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The Effects of Insolation Variation For Grid-connected Dispersed Photovoltaic Distributed Generations

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ABSTRACT

The overwhelming increase in the penetration level of photovoltaic (PV) distributed generation (DG) into the electric utility grid in disperse locations and the variation of temperature and solar insolation across the PV-utility integration area calls for the evaluation of the quality of power injected into the grid under such conditions. The effects of insolation variation were investigated and it was found that the injected power follows the trend of the cumulatively averaged insolation of the connected DGs and the grid current's total harmonic distortion is much less than the maximum standard allowable value of 5% for even the steepest insolation variations. The grid current waveform varies in proportion with the insolation at constant interconnection voltage, which varies insignificantly by 0.07%. The efficiency of the inverter controller is evaluated based on its absolute reference signal tracking capability. The performance is evaluated based on a simulation of 1 MW, dispersed four-DG, grid-connected PV system implemented with MATLAB Simulink and SimPowerSystems Toolbox.

***Keywords**:* Distributed Generation, Insolation Variation, Photovoltaic, Total Harmonic Distortion

1. INTRODUCTION

The grid-connected photovoltaic (PV) distributed generation (DG) system is experiencing an overwhelming growth which highlights the need for addressing utility-integration issues due to the increasing levels of penetration [1]. Among others, the issue of considering the benefits of PV-grid integration rather than being a liability is paramount [1]. The main function of the PV DG is the conversion of solar energy into electrical energy and for its integration with the electric power utility system a DC to AC inverter is used as an interface. The inverter is adequately controlled, using various control strategies, to synchronize and inject pure sinusoidal electric power into the grid at unity power factor (UPF). The most commonly used inverter control technique is the current control which uses the grid current as a reference and the grid voltage as a reference for synchronization. The control algorithm should be robust enough for disturbance rejection and fast reference signal trajectory tracking. [2], [3] and [4].

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Renewable energy resources, particularly the PV DGs, are naturally intermittent and operate based on the variations of solar irradiance and temperatures peculiar to the areas they are located [5] and [1]. These variations can be brought about as a result of passing cloud, dust, etcetera [6] and [7].

The variations in insolation due to cloud cover could be sudden, and therefore, subject the electric power system to indiscriminate power disturbances similar to those caused by the demand-side random load variations [8]. The current's total harmonic distortion of the grid injected current due to any variation should not be more than 5% [9] as in the IEEE 1547 standard requirements for the electric grid-interconnection[10]. In this paper, a study of the effects of insolation variations to the grid-injected power was carried out for a system with multiple PV DGs penetration. The single line diagram of the studied system, in Fig. 1 is implemented in MATLAB Simulink and SimPowerSystems Toolbox.

2. SYSTEM USED FOR THE STUDY

A 1MVA grid-connected PV system is used in this study as shown in Fig. 1. It comprises of four inverter based DGs located in different parts of the electric grid network. Each DG commits a 0.25 MW real power into the grid. The PV part uses the SunPower SPR-315E-WHT-D solar modules. The module's maximum power is 315.07 W corresponding with 54.7V and 5.76A maximum voltage and current values respectively. For generating 0.25MW at 400 V AC voltage, an array of 8 series modules and 103 parallel strings are required. A DC-DC maximum power tracking is used to harness maximum possible power at all times. Each DG site has its peculiar irradiance variation and temperature as shown in Fig. 2 and Table 1 respectively. Fig. 3 shows the cumulative average of the insolation as seen by the electric grid.

