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Investigating the Impacts of ANM Schemes on DG Maximisation

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SUMMARY

In the last decade, environmental and fuel security concerns have altered significantly how most governments' approach their energy agendas. Indeed, several energy targets to create a diversified energy portfolio have been placed around the globe. Renewable and low-carbon generation technologies are expected to increase their share in the energy mix in the coming years, whereas a significant proportion of new developments will be connected to distribution networks. Distribution Network Operators (DNOs) now face a scenario where the distribution circuits are no longer passive and technical issues such as voltage control, fault levels, power losses, etc. need to be assessed to allow the adequate integration of Distributed Generation (DG). Additionally, the intermittent characteristics of renewable technologies make this scenario even more challenging from both technical and economic points of view. Consequently, the traditional management of the system is unlikely to efficiently integrate the various new participants. In fact, the current 'fit and forget' approach for connecting DG might sterilise the network's ability to integrate further generation capacity.

Active Network Management (ANM), i.e., the use of real-time control and communication systems to better integrate and exploit the different network assets and participants, is a promising approach where several schemes such as coordinated voltage control, dynamic rating, energy curtailment, power factor control and automatic restoration can be applied. However, various technical, – and more importantly – regulatory and commercial challenges are restricting the deployment of ANM schemes.

In this work, a multi-period steady-state analysis is proposed for maximising the connection of intermittent DG through an optimal power flow (OPF)-based technique. Here, Active Network Management schemes are considered in order to investigate their impacts on generation capacity maximisation. Coordinated voltage control, energy curtailment and power factor control are used as means to allow maximum absorption of wind power while respecting voltage statutory limits and thermal constraints.

A simplified version of a generic medium voltage UK distribution network considering different loading levels and discretised variability of wind power generation is analysed over a year. Results are presented for different loading-generation cases, remarking how different ANM strategies affect the operation and penetration of new generation capacity.

KEYWORDS

Distributed Generation, Active Network Management, Distribution Networks, Optimal Power Flow, Wind Power

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1. Introduction

In 2007, European leaders signed up to an EU-wide target where 20% of their overall energy needs have to be sourced from renewables by 2020. The electricity sector was considered in 2001 with a target of 21% by 2010. Although being the latter not a binding target, EU Member States have since created different incentives to increase the connection of new low-carbon generation capacity. Countries worldwide have also adopted different targets and incentives. A significant share of the total expected new generation capacity will certainly be integrated to the distribution network. The pace of connection of Distributed Generation (DG) will vary from country to country depending on the particular characteristics of its distribution networks, but mainly due to planning issues for both Distribution Network Operators (DNOs) and developers. However, it is also important to acknowledge that distribution circuits lack of investments on new technologies that enable the better integration of further DG capacity. Indeed, the current ‘fit and forget’ approach for connecting new developments, where no integration strategy is in place, can potentially sterilise the network’s ability to connect more generation [1].

It is certain that several challenges have to be faced by DNOs as distribution circuits are no longer passive due to the increased connection of DG [2]. However, ‘fit and forget’ integration makes technical issues such as voltage, thermal limits and fault levels to constraint the capacity of new developments. Additionally, intermittent generation, such as wind power, presents DNOs with more complexities if the aim is to maximise the harvesting of renewable sources [3-5]. In this context, Active Network Management (ANM), i.e., the use of real-time control and communication systems to better integrate and exploit the different network assets and participants, represents a promising approach where several schemes such as coordinated voltage control, dynamic rating, energy curtailment, power factor control and automatic restoration can be applied [6-11]. Nonetheless, while the various technical benefits of adopting ANM schemes are accepted by industrialists and academics, its wide deployment is uncertain due to regulatory and commercial barriers.

While distribution engineers are not able to forecast the actual commissioning of new generation capacity, evaluating the network’s maximum DG capacity is important to provide them with alternatives in decision making, and to estimate the investments required to allow the connection of new developments. Since high penetration levels of DG may affect the interaction between distribution and transmission networks, it is also critical an overall assessment of the maximum generation capacity that might be delivered upstream in order to evaluate the necessity of future reinforcements, or alternatively, to identify areas where DG deployment should be constrained.

