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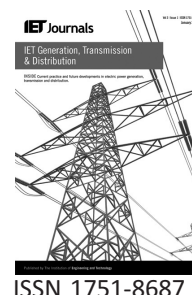
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Evaluating maximum wind energy exploitation in active distribution networks

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Abstract: The increased spreading of distributed and renewable generation requires moving towards active management of distribution networks. In order to evaluate maximum wind energy exploitation in active distribution networks, a method based on a multi-period optimal power flow analysis is proposed. Active network management schemes such as coordinated voltage control, energy curtailment and power factor control are integrated in the method in order to investigate their impacts on the maximisation of wind energy exploitation. Some case studies, using real data from a Danish distribution system, confirmed the effectiveness of the proposed method in evaluating the optimal applications of active management schemes to increase wind energy harvesting without costly network reinforcement for the connection of wind generation.

1 Introduction

The international concern over climate change is driving European countries to reduce carbon-dioxide emissions by means of political and regulatory pressure and to increase the total electrical supply energy from renewable sources. Electricity market liberalisation and the priority given to renewable sources under EU directive 03/54/EC along with the worldwide promotion of renewable encourage the development of the distributed generation (DG) and renewable sources.

The connection of large amounts of DG to distribution systems presents a number of technical challenges to distribution network operators (DNOs) [1–6]. These challenges are partly caused by the mismatch between the location of energy resources and the capability of local networks to accommodate new generation. Particularly, the location of wind turbines (WTs) is determined by the local wind resources and geographical conditions. However, the current capacity of the network to which the WTs will be connected may not be sufficient to deliver the generated wind power. As a result, network reinforcement needs to be planned by the DNOs. Since such network reinforcement usually calls for high capital investment, DNOs would like to explore less costly means that can

improve the capability of the network to accommodate new generation. One way is to make the best use of the existing network by encouraging development at the most suitable locations [3–6]. In order to do this, DNOs require a reliable and repeatable method of quantifying the capacity of new DG that may be connected to distribution networks without the need for reinforcement.

The challenge of identifying the best network location and capacity for DG has attracted significant research effort, albeit referred to by several terms: optimal ‘capacity evaluation’ [3–7], ‘DG placement’ [8] or ‘capacity allocation’ [9–11]. These optimisation problems apply different numerical algorithms with various objectives and constraints. For example, genetic algorithms are used to find the optimal location of DG [12–14]. Several other algorithms are adopted to handle optimisation problems with discrete variables [9, 15]. Other approaches require network locations of interest to be pre-specified with algorithms guiding capacity growth within network constraints [7–9, 16].

Nevertheless, as values associated with WTs are time- and location-dependent, methods that simply consider one specific power value at a specific moment are not able to account for time dependence. Therefore, WTs optimal

allocation should consider their capability of delivering power at the right time and WT's should be located at the right place to be able to deliver energy while satisfying network constraints. Simulating load and generation variations during a year and computing the WT's delivered energy allows including the time dimension, when compared with methods that simply consider the power at one specific point in time [16]. In order to account for load and generation time interdependences, some approaches focused on the concept of energy from DG [1, 17]. In [1], a method that maximises the amount of energy that may be reaped from a given area, on the basis of the available energy resources, and minimises DG connection costs, losses and technical constraints has been proposed and implemented. In [17], a method that evaluates annual energy in order to measure the risk of unserved energy for each planning option is described. The added value of computing the annual energy in determining the extent of the distribution planning problem is demonstrated. However, active management schemes are not considered in either method to exploit higher energy from DG.

In this work, the maximum wind energy exploitation in a distribution network is evaluated under different active management schemes during a given time horizon. The evaluation is based on a multi-period optimal power flow (MP-OPF) algorithm, which takes into account distribution network constraints. Such a MP-OPF, derived from the OPF methods of [3–6, 18] considers the time-varying characteristics of the load demand and wind power generation. The algorithm also integrates active management schemes such as coordinated voltage control, energy curtailment and power factor control. The analyses are demonstrated using a 69-bus 11 kV radial distribution network. Section 2 describes the active management schemes adopted in the MP-OPF which is described in Section 3. Sections 4 and 5 present and comment some case studies. A discussion on the presented results is given in Section 6. Conclusions are drawn in Section 7.

2 Evaluating maximum wind energy exploitation in active distribution networks

Active management represents an alternative approach to enable national targets for renewable energy and increase the penetration of WT's into the existing distribution networks [19, 20]. It has, indeed, the potential to maximise DG penetration level while minimising DG-related network reinforcements [21–30]. In [28], it is demonstrated that networks endowed with active management schemes can potentially accommodate up to three times as much generation.