2.1. Inverter Control

The interface of the PV systems with the electric grid is achieved by using voltage source converters (VSCs). The inverter DC input is supplied by the output of the PV system's DC-DC converter, regulated with respect to the PV voltage and referenced voltage value. This regulator is known as the outer control loop which further forms the reference value for the inverter inner current control loop [11]. This reference current is compared with the grid current in the synchronous reference frame, the details of which can be found in [12] and [13]. The grid sinusoidal voltages and currents are measured at the Feeder Bus and transformed to their DC representations for control action using Park's Transformation [14] as in (1) where f_x could be voltage or current quantity. In the control system structure shown in Fig. 4, V_{abc} and I_{abc} are the grid voltages and currents transformed into the V_{dq0} and I_{dq0} respectively. The difference between V_{dc} and V_{dcref}, themeasured PV voltage and the DC-DC converter output voltage respectively, is regulated to generate the current controller reference, I_{dref} which isfurther compared with the transformed grid current, I_d.The reference q-axis component of the grid current, I_{qref} is set to zero to realize the generation of power at UPF. The resulting outputs of the current controllers, V_{dref} and V_{qref} are used to drive the pulse-width modulation (PWM) system for inverter switching. For power reference trajectory tracking, the reference currents, I_{dref} and I_{qref} can be determined using (2) and (3), where V_d is the d-axis of the peak phase voltage obtained from the transformation in (1) [15].

$$\begin{bmatrix} f_d \\ f_q \\ f_0 \end{bmatrix} = \sqrt{\frac{2}{3}} * \begin{bmatrix} \cos(\omega t) & \cos(\omega t - 2\pi/3) & \cos(\omega t + 2\pi/3) \\ -\sin(\omega t) & -\sin(\omega t - 2\pi/3) & -\sin(\omega t + 2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} * \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \tag{1}$$

