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High PV Penetration Impact on European-based LV Residential Network

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Abstract

The impact of high PV penetration into the grid particularly at the distribution side has been extensively studied. However, most of the available research focuses on North American style systems. This project aims to investigate the effect of high PV penetration at a residential area in a European-based distribution network, which is electricity supply system Malaysia is based on. The modeling is done using OpenDSS while the network model used is the IEEE European Low Voltage Test Feeder which consists of 55 loads representing a generic housing area. Each load point is then equipped with a 4 kW PV system-representing a typical size for a house installation. PV output variability is then introduced into the modeling using two sample days of actual irradiance variability obtained from UTeM Malaysia; one for clear day and another for a high variability day. Voltage unbalance, voltage rise and reverse power flow were analyzed. One significant finding of this project is that voltage rise exceeds the standard of 1.05 pu during noon. Besides that, the high variability days significantly affect the mitigation measures required to manage reverse power flow.

Keywords: *solar photovoltaic, distribution network, PV penetration level, distributed generation*

1. Introduction

Grid connected photovoltaic (PV) continues to experience exponential growth due to its positive outlook on being a clean source of energy. However, concerns emerge on the adverse impact PV can have on the grid due to its inherent nature of unpredictability and extreme fluctuation. To avoid the problems that can be caused by grid-connected PV, utilities tend to be conservative in the magnitude of PV systems allowed to be connected to the grid. Among the problems that can occur are voltage unbalance, voltage rise and reverse power flow.

Voltage unbalance happens when the voltage magnitude or phase angle between any two or more phases in the network is dissimilar [1]. As an example, when there is higher PV penetration at Phase 1 compared to Phases 2 and 3, voltage will be higher at Phase 1. As the voltage magnitude is not the same for each phases, the voltage is unbalanced and overvoltage can occur at phase 1. This occurs when the installation capacity of integrated PV to the grid between phases are not balanced. This scenario is supported by [2] and [3] where the researchers found that uncontrolled installation of PV grid integration on each phase at the distribution network does make the grid become unbalanced. This situation creates uneven voltage rise as PV penetration on each of the phases is distributed unequally. Therefore, voltages are unbalanced in the network and disrupt the stability of the grid.

The voltage rise issue occurs at both urban and residential areas. Many researchers have investigated this issue as PV grid penetration is expected to increase annually as PV price continues to fall [2], [4]. Voltage rise happens when the PV power supplied to the grid undergoes a sudden spike or drop in a short period of time due to an abrupt change in weather conditions. PV power fluctuation depends on weather conditions and affects the voltage fluctuation in distribution networks. Therefore, voltage rise occurs due to the fluctuation of voltage on the grid. Usually, in the traditional distribution network, the voltage should fluctuate in the range of 0.95 p.u. to 1.05 p.u. But, the moment PV power penetration is high, the voltage fluctuation can go beyond 1.05 p.u. when the voltage rise occurs. This statement have been proved by [5], where in the investigation, when there is no penetration of PV on the network, the voltage magnitude is constant which is 0.9690 p.u. When there is penetration of PV, the

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magnitude voltage rise and fall between 1.02 p.u. to 1.14 p.u. during each hour. It shows that voltage rise occurred because of PV penetration.

Meanwhile, reverse power flow occurs on the grid when the power supplied to the grid by PV is higher but during that period the load is low. This is the moment when the grid operation at the distribution side becomes most challenging [6]. In the traditional distribution system, the generated power is distributed in one way from feeder to customer, where voltage at the feeder is higher than the connection point at the load side. But during the afternoon, PV may generate power that exceeds consumer demand. Therefore, the voltage at the load side is higher than the feeder. As a result, direction of power flow is reversed as most of the time the grid-connected PV system will send the extra electrical power back to the normal mains electrical grid rather than store the extra power in batteries. Now power flows from the connection point at the load side to the feeder. This situation creates over voltage at the feeder and according to [7] and [8], when over voltage occurred at feeder due to reverse power flow, voltage regulator and protection device coordination is affected.