Active management can be realised, for instance, through generation dispatch, transformer tap adjustment or reactive power compensators. In [20], WT's generation curtailments

during low demand, reactive power management using a reactive compensator and area-based on-load tap-changer (OLTC) coordinated voltage control have been used in the active management.

In [21, 22], a multi-period steady-state analysis for maximising the capacity of wind generation through an OPF-based technique with active management features has been proposed. However, since wind capacity rather than wind energy is maximised, WT's allocation does not allow maximum wind energy exploitation. Moreover, short-circuit level is computed with a simplified approach.

The more advanced and emerging concept of active management is based on real-time measurements of the distribution network parameters and employs real-time control of generators, tap-changing transformers, reactive power compensators and communication among the generators and voltage control devices [29].

The MP-OPF proposed here improves the methods proposed in [18, 21, 22] by accounting for load and generation time interdependences and by focusing on the concept of energy from WT's. The proposed method allows, in fact, finding the optimal WT's capacities allocation in order to maximise wind energy exploitation under different active management schemes, briefly described in the following section.

2.1 Coordinated OLTC voltage control

Traditional control strategies of OLTCs are either based on the voltage regulation at a single busbar or voltage drop compensation on a particular line [20]. Such voltage control strategies are based on local measurements and are suitable for traditional distribution systems with unidirectional power flow. However, these strategies may cause problems in distribution networks with bi-directional power flows. On the other hand, the area-based control strategy of OLTCs is based on measurements from various locations of the network. In this way, the voltage regulation of OLTCs can be based on the voltage information of the bus that has the most severe over-voltage problem [20]. Consequently, the maximum wind energy penetration level may be increased by the implementation of the control strategy.

2.2 Energy curtailment

In order to alleviate the over-voltage problem, it may be necessary to curtail a certain amount of wind energy injected into the network [20]. Although the output wind energy is reduced, the WT developer may still gain more profits due to the possibility of installing more WT's [29].

In the proposed method, wind energy may be curtailed during certain periods in order to alleviate any voltage or thermal constraint violation. For example, for a specific

period, there are different possible combinations of load demand and wind power. Wind energy is curtailed at the combination of minimum demand and maximum wind power. The same strategy is applied to each of the periods analysed.

In the method, energy curtailment is implemented in each period by introducing a negative generation variable to represent the curtailed energy from each WT. For a given period, the maximum energy that can be curtailed from a given WT is set to a fraction of the potential energy that the WT could have produced without energy curtailment.

2.3 Coordinated generator reactive power control

The recent grid codes of many countries, such as Denmark, Germany, Italy, Ireland and the UK, require that WTs should provide reactive power control capabilities and that network operators may specify power factor or reactive power generation requirement for grid-connected WTs [31].

In practice, a grid-connected WT needs to fulfil the specific requirement depending on the regulation of the country. For example, in the Danish grid code for grid-connected WTs, reactive power generation is confined to a control band with respect to active power generation (with a power factor between 1.00 and 0.995 lagging). The German grid code specifies different reactive power limits according to voltage value at interconnection (with a power factor ranging between 1.00 and 0.925 lagging). The Irish grid code requires a power factor between 0.835 leading and 0.835 lagging when the active power output level is below 50% of the rated capacity. In Italy and the UK, the power factor at a WT's terminal should be between 0.95 leading and 0.95 lagging.

Although it is important to fulfil the grid code when connecting a WT, this paper intends to illustrate the concept of the proposed method, but not to design a WT that fulfils a specific requirement. WTs, especially those with power electronic controllers, are able to provide necessary reactive power support to the grid. The reactive power generation can be dispatched centrally by the DNOs [32]. In other words, power factors of WTs can be controlled so that wind energy penetration level in the network is maximised. The proposed control scheme requires WTs to generate reactive power during load peak hours and low generation, and to absorb reactive power during load off-peak hours and high generation.

3 Multi-period optimal power flow

The optimisation method aims to find the optimal locations and capacities of WTs so that the wind energy exploitation in the network is maximised. Such an objective is subject to a number of technical constraints imposed by regulations,

including bus voltage limits, line/transformer thermal limits and system short-circuit levels. By fulfilling these constraints, the network reinforcement due to the connection of WTs may be avoided. In addition, such a method can be used to investigate the impact of the foregoing active management strategies on the maximum wind energy penetration level in the network.

