POWER QUALITY ANALYSIS OF DISTRIBUTION NETWORK WITH LARGE SCALED PHOTOVOLTAIC DISTRIBUTED GENERATION SYSTEM

Kyaw Myo Lin*, Yan Aung Oo and Pyone Lai Swe
Department of Electrical Power Engineering, Mandalay Technological University, Mandalay, Myanmar
+95-5-256126590 and *kmlep2381@gmail.com

Abstract: *This paper investigates the dynamic behavior of practical distribution network with integration of photovoltaic distributed generation (PVDG). This paper also aims to access the power quality issues such as voltage variation and reactive power control, flicker voltage range as well as total demand distortion (TDD) and total harmonic distortion (THD) with large PVDG penetration. One practical distribution network of EPRI is selected as case study with 7.5 MW PVDG. Power quality issues are investigated by modeling and simulation with Open Distribution System Simulator (OpenDSS). Investigation and observation with simulated results confirmed that the proper usage of inverter control capability should be from unity to 0.9 leading and lagging. It is concluded that large integration of PVDG may not cause any extensive voltage deformation on steady state functioning conditions of distribution system.*

Key words: *Distribution feeder, Frequency domain simulation, OpenDSS, Power quality, PV power plant, Time series analysis, Voltage fluctuation*

1. Introduction

Nowadays, the solar photovoltaic power plant becomes one of the most prominent renewable dispread generations. The photovoltaic distributed generation (PVDG) launches the uncertainties in planning and operation of distribution feeders.. The PVDG can boost the operation of power system not only improving the voltage profile but also reducing the energy losses of distribution networks and the loading of transformer tap changers (LTC) during peak load conditions [1].

Whenever installing PVDGs into the distribution systems, the impact on performance indices associated with resistive losses, distribution feeder loading and power quality must be considered. Therefore, some researchers observed the assessment of impact of PVDGs on voltage unbalance and harmonics [2-3]. M. Farhoodnea et.al observed the effects of installing grid-connected PV systems on the dynamic behaviour of distribution network under different weather conditions by using MATLAB/SIMULINK [4]. However, the simulations are performed based on small-scale test system in short-time periods with average load data profiles. In this paper, the Open Distribution System Simulator (OpenDSS) [5] developed by Electric Power Research Institute (EPRI) is applied to perform the simulations for analysing PVDG impacts on power quality problems of distribution network. Several studies have been carried out to access the impacts of DG in power distribution system using OpenDSS [6-7].

The main objective of this research paper is to accurately analyse the effects of integrating large scale grid-connected PVDG on the dynamic operation and control of the distribution system. And then, this paper focuses on investigating the power quality problems such as voltage variation and reactive power control through inverter technology, voltage flicker and total demand distortion (TDD) and total harmonic distortion (THD) caused by the presence of high-penetrated PVDGs.

The rest of the paper is organized as follows. Section 2 explains about the impact of PVDG on distribution system. The open source software and PVDG modeling are expressed in section 3. Practical test system used in this paper and its parameters are presented in section 4. Simulation results are discussed in section 5. Section 6 concludes the summary of the research work.

2. Power Quality Impact of PVDG on Electric Power Distribution System

The integration of PVDG in power systems can improve congestion in transmission lines, provide peak shaving and support the general requirement of grid. However, inappropriate coordination and allocation of PVDG may have an effect on the power quality of network [8].

The installation of PVDG in distribution systems changes the power system normal operation and causes the several problems such as bi-directional power flow, voltage variation, breaker non-coordination, undulation in the short circuit levels and islanding operation [9]. Therefore, it should be observed possible impact of large scale PVDGs on distribution systems to provide feasible solutions before practical implementations.

2.1. Inrush Current at Connection Time

The small inevitable voltage difference between PVDGs and grid may introduce an inrush current flowing between the PV systems to the distribution network at the connection time and decaying to zero at an exponential rate. Thermal stress, nuisance trips and other problems may be faced because of inrush current.

