DISTRIBUTED GENERATION AND SMART GRID DEVELOPMENT: CASE STUDIES IN DIFFERENT EUROPEAN COUNTRIES

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ABSTRACT

This paper presents modelling approaches and results relevant to smart distribution system development with DG in European grids as from the work performed by Imperial College in the EC FP6 "More Microgrids" project. The studies are based on real data and DG/consumption scenarios of distribution networks as provided by project partners from different European countries. Comparison among the different networks enables to get strategic information on common trends and differences. In addition, being based on real network data, the results provide an invaluable opportunity to gain insights on impact, benefits and main drivers of DG and Smart Grids on real large-scale networks, differently from most studies based on small test or ideal networks.

INTRODUCTION

The spread of distributed generation (DG) connected across the distribution network, even at the low voltage (LV) level, has substantial implications for power flow patterns and more generally for network operation and development. Reverse flows may be expected , caused by uncontrolled generation producing more output than the one that can be consumed by local demand. For relatively small DG penetration levels, mainly network benefits such as losses reduction, voltage support, and investment deferral [1][2] are likely to arise, which top up benefits such as emission reduction - for instance due to utilization of distributed cogeneration close to the final heat users [3]. However, with increasing bi-directional flows it will be more and more difficult for the distribution network operator to maintain a passive operation approach (considering for instance DG as negative load) without investing heavily in network reinforcement. In this respect, Smart Grid solutions with coordinated control of distributed energy resources can support the most cost effective solutions for distribution network development in the presence of DG. In particular, *Active Management* (AM) [4] will become a key approach to enable integration of local generation and higher network utilisation without resorting to network reinforcements. On the other hand, smart integration of DG in distribution networks can be seen as a promising alternative to classical asset based solutions (network reinforcement) to accommodate load growth, besides providing invaluable environmental benefits.

Within this framework, this paper presents modelling approaches and results relevant to smart distribution system development with DG in European grids. More specifically, the material presented here sums up the work performed by Imperial College in the EC FP6 "More Microgrids" project [5]. The studies are based on real data and DG/consumption scenarios of distribution networks as provided by project partners from different European countries, namely, FYROM, Germany, Netherlands, Poland, and UK. Given the large variety of characteristics, comparison among the different networks enables to strategically highlight common trends and differences. In addition, being based on real network data, the analyses and the results provide an opportunity to gain insights in understanding the impact, benefits and main drivers of DG and Smart Grids on real large-scale networks, differently from most studies that are based on small test networks or ideal cases.

MODELLING ASPECTS AND STUDIES

The studies have been performed through the so called Generic Distribution System (GDS) model developed by Imperial College [5] that allows the representation of typical European multi-voltage distribution networks designed in top-down hierarchical structure. By analyzing multiple voltage levels, impacts and benefits of DG can be comprehensively studied on a system level. In addition, utilization of hourly generation/load patterns and power flows across an annual time span allow deeper understanding of the relevant drivers. A representation of a typical GDS model for the UK is shown in Figure 1.

The main focus of the analysis has been on identifying the most cost effective strategies for network evolution, taking into account potential reinforcement required to accommodate DG (due to voltage, thermal or fault level issues), as well as potential benefits coming from load growth support. Different strategies for AM at different voltage levels have also been considered, namely, *coordinated control of on-load tap changers*, *reactive power control*, and *generation curtailment* where needed. In particular, AM strategies have been compared to a classical *fit & forget* (*passive management* - PM) approach, so as to highlight the need and benefits of controllability both in Microgrids and at higher voltage levels, within a full Smart Grid framework. The studies have been based on a Cost Benefit Analysis approach, whereby benefits have been evaluated against additional operational costs (namely, losses) and the cost of infrastructure required for implementation of intelligent

control (communication infrastructure, automation, etc).
The studies have been divided into two groups according to the scenarios examined and the methodology undertaken for network development evaluation.

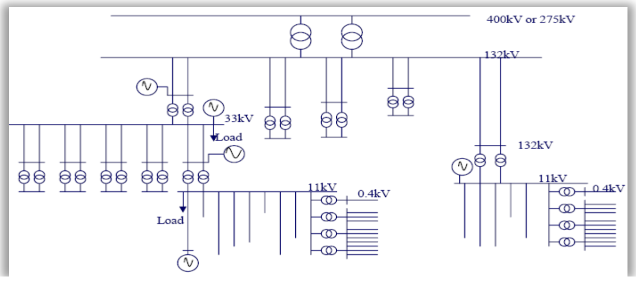

Figure 1. Schematic example of GDS network model (UK).