IET Corrected Proof

The proposed approach, based on the non-linear programming formulation of the MP-OPF described in [18, 21, 22], has been modified in order to maximise the wind energy exploitation and to include active management schemes, the time-varying characteristics of the load demand and wind power generation and the system short-circuit constraints.

The MP-OPF is formulated as

$$\begin{aligned} & \text{maximise} \sum_{j=1}^{N_j} \sum_{g=1}^{N_G} E_g^j(P_g, \mathbf{x}_j) \\ & \text{subject to} \\ & \mathbf{h}(\mathbf{x}_j) = 0 \\ & \mathbf{g}(\mathbf{x}_j) \leq 0 \end{aligned} \quad (1)$$

where $E_g^j(P_g, \mathbf{x}_j)$ is the wind energy generated during the time period j by the g th WT with rated capacity P_g , N_j is the total number of periods in a year corresponding to different combinations of load demand and wind power generation and N_G is the number of WTs (indexed by g).

The vector \mathbf{x}_j consists of a set of controllable quantities and dependent variables during each period j . The optimisation variables include the capacity of each WT, and for each period j , the secondary voltage of the OLTC, the power factor angle, the curtailed energy of each WT and the import/export power at the interconnection to the external network.

The equality constraints $\mathbf{h}(\mathbf{x}_j)$ represent the static load flow equations such as Kirchhoff current law $\forall j \in J$ and $\forall b \in B$, where J is the set of periods (indexed by j), B is the set of buses (indexed by b) and Kirchhoff voltage law, $\forall j \in J$ and $\forall l \in L$, where L is the set of lines (indexed by l).

The inequality constraints $\mathbf{g}(\mathbf{x}_j)$ are listed in the following:

- Capacity constraints for the interconnection to external network (slack bus) $\forall j \in J, \forall x \in X$

$$\begin{aligned} P_x^- & \leq P_{x,j} \leq P_x^+ \\ Q_x^- & \leq Q_{x,j} \leq Q_x^+ \end{aligned} \quad (2)$$

where X is the set of external sources (indexed by x), $P_{x,j}$ and $Q_{x,j}$ are the active and reactive power outputs of x , respectively and

P_x^-, P_x^+ and Q_x^-, Q_x^+ are the min/max active and reactive power outputs of x , respectively.

- Capacity constraints for the WTs: maximum capacity that may be installed at each site $\forall j \in J, \forall g \in G$

$$\begin{aligned} P_g^- &\leq P_{g,j} \leq P_g^+ \\ Q_g^- &\leq Q_{g,j} \leq Q_g^+ \end{aligned} \quad (3)$$

where G is the set of WTs (indexed by g), $P_{g,j}$ and $Q_{g,j}$ are the active and reactive power outputs of g , respectively, and P_g^-, P_g^+ and Q_g^-, Q_g^+ are the min/max active and reactive power output of g , respectively.

- Voltage-level constraints $\forall j \in J, \forall b \in B$

$$V_b^- \leq V_{b,j} \leq V_b^+ \quad (4)$$

where $V_{b,j}$ is the voltage at b , V_b^+ and V_b^- are the max/min voltage at b , respectively.

- Flow constraints for lines and transformers $\forall j \in J, \forall l \in L$

$$\sqrt{(f_{l,j}^P)^2 + (f_{l,j}^Q)^2} \leq f_l^+ \quad (5)$$

where $f_{l,j}^P$ and $f_{l,j}^Q$ represent the active and reactive power injection onto l , respectively, and f_l^+ the maximum power flow on l .

- Short-circuit-level constraint: the requirement of not exceeding the design short-circuit capacity in typical radial networks, fed by a MV/LV substation and with wind generation, should be satisfied as it could constrain new generation capacity. WTs connected to the distribution network may contribute to the short-circuit level at the distribution substation. The upstream grid provides the dominant contribution to the short circuit capacity, which rapidly diminishes downstream the network due to the series impedance of the lines. The short-circuit requirement normally needs to be checked at the MV (or LV) busbars of the substation [33]. Therefore, given the typical radial arrangement of distribution networks, the maximum short-circuit level will be obtained when considering a three-phase short-circuit at the low-voltage side of the substation.

The magnitude of the expected short-circuit current $|I_{cc}|$ at the low-voltage side of the substation, calculated from the phasor sum of the maximum short-circuit currents from the upstream grid, through the step-down transformer, and from the WTs connected to the distribution network, is, therefore, limited by the design short-circuit capacity I_{cc}^{\max} .

$$|I_{cc}| \leq I_{cc}^{\max} \quad (6)$$

The grid contribution is calculated according to IEC 60909 [34–37] and the contribution of WTs is computed according to the method proposed in [33].

