INVESTIGATING THE BENEFITS OF MESHING REAL UK LV NETWORKS

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ABSTRACT

The increasing penetration of domestic-scale photovoltaic (PV) systems in low voltage (LV) networks could result in a number of issues such as voltage rise, congestion and higher energy losses. In this work, in order to minimise these undesired effects and increase the hosting capability of the networks, the meshed operation of LV feeders is studied as a possible solution. A Monte Carlo-based technique that considers 1-min resolution load and generation profiles is implemented for different PV penetrations to assess the benefits from meshed operation in 15 real residential, underground LV networks from the North West of England. In particular, the connection of pairs of feeders is investigated and compared with radial cases. The results show that meshed operation does increase the PV hosting capability of the networks. Furthermore, as a general rule, the most beneficial meshing is that where the pair of feeders has a 2:1 proportion in the number of customers.

INTRODUCTION

Thanks to different incentives created by governments around the world, the adoption of residential-scale photovoltaic (PV) systems continues to increase. In the UK, the Feed-in Tariff programme [1] has resulted in an aggregated capacity currently approaching 2 GW [2]. While the overall PV penetration can be considered not significant, clusters found in low voltage (LV) networks are already posing technical challenges to Distribution Network Operators (DNOs). Therefore, with larger volumes of PV capacity more LV networks are expected to experience issues such as significant voltage rise, congestion and higher energy losses [3], [5].

To date, residential LV networks are typically operated as radial. Some feeders are likely to have different number of customers (and therefore demand) than others. Similarly, in the presence of PV systems, some feeders are likely to have different penetrations (i.e., percentage of houses with PV systems). Due to this potential uneven presence of load and PV generation, the meshing (i.e., connection) of two feeders could help minimising PV impacts and, thus, increasing the overall PV hosting capabilities. In this work, focus is given to the connection of two feeders due to practicality and simplicity. However, more simultaneous connections can also be investigated [4].

This paper investigates the meshing of 15 real residential, underground LV networks. The results from over 50 different meshing cases are analysed in detail. To cater for the uncertainties inherent to load and PV generation (i.e., size, behaviour, location), a Monte-Carlo methodology previously developed in [5] is implemented. One-minute resolution daily load and generation profiles are adopted considering the three-phase four-wire nature of the studied LV feeders.

Two metrics that capture the daily behaviour of the LV feeders are used to measure the performance of radial and meshed cases: the percentage of customers with voltage problems (according to the standard BS EN50160), the utilization level of the feeders. In order to understand the relationship between feeder parameters (such as number of customer, length, etc.) and the first occurrence of voltage problems, a regression analysis is carried out. The corresponding results are then compared to extract the most suitable and practical parameter that can be used to produce meshing design rules.

This work is structured as follows: section II presents the methodology. Section III presents case studies and the corresponding discussion. Finally, conclusions are drawn in section IV.

METHODOLOGY

This section presents the real LV networks used in the study as well as the corresponding load and PV generation profiles. Finally, the Monte Carlo-based approach used to quantify the impacts of PV systems in radial and meshed networks.

Real LV Networks

Fifteen real underground, residential LV networks from the North West of England part of the Low Carbon Networks Fund Project "LV Network Solutions" [6] are analysed. Some of these networks are shown in Fig. 1. It can be seen that certain points of many feeders (different colours) are very close to each other. This is because although they are operated radially, link boxes exist to allow post-fault reconfiguration.