2.2. Over-voltage

To utilize the solar power/energy with high or full efficiency, most the PV plants are usually designed to function near unity power factor. Therefore, the PVDG system only injects the active power into grid, which may vary the flow of reactive power in systems. Because of absence of reactive power, the voltage profiles of nearby buses will be increased. The produced over-voltages will have negative effects on the operation and control of the utility as well as the customer sides.

2.3. Fluctuation of Output Power of PVDG

Power fluctuation occurs due to the variations in solar irradiance caused by weather conditions – sunny or cloudy and the topology of PV system. The output power fluctuation of PV systems is one of the main factors that may cause severe operational problems for the utility grid. The main problems like power swings in lines, over/under loadings, unacceptable voltage fluctuations and voltage flickers will be caused due to output power fluctuation.

2.4. Harmonic Impact of PVDG

Grid-connected PVDG may bring in harmonic distortion in the system depending on the power converter technology used. The experimental results indicated that the values of total harmonic distortion (THD) depend on the output power of the inverter [10]. Moreover, the interaction between grid components and PVDG units amplifies harmonic distortion.

2.5. Fluctuation of System Frequency

The small size of PV systems causes the frequency fluctuation to be negligible compared with other renewable energy based resources. However, this issue may become more and more severe by increasing the penetration levels of PV systems. Frequency fluctuation may change the winding speed in electro motors and may damage generators.

3. The OpenDSS and PVDG Modeling

The Open Distribution System Simulator (OpenDSS) is an open source, general purpose frequency-domain simulation tool [11]. It is a 3-phase distribution system analysis power flow solver that can handle unbalanced phases. There are a lot of circuit components to analysis for DG integration It also includes a lot of calculation modes for power flow studies including snapshot mode, direct mode, daily mode, yearly mode, peak day mode and duty cycle mode. Therefore, it is well-matched for evaluating the impacts of high-penetration PVDGs on utility distribution systems.

The PV system model in OpenDSS combines a solar PV array model with selected characteristics of the inverter typically needed for the assessment of distribution system impacts, such as efficiency curve, maximum power point tracking (MPPT), cut-in/cut-out as function of DC voltage and reactive power control [11].

In this model, an active power, P_{out} is injected into the grid connection mode. It is a function of irradiation, temperature, inverter efficiency and the rated power at the maximum power point, P_{mpp} which is defined for selected temperature, usually $25^\circ C$ and an irradiation of $1\ kW/m^2$. The block diagram showing model conceptual properties is depicted in Fig.1.

The model is also intended to be used in simulations using time step sizes of 1-5 s or longer. Thus, it is usually sufficient to take for granted that the maximum power point tracking (MPPT) algorithm completes its function. The real output power of PV system can be provided as:

$$P_{out}(t) = P(t) \times eff(P(t)) \quad (1)$$

where,

$$P(t) = P_{mpp}(1kW/m^2) \times irrad(t) \times irrad_{Base} \times P_{mpp}(T(t)) \quad (2)$$

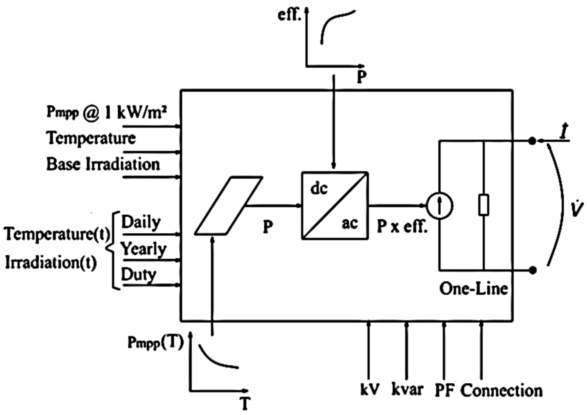

Fig. 1. PV System Model

and, P(t) is output power of the PV array at a specific time, t, $P_{mpp}(1kW/m^2)$ is rated power at the maximum power point and a selected temperature, irrad(t) is per unit irradiation value at t, $irrad_{Base}$ is base irradiation value for shape multipliers, $P_{mpp}(T(t))$ is P_{mpp} correction factor as function of the temperature at t and eff(P(t)) is inverter efficiency for a given P(t).

