Power Quality Analysis of Distribution System Integrated with Multiple PVs

Sathish K R, T Ananthapadmanabha

Abstract: In this work, the Impact of integration of multiple Photo Voltaic distributed generators (PV-DGs) on power quality of the distribution system is analyzed under static and dynamic loads. Major power quality parameters considered for the analysis are voltage deviation (Vₚₑₒₜ), Total Real power and reactive power line losses (Pₑₒₜ & Qₑₒₜ) and Total Harmonic Distortion of Voltage at Buses (THDₑₒₜ). Test system considered for the study is the IEEE-9 bus test system and types of loads considered are Static RL and Induction motors. Modeling and simulation of test system, PVs and Induction motor loads are carried out in MATLAB/SIMULINK software package.

Keywords: Power Quality; loss measurement; Power system Harmonics; PV-Photovoltaic system.

I. INTRODUCTION

Presently, the solar photovoltaic electric power generator becomes a significant renewable distributed generation. The integration of photovoltaic distributed generators (PV-DG) leads to precarioussness in distribution system planning and operation. The integration of PV-DGs can increase the performance of the Distribution system like an increase in voltage profile, reduction of line losses and reduction of burden over the grid and tap changers of the transformers [1].

When PV-DGs is integrated into the distribution systems, the impact of Integration should be analyzed by considering performance indicators like Quality of voltage, line losses, feeder loading, harmonic distortion, and frequency fluctuations. Hence, some researchers observed the assessment of the impact of PV-DGs on voltage unbalance and harmonics [2, 3]. M. Farhoonreta et.al observed the effects of installing grid-connected PV systems on the dynamic behavior of the distribution network under different weather conditions by using MATLAB /SIMULINK [4]. However, the simulations are performed based on the small-scale test system in short-time periods with average load data profiles. In this paper, the Open Distribution System Simulator (Open DSS) [5] developed by Electric Power Research Institute (EPRI) is applied to perform the simulations for analyzing PVDG impacts on power quality problems of distribution networks. Several studies have been carried out to ccess the impacts of DG in the power distribution system using Open DSS [6, 7]. The main objective of this research paper is to accurately analyze the effects of integrating multiple PV-DGs on the power quality of the distribution system under static and dynamic loading conditions.

II. MATHEMATICAL MODELING OF PV-DG

The equivalent circuit of a PV cell is shown in Fig. 1. The current source Iₚʰ represents the cell photocurrent. Rₛ and Rₛ are the intrinsic shunt and series resistances of the cell, respectively. Usually, the value of Rₛ is very large and that of Rs is very small, hence they may be neglected to simplify the analysis. Practically, PV cells are grouped in larger units called PV modules and these modules are connected in series or parallel to create PV arrays which are used to generate electricity in PV generation systems. The equivalent circuit for the PV array is shown in Fig. 2

\[ I_{ph} = \frac{I_{sc} + K_i (T - 298) + I_s}{1000} \]

Where, \( I_{ph} \): photo-current (A); \( I_{sc} \): short circuit current (A); \( K_i \): short-circuit current of cell at 25°C and 1000 W/m²; T: operating temperature (K); \( I_r \): solar irradiation (W/m²). Module reverse saturation current \( I_{rs} \)

\[ I_{rs} = \frac{V_{oc}}{V_{oc} + \log_{10} \left( \frac{n}{k} \right)} \]

Power quality analysis includes percentage voltage deviation, line loss reduction and total harmonic distortion of Voltage (THD) caused by the integration of PV-DGs. The rest of the paper is organized as follows. Section 2 Explains about the Modeling of PV-DG in MATLAB/ SIMULINK software package. Test system used in this paper and its parameters are presented in section 3. Power flow results of test system when PV-DGs are integrated are discussed in section 4. Section 5 concludes the summary of the work carried out.

