STRATEGIC INVESTMENT IN DISTRIBUTION NETWORKS WITH HIGH PENETRATION OF SMALL-SCALE DISTRIBUTED ENERGY RESOURCES

Nuno SILVA
Imperial College London – United Kingdom
n.silva@imperial.ac.uk

Goran STRBAC
Imperial College London – United Kingdom
g.strbac@imperial.ac.uk

ABSTRACT

In contrast with traditional approaches to optimal network design based either on the analysis of a small specific area or on idealistic networks, the proposed method determines optimal network design policies by evaluating alternative strategies on many statistically similar networks. The software is then a statistical assessment of a number of hypothetical but realistic networks (consumers distributions, types, numbers, network length, components, number of substations, etc), created using the concepts of fractal theory. Evaluating the cost of each particular design over a number of statistically similar networks allows statistically significant conclusions to be drawn.
Modelling each load individually will reveal problematic operating conditions which were not considered when using a smooth load profile. Thus, each and every domestic load was represented by a different load profile and the impact on losses was evaluated.
The software tool also allows the simulation of penetration of micro generation such as CHP and PV in the realistic distribution networks to determine the effect of DG in the LV system.

INTRODUCTION

In the last decade the EU has been developing significant amounts of Distributed Generation (DG) of various technologies in response to the climate change challenge and the need to enhance fuel diversity. It is expected that the amount of DER in distribution networks increases even more in the near future. Keeping this in mind and knowing that after the massive network development on the late 50s and early 60s, the assets useful life is coming now to an end, it is now a golden opportunity to replace the network components preparing for the future and developing cost effective, secure and optimal design strategies [1].
The impact of micro-generation on networks has not been a significant issue to date. There have not been clustering problems in existing networks as a result of customers choosing to install micro-generators, either as a new device or as a replacement (for example, of a previous heating system). Depending on the assumptions made, a range of projections have indicated the amount of micro-generation installations possibly reaching as high as 21GW by 2050[2]. In the future, local authorities may require developers to install smaller generators on new buildings as a requirement of obtaining planning consent. Where there are new housing developments that contain micro-generation, the network will specifically be designed to cater for the technical issues. However, a scenario that could create a real challenge is where there is a high penetration of domestic Combined Heat and Power (CHP) on existing networks that are not designed for bi-directional power flow. This might arise if domestic CHP became the dominant choice, through either scheme economics (as prices fall and the value of energy generated rises) or mandated standards (e.g. changes to building regulations).
The operation of micro-generation connected to the low voltage (LV) network can cause statutory voltage limits, recommended voltage unbalance levels and switchgear fault ratings to be exceeded. However, the level at which this happens will depend upon the generator and network characteristics [3]. There are a range of distribution network designs and operating practices and thus the impact will vary accordingly. In this paper, the software tool can create different types of realistic networks to study this impact.
The effect of micro-generation on network losses is another aspect of DG integration that requires due consideration. For a traditional distribution network, power normally flows from the grid supply point down through the voltage levels. Injection of power from DG changes the pattern of power flow and therefore the energy losses during the transportation of electrical energy. The relationship between DG and network losses is quite complex and dependent on location of connection, its operation/export profile, the type of network and the interaction between demand and generation. A DG connection could either decrease or increase losses [3].

NETWORK CREATION AND OPTIMIZATION

In contrast with traditional approaches to optimal network design which are based either on the analysis of a small specific area or on idealistic networks, the proposed methodology determines optimal network design by evaluating alternative strategies on many statistically similar networks [4]. The position of consumers influences the amount of equipment used to serve them. Therefore, simple geometric models or randomly placed points used in previous researches are not adequate. Realistic consumer sets are generated in terms of their position, distribution of consumer types and demand.
A number of realistic consumer layouts are created with specific characteristics of actual cities and rural areas in terms of consumer distributions, types, numbers and load density. This settlement mimics the human behaviour following some economic laws which lead to distributions

of fractional dimension (fractal theory) [4]. The consumers are then connected with a portion of straight lines. The branching rate (quotient of the number of T-junctions and total number of nodes of the generated network) depends on the algorithm that determines the next consumer to be connected to the existing network. This way, it is possible to control the branching rate of the generated networks.
The position of the distribution substations are chosen to be at local centres of high load density. The supply zone of each substation will depend on the total number of substations of the network. Fewer substations will supply a larger region size. The number of substations is an input parameter; keeping all other parameters constant, the effect of using different number of substations on losses can be investigated and an optimal number can be found.
Using simple single/phase load flow calculations, both voltages and currents are determined and normally open points can be found (where minimum voltage is registered). The entirely meshed network is then divided into a number of radial networks (depending on the number of substations) representing the operation of typical LV networks.
The load flow calculations were performed for every hour over a year following typical daily load profiles for eight types of customers. These types of load will be distributed among the consumers layout and represent the different types of domestic, commercial and industrial consumers.
Depending on the type of the network, the number of consumers assigned to each type of load will be different.

