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Impact of High Penetration Level of Grid-Connected Photovoltaic Systems on the UK Low Voltage Distribution Network

S. Ali, N. Pearsall and G. Putrus

School of Computing, Engineering and Information Sciences
Northumbria University
Newcastle upon Tyne, UK
E-mail: a.salem@unn.ac.uk

Abstract. The connection and use of Renewable Energy Sources (RES) such as Grid-Connected Photovoltaic (GCPV) systems in distribution networks have been increasing over the last few decades. The grid-connected PV system is one of the most promising renewable energy solutions which could offer many benefits to both the end user and the utility network. Such systems may cover the consumer's own power demand and reduce electricity bills, while feeding any surplus power into the grid or use the grid as a backup system in times of insufficient PV generation. However, integrating a high penetration level of small-scale grid-connected PV systems into the low voltage distribution network (LVDN) could cause operational problems. One of the technical issues is a possible voltage rise along distribution feeders as a result of reverse power flow, especially at low demand and high generation conditions. This paper assesses the effect of high penetration levels of small-scale grid-connected PV systems on the voltage quality of a residential electricity distribution network in the UK. Different scenarios for both penetration and solar irradiation level are considered under various loading conditions. The MATLAB/Simulink software package was used to carry out this assessment.

Key words

Distribution networks, PV systems, power quality, voltage rise

1. Introduction

In recent years, both demand for electricity and fossil fuel costs have grown rapidly and energy security concerns and global warming issues are becoming more important. These concerns are directing energy research attention towards renewable energy sources, such as solar and wind energy in order to contribute to the growing energy demands and reduce the need for fossil fuels. Moreover, cost reduction of PV panels and technical progress in power electronic conversion and semiconductor devices make photovoltaic (PV) systems one of the most promising renewable energy sources. Recent reports indicated that in 2010, production of PV modules more than doubled, reaching a world-wide volume of 23.5 GW, and most of this production was for grid-connected applications[1],[2]. Grid-connected PV systems have many technical advantages such as flexibility, simplicity to install in any area where the solar irradiation is available, being non-polluting, emitting no noise and requiring little maintenance [3],[4]. Therefore, many countries are encouraging households to install PV systems in order to generate their own power, to reduce electricity bills and to increase the contribution of renewable energy to limit carbon dioxide (CO_2) emissions.

Electricity generation in the UK is still largely sourced from fossil fuels, which causes the release of harmful gases into the atmosphere including CO_2. The use of PV systems and other types of renewable energy sources like large and small-scale wind turbines and hydroelectric units will help to reduce the gas emissions thereby helping government to achieve 15% of its energy from renewable sources to meet their binding 2020 target[5],[6]. The UK government has introduced a Feed-In Tariffs (FIT) scheme to encourage households to install small-scale grid-connected photovoltaic systems[7],[8]. The Department of Energy and Climate Change (DECC) reported that the total amount of installed solar power in the UK has increased from 26 MW before the scheme started at the beginning of April 2010 to 77.7 MW at the end of November 2011[9].

The rated output of a typical UK domestic grid-connected PV system is in the region of a few (1-5) kW [10], based on the average space available on the roof of a residential house and the system efficiency. During the day PV output power will be consumed within the building when there is active load and any excess will be injected into the public grid. Feeding power to the grid could happen during the hours of daylight when the generated power is higher than the load demand due to a high solar irradiation level, especially in sunny weather conditions (summer season). Figure 1 shows a typical daily load profile [11] and the output power of a 3 kW PV system on a clear summer day in the UK. Summer load profile is considered as it provides a good example when there is more energy being produced by the PV than is consumed by the local load across the middle of the day. The presence of a high penetration of GCPV systems in a low voltage distribution network within a relatively small area, referred to hereafter as clustered, may have an impact on the power quality and reliability of the existing distribution network.

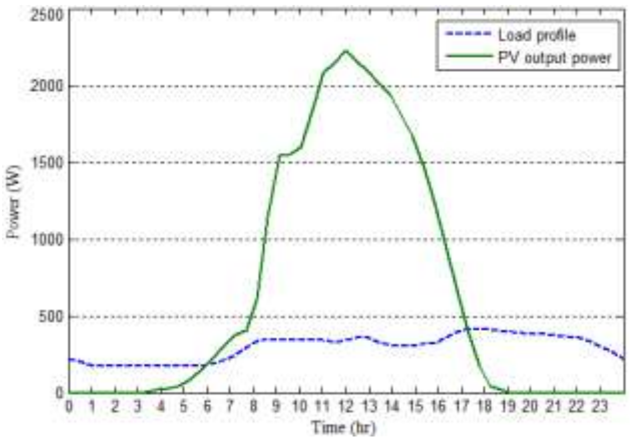

Fig.1. Typical summer daily load profile and PV output power for a clear summer day

In this case, the main issue to be expected is the PV system would be exporting active power to the grid which could result in overvoltage as the diagram in Figure 2 illustrates.

