MAXIMIZING THE ACCOMMODATION OF DISTRIBUTED WIND POWER GENERATION

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ABSTRACT

Wind power is the fastest growing renewable power source worldwide. The maximization of its deployment in a given network has to consider the inherent variability of the resource while strategically minimizing potential drawbacks and fulfilling technical requirements. In this work, a steady-state analysis considering the assessment of energy exports to the grid, losses and short-circuit levels is proposed, while taking into account time-varying loads and generation, and satisfying voltage and thermal limits. A multiobjective programming approach, based on the non-dominated sorting genetic algorithm (NSGA), has been developed to find a set of optimal connection points for such purpose. The approach has been applied to a medium voltage distribution network considering hourly demand and wind profiles for part of the United Kingdom.

INTRODUCTION

Several factors, such as deregulation of power systems, environmental concerns and the promotion of energy diversification, have made governments worldwide support and incentivize renewable generation in transmission and distribution systems. Current policies have stimulated deployment of such technologies, led by wind power. This scenario presents distribution networks with a significant challenge [1], [2].

For a significant wind presence, inherent time-varying behavior of distributed wind power generation (DWPG) and that of network demand, need to be taken into account. Considering solely critical scenarios of loading and generation (e.g. maximum generation and minimum demand) may mask the negative impacts or overestimate the benefits.

Here, a time-varying approach is applied to both load and generation, and a steady-state analysis of energy exports to the grid, losses, and short circuit levels is presented. The aim is to maximize the accommodation of DWPG and the benefit it may bring to the distribution company as well as to assess the potential of a given distribution network to accept it within voltage limits, which are relevant in such developments [3]-[6]. For this purpose, the problem will be analyzed by means of multiobjective optimization based on the non-dominated sorting genetic algorithm (NSGA) [7]. As result, a set of configurations known as the Pareto-optimal solutions, corresponding to those configurations where the objectives are treated independently, i.e., no objective biases another, will be obtained. The approach has been applied to medium voltage distribution networks considering hourly demand and wind profiles for part of the United Kingdom. Results are presented and discussed.

MULTIOBJECTIVE OPTIMIZATION

The combinatorial nature of the DWPG insertion problem requires optimization tools. Since genetic algorithms (GAs) have presented suitable characteristic for such a task [8] and considering the multiple objectives to be analyzed, here the multiobjective optimization algorithm will be based on the non-dominated sorting genetic algorithm (NSGA) [7]. This algorithm varies from simple GAs in the way the selection operator works: two subsets of the population are considered, the Pareto-optimal solutions list and the remaining configurations. The former is composed by the Pareto-optimal solutions based on the following concepts:

- *Dominance*: Given a multiobjective problem with k objective functions to be simultaneously minimized, solution x_1 dominates solution x_2 if x_1 is better than x_2 for at least one objective and is not worse for any other.
- *Non-dominance*: A solution x_1, which dominates any other solution x_2 is a non-dominated solution. Solutions that are non-dominated over the entire search space are called Pareto-optimal solutions.

The procedure to be used for analyzing the dominance or otherwise of each solution in a given generation should be efficient in a way that all non-dominant solutions are taken into account, ensuring a diversified Pareto-optimal solutions list.

The characteristics of the Evolutionary Algorithm (EA) which incorporates the Pareto optimality criterion are those presented in [8], whereas the objective function is evaluated in terms of non-dominance and the Pareto-optimal solutions becomes the elite list.

Objective Functions

Three objectives are to be taken into account: energy exports to the grid, real power losses and short-circuit levels. Since load and generation patterns are being considered, energy export and power losses will vary considerably as a function of time. Therefore, the latter objective functions will consider the total amount of energy exported and lost, respectively, based on hourly periods to a horizon of a year. Short-circuit levels are related to the DWPG configuration rather than the demand and generation fluctuations making the analysis more complex and time demanding depending on the network size.

For the *k*-th distribution network configuration with DWPG the objectives functions considered are set out in the following subsections:

1) Energy Export

Given the environmental benefits and the current cost-effectiveness of wind power, energy exports must be maximized.

$$\text{Maximize} \quad \sum_{i=1}^{NH} \mathrm{Re}\{EE_i^k\} \tag{1}$$

where EE_i^k is the total complex power exported through the substation for the *k*-th distribution network configuration during hour *i* and *NH* is the total of hours in a year.

2) Real Power Losses

While DWPG may unload lines and reduce losses, the reverse power flows from several DWPG units can give rise to excessive losses.

$$\text{Minimize} \quad \sum_{i=1}^{NH} \mathrm{Re}\{Losses_i^k\} \tag{2}$$

where $Losses_i^k$ is the total complex power losses for the *k*-th distribution network configuration during hour *i*.

