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Performance assessment of a three-phase distribution network with multiple residential single-phase PV systems

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Abstract: About 90% of solar photovoltaic (PV) systems installed in the UK belong to the category of residential systems with individual ratings <4 kW. With the falling cost of PV systems, the number of residential PV systems being installed can be expected to grow. The literature discussing the impact of PV on the electric power system typically uses a clustered model, lumping all single-phase PV systems into a single three-phase PV system at 11 kV or higher voltage, thereby ignoring the impact of the distribution of PV systems and the unbalances. This study aims to analyse the performance of a distribution network with multiple single-phase PV systems. The main contribution of the study is the quantification of the percentage of PV penetration at which the presence of PV may adversely affect the performance of the distribution network and the usage of a more probable worst-case scenario than a theoretical worst-case scenario. The use of PV for reactive power compensation to improve the power factor at the substation is also studied. Though voltage profile is generally discussed as the parameter worst affected by the presence of PV, the analysis indicates that it is the last parameter to be adversely affected.

1 Introduction

The total installed capacity of photovoltaic (PV) systems in the UK has reached around 11 GW (end of September 2016), some 30% higher than the capacity by the end of September 2015 [1]. Though the PV systems with individual capacities of ≤4 kW only contribute 22% of the total capacity, they contribute more than 90% of installed PV systems by number. Their share in installed capacity in the UK has increased over the years reaching 46% of installed capacity in the month of September 2016. As the cost of PV systems decreases and the awareness of climate change and emission reduction increases, this trend is expected to continue. The main characteristics of PV systems of individual capacities between 0 and 4 kW are: they are single phase in nature, they are connected to residential distribution networks (which are characteristically different from the transmission network), they are distributed over a wider area and they are closer to the loads. The presence of PV systems affects the performance of the power network to which they are connected. The performance parameters affected by the presence of PV are voltage profile, real and reactive power flows, power factor and total harmonic distortion (THD).

The impact of PV systems on the voltage profile is the most studied performance parameter [2–8] and the majority of the research uses load flow-based analysis. A load flow-based approach is used to identify the impact of distributed generation at 50%, both PV and combined heat and power (CHP) on a typical UK distribution network in [3]. This approach commonly models the PV system as a negative load with constant power [3–7]. It is suitable to analyse the performance at transmission level, where the phases are balanced and the fluctuations due to the distribution of loads and generation are averaged, which is not true for a residential distribution network where small PV systems are typically installed. Though a dynamic model is used to evaluate the voltage profile of a distribution network representative of the UK in [8], the authors only consider three different percentage levels of penetration and do not describe the type of model used for PV systems. The work presented here aims to evaluate the impact of PV systems on the distribution network considering the unbalanced nature of the distribution network and a dynamic model of the PV systems at different penetration levels and different load and solar irradiation conditions.

The next parameter that is affected by the presence of PV is the current harmonics, which is identified as a parameter that violates the standards under certain scenarios in [9]. However, the measurements in [10] show that the total harmonics are well within the limits in a network with 19 single-phase PV systems. The authors of [11] observe that the harmonics introduced by PV are dependent on the existing harmonics in the transmission network introduced by non-linear loads in the network. This paper aims to evaluate the impact of PV on the distribution network assuming linear loads i.e. with no existing harmonics in the grid.

Another parameter that is affected by the presence of PV systems is the net power flow at the substation. When power generated by the PV systems is higher than the load in the feeder supplied by the substation, it results in a reversal of the direction of power flow at the substation. Though reverse power flow is mentioned as a factor to be considered in the dynamic performance, it has not been discussed in detail in any of the above studies on steady-state performance of the distribution network with PV or as a factor affecting the contribution of the PV system. The power factor at the substation is also affected by the presence of PV systems. Currently, all commercial PV inverters operate at unity power factor. This affects the power factor as seen by the network operator. This paper also observes the variation of power factor with increasing penetration of PV systems.