4. Case Study Distribution System

This section presents about case study distribution feeder: EPRI Ckt24 provided with the OpenDSS download [12]. Some technical parameters of network such as feeder loads and substation transformer and its LTC are modified according to EPRI recommendation. Active and reactive power measurements on each feeder during one year are applied for simulation.

4.1. Technical Details of Distribution Network

The general topography of real case test system highlighting major components is depicted in Fig.2. The distribution system is voltage rating of 34.5 kV with peak load of 28.45 MW. The network distributes several 13.2 kV step-down transformers and the longest three-phase path is 6.88 km with 13.2 kV rating. The main characteristics of real case study network are listed in Table 1.

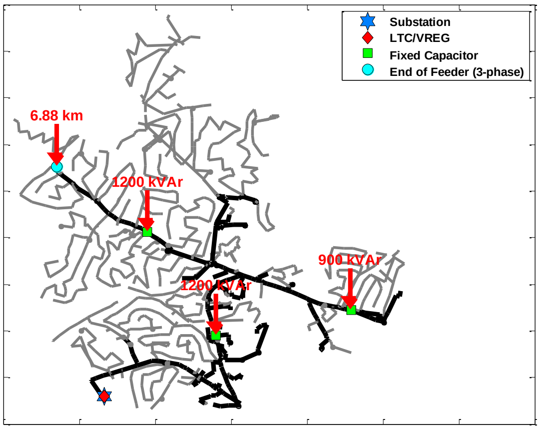

Fig. 2. Topography and major components of distribution test system

Table 1
Main Characteristics of Test System

Sr.No	Characteristic	Value
1	System Voltage (kV)	34.5
2	Number of Customers	3885
3	Service Transformer connected kVA	69373
4	Total Feeder kVAr	3300
5	Sub-transmission Voltage (kV)	230
6	3 -Φ SCC at Substation Secondary (MVA)	422
7	Total Primary Circuit (km)	119.091
8	Percent Residential by Load	87
9	Number of Feeders on the Substation Bus	2

The rating of substation transformer is 230/34.5 kV having LTC set-point of 123V with LDC of R=7V and X=0V (volts at rated CT current). There are three fixed capacitors totally 3.3 MVAr (1200 kVAr, 1200 kVAr and 900 kVAr) and there is no VREGs for distribution feeder.

4.2. Load Shape of Ckt24

In this study, constant power load models were used for the feeder loads. For all three phase loads, the load shapes used were taken from the data provided by EPRI throughout the whole period of 2016 [12]. The maximum daytime load is 28.45 MW (100%) and minimum daytime load is 6.06 MW (21%) as of September 2016. The yearly load profiles of each phase and average load profile are shown in Fig. 3. These load profiles are used for time series analysis of test system.

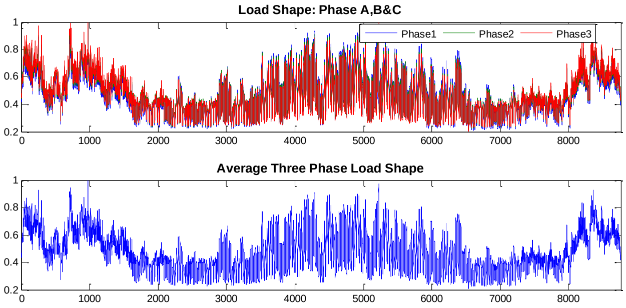

Fig. 3. Yearly profiles of load shapes of Ckt 24 network

5. Simulation Results and Discussion

To investigate the impacts of PVDG on distribution network, three-phase distribution system modelling of EPRI Ckt24 feeder is done using OpenDSS. MATLAB communicates with OpenDSS through the COM interface to obtain the circuit parameters such as line impedances, line lengths, and load ratings.

