PSCAD Simulation of Grid-Tied Photovoltaic Systems and Total Harmonic Distortion Analysis

Abdulrahman Kalbat
Electrical Engineering Department
Columbia University in the City of New York
New York, NY 10027
Email: ak3369@columbia.edu

Abstract—With the increasing fears of the impacts of the high penetration rates of Photovoltaic (PV) systems, a technical study about their effects on the power quality metrics of the utility grid is required. Since such study requires a complete modeling of the PV system in an electromagnetic transient software environment, PSCAD was chosen. This paper investigates a grid-tied PV system that is prepared in PSCAD. The model consists of PV array, DC link capacitor, DC-DC buck converter, three phase six-pulse inverter, AC inductive filter, transformer and a utility grid equivalent model. The paper starts with investigating the tasks of the different blocks of the grid-tied PV system model. It also investigates the effect of variable atmospheric conditions (irradiation and temperature) on the performance of the different components in the model. DC-DC converter and inverter in this model use PWM and SPWM switching techniques, respectively. Finally, total harmonic distortion (THD) analysis on the inverter output current at PCC will be applied and the obtained THD values will be compared with the limits specified by the regulating standards such as IEEE Std 519-1992.

Index Terms—EMTDC, photovoltaic systems, power system harmonics, power system simulation, PSCAD, total harmonic distortion.

I. INTRODUCTION

The future plans for smart grid deployment , which mainly depend on the concept of distributed generation, make grid-tied photovoltaic systems more attractive solution, especially in regions with the high solar irradiation values. With the continuous advancement in power electronics and the increasing number of consumer appliances which utilize power electronics, both the customers and the utility operators are more aware of the importance of power quality of the utility grid. One of the most important power quality issues is harmonic distortion which is mostly caused by nonlinear power electronic based loads that are connected to the grid. Connecting PV systems to the utility grid, which is already being injected with harmonics from nonlinear loads, will introduce more stress on the power quality of the grid. All previously addressed issues makes it clear that more studies should be conducted on the effects associated with the high penetration rates of photovoltaic system on the power quality of the utility grid. Total Harmonic Distortion analysis could be used to measure the magnitude of the harmonic distortion in any power network.

Since such study requires a complete modeling of the PV system in an electromagnetic transient software environment,

PSCAD was chosen to simulate the grid-tied PV system in this paper. PSCAD is a powerful and flexible graphical user interface to the world-renowned EMTDC simulation engine but it does not provide power flow solutions. Another feature of PSCAD is its ability to interface with Simulink. This feature enables the researchers to combine the flexible power systems simulation of PSCAD with the rich and ready-to-use control systems library of Simulink which helps in minimizing the modeling time. Also, PSCADs interface is designed in a way that is easily used by researchers and developers in the power systems field [1].

In section II of this paper, a detailed description of the grid-tied photovoltaic system PSCAD model will be given. The description include a detailed discussion of the different components of the PV model along with the operation, modeling and control principles of each component. Also, the effects of variable atmospheric conditions on the output of some components will be presented. The output signals of most important stages of the system will plotted. In section III, the Total Harmonic Distortion (THD) analysis will be applied to the PSCAD model and the obtained results will be discussed by comparing them to the IEEE Std 519-1992.

II. PSCAD MODEL OF GRID-TIED PHOTOVOLTAIC SYSTEM

The PSCAD model used in this paper is based on [2] and it mainly consists of PV array model, DC link capacitor, DC-DC converter, three phase inverter, AC filter, transformer and utility grid equivalent model, as shown in Fig. 1. In this section, the tasks and some of the important parameters which define each components model will be discussed. The tasks of the different additional control circuits which are used to control some components in the main model will be also discussed. The effects of variable atmospheric operation conditions (irradiation and temperature) will be discussed for some components.

