OPTIMAL DESIGN POLICY AND STRATEGIC INVESTMENT IN DISTRIBUTION NETWORKS WITH DISTRIBUTED GENERATION

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ABSTRACT

The operation of microgeneration connected to the distribution network can cause statutory voltage limits, recommended voltage unbalance levels and switchgear fault ratings to be exceeded. However, there are a range of distribution network designs and operating practices and thus the impact will vary accordingly.

Relating losses, voltages, currents and load unbalanced ratio leads to conclusions about the way to operate an existing network or optimise a new one with small-scale distributed generation. The aim was to investigate and develop methodology for evaluation of the long-term loss-inclusive optimal network design strategies and to determine the effect of the penetration of microgeneration such as CHP and PV in realistic distribution networks.

The overall conclusion is that to accommodate microgeneration penetration into existing networks, no major capital investment is required. 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, microgeneration exports will not be sufficient to result in any need for network investment.

However, if the network was to be planned accounting with DG, the optimal design policy adopted for distribution networks would change when compared to networks with no microgeneration.

INTRODUCTION

Up to now, electrical distribution networks have been designed and operated based on the assumption that the current always flows from the substations to the final customers on HV and LV networks, without ever going the other way. On the other hand, recent technical developments and deep changes in the electricity industry are expected to favour the fast spreading of Distributed Generation (DG).

The integration of DG into the distribution network presents challenges, as the UK's low voltage network was neither designed nor built for the integration of distributed generation. The operation of microgeneration 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 [1]. There have not been clustering problems in existing networks as a result of customers choosing to install microgenerators, either as a new device or as a replacement (for example, of a previous heating system). There are very few real tests of the impact of large scale penetration of DG units on distribution networks. Demonstrations of geographic clusters of microgenerators have tended to be on new-build housing, and therefore with new electricity networks, thus giving little indication of likely effects if similar penetrations were to be installed within existing networks.

Since there is a range of distribution network designs and operating procedures across Britain, each DNO will need to examine its own network to understand when network reinforcements or modifications to operating procedures will be necessary. Furthermore, previous studies in the UK have tended to use simplistic models of both networks and loads [2-3]. The flexibility of the presented tool allows the study of the impact of microgeneration on generic network and, hence, it is possible to model any type of network as the user wants. This will permit that statistical conclusions can be taken about the operation and optimisation of the network. Moreover, these conclusions can be applied by each network operator to their characteristic networks, being either rural or urban systems.

NETWORK CREATION AND OPTIMIZATION

In order to study the impact of microgeneration on distribution networks, typical urban and rural systems were generated by the developed software. Contrasting 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. 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].

An urban network was created as a base case with 5MVA/km^2 of load density supplied by different scenarios of number of substations in order to assess the impact of DG on losses, voltage and loading of conductors depending on the number of substations. The same approach is used for rural systems, which have load density of 0.2MVA/km^2. The load flow calculations were performed for every half-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.

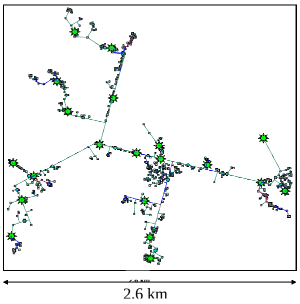

Fig 1 - Example of a rural network with 0.2MVA/km^2 of load density and 3 substations/km^2

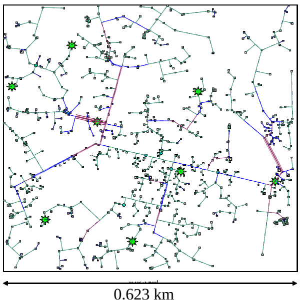

Fig 2 - Example of a urban network with 5MVA/km^2 of load density and 20 substations/km^2

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 optimized based on the minimum life-cycle cost methodology. This method balances the annuatized 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.

LOAD AND GENERATION 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 type, load imbalance and DG penetration.

The way load is modelled can impact studies about losses [4]. 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 microgeneration. This would however cause the network to be unbalanced and hence, traditional methods that consider a three-phase balanced system would provide misleading results. 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 most common and the majority of microgenerators are of single-phase connection.

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 and was modelled for each domestic customer [4].

Penetration level is defined as the percentage of dwellings (domestic, commercial and industrial) with one or more generators connected capable of exporting energy (excess of energy not consumed by the local load) to the grid. All generators are assumed to be operating at a unit power factor or to have their power factor corrected to unit.

Domestic scale micro CHP systems are driven by the heat demand of a dwelling and were considered to have 1.1kWe capacity. Their after-diversity generation profile is show in Fig. 3 for a domestic and commercial customer.