5.1. Steady-State Analysis and PVDG Hosting

To study the impact of PVDG on the distribution system, time series analysis simulation was carried out. Fig. 4 illustrates the geographical voltage profile in the EPRI Ckt24 as a function of distance without integrating PVDG.

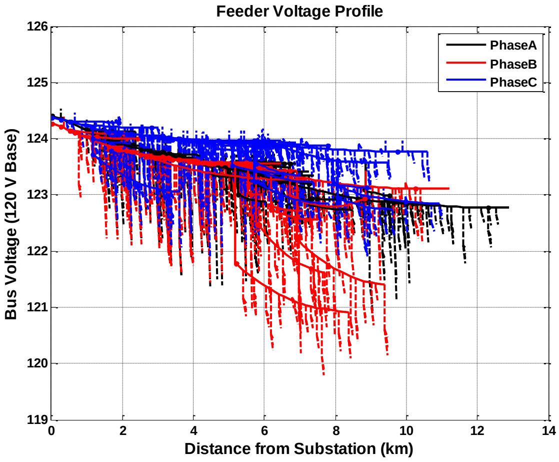

Fig. 4. Distribution network voltage visualization with respect to distance

The Cartesian references showing the distance from substation in x-axis and voltage magnitude (profile) in vertical axis are used in this figure. Each colour is being a symbol of a separate phase, while the solid lines stand for primary voltages and the dashed lines correspond to secondary voltages.

For integrating PVDG, the test system was analysed using the hosting capacity methodology proposed by Kyle Coogan et.al [13] considering location PV limits and violations associated with each. In this allocation, the maximum PV at each location was determined by the PV size just before any limiting factor was exceeded anywhere on the feeder.

Only the PVDG allocation along the 3-phase feeder backbone was considered for simplification of the analysis and visualization The optimal allocation is 7.5 MW at the bus namely 'n292212' distance of 2.2196 km away from the substation with coordinates of [31.6136, -80.9380].

5.2. Voltage Variation with Different Penetration Level

Time series simulation method is applied to study the voltage variation analysis of test system with 7.5 MW centralised PVDG which is equal to 26.36 % of system peak load. The simulation was run through yearly of 2016. This was the longest period with available time-coincident load and local irradiance data.

Fig. 5 compares the voltage profile visualization showing service range for base case (without PVDG) and with PVDG. Fig. 6 demonstrates geographical visualization of steady-state condition with 3885 load voltages. The yearly average power profile comparing with and without PVDG of system is shown in Fig. 7.

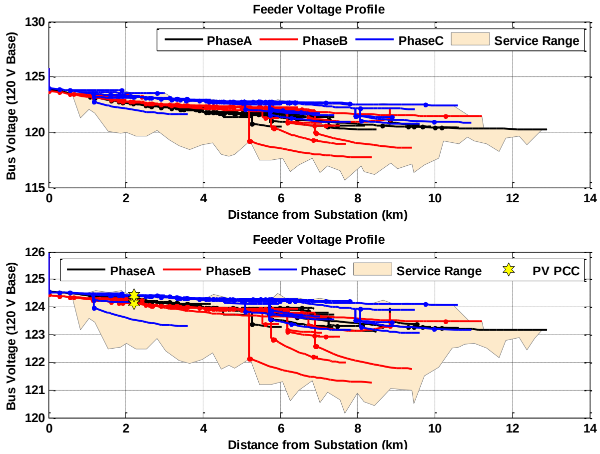

Fig. 5. Voltage profile visualization of distribution test system

In order to study voltage variation with reactive power support considering different penetration level, firstly the PVDG penetration level is defined as follows:

$$\text{Penetration} = \frac{\text{PV power generation}}{\text{Feeder head power} + \text{PV power generation}} \quad (3)$$

Based on (3), the penetration level in this study with 7.5 MW PVDG is 43.48% , the maximum feeder voltage is 1.0498 pu (nearly 1.05 pu).