Studies based on partners' DG scenarios

A first stream of analyses has been based on the data provided by project partners regarding the envisaged demand and DG penetration at all voltage levels in future temporal snapshots. In this case, a *dynamic assessment* for network development has been carried out by taking optimal decisions on network investment including selection of optimal AM strategies at different milestone times. Since the data concerning DG penetration evolution were typically given for four future snapshots t_0, t_1, t_2, and t_3 until 2030, it has been assumed that connection of new DG and network reinforcement will only take place in these snapshots (and consequently GDS simulations have been run only for these snapshots). This allows both to simplify the analysis and to avoid uncertain assumptions relevant to intermediate years.
In each snapshot, GDS simulations have been run for two cases, namely, i) *base case*, where no DG is connected and problems are in case solved by network reinforcement; and ii) *test cases*, with the DG foreseen for this snapshot and all the possible reinforcement strategies (PM, AM without tap changers, AM with tap changers) are compared based on their overall cost.
The comparison among the different strategies and the decision about the optimal strategy to undertake are made in each snapshot taking into account the total network cost (reinforcement cost and cost of losses) in the next time window. However, the reinforcement cost (*RC*) refers to the total life cycle of the installed equipment (assumed equal to 20 years in this work), while snapshot decisions only refer to the time window between two consecutive snapshots. Therefore, the (present value of the) *residual value* (*RV*) of the assets at the end of the time window (when the successive scenario and decision snapshot occurs) is subtracted from the *RC* so as to allow a level playing field cost comparison among the relevant strategies involved. For example (Figure 2), the cost of reinforcing the network in the time window t_0 to t_1 is equal to the present value (*PV*) of the reinforcement cost incurred in t_0 minus the present value of *RV* of this investment in t_1. It has been assumed that the residual value of the assets only depends, in a linear fashion, on the number of years they have been used and that the asset cost increases with an annual inflation rate of 3%.
Likewise, the cost of losses for every considered time window is brought to the same playing field by calculating the *PV* of the annual cost of losses for each of the years in the time window. In particular, again with reference to Figure 2, the cost of losses in the time window $t_0 \div t_1$ is equal to the sum of the *PV* of the cost of losses in t_0 and each of the intermediate years between t_0 and t_1. Yearly losses have been estimated through interpolation based on the load increase rate and with the price of energy increasing with the annual inflation rate.
Summing up all the involved cost entries, the *total network cost* (*NC*) in the window $t_0 \div t_1$ will then be:

$$NC_{t0-t1} = RC_{PV} - RV_{PV} + \sum CL_{PV}$$

where RC_{PV} is the *PV* of the reinforcement cost incurred in t_0, RV_{PV} the *PV* of the residual value of this reinforcement in t_1, and $\sum CL_{PV}$ the sum of the *PV*s of the cost of losses in all the years in the time window.

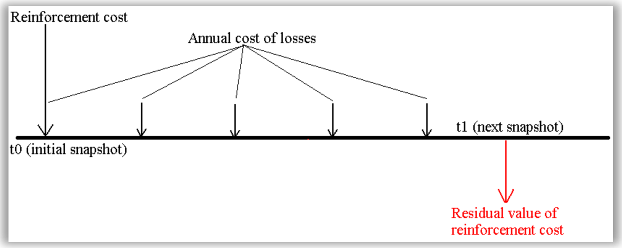

Figure 2. Economic model for total network cost calculation.

In the *test cases* (*with DG*), the reinforcement strategy that gives the lowest total network cost in the next time window is the one that will be selected. In the considered example, the strategy that gives the lowest network cost in $t_0 \div t_1$ will be selected for reinforcing the network in t_0 (*optimal reinforcement strategy* in t_0). This decision will affect the future structure of the network since this optimally reinforced network will constitute the input network for the GDS simulation for t_1, etc. A schematic flow of the methodology comparing the cases with and without DG is shown in Figure 3. Hence, by following this approach a *"dynamic" assessment* of the impact of DG and AM on network evolution and investment has been performed for the considered European countries.