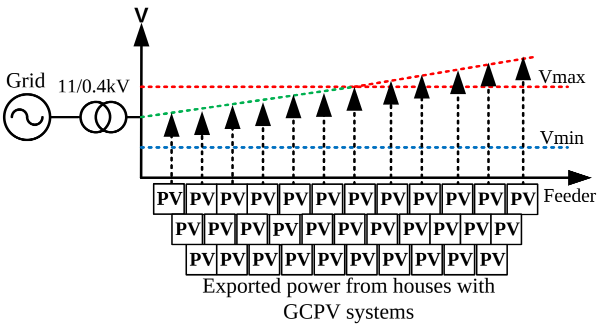

Fig.2. Voltage rise due to clustered PV systems

Overvoltage could affect household appliances and lead to other technical challenges such as safety and protection problems in the network especially if other different types of distributed generation such as small-scale wind turbines are also integrated into the grid[12]. In this paper, the Matlab/Simulink package is used to investigate the occurrence of overvoltage due to a high penetration level of GCPV system on the UK residential low voltage distribution network

2. Network modelling

A. *Distribution network model*

To assess the impact of different penetration levels of grid-connected PV systems, actual data for both the network and a typical house load profile have been used to build a realistic model. This network is fed at a primary 500 MVA substation which consists of two 33/11 kV 20 MVA transformers to supply six 11 kV outgoing feeders, with each feeder supplying eight 11/0.4 kV substations. Each 11/0.4 kV substation supplies 384 properties which are distributed along four outgoing radial feeders. In total, the network supplies 18,432 properties. In order to simplify the analysis, only one 400 V feeder together with its connected loads and GCPV systems was modelled in detail whilst the rest were simplified as a lumped load. Figure 3 presents a schematic diagram of this network.

B. *Simulink network model*

The Matlab/Simulink and Power System Block-set were used to simulate the low voltage distribution network shown in Figure 3 with high penetration levels of GCPV systems. Details of the 400 V feeder with loads and the grid-connected PV systems are illustrated in Figures 4 and 5, respectively. All the feeders are underground cables only, with different specifications as summarised in Table I. Each 400 V feeder is connected to 384 houses. In order to simplify the model, houses are assumed to be distributed along the feeders and lumped in seven groups. Each house was assumed to have a 3 kW grid-connected PV system.

Table I. Specification of the underground cables

	Voltage level	Resistance/km	Reactance/km
Cable	400 V 230 V	025 0.44	0.07 0.07
Cable 95 mm^2(XPLE)	11 kV	0.247	0.1
Cable 185 mm^2(XPLE)	11 kV	0.128	0.091

