# Multi-Stage Power Distribution Planning to Accommodate High Wind Generation Capacity

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***Abstract*—The increasing integration of wind power and other distributed energy resources into modern power distribution systems has made the power distribution planning (PDP) a very interesting and challenging optimization problem. This paper proposes a long-term, multi-stage PDP method for the optimal reconductoring of feeders in order to efficiently meet the load growth demand and optimally accommodate a high wind generation capacity. The proposed PDP method considers various active network management (ANM) schemes and it is formulated as a mixed-integer quadratically constrained programming problem. Results on an 18-bus test system indicate that the proposed PDP method can efficiently accommodate high wind generation capacity with simultaneous reduction of the network investment and operational costs, highlighting the importance of ANM.**

***Index Terms*—Multi-stage planning, network reinforcement, power distribution planning, MIQCP, wind power.**

## I. Nomenclature

*Sets*

| | |
|---|---|
| $N$ | set of buses |
| $T$ | planning period |

*Parameters*

| | |
|---|---|
| $b_{ij,a}$ | susceptance of type $a$ feeder between buses $i$ and $j$, $\Omega^{-1}$ |
| $C_a$ | installation cost of conductor $a$, \$/km |
| $C_L$ | upgrade cost of substation, \$/MWh |
| $g_{ij,a}$ | conductance of type $a$ feeder between buses $i$ and $j$, $\Omega^{-1}$ |
| $I_a^{\max}$ | maximum current magnitude of conductor $a$, A |
| $L_{ij}$ | length of feeder between busses $i$ and $j$, km |
| $P_{D,i}$ | active power demand of bus $i$, MW |
| $Q_{D,i}$ | reactive power demand of bus $i$, MVar |
| $r$ | interest rate |
| $S_{wdg,i}$ | rated wind apparent power at bus $i$, MVA |
| $U^{\min}/U^{\max}$ | min/max voltage magnitude squared, $V^2$ |
| $\phi^{\min}/\phi^{\max}$ | min/max angle of the DG unit's power factor |

*Variables*

| | |
|---|---|
| $CF_i$ | curtailment factor of the wind generation at bus $i$ |
| $E_{Losses}$ | annual energy losses, MWh |
| $I_{ij}$ | current magnitude between buses $i$ and $j$, A |
| $P_{G,i}$ | active power generation of bus $i$, MW |
| $P_{wdg,i}$ | active wind power generation of bus $i$, MW |
| $Q_{G,i}$ | reactive power generation of bus $i$, MVar |
| $Q_{wdg,i}$ | reactive wind power generation of bus $i$ , MVar |
| $U_i$ | voltage magnitude squared of bus $i$, $V^2$ |
| $V_i$ | voltage magnitude of bus $i$, V |
| $z_{a(i,j)}^t$ | binary variable for the placement of type $a$ feeder between buses $i$ and $j$ at year $t$. |
| $\theta_i$ | Angle of bus $i$, degrees |
| $\phi_i$ | Angle of the DG unit's power factor at bus $i$, rad |

## II. Introduction

The main objective of the power distribution planning (PDP) is to design the distribution network in order to efficiently meet the load growth demand. The PDP problem determines the optimal location and size (capacity) of future substations and/or feeders in the most economic and reliable way. In the last years, the high penetration of distributed generation (DG) technologies, energy storage and the active demand response have transformed the PDP into a more complicated and challenging problem. The PDP constitutes a mixed-integer non linear programming problem (MINLP).

A comprehensive review of PDP models and methods can be found in [1]–[3]. The PDP can be modeled either as a static or as a multi-stage problem. In the static (or single-stage) PDP, the solution is determined in only one stage of the planning period, while in the multi-stage PDP, the planning requirements are determined in successive stages along the planning period. In [4] and [5], the PDP problem is simplified to a mixed-integer linear programming (MILP) problem and a multi-stage planning scheme investigates the impact of dispatchable distributed generation (DDG) for various load levels. The multi-stage PDP with the integration of DDG is also solved by the discrete particle swarm optimization (DPSO) method [6] and by a back propagation approach based on a cost-benefit analysis [7]. Furthermore, the high penetration of renewable energy sources (RES) has exposed the PDP in further challenges. In [8], the trade-offs between the optimal DG placement and the conventional grid reinforcement are evaluated through a multi-objective optimization scheme and the importance of tariff schemes is highlighted. In [9], the proposed PDP method based on a genetic algorithm (GA) suggests that the joint integration of RES and demand response leads to planning solutions with smaller investment cost on network components and with higher environmental benefits than integrating RES alone.