A. PV Array

Photovoltaic cell is the basic semiconductor device that generates electricity by the photovoltaic effect when exposed to radiant energy such as sunlight [3]. The default parameters' values were used to define the PV module in PSCAD. The
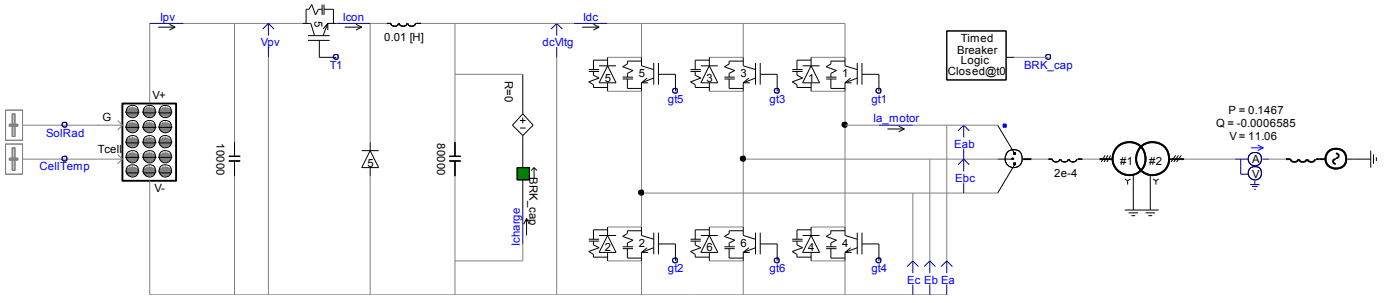
Fig. 1. Grid-Tied PV model in PSCAD.

model enables the user to specify the number of series and parallel cells per module and the number of modules connected in series and in parallel which helps in building PV systems with high power rating. By using the default values, the final output of the single module is 650 watt and 260 kilo-watt for the total 400 modules. Increasing the input irradiation value would increase the short circuit current of the PV while increasing the input temperature value would decrease the open circuit voltage of the PV.

B. DC Link Capacitor

The DC link minimizes the ripple of the PV source current by using a large capacitor. It is assumed in determining the size of DC link capacitor that the output current is ripple free. The voltage across the Dc link capacitor is controlled by the DC-DC converter as discussed next.

C. DC-DC Converter for MPP Tracking

DC-DC converter is used for Maximum Power Point Tracking (MPPT) by controlling the voltage across the DC link capacitor and the PV array. This is achieved by first creating a reference voltage that is then supplied to a PI controller which creates switching signals that force the voltage across the PV array to follow the reference voltage. These two stages are discussed next.

1) Maximum Power Point Tracking (MPPT): The model used for creating the reference voltage is shown in Fig. 2. First, photovoltaic output current (Ipv) and output voltage (Vpv) are passed through a first order low pass filter with a magnitude of G = 1 and a time constant of T = 0.01 seconds in order to filter out the high frequency components or harmonics from these signals. The filtered current and voltage signals (I_{pvF} and V_{pvF}) are then fed into the MPPT control block that uses the Incremental Conductance Tracking Algorithm. An algorithm that is based on the fact the slope of the PV array power curve shown in Fig. 3 is zero at the Maximum Power Point (MPP), positive on the left of the MPP, and negative on the right. The MPP can thus be tracked by comparing the instantaneous conductance (I/V) to the incremental conductance ($\Delta I/\Delta V$) [4] as in (1):

$$\begin{cases} \Delta I/\Delta V = -I/V, & \text{at MPP} \\ \Delta I/\Delta V > -I/V, & \text{left of MPP} \\ \Delta I/\Delta V < -I/V, & \text{right of MPP} \end{cases} \quad (1)$$
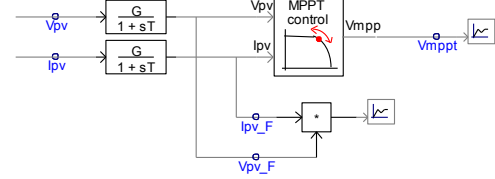

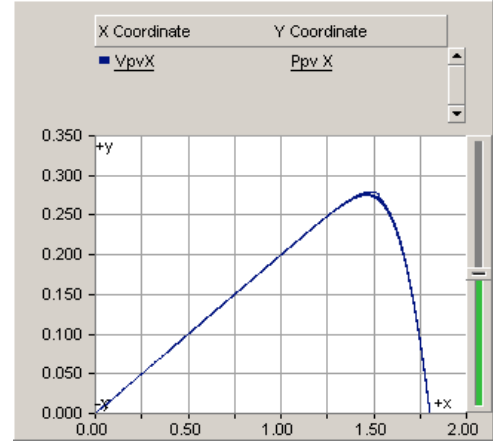Fig. 2. Maximum power point tracking model in PSCAD.

