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MINIMIZE DISTRIBUTION NETWORK LOSSES USING WIND POWER

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Abstract

The increased penetration of weather-dependent distributed generation, such as wind power plants and photovoltaics, in distribution networks, presents new challenges for the distribution system operators to improve their networks' operation by effectively utilizing the available resources. A higher amount of distributed generation also directly translates to more power losses in the network. In this regard, wind power plant capabilities can prove valuable to avoid network congestion, maintain supply and reduce network losses. This paper aims to minimize losses in distribution networks with a large share of wind power plants by optimizing the reactive power flow through the distribution networks by controlling reactive power set-points of wind power plants using genetic-algorithm based optimization. The study is conducted on a real Danish distribution network, with a large share of controllable wind power plants, under varying wind and load conditions using actual measurements. The results show that the reactive power support from wind power plants can reduce network losses by $\approx 2.5\,\%$ (103 MWh) with a 0.25 % uncertainty in the mean loss reduction. However, the uncertainty in loss reduction depends on the loss in the network without using wind power plant capabilities. This work successfully demonstrates that the control capability of wind power plants can support distribution system operators by reducing losses in distribution networks.

1 Introduction

The involvement of weather-dependent generation sources in the electricity grid is increasing as a result of rising awareness towards climate change. Wind power plants (WPPs) and photovoltaic systems (PVs) connected to distribution networks are amongst the most widely deployed weather-dependent distributed generation (DG) sources today. The total installed wind capacity in Europe currently was 205 GW in the year 2019 according to [1], while new installation of onshore wind generation and PVs also saw an upward trend in the year 2019 [1, 2]. In Denmark alone, about 3.1 GW ($\approx 50\%$) of total installed wind capacity is distributed wind. The ever increasing share of weather-dependent generation in the distribution grid poses serious challenges to the distribution system operators (DSOs). Thus, it becomes imperative to actively incorporate control capabilities of weather-dependent generation to aid and improve the operation of distribution grids.

According to the European grid codes [3, 4], the DGs are required to share some of the duties carried out today by the conventional power plants, such as providing support to the grid in terms of active power control, reactive power supply, maintaining power quality, fault-ride through capability and protection. The main role for such technical requirements is played today by the power electronics existing inside DGs. At the distribution level, integration of wind turbines (WTs) offer several benefits, like reducing congestions and power losses in the transmission lines, active support in terms of voltage stability, improved load shedding, as discussed in [5]. Due to the current widely available low-cost power electronics, WTs are a prevalent choice among different options of DGs to support the network, especially when the benefits for the DSOs are not only technical but also economical [6].

In spite of the development in DGs' control capabilities over the last decade due to the presence of power electronics, there is still a gap in the effective use of the DG capabilities in distribution networks. For example, the additional electricity production from WTs has an impact on the network losses that may change the reactive power flow and thus the variation of the voltage profile throughout the distribution feeders. Distribution system losses specially have become a greater concern in any power system [7, 8]. An assessment of distribution system losses due to the increased penetration of DGs is presented in [8–11]. Although the network losses decrease at a low level DG penetration, with higher penetration, losses are found to increase up-to 200 % [11]. Several studies have been conducted over the years considering loss minimization in the network with DG [12–16]. For example, authors in [13, 17, 18] focus on DG allocation and placement strategies in order to accommodate maximum amount of DG capacity in the concerned network while facilitating low network losses. An example of determining optimal capacitor locations in the grid with the help of Genetic Algorithm (GA) can be found in [19]. While using reactive power capability of WTs for network loss reduction and voltage stability is also demonstrated in [12, 20**?**]. In case of reactive power regulation in high penetration of wind energy parameters such as optimal setting of reactive power sources including transformer, OLTCs, shunt reactors, capacitors, flexible AC transmission devices (FACTS) and switchable cables are studied to minimize power losses [12]. A compilation of studies on loss minimization using DG allocation, capacitor placement and network reconfiguration can be found in [7]. However, the available literature insufficiently covers the question of loss minimization in a distribution network by using the control capabilities of already existing DGs.

The main objective of this paper to minimize distribution network losses utilizing the reactive power capabilities of WPPs in a real distribution network with measurement data. The presented research is a subsequent study to the loss analysis presented in [9], wherein a detailed analysis of the active and reactive power flows in a real distribution network based on actual measurements, as well as of the co-relation between the consumption, wind power production, and network losses is performed and presented in details. For the purpose of effectively employing control capabilities of the WPPs, Genetic algorithm (GA) is implemented with reactive power set points of the WPPs as control parameters subject to the network constraints. The algorithm is implemented in an offline setup to provide a proof of concept for this research. Section 2 provides a brief overview of the network model, available data for analysis and the optimization algorithm (GA). In addition it also touches upon the implementation of the proposed methodology via a SCADA system. The results of this optimization are presented in Section 3 and relevant conclusions of the investigation are given in Section 4.