3) Single-phase Short Circuit Levels

This objective is related to the protection and selectivity issues arising from the variation of maximum short circuit current between the situations with and without DWPG. This objective indicates the potential impact on existing protection devices. As these were planned for a network without DG the impact should be minimized.

$$\text{Minimize} \quad \max\left(\frac{I_{SC\,i}^{\;k}}{I_{SC\,i}^{\;0}}\right) \tag{3}$$

where $I_{SC\,i}^{\;k}$ is the single-phase fault current value in node *i* for the *k*-th distribution network configuration; and $I_{SC\,i}^{\;0}$ is the equivalent for the distribution network without DWPG.

Additionally to these three objectives, considering quality of supply standards, each configuration should satisfied voltage and thermal constraints:

$$V_{\min} \le \left|\bar{V}_i\right|_1^{NN} \le V_{\max} \tag{4}$$

$$\left|\bar{I}_j\right| \le I_{j\max} \tag{5}$$

where, $V_{\min}$ and $V_{\max}$ are the lower and upper voltage limits for the voltage at node *i*, $\bar{V}_i$; *NN* is the number of nodes; $I_{j\max}$ is the maximum current capacity through the conductor of line section *j*; $\bar{I}_j$ is the complex current flowing through line section *j*.

CASE STUDY

The IEEE 34-bus three-phase medium voltage radial feeder [9] was used in the analysis (Fig. 1). Its total demand is 1770 kW with 72% of the loads are concentrated 56 km far away from the substation. Line-to-line base voltage is 24.9 kV, with 1.05 p.u. at the substation (node 0). The network is simplified by not considering the 24.9:4.16 kV in-line transformer in the original IEEE 34 test feeder and modeling the entire feeder at a single voltage level. The automatic voltage regulators are also not represented due to the presence of DWPG units.

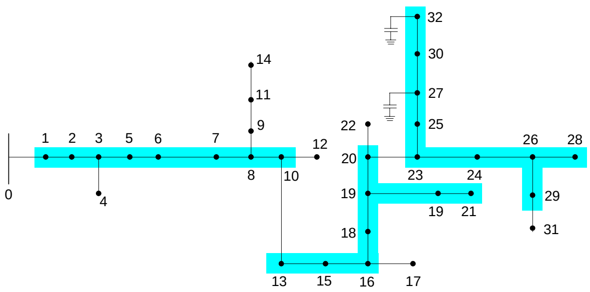

Fig. 1. IEEE-34 test feeder considering one wind speed zone.

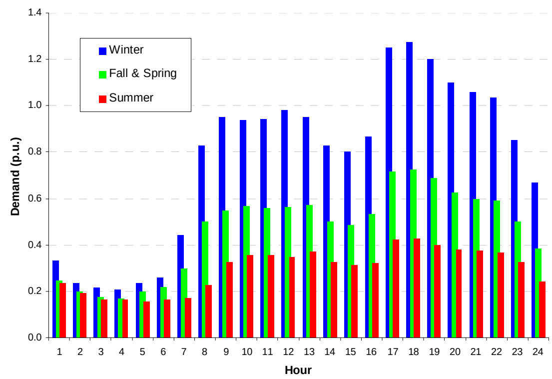

Fig. 2. Seasonal daily load profiles.

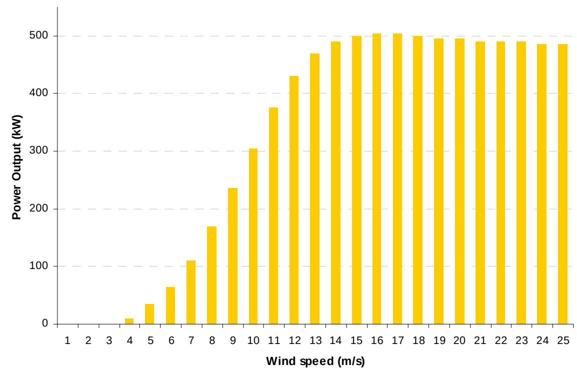

Fig. 3. 500 kW wind turbine power curve.

Typical load profiles shown in Fig. 2 are based on patterns in the UK [10] adjusted to meet the design values for the feeder.Hourly wind speed measurements taken from UK Meteorological Office weather stations in central Scotland in 2003, were used. Possible connection points (three-phase connection available) for wind turbines are those within the shadowed area presented in Fig. 1.

