Voltage profile improvement of weak grid with solar PV integration

Sandeep Vuddanti¹, Varun N. John², Surender Reddy Salkuti³
1Department of Electrical Engineering, National Institute of Technology Andhra Pradesh, India
2Department of Electrical Engineering, Central University of Karnataka, Kalaburagi, India
3Department of Railroad and Electrical Engineering, Woosong University, Daejeon, Republic of Korea

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.

This is an open access article under the CC BY-SA license.

Corresponding Author:
Surender Reddy Salkuti
Department of Railroad and Electrical Engineering
Woosong University
17-2, Jayang-Dong, Dong-Gu, Daejeon 34606, Republic of Korea
Email: surender@wsu.ac.kr

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].

![Block diagram of overall system](image)

**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],

$$I = I_{pv} - I_o e^{(qV_{avg})/(kT)}$$

(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.

Voltage profile improvement of weak grid with solar PV integration (Sandeep Vuddanti)
\[ I = I_{pv} - I_o \left[ e^{\left( \frac{V + R_s I_{pv}}{Vt} \right)} - \frac{V + R_s I_{pv}}{R_p} \right] \]  

(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 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].

\[ V_t = \left( N_s kT \right) / q \]  

(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],

\[ I_{pv} = \left( I_{pv,n} + K_I \Delta T \right) G / G_n \]  

(4)

\[ I_o = \left( I_{sc,n} + K_o \Delta T \right) / e^{\left( \frac{(V_{oc,n} kT \Delta T)}{\eta VT} \right) - 1} \]  

(5)

The values of \( K_I \) and \( K_o \) 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/m². 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,

\[ I_m = N_p I_{pv} - N_p I_o e^{\left( \frac{V + R_s N_s}{N_p} \right) - 1} - \left( \frac{V + R_s N_s}{R_p N_p} \right) \]  

(6)

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,

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.

\[ \frac{V_o}{V_i} = \frac{I_o}{I_i} = \frac{T_s}{T_{off}} = 1/(1 - D) \]  

(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 through a PI controller as shown in Figure 5 [24, 25]. The PI controller was tuned by trial and error method.

![Figure 4. Boost converter](image)

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].

![Figure 5. PI control for varying the duty cycle in accordance with the varying input voltage](image)

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 \( i_a, i_b, i_c \) 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].
\[
\begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
    \sin \theta & \sin \left( \theta - \frac{2\pi}{3} \right) & \sin \left( \theta + \frac{2\pi}{3} \right) \\
    \cos \theta & \cos \left( \theta - \frac{2\pi}{3} \right) & \cos \left( \theta + \frac{2\pi}{3} \right)
\end{bmatrix} \begin{bmatrix}
    i_{LA} \\
    i_{LB} \\
    i_{LC}
\end{bmatrix}
\]

(8)

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.

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

Figure 9. Voltage and current profiles of PV 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 depict 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.

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 depict 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
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.

ACKNOWLEDGEMENTS

This research work has been carried out based on the support of “Woosong University’s Academic Research Funding-(2020-2021)".

REFERENCES

[1] K. Kok et al., “A Society of Devices: Integrating Intelligent Distributed Resources with Transactive Energy,” IEEE Power and Energy Magazine, vol. 14, no. 3, pp. 34-45, 2016.
[2] S. Grunau et al., “Effect of wind-energy power injection into weak grids”. Available. [Online]: https://www.tf.uni-kiel.de/etit/LEA/en/research/Publications/publications2012/grunau_ewea_2012.pdf
[3] M. G. Villalva et al., “Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays,” IEEE Transactions on Power Electronics, vol. 24, no. 5, pp. 1198-1208, 2009.
[4] C. S. Sachin et al., “Design and simulation for sliding mode control in DC-DC boost converter,” 2nd International Conference on Communication and Electronics Systems, Coimbatore, 2017, pp. 440-445.
[5] T. Shanthi et al., “Power electronic interface for grid-connected PV array using boost converter and line-commutated inverter with MPPT,” International Conference on Intelligent and Advanced Systems, Kuala Lumpur, 2007, pp. 882-886.

[6] J. Susanto et al., “A framework to technically evaluate integration of utility-scale photovoltaic plants to weak power distribution systems,” Applied Energy, vol. 231, pp. 207-221, Dec. 2018.

[7] O. B. Adewuyi et al., “Security-constrained optimal utility-scale solar PV investment planning for weak grids: Short reviews and techno-economic analysis,” Applied Energy, vol. 245, pp. 16-30, Jul. 2019.

[8] E. Rakhshani et al., “Integration of Large-Scale PV-Based Generation into Power Systems: A Survey,” Energies, vol. 12, pp. 1-19, 2019.

[9] Q. Alsafasfeh et al., “Solar PV Grid Power Flow Analysis,” Sustainability, vol. 11, no. 6, pp. 1-25, 2019.