By analysing these factors, several actions can be taken depending on the requirement. The first option is by introducing energy storage. Since the price is expensive, the determination of optimum size and location of energy storage would depend on the characteristic of the voltage profile [9]. Another option is to limit the penetration level to avoid exceeding the statutory limit [10].

Therefore, the objective of this research is to investigate the impact of high PV penetration on a residential distribution network. The analysis is done using a generic LV network that mimics the distribution network in Malaysia. The analysis focuses on the three aspects mentioned previously, with the network being developed using OpenDSS.

2. Research Method

Figure 1 shows the approach of this research work. First a generic distribution network is selected for simulation. The system chosen for the study is the European Low Voltage Test Feeder. It has a base frequency of 50Hz, three-phase step-down transformer at substation rated MVA of 0.8 with rated voltages of 11/0.416 kV, and a Delta/grounded-Wye connection, the resistance and reactance of the windings are 0.4% and 4% (use the kVA and kV base of the high-voltage winding), respectively and 205 lines, 906 buses, 55 loads connected in single phase with 0.23 kV, 0.95 power factor in Wye-connection.

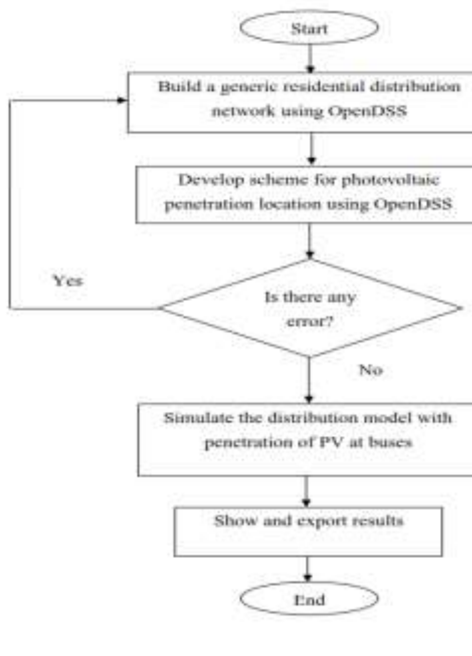


Figure 1. Flow chart for the research work

Next, the model is developed using OpenDSS where the mapping for this network is depicted in Figure 2. OpenDSS is an open source software that is a comprehensive electrical system simulation tool for electric utility distribution systems developed by the Electric Power Research Institute (EPRI) [11]. The software is script-based, making it extremely flexible. It has the capability to model unbalanced, multi-phase power distribution networks, both North American and European style and supports utility distribution network analysis.

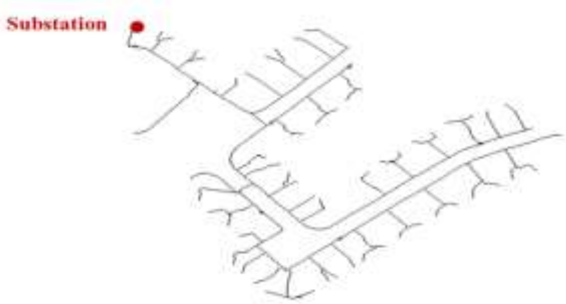
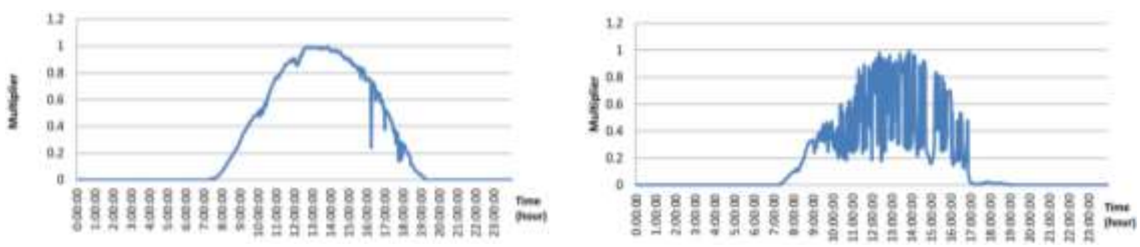


Figure 2. Single-line diagram for the European Low Voltage Test Feeder

Besides that, OpenDSS software is used to generate photovoltaic (PV) penetration on selected feeders or buses. PV penetration is simulated on selected feeders or buses to analyze variation of voltages at the distribution network for residential areas. Two types of simulation are conducted. First, the maximum 100% PV penetration is distributed unequally into all three phases on different buses with clear sky irradiance PV profile. Second, the maximum 100% PV penetration is distributed unequally into all three phases on different buses with high variability irradiance PV profile.