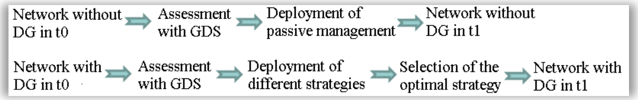

Figure 3. Dynamic distribution network evolution model.

Studies based on Microgrid scenarios

A second stream of analyses has been more focused on assessing the sensitivity of the impact of Microgrid parameters with *micro-DG only* (no DG at upper voltage levels) on distribution networks. The Microgrids considered here consist of a mix of Micro-CHP (Combined Heat and Power) and Micro-PV (Photovoltaic) systems, and has involved studies of the impacts of micro-DG and AM based on distribution networks in their current forms (*static assessment* referred to one given network only – no dynamic network evolution has been investigated in this case). The micro-DG country-specific shares considered are presented in Table 1. This analysis allows a straightforward quantification of the impact of Microgrids with AM with respect to the level of micro-DG penetration and demand at LV, with the aim of identifying the main drivers for costs and benefits. More specifically, the analysis performed has investigated three scenarios for micro-DG penetration (installed DG capacity at LV equal to 50%, 100% and 150% of current peak load at LV) and two scenarios for the load at LV (110% and 150% of current load at LV). In the rest of the voltage levels, the load has been considered fixed and equal to its current value, with no DG connected.

The aforementioned scenarios refer to individual network snapshots and consequently the model used in this part of the analysis is much simpler than the dynamic model presented above. In particular, the total network cost and reinforcement strategy for each scenario can be based on an equivalent annual assessment, by annuatizing the reinforcement cost as:

$$ARC = RC * \frac{d*(1+d)^N}{(1+d)^N-1}$$

where ARC is the annuatized reinforcement cost, d is the discount rate (assumed equal to 7%) and N is the recovery period of the capital investment for reinforcement (assumed equal to 20 years). Hence, the total network cost for the examined scenario is:

$$NC = ARC + ACL$$

where ACL is the annual cost of losses from GDS simulations. Based on NC, the optimal reinforcement strategy for all scenarios has then been identified.

Table 1. CHP and PV shares in the Microgrid scenarios.

	UK	*Germany*	*Netherlands*	*Poland*	*FYROM*
CHP	95%	60%	60%	60%	20%
PV	5%	40%	40%	40%	80%

MAIN FINDINGS

From the different types of analysis run, some key outcomes have been identified, as summarised below.

First of all, the contribution of micro-generation to decreasing upstream power flows leads to:

- substantial value (in terms of capacity release) in the Polish, FYROM, and UK networks, where reinforcement is demand-driven;
- zero value in the very strong Dutch network;
- negative value in the (also quite strong) German network, where the envisaged DG penetration is likely to create fault level problems.

In a similar manner, although the effect of DG on losses was beneficial in most cases, there are situations in the Dutch network where DG creates significant reverse power flows and therefore increases distribution losses.

For relatively weaker networks (Poland, FYROM, UK), in those cases where a part of the required reinforcement is related to voltage problems, the application of AM reduces significantly the reinforcement cost (in Figure 4 the case with PM is even negative since voltage rise due to DG calls for more intense network reinforcement relative to the case without DG), at the expense of higher losses in the network (Figure 5). This is due to the higher network exploitation enabled by AM, while in the PM case the feeders are upgraded and thus the losses decrease.

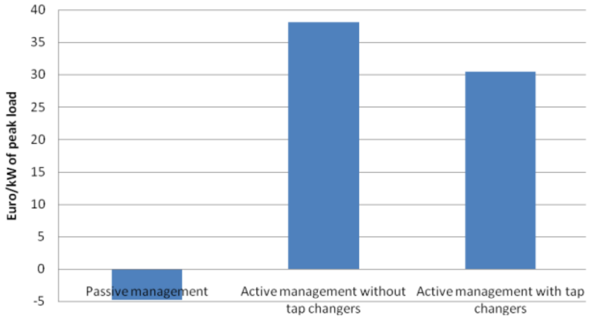

Figure 4. Example of reinforcement cost reduction owing to DG under different management strategies between two scenario snapshots (Poland).