The additional constraints derived from the active management schemes are coordinated OLTC voltage constraint, curtailed energy and WTs power factor angles.

- Curtailed energy constraint $\forall j \in J$

$$CE_g^j \leq CE_{g \max}^j \quad (7)$$

where CE_g^j represents the amount of curtailed energy from generator g during period j and $CE_{g \max}^j = C_f^j \times E_g^{j-\max}$ the maximum permitted curtailed energy from generator g during j , where C_f^j is the curtailment index, varying in the range $[0, 1]$ and $E_g^{j-\max}$ is the maximum energy that generator g could have produced during j without curtailment.

- Coordinated OLTC voltage constraint $\forall j \in J$

$$V_{OLTC}^- < V_{j,OLTC} < V_{OLTC}^+ \quad (8)$$

where $V_{j,OLTC}$ is the secondary voltage of the OLTC during j , V_{OLTC}^- and V_{OLTC}^+ are the (max/min) voltage of the OLTC, respectively.

- Coordinated generator reactive power constraints, $\forall j \in J, \forall g \in G$

$$\varphi_g^- < \varphi_{g,j} < \varphi_g^+ \quad (9)$$

where $\varphi_{g,j}$ is the power factor angle of g during j , φ_g^- and φ_g^+ are the (max/min) power factor angle of g , respectively.

The proposed method has been implemented in Matlab[®] and is based on MATPOWER suite [38] and demonstrated through the study system described in the following section.

4 Study system

The following analyses are based on a 69-bus 11 kV radial distribution system whose data are given in [39]. The four feeders are supplied by two identical 6 MVA 33/11 kV transformers. Fig. 1 shows the distribution system and the potential WT locations, selected to demonstrate the capabilities of the method.

4.1 Modelling of time-varying load and wind power generation

For the modelling of time-varying load and wind power generation, real data from the local distribution network in Nordjylland in Denmark have been used and processed. In order to account for the seasonal, weekly and daily variation of load, the measured data are grouped by summer/winter, weekday/weekend and 24 h. In order to account for the seasonal and daily variation of wind power generation, the measured data are grouped by summer/winter and 24 h. In particular, the 365 days of the year have been divided into 153 winter days and 212 summer days and, for each week

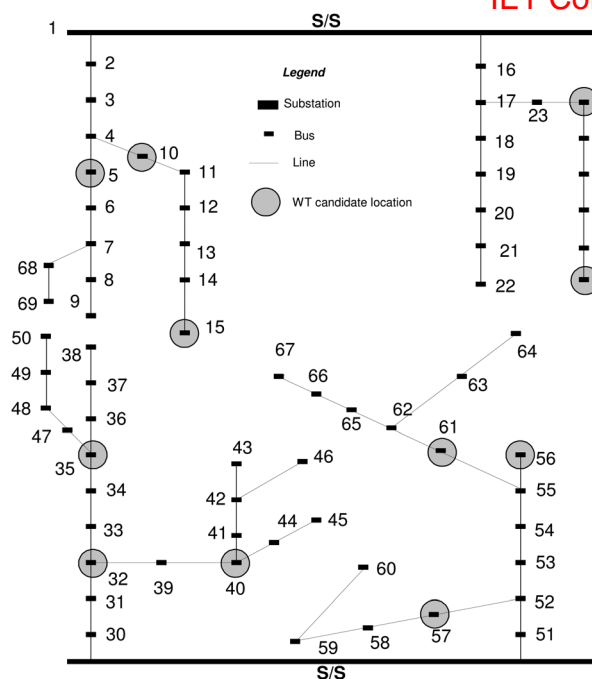


Figure 1 69-Bus network indicating potential locations for WTs

into 5 weekdays and 2 weekend days. As a result, there are 96 groups for load and 48 groups for wind power generation.

From each group of load, for example, 12 o'clock in a summer weekday, a load duration curve is obtained and then discretised into four states. A similar approach is applied to the wind power generation, but discretised into six states. The discretisation is demonstrated in Fig. 2. As a result, for one group of load, there are four load states with corresponding six wind power generation states.

Each type of day consists of 24 h, each of which can have 24 (6×4) different combinations of load-generation; therefore a total of 2304 load flows ($2304 = 4_{\text{day_types}} \times 24_{\text{hours}} \times 24_{\text{load-generation}}$) with different load-generation combinations have been analysed in the MP-OPF. In order to create the multi-period interdependency, at each iteration of the MP-OPF, a unique set of WTs capacity variables correspond 2304 sets of power flow variables.

