Voltage profile improvement of weak grid with solar PV integration

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Article Info

ABSTRACT

The objective of this paper is to improve the voltage profile of the grid in pertinence to grid due to power injection from distributed solar photovoltaic (PV) arrays. Weak grids are modeled as worldwide adaptation of net metering, transactive energy systems, and the possibility of further deterioration of power quality with higher grid penetration. In this paper, a solar PV integrated weak distribution grid modelled as the PV arrays being frequently connected in rural areas, due to various reasons like cheap real estate and lack of accessibility. In this paper, three case studies of PV generation are simulated, i.e., scheduled solar PV generation less than load requirement, PV generation equal to load requirement, and PV generation more than load requirement, by considering the daily solar irradiation and load demand profiles of a residential area under study.

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1. INTRODUCTION

The photovoltaic (PV) industry has shown great progress in product development and implementing mass production techniques effectively in making PV popular and affordable in the renewable energy sector. The price per watt of PV panels has dropped from \$76 in 1977 to \$0.57/W in 2015. With the greenhouse and global warming issues on the rise, PV energy appears to be perfect solution. In spite of all these pros that back the PV panels, it has not been widely adopted and implemented in India, which at present depends predominantly on coal to meet its power demand. The expenses of PV residential installation are too high for the Indian middle class and hence not seen as a potential investment. The PV panels can be made an affordable investment upon widely adapting to the net metering system, enabling the customers to use the PV facility without the additional expenses of energy storage systems, yet with good reliability. The concept of net metering and transactive energy has been widely discussed recently in the international domain of power and energy recently. Grid wise architecture council (GWAC) defines transactive energy as a set of economic and control mechanisms that allow the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter [1].

In addition, the dynamic interaction of the distributed generation (DG) with a weak grid can degrade the power quality of the entire power network even if the resonance is not an issue. The grid is considered as weak if the short circuit ratio (SCR) indicator or the inductance resistance ratio (IRR) indicator has values

below 10 and 0.5 [2]. At the instants of excess generation and minimum load consumption there is also a possibility of voltage swells, which can lead to grid instability. Modeling of PV array with the comparison of different models and degrees of complexity is proposed in [3]. The boost design was based on [4] but it lacked PI controller design. The 4-leg inverter is designed based on [5], and it provides a good comparison among various control techniques. A structured methodology for analyzing the grid connection studies to determine the integration of solar PV units into the weak distribution networks is proposed in [6]. A comprehensive approach for large-scale solar PV injection into weak grids and its influence on the system's voltage stability is described in [7]. E. Rakhshani *et al.* [8] presents a comprehensive methodology of current research trend on the analysis and control of power grid with grid connected solar PV based power generations. Q. Alsafasfeh *et al.* [9] proposes a maximum integration capacity optimization model of solar PV power according to different power factors for the PV power. A hybrid power system with wind-solar PV generations along with an enhanced control approach for the grid connected wind energy conversion system (WECS) considering uncertainties has been proposed in [10].

P. M. Ariyaratna *et al.* [11] describes the possibility of enhancing the power network's PQ with the help of wind and solar PV based DGs in weak power grids. A new analytical methodology to mitigate the slow and fast voltage fluctuations in LV distribution feeder has been presented in [12]. O. B. Adewuyi *et al* [13] describes the design guidelines of key parameters for PVT based solar systems and a suitable energy storage approach. M. Mohanan *et al.* [14] proposes a voltage stability-based methodology for large scale PV power penetration into the susceptible power grid. The quality of power in India is widely criticized for its large tolerance in voltage and frequency ranges of operation. The lack of good quality and conditioned power is visible even in the metro cities of this nation. There is a great chance of further deterioration of power quality with high levels of grid penetration that will come with the implementation of net metering system. Hence, it is relevant to study the impacts PV penetration can have on the grids, exceptionally the weak grids. The major objectives of this paper are to model a PV integrated weak distribution grid, and to study the voltage profile of the grid in pertinence to grid due to power injection from distributed PV arrays.