Fig. 3. Characteristic PV array power curve at STC. PV array power output in kWatt (y-axis) and PV array voltage in kV (x-axis).

Based on the previous three cases, the MPPT generates a reference voltage (Vmppt) at which the PV array is forced to operate. The algorithm decrements or increments Vmppt to track the maximum power point when operating under varying atmospheric conditions. This reference voltage Vmmpt is used as an input to the DC-DC Converter Control model discussed next.

2) DC-DC Converter Control: DC-DC converter is an electronic circuit that is used either to step down the input voltage (buck converter) or to step up the input voltage (boost converter). In this PSCAD model, buck converter was used that consists of a Pulse Width Modulation circuit (shown in Fig. 4), Insulated Gate Bipolar Transistor (IGBT) switch, inductor, capacitor and free-wheel diode [5], as shown in Fig. 1.

The difference between the solar panel output voltage (Vpv) and the reference voltage (Vmppt) is used as an input to the Proportional-Integral (PI) controller, shown in Fig. 4, which
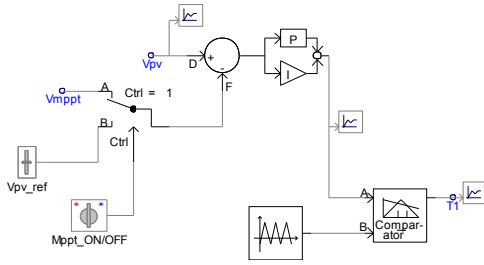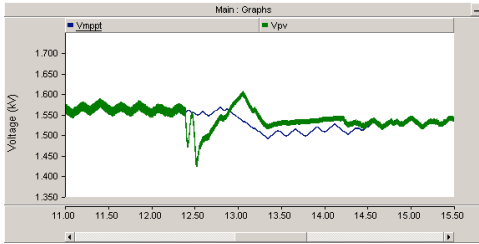
Fig. 4. DC-DC Converter Control model in PSCAD.

Fig. 5. MPPT reference voltage (Vmppt) and PV array output voltage (Vpv) at 1000 W/m^2 and 500 W/m^2.

then, based on this difference, controls the duty cycle of the PWM pulse. The duty cycle, defined as the fraction of the period during which the switch is on, ranges between 0 and 1. A duty cycle value of 0.5 means on and off time are equal, a value greater than 0.5 means on time is greater and a value less than 0.5 means off time is greater [6]. The PWM signal (T1) was generated by using a comparator which has the duty cycle signal at port A and a saw-tooth wave at port B which ranges from 0 to 1. The comparator sets its output to 1 whenever A is greater than B and 0 otherwise creating pulses with a magnitude of 1 and with pulse widths which depend on the duty cycle.

By supplying the gate terminal of the IGBT switch with the PWM signal (T1), the converter could be switched on (when T1 = 1) and off (when T1 = 0) and for the time durations which are determined by the widths of the pulses.

When the IGBT switch is on, the free-wheel diode is reverse biased (open circuit) and current flows through the inductor causing it to be charged with energy which helps in limiting the slew rate, maximum rate of change of the output voltage, of the switch. The capacitor is also charged and provides a filtering action by minimizing the voltage ripple produced at the output of the buck converter.

When the IGBT switch is off, the free-wheel diode is forward biased (short circuit for ideal diode) providing a path for the discharge current from the inductor. The capacitor is also discharged.