The maximum load level of each bus given in [39] is scaled down for the use in the 69-bus network: the corresponding maximum loading levels and annual losses calculated without WTs are summarised in Table 1.

Table 1 Maximum network loading and annual losses with no DG

| Active power, MW | Reactive power, MVar | Losses, MWh |
|------------------|----------------------|-------------|
| 2.90 | 1.99 | 178 |

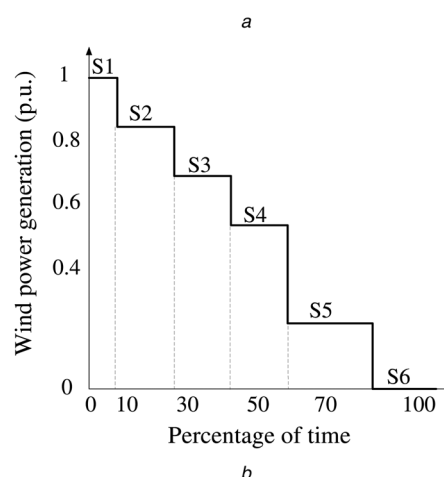
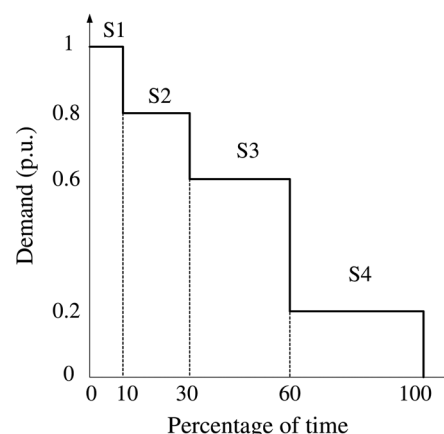


Figure 2 Discrete states

a Load

b Wind power generation at a given hour

4.2 Short-circuit calculations

The short-circuit capacity of the grid is assumed to be 1000 MVA. The grid is connected to the transformers through a series inductive impedance of 8%. Losses for the substation's transformers are not considered. The designed short-circuit capacity for the 11 kV network is assumed to be 200 MVA. As recommended by the IEC standard [34–37], the R/X ratio for the corresponding equivalent impedance is assumed to be 0.1. The voltage factor used to consider the variations of the system voltage is assumed to be 1.1 [33]. The WTs are connected to the 11 kV network through a 0.69/11 kV transformer with a series impedance of 4% and a rated resistive component of the short-circuit voltage of 1.2% [33]. In order to evaluate the WTs' contribution to the short-circuit level at each bus, the equivalent short-circuit impedances of WTs and transformers have been computed for each bus according to the installed WT capacities and to the parallel connections of WTs.

4.3 Network operation constraints

Voltage limits are taken to be $\pm 6\%$ of nominal and feeder thermal limits are 5.1 MVA (270 A/phase). The substation

power exports to the upstream grid are limited to the capacity of the transformers (12 MVA). In order to demonstrate the capabilities of the energy curtailment scheme, it has been assumed that wind energy can be curtailed only during the period in which the combination of minimum demand and maximum wind power occurs. It has been assumed that energy output from each WT should be no less than 90% of the potential wind energy that could have been produced (a curtailment index C_f^j equal to 0.9). Energy curtailment during such periods should alleviate over-voltage problems.

Power factor is assumed to vary between 0.9 leading and 0.9 lagging when the coordinated generators reactive power control option is considered. Otherwise, WTs are assumed to operate with a fixed power factor of 0.95 lagging (absorbing reactive power). The short-circuit limit constraint of 200 MVA has been assumed accordingly to the designed short-circuit capacity for the network.

5 Scenario studies

The MP-OPF has been applied to the 69-bus network for evaluating its annual maximum wind energy exploitation. Such evaluation is carried out considering seven different active management scenarios as listed in Table 2.

The scenarios consider combinations of three active management options: coordinated OLTC voltage control, energy curtailment and WTs reactive power control. For each scenario, the annual wind energy production and energy losses of the network are examined. In addition, the corresponding optimal capacity allocation of WTs in the network is determined. These results are shown in Figs. 3 and 4 and summarised in Table 3 for scenarios A–D, and in Table 4 for scenarios E–G.