To represent 100% PV penetration, each of the 55 loads is then installed with a 4 kW PV system. The profile of the PV power output is based on actual irradiance data from a measurement site in UTeM, Malaysia where the irradiance is recorded for every second and averaged into one minute values. It consist of two sample days—one for clear sky day and another for a high variability day as shown in Figure 3.



(a) (b)

Figure 3. Irradiance profile for (a) clear sky day (b) high variability day

3. Results and Analysis

3.1. Base case (without PV)

The behavior of electrical characteristics at the upstream of distribution network is measured at the low voltage side of transformer. During 0% penetration of PV power at the distribution network, there exists some mild variation throughout the day and between the three phases due to difference in load usage but, the voltage profile remains stable. There is only a small voltage drop of 0.5 V in phase B due to a spike in power usage a few minutes after 9 am as shown in Figure 4.

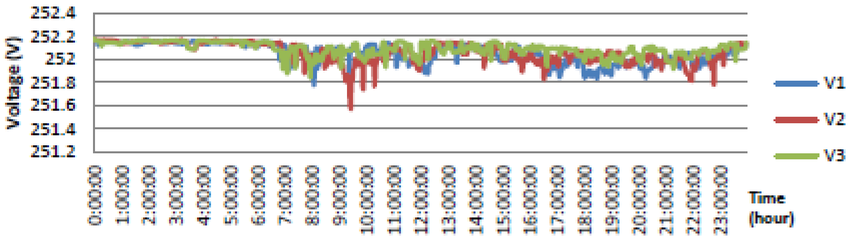


Figure 4. Voltage profile without PV penetration at distribution transformer

Figure 5 shows that the voltage remains consistently within the range of Standard IEEE which is 0.95 to 1.05 p.u. bandwidth. This is expected since the load magnitude is comparatively low. The result does not show any voltage rise occurred.

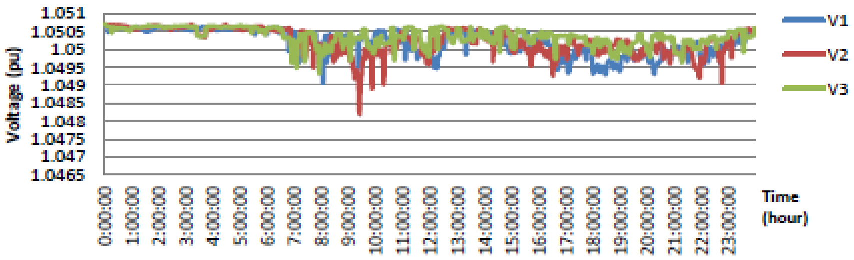


Figure 5. Voltage profile without PV penetration at the distribution transformer in per unit

There is no reverse power flow at the upstream as shown in Figure 6 as the variation of power is positive. The results show that the profile matches what we would expect from a typical residential network when there is 0% PV power penetration.

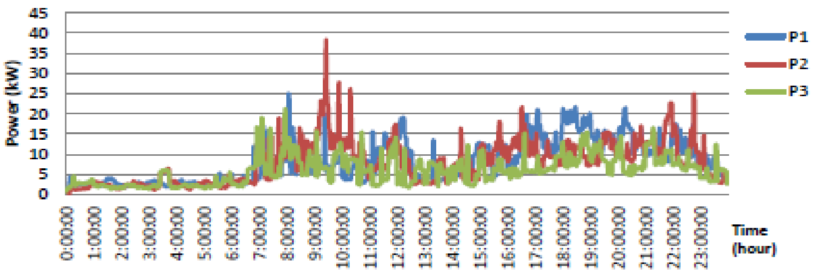


Figure 6. Power profile without PV penetration at the distribution transformer

3.2. Case with PV penetration

3.2.1. Voltage unbalance

Simulation results show that voltage unbalance occurred due to PV power penetration on each of the phases is distributed unequally. In this project, PV is distributed unevenly within each phase where Phase 1 is connected with 21 photovoltaic, Phase 2 is connected with 19 photovoltaic while Phase 3 is connected with 15 photovoltaic and it is 100% PV with 4 kW power penetration in the network.