2.   MODELING OF THE SYSTEM

The major objective of this section is to model a solar PV integrated weak distribution grid. This work also presents the voltage profile of the grid in pertinence to grid due to power injection from distributed PV arrays. The block diagram of overall system has been depicted in Figure 1. Modeling of different components of this system is explained next [15].
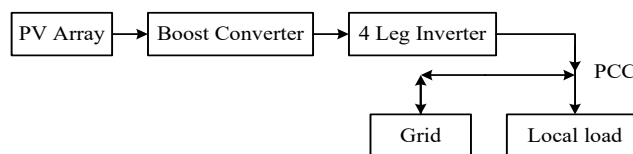
Figure 1. Block diagram of overall system

2.1. Modeling of PV array

It was necessary to model a PV device instead of just using a DC source, as the variation of the PV unit's output according to irradiation and temperature is relevant to the study. The modeling was done using the mathematical models presented in [3]. An ideal PV cell is modeled as a current source that is in parallel with a diode. Here Shockley diode equation is used to model the diode. The ideal PV cell output current is given by [16],

$$I = I_{pv} - I_o e^{\left(\left(\frac{qV}{akT}\right)-1\right)} \tag{1}$$

In the practical model of PV cell, the series and parallel resistances are also considered. The value of the series resistance (R_s) depends on contact resistance of p-n junctions and contact resistance with metal plate. Its effect is dominant when the PV array is operated in the voltage source domain. The value of parallel resistance (R_p) depends on the leakage current which is primarily dependent on the fabrication technique used [17]. Accommodating the additional current loss due to the series and parallel elements to the ideal PV cell equation, we get (2) and the model is as shown in the Figure 2.

$$I = I_{pv} - I_o \left[e^{\left(\left(\frac{V+R_SI}{V_ta} \right) - 1 \right)} \right] - \left(\frac{V+R_SI}{R_p} \right) \tag{2}$$

where I is PV cell current output, I_{pv} is light generated current, I_o is reverse saturation current or leakage current of diode, V is voltage at PV cell terminals, R_s is resistance in series with PV cell, R_p is resistance in parallel with PV cell, a is diode ideality constant, N_s is number of solar PV cells in series, N_p is number of PV cells in parallel, K is Boltzmann constant, T is temperature, q is charge of an electron, V_t is thermal voltage of PV array with N_s cells in series [18].
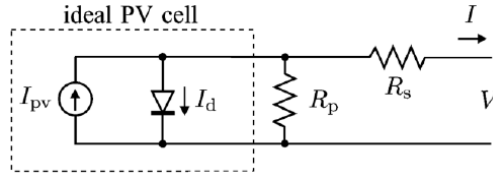
Figure 2. Practical single diode model of a PV cell

In (2), the thermal voltage of PV array with N_s cells in series is calculated by using,

$$V_t = (N_s kT)/q \tag{3}$$

The light generated current (I_{pv}) and diode saturation (I_o) current are dependent on temperature and solar irradiance, and they are expressed as [19],

$$I_{pv} = \left(I_{pv,n} + K_I \Delta T \right) G/G_n \tag{4}$$

$$I_o = (I_{sc,n} + K_I \Delta T)/e^{((Voc,n\ Kv\ \Delta T)/\alpha Vt - 1)} \tag{5}$$

The values of K_I and K_v are available in the data sheet of PV module [20]. G is the irradiation constant and G_n is the nominal irradiation constant which is $1000W/m^2$. The data sheets will also give the values of nominal short circuit current and open circuit voltage values. The current generated at nominal temperature is considered to be equal to nominal short circuit current, and it is a feasible approximation. Solar PV array model is depicted in Figure 3. Modeling an array of PV cells need to take into account the number of cells in parallel and series [21, 22]. N_s and N_p affects the output current by a factor of N_s/N_p. The solar irradiation current (I_m) is generated by using,