5.1 Scenario A: no active management options

The annual wind energy production reaches 29 864 MWh when no active management strategies are employed. In the

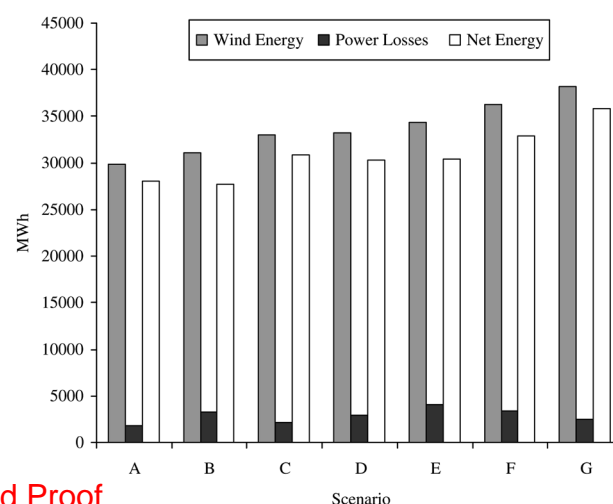


Figure 3 Annual wind energy production and losses

meanwhile, the annual losses of the network rise to 1775 MWh, which is almost 9 times higher than the case when no WTs are connected. The installed capacity is limited by the maximum voltage limit. The network losses are increased significantly as the injected wind power is much higher than the total load demand of the network. Four of the seven WTs would be larger than 2 MW and account for 85% of the total.

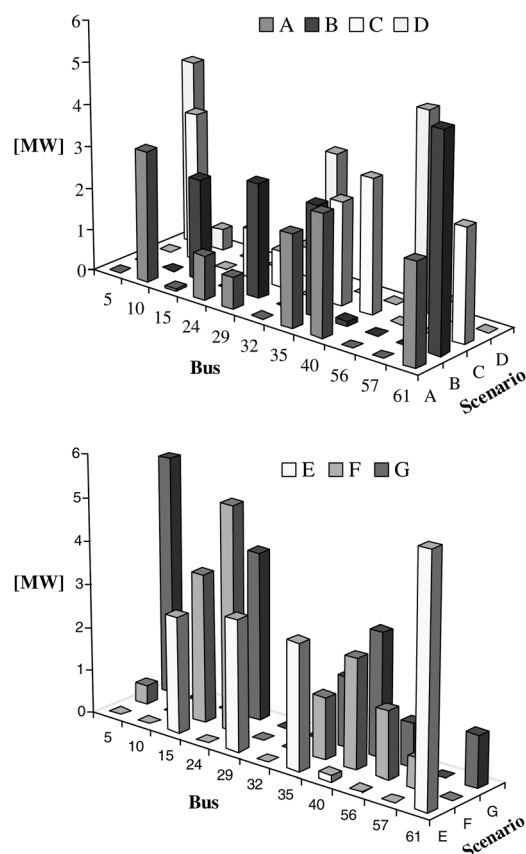


Figure 4 Optimal capacities

Table 2 Different active network management scenarios

| | Coordinated OLTC voltage control | Energy curtailment | Generators reactive power control |
|---|----------------------------------|--------------------|-----------------------------------|
| A | | | |
| B | + | | |
| C | | + | |
| D | | | + |
| E | + | + | |
| F | + | | + |
| G | + | + | + |

Table 3 Optimal capacities, annual wind energy production and losses

| Location | | Scenarios | | | |
|-----------------------------------|--------------------------|-----------|--------|--------|--------|
| | | A | B | C | D |
| capacity, MW | 5 | 0.0 | 0.0 | 0.0 | 4.4 |
| | 10 | 3.1 | 0.0 | 3.6 | 0.5 |
| | 15 | 0.1 | 2.4 | 0.0 | 0.0 |
| | 24 | 1.1 | 0.0 | 1.2 | 0.0 |
| | 29 | 0.8 | 2.7 | 0.9 | 0.7 |
| | 32 | 0.0 | 0.0 | 0.0 | 3.2 |
| | 35 | 2.2 | 2.6 | 2.5 | 0.0 |
| | 40 | 2.9 | 0.1 | 3.2 | 0.0 |
| | 56 | 0.0 | 0.0 | 0.0 | 4.8 |
| | 57 | 0.0 | 0.0 | 0.0 | 0.5 |
| | 61 | 2.5 | 5.2 | 2.7 | 0.0 |
| | total | 12.6 | 13.1 | 14.0 | 14.1 |
| objective function breakdown, MWh | wind energy | 29 864 | 31 068 | 33 069 | 33 239 |
| losses, MWh | losses | 1775 | 3330 | 2163 | 2901 |
| | (wind energy) – (losses) | 28 089 | 27 738 | 30 906 | 30 338 |