Link box is more clearly shown in Fig. 2 (highlighted in grey). These elements will be used to explore the connection of the corresponding feeders. Furthermore, to

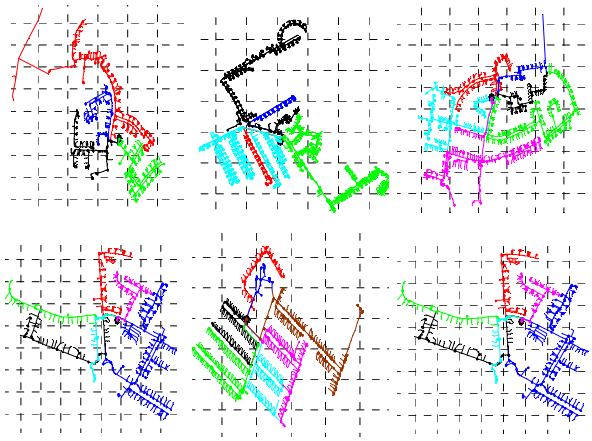

Fig. 1 Examples of studied UK LV networks.

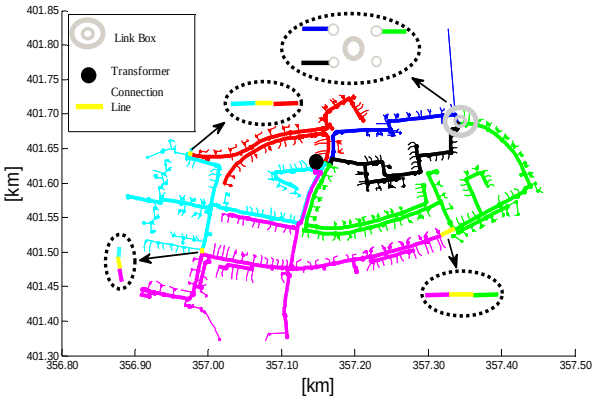

Fig. 2 Link ways (small grey circles), Link boxes (bold grey circle) and transformer (black circle) on the network. Each colour shows different feeders.

investigate other potential cases, connections will also be created for those feeders with suitable geographical points. Examples of this are highlighted in yellow in Fig. 2. Note that the ampacity of these new connections matches the lowest of the lines being connected. Three phase (thick lines) and single-phase lines (thin lines) are also illustrated in the figure. It can be observed that all connection lines are placed between three-phase conductors of different feeders.

Creation of loads and PV profiles

Time-series load and generation profiles have to be modelled so that the performances of LV feeders can be realistically assessed. One-minute resolution residential and PV profiles are created using the CREST tool [7]. The daily demand, PV and net demand profiles of one house with two people are illustrated in Fig. . The load profiles are produced following UK statistic [8] in which the percentage of houses with one person, 2, 3 and 4 people is 29, 35, 16 and 20%, respectively. The sizes and proportion of PV systems are determined also according to UK statistics [1]. The proportion of PV

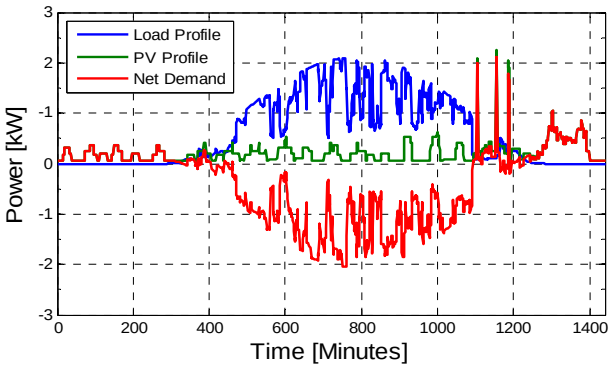

Fig. 3 Load and generation profile (one minute resolution) of one house in Manchester (weekday, July)

systems with 1, 1.5, 2, 2.5, 3, 3.5 and 4 kW is 1, 8, 13, 14, 12 and 37%, respectively. For simplicity and to consider the most severe scenarios, weekdays of July (summer) are considered in this work. In addition, the same sun irradiance (average from 1,000 samples produced by the CREST tool) is used for all PV installations but scaled to the corresponding PV size.

Monte Carlo analysis

The probabilistic approach presented in [5] was adopted to cater for the nature of load and PV. For each radial and meshed operation of a given pair of feeders, one hundred simulations are carried out from zero to one 100% PV penetration level. Average values of key performance metric are captured for each penetration level (percentage of houses with PV systems).