This continuous charging and discharging process of the inductor and the capacitor forces PV output voltage (Vpv) to track and follow the reference voltage (Vmppt) to operate at the MPP, as shown in Fig. 5, even when the irradiation decreased from 1000 W/m^2 to 500 W/m^2.
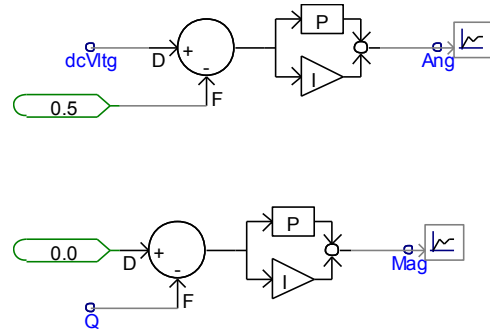

Fig. 6. Simple P and Q regulation model in PSCAD

D. Three Phase Inverter

In order to be able to tie a PV system with the utility grid, the DC output power of the DC-DC converter should be converted into a three phase AC power using a three phase inverter. IT is part of inverters task to keep the DC voltage across its input (DC-DC converters output) at a constant value. In this PSCAD model, the three phase inverter consists of a simple P and Q regulation circuit, a firing pulse generator and a three phase inverter bridge.

1) Simple P and Q Regulation: In order to establish a constant DC bus voltage (dcVltg) between the DC-DC converter and the inverter, a PI controller, shown in Fig. 6, is used to set this voltage at 0.5 kV. The output of the controller (Ang) will be used as an input to the firing pulse generator which will be discussed next.

The second PI controller sets the reactive power (Q) of the grid to zero which forces the inverter to operate at unity power factor so that it produces sinusoidal voltage and current which are in phase. The output of this controller (Mag) will be also used as an input to the firing pulse generator.

2) Firing Pulse Generation: The switching signals of the 6 IGBT switches of the 3-legged inverter bridge shown in Fig. 1 were generated using a Sinusoidal Pulse Width Modulation (SPWM) technique shown in Fig. 7. It starts with creating three sinusoidal modulating waves with a frequency of 60 Hz and a phase shift equal to the output of the previous PI controller (Ang) with additional shifting of -120 and 120 degrees. The magnitude of the modulating waves is equal to (Mag) from the previous PI controller. Then, the three sinusoidal modulating waves were compared with a triangular carrier wave with magnitude ranging between -1 and 1. Switching signals gt1, gt3 and gt5 were generated by setting the output of the comparator to 1 whenever the modulating wave is greater than the carrier wave and 0 otherwise. Since the operation of the two switches in each of the three legs of the inverter bridge should be complementary to produce the final sinusoidal wave, the switching signals gt4, gt6 and gt2 were generated by inverting the switching signals gt1, gt3 and gt5, respectively [7].

3) Three Phase Inverter Bridge:
By applying the previously generated switching signals (gt1 to gt6) to the 6 IGBT switches shown in Fig. 1, the inverter
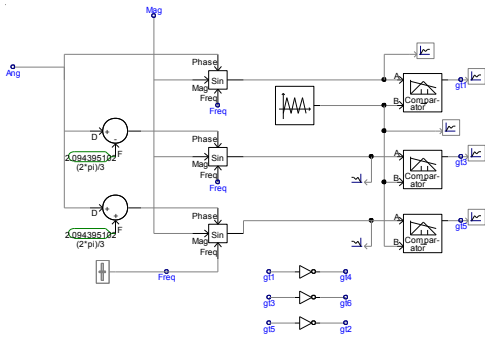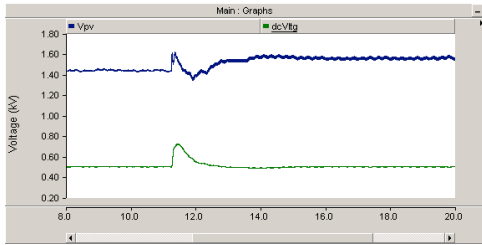
Fig. 7. Firing pulse generation model in PSCAD

Fig. 8. PV array output voltage (Vpv) and DC-DC converter output voltage (dcVltg) at 200 W/m^2 and 1000 W/m^2.
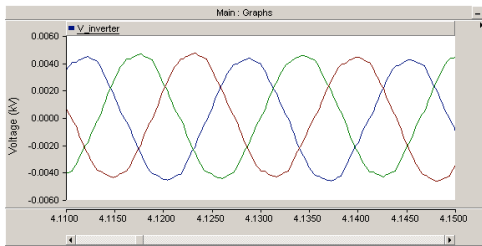

Fig. 9. Close up view of the inverter output Line-Neutral voltage at 1000 W/m^2.

kept its input DC voltage (dcVltg) at a constant value of 0.5 kV, as shown in Fig. 8, even when the irradiation increased from 200 W/m^2 to 1000 W/m^2). It also converted the constant DC voltage at its input (dcVltg) to an AC voltage which is shown in Fig. 9 which clearly shows the distortion present in inverter's output.