2 Methodology

A sample distribution network which is part of an actual network in the UK is chosen for analysis [12]. For the purpose of analysis, one

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low-voltage feeder (supplied from a 500 kVA transformer) together with its connected loads is modelled in detailed. The other three low-voltage feeders, supplying 327 houses, are modelled as lumped load as shown in Fig. 1. The detailed feeder has 57 houses distributed uniformly across all the phases from the substation but not uniformly distributed across all buses, which is quite typical for a practical distribution network. Buses 5 and 6 are split feeders from bus 4. The details of the number of houses in each phase and each bus are given in Table 1. The percentage penetration of PV systems is defined as the ratio of the total rating of the PV systems in kWp to the after diversity maximum demand (ADMD) of the distribution network under consideration as

$$\%\,\text{penetration} = \frac{\text{PV rating}}{\text{ADMD} \times \text{no. of houses}} \tag{1}$$

The ADMA for the network under consideration is 1.3 kVA. The distribution network including the on-load tap changer at 33 kV is modelled in Matlab SIMULINK. PV systems with individual capacity of 2.5 kWp are chosen as it is close to the average individual PV system capacity in the range of 0–4 kW installed in the UK [1]. The PV system modelled in Simulink comprises ten PV modules/panels of 250 Wp each connected in series and then connected to an inverter of 2.5 kVA rating. The inverter has a nominal rating which is same as the total module rating as most commercial inverters operate at close to unity power factor and efficiency >95% [13]. The block diagram of the PV system is as shown in Fig. 2. The inverter is modelled as a two-stage inverter with a boost DC/DC converter followed by a DC/AC converter. The DC/DC converter performs the maximum power point tracking (MPPT) using the Perturb & Observe (P&O) technique. The duty cycle of the DC/DC converter is varied in accordance with the amount of solar irradiation that is falling on the solar panel to ensure a constant DC voltage at the end of the converter. The DC/AC inverter uses *d–q* control strategy to control the magnitude and shape of the output current waveform. This enables control of real and reactive power independent of each other unlike other strategies of hysteresis control and proportional integral control. An LCL filter is used at the end of the converter to reduce the overall harmonics in the current waveforms.

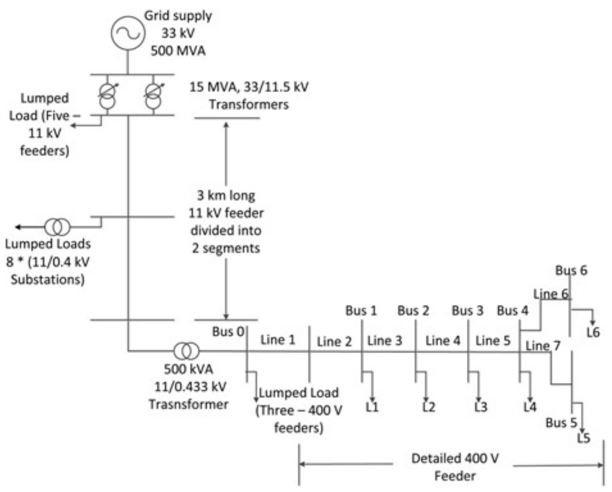

Fig. 1 *Distribution network used for analysis, representative of UK electricity distribution system*

Table 1 Details of number of houses per bus per phase

Bus no.	1	2	3	4	5	6
Ph A	4	2	5	2	4	2
Ph B	4	3	5	1	4	2
Ph C	3	3	5	1	5	2

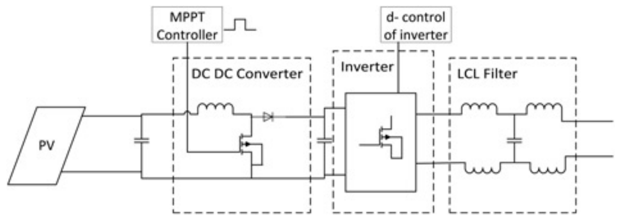

Fig. 2 *Block diagram of a two-stage PV inverter with LCL filter*

To analyse the performance of the distribution network with PV, the penetration of PV systems is varied from 0 to 100% in steps of 10%. The PV systems are considered to be uniformly distributed across three phases and are either clustered towards the end of the feeder/distribution network (away from substation) or near the substation. For scenarios of PV at the far end of the feeder, PV is distributed starting from the houses in bus 6 to bus 1, as bus 6 is the farthest from the substation. The analysis is performed for two values of solar irradiation, viz. 1000 W/m^2 (solar irradiation at standard test conditions of the PV modules) and 800 W/m^2 (more common maximum solar irradiation in the UK). The distribution network is either at minimum loading condition of 152 W at 0.95 pf lagging [12] or at 500 W at 0.95 pf lagging (the day time minimum load being higher than the after diversity minimum demand of the distribution network [14, 15]). The on-load tap changer at 33 kV controls the tap settings depending on the loading of the distribution network and is set to maintain the secondary voltage of the transformer at 433/250 V.