2 System Description

An overview of the network model, available real distribution network measurement data and the proposed methodology to minimize losses using reactive power capabilities of WPPs are described in the following.

2.1 Network Model

A real Danish real 60 kV distribution network model, illustrated in Fig. 1, is considered for this investigation. The network model consists of:

- **25 buses rated at 60 kV**
- **23 substations of 60/10 kV**, classified into the following 3 categories,
  1. consumer substations: only consuming active power
  2. prosumer substations with uncontrollable generators consuming and generating active power
  3. prosumer substations with controllable generators consuming and generating active power
- **3 controllable WPPs** rated at 12 MW, 15 MW and 15 MW, respectively. All WPPs consist of WTs equipped with full-scale frequency converters (e.g. Type IV), having thus enhanced reactive power control capabilities.
- **23 OLTC transformers**, consisting of 22 60/10 kV transformers connecting 10 kV load-buses with 60 kV distribution grid buses and one 60/150 kV transformer connecting the 60 kV distribution network to the 150 kV transmission network.
- **22 aggregated loads** connected at 10 kV, including small generation units like WTs, distributed photovoltaic units (PV), combined heat and power plants, etc.

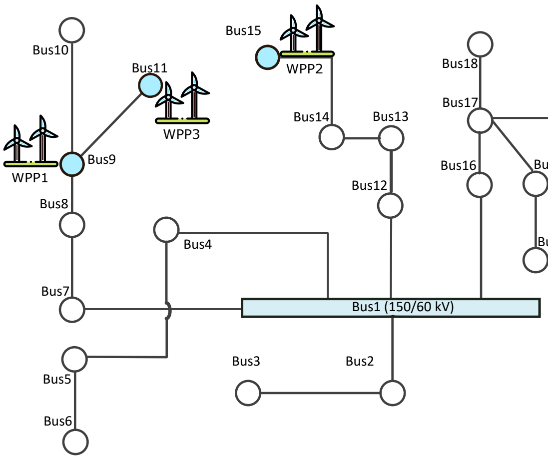

Fig. 1. 60kV Distribution network model

2.2 Available Data

This section describes the available measurement data consisting of load time-series and WPP generation time-series. These data can be categorized into static and dynamic data as follows:

- **Static Data** - are network topology, transformer parameters, WPP parameters, P-Q capability curve of WPP etc.
- **Dynamic Data** - are SCADA measurements of reactive and active power, voltage, and current from 150 kV and 60 kV bus bars and feeders.

The dynamic data is available from December 2014 to September 2015 at a resolution of 1 hour. Table 1 highlights some of the key features of the available data. Notice that the average loading at 150kV substation is -8.19 MW, i.e. a reverse power flow from the distribution to the transmission network. This highlights the high generation capacity available in the distribution network. The maximum generation at the 150 kV substation, i.e. the maximum reverse power flow from the distribution network to transmission network is 103.04 MW which is higher than the maximum consumption by the distribution network at the 150 kV substation, i.e. 58.38 MW. It is worth noticing that, the total installed capacity of controllable WPPs is 45 MW, which is less than the total generation possible from the distribution grid. These numbers indicate that there is a large amount of undetectable generation in the distribution network. Excessive reverse power flow in the distribution network due to high share of WPPs is a leading cause for higher power losses in the network, as also described in [8, 9].

Authors in [9] also present a statistical analysis for the data presented. The results from this analysis indicate a proportional relation between wind power generation and network losses. It

Table 1 Available data characteristics

Max. Loading (Consumption) at 150 kV substation	58.38 MW
Avg. Loading at 150 kV substation	-8.19 MW
Max. Loading (Generation) at 150 kV substation	103.04 MW
Installed Wind Power connected to 60kV	45MW
Max. Wind Power Generation from controllable WPPs	40.6 MW
Avg. Wind Power Generation from controllable WPPs	13.2 MW

is also established that although a high wind power generation occurs for small duration, it contributes for major portion of the energy loss $\approx 70.7\,\%$ [8].

2.3 Methodology implementation - overview

Fig. 2 provides an overview of how the implemented proposed optimization methodology, based on GA, interacts with the distribution network through the DSO SCADA system. The DSO SCADA provides real-time measurements data for the optimization, evaluation, and validation of the proposed methodology. The algorithm, GA in this case, calculates the control variables, namely the reactive power set-points for the WPPs, and relays them back to the SCADA system, which sends them further to the distribution network.