E. AC Filter

Based on the previous observations related to the output voltage of the inverter and the distortion involved, an AC filtering stage is required to further smoothen the output [8]. In this model, the AC filter was implemented using the inductor shown in Fig. 1. The inductor improved the shape of the output voltage of the inverter to an almost sinusoidal wave as shown in Fig. 10.

F. Transformer

Transformers in grid connected PV systems act as galvanic isolation and can be used for voltage adjustment if required. There are three main methods used by the inverters for
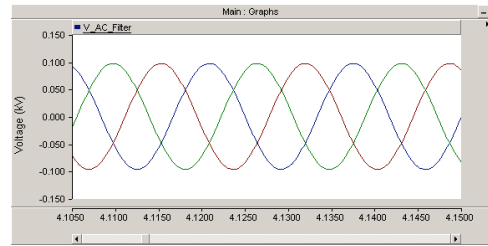

Fig. 10. Close up view of the AC filter output Line-Neutral voltage at 1000 W/m^2.

TABLE I
VOLTAGE RATING FOR ELECTRIC POWER SYSTEM AND EQUIPMENT

Voltage Class	Nominal Line-Line RMS Voltage
Low Voltage	$< 600\ V$
Medium Voltage	$600\ V - 69\ kV$
High Voltage	$69\ kV - 230\ kV$
Extra High Voltage	$230\ kV - 1100\ kV$
Ultra High Voltage	$> 1100\ kV$

galvanic isolation: low frequency transformer, high frequency transformer and transformer-less inverters. Most commonly used method for galvanic isolation is using the conventional low frequency transformer operating on grid frequency. By controlling AC current, the power that is fed into the grid can be controlled. This is a tried and tested method and is being used right from the start of the PV technology. But this has some disadvantages like heavy weight, high cost, additional losses and non-unity power factor, especially at low load conditions. One way to omit the bulky transformer is to use high frequency transformers. Another emerging topology is the transformer-less inverter which has less overall losses, lighter in weight and it is cheaper than conventional grid frequency transformer topology. In addition, topology without transformer increases the control over the system voltage and power since transformer limits the control of the grid current [9] [10].

A conventional, operating on grid frequency (60 Hz), step up, wye-wye, three phase transformer (230 V / 11 kV) was used in the PSCAD model as shown in Fig. 1. The low voltage side of the transformer (230 V) was connected to the inverter while the high voltage side (11 kV) was connected to the grid.

G. Utility Grid

The utility grid system is represented only as an equivalent 11 kV and 60 Hz source behind the system inductive impedance as shown in Fig. 1. Based on [11], which provides ranges of voltage ratings for electric power systems in the US as shown in Table I, the utility grid (11 kV) in this PSCAD model falls within the medium voltage (MV) power systems range.

III. TOTAL HARMONIC DISTORTION (THD) ANALYSIS

Harmonics are sinusoidal components of a periodic wave having a frequency that is at multiples of the fundamental

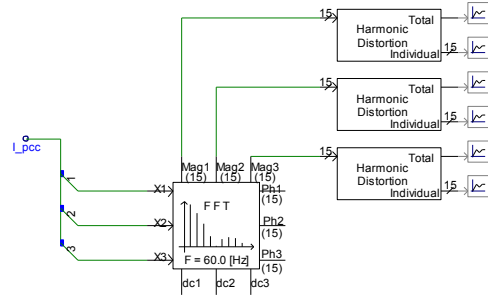| Odd Harmonic	Distortion Limit
$3^{rd} - 9^{th}$	$< 4.0\ \%$
$11^{th} - 15^{th}$	$< 2.0\ \%$
$17^{th} - 21^{st}$	$< 1.5\ \%$
$23^{rd} - 33^{rd}$	$< 0.6\ \%$
Above the 33rd	$< 0.3\ \%$