Table 4 Optimal capacities, annual wind energy production and losses

| Location | | Scenarios | | |
|-----------------------------------|--------------------------|-----------|--------|--------|
| | | E | F | G |
| capacity, MW | 5 | 0.0 | 0.4 | 5.5 |
| | 10 | 0.0 | 0.0 | 0.1 |
| | 15 | 2.7 | 3.4 | 0.0 |
| | 24 | 0.0 | 5.2 | 3.9 |
| | 29 | 3.0 | 0.0 | 0.0 |
| | 32 | 0.0 | 0.0 | 0.0 |
| | 35 | 2.9 | 1.4 | 1.6 |
| | 40 | 0.1 | 2.5 | 2.9 |
| | 56 | 0.0 | 1.6 | 1.0 |
| | 57 | 0.0 | 0.7 | 0.0 |
| | 61 | 5.8 | 0.0 | 1.2 |
| | total | 14.6 | 15.3 | 16.2 |
| objective function breakdown, MWh | wind energy | 34 403 | 36 294 | 38 272 |
| losses, MWh | losses | 4044 | 3434 | 2482 |
| | (wind energy) – (losses) | 30 359 | 32 860 | 35 790 |

5.2 Scenario B: coordinated OLTC voltage control

As compared to scenario A, the annual wind energy production is increased by around 4% and, because of the increment of reverse power flow during low demand–maximum generation periods, the total network losses are increased by around 87%. As the increment of the losses is higher than the increment of the produced energy, the difference between wind energy and network losses, here named ‘net energy’, declines to 1%. The installed capacity is limited by the transformers thermal constraint. This active management scheme tends to concentrate about 40% of the total WT’s capacity at bus 61, whereas the remaining 60% is connected at buses 15, 29 and 35.

5.3 Scenario C: energy curtailment

The annual energy produced reaches 33 069 MWh and is increased by around 11% as compared to scenario A. In the meanwhile, annual losses increase by around 22%, if compared to the scenario A, and decrease by around 35%, if compared to the scenario B. This is due to energy curtailment that allows reducing reverse power flow during low demand–maximum generation periods. The net energy increases by approximately 10% if compared to the scenario A. Four of the seven WT’s (at buses 10, 35, 40 and 61) are larger than 2 MW, which account for 86% of the total capacity. The installed capacity is limited by voltage constraints. The total curtailed energy is around 112 MWh, which is 0.36% of the total produced energy.

5.4 Scenario D: WT’s reactive power control

As compared to scenario A, the annual energy production in scenario D is increased by around 11%, and the total network losses are increased by around 63%. Consequently, the net energy is increased by approximately 8%. The installed capacity is limited by the transformers thermal constraint. This active management scheme tends to concentrate WT’s capacity at bus 5 (about 32% of the total), at bus 56 (about 34% of the total) and at bus 32 (about 34% of the total). Owing to WT’s reactive power control, the power factors used by the WT’s vary according to the demand and generation levels. WT’s tend to generate reactive power during high demand–minimum generation periods and to absorb reactive power during low demand–maximum generation periods. In particular, during low demand–maximum generation periods, WT’s absorb reactive power with power factors equal or close to the specified limit in order to satisfy voltage constraints.

5.5 Scenario E: coordinated OLTC voltage control and energy curtailment

The annual energy production reaches 34 403 MWh and is increased by around 15% as compared to scenario A. Nevertheless, annual losses reach 4044 MWh, with an increase of around 128% if compared to the scenario A

and by around 87% if compared to scenario C. The net energy is increased by 8%. Thus, with the addition of the coordinated OLTC voltage control to the energy curtailment option, the increase in losses outweighs the higher wind energy production. This leads to a lower net energy as compared to the scenario C, where only energy curtailment scheme is assumed. The total curtailed energy is around 116 MWh, which is 0.38% of the total produced wind energy. Four of the seven WT’s (at buses 15, 29, 35 and 61) are larger than 2 MW, which account for 99% of the total capacity that is limited by the transformers thermal constraint.

5.6 Scenario F: coordinated OLTC voltage control and generators reactive power control

As compared to scenario A, the annual energy production in scenario F is increased by around 21%, and the total network losses are increased by around 93% with a net energy increased by 17%. Five of the seven WT’s (at buses 15, 24, 35, 40 and 56) would be larger than 1 MW, which accounts for 93% of the total capacity that is limited by voltage constraints.