The passive operation of the distribution systems and the uncertain generation output of the RES may lead to further investment costs on new or existing feeders in order to avoid overloads due to strong generation. The installation of energy storage systems (ESSs) could alleviate the negative effects of intense generation, but their installation cost is high and certain incentives should be given in order to be profitable. On the other hand, the adoption of active network management (ANM) schemes, such as Volt/VAR control, generation curtailment, real-time reconfiguration, etc., could reduce the investments on new network components.

This paper deals with the multi-stage distribution system planning in the presence of high wind generation capacity considering ANM, such as DG reactive control and generation curtailment. The planning horizon is divided into successive stages and the proposed model defines the optimal conductor size of the network's feeders in order to efficiently meet the load growth demand and optimally accommodate high wind generation capacity. To decrease the computational burden the PDP problem is formulated as a mixed-integer quadratically constrained programming (MIQCP) problem, appropriately adopting the general methodology of [10]. An 18-bus test system [11] is used to demonstrate the efficiency of the proposed method.

## III. PROBLEM FORMULATION

For the PDP problem, the following assumptions are taken into account:

- The planning period is divided into stages with fixed duration. The planning decision on feeders' reconductoring can be taken in each stage.
- The distribution network topology is fixed and no additional buses are considered to be added during the planning period.
- All DG units are a private investment, which means that the location and size of these units are known and they are decided by the private investor in accordance with the technical rules set by the Distribution System Operator (DSO).
- The profile of a typical day with an hourly time frame is assumed to represent the load demand and its corresponding uncertainties are modeled with the normal probability distribution function (pdf).
- Weibull pdf is used to capture the uncertainties of the wind velocity and, thus the uncertainties of the wind generation.
- The selection of the feeders' conductor size is determined for the maximum stress conditions. As maximum stress conditions the maximum load with no generation and the minimum load with maximum generation are considered.
- The determination of the energy losses is obtained through a probabilistic power flow analysis.
- The Active management is limited: a) to the coordinated active and reactive dispatch of the DG units and b) to the generation curtailment of the DG.

The proposed method deals with the minimization of the investment cost in feeders' reconductoring and the minimization of the operational costs during a long term planning period. The PDP problem is modeled as MIQCP with the objective function (1) subject to the constraints (5)–(12).

$$\min f = \sum_{t \in T} \frac{1}{(1+r)^t} \left( \sum_{i,j \in N} \left( C_a \cdot L_{ij} \cdot z^t_{a_{(i,j)}} \right) + C_L \cdot E_{Losses} \right) \quad (1)$$

The first part of the objective function (1) represents the investment cost of the feeders' reconductoring and the second part represents the cost of the energy losses.

The $2N$ nonlinear power flow equations are replaced with $2N$ linear equations (5), (6) and $N$ quadratic constraints (7), as follows $(\forall i, j \in N)$:

$$U_i = V_i^2 \quad (2)$$

$$W_{ij} = V_i \cdot V_j \cdot \cos(\theta_i - \theta_j) \quad (3)$$

$$H_{ij} = V_i \cdot V_j \cdot \sin(\theta_i - \theta_j) \quad (4)$$

$$P_{G,i} + P_{wdg,i} - P_{D,i} = \sum_{i,j \in N} \left( g_{ij,a} \cdot U_i + g_{ij,a} \cdot W_{ij} - b_{ij,a} \cdot H_{ij} \right) \quad (5)$$

$$Q_{G,i} + Q_{wdg,i} - Q_{D,i} = -\sum_{i,j \in N} \left( b_{ij,a} \cdot U_i - b_{ij,a} \cdot W_{ij} + g_{ij,a} \cdot H_{ij} \right) \quad (6)$$

$$U_i \cdot U_j - W_{ij}^2 - H_{ij}^2 = 0 \quad (7)$$

The remaining inequality constraints of the optimization procedure are as follows:

$$I_{ij}^2 = (g_{ij,a}^2 + b_{ij,a}^2) \cdot (U_i + U_j - 2W_{ij}) \quad \forall i, j \in N \quad (8)$$

$$I_{ij}^2 \le \left( I_a^{\max} \right)^2 \cdot z^t_{a_{(i,j)}} \quad \forall i, j \in N \quad (9)$$

$$U^{\min} \le U_i \le U^{\max} \quad \forall i \in N \quad (10)$$

$$\sum_{t\in T}\sum_{i,j\in N} z^{t}_{a_{(i,j)}} \leq 1 \qquad \forall i,j \in N \tag{11}$$