$$I_m = N_p I_{pv} - N_p I_o e^{\left(\frac{V + \frac{IR_SN_S}{N_p}}{N_S V_t a} - 1 \right)} - \left(\frac{V + \frac{IR_SN_S}{N_p}}{\frac{R_pN_S}{N_p}} \right) \tag{6}$$
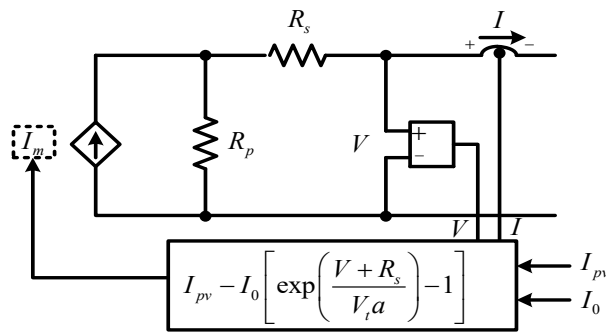

Figure 3. Solar PV array model

2.2. Modeling of boost converter

The DC/DC converters are used to convert an unregulated DC voltage, obtained from solar PV array due to the fluctuating changes in temperature and solar irradiation [23]. In the boost converter, the average DC output voltage is controlled to be equated to the desired value that needs to be fed into the inverter. The boost has been designed for a DC voltage of 600V [4]. The circuit diagram of the boost converter is depicted in Figure 4.

$$V_o/V_i = I_i/I_o = T_s/T_{off} = 1/(1-D) \qquad (7)$$

Where $T_s = (T_{on} + T_{off})$ is time period of switching, and $D = T_{on}/T_s$ is duty cycle. A PI controller is used to control the output voltage with the variations in the boost input. The output voltage of the boost is compared with the reference voltage and the error is fed back to the IGBT gate trough a PI controller as shown in Figure 5 [24, 25]. The PI controller was tuned by trial and error method.
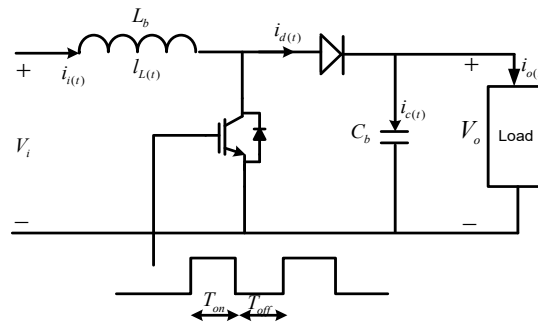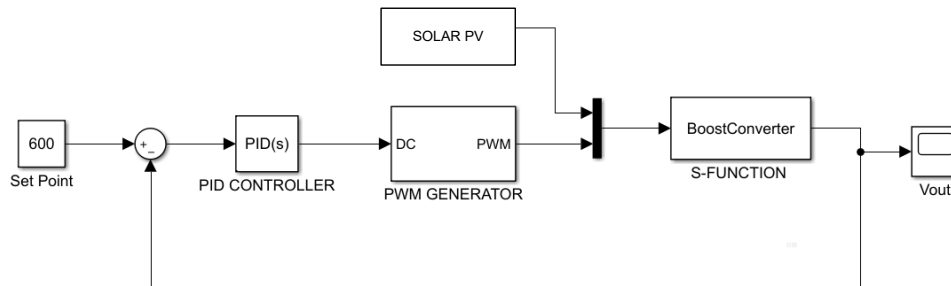

Figure 4. Boost converter

Figure 5. PI control for varying the duty cycle in accordance with the varying input voltage

2.3. Modeling of a four leg inverter

A 3 phase four leg inverter was modeled as it employs an additional inverter leg which permits to modify neutral point voltage as shown in Figure 6 [26]. The proposed control strategy based on stationary and synchronous frame controllers can reduce the phase voltage unbalance. The pulse width modulation (PWM) scheme is used to remove low order harmonic distortion from the inverter voltage [27].