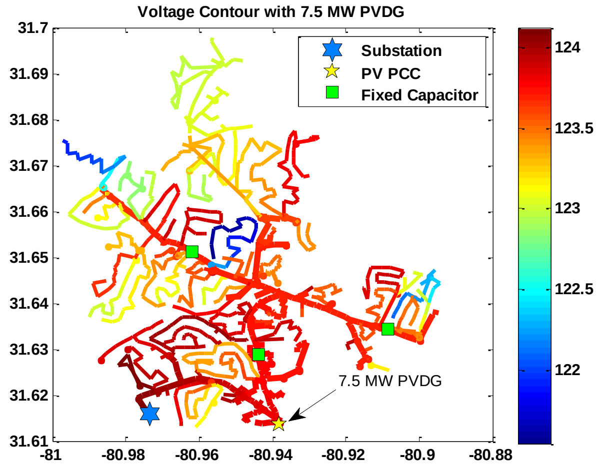

Fig. 6. Geographical visualization of distribution test system

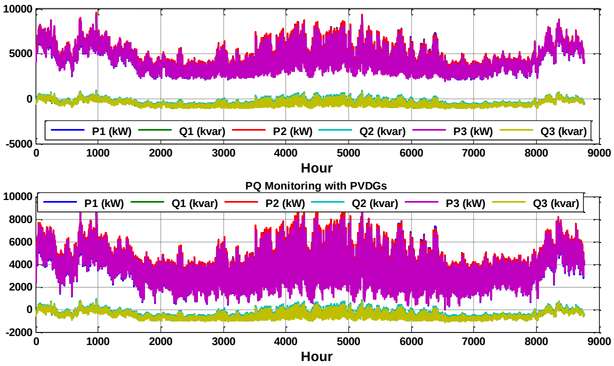

Fig. 7. Yearly substation load with and without PVDG

To observe and investigate the enhancements in hosting capacity of PV by letting reactive power support from large PVDG with different power factors, the penetration level of PVDG at the base hosting capacity were increased by 10%, 15%, 25% and 50%, respectively and the voltage profiles were recorded and analysed. The maximum voltage profiles on the substation under the proposed PVDG penetration scenarios are summarized in Table 2. The power factor is considered up to 0.9 from 0.99 (close to unity).

Table 2
Maximum Voltage Profile (pu) at Different Penetration Levels

Power Factor (lag)	**Base Hosting Capacity**	**10% above Hosting Capacity**	**15% above Hosting Capacity**	**25% above Hosting Capacity**	**50% above Hosting Capacity**
0.99	1.0466	1.0468	1.0472	1.0512	1.0538
0.97	1.0433	1.0442	1.0451	1.0461	1.0475
0.95	1.0398	1.0400	1.0401	1.0411	1.0421
0.93	1.0371	1.0379	1.0391	1.0399	1.0401
0.9	1.0342	1.0342	1.0342	1.0345	1.0345

It can be seen from the table that, the inverters of PVDG absorbed the reactive power at the power factor of 0.9. The reactive power support from the inverters allows the PV penetration to be increased by an additional 50% above the base hosting capacity without violating the ANSI voltage limits [14].

Based on the results shown, the PVDG inverters should also have the capability to adjust the PV operating power factor from unity to 0.9 lagging/leading.

5.3. Voltage Flicker Analysis

According to IEEE Std 1453 [15], it should be predictable by assessing the effects of 100% change in PV power output. In this study, time series simulation method is applied for simulation of flicker meter to investigate the time-series voltage parameters. The resultant voltage profiles were assessed against with IEEE 1453 criteria and ANSI voltage limits [14]. According to IEEE 1453 recommended practice, a 7200 seconds (2 hours period) was chosen with largest voltage ramp during ten minutes period. The resultant voltage profile after performing time series power flow is shown in Fig.8, which was recorded on side of the PCC for PVDG.