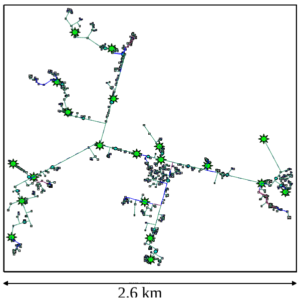

Fig 1 - Example of a rural network with 0.2MVA/km^2 of load density and 3 sunstations/km^2

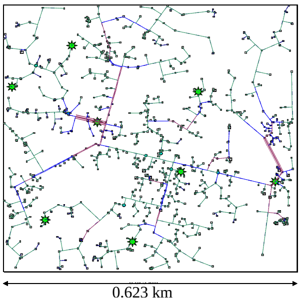

Fig 2 - Example of a urban network with 5MVA/km^2 of load density and 20 sunstations/km^2

After the yearly calculations together with the price of electric energy, the cost of system losses (cables losses, transformer iron losses and load losses) is calculated. The network's components are then optimised based on the minimum life-cycle cost methodology. This method balances the annualised capital investments and maintenance costs against the cost of system operation (losses in this case). Optimal cable and transformer sizes throughout the network are determined. At the end, the limits of the voltage at the entry point of the premises of each consumer should meet the statutory requirements [6].

DOMESTIC LOAD MODELING

Losses on distribution networks are a very important issue and there has always been an attempt to reduce them in order to minimize operational costs. In this paper, losses are calculated according to the topology of the network, cables length, load type, power factor, transformer sizes and types and load imbalance.
The way load is modeled will impact studies about losses [8]. Therefore, a particular focus on this matter was taken into account and different scenarios were studied.
The operation of distribution networks is approached considering the existence of single and three-phase loads and micro-generation. This would however cause the network to be unbalanced and hence, traditional methods that consider a three-phase balanced system would provide misleading results.
Individual customers of the same type use electricity in different ways and at different times. Residential demand also depends on the house occupancy and their economic activity, natural seasonal cycle of day length and ambient temperature. Hence, domestic load has a stochastic nature.
In previous studies, depending on the type, consumers were assumed to have an identical load at a given time and smooth 24-hour load curves were used to represent the average behavior of each customer in each class. However, a single residential customer has a load curve not so smooth and with bigger oscillations.
Load was considered to be single or three-phase depending on the size of the consumer. Domestic consumers were considered to have single-phase connection and their load profile was created individually for each and every customer. Therefore, a comparison between using the same load profile (smooth load profile seen by the GSP) and modeling each consumer's load profile (representing the peaks due to appliances connection) was carried out.
The diversified load profile is constituted by 9 characteristic days so that seasonal behavior is represented as well as the differences between weekdays, Saturday and Sunday. These are smooth curves created when a large number of consumers is averaged, i.e., this is the load profile of the consumers from the GSP point of view as shown in Fig 3.

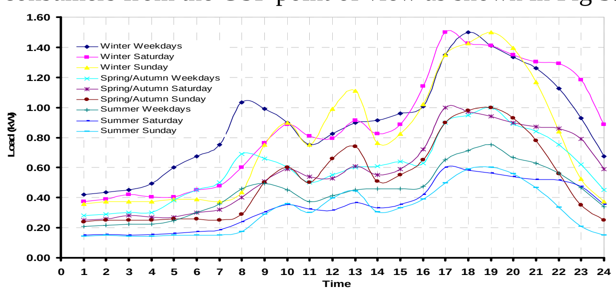

Fig 3 - Nine characteristic days load profile

Due to be quadratic relationship between losses and power flow, the use of undiversified load might be significant in the calculation of losses, where the presence of "needle peaks" is expected to lead to higher losses than the case where the smooth diversified load profile was used. This can only be verified when we have a small number of consumers since as the number of consumers grows, the gathering of individual load profiles will start resembling more like the smooth profile seen from the GSP.