Therefore, voltage magnitude is dissimilar in each phase. As Phase 1 is connected with more photovoltaic compare to Phase 2 and Phase 3, voltage is higher at Phase 1 than other phases as shown in Figure 7 and Figure 8 where this scenario applies in both clear sky day and high variability day.

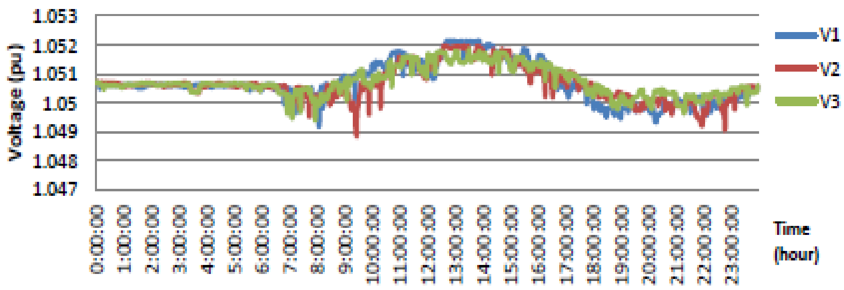


Figure 7. Voltage profile with 100% PV penetration during a clear sky day

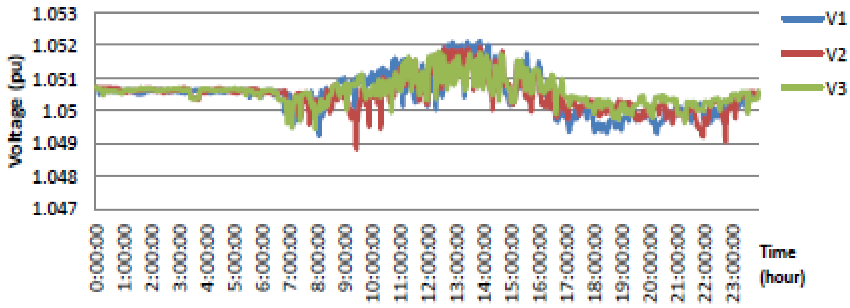


Figure 8. Voltage profile with 100% PV penetration during a high variability day

The voltage unbalance between phases is similar to base case findings. High PV penetration levels do exhibit unbalanced properties. However, it does not have any significant difference compared to the unbalanced nature already present in the network due to different load profiles. Therefore, high PV penetration has minimal impact on the existing grid. According to researcher in [12], the unbalanced voltage can be reduced by control the installation of PV power in each of the phases equally. Furthermore, the analysis reveals that any impacts at load side do affect the upstream section of the distribution network.

3.2.2. Voltage rise

The voltage profiles in Figure 7 and 8 also show that there is a voltage rise that exceeds 1.05 p.u. between 10 am to 4 pm. This rise follows the pattern of the irradiance profile and peaks during solar noon. Voltage rises critically within that period of time with 100% of PV power penetration in the network. Therefore, PV power fluctuation depends on weather conditions and affects the voltage fluctuation in distribution networks.

This is a concern particularly for utilities as the rated PV system is only fixed at 4 kW. Larger systems installed at the distribution side could have a more pronounced effect on the voltage level. In the analysis, at both downstream and upstream, the three phase voltages critically rise when the voltage magnitude exceeds 1.05 p.u.

3.2.3. Reverse power flow

Reverse power flow occurs PV generation is high while at the same time load demand is low. This situation is depicted in Figure 9 where the PV generation is represented by the red line while the blue line shows the load demand profile. As a result, the current is reversed during this time period as shown in Figure 10 where the red line show the current flow without PV while blue line with PV.