Figure 1 PV-Cell Equivalent Circuit

\[ I_{ph} \]

\[ \frac{V_{oc}}{V_{oc} + \log_{10} \left( \frac{n}{k} \right)} \]
The module saturation current $I_o$ varies with the cell temperature, which is given by:

$$I_o = I_{T2}\left(\frac{T}{T_r}\right)^2 \exp\left[\frac{q*E_g}{nk}\left(1 - \frac{1}{T}\right)\right]$$

Here, $T_r$: Nominal temperature = 298.15 K; $E_g$: bandgap energy of the semiconductor, = 1.1 eV; The current output of PV module is:

$$I = I_p = I_{sh} = I_o = \left[\frac{V}{N_p} + \frac{1}{n} \left(1 + \frac{R_s}{N_p} \right)\right] - I_{sh}$$

With $V = K*V$ and $I = \frac{V}{N_p + 1 + \frac{R_s}{R_{sh}}}$

Here: $N_p$: number of PV modules connected in parallel; $R_s$: series resistance (Ω); $R_{sh}$: shunt resistance (Ω); $V_d$: diode thermal voltage (V). The complete model of PV-DG in SIMULINK is as shown in figure 3:

PV array is a DC electrical source which cannot be interfaced with the AC Distribution system directly. Hence Voltage Source Converter (VSC) is used to convert DC to 3-phase AC of 260V @ 50 Hz. VSC controller regulates the output of VSC such that output of PV-DG is synchronized with the Distribution system Load.

III. TEST SYSTEM DESCRIPTION AND BASE-CASE RESULTS

Test system considered for the study is a modified IEEE 9 bus radial distribution system [9] as shown in fig. Operating voltage and frequency of the considered system is 11KV & 50HZ with 100MVA base. Modeling and Simulation of test systems are carried out in MATLAB/SIMULINK software package.

Two scenarios are considered for the study i.e.:
1. Scenario 1: Loads are modeled as Static RL &
2. Scenario 2: Loads are modeled as Induction motor.

Power/Load flow Simulation results of test system in scenario 1(S1) without the integration of PV-DGs (Base case) are mentioned in Table 1.0 & 1.1. Where $V_b$, $P_b$ & $Q_b$ are Bus Voltage in per unit, Bus real power flow and reactive power flow respectively.

| Bus No. | $V_b$ in PU | $P_b$ in KW | $Q_b$ in KVAR | $V_D$ % | %THD($V_b$) |
|--------|-------------|-------------|---------------|--------|-------------|
| 1      | 0.9971      | 1190.24     | 478.24        | 0.28   | 0           |
| 2      | 0.9949      | 1007.15     | 426.46        | 0.515  | 0           |
| 3      | 0.9853      | 904.03      | 382.92        | 1.490  | 0           |
| 4      | 0.9793      | 726.39      | 336.84        | 2.113  | 0           |
| 5      | 0.9674      | 567.84      | 155.09        | 3.372  | 0           |
| 6      | 0.9635      | 415.70      | 97.66         | 3.789  | 0           |
| 7      | 0.9566      | 340.99      | 86.15         | 4.540  | 0           |
| 8      | 0.9461      | 233.32      | 29.86         | 5.700  | 0           |
| 9      | 0.9388      | 144.54      | 17.63         | 6.519  | 0           |

In Table 1.0 it can be observed that voltage deviation is more than 5% at Bus 9 & 8 and % Total harmonic distortion of voltage at all buses is Zero.

Similarly, Power/Load flow Simulation results of the test system in scenario 2 (S2) without the integration of PV-DGs (Base case) are mentioned in Table 3 & 4.
In Table 3 it can be observed that the voltage deviation is decreased compared to the base case. Table 7 indicates the results of Total line losses after integration of PV-DGs in scenario 1 and it can be observed that after the integration of PV-DGs to the considered test system, Voltage deviation at all buses decreases compared to the base case.