$$z^{t}_{a_{(i,j)}} \in \{0,1\} \tag{12}$$

The active and reactive power balance of the system is given in (5) and (6), respectively. The square of the current magnitude is calculated according to (8). The limit of the current flow of the branch with conductor type *a* that connects bus *i* to *j* is represented by (9). Constraint (10) represents the limits of the voltage magnitude for all system's buses. In order to ensure that there will be at most one change on every feeder's conductor type during the whole planning period, constraint (11) is applied. Constraint (12) depicts the binary nature of the decision variable $z^{t}_{a_{(i,j)}}$. A conductor type *a* is selected (not selected) for the branch that connects bus *i* to *j* during the year *t* if the corresponding value of (12) equals to one (zero).

The PDP problem described by (1) and (5)–(12) refers to the passive management of the distribution system, in which no active management of the wind generation units is applied. In this paper, different ANM schemes are incorporated for the solution of PDP problem.

### A. Reactive Power Control of the Wind Generation

The coordinated active and reactive power dispatch of the wind generation units can be beneficial for the distribution systems by preventing some constraint violation and by possibly deferring investments on new network components. Considering the small angle approximation for the power factor of the DG units, the ANM scheme can be implemented in the optimization procedure by modifying (5) and (6):

$$\sin\phi_i \approx \phi_i \tag{13}$$

$$\cos\phi_i \approx 1-\frac{\phi_i^2}{2} \tag{14}$$

$$S_{wdg,i} = \sqrt{P^2_{wdg,i} + Q^2_{wdg,i}} \tag{15}$$

$$P_{wdg,i} = S_{wdg,i}\cdot\left(1-\frac{\phi_i^2}{2}\right) \tag{16}$$

$$Q_{wdg,i} = S_{wdg,i}\cdot\phi_i \tag{17}$$

$$P_{G,i} + S_{wdg,i}\cdot\left(1-\frac{\phi_i^2}{2}\right) - P_{D,i} = \sum_{i,j\in N}\left(g_{ij,a}\cdot U_i + g_{ij,a}\cdot W_{ij} - b_{ij,a}\cdot H_{ij}\right) \tag{18}$$

$$Q_{G,i} + S_{wdg,i}\cdot\phi_i - Q_{D,i} = -\sum_{i,j\in N}\left(b_{ij,a}\cdot U_i - b_{ij,a}\cdot W_{ij} + g_{ij,a}\cdot H_{ij}\right) \tag{19}$$

$$\phi^{\min} \leq \phi_i \leq \phi^{\max} \tag{20}$$

For small values of the angle $\phi_i$ in radians, its sine and cosine can be approximated with (13) and (14), respectively, with relatively small error. Therefore, the apparent, active and reactive power of the wind generators are given by (15), (16) and (17), respectively. Equations (5) and (6) that represent the active and reactive power balance can be modified to (18) and (19), respectively. The range of the wind generator's power factor is represented by (20). For example, if the power factor of a wind generator varies from 0.9 inductive to capacitive, the value of $\phi_i$ varies from $-25.84^\circ$ to $25.84^\circ$. Thus, the PDP problem with the control of the power factor of the DG units is modeled as MIQCP problem with the objective function (1) subject to (7)–(12), (15)–(20).

### B. Generation Curtailment of the Wind Generation

The adoption of the generation curtailment of the wind generation as an ANM scheme can limit the overloads caused by high generation. This strategy can decrease the wind generation output according to (22) in order to avoid any constraint violation and it could lead to zero additional investment costs. However, high amounts of curtailed wind generation should be compensated to the DG investors depending on the regulation. Thus, only moderate generation curtailment could actually benefit the DSOs.

The generation curtailment could easily be adopted in the optimization procedure by adding a continuous variable as curtailment factor to the active power balance (5) of the system, as follows:

$$P_{G,i} + P_{wdg,i}\cdot CF_i - P_{D,i} = \sum_{i,j\in N}\left(g_{ij,a}\cdot U_i + g_{ij,a}\cdot W_{ij} - b_{ij,a}\cdot H_{ij}\right) \tag{21}$$

$$0 \leq CF_i \leq 1 \tag{22}$$

The PDP problem considering generation curtailment as active management is formulated by (1) subject to (6)–(12), (21)–(22).