3 Performance of distribution network with PV

The performance of the distribution network is observed in terms of the voltage profile, THD, net real power flow and power factor at the substation. The substation is considered as bus '0' in the analysis.

3.1 Voltage profile

Fig. 3 shows the voltage profile for minimum load of 152 W and maximum solar irradiation of 1000 W/m^2. It can be seen that the voltages across the three phases are not the same, even though the distribution of PV is uniform. This is attributed to the fact that even though the net number of houses and net PV in each phase is uniform, it is not uniformly distributed across the different buses,

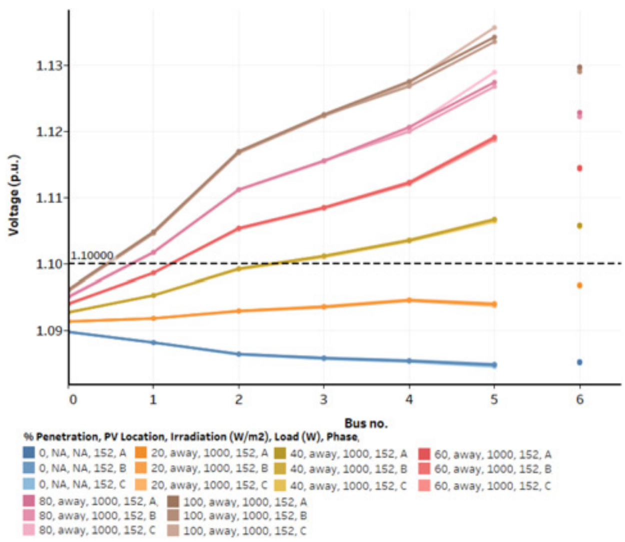

Fig. 3 *Voltage profile of the distribution network for different penetration levels of PV at minimum load of 152 W and maximum solar irradiation of 1000 W/m^2*

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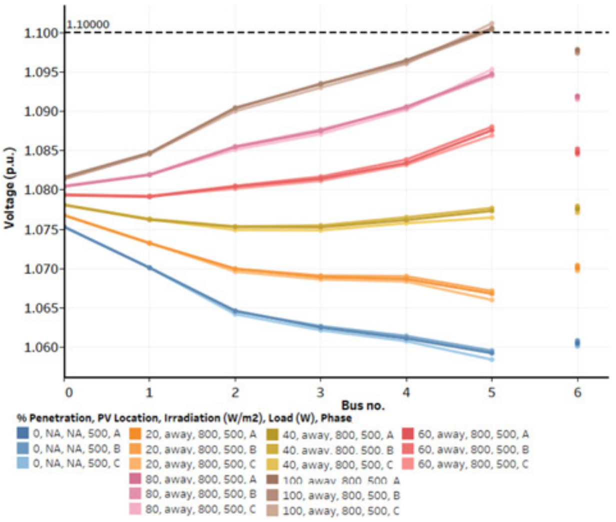

Fig. 4 *Voltage profile of the distribution network for different penetration levels of solar PV at load of 500 W load and solar irradiation of 800 W/m²*

which can occur in a practical distribution network. The difference is more clearly visible in bus 5, where the unbalance increases with the increase in penetration of PV systems. The unbalance at bus 5 with no PV is around 0.035% and with 100% is around 0.2%. Though the absolute values of unbalance are not high, the percentage increase in unbalance for increase in PV penetration is around 400%. This implies that if the initial unbalance at a bus is high, the introduction of PV will accentuate the unbalance which can affect the performance of any three-phase load connected to that bus. Fig. 4 shows the voltage profile for the day time minimum load of 500 W per house and more common solar irradiation of 800 W/m^2. The probability of occurrence of this scenario is higher than the worst-case scenario as 1000 W/m^2 is not a common occurrence in the UK and minimum day time load of the distribution network is always higher than the after diversity minimum demand. From the figure it can be seen that only under 100% penetration does the voltage at the far end of the feeder reaches the limit of 1.1 p.u. (256 V). For this more probable operating scenario, the voltage rise at the far end of the feeder due to clustering of PV at the far end does not form a factor limiting the contribution of PV systems.