Every residential daily load's behaviour shows rapid shifts from "load valleys" to high peaks due to the random and frequent "switch on/off" of appliances (central heating, water heaters, microwaves, lights, air-conditioning, refrigerator, etc). Using the diversified load profile as base model, load peaks and valleys were created according to a probability density function so that bigger load oscillations are less likely to happen but tend to occur during hours when the base load is higher. Figure 4 shows the load profile for an individual consumer modeled for 5 minutes. In non-diversified load model, spikes can go up to 8kW whereas in the smooth profile the maximum load is 1.4kW. To ensure that annual energy is the same, daily energy needs to be always equal in both load models. The profile with 30 minute time resolution is derived by averaging the 5 minutes profile. When performing the simulations, this profile was used since it would still represent load peaks while drastically reducing computing time.

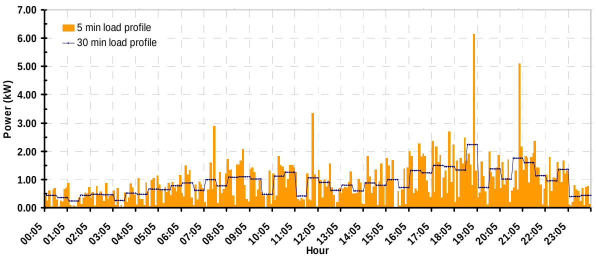

Fig 4 - Individual non-diversified load profile

Over the optimized network, a three-phase load flow was implemented in order to analyse single-phase loads in the system and all the inherent effects such as load diversity (single-phase domestic consumers) and load imbalance. Half-hourly load flow analysis throughout a year was performed and line and transformer calculated.

Impact of load diversity and number of substations

In order to assess the losses issue on distribution networks, several case studies were performed on realistic LV networks. Simulations have been carried out on 0.4kV networks supplied from 11/0.4kV substations.

Figure 5 and 6 show the annual losses as a percentage of the total annual energy. Both urban and rural cases are considered with different number of substations per km^2.

It is possible to notice that annual losses in rural networks are much higher than in the urban case. Also, the losses decrease exponentially with the increase of the number of substations. In fact, the more substations supplying the network, the shorter the length of the cables will be. Moreover, the number of consumers supplied by the same substations will be fewer and the current of the cable will be smaller causing the losses to decrease.

As expected, for high load densities (urban case) with a high number of substations, losses are relatively low (less than 2.4%) due to small and very densely populated areas supplied by a small number of transformers and short and large cross-section cables. This means that there will be more consumers supplied by the same substation which will lead to an increase in the size of the transformer used. Having the cost of all the network components, the cost of installation and maintenance as well as the cost of yearly losses, the total cost per year can be calculated and the optimal number of substations can be found.

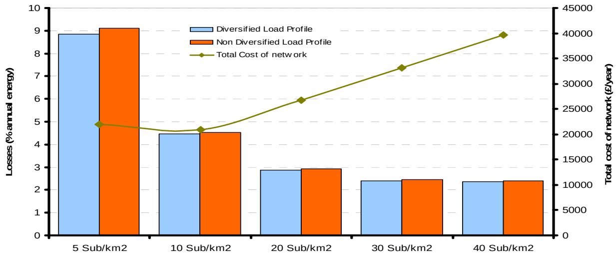

Fig 5 - Annual losses and total cost per year of urban network with 5MVA/km^2 as a function of the number of substations using diversified and non-diversified load profiles

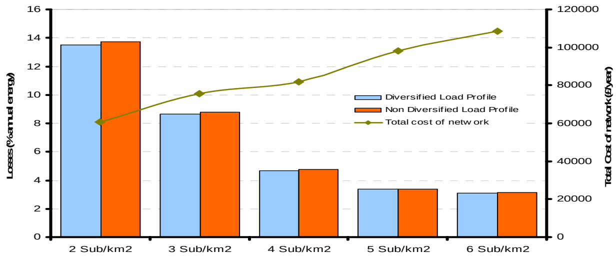

Fig 6 - Annual losses and total cost per year of rural network with 0.2MVA/km^2 as a function of the number of substations using diversified and non-diversified load profiles

Comparing the scenarios using diversified load profiles with the case where we use individual load profiles (non-diversity), the losses are always bigger in the second case. As explained before, the needle peaks which are present when modeling each individual customer are responsible for that increase since they influence the quadratic relationship between losses and power flow. Given that a big sample of users was used, the difference in the value of annual losses is not too large but when considering relatively small networks, the difference can be significant.