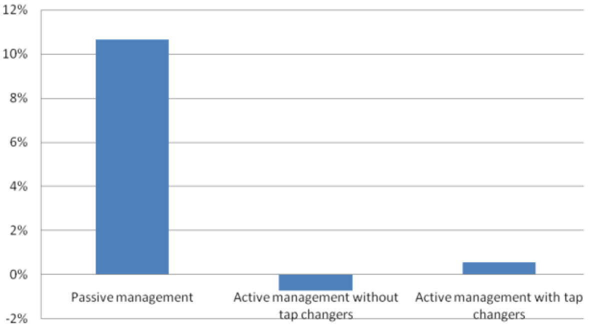

Figure 5. Example of losses reduction (% of base case) owing to DG under different management strategies between two scenario snapshots (Poland).

In every case that AM is deployed, its overall effect on the total network cost is positive, since the positive impact on reinforcement cost is much higher than costs of losses and implementation. The overall network cost can thus be computed as sum of reinforcement and losses costs, which can be used as a measure of the value of DG for network operators. This is for instance shown in Figure 6 for different levels of DG penetration and for a scenario characterized by low load, in correspondence of the optimal network management strategy found.

A substantial difference can be appreciated between the benefits of Microgrids in the relatively weaker distribution networks of Poland, FYROM and UK and the relatively stronger networks of Germany and Netherlands. More specifically, while in the former there is significant room to reduce the total network cost, and this changes with the penetration level, the positive or negative impact is marginal in the latter (Figure 6).

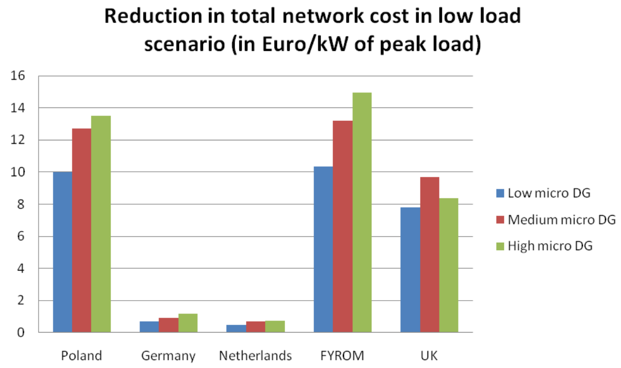

Figure 6. Example of comparative impact of Microgrids on total network cost (reinforcement and losses).

COMMENTS ON THE RESULTS

In terms of *DG penetration level* it can be said that benefits arise at low penetration levels of DG without significant drawbacks, while for higher penetration levels of DG, losses can sometimes increase due to counter-flows, which could even lead to overtake circuit thermal ratings. In addition, voltage rise issues might arise as well in the presence of long (rural) feeders and high generation levels, uncorrelated with demand.

In terms of *network characteristics*, strong networks with overrated circuits and relatively short feeders can accommodate DG without significant problems while operation benefits hold, although sometimes not significant. On the other hand, weak networks with smaller circuit capacities and longer feeders may exhibit problems that might be significantly mitigated by DG (when problem are demand-driven), whereas on the other hand local generation might create voltage rise issues calling for network upgrade. For weak networks, at most penetration levels, AM of different forms (generation curtailment, load controllability, adoption of on-line tap changer coordinated with reactive power control, etc.) can help put off network reinforcement.

Considering the *scope for AM*, also including coordination between Microgrids and the upper voltage levels when problems occur at MV, smart network operation typically leads to higher operational (mainly losses-related) costs due to higher (and more efficient) deployment of the existing assets. The trade-off between additional losses and cost of implementation of (optimal) AM strategies on the one hand, and network upgrade cost on the other hand, needs to be thoroughly assessed, according to the models illustrated. In the studies, the cost balance is always in favour of AM implementation.

CONCLUSIONS

In this paper, the main findings of the studies performed by the authors for European distribution networks in the More Microgrids project have been presented. Generally speaking, there is significant potential for Microgrids to contribute to a more economical and sustainable operation and development of current electricity systems. In particular, deployment of DG with AM in distribution networks can minimise and postpone network reinforcements while maximising the asset utilisation and integrating larger shares of clean DG. Since the main driver for benefits is the correlation between generation and demand, the possibility of modulating local generation and controllable loads in Microgrids can further increase the relevant benefits and minimise the negative network impacts. A crucial outcome of the comparison among different networks and network management strategies in the presence of DG has been that benefits and impacts, as well as mitigation actions and further benefits brought by intelligent control, are significantly related to the strength of the network. Hence, benefits can be substantial in relatively weak networks but only marginal for stronger networks.

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