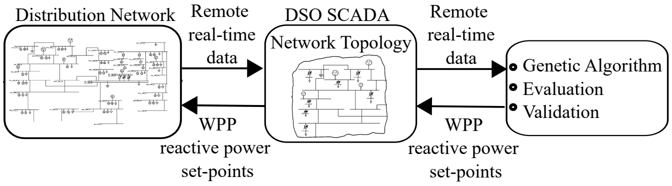

Fig. 2. Implementation Overview

It is worth mentioning that in the present study an offline implementation is performed with the available data to demonstrate the capabilities for loss minimization by controlling WPPs.

2.4 Genetic Algorithm

Genetic Algorithms are a class of stochastic relaxation techniques that are applicable to the solution of a wide variety of optimization problems, by emanating the evolutionary behavior of biological systems. In contrast to sequential methods that generate a single potential solution from the last at every iteration, a genetic algorithm maintains a large population of candidate solutions. Each population is generated from its predecessor by applying a set of stochastic transition operators. During each generation, the fitness of each solution is evaluated, and solutions are selected for reproduction based on their fitness. Selection embodies the principle of 'Survival of the fittest'. 'Good' solutions are selected for reproduction while 'Bad' solution are eliminated. The 'Goodness' of the solution is determined by its fitness value.

The flowchart for the GA is illustrated in Fig.3. The principal objective of this optimization is to minimize the losses in the grid denoted by L. Thus, L equates to the sum of losses in all 60 kV feeders given as,

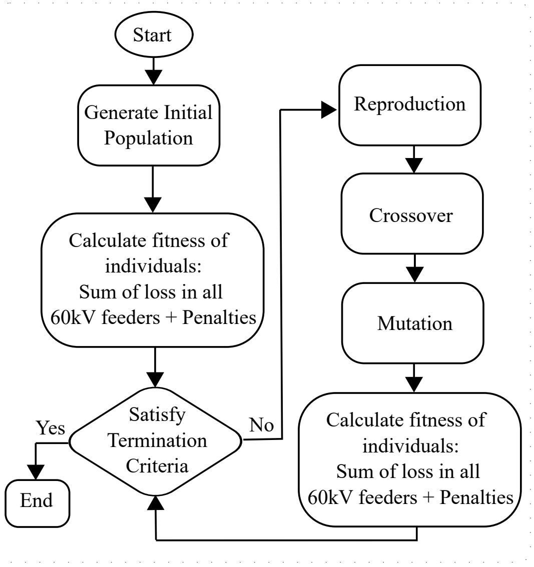

Fig. 3. Genetic Algorithm Flowchart

$$L = \sum P_{loss,60\,kV} \tag{1}$$

The optimization problem is implemented considering a set of constraints, e.g. network constraints and WPP constraints. The loss value L is penalized upon violation of the these constraints.The following network constraints are included in the optimization:

- MVAR flow $\leq$ 0.48 $\times$ MVA capacity of 150 kV /60 kV transformer
- Loading of 60 kV feeders < 100 %
- Loading of 60 kV /10 10 kV transformers < 100 %
- 59 kV < Voltage at 60 kV busbars < 66 kV

The main idea of the proposed optimization methodolody is to allow WPPs to participate through absorbing and supplying reactive power in the minimization of the distribution network losses. In this respect, it is worth underlying that, the reactive power capabilities of WTs are highly dependent on the size of their power electronics. The WPP constraints, determined based on the size of the WTs' power electronics, are given by the following:

$$Q_{WPP_i}^{lower} < Q_{WPP_i} < Q_{WPP_i}^{upper} \tag{2}$$

where $i \in 1,2,3$ in the considered network, $Q_{WPP_i}^{lower}$ and $Q_{WPP_i}^{upper}$ are the lower and upper reactive power bounds for the WPP, respectively, while Q_{WPP_i} is the reactive power set-point of WPP_i.

The following assumptions are considered in the present offline implementation:

- Uncertainty in the measurement data not considered in the calculation
- Since, loss minimization algorithm is time consuming, only 500 randomly chosen samples out of available data are used for statistical analysis for loss minimization. It is assumed that the 500 chosen samples are representative of the entire data.
- In order to reduce the uncertainty in mean loss reduction, the total power loss before optimization is divided into 4 bins (0-500, 500-1000, 1000-1500, >1500) based on power losses, when WPPs capabilities are not use.

The GA terminates when difference between average fitness of the population and maximum fitness reaches less than a certain tolerance value.