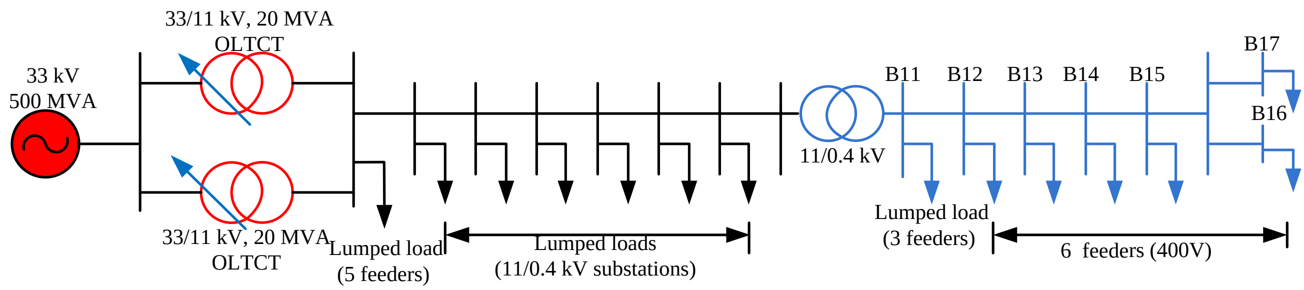

Fig.3. Low voltage distribution network

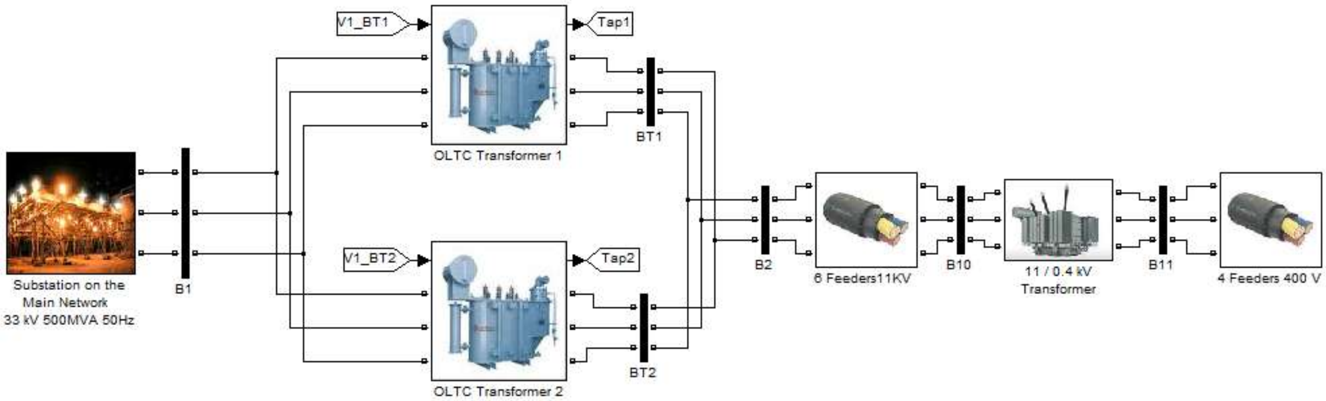

Fig.4. Low voltage distribution network model in Simulink

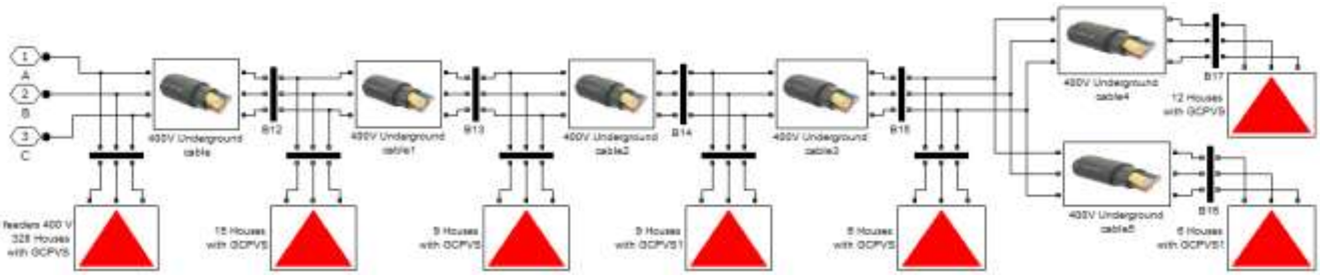
Fig.5. Detailed 400 V feeder with loads and PV systems

3. Simulation results and analysis

Initially, the network model was simulated with the variation of a typical daily load profile and without PV systems. The voltage at each node along the 400 V feeder (B11 to B17) was measured and the voltage profile is presented in Figure 6. The voltage profile indicates that the voltage level remains within the statutory limits (+1.1 and -0.94 p.u.) of the nominal voltage (400 V) despite a small dip at 5.00 p.m when most of the people return home.

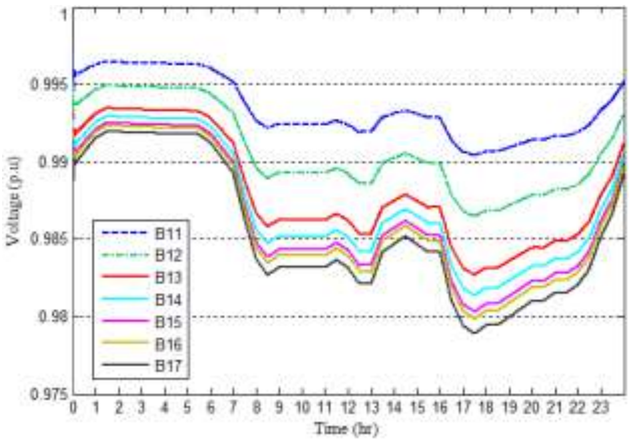

Fig.6. Voltage profile along the 230/400 V feeder without PV systems

In the second part, the network was simulated over 24 hours with the same typical summer load profile and different scenarios of PV penetration levels.

In the first scenario, a 25% penetration level of GCPV systems is considered (that is, 25% of the houses have GCPV systems) and the voltage profile along the 230/400 V feeder (B11 to B17) is determined and presented in Figure 7. The voltage profile indicates that under these conditions, the voltage level remains within the statutory limits (+1.1 and -0.94 p.u) of the nominal voltage 230/400 V.