Table 5: % Voltage Deviation after integration of PV-DGs– S1

| Bus No. | %VD | 1-PV | 2-PVs | 3-PVs | 4-PVs |
|---------|-----|------|-------|-------|-------|
| 1       | 0.27545 | 2.0617 | 0.25531 | 0.24564 | 0.24564 |
| 7       | 0.50140 | 0.48894 | 0.47743 | 0.46650 | 0.46650 |
| 2       | 1.41310 | 1.34134 | 1.27189 | 1.20312 | 1.20312 |
| 3       | 1.97764 | 1.84990 | 1.72543 | 1.60147 | 1.60147 |
| 4       | 3.06623 | 2.77606 | 2.49233 | 2.20900 | 2.20900 |
| 5       | 3.04054 | 3.03911 | 2.68179 | 2.32500 | 2.32500 |
| 6       | 3.97409 | 3.43594 | 2.91015 | 2.38572 | 2.38572 |
| 7       | 4.70113 | 3.75569 | 2.83615 | 2.32383 | 2.32383 |

Figure 5: Power Quality indicators- Scenario 1

Table 7: Total line losses after integration of PV-DGs– S1

| No. of PV-DGs | 1-PV | 2-PVs | 3-PVs | 4-PVs |
|---------------|------|-------|-------|-------|
| P_{TL} in kW  | 17.4721 | 12.45958 | 9.161486 | 6.828794 |
| Q_{TL} in KVAR| 26.93 | 21.09035 | 16.64096 | 13.10889 |

Table 5 summarizes the results of Voltage Deviation at all buses after the integration of PV-DGs in scenario 1 and it can be observed that after the integration of PV-DGs to the considered test system, Voltage deviation at all buses decreases compared to the base case.

Table 6: % THD of Vb after integration of PV-DGs– S1

| Bus No. | %THD of Vb | 1-PV | 2-PVs | 3-PVs | 4-PVs |
|---------|------------|------|-------|-------|-------|
| 1       | 0.01       | 0.01 | 0.02  | 0.02  | 0.02  |
| 2       | 0.02       | 0.03 | 0.05  | 0.06  | 0.06  |
| 3       | 0.04       | 0.07 | 0.10  | 0.13  | 0.13  |
| 4       | 0.05       | 0.08 | 0.12  | 0.16  | 0.16  |
| 5       | 0.07       | 0.13 | 0.18  | 0.24  | 0.24  |
| 6       | 0.08       | 0.15 | 0.21  | 0.27  | 0.27  |
| 7       | 0.10       | 0.17 | 0.24  | 0.32  | 0.32  |
| 8       | 0.13       | 0.23 | 0.33  | 0.40  | 0.40  |
| 9       | 0.17       | 0.30 | 0.39  | 0.46  | 0.46  |

Table 5 summarizes the results of Voltage Deviation at all buses after the integration of PV-DGs in scenario 1 and it can be observed that after the integration of PV-DGs to the considered test system, Voltage deviation at all buses decreases compared to the base case.

Table 5: % Voltage Deviation after integration of PV-DGs– S1

| Bus No. | %VD | 1-PV | 2-PVs | 3-PVs | 4-PVs |
|---------|-----|------|-------|-------|-------|
| 1       | 0.27545 | 0.26517 | 0.25531 | 0.24564 | 0.24564 |
| 2       | 0.50140 | 0.48894 | 0.47743 | 0.46650 | 0.46650 |
| 3       | 1.41310 | 1.34134 | 1.27189 | 1.20312 | 1.20312 |
| 4       | 1.97764 | 1.84990 | 1.72543 | 1.60147 | 1.60147 |
| 5       | 3.06623 | 2.77606 | 2.49233 | 2.20900 | 2.20900 |
| 6       | 3.04054 | 3.03911 | 2.68179 | 2.32500 | 2.32500 |
| 7       | 3.97409 | 3.43594 | 2.91015 | 2.38572 | 2.38572 |
| 8       | 4.70113 | 3.75569 | 2.83615 | 2.32383 | 2.32383 |

Table 4: Total line losses- Base case (S2)

| P_{TL} in kW | 665.19882 |
|-------------|-----------|
| Q_{TL} in KVAR | 589.76037 |

In Table 3 it can be observed that the voltage deviation is more than 5% at Bus 3 to Bus 9 and % Total harmonic distortion of voltage at all buses is more than 2% at Bus 6 to Bus 9. From Table 3 & 4 it can be observed that both line losses are more when loads are induction motors rather than static RL load.