In this work, a multi-period steady-state analysis is proposed for maximising the connection of intermittent DG through an Optimal Power Flow (OPF)-based technique. Here, Active Network Management schemes are considered in order to investigate their impacts on generation capacity maximisation. Coordinated voltage control, energy curtailment and power flow control are used as means to allow maximum absorption of wind power while respecting voltage statutory limits and thermal constraints. A simplified version of a generic medium voltage UK distribution network considering different loading levels and discretised variability of wind power generation is analysed over a year.

This paper is structured as follows: Section 2 briefly presents the OPF formulation adopted for this study. Section 3 corresponds to the case study where maximum DG capacity is analysed by the ANM-adapted OPF. Results are presented remarking how different ANM strategies affect the operation and penetration of new generation capacity. Finally, the conclusions are drawn in Section 4.

2. Optimal Power Flow-based DG Maximisation

Treating capacity allocation of DG as an optimisation problem presents several complexities that depend on the network’s characteristics such as capacity headroom, fault levels, power losses, topology, demand behaviour, etc. Several optimisation techniques have been proposed in the last years for optimally siting and sizing DG, including the use of meta-heuristics [5, 12], linear programming [13] and analytical approaches [14]. Here, building on previous work [1, 11], the well established

Optimal Power Flow technique is tailored to maximise the total DG capacity in a given network, while considering Active Network Management schemes and the corresponding network constraints. The basic and ANM-adapted OPF formulations aimed at maximising the total DG capacity *P* across *n* generators (indexed by *g*) are presented below.

$$Maximise \sum_{g=1}^{n} P_g$$

$$\text{subject to:}\quad \textbf{OPF + ANM}\begin{cases}\textbf{Basic OPF}\begin{cases}\bullet\ \text{real and reactive nodal power balance}\\ \bullet\ \text{voltage level constraints}\\ \bullet\ \text{voltage angle set to zero for the reference bus}\\ \bullet\ \text{thermal limits (lines and transformers)}\\ \bullet\ \text{constant power factor operation of DG units}\end{cases}\\ \bullet\ \text{coordinated voltage control}\\ \bullet\ \text{power factor control}\\ \bullet\ \text{generation curtailment}\end{cases} \qquad (1)$$

ANM schemes make possible the optimal use of the network's assets by dispatching generation, controlling transformer on-load tap changers (OLTC) and voltage regulators, managing reactive power and automatically restoring the system [6-11]. In this work, only those variables and constraints derived from the schemes presented above (OPF+ANM) were incorporated into the non-linear programming formulation of the OPF. Ultimately, the time-varying characteristics of demand and generation are taking into account in form of loading and power output levels, respectively. The multi-periodicity is achieved by relating each demand-generation combination to its time duration. This allows each period to have a different set of power flow variables, whereas a single set of generation capacity variables is used during the whole analysis, thus creating the multi-period interdependency. The proposed OPF was coded in the AIMMS optimisation modelling environment [15].

3. Impacts of ANM Schemes

In this section the different impacts of ANM schemes on the distribution network operation and its ability to cope with further generation capacity, are investigated. Initially, a test network will be studied considering maximum loading and non-intermittent generation, i.e., a single-period analysis. In the sequence, time-varying demand, in form of loading levels, is analysed. Finally, discretised variability of wind power generation is also taken into account in the multi-period analysis.

3.1. 16-bus Network

Fig. 1 shows the one-line diagram of the simplified EHV1 Network, which corresponds to a rural circuit. Specific data for this 16-bus 33kV radial network is available in [16]. The feeders are supplied by two identical 30MVA 132/33kV transformers. Grid Supply Point (GSP) voltage is assumed to be nominal. In the original configuration (no DG), the OLTC at the substation has a target voltage of 1.036pu at the busbar. A voltage regulator (VR) is located between buses 8 and 9, whereas bus 9 has a target voltage of 1.03pu. Voltage limits are taken to be ±6% of nominal. The total maximum load demand of the original network, i.e., without DG, is 38.16MW. The losses in this case account for 2.22MW.