Fig. 11. PSCAD circuit to calculate total current harmonic distortion at PCC.
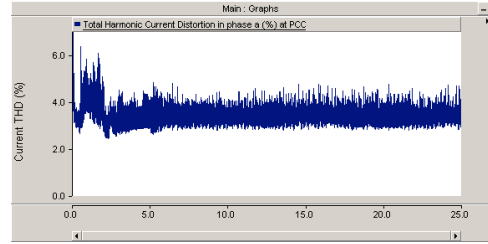

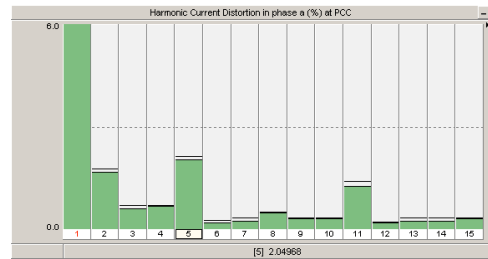Fig. 12. THD (%) of the current in phase a at PCC and measured at STC.

Fig. 13. Individual harmonic distortion (%) of the current in phase a at PCC and measured at STC. In the x-axis is shown the index of the harmonic with the fundamental frequency having harmonic index that is equal to 1.

frequency. Harmonics in PV systems are generated by the converters which use switching techniques that generate signals that are not perfect sinusoidals. Connecting PV systems to the utility grid, which is already being injected with harmonics by the non-linear loads connected to the power network, will add a stress on the power quality of the grid.

In order to maintain acceptable levels of grid power quality, standards that regulate the effects of PV systems on the utility grid should be developed. One such standard is IEEE Std 929-2000 "IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems" [12] which ensures compatible operation of photovoltaic (PV) systems that are connected in parallel with medium and high voltage level electric utility. It is recommended by the previous standard that the harmonic distortion at the Point of Common Coupling (PCC), which is the point at which the PV system is tied with the grid, should comply with IEEE Std 519-1992 [13]. In this PSCAD model, PCC lies between the transformer and the grid.

The PV system output should have low current distortion levels to ensure that no adverse effects are caused to other equipment connected to the utility system. The key requirements of clause 10 of IEEE Std 519-1992 are summarized as the following:

- Total harmonic current distortion shall be less than 5% of the fundamental frequency current at rated inverter output.
- Each individual harmonic shall be limited to the percentages listed in Table II. The limits in Table II are a percentage of the fundamental frequency current at full system output. All even harmonics in these ranges shall be <25% of the odd harmonic limits listed.

In order to calculate the Total Harmonic Distortion (THD) of the current at the PCC, the PSCAD standard blocks shown in Fig. 11 were used. The Fast Fourier Transform (FFT) block was used to determine the harmonic magnitude of the line current at PCC in each phase (a, b and c) as a function of time. The resulting harmonic magnitude was then used as an input to the Harmonic Distortion block which measures both the total and individual harmonic distortion in percentage (%).

The FFT block was configured to output the magnitude of 15 harmonics with the fundamental frequency at 60 Hz. Inputs to this block were the three RMS values of the three line currents at PCC. Harmonic Distortion block was configured to output THD and individual harmonic distortions in percent.

In Fig. 12 is shown the THD of the current in phase a at PCC and measured at STC which was plotted as a percentage that varies with time. It is noticed from this figure that the THD is oscillating around 4% which is less than the 5% limit established by the previously discussed standard.

In Fig. 13 is shown the harmonic distortion of the current in phase a at PCC and measured at STC which is visualized using a polymeter in PSCAD that associates the harmonic distortion (%) with its harmonic index (1 to 15). By comparing the value of each harmonic in Fig. 13 with the range given in Table II, it was found that none of the harmonics violates the specified limits.