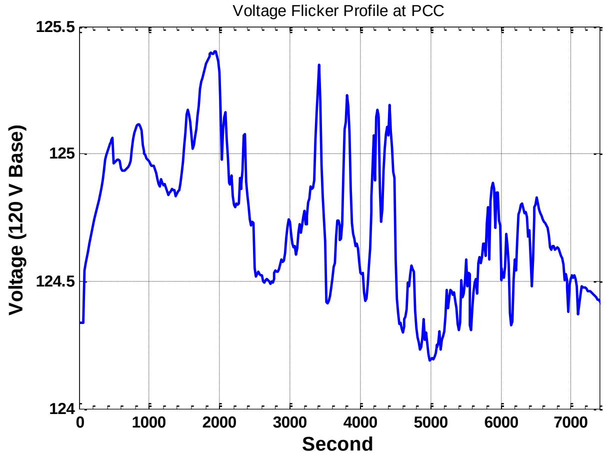

Fig. 8. Voltage profile with 2 hour period bracketing the large ramp

It can be observed that a large percentage of the 1 second simulations are outside of ANSI A and B voltage ranges [14]. The large PV size (7.485 MW) relative to feeder loading causes the rise of voltage profile. Since the flicker calculation is only concerned with voltage differences and not absolute voltages, the high voltage profiles does not impact the results.

The largest MW ramp during the 2-hour period was a 6.83 MW down ramp which occurred over a 30 minute period a little over 1 hour into the 2 hour period. Using the flicker meter, the short-term voltage flicker calculated for large voltage-ramp was 0.085. This value is well below the planning level of 0.9. According to these results, it can be said that the flicker voltage associated with the largest voltage ramp was not a serious problem for the case-study distribution feeder.

5.4. Harmonic Analysis

Harmonics studies were carried out with two different scenarios to check up TDD and THD. These two case-studies were considered for base operating case categorized as

1) High harmonic injection during a sunny day and
2) High harmonics injection during a cloudy day.

According to EPRI 2016 data, sunny day of May 28 and cloudy day of June 21 load and irradiation data were considered for these scenarios.

The frequency-domain harmonic analysis for EPRI Ckt-24 test system was performed for analysis. The frequency scan studies were carried out at the main substation as well as PCC bus of PV plant. The power outputs from the PVDG of both case studies were recorded and the respective current TDD and voltage THD were also derived and plotted.

It can be noted that injected harmonics magnitudes vary with respect to the amount of solar power generation. The snapshot diagrams of maximum TDD for harmonics generated on sunny day and cloudy day are illustrated in Fig. 9 and Fig.10, respectively.

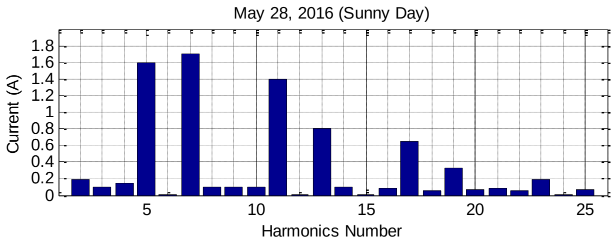

Fig. 9. High harmonics data set on sunny day

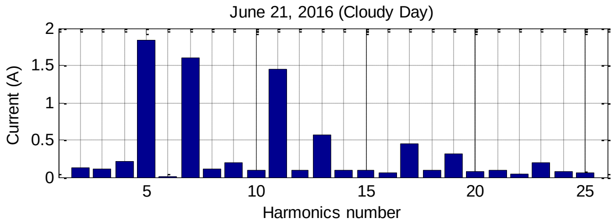

Fig. 10. High harmonics data set on cloudy day

Tables 3 and 4 summarize all the evaluated harmonic parameters for respective scenarios. All calculated harmonics parameters were summarized in Table 3and Table 4, respectively.