3.2 THD

The THD of the voltage is not affected by the presence of multiple single-phase PV systems. This can be attributed to the fact that individual inverters adhere to the standards to limit the voltage and current THD to <5% and also to the assumption that the loads are linear in nature.

3.3 Net power at the substation

The net power at the substation becomes negative at <20% penetration of PV systems under minimum load and maximum solar irradiation of 1000 W/m^2 (Fig. 5). This implies that with just 42 of 384 houses having a single-phase PV system of 2.5 kWp each would result in a reverse power flow at the supply transformer of the feeder when worst-case scenario is considered. The net power at the substation becomes negative only after 50% penetration if the day time minimum load and maximum probable solar irradiation is considered. That is, when 105 of 384 houses (around 30% of houses) have PV installed, reverse power flow at the substation occurs at the more probable scenario. For this scenario, more PV can be installed without causing problems, with the increase in PV being ∼200% if we consider the number of houses or 150% if we consider the rating of the PV systems.

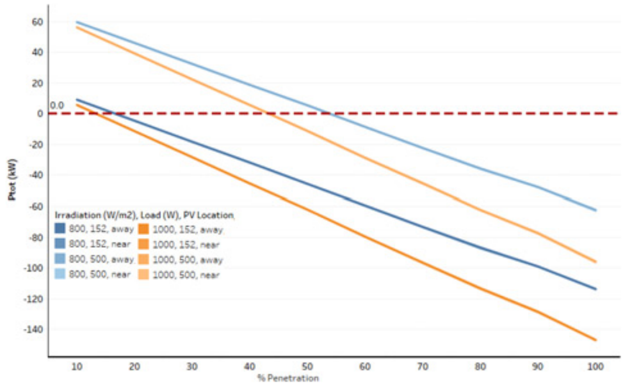

Fig. 5 *Net power at substation for different penetration levels of PV systems*

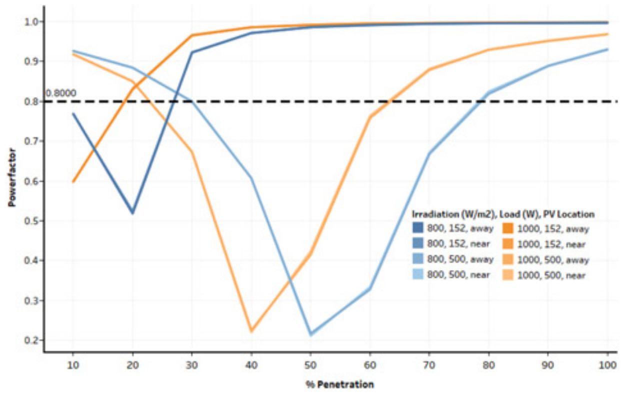

Fig. 6 *Power factor at substation for different penetration levels of PV systems*

3.4 Power factor at the substation

It is preferred to have a power factor as close to unity as possible as a lower power factor means the grid capacity has to be higher to transfer the same amount of real power to the loads. As most commercial PV inverters are operating at or close to unity power factor, the reactive power requirement of the loads remain unchanged with the installation of PV systems. As seen from the substation, this implies that the power factor deteriorates with increasing penetration of PV as shown in Fig. 6. This is irrespective of the load power factor. The increase in power factor after it reaches its minimum is due to the reversal of direction of real power flow. It can also be observed from Fig. 6 that when the load in the feeder increases or the solar irradiation level reduces the percentage contribution of PV can reach higher values without decrease in power factor at the substation. It should however be noted that the deterioration of power factor does not indicate an increase in reactive power requirement of the loads which commonly occurs in a system with low power factor. The distribution network operator should look at the absolute value of reactive power before deciding on taking actions to improve the low power factor at the substation level.