Fig. 3 presents the power curve for a 500 kW wind turbine (50 m high) used to derive the hourly power output by combining it with relevant wind speed.

APPLICATION

The algorithm was applied to IEEE-34 distribution network considering the time characteristics of loads and wind production. Each network configuration was used for 8760 hourly power flows. The three-phase four-wire power flow algorithm will be utilized. Short circuit analysis was performed based on symmetrical components and using sequence impedances presented in [2]. Voltage limits are set to 6% of nominal. Thermal constraints are according to the current capacity of each conductor.

In order to show how the reference voltage (substation) may restrict the deployment of wind turbines due to the resulting voltage profile, a single wind turbine is placed at each possible connection point at each of unity, 0.9 lagging and leading power factors. Three reference voltages (*Vref*) are also analyzed: 1.05 (original network), 1.03 and 1.00p.u. Results are presented in Figures 4 and 5. Maximum and minimum voltages were obtained by averaging the daily maximum and minimum voltages taken at 4a.m. (minimum load) and 6p.m. (maximum load), respectively. All thermal constraints were fulfilled.

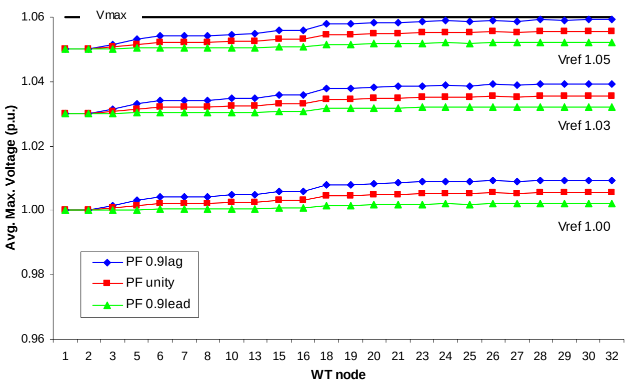

Fig. 4. Maximum nodal voltages found for a single wind turbine per node.

While no voltage surpasses the upper limit at any scenario, setting the substation at 1.00p.u. no configuration can keep the voltage drop above the lower limit. At 1.03p.u., one wind turbine located either at node 1, 2 or 3 will not satisfy the minimum voltage, while at node 5 it will depend on the power factor.

This analysis reveals the importance of adequately setting both the reference voltage and generator power factor, in allowing maximum accommodation of wind turbines.

By using the multiobjective programming technique proposed previously, it is possible to explore configurations with diverse numbers of wind turbines in order to find those arrangements that maintain a compromise between the maximization of exported energy and the minimization of both power losses and short-circuit levels, while fulfilling the specified voltage limits.

The simulations were performed with turbine power factors of 0.9 lagging. Figures 6, 7 and 8 present the sets of Pareto-optimal solutions considering substation voltages of 1.05, 1.03 and 1.00p.u., respectively. The regions indicate configurations with the same number of wind turbines.

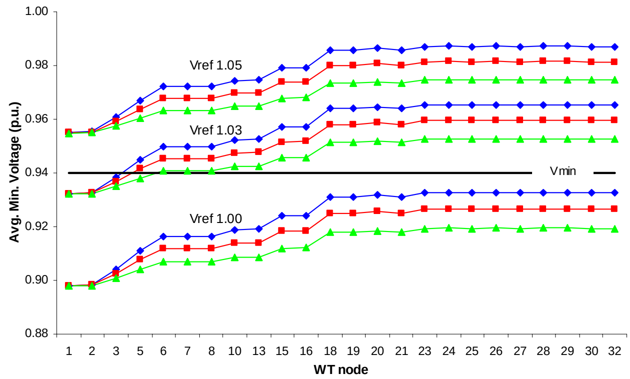

Fig. 5. Minimum nodal voltages found for a single wind turbine per node.

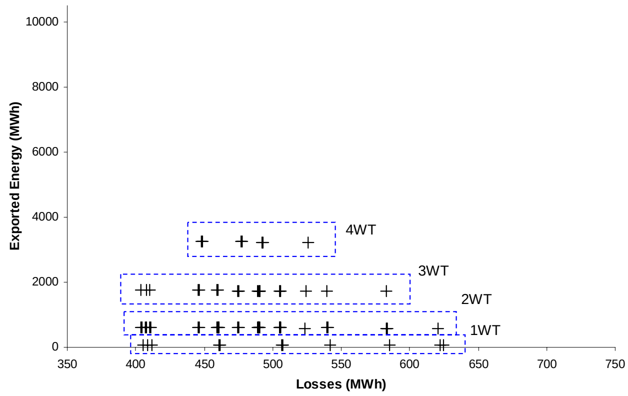

Fig. 6. Pareto-optimal solutions – maximization of export, minimization of losses and short-circuit levels for *Vref*=1.05p.u.

