand on the supply transformer may have to be reduced if the transformer is overloaded.
- ✓ Similarly, the current ratings of buses and cables may have to be reduced.

7 Artificial Intelligence:

Problems related to harmonics faced by power utilities can be avoided by efficiently estimating/predicting the harmonics using artificial intelligence techniques. Techniques like Artificial Neural Networks can be used for efficient estimation of harmonics in power distribution networks.

Conclusions:

This article described the basic configuration of PV inverters. PWM technique is described which generates harmonics in PV inverters. Also, effects of harmonics and various mitigation techniques are discussed. To ensure a high quality of the PV plants generated power, power system security and stability, some of the new power quality requirements are recommended by different codes and standards. These power quality requirements regulate the installation of power systems and ensure the grid stability.

IEEE-519 & IEEE 1547 standards provide guidelines for grid-tied PV inverters to limit harmonics.

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