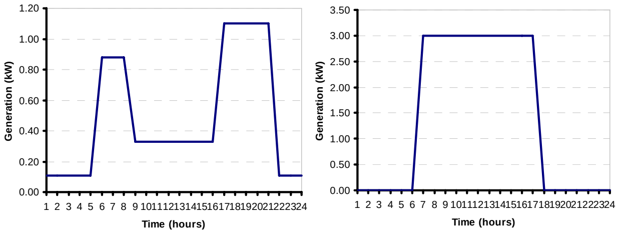

Fig 3 – Micro CHP generation profile for domestic consumer (left) and commercial consumer (right)

Simulations were held for different percentages of consumers with an installed micro CHP unit in their premises for different seasons throughout the year.

The different types of generation profiles, varying its peak and shape, need to reflect the impact of diversity, recognising different living patterns in households, as well as commercial users and also industrial installations. The after diversity generation profiles for the three different seasons of the year considered for a maximum PV generator output of 1kW [5] and are illustrated in Fig 4.

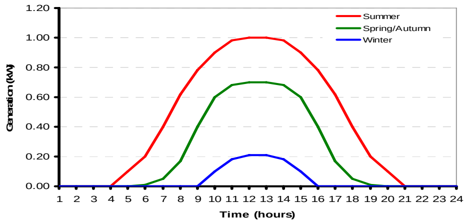

Fig 4 – Micro CHP generation profile for domestic consumer (left) and commercial consumer (right)

EFFECTS OF DG IN EXISTING NETWORKS

Losses - Fig. 5 shows the impact of increasing penetration of micro CHP on overall network losses. It is possible to see the decrease on losses with the increase in the penetration. 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 generating units. 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 generation exceeds minimum loads 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. However, in the present study, there are no circumstances to register the occurrence of reverse power flow through distribution transformers reaching or exceeding their ratings.

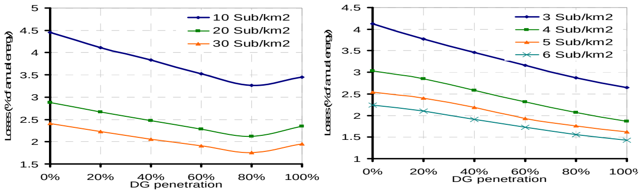

Fig 5 - Value of losses for the urban (left) and rural area (right) for different substations number and CHP scenarios

For PV technology, both in the urban and rural cases, losses decrease for all scenarios of penetration as Fig 6 illustrates. Also there are no circumstances to register the occurrence of reverse power flow through distribution transformers reaching or exceeding their ratings.

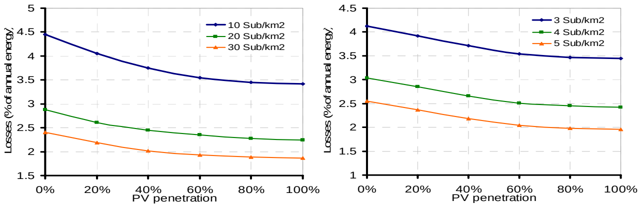

Fig 6 - Value of losses for the urban (left) and rural area (right) for different substations number and PV scenarios

Even when installed in all premises, the average capacity of each microgenerator is less than the after-diversity maximum demand which was the basis for the selection of the transformer rating.

PV arrays generate their greatest output during daylight hours when the domestic load is lower and does not contribute at all in the evening when losses are high. Its impact is somehow less than micro CHP technology.

Voltage - DNOs have the obligation to supply their customers at all points in the network at a voltage within specified limits. In UK, voltage levels are requested to be within +10% and -6% of the default voltage. LV feeders have to be designed in such a way so as to provide even the most remote consumers with acceptable voltage levels at both maximum and minimum loads.

On the several studies held it was possible to verify that, although there is a voltage rise (both in minimum and maximum values), the statutory limits are always respected. In all cases for both urban and rural networks, the variation of value of voltage is kept within limits of 16%. This means that the voltage for all the customers in these cases could be maintained within current limits of +10%/-6% on 230V., although this would eventually require that mean voltage levels would need to be controlled by primary substation automatic voltage control set points or tap changers on distribution transformers.

In Fig7 the daily voltage profile for a balanced urban and rural network is shown for the situations when there is no penetration of microgenerators and for 50% and 100% of customers having micro CHP installed on their premises.

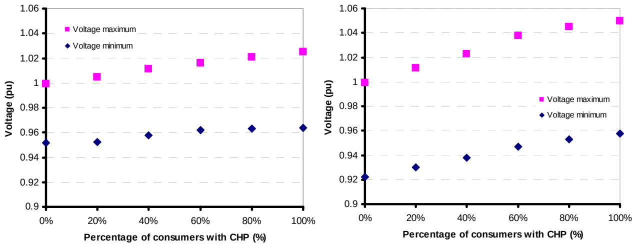

Fig 7 - Voltage daily profile for urban (left) and rural (right) networks with balanced load and different CHP penetration scenarios

The voltage rise effect is especially noticeable when the CHP unit kicks off at 6am and in the evening. There is a raise on voltage peaks and average with the increase in penetration. For urban areas, voltage average is augmented about 2% when 100% penetration threshold is achieved. Also, during the morning period, the voltage rises over 1.02pu which means there is an export onto the network and reverse power flow occurs through the distribution transformer. However, all voltage regulatory constrains are kept within a considerable margin.