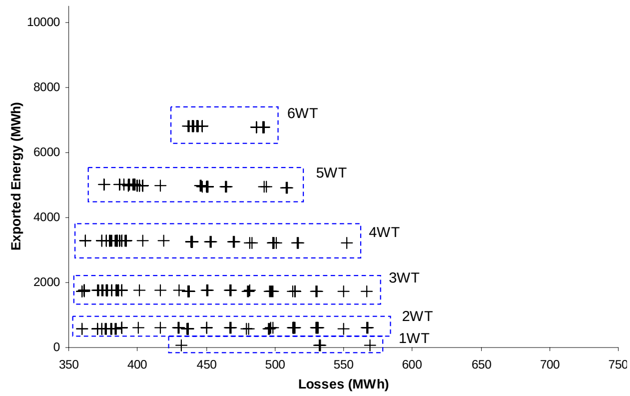

Fig. 7. Pareto-optimal solutions – maximization of export, minimization of losses and short-circuit levels for *Vref*=1.03p.u.

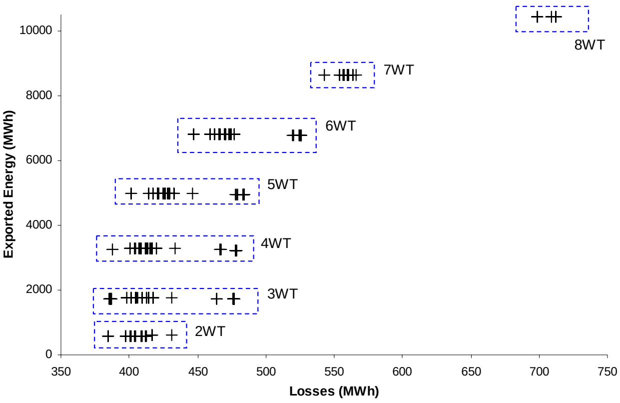

Fig. 8. Pareto-optimal solutions – maximization of export, minimization of losses and short-circuit levels for *Vref*=1.00p.u.

Using *Vref*=1.05p.u. led to 65 configurations, with 209 and 169 arrangements found at 1.03 and 1.00p.u., respectively. The latter setting provided a scenario where configurations with more wind turbines could be included. Due to short range for voltage rise when considering the original reference voltage, four wind turbines located at certain nodes were found to offer the largest number possible. Also, it can be verified that, as found in Fig. 5, Fig. 8 does not provide any configuration with two wind turbines. No thermal limits were exceed at any case.

Table I summarizes the characteristics of those configurations that produced the maximum exported energy. It is observed that, while the average minimum voltages are distant from 0.94p.u., the average maximum voltages are very close to the upper limit which highlights the importance of careful substation voltage. In the original network losses amounted to 627.59 MWh; only two of the three maximum-exported-energy cases reduced that value. Nevertheless, an economic analysis should be performed in order to identify the real benefit despite limited loss reduction (or even increases), taking also into account the impact on the protection scheme.

Table I. Pareto-optimal configurations with maximum exported energy.

Vref (p.u.)	# WT	Insertion Points	Exported Energy (MWh)	Losses (MWh)	Short Circuit Level	Avg. Min. Voltage (p.u.)	Avg. Max. Voltage (p.u.)
1.05	4	1, 2, 3, 16	3251.1	448.1	16.6	0.9851	1.0595
1.03	6	1, 2, 3, 5, 13, 23	6812.3	436.9	24.8	0.9876	1.0593
1.00	8	1, 2, 3, 5, 8, 10, 21, 23	10435.3	698.7	33.7	0.9681	1.0556

CONCLUSIONS

Due to the particular characteristics of wind power generation and its increasing role in distribution networks worldwide, a multiobjective optimization algorithm was proposed aimed at finding a set of network configurations with wind turbines where each of them represents a unique Pareto-optimal compromise between the maximization of energy export and the minimization of both power losses and short-circuit levels, while accounting for the variability of load and generation, and voltage and thermal constraints.

While the capability of wind power generators to adopt power factors beneficial for the network will depend on the technology, as well as on the incentives or regulations involved, setting substation voltages appears to be a more direct procedure.

Despite the limitations of utilities in specifying the connection point of a generation unit, the multiobjective optimization analysis permits knowledge of where generation could bring the most benefits for the distribution network.

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