$$I_{dref} = (2/3) * (P_{ref} / V_d) \tag{2}$$

$$I_{qref} = (2/3) * (Q_{ref} / V_d) \tag{3}$$

Table 1
DG Sites Location

DG	*Location*	*Temperature (°C)*
DG1	1	40
DG2	2	35
DG3	3	25
DG4	4	45

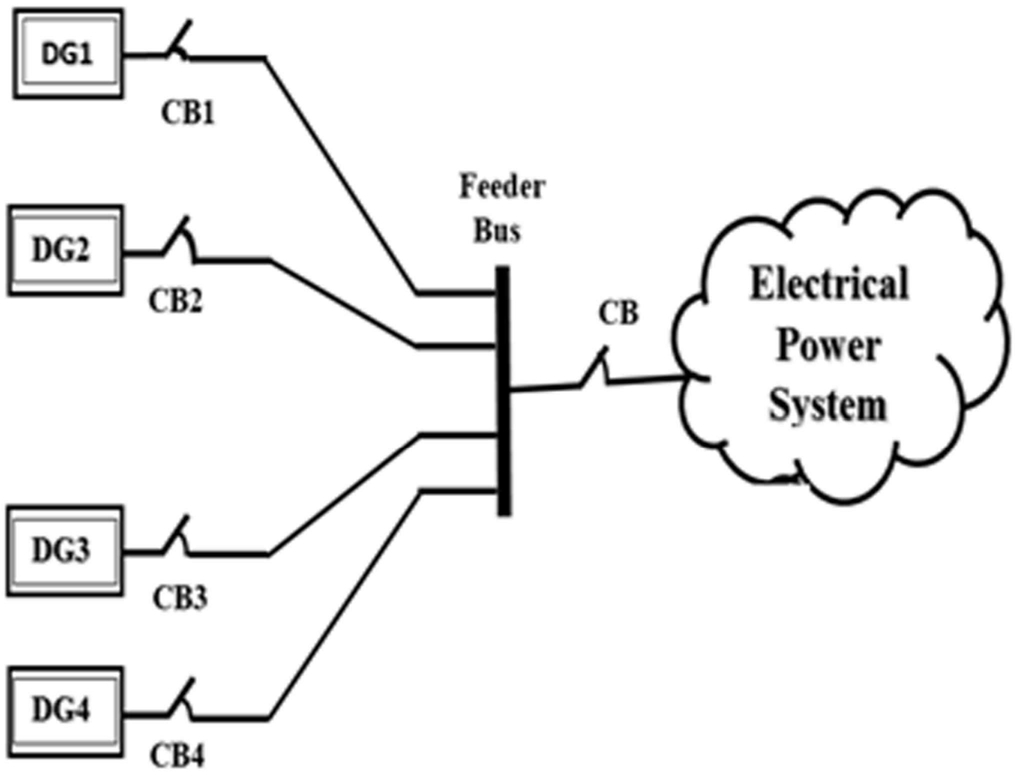

Figure 1: Single Line Diagram of Grid-Connected Dispersed DGs

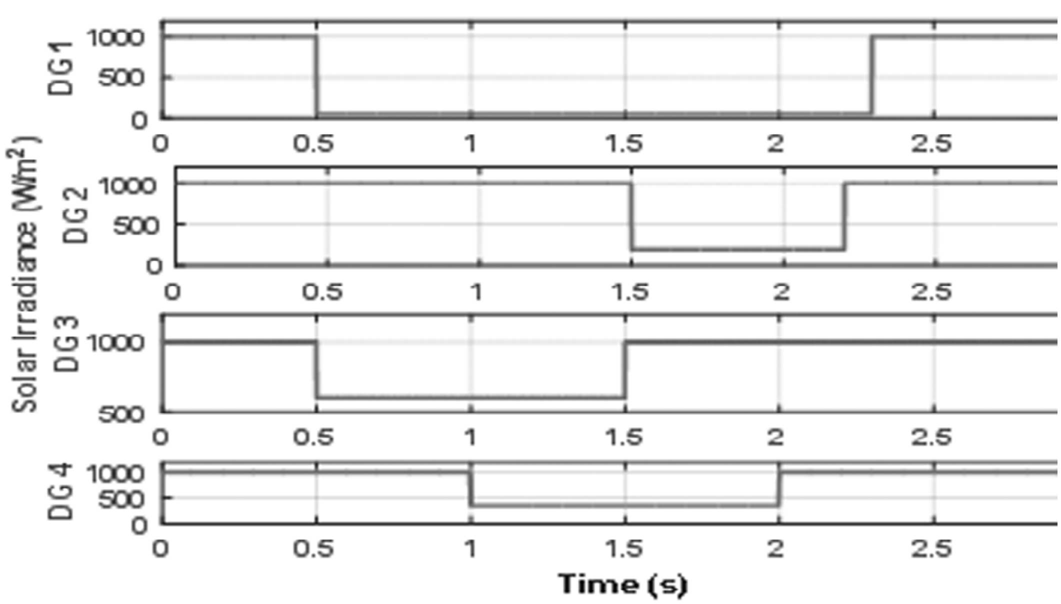

Figure 2: Variation of DG Sites Solar Irradiance

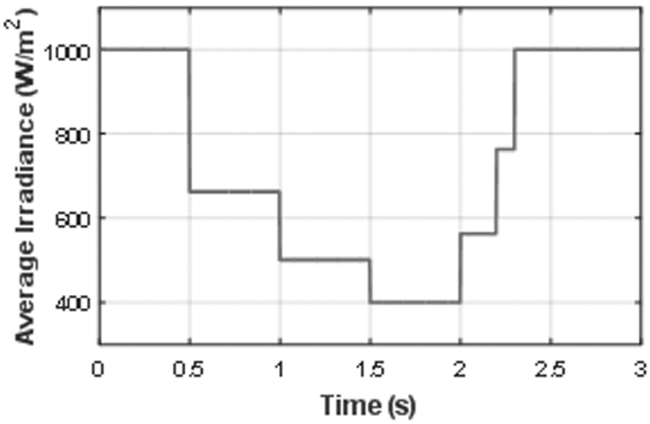

Figure3: Averaged DG Sites' Solar Irradiance

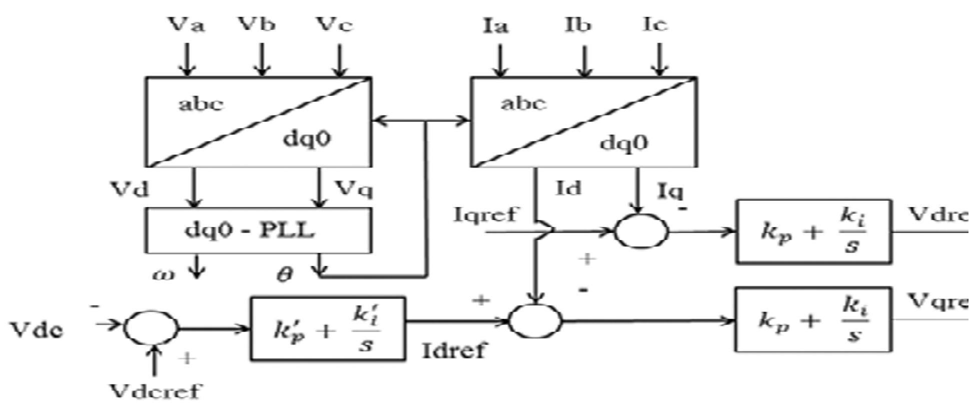

Figure 4: Inverter Current Control Structure [4]

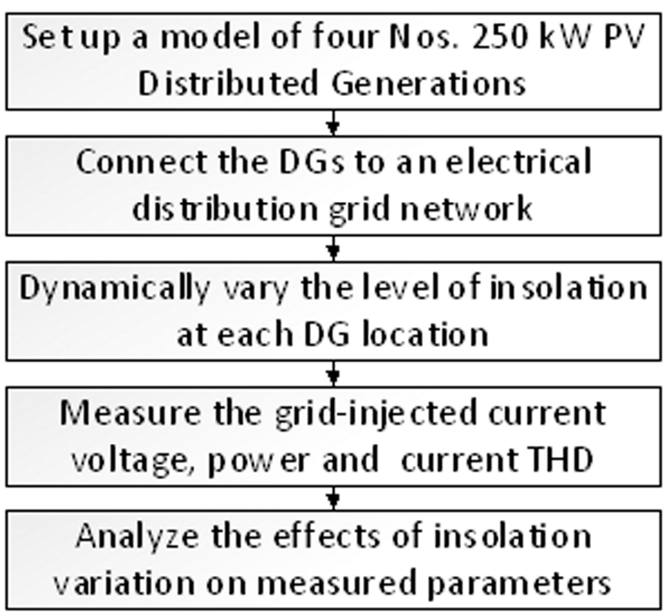

Figure 5: System Flowchart

3. METHODOLOGY

The respective dispersed, 250 kW DGs are connected to the grid, or electric power system through the Feeder Bus, injecting a total power of 1MW. Each DG is connected via one of the circuit breakers CB1-

CB4 whereas the whole system is connected by CB as in Fig. 1. The temperature and site number of the DGs are shown in Table 1. The overall system is implemented using the MATLAB Simulink and SimPowerSystems Toolbox. The simulation time is three seconds and the system is subjected to insolation variations of Fig. 2. The averaged sites insolation is shown in Fig. 3. The voltages, currents, injected power and total harmonic distortion (THD) of current are monitored at the grid side in order to analyze the effects of the insolation variation as in Fig. 5.

4. RESULTS AND DISCUSSION

The effect of temperature variation on the maximum power point and current can be seen in Fig. 6. As the temperature increases from the nominal value of 25°C to 45°C, the maximum power point decreases with the decrease in the open-circuit voltage caused by the PV's maximum voltage output dependence on module temperature . In Fig. 7, it can be seen that the injected real power follows the pattern of the averaged insolation in Fig. 3. The reactive power injected into the grid is zero, after the system steady state. This confirms the PV control system's operation at UPF following the setting to zero of the quadrature axis current reference, I_{qref} of the inverter control system. This indicates that the reactive power follows the set zero reference value.

It can also be seen from Fig. 8 that the grid injected current significantly follows the trend of the insolation variation which in turn dictates the variation in the grid injected power. The effect of the variation in the grid voltage is very insignificant since the grid is assumed to be stiff, therefore fixing the PV system voltage constant. The percentage variation in voltage corresponding with the maximum and minimum insolation variations is 0.07%, which is infinitesimally small in comparison with the standard utility allowable variation of between 88% and 110% of the nominal voltage value. This is confirmed by trace 2, Fig. 9 (b), where the grid voltage remains fixed, despite the glaring variations in insolation.