5.7 Scenario G: coordinated OLTC voltage control, generators reactive power control and energy curtailment

The annual energy production reaches 38 272 MWh and is increased by around 28% as compared to scenario A. Annual losses are increased by around 40% and the net energy is increased by 27%. The total curtailed energy is around 129 MWh, which is 0.36% of the total produced wind energy. The installed WT’s capacity of about 16.2 MW is concentrated in six of the seven WT’s (at buses 5, 24, 35, 40, 56 and 61) with capacities larger than 1 MW and is limited by the short-circuit constraint, mainly due to the high wind capacity of about 5.5 MW installed at bus 5 that is connected to the MV/LV substation through low impedance wires.

5.8 WT’s short-circuit-level contribution

The short-circuit-level contribution of the upstream grid is 141.62 MVA, whereas the WT’s provide different short-circuit contributions in the considered scenarios, as shown in Table 5. The lower short-circuit contributions observed in scenarios B and E are mainly due to the higher installed capacities at buses 15 and 29, characterised by high impedances of the wires connecting these buses to the MV/LV substation.

6 Discussion

Simulation results show that the active management schemes are able to increase the total amount of wind energy exploitation. Different active management schemes provide different optimal solutions to the location and size of WT’s. If the locations of WT’s are restricted to certain buses, a

Table 5 Short-circuit levels

| Scenarios | Short-circuit level | | | | | | |
|-----------------------|---------------------|--------|--------|--------|--------|--------|--------|
| | A | B | C | D | E | F | G |
| WTs contribution, MVA | 51.60 | 35.55 | 54.28 | 51.60 | 37.01 | 53.11 | 58.38 |
| total, MVA | 193.22 | 177.17 | 195.90 | 193.22 | 178.63 | 194.73 | 200.00 |

corresponding active management scheme can be selected on the basis of the presented MP-OPF.

It is worth pointing out that, in order to select the most appropriate active management scheme, each scheme or a combination of them should be evaluated considering the economic profits under different scenarios. For the evaluation of the economic feasibility of each scheme, the main factors to be considered include reduction in network power losses, increment of renewable energy production, deferral of network investment and the benefits compared to traditional network reinforcement strategies. These factors should be carefully examined to evaluate the feasibility of a project before carrying out investments. Some researches [23, 27, 30] evidenced the economic benefits of active management as compared with traditional network reinforcement strategies, pre-figuring a widespread implementation of active management in future distribution networks.

In the near future, active management is thus expected to provide higher profits to the DG developers by allowing them connecting more WTs. It will represent an effective and indispensable solution for DNOs to integrate and operate WTs in distribution networks and to defer network investments caused by annual load growth and/or DG connections [23, 30]. It will, therefore, contribute to reducing the tensions between DG developers, who aim at maximising their profits by increasing energy production, and DNOs, who aim at minimising network operating and investment costs [3, 6].

Nevertheless, practical implementation of active management schemes requires additional commercial arrangements and financial evaluations. New market rules should be implemented to offer economic benefits to DNOs in order to drive them to provide the active management service to DG developers. In the case of renewable DG, these rules should also take into account the contribution of active management to achieve government targets associated with renewable sources. On the other hand, new revenue mechanisms should be developed so that DG developers and DNOs share the benefits as well as the costs of active management [3, 6].

In this paper, wind energy production is maximised in order to achieve government targets associated with renewable sources, however, the proposed method can be easily reformulated with other objectives and adapted to

different revenue mechanisms adopted for the DNOs. These objectives can be the minimisation of power losses from the perspective of DNOs [4] or the maximisation of the benefits due to the deferment of investments [6].

Further simulations with larger networks, not presented here, have demonstrated the scalability of the proposed method and its applicability to larger networks [6]. The method is also able to cope with a larger number of control variables [6, 18] and although this will lead to an increase in the computing time, this is not a constraint as the method is intended for long-term planning studies. Different types of WTs (with different power curves) and different load profiles (by considering a mix of industrial, commercial and residential customers) for each node can be easily introduced in the method. Moreover, different wind profiles for each candidate bus can be introduced.

7 Conclusions

This paper evaluates the maximum wind energy exploitation in active distribution networks using a MP-OPF method. The proposed method has been demonstrated on a 69-bus distribution network. The load and wind power data are measured from a Danish distribution system.

Simulation results, considering different active management schemes, confirmed that the proposed method allows finding the optimal allocation of WT capacities, and thus can be used to assist network operators during system planning processes. Furthermore, the method is able to explore the maximum wind energy that can be delivered through the network with different active management options.

8 References

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