A simple approach to evaluate the ability of a network for connecting new generation capacity is to perform a power flow analysis with different DG outputs. Considering the initial OLTC and VR settings, and unity power factor for the DG unit connected to bus 16, i.e., no ANM scheme in place, Fig. 2 shows how losses, voltages and capacity usage are affected. As expected, the higher the DG capacity, the higher the loss increase and voltage rise (*Vmax*). Indeed, in Fig. 2, it is due to voltage constraints that DG capacities greater than 3MW become unfeasible. Also, it can be observed through the *Maximum capacity usage* that the power supply from the GSP decreases significantly. Nonetheless, from 9MW of DG capacity it is the thermal (power transfer) capability of the line connecting the generator (15-16) that might become an important constraint – apart from voltages – if larger capacities are considered. While this approach is straightforward, it is not possible to determine the actual potential of the network for connecting DG when considering different ANM schemes.

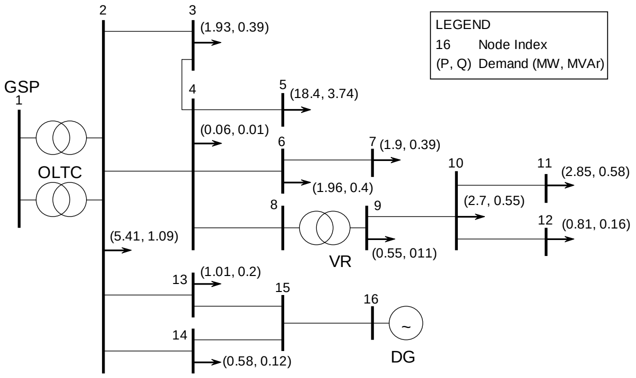


Fig. 1 UK GDS Simplified EHV1 Network [16] during maximum load conditions.

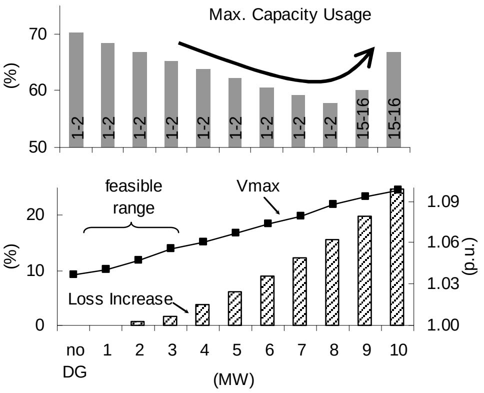


Fig. 2 (Top) Maximum capacity usage, and (Bottom) maximum voltage and loss increase for different capacities of non-intermittent DG during maximum load. Fixed busbar and VR voltages. DG operating at unity power factor.

3.2. Maximum Demand: Single-period Analysis

Initially, the coordinated voltage control and power factor control schemes are studied in the maximum demand – non-intermittent DG case. By controlling the OLTC at the substation, and, consequently, the corresponding voltage at the busbar, depending on the loading level, more DG capacity might be connected. Additionally, if voltage regulators present in the network are also integrated in the control strategy, even further DG capacity might be achieved. As for the power factor control, here a ‘dispatchable’ operational range will be considered. Thus, in the OPF formulation, voltages at the busbar and the regulated bus of the VR (i.e., bus 9), as well as the power factor of the DG connected to bus 16, will be treated as variables rather than fixed parameters, while maintaining the resulting values within their corresponding limits.

The OPF-based optimal DG capacity and the corresponding increase in losses (compared to those of the original configuration) considering the implementation of coordinated voltage control (CVC) and various power factor settings are presented in Fig. 3.

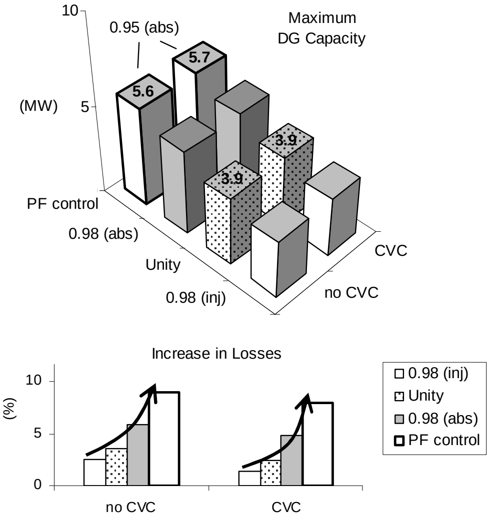
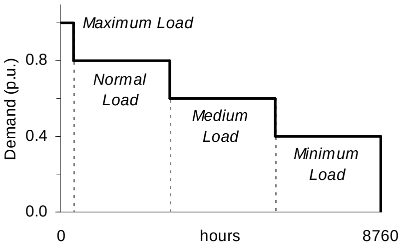


Fig. 3 (Top) Maximum DG capacity and corresponding (Bottom) increase in losses applying voltage and power factor control strategies.