By comparing the data shown in these two tables, it can be said that the total harmonic distortion of voltage waveforms on cloudy day is much higher than that of sunny day because the greater significantly harmonics generation was increased than that of sunny day.

Table 3
Power, Voltage and Harmonic Distortion for High Harmonics Injection on Sunny Day

Quantities	Substation	PVDG PCC
Power: P+jQ (MVA)	4.55+j1.189	1.986-j0.051
Fundamental Voltage (kV/ph)	20.561	20.302
Fundamental Current I_f(A)	261.053	48.312
Current TDD(%)	-	1.608
Voltage THD (%)	0.412	0.173
Harmonic Distortion (V)	0.075	0.1913

Table 4
Power, Voltage and Harmonic Distortion for High Harmonics Injection on Cloudy Day

Quantities	Substation	PVDG PCC
Power: P+jQ (MVA)	4.318+j1.119	2.067-j0.152
Fundamental Voltage (kV/ph)	20.522	20.012
Fundamental Current I_f(A)	242.591	52.929
Current TDD(%)	-	1.506
Voltage THD (%)	0.412	0.153
Harmonic Distortion (V)	0.756	0.1953

However, according to IEEE Standard 519, the voltage THD of the system was still within the tolerable limits per criteria.

6. Conclusion

In this paper, the investigations on the effects of large PVDG penetration on power quality problem in practical distribution system are presented. Snap-shop and time series analysis routine of OpenDSS are conducted on EPRI Ckt-24 practical distribution test system with MATLAB providing visual user interface.

According to simulation results and investigations, it can be confirmed that the inverters used for large PVDG integration should have the capability to control and adjust the PV operating power factor from unity to 0.9 leading/lagging for high penetration as 50% above the base hosting capacity. It can also be said that the flicker associated with largest voltage ramp was not the problem for the distribution network. The research findings also indicated that harmonic current at each level and steady state total harmonic distortion are within the acceptable limits specified by IEEE Standard 519 for large PVDG penetration of 43.48% of base hosting capacity.

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 gird-connected photovoltaic systems in distribution networks*," Przeglad Elektrotechniczny, 2013, Vol. 89 (2A), pp. 208-213.
5. EPRI: *Distribution system Simulator, OpenDSS*, 2016. Available: http://sourcefore.net/projects/electridsss/
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. Dugan , Roger C., Smith, Jeff: *Open source modeling of advanced inverter functions for solar photovoltaic installations*, IEEE/PES Transmission and Distribution Conference & Exposition, Chicago, USA, 14~17 April, 2014.
9. EPRI: *Common Functions for Smart Inverters*, 4th Edition, Palo Alto, CA, Tech. Rep. 3002008217, December 2016.
10. Jenkins, N. and Strbac, G.: *Effects of small embedded generation on power quality*, Proceedings of the IEE Colloquium on Issues in Power Quality, November, 1995, pp. 6/1-6/4.
11. Roger C Morgan: *Reference Guide: The Open Distribution System Simulator (OpenDSS)*, Electric Power Research Institute, March 2016.
12. EPRI: *EPRI Test Circuits (Ckt24)*, 2016. Available: http://ewh.ieee.org/soc/pes/dsacom/testfeeders/
13. Kyle Coogan et.al: *Locational dependence of PV hosting capacity correlated with feeder load*, IEEE PES T&D Conference and Exposition, Chicago, IL, USA, 2014.
14. Americal National Standards Institute: *ANSI C84.1: Electric Power Systems and Equipment-Voltage Ratings*, 2016.
15. IEEE Standard 1453-2015: *IEEE Recommended Practice for the Analysis of Fluctuating Installations on Power Systems*, 2015.
16. IEEE Standard 519-2014:*IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems*, 2014