4 Impact of reactive power compensation using PV systems

To observe the impact of reactive power supply by PV systems, the PV systems were made to operate at 0.98 and 0.95 pf lagging (using a generator convention i.e. exporting/supplying reactive power). The UK guidelines allow the operation of PV systems between 0.95 pf lagging and 0.95 pf leading [16], though commercial inverters are typically set to operate at unity pf. The simulations are performed for penetration levels from 0 to 100% in steps of 20%. From

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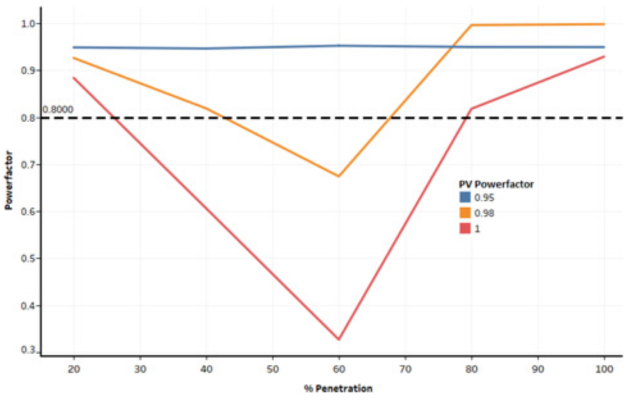

Fig. 7 *Power factor at substation for different penetration levels of PV systems operating at different lagging power factors, 500 W and 800 W/m² solar irradiation*

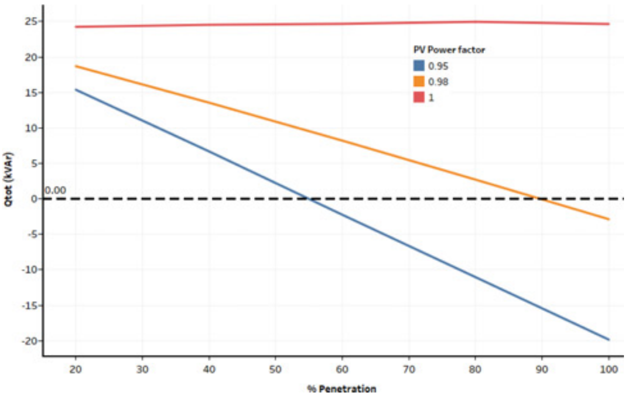

Fig. 8 *Net reactive power at substation for different penetration levels of PV systems operating at different lagging power factors, 500 W load and 800 W/m² insolation*

Fig. 7, it can be observed that the power factor at the substation is best under all penetration levels when PV systems are operating at 0.95 pf lagging. However, the 0.95 pf lagging results in the voltage at the substation reaching the upper limit at 60% penetration whereas 0.98 pf lagging violates the voltage limit at only around 80% penetration. Fig. 8 shows the net reactive power at the substation for different penetration levels and differs for PV systems operating at different lagging power factors. The reactive power reversal under 0.95 pf lagging is around 60% which is almost at the same percentage under which reversal of real power occurs. The contribution of PV can be increased up to 60% without adversely affecting the performance parameters of the distribution network, when the PV is operating at 0.95 lagging power factor. Beyond this percentage, action has to be taken to handle the reverse power from the feeder.

5 Conclusion

The paper discusses the performance of a typical UK distribution network with multiple single-phase PV systems. The parameter that is most affected is the net power flow at the substation. The net power at the substation becomes negative at 20% penetration for worst-case scenario. However, the penetration can increase up to 50% if the more probable worst-case scenario of higher day time load and lower maximum solar irradiation is considered. Another parameter that is affected by PV is the net power factor at the substation, which is directly related to the amount of power a PV system can supply. The results indicate that the day time minimum load of the feeder under consideration and the more common solar irradiation level at that geographic location should be used rather than a rule of thumb while deciding the maximum allowable contribution of PV systems in the feeder.

Though voltage rise is often discussed as a major concern under higher penetration of PV systems, this is the last parameter to be adversely affected. The ability of PV inverters to supply reactive power, if used, could result in the voltage profile violating the upper limit at lower penetration levels. However, even with reactive power being supplied by PV, the voltage profile is not violated for around 60% PV penetration. To facilitate more contribution from PV systems above 60%, the first steps necessary would be to improve the capacity of the distribution network to handle the reverse power flow. The possible solutions include addition of battery storage, curtailment and changes to protection co-ordination.

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