IV. INTEGRATION of PV-DG’S

In each Scenario many cases are worked out depends on the number of PV-DGs to be integrated to maintain all bus voltages within the acceptable limits i.e. %VD<5%

Scenario 1(S1): In this Scenario, four 100KW PV-DGs are integrated into the test system at Bus 9 and Bus 8 to maintain all bus voltages within permissible limits. When each PV-DG is integrated into the test system, afterload flow simulation total Line losses, %VD and %THD of Vb at all buses are recorded and Consolidated Results are tabulated as follows.
Scenario 2(S2): four 100KW and one 200KW PV-DGs are integrated into the test system at Bus 9 to maintain voltages at all buses within permissible limits. When each PV-DG is integrated into the test system, after load flow simulation total Line losses, %VD and %THD of Vb at all buses are recorded and Consolidated Results are tabulated as follows.

Table 8: % Voltage Deviation after integration of PV-DGs – S2

| Bus No. | 1-PV | 2-PVs | 3-PVs | 4-PVs | 5-PVs |
|---------|-----|-------|-------|-------|-------|
| 1       | 1.1833 | 0.9449 | 0.9485 | 0.9528 | 0.4177 |
| 2       | 2.5978 | 2.0451 | 2.0668 | 2.0896 | 0.8461 |
| 3       | 6.5699 | 5.0967 | 5.1021 | 5.1125 | 1.9384 |
| 4       | 9.0017 | 6.9022 | 6.8714 | 6.8492 | 2.4455 |
| 5       | 15.8618 | 11.7642 | 11.6119 | 11.4793 | 3.4085 |
| 6       | 18.9364 | 13.8279 | 13.6107 | 13.4187 | 3.6191 |
| 7       | 24.2433 | 17.2469 | 16.8391 | 16.4703 | 3.6668 |
| 8       | 36.2490 | 24.5003 | 23.5293 | 22.6392 | 2.9960 |
| 9       | 44.7140 | 31.5739 | 29.7725 | 28.1217 | 1.5296 |

Table 9: % THD of Vb after integration of PV-DGs – S2

| Bus No. | 1-PV | 2-PVs | 3-PVs | 4-PVs | 5-PVs |
|---------|-----|-------|-------|-------|-------|
| 1       | 0.22% | 0.24% | 0.24% | 0.24% | 0.30% |
| 2       | 0.47% | 0.53% | 0.53% | 0.54% | 0.69% |
| 3       | 1.02% | 1.16% | 1.16% | 1.17% | 1.52% |
| 4       | 1.29% | 1.48% | 1.48% | 1.48% | 1.96% |
| 5       | 1.93% | 2.28% | 2.27% | 2.27% | 3.12% |
| 6       | 2.12% | 2.56% | 2.54% | 2.54% | 3.56% |
| 7       | 2.38% | 2.96% | 2.92% | 2.93% | 4.27% |
| 8       | 2.67% | 3.56% | 3.47% | 3.46% | 5.61% |
| 9       | 2.89% | 3.66% | 3.59% | 3.60% | 6.61% |

Table 10: Total line losses after integration of PV-DGs – S2

| No. of PV-DGs | 1-PV | 2-PVs | 3-PVs | 4-PVs | 5-PVs |
|---------------|-----|-------|-------|-------|-------|
| Pn, in KW     | 666.205 | 423.64 | 414.46 | 363.106 | 29.138 |
| Qn, in KVAR   | 588.92 | 423.64 | 417.39 | 365.80 | 33.951 |

Table 8 summarizes the results of Voltage Deviation at all buses after the integration of PV-DGs in scenario 2 and it can be observed that after the integration of PV-DGs to the considered test system, Voltage deviation at all buses decreases compared to the base case.

Table 9 summarizes the results of Total Harmonic distortion of Voltage at all buses after integration of PV-DGs in scenario 2 and it can be observed that after integration of PV-DGs to the considered test system, %THD of voltage at all buses increases compared to the base case.