For a given pair of feeders (within the same LV network), and a given PV penetration, a daily minute-by-minute time-series power flow analysis is carried out using OpenDSS [9] and considering their inherent unbalance nature (i.e., adopting three-phase four-wire models). For each simulation, the impacts on voltage are assessed according to the BS EN50160 standard [10]. In addition, to understand the utilization of assets, the hourly maximum current at the head of each feeder is divided by its ampacity.

To quantify the benefits brought by meshing a pair of feeders, the average values of the above metrics are obtained from 100 simulations (for a given PV penetration) for both radial and meshed cases.

CASE STUDY

In this section, the Monte Carlo approach is applied to 15 residential, underground radial UK LV networks. The analysis provides insights into when and what type of feeders experience problems according to two performance metrics: the percentage of customers with voltage problems (according to the standard BS EN50160) and the utilisation level of the feeders.

Due to the probabilistic nature of the analysis, technical problems have to be quantified in a fair way. A voltage problem in a feeder, for a given PV penetration, is only considered when at least, in average (from 100 simulations), one customer has voltage problems. For congestion, a problem is considered when, in average, the feeder utilisation exceeds 100%.

Occurrence of Problems: Radial and Meshed

For the radial case, results show that, at some PV penetration, 29% of the 73 feeders will experience voltage problems level and 14% will have congestion issues. More importantly, 95% of the latter experiences voltage problems at a much earlier PV penetration. These results confirm previous analysis carried out in [11]. Overall, from those feeders with problems, cases related to voltage appear with around 40% of the houses with PV systems whereas congestion issues emerge at around 70%. This means that, with PV systems, the voltage problem is the main constraint on the networks' hosting capabilities.

To analyse the meshed operation, 19 feeders presenting problems (when radially operated) at some PV penetration are first selected. 52 different cases are then created by meshing (connection of two feeders) these 19 feeders with other types of feeders from the whole population of 73. From these 52 meshed cases, 76% will experience voltage problems at around 60% of PV penetration while 73% will have congestion issues only above 90%. In all cases, again, voltage problems appear earlier than congestion issues. Note that this much larger number of cases with problems is because each pair of feeders has at least one with problems (at some PV penetration) when radially operated.

Relating Problems to Feeder Characteristics

In order to simplify –to some extent– the quantification of the benefits brought from meshing, it is important to identify a parameter that describes the corresponding type of feeders. This parameter, however, has to be not only practical but also be able to adequately correlate PV penetration and the potential technical problems.

For this purpose, for each feeder in the radial case (and pair of feeders in the meshed case), the value of a given parameter is plotted against the PV penetration that leads to the first occurrence of a problem. A regression analysis is then carried out and the coefficient of determination (R^2) is calculated for each parameter. The values of R^2 range from 0 to 1 with 1 representing a perfect statistical correlation between the parameter investigated and the PV penetration (that leads to the first occurrence of a problem), and 0 representing no statistical correlation.

The nine feeder parameters investigated include impedances, length, number of customers (Cust), daily energy losses (ELosses) and the utilisation level (UL, at the head of the feeder). The last two parameters are calculated considering the load-only scenario, i.e., no PV. In terms of impedances and length, the calculation of the corresponding parameters is done considering single phase, three phase and total values. For example, for the three-phase impedance (3ϕ Imp), three-phase segments within a feeder are added together. For the single-phase impedance (1ϕ Imp), single-phase segments (mostly service cables), are added up. The total impedance (T-Imp) is the sum of 3ϕ Imp and 1ϕ Imp. This is done similarly for the parameters related to length (3ϕ Length, 1ϕ Length, and T-Length). It is important to highlight that in meshed operation all the parameters are calculated considering both feeders.