IMPACT OF DG IN THE LV NETWORK

Using the optimized rural and urban networks, the impact of penetration of DG can be assessed. For the present case study, domestic CHP was used with the capacity of 1.1kW for domestic dwellings and bigger or more units for commercial and industrial customers.

The connection to a distribution network of any load or generation will influence the currents and voltages within that network. Voltage is required to be within specified statutory limits and the currents flowing through the network must not cause the voltage to be outside those limits restricting the maximum current flow. Similarly, components such as cables, transformers and protective fuses must be operated within thermal limits. The voltage regulation limit will usually be reached before the thermal limit of a line or cable. Therefore, when assessing the impact of small scale generation, voltages and currents must be known and so appropriate load flow calculations are required. Having implemented a three-phase load flow, it is possible to consider single-phase loads as well as single-phase generators. This is of vital importance since in LV networks, single-phase systems are the most common and almost all micro-generators are of single-phase connection. Penetration level is defined as the percentage of dwellings (domestic, commercial and industrial) with one or more generators connected.

Loads and micro-generators connected close to substations are less likely to perturb voltage than those located at the end of the feeder where impedance is the greatest.

Results for networks with micro CHP penetration

Using the previous optimized networks, different studies were performed for urban and rural types of networks. These had typical values for load density of 5MVA/km^2 and 0.2MVA/km^2 respectively and different scenarios were considered for the number of substations supplying the load. It is possible to see the decrease on losses with the increase in the penetration of DG.

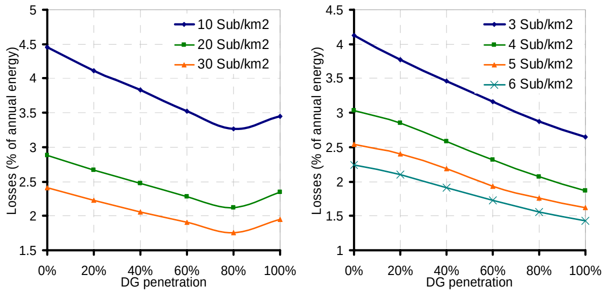

Fig 7 - Value of losses for the urban (left) and rural (right) area for different substations number and DG scenarios

Although in the rural case losses decrease for all scenarios of penetration, in the urban case the minimum is reached when having 80% of customers with installed CHP. Since in urban areas there are more industrial consumers who will have bigger generation capacity distributed among fewer substations, when high penetration of DG happens, the net export increases causing reverse power flow. Given that in previously used models, cables/lines were designed for a very low utilization, the main concern is whether transformers could be overloaded by export of energy from the network. This was not the case due to the fact that CHP generation profile was modeled following the consumer's consumption (thermal needs mach the time of electrical peaks). Although load profile is different for each domestic consumer, generation profile is considered to be the same changing only according to the type/size of the customer.

Concerning the voltage limits, although there is a voltage rise (both in minimum and maximum values), the statutory limits are always respected.

CONCLUSIONS

A software tool was created to allow evaluation of alternative distribution systems planning strategies for LV networks. It allows statistical evaluation of the cost of different design policies using many similar realistic consumer settlements and networks. Using an algorithm based on fractal theory, the position of consumers can be modeled in a realistic way and the network path connecting them can be controlled creating typical urban and rural networks.

Optimum design of the networks was determined minimizing annual costs of equipment, its installation, maintenance and losses, while meeting all the technical and statutory constrains.

Results match current practice where urban networks are served by fewer substations with high capacity transformers and cables with large cross-sections. The main constrain in rural areas is voltage drop and so, more and smaller transformers should serve a large sparsely populated area.

In order to accurately simulate the impact of DG in LV networks, three-phase software was implemented to deal with single-phase loads and generation and unbalances created. Also, as domestic loads are the majority of the loads in LV systems, each consumer was modeled individually to represent a non-diversified load profile. This has an impact on losses comparing with the simulations using the diverse smooth load profiles.

The overall conclusion is that to accommodate micro generation penetration, no additional capital investment is required in LV networks. The need for reinforcement of the network components will depend on the level of generation and on the extent to which reverse power flows happens. In most parts of the network, micro-generation exports will not be sufficient to result in any need for network investment.

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