Table 10 indicates the results of Total line losses after integration of PV-DGs in scenario 2 and it can be observed that after the integration of PV-DGs to the test system line losses decreased compared to the base case.

In Fig.6 it can be observed that after integration of PV-DGs to the test system under scenario-2 Real and reactive power line losses reduced by 95.62% and 94.2% respectively, Voltage deviation at Bus 9 reduced by 95.11% and THD of Voltage at Bus 9 increased to 6.61%.

**V. CONCLUSION**

Effect of integration of PV-DGs on power quality of distribution system under two different loading conditions i.e.: Static RL & Induction motors is presented. Under static RL loading condition integration of PV-DGs will not alter the power quality of the distribution system much since voltage harmonic distortion and voltage magnitude at PV-DG connected buses are within the limits. Under Induction motor loading condition integration of PV-DGs leads to voltage harmonic distortion of more than 5% at DG connected bus. The major scope of this work is significant input for the design of the Power quality controller to be placed in the distribution system connected with PV-DGs. In future work other power quality indicators like THDi, Voltage rise and drops, frequency deviations, etc will be considered for the study.

**ACKNOWLEDGMENT**

This research was supported by Visvesvaraya Techno-logical University, Jnana Sangama, Belagavi -590018

**REFERENCES**

1. Omarn, M.A. et al.: A study of the impacts of power fluctuations generated from large PV systems, IEEE PES/IAS Conference on Sustainable Alternative Energy, 2009.
2. Ruiz-Rodriguez, F. J., Hernandez, J. C., Jurado, F.: Voltage unbalance assessment in secondary radial distribution networks with single-phase photovoltaic systems, International Journal of Power and Energy System, 2015, Vol. 64, pp. 646-654.
3. Hernandez, J. C., Ortega, M. J., Medina, A.: Statistical characterization of harmonic current emission for large photovoltaic plants, International Transactions on Electrical Energy System, 2014, Vol.24, No.8, pp. 1134-1150.
4. Farhoodnea, M. et al.: Power quality analysis of grid connected photovoltaic systems in distribution networks,“ Przegląd Elektrotechniczny, 2013, Vol. 89 (2A), pp. 208-213
5. EPRI: Distribution system Simulator, OpenDSS, 2016. Available: http://sourcefore.net/projects/electridss/
6. Paulo Radatz et.al: Assessing maximum DG penetration levels in a real distribution feeder by using OpenDSS, IEEE 17th International Conference on Harmonics and Quality of Power (ICHQP), Belo Horizonte, Brazil, 16–19 October, 2016.

7. Smith, J. W.: Distribution modeling and analysis of high penetration PV, IEEE Energy Society General Meeting, Detroit, MI, USA, 2011.

8. Xuan Hieu Nguyen1 and Minh Phuong Nguyen2: Mathematical modeling of photovoltaic cell/module/arrays with tags in Matlab/Simulink Environmental System Research (2015) DOI 10.1186/s40068-015-0047-9

9. Om Prakash Mahela, Sheesh Ram Ola, Lalit Goyal “Optimal Capacitor Placement for Loss Reduction in Radial Distribution Feeder” IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE) e-ISSN:2278-1676 Volume 4, Issue 6 (Mar - Apr. 2013), PP 43-48

AUTHORS PROFILE

Sathish K R M.Tech in Power Electronics from UVCE, Bengaluru, India. Currently pursuing Ph.D. in Visvesvaraya Technological University, Belgaum and his research area are Electrical Power System. Presently working as an Assistant Professor in the Department of Electrical and Electronics Engineering, ATME College of Engineering, Mysuru -28.

Dr. T. Ananthapadmanabha received a B.E. degree in Electrical Engineering in 1980, an M.Tech degree in Power Systems (1st Rank) in 1984, and a Ph.D. degree (Gold Medal) in 1997 from University of Mysore, Mysuru. He has served the Engineering Educational stakeholders for over three decades. He is the former Principal of NIET, Mysuru, Karnataka, India. His research Interest includes Reactive Power Optimization, Voltage Stability, Distribution Automation, and AI applications to Power Systems.