2.4. Inverter control: synchronous reference frame pi controller (SRF-PIC)

The control strategy is based on i_d-i_q theory in which load current and inverter current sensing are required. In this work, the time domain based synchronous reference frame theory is used. The structure of synchronous reference frame (SRF) approach includes PI controller for dc-link capacitor voltage regulator and PLL circuit for vector orientation [28, 29]. The 3 phase load currents i_{La}, i_{Lb}, i_{Lc} in stationary coordinates are converted into 2 phase quadratic axis (q) and direct axis (d) rotating coordinates currents i_d and i_q using (8). The i_d-i_q control was implemented as shown in Figure 7, where the phase angle was obtained from a phase lock loop (PLL) block fed from the grid side voltage. The hysteresis current control method was used to control the firing of the inverter [30, 31].

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} sin\theta & sin\left(\theta - \frac{2\pi}{3}\right) & sin\left(\theta + \frac{2\pi}{3}\right) \\ cos\theta & cos\left(\theta - \frac{2\pi}{3}\right) & cos\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{8}$$
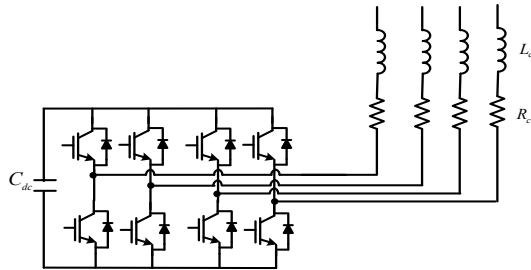
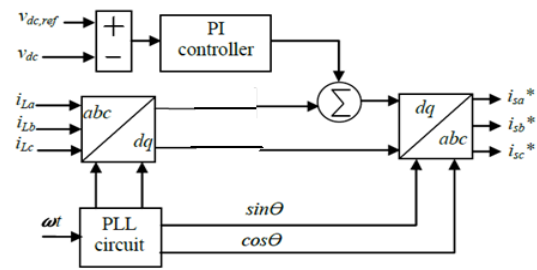Figure 6. Four leg 3phase inverter circuit

Figure 7. i_d-i_q control

3. SIMULATION RESULTS AND DISCUSSION

The solar irradiation and load profiles of an average summer day are considered in this paper for conducting the simulation studies, and they are depicted in Figures 8 (a) and (b), respectively. The time zone of interest for this study is the region near 12 noon, where the load demand is minimum and irradiation is maximum. In this paper, 3 case studies of PV generation are simulated, and they are discussed next.
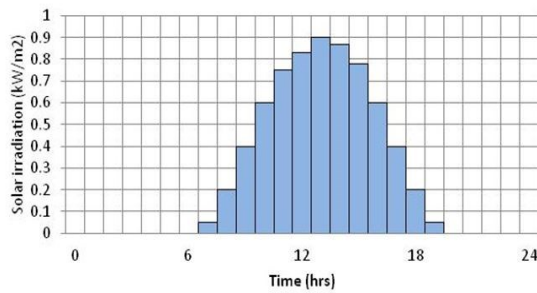
(a)
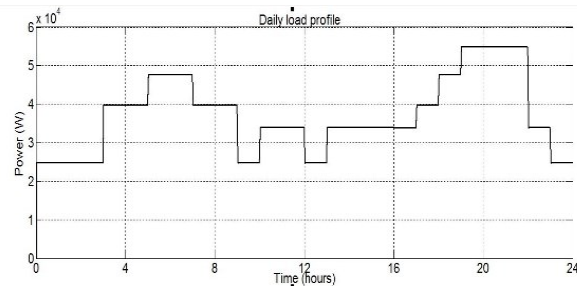
(b)

Figure 8. (a) Daily solar irradiation profile, and (b) Daily load profile of a residential area under study