The effectiveness of the system inverter controllers in terms of trajectory tracking is eminent in Fig. 9 (a). The system is made to track a reference active power that varies from zero through 500 kW to 1 MW. It can be seen that the system tracks the reference power trajectory with good speed and accuracy devoid of transients in the response. The current in trace 3, Fig. 9 (c) follows the power variation in proportion with the injected power levels. The reactive reference current, Iqref determined by (3) is zero since the desired injected reactive power is zero for UPF operation. Similarly, Idref is calculated from (2) as: 0, 16.33A and 32.66 A respectively for the reference real power trajectory of 0, 500 kW and 1MW.

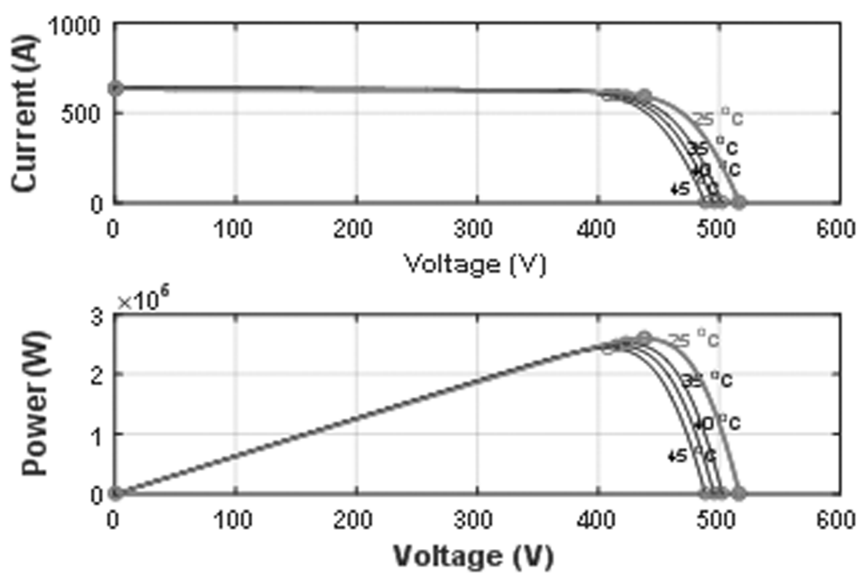

Figure 6: Effects of temperature variation at DG Sites.