By expanding the harmonic index to 63 as shown in Fig. 14, it was found that harmonics with indices from 38 to 46 were violating the distortion limits, which is 0.3%. Based on this, one can conclude that these distortions were introduced to the PCC because of the insufficient filtering stages implemented in the PSCAD model. Another reason is the simplicity of the controls used in generating the switching signals of the inverter.
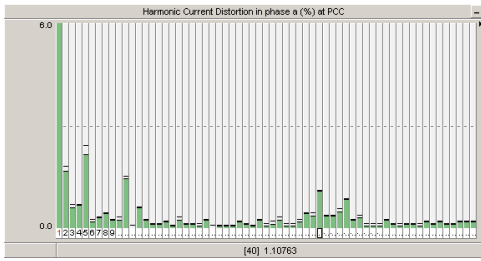
Fig. 14. Individual harmonic distortion (%) of the current in phase a at PCC and measured at STC. The number of the monitored harmonics was expanded to 63.
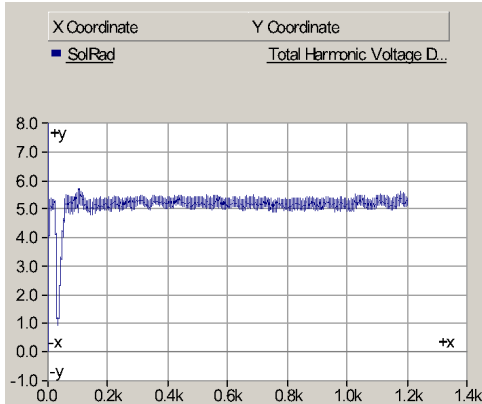

Fig. 15. Voltage THD (%) in phase a at PCC (y-axis) measured at solar irradiation varying between 0 to 1200 W/m^2 (x-axis).

Fig. 16. Current THD (%) in phase a at PCC (y-axis) measured at solar irradiation varying between 0 to 1200 W/m^2 (x-axis).

using PWM and SPWM for DC-DC converter and inverter, respectively, were tracked using the PSCAD model. Some of the standards which regulate the interfacing of PV systems with the utility grid were discussed. Finally, total harmonic distortion analysis on the output current of the inverter at PCC and at STC was conducted using standard PSCAD blocks (FFT and Harmonic Distortion blocks) and then compared with the limits specified by IEEE Std 519-1992 standard.

Standards which impose limits on the voltage THD levels in power networks were established, but it is a common practice, especially in the case of grid-tied PVs, to pay more attention to current THD analysis. In order to justify this practice, the voltage and current THD values of the PSCAD model at PCC were plotted at variable solar irradiation values as shown in Fig. 15 and Fig. 16, respectively. As shown in Fig. 15, there is no noticeable effect of variable solar irradiation values on the voltage THD values which remains almost constant. On the other hand, it is shown in Fig. 16 that by increasing the solar irradiation values, the current THD values were decreasing. One could conclude that current THD analysis are more important than voltage THD analysis in the case of grid-tied PV systems that are operating under varying solar irradiation. Also, PV systems operating under low solar irradiation values inject more current harmonics into the utility grid than at high irradiation values. This might force PV system operators to either use better filtering techniques or even disconnecting the PV system from the grid to avoid paying the high THD levels penalty specified by the utility operator.

IV. CONCLUSION

In this paper, the tasks of the different components of grid-tied PV system PSCAD's model were discussed. Also, the effect of varying the atmospheric conditions (irradiation and temperature) on the PV system was justified with graphs. The control stages involved in generating the switching signals
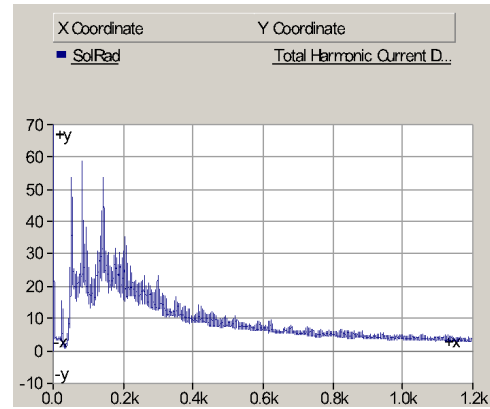
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