3.1. Case 1: Solar PV generation less than load requirement

In this case, the solar PV generation is considered less than the load demand of 30 kW. Figures 9, 10 and 11 depicts the voltage and current profiles of PV side, load side and grid side, respectively. From Figures 9, 10 and 11, it can be observed that all the three profiles of voltage and current are in phase, and the solar PV and grid partially meets the load demand.
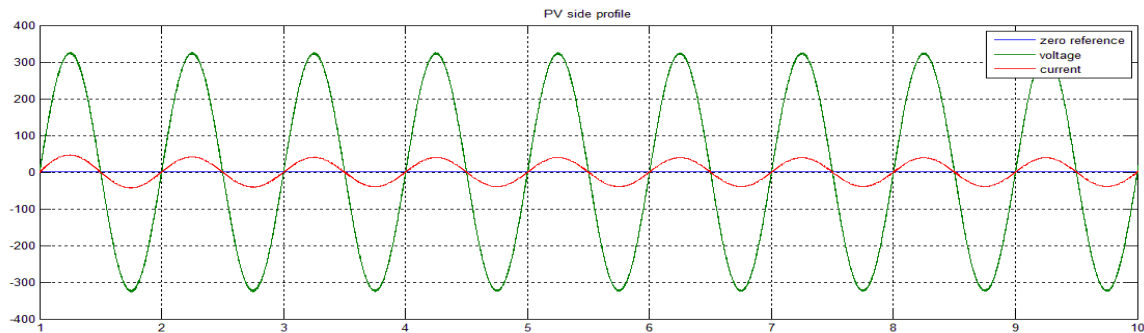
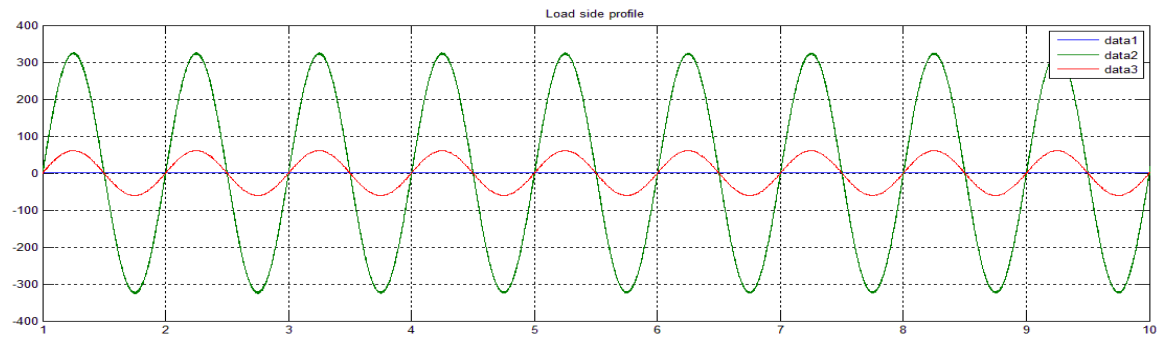Figure 9. Voltage and current profiles of PV side for case 1

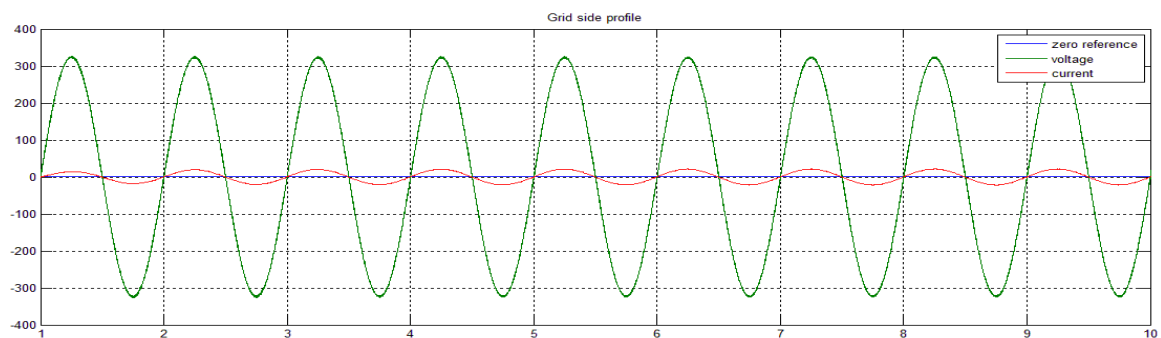Figure 10. Voltage and current profiles of load side for case 1