Loading Level	% of Time	Duration (H)	MW	MVAr	Losses (MW)
Minimum	33	2890.8	15.26	3.10	0.31
Medium	33	2890.8	22.90	4.64	0.73
Normal	30	2628	30.53	6.19	1.36
Maximum	4	350.4	38.16	7.74	2.22

Fig. 4 (Top) Load duration curve. (Bottom) Characteristics of adopted loading levels.

In this case, small gains in capacity were found when implementing CVC compared to the passive management of both the OLTC and VR. However, the new voltage control proved to be more efficient in terms of losses. Also, due to the characteristics of the analysed network, 0.98 lagging power factor (absorbing reactive power) allows more DG capacity to be connected at bus 16 than the other fixed power factor strategies. Nonetheless, granting a ‘dispatchable’ power factor (PF control), here with a typical range of 0.95 lagging to 0.95 leading, it is possible to find the optimal setting for generation maximisation. Thus, the power factor control of the generator in addition to the coordinated voltage control of OLTC and VR, could make possible a DG penetration of 15% (respect to the maximum demand), although with a loss increase of 8%.

3.3. Time-varying Demand: Multi-period Analysis

Although the maximum demand analysis provides the distribution engineer with an idea of the non-intermittent capacity that might be connected to a given network, lower demand levels could have an impact on the capacity of new developments. The adopted load duration curve and the corresponding characteristics are given in Fig. 4 for a year. Thus, four different loading periods will be evaluated while considering in each of them a constant power output of the DG. Annual demand and losses amount to 204GWh and 7362MWh, respectively.

At times of minimum demand high penetration of DG could result in excessive voltage rise. However, in the studied network, it is the maximum demand in the neighbouring feeders combined with voltage constraints that mainly restrict DG capacity. In order not to reduce the generation capacity it is possible to apply curtailment of the power to alleviate such problems. Power curtailment, another ANM scheme, is incorporated in the OPF formulation by adding an extra variable, to act as a negative generation (or positive demand) at the same location of a given DG unit. While limiting the power production of the DG unit requires special commercial arrangements and should be assessed on financial grounds, here different levels of curtailment will be investigated to evaluate their impacts on DG capacity maximisation.

Fig. 5 shows the OPF-based maximum DG capacities obtained for different ANM strategies: power factor, coordinated voltage control (CVC), and power curtailment. For the latter, curtailed energy was restricted to a percentage of the total energy that otherwise would have been delivered. It can be observed that, when no curtailment is adopted, the incorporation of the loading levels did not affect the optimal results obtained for maximum demand using CVC (Fig. 3). This is mainly due to the flexibility provided by such scheme. Nonetheless, without CVC, the multi-periodicity, i.e., lower demand levels, did affect the optimal capacity, reducing it by 7%.

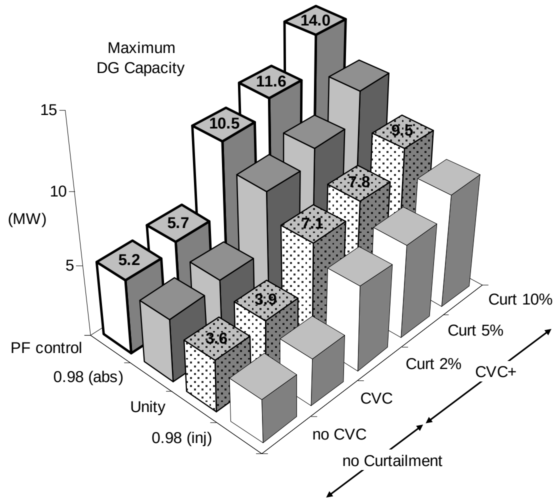


Fig. 5 Maximum DG capacity considering different power factor and curtailment strategies. Both the OLTC and VR are integrated in the CVC.