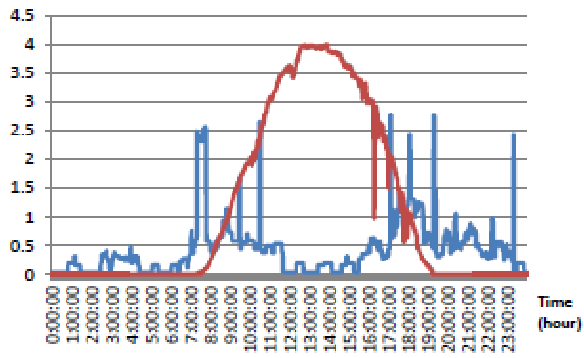


Figure 9. PV penetration higher than load demand

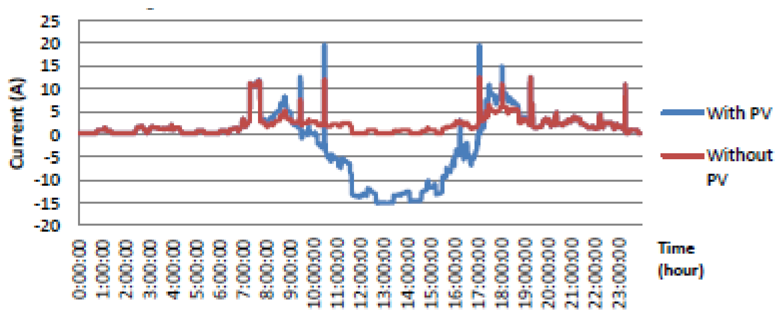


Figure 10. Current flow seen at the transformer side

The inverted current shows that the generation power of photovoltaic behave as a negative load. The negative current flow seen by the transformer is because during the day, electrical load usage in houses are low since many residents typically go for work or school. On the other hand, PV generation is at its highest during the afternoon. This mismatch is the reason why current flows back to the transformer. Concerns arise on the effect of this reverse flow, since the conventional distribution network is only designed for a unidirectional power flow from generation to the load. Furthermore, during this period, the distribution grid stability might be compromised.

Figure 11 and 12 shows the effect of reverse power flow for all three phases. Since load usage at all phases is considered minimal during the afternoon, a significant amount of reverse power flow can be seen. Besides that, by comparing the two figures, high variability irradiance profile has more impact towards the distribution system than clear sky irradiance profile. This is because high variability profile fluctuates more frequently compared to clear sky irradiance profile, where this behavior of PV power penetration can cause protection equipment start to lose coordination for tripping under fault conditions.