Figure 11. Voltage and current profiles of grid side for case 1

3.2. Case 2: Solar PV generation equal to load requirement

In this case, the solar PV generation is considered equal to the load demand of 30 kW. Figures 12, 13 and 14 depicts the voltage and current profiles of PV side, load side and grid side, respectively. From Figures 12, 13 and 14, it can be observed that all the three profiles of voltage and current are in phase, and the grid current is almost zero. In this case, the grid power is very close to zero as PV alone can meet the load demand.
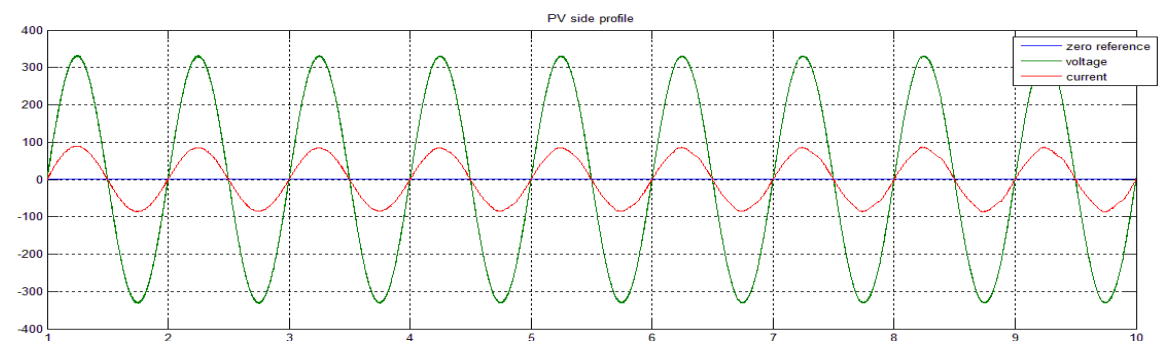

Figure 12. Voltage and current profiles of PV side for case 2

3.3. Case 3: Solar PV generation greater than load requirement

In this case, the solar PV generation is considered greater than the load demand of 30 kW. Figures 15, 16 and 17 depicts the voltage and current profiles of PV side, load side and grid side, respectively. From the above Figures 15, 16 and 17, it can be observed that the current and voltage are completely out of phase on the grid side profile. In this case, the solar PV is injecting the excess power into the grid after having met the load demand. The relationship between solar PV injection and grid voltage is depicted in Figure 18. From this figure, it can be observed that the grid voltage is linearly increased with the PV power injection and crossed the 20% steady state voltage limit close to 300 kW of solar PV injection. Here, the load demand was 30 kW and it crossed the steady state voltage limit when solar PV generation was close to 3 times the load requirement.
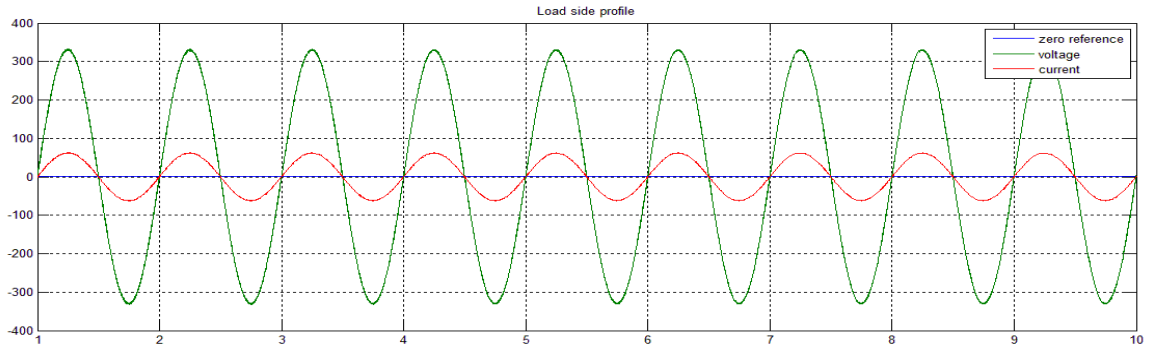
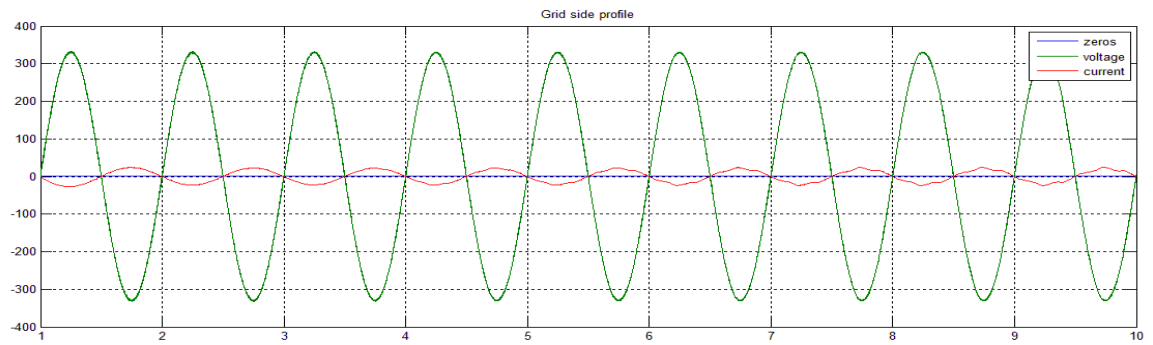Figure 13. Voltage and current profiles of load side for case 2