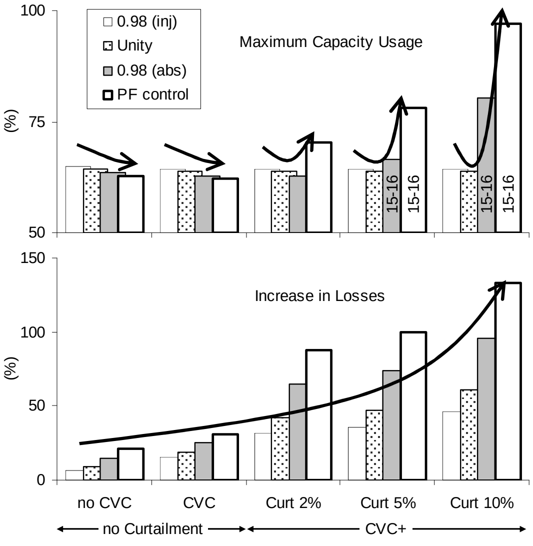


Fig. 6 (Top) Maximum capacity usage of the lines and (Bottom) increase in losses for the cases considered in Fig. 5.

Power curtailment, on the other hand, allows much greater DG capacities to be connected. With CVC and power factor control in place, a 2% limit of energy curtailment enables an expansion of more than 84% of generation capacity when compared to the case with no curtailment, i.e., a DG penetration of 27% (relative to peak demand). This figure exceeds 36% when the energy curtailment limit is set to 10%.

The impacts of the different ANM strategies on the capacity usage of the assets and the annual energy losses are shown in Fig. 6. When curtailment is not allowed, the maximum capacity usage of the GSP decreases when power factor control is used. However, due to the large volumes of DG obtained with energy curtailment, the line connecting the generator (15-16) becomes a potential binding constraint. In terms of energy losses, as expected, the larger the generation capacity the larger the increase relative to the non-DG scenario. CVC and power factor control, with no curtailment, lead to 31%, whereas a 2% limit for curtailment can increase energy losses up to 88%.

3.4. Time-varying Demand and Generation: Extended Multi-period Analysis

The inherent intermittency of renewable DG technologies, such as wind power, requires adaptable control strategies to allow high penetrations of new generation capacity. Fig. 7 (left) shows the Weibull probability distribution (mean wind speed of 8m/s) and a typical wind power curve utilised to produce the corresponding cumulative distribution function. To capture the time duration of different generation levels the cumulative distribution function is discretised in five bands (Fig. 7, right). Fig. 8 presents how the multi-period analysis is extended by considering in each band of the load duration curve the discretised wind power outputs. In this way, while the maximisation of the nominal capacity of the wind generator is still the objective function (equation (1)), its generation profile should follow the pattern shown in Fig. 8 for the corresponding demand-generation combination.

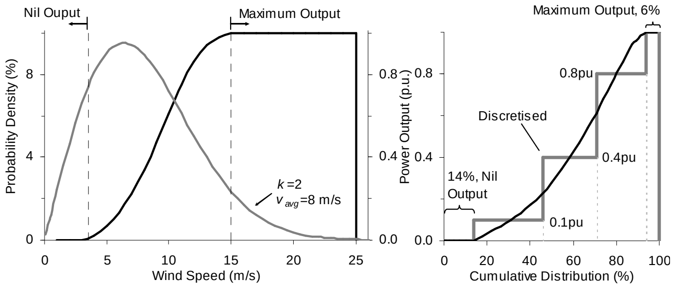


Fig. 7 (Left) Weibull distribution and wind turbine power curve. (Right) Cumulative distribution of wind power output.

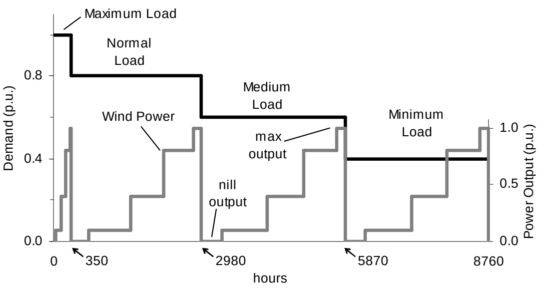


Fig. 8 Multi-periodicity: Load duration curve and wind generation levels.