3 Result

The proposed optimization method to minimize the losses in distribution networks, by utilizing wind turbines control capabilities is discussed in the following. To calculate the loss reduction due to WPPs actively participating in the distribution grid, the total losses before WPP participation need to be calculated. Table 2 depicts the energy loss results before optimization, namely without WPP participation. Notice that, when WPPs are not used actively to reduce the losses, the considered distribution grid has power losses in the range of 0-500MW for ≈ 72 % of the total time; however, their contribution to the total energy loss is <25 %. It is worth noticing that the maximum contribution to the total energy loss is from the bin with power loss >1500 MW. This is the region of high-generation from WPPs and low-loading in the distribution grid.

Table 2 Energy loss without use of WPP control capabilities

Power Loss [MW]	No. of Hours	Energy Loss [MWh]
0-500	6321	949
500-1000	967	695
1000-1500	674	833
> 1500	798	1539
Sum	8760	4016

The mean and uncertainty in loss reductions along with the energy savings for all bins are tabulated in Table. 3. The energy savings in this table are calculated by taking a difference between the network losses without using WPP capabilities and network losses when WPP capabilities are used. The uncertainties for the loss reduction for all bins are assumed independent of each other. Notice that uncertainty in loss reduction is high for low values of 'loss before optimization' and low for high values of 'loss before optimization'. Fig. 4 gives pictorial depiction of loss reduction in [%] with respect to total loss before optimization for 500 samples selected at random with a scatter plot. The dependence of certainty in loss reduction upon the total loss before optimization can be seen from this figure. For example the percentage loss reduction for lower values of loss before optimization (0-500 MW) varies between 0-23 %, which results in a high loss reduction uncertainty for this bin.

Table 3 Energy savings with use of WPP control capabilities

Power Loss [MW]	Loss Reduction [%] Mean	Loss Reduction [%] Uncertainty	Energy Savings [MWh]
0-500	3.86	0.25	36.6 ± 2.38
500-1000	0.89	0.10	6.2 ± 0.69
1000-1500	1.84	0.11	15.33 ± 0.92
> 1500	2.91	0.08	44.78 ± 1.23
Sum			103 ± 2.92

Table 3 also quantifies the energy savings [MWh] for each bin. It should be noticed that by using the proposed optimization methodology, a total energy saving of 103 ± 2.92 MWh is achieved for 1 year based on the representative data.

4 Conclusion

An optimization methodology based on genetic algorithm (GA) to minimize losses in distribution networks with a large share of wind power has been described in this paper. The principal goal of the proposed methodology is to minimize the distribution network losses by optimizing the reactive power flow through the distribution networks, by employing the reactive power set-points of wind turbines. The present investigation have shown that 103 MWh of energy savings is possible to achieve by controlling wind power plants (WPPs) reactive power set-points with an uncertainty of ± 2.92 MWh. The results demonstrates that WPPs can actively participate in distribution grids to reduce the power losses, by locally supplying / absorbing reactive power. In addition to WPPs, other agents such as tap-changing transformers, capacitor banks etc.

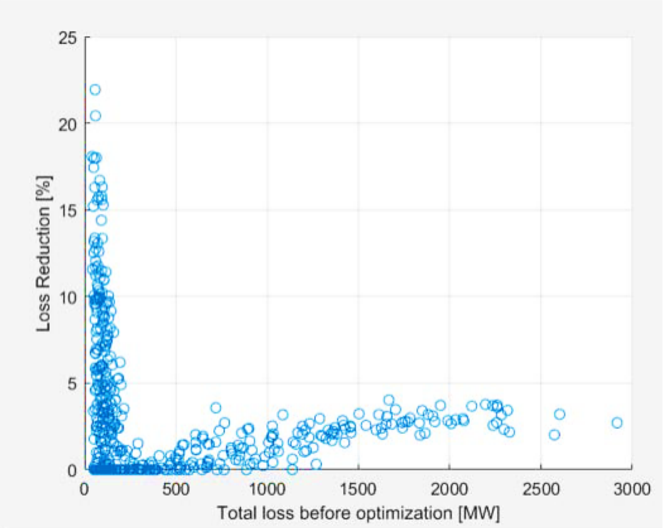

Fig. 4 Scatter plot for loss reduction [%] with respect to loss before optimization [MW]

can also be controlled, along with WPPs, to further reinforce energy savings. A suggestion for future work can be to quantify the impact of altering distribution grids' reactive power demand on the TSO/DSO interface. Thus, a holistic optimization can be developed for MV and LV network considering additional assets like PV, tap-changers, other DGs.

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