The results carried out for radial and meshed operation are summarised in Fig. 4. It can be observed that the use of ELosses leads to the largest R^2. This parameter, however, is not practical as it requires time-series power flow simulations (or monitoring devices at households and at the head of each feeder). Thus, the second best parameter, the number of customers (Cust), is selected as this is information DNOs have readily available.

The number of customers will be used to produce *Improvement Matrix* that can easily provide the extent of the benefits from meshing a problematic feeder with neighbouring ones. For simplicity, the number of customer is divided into ranges (Table I)

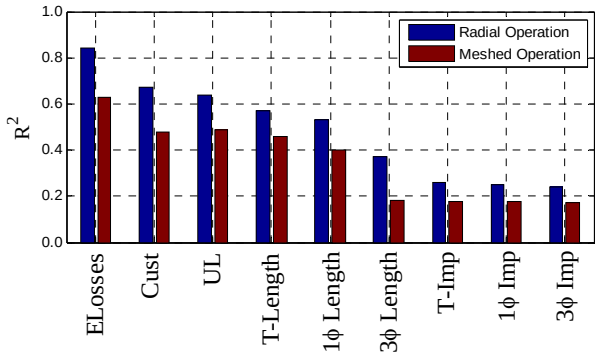

Fig. 4 Coefficients of determination for the nine parameters

Table I - Characteristics of Feeders used for Meshed Operation

Range of Customers	Number of Feeders	Average		
		Number of Customers	Total Length [m]	3ϕ Length [m]
0-20	5	14	517	306
21-40	8	28	780	408
41-60	5	51	1373	664
61-80	5	65	1435	872
81-100	4	86	2302	1137
101-120	2	107	2867	1365
121-140	2	133	3148	1429
141-160	2	155	4104	1418

Improvement Matrix: PV Penetration Boost

Given that there are –in average– five feeders in each of the studied networks, there are ten potential pairs of feeders per network. The challenge here, however, is to assess the benefits that each potential connection can bring to a feeder prone to technical problems at certain PV penetrations. Moreover, for practical purposes, this assessment has to be done in a straightforward manner.

To quantify the improvement from meshing a pair of feeders, the hosting capability of each feeder is first calculated by taking the average value of 100 simulations for a given PV penetration level. When this average value is at least one customer, the hosting capability is then considered to have reached its maximum. The hosting capability representing the pair of radial feeders is that of the feeders with the lowest value. For the meshed case, a similar approach is considered. Finally, the improvement is calculated by subtracting the hosting capability of the meshed case by that of the radial case. An example of the PV penetration improvement is presented in Table II. In radial operation, Feeder 1 has a limit of 40% of PV penetration while for Feeder 2 is 90%. Thus, the hosting capability representing the pair is 40%. For the meshed case, the hosting capability is 60%. Therefore, the maximum PV penetration improvement is 20% (i.e., 60% minus 40%).

The 52 different meshed operations to be studied are first classified based on the customer number ranges (as shown in Table I). The combination of the different ranges (types of feeders based on number of customers) creates an 8x8 symmetrical matrix. By populating each combination of ranges with the average maximum PV penetration improvement for the corresponding meshed cases, the *Improvement Matrix* is created. The populated *Improvement Matrix* is presented in Fig. 5. Note that diagonal entry for the 141-160 range is white since there is no pair of feeders for this case.

Table II - Max PV penetration in radial and Meshed Cases

Feeder	Radial Operation	Meshed Operation
1	40	60
2	90	

It can be seen from Fig. 5 that the (absolute) maximum PV penetration improvement that can be achieved from meshing different types of feeders varies from 0 to around 40%. One cluster with the least benefits is found when pairing feeders with less the 60 customers. This is, however, not an issue given that radial feeders with less than 60 customers show in most scenarios no voltage problems (particularly for less than 40). For feeders with more than 60 customers, the advantages vary according to the customer number of the pairing feeder.