The maximum wind power capacity that can be connected to node 16 of the EHV1 network was investigated considering the cases presented in Fig. 5. The corresponding results are shown in Fig. 9. When curtailment is not considered, the variability of the wind has no influence on the OPF-based maximum capacity since it is during the critical demand-generation scenarios that major constraints appear, thus the same results obtained in Fig. 5. For this particular network, higher demand levels restraint further DG capacity due to the voltage requirements of the neighbouring feeders. Nonetheless, as expected, curtailment combined with the intermittency of wind power indeed allows more generation capacity to be connected. It can be observed that when the CVC and power factor control schemes are in place, a 2% limit of energy curtailment doubles the wind power capacity, reaching 33% of penetration relative to peak demand. This figures goes up to 47% when the curtailment limit is set to 10%.

In terms of capacity usage of lines and transformers, Fig. 10 presents the maximum values found for each studied combination of ANM schemes. Since nil wind power output was considered in the analyses, peak demand is responsible for using 70% of the transfer capacity available through the 132/33kV transformers (as also shown in Fig. 2). However, with greater generation capacities, it is the line connecting the wind farm the one that reaches its maximum transfer capacity. As for losses, due to the natural variability of wind power, annual energy losses do not increase as much as when the DG is considered to provide a steady output (see Fig. 6). However, when curtailment is possible, losses raise significantly, surpassing 30% for full ANM deployment with 2% limit of energy curtailment. Annual energy losses double if the curtailment limits is raised to 10%.

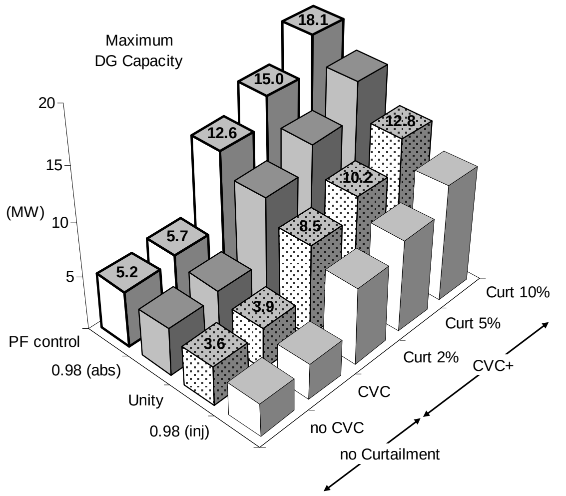


Fig. 9 Maximum DG capacity considering different power factor and curtailment strategies. CVC of OLTC and VR is in place.

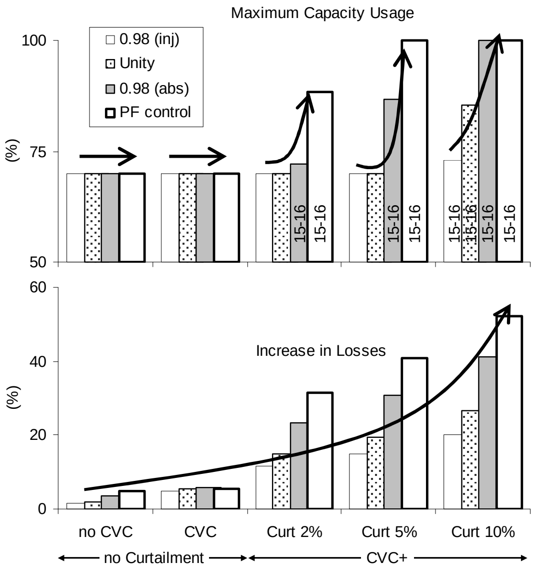


Fig. 10 (Top) Maximum capacity usage of the lines and (Bottom) increase in losses for the cases considered in Fig. 9.

The coordinated voltage control of both the OLTC and VR relies on the adaptability of their corresponding tap settings. The proposed OPF-based methodology finds the optimal settings for each period in order to maximise the DG capacity connected to node 16, while fulfilling thermal and voltage constraints. Consequently, the multi-periodicity of this approach leads to multiple settings of the variables involved. In Fig. 11, the various tap positions for the OLTC and the VR are presented for the cases when no curtailment is considered, and when a 2% limit is allowed. While real values, instead of integer, were adopted in the OPF formulation, the results clearly show the active participation of the tap settings in achieving voltages that allow the further generation capacity.