## IV. Results and Discussion

The proposed model for the long-term dynamic distribution system planning is tested in an 18-bus test system [11], shown in Fig. 1, in order to investigate its performance. The conductor type of the lines, the length of the lines and the load demand of every bus in the reference year are shown in Table I. The available conductors during the planning period are presented in Table II. The examined planning period is 10 years and the load growth rate is considered 3% per year. The interest rate is equal to 7.5% and the cost of energy losses is 50 \$/MWh. During the planning period, it is planned to be installed a wind farm with rated capacity 4MVA at bus 8 during the second year of the planning period and another wind farm with rated capacity 4 MVA at bus 26 during the sixth year of the planning period.

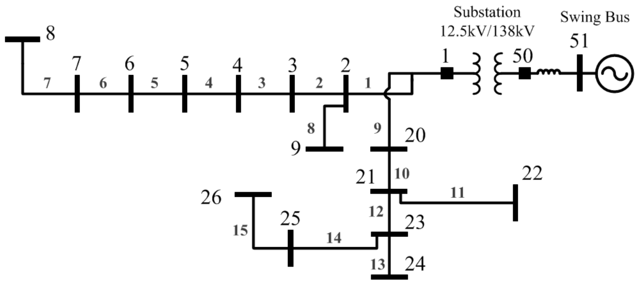


Figure 1. 18-bus test system.

TABLE I. 18-BUS TEST SYSTEM DATA FOR THE REFERENCE YEAR

| # | Bus | | Conductor Type | Length (km) | $P_j$ (MW) | $Q_j$ (MVar) |
|---|---|---|---|---|---|---|
| | From $i$ | To $j$ | | | | |
| 1 | 1 | 2 | 4 | 0.51 | 0.20 | 0.12 |
| 2 | 2 | 3 | 4 | 0.71 | 0.40 | 0.25 |
| 3 | 3 | 4 | 4 | 0.37 | 1.50 | 0.93 |
| 4 | 4 | 5 | 3 | 1.06 | 3.00 | 2.26 |
| 5 | 5 | 6 | 1 | 0.35 | 0.80 | 0.50 |
| 6 | 6 | 7 | 1 | 0.73 | 0.20 | 0.12 |
| 7 | 7 | 8 | 1 | 0.91 | 1.00 | 0.62 |
| 8 | 2 | 9 | 1 | 0.73 | 0.50 | 0.31 |
| 9 | 1 | 20 | 2 | 1.23 | 1.00 | 0.62 |
| 10 | 20 | 21 | 1 | 0.94 | 0.30 | 0.19 |
| 11 | 21 | 22 | 1 | 2.04 | 0.20 | 0.12 |
| 12 | 21 | 23 | 1 | 1.69 | 0.80 | 0.50 |
| 13 | 23 | 24 | 1 | 1.24 | 0.50 | 0.31 |
| 14 | 23 | 25 | 1 | 1.59 | 1.00 | 0.62 |
| 15 | 25 | 26 | 1 | 0.94 | 0.20 | 0.12 |

TABLE II. TECHNICAL CHARACTERISTICS OF AVAILABLE CONDUCTORS

| Type | R (Ω/km) | X (Ω/km) | Thermal limit (MVA) | Investment cost ($10^3$ $/km) |
|---|---|---|---|---|
| 1 | 1.05 | 0.3833 | 4.80 | 8.10 |
| 2 | 0.728 | 0.3725 | 6.00 | 9.60 |
| 3 | 0.465 | 0.3587 | 7.90 | 12.30 |
| 4 | 0.323 | 0.3478 | 9.85 | 15.00 |
| 5 | 0.291 | 0.3437 | 10.52 | 16.90 |
| 6 | 0.23 | 0.3317 | 12.17 | 18.90 |
| 7 | 0.173 | 0.3227 | 14.50 | 21.60 |

The load profile of each bus is consisted of different load levels, as shown in Fig. 2, and each load level represents the mean value of the load demand for certain duration with standard deviation assumed to be 10% of the mean value. The technical characteristics of the available wind turbines are $V_{ci} = 4\ m/s$, $V_n = 15\ m/s$ and $V_{co} = 25\ m/s$ and the shape and scale factor of the Weibull pdf are considered 1.93 and 7.94, respectively.

Three scenarios have been examined for the solution of the PDP. In Scenario I, the PDP is solved without considering any control on the wind generation output (passive management) and the results are shown in Table III. In Scenario II, the PDP is solved considering the control of the reactive output power of the wind generation units and the results are given in Table IV. In Scenario III, the adoption of the wind generation curtailment is considered for the solution of the PDP and the results are shown in Table V.


Figure 2. Load profile.