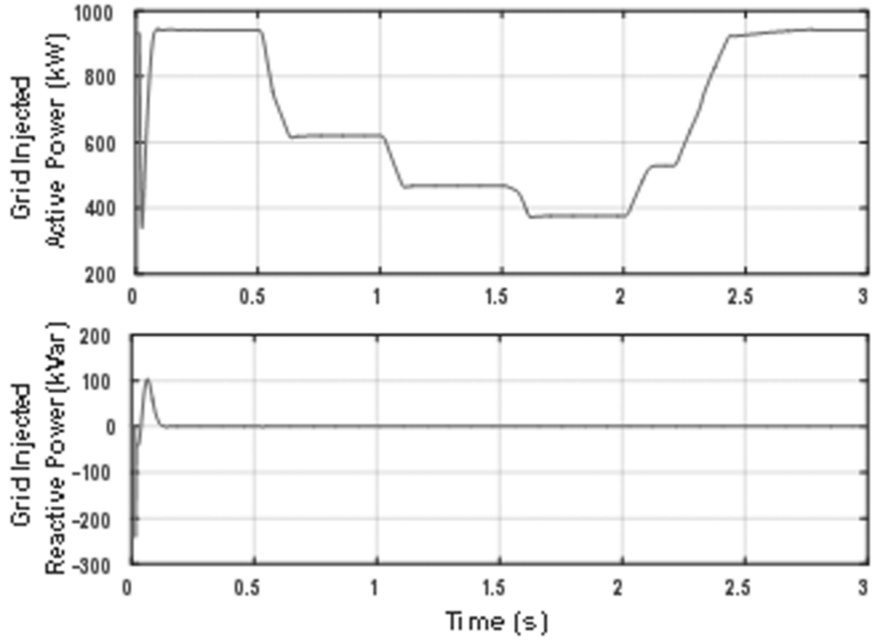

Figure 7: Effects of Insolation Variation at Injected Power

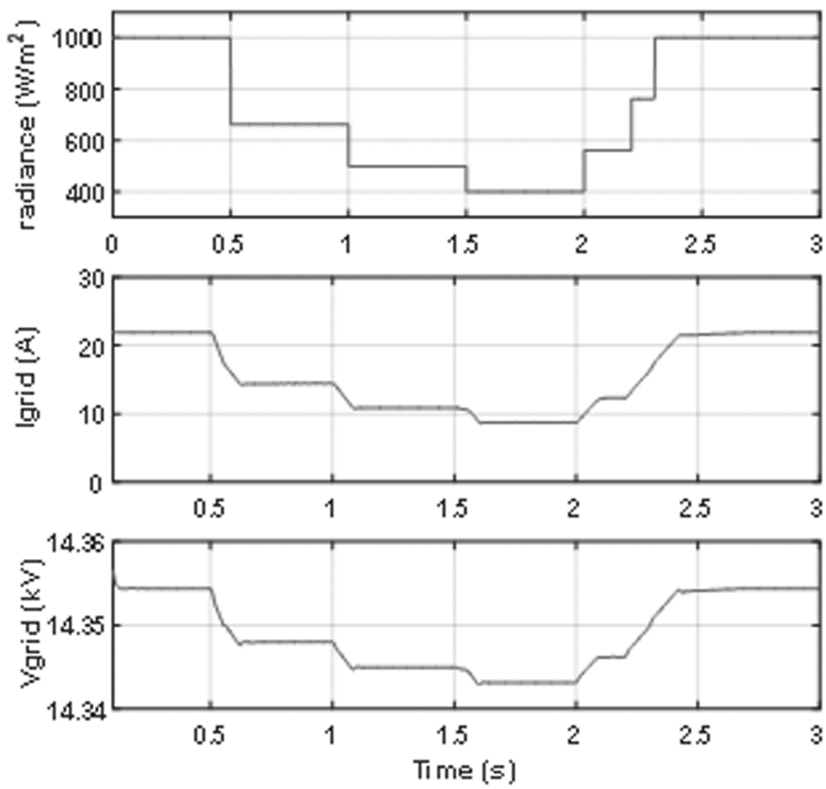

Figure 8: Effects of insolation variation on current and voltage

The grid current's THD resulting from the insolation variation is shown in Fig. 10. It can be seen that the maximum value is less than the IEEE 1547 standard stipulated value of 5%.

5. CONCLUSION

A 1 MW grid-connected PV system comprising four 250 kW, dispersed DGs is implemented using the MATLAB Simulink SimPowerSystems Toolbox to study the effects of insolation variation in the grid-