Figure 14. Voltage and current profiles of grid side for case 2
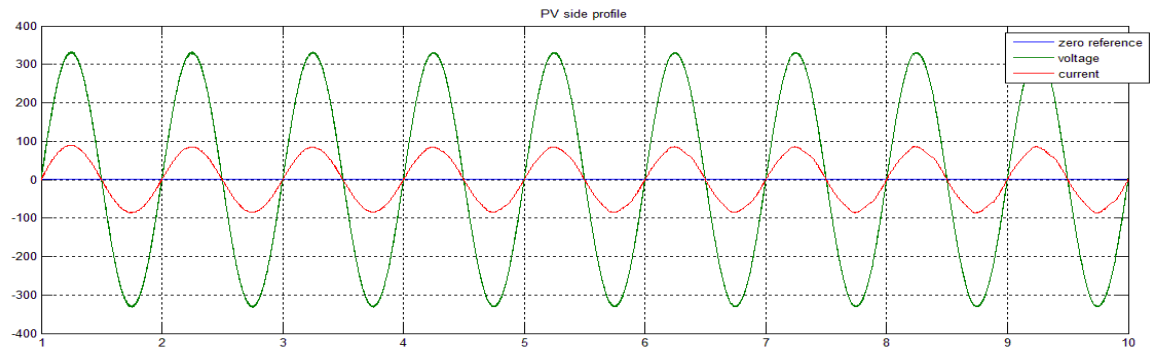

Figure 15. Voltage and current profiles of PV side for case 3
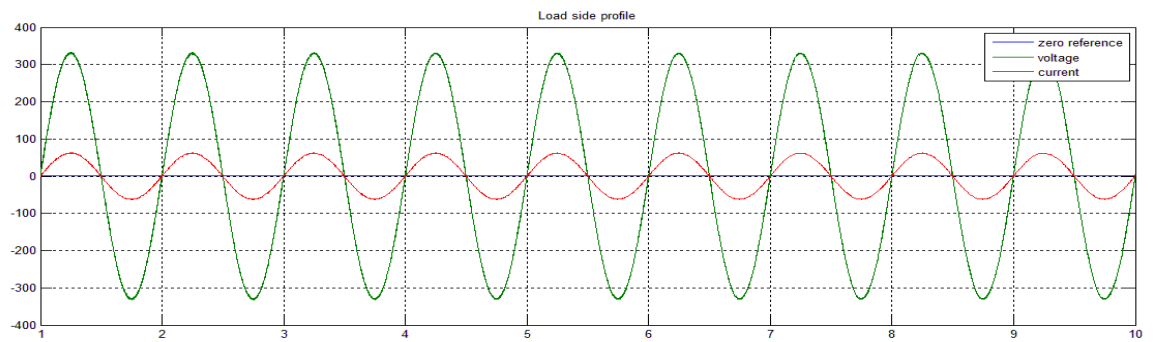