Scenario I yields the solution with the higher investment cost and with the higher energy losses compared with the other two scenarios. The lack of control of the wind generation output can have negative effects on the planning of the distribution system. The overloads caused by high wind generation and minimum load demand leads to the reconductoring of some of the existing feeders. On the other hand, the application of active management in the PDP leads to solutions with lower investment and operational costs as shown in Tables IV and V. From the ANM schemes that were examined in this paper, the most promising results were given by the adoption of the generation curtailment (Scenario III). The application of generation curtailment to the wind generators results to a planning solution with 35.5% lower investment cost and 14.6% lower operation cost compared with the planning solution of Scenario I (passive management) of the distribution system. Furthermore, the reactive output power control of the wind generators also benefits the planning of the distribution system as shown in Table IV, since it results to a planning solution with reduced investment cost on network components and with lower annual energy

TABLE III. PLANNING SOLUTION OF SCENARIO I (PASSIVE MANAGEMENT)

| # | Bus | | Conductor Type | Year for line reconductoring |
|---|---|---|---|---|
| | From $i$ | To $j$ | | |
| 1 | 1 | 2 | 6 | 3 |
| 2 | 2 | 3 | 5 | 5 |
| 3 | 3 | 4 | 5 | 7 |
| 4 | 4 | 5 | 4 | 7 |
| 5 | 5 | 6 | 1 | – |
| 6 | 6 | 7 | 2 | 2 |
| 7 | 7 | 8 | 2 | 2 |
| 8 | 2 | 9 | 1 | – |
| 9 | 1 | 20 | 3 | 5 |
| 10 | 20 | 21 | 2 | – |
| 11 | 21 | 22 | 1 | – |
| 12 | 21 | 23 | 2 | 3 |
| 13 | 23 | 24 | 1 | - |
| 14 | 23 | 25 | 2 | 6 |
| 15 | 25 | 26 | 2 | 6 |
| **Investment Cost ($)** | | | 82 689 | |
| **Cost of Energy Losses ($)** | | | 107 410 | |
| **Total Cost ($)** | | | 190 099 | |

TABLE IV. PLANNING SOLUTION OF SCENARIO II (REACTIVE POWER CONTROL OF WIND GENERATION)

| # | Bus | | Conductor Type | Year for line reconductoring |
|---|---|---|---|---|
| | **From *i*** | **To *j*** | | |
| 1 | 1 | 2 | 6 | 3 |
| 2 | 2 | 3 | 5 | 5 |
| 3 | 3 | 4 | 5 | 7 |
| 4 | 4 | 5 | 4 | 7 |
| 5 | 5 | 6 | 1 | – |
| 6 | 6 | 7 | 1 | – |
| 7 | 7 | 8 | 2 | 2 |
| 8 | 2 | 9 | 1 | – |
| 9 | 1 | 20 | 3 | 5 |
| 10 | 20 | 21 | 2 | – |
| 11 | 21 | 22 | 1 | – |
| 12 | 21 | 23 | 2 | 3 |
| 13 | 23 | 24 | 1 | – |
| 14 | 23 | 25 | 1 | – |
| 15 | 25 | 26 | 2 | 6 |
| **Investment Cost ($)** | | | 66 745 | |
| **Cost of Energy Losses ($)** | | | 98 020 | |
| **Total Cost ($)** | | | 164 765 | |

TABLE V. PLANNING SOLUTION OF SCENARIO III (WIND GENERATION CURTAILMENT)

| # | Bus | | Conductor Type | Year for line reconductoring |
|---|---|---|---|---|
| | **From *i*** | **To *j*** | | |
| 1 | 1 | 2 | 6 | 3 |
| 2 | 2 | 3 | 5 | 5 |
| 3 | 3 | 4 | 5 | 7 |
| 4 | 4 | 5 | 4 | 7 |
| 5 | 5 | 6 | 1 | – |
| 6 | 6 | 7 | 1 | – |
| 7 | 7 | 8 | 1 | – |
| 8 | 2 | 9 | 1 | – |
| 9 | 1 | 20 | 3 | 5 |
| 10 | 20 | 21 | 2 | – |
| 11 | 21 | 22 | 1 | – |
| 12 | 21 | 23 | 2 | 3 |
| 13 | 23 | 24 | 1 | – |
| 14 | 23 | 25 | 1 | – |
| 15 | 25 | 26 | 1 | – |
| **Investment Cost ($)** | | | 53 315 | |
| **Cost of Energy Losses ($)** | | | 91 711 | |
| **Total Cost ($)** | | | 145 026 | |

losses compared with the planning solution of Table III.