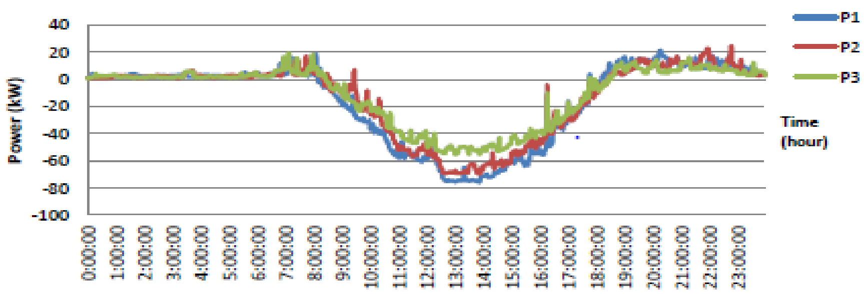


Figure 11. Reverse power flow during a clear sky day

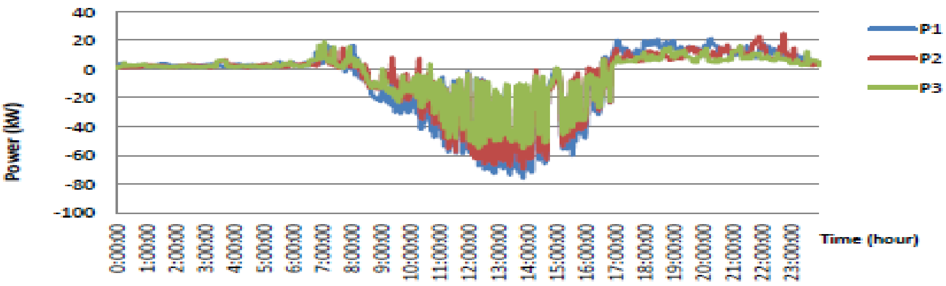


Figure 12. Reverse power flow during a high variability day

In addition, PV generation at the consumer side will reduce the total power flow from transformer side which means kWh reduction from transformer point of view. Lastly, power reduction or the reversed behavior of power when there is PV power penetration does impact on voltage profile where voltage profile increases.

4. Conclusion

In conclusion, to evaluate the potential effects of high PV penetration in a Malaysian distribution network, a generic residential distribution network is simulated using OpenDSS. Two cases are studied, first with 100% PV penetration during a clear day and second during a high variability day. In this project, the penetration of PV power is distributed unequally among three phases creates the unbalanced small scale three phase distribution network environmental study. The power generation of PV is penetrated with maximum 100% penetration where each of the PV generator power is set 4 kW to study the impact of PV system in a residential area.

Through this research, the potential impacts of voltage unbalanced, voltage rise and reverse power flow caused by high PV penetration are studied. The simulation shows that voltage rise exceeds the standard 1.05 p.u. threshold during noon for both clear and high variability days where the voltage rise occurred at load side is higher than at the low voltage side of the transformer. Besides that, the high variability irradiance has more impact than clear sky irradiance during reverse power flow as the fluctuation of high variability irradiance is more when compared to clear sky irradiance. Furthermore, the change in voltage and current behavior at the load sides do affect the upstream at low voltage side of the transformer in distribution system.

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References

[1] Karimi M, Mokhlis H, Naidu K, Uddin S, Bakar AHA. Photovoltaic penetration issues and impacts in distribution network - A review. *Renew. Sustain. Energy Rev.* 2016; 53: 594-605.
[2] Yan R, Saha TK. Investigation of voltage variations in unbalanced distribution systems due to high photovoltaic penetrations. *IEEE Power Energy Soc. Gen. Meet.,* 2011: 1-8.
[3] Wong J, Lim YS, Tang JH, Morris E. Grid-connected photovoltaic system in Malaysia: A review on voltage issues. *Renew. Sustain. Energy Rev.* 2014; 29: 535-545.
[4] A Mohammadi, SH Hemati. High penetration PV in distribution networks, design and control. *Indonesian Journal of Electrical Engineering and Computer Science.* 2016; 1(2): 238-248.
[5] Putra JT, Bs MI. Impact of High Penetration of Photovoltaic Generation on Voltage Fluctuation of Transmission and Distribution Systems. *Department of Electrical Engineering and Information Technology UGM.* 2015: 333-336.
[6] Tzanetopoulou C. Impacts of high penetration of PV in distribution grids and mitigation strategies. EEH Power Systems Laboratory. ETH Zurich. 2013.

[7] Kenneth AP, Folly K. *Voltage rise issue with high penetration of grid connected PV.* IFAC Proc. 2014; 19: 4959-4966.
[8] Liu E, Bebic J. Distribution System Voltage Performance Analysis for High-Penetration Photovoltaics. *Natl. Renew. Energy Lab.* 2008.
[9] SH Hemati, A Mohammadi. Power Control of High Penetration PV in Distribution Network. *Indonesian Journal of Electrical Engineering and Computer Science.* 2015; 15(2): 217-228.
[10] Petinrin JO, Agbolade JO, Shaaban M. Voltage Regulation in a microgrid with Hybrid PV/Wind Energy. *Indonesian Journal of Electrical Engineering and Computer Science*. 2015; 14(3): 402-409.
[11] Electric Power Research Institute. Introduction to the OpenDSS. Training Material. 2009: 1-4.
[12] Aramizu J, Vieira JCM. Analysis of PV generation impacts on voltage imbalance and on voltage regulation in distribution networks. *IEEE Power Energy Soc. Gen. Meet.* 2013.