[10] A. Parida et al., “An improved control scheme for grid connected doubly fed induction generator considering wind-solar hybrid system,” International Journal of Electrical Power & Energy Systems, vol. 77, pp. 112-122, 2016.

[11] P. M. Ariyaratna et al., “The simultaneous mitigation of slow and fast voltage fluctuations caused by rooftop solar PV by controlling the charging/discharging of an integrated battery energy storage system,” Journal of Energy Storage, vol. 26, Dec. 2019.

[12] H. Chen et al., “Assessment and parametric analysis of solar trigeneration system integrating photovoltaic thermal collectors with thermal energy storage under time-of-use electricity pricing,” Solar Energy, vol. 206, pp. 875-899, Aug. 2020.

[13] O. B. Adewuyi et al., “Multiobjective mix generation planning considering utility-scale solar PV system and voltage stability: Nigerian case study,” Electric Power Systems Research, vol. 168, pp. 269-282, Mar. 2019.

[14] M. Mohanan et al., “Optimized Power System Management Scheme for LSS PV Grid Integration in Malaysia Using Reactive Power Compensation Technique,” Global Challenges, vol. 4, no. 4, pp. 1-12, Apr. 2020.

[15] H. Rauf et al., “Complementing hydroelectric power with floating solar PV for daytime peak electricity demand,” Renewable Energy, vol. 162, pp. 1227-1242, Aug. 2020.

[16] S. R. Salkuti, “Comparative analysis of electrochemical energy storage technologies for smart grid,” TELKOMNIKA Telecommunication, Computing, Electronics and Control, vol. 18, no. 4, pp. 2118-2124, Aug. 2020.

[17] O. Garfi et al., “Impacts of photovoltaic power source intermittence a distribution network,” International Journal of Electrical and Computer Engineering, vol. 9, no. 6, pp. 5134-5142, Dec. 2019.

[18] R. O. Bawazir et al., “Comprehensive overview of optimizing PV-DG allocation in power system and solar energy resource potential assessments,” Energy Reports, vol. 6, pp. 173-208, Nov. 2020.

[19] T. Sarkar et al., “Optimal design and implementation of solar PV-wind-biogas-VRFB storage integrated smart hybrid microgrid for ensuring zero loss of power supply probability,” Energy Conversion and Management, vol. 191, pp. 102-118, Jul. 2019.

[20] E. L. de Aguiar et al., “Distributed Renewable Power Sources in Weak Grids - Analysis and Control,” IntechOpen, May 2016.

[21] M. I. Abushour et al., “Operational performance of a PV generator feeding DC shunt and induction motors with MPPT,” International Journal of Electrical and Computer Engineering, vol. 9, no. 2, pp. 771-782, Apr. 2019.

[22] H. Hâberlin, “Photovoltaics system design and practice,” John Wiley & Sons, 2012.

[23] H. Li et al., “Three-layer voltage/var control strategy for PV cluster considering steady-state voltage stability,” Journal of Cleaner Production, vol. 217, pp. 56-68, Apr. 2019.

[24] A. Benali et al., “Voltage profile and power quality improvement in photovoltaic farms integrated medium voltage grid using dynamic voltage restorer,” International Journal of Power Electronics and Drive System, vol. 11, no. 3, pp. 1481-1490, Sept. 2020.

[25] K. Padmanathan et al., “Integrating solar photovoltaic energy conversion systems into industrial and commercial electricity utilization-A survey,” Journal of Industrial Information Integration, vol. 10, pp. 39-54, Jun. 2018.

[26] R. Meenal et al., “Review on mathematical models for the prediction of Solar radiation,” Indonesian Journal of Electrical Engineering and Computer Science, vol. 15, no. 1, pp. 54-59, Jul. 2019.

[27] S. A. Aleem et al., “A Review of Strategies to Increase PV Penetration Level in Smart Grids,” Energies, vol. 13, no. 3, 2020.

[28] S. Hashemi et al., “Methods and strategies for overvoltage prevention in low voltage distribution systems with PV,” IET Renewable Power Generation, vol. 11, no. 2, pp. 205-214, 2017.

[29] D. Almeida et al., “Mitigation of overvoltage due to high penetration of solar photovoltaics using smart inverters volt/var control,” Indonesian Journal of Electrical Engineering and Computer Science, vol. 19, no. 3, pp. 1259-1266, Sept. 2020.

[30] S. Narasimha et al., “An improved closed loop hybrid phase shift controller for dual active bridge converter,” International Journal of Electrical and Computer Engineering, vol. 10, no. 2, pp. 1169-1178, Apr. 2020.

[31] R. Mahat et al., “Techno-Economic Analysis of PV Inverter Controllers for Preventing Overvoltage in LV Grids,” International Symposium on Power Electronics, Electrical Drives, Automation and Motion, Sorrento, Italy, 2020, pp. 502-507.