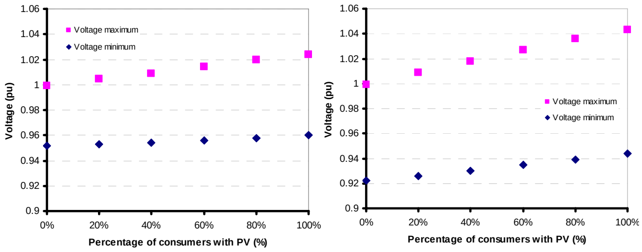

Fig 8 - Voltage daily profile for urban (left) and rural (right) networks with balanced load and different PV penetration scenarios

In rural networks, when penetration level increases, the average voltage rises about 3% although even in the morning peak generation, the voltage does not go over 1.05pu, i.e., it stays within the voltage statutory limits. Also, the maximum amplitude is lower than the total 16% permitted and so no reinforcements are predicted for these conditions.

Fault level - Engineering Recommendation P25/1 and P26 requires prospective single- phase short circuit level to be limited to 16kA and three-phase to 25kA at the point of connection of the service cable. For high load density regions, such as urban areas, many premises are supplied from a single distribution substation representing the critical scenario. Even considering 100% penetration of dCHP, the fault level was checked and no problems were registered.

Fault levels have not been a problem because all the PV systems are equipped with power electronic interfaces.

EFFECTS OF DG IN OPTIMAL NETWORK DESIGN

The traditional approach of selecting network design is through minimising life-cycle costs of ownership and operation of the network. Life-cycle costs are composed of cost of investment and cost of losses. A minimum life-cycle cost methodology that balances the capital investment against the cost of the system losses is used as a basis for circuit design. This approach requires the evaluation of circuit annual losses and their costs for various network design options. Corresponding annuitised investment costs are then associated with these options, which enables a total life-cycle cost to be evaluated. Finally, a solution with the minimum life-cycle cost is then selected provided that the thermal and voltage constraints are satisfied.
Fig 9 illustrates the losses performance and total network costs for an urban network with different substation/km^2.

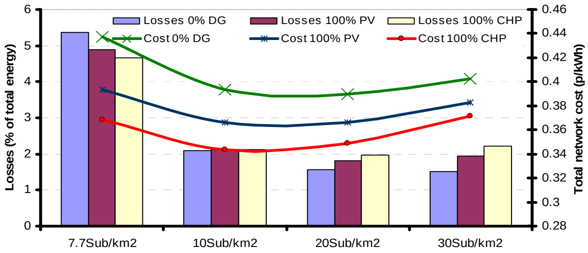

Fig 9 – Value of losses and total network costs for an urban network with different substations number and including DG

The network was planned considering scenarios without DG and including PV and micro CHP. It is possible to notice that the network costs decrease with the presence of DG. Furthermore, CHP is the technology that most favour the network representing the minor investment cost. Moreover, although urban network design is very robust, when considering all dwelling to have installed micro CHP, the optimal substation number changes leading to a lower cost.

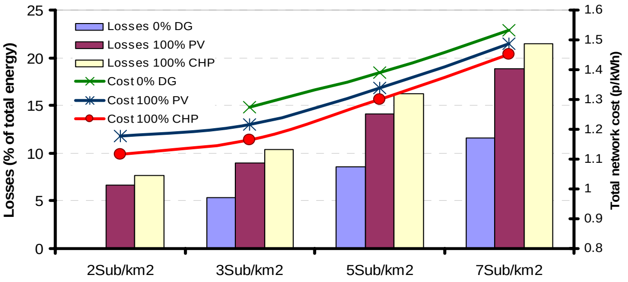

Fig 10 - Value of losses and total network costs for a rural network with different substations number and including DG

In rural networks, differences tend to be bigger. Since rural network design is driven by voltage limits, the minimum cost is achieved with the minimum number of substations that fulfils voltage constrains. However, when considering no microgeneration, the minimum is achieved with 3subs/km^2. When planning the network considering either PV or CHP, the voltage drops are smoothened and optimum number of substation is reduced. As a consequence, the overall investment costs are considerably lower, resulting in a reduction of about 15%.

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.
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.
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 creating unbalances.
The overall conclusion is that to accommodate microgeneration penetration into existing networks, 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, microgeneration exports will not be sufficient to result in any need for network investment and a setting distribution transformers taps would be sufficient.
However, considering DG when planning distribution network can change optimal design policy, In fact, it was shown that network costs would decrease and particularly micro CHP would have positive effects since it matches load profile more closely.

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