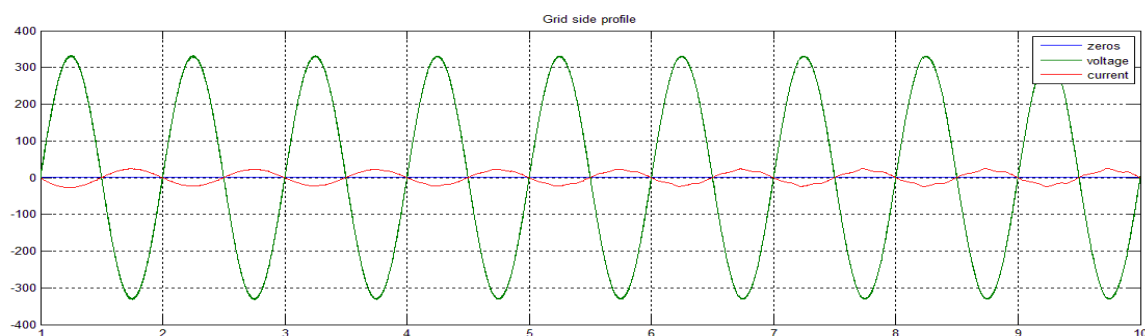Figure 16. Voltage and current profiles of load side for case 3

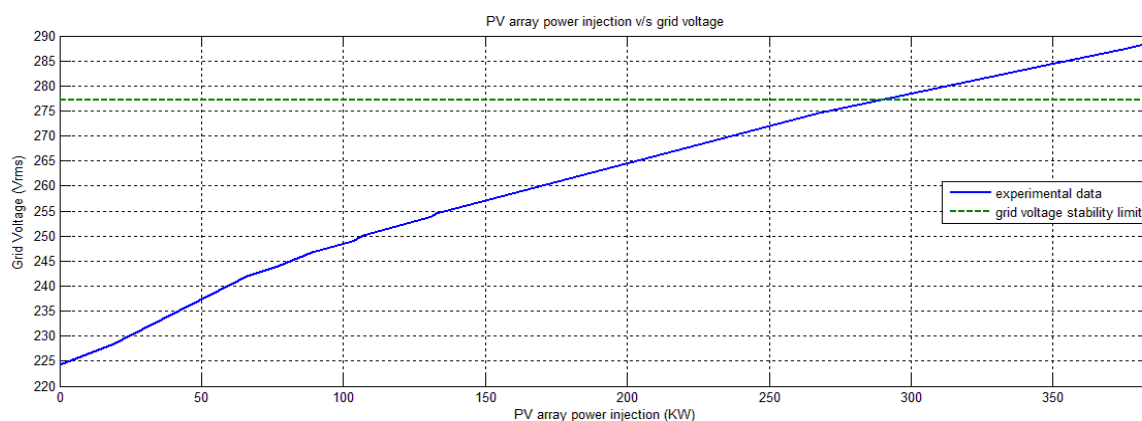Figure 17. Voltage and current profiles of grid side for case 3

Figure 18. Plot of solar PV injection and grid voltage

4. CONCLUSION

In this paper, the relation between solar PV power injection and grid voltage for a load of 30 kW is studied. Various scenarios are considered in this work, such as all the loads are residential, each one of them have an installed capacity that's double that of their peak requirement and the minimum load during the day is one third of the peak load and coincide with maximum PV power injection. It can be concluded that the grid will remain within the voltage limits prescribed by IEEE standards if power injection into the grid is only from residential sources. Even so, if there is any large-scale PV injection which is above that of the scenario proposed, there are chances of the voltage swell in the grid beyond permissible levels. Hence, PV installations should be monitored and restricted to not cross the maximum limit of PV injection. If there is excess PV injection there has to be additional facilities like energy storage systems to absorb the excess real power, in order to maintain the grid voltage within permissible levels.

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