Fig. 3 illustrates the impact of the integration of different wind generation capacities on the investment cost on network components made by the DSO for the aforementioned planning strategies. The planning strategy that preserves the passive management of the distribution system leads to near linear increase of the network investment costs as the capacity of the wind generation increases. The implementation of the reactive control of the wind generators also results to linear increase of the network investment costs. However, the results of this ANM scheme are more beneficial for the system than the preservation of the passive management.

The ANM scheme that would allow a significant deferral of the investment costs, as shown in Fig. 3, is the curtailment of the active wind generation. This strategy allows theoretically the cut-off of every wind generator up to its total generation (100% generation curtailment) for preserving the non viola-

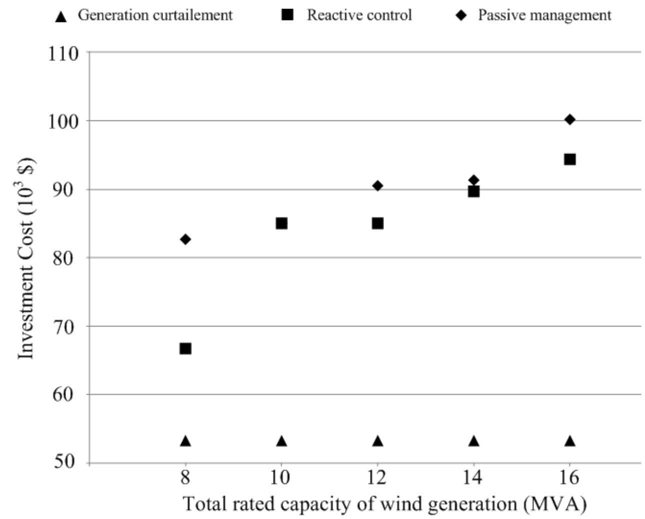


Figure 3. Network investment cost made by DSO to accommodate various rated wind generation capacities for the 18-bus system for different network management schemes.

tion of the technical constraints of the network. . Unlike the reactive power support, a major curtailment of the wind generation could cause loss of profit for the owner of the DG units and the DSO may have to refund the owner, depending on the regulatory framework. Fig. 4 shows the total wind energy curtailed as a percentage of the total wind generation for different rated capacities of wind generators. As it was expected when the installed rated capacity of the wind generation is relatively small (8MVA) the energy curtailed is estimated to be 3.05% of the total energy produced from the wind generation units in order to achieve the planning solution with the lower investment cost. This ratio increases significantly as the installed capacity of the wind generation increases. If the curtailed wind energy is compensated, this ANM may not be profitable for the DSO. Thus, only a limited

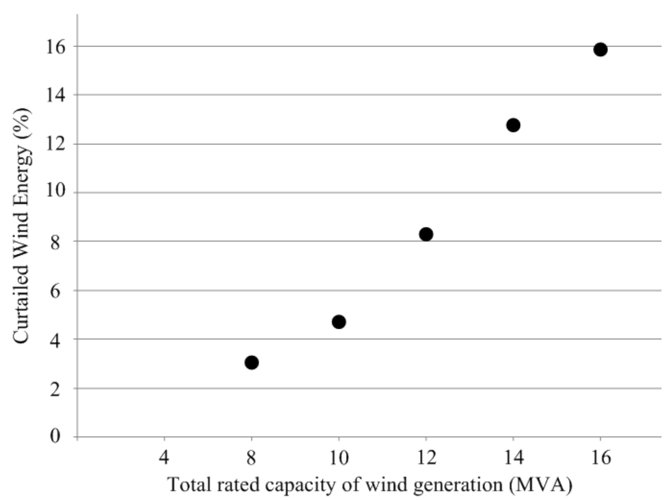


Figure 4. Total wind energy curtailed (%) as a percentage of the total wind generation for different rated capacities during the planning period.

generation curtailment in extreme and rare conditions could be beneficial in practice for the DSO.

## V. CONCLUSION

A mixed integer quadratically constrained programming model was presented in this paper for the solution of the multi-stage PDP problem considering active management of the installed wind generation units. The examined ANM schemes include the reactive control of the wind generators and the wind generation curtailment. The results show that including the operational aspects of the active management in the power distribution planning can lead to solutions with lower network investment cost and with decreased energy losses compared with the traditional passive management of the distribution systems. Even though the generation curtailment yielded the best results, the compensation of the curtailed wind energy may be a reason for not applying this planning strategy.


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