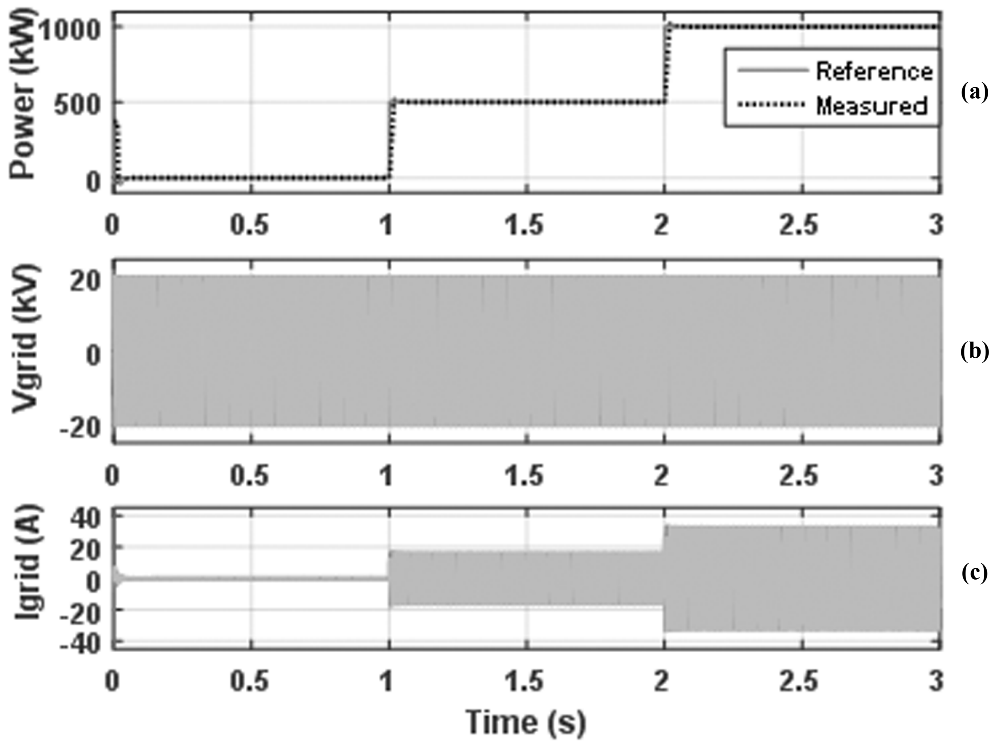

Figure 9: (a) Power trajectory tracking (b) voltage variation (c) current variation

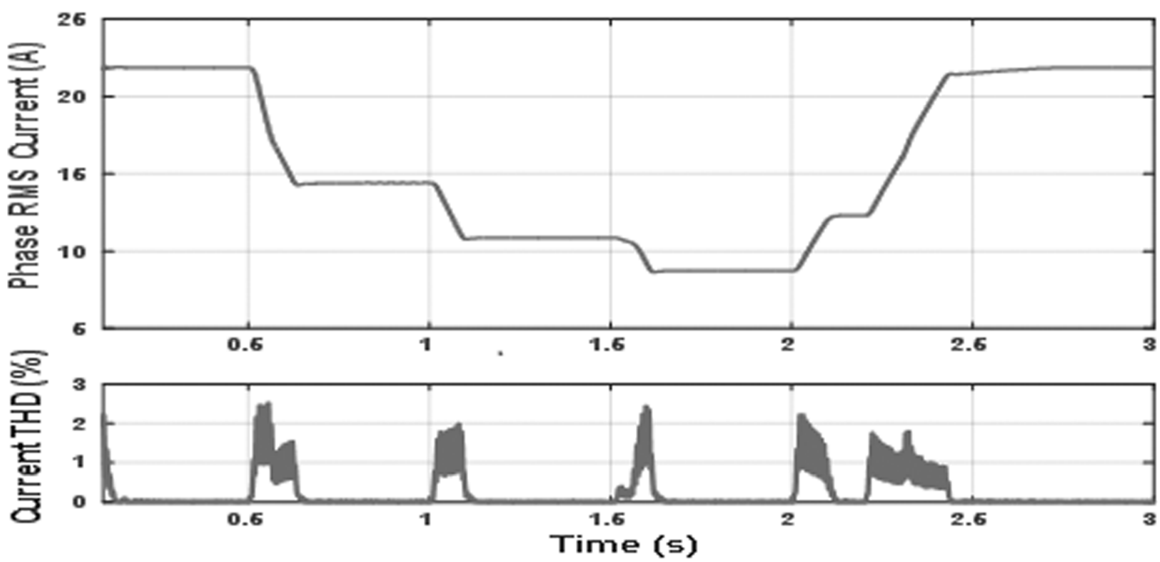

Figure 10: Effects of Insolation Variation on Grid Current THD.

injected power. As dynamic variations of loads in an electric system create some disturbances that may be consequential to the system's power quality, sudden variations in insolation level in dispersed DGs interconnected to the electric grid may present similar consequences. The grid being stiff, that is, its voltage and frequency being constant, the effects of insolation variation is eminent only on the grid current. The maximum voltage variation recorded in the study with respect to the insolation change is 0.07%, indicating insignificant grid-voltage variation. The cumulative injected current into the electric grid network, contributed by all the dispersed DGs is proportional to the DGs averaged insolation level and the consequential quality of the grid power with respect to the insolation variation is determined by the use of current's THD, which is always found to be much less than the maximum IEEE 1547 standard allowable value of 5%.

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