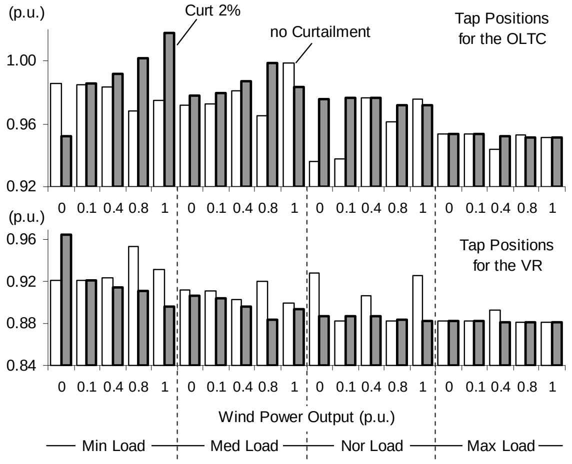


Fig. 11 (Top) Tap positions for the OLTC and (Bottom) VR during each analysed period considering the cases with no curtailment and with 2% limit. CVC and power factor control are in place.

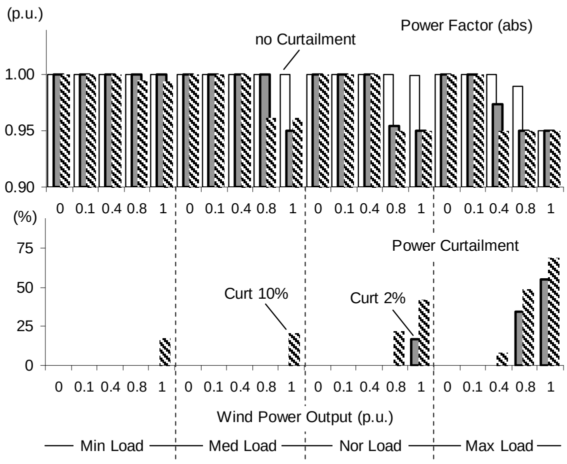


Fig. 12 (Top) Power factor settings and (Bottom) power curtailed during each analysed period considering the cases with no curtailment, and 2% and 10% limit. CVC and power factor control are in place.

Due to the adopted ANM schemes, the power factor used by the wind farm, as well as the corresponding power curtailment, also vary according to the demand and generation levels. Fig. 12 (top) shows the power factors adopted in each period for the case with 10% curtailment limit and those considered in Fig. 11. Given the complex power (MVA) flow limits of the 132/33kV transformers and the lines, unity power factor is used most of the time in order to integrate larger volumes of DG capacity. However, as a result of the restrictive voltage constraints mainly during higher levels of demand and generation, the wind farm becomes inductive (i.e., absorbing reactive power) with power factors equal or close to the specified limit of 0.95. It is important to notice, however, that while inductive power factors in the studied EHV1 network enable more generation capacity, the overall need of reactive power from the GSP might have negative effects from the transmission point of view. Also shown in Fig. 12 is the power curtailment for each analysed period. Clearly, the 10% limit of energy curtailment requires more capacity and more periods to be curtailed than the 2% limit. Higher demand and generation levels, again, require the major power curtailments due to the limitations imposed by the neighbouring feeders.

4. Conclusions

Land availability and planning permissions are among the main factors for new generation capacity to be connected to the distribution network. Good source availability plays also a very critical role on the economic feasibility of a new development. Nonetheless, it is important for DNOs to understand the capabilities of their networks from both technical and commercial points of view. The OPF-based technique presented here is useful from such distribution planning perspective. The use of Active Network Management schemes clearly presents several technical benefits that allow the integration of further generation capacity to distribution networks. It is important, however, that each ANM solution, or the combination of them, should be assessed in a case-by-case basis since network characteristics drive the performance and cost-effectiveness of each scheme. Power curtailment proved to have a significant impact on connecting larger volumes of DG, however its actual implementation will also depend on commercial negotiations (e.g., in the UK, special bilateral contracts between the DNOs and the generator owners). Finally, while ANM schemes are yet to be widely deployed in distribution networks, the impact of high penetrations of DG on the transmission system, particularly the reactive power draw from the grid, needs also to be studied.

ACKNOWLEDGEMENTS

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