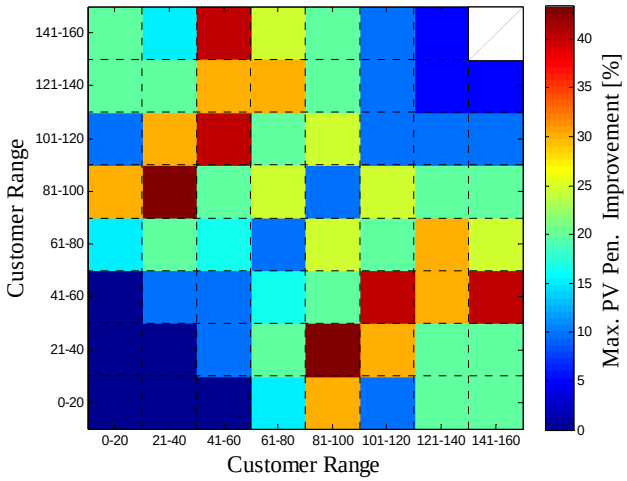

Fig. 5 Maximum PV penetration improvement from meshed operation

Pairs of similar feeders in terms of customer number (i.e., diagonal in the *Improvement Matrix*) have a low absolute improvement of maximum PV penetration (approximately 5%). The same effect is found when meshing feeders with more than 100 customers. This is explained by the fact that in highly loaded feeders voltage problems appear at low penetration levels. The corresponding meshing is therefore not able to significantly improve the PV penetration given that both feeders reach their bottleneck relatively soon.

The most striking observation that emerges from Fig. 5 is that, if the customer number of a given feeder is almost as twice as that of the connected feeder, the hosting capability of the corresponding mesh is significantly increased. For instance, in Fig. 5, feeders with customer number between 101 and 120 result in a large improvement when meshing with feeders in the 41 to 60 range. This can be explained by the fact that dissimilar feeders (in terms of customer number) have also dissimilar PV hosting capabilities when radially operated. Therefore, the higher ability of one of the feeders to host PV provides an overall boost to the meshed operation of the corresponding pair of feeders.

The values presented in the *Improvement Matrix* as well as the 2:1 customer number relationship found for the most beneficial meshing are practical and therefore implementable by DNOs as decision making tools when adopting meshing. However, it is important to highlight that these results cannot necessarily be generalised as they are, currently, limited to the number of cases analysed and types of circuits (residential, underground three-phase networks with single-phase connected loads), as well as to the sun irradiance and demand nature of the UK.

CONCLUSIONS

In this work, in order to minimise the undesired effects from PV systems (e.g., voltage rise and thermal overloads) and increase the hosting capability of the networks, the meshed operation of LV feeders is studied as a possible solution. For this purpose, 15 real, residential, underground UK LV networks are analysed using a Monte Carlo–based approach. The effectiveness of meshing is quantified comparing radial and meshed operation in terms of the maximum PV penetration capability considering one–minute resolution daily load and generation profiles.

The initial analysis of impacts for both radial and meshed cases (52 in total) allowed identifying the number of customers per feeder (or corresponding pair) as the most accurate and practical to adequately correlate PV penetration and the potential technical problems. This parameter was then used to produce an *Improvement Matrix* considering different ranges of customer numbers and the absolute increase in PV penetration brought by the corresponding meshing.

It was found that the benefits, in terms of PV hosting capabilities, from meshing radial feeders varies significantly (from 0 to over 40%) according to the corresponding number of customers. The most interesting finding, however, is that the most beneficial meshing is that where the pair of feeders has a 2:1 proportion in the number of customers. In addition, meshing similar feeders in terms of customer number gives the lowest improvements.

The above three key findings, i.e., customer number as a practical and accurate parameter, the *Improvement Matrix*, and the 2:1 relationship for the best meshing selection, can be used by DNOs to create practical and implementable rules for the selection of feeders to be meshed and hence help accelerating the adoption of low carbon technologies.

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