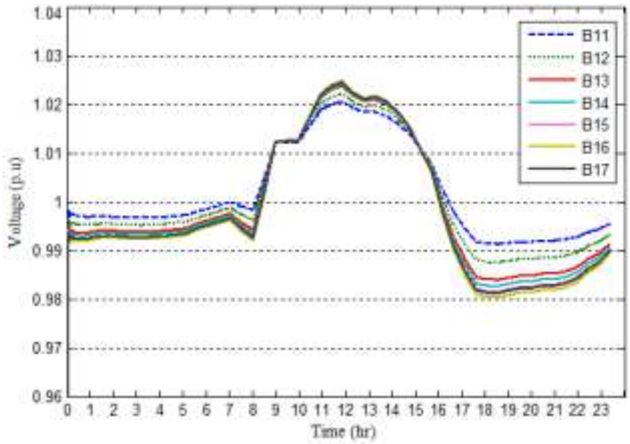

Fig.7. Voltage profile along the 230/400 V feeder with 25% PV penetration level

In the second scenario, the network was simulated with 50% and 100% penetration levels and the node voltages are determined, as before, and presented in Figures 8 and 9, respectively.

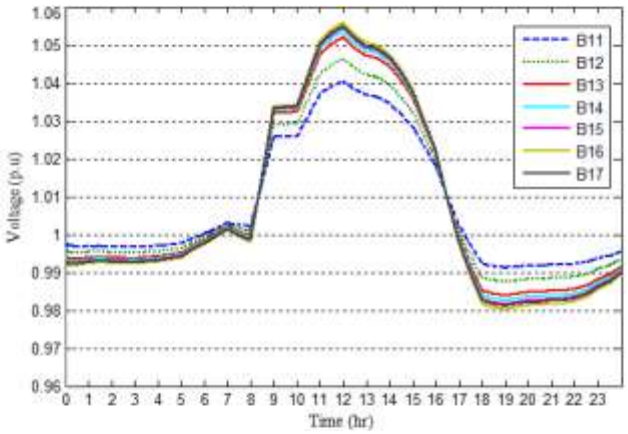

Fig.8. Voltage profile along the 230/400 V feeder with 50% PV penetration level

Figure 8 shows that, when the PV penetration level was increased to 50% the voltage level along the feeder is still within the statutory limits (+1.1 and -0.94 p.u). In the third scenario, the penetration level is increased to 100% which is the worst case condition since it assumes maximum penetration of PV (every house has an installed PV system). The results of this scenario indicated that the voltage level along the 230/400 V feeder increases above the statutory limits of the nominal voltage 230/400 V in the time between 11.00 a.m. to 2.00 p.m. (midday where load is expected to be low and PV generation is high), whereas the voltage level at the beginning of the feeder (B11 and B12) remained just under the statutory limits.

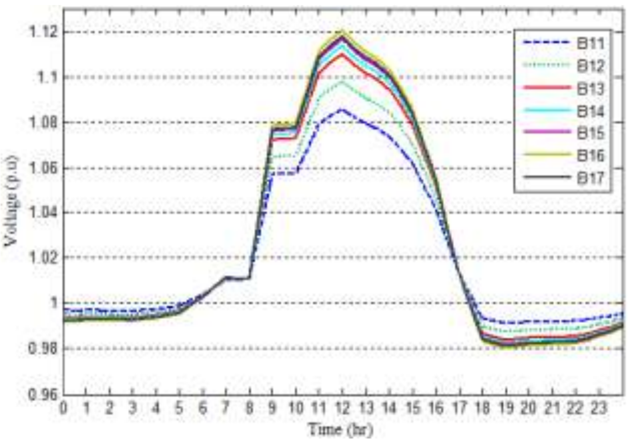

Fig.9. Voltage profile along the 230/400 V feeder with 100% PV penetration level

4. Conclusions

In this paper, a dynamic model of a typical UK low voltage distribution network with high penetration of grid-connected PV systems has been developed using MATLAB/Simulink. This model is being used to investigate the impact of high penetration levels of grid-connected PV systems on the voltage quality of the UK residential low voltage distribution network. The key results that are derived from the simulation study show that, under certain conditions, GCPV systems can affect the voltage quality of the network. This impact becomes more significant with higher solar irradiation level and low demand conditions, as would be expected. Therefore, proper voltage control, for example implementing storage systems or restructuring the network may be necessary in order to accommodate a high penetration of PV systems. In this context, future work will extend the analysis to investigate the voltage profile of the network with the integration of electric vehicles (EV) as storage system to optimise the provision of power from PV systems and support the network (supply/demand matching).

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