MAXIMIZING THE ACCOMMODATION OF DISTRIBUTED WIND POWER GENERATION

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ABSTRACT

In the last decade energy policies and technological progress in development of wind turbines have made wind power the fastest growing renewable power source worldwide. The maximization of its deployment in a given network will have to consider the inherent variability of this 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 the insertion of new power generation from renewable sources to both transmission and distribution systems. Thus, current policies have paved the current raising deployment of such technologies, led by wind power. This scenario presents distribution networks – generally not planned to be active – with a significant challenge [1], [2].

In this context, given its significant presence, the inherent time-varying behavior of distributed wind power generation (DWPG) and the corresponding network's 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. While the aim is to maximize the accommodation of DWPG, in order to harness the most benefits that such technology may bring to the distribution company as well as to assess the potential of a given distribution network, its placement will be restricted to voltage limits, which appear to be specially 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 ALGORITHM

The combinatorial nature of the DWPG insertion problem requires optimization tools. Since genetic algorithms 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 genetic algorithm 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. A solution x_1 dominates a solution x_2 if x_1 is better than x_2 for at least one objective f_i and is not worse for any other f_j, where j, $i=1,2,\dots,k$ and $j \neq i$.
- *Non-dominance*: A solution $x_1 \in P$ ($P \subseteq S$, where S is the entire search space of the problem), which dominates any other solution $x_2 \in P$ is called a non-dominated solution in P. Solutions that are non-dominated over the entire search space S are called Pareto-optimal solutions (Pareto's optimality criterion).

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, within a horizon of a year divided by hourly periods. On the other hand, short-circuit levels are related to the DWPG configuration rather than the demand and generation fluctuations. In this way, depending on the network size, this approach makes the analysis more complex and time demanding.

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, its generation should not be limited and, consequently, energy export must be maximized. To this effect, the following expresses the corresponding objective function:

$$\text{Maximize} \quad \sum_{i=1}^{NH} \mathrm{Re}\left\{EE_i^k\right\} \qquad (1)$$

where, EE_i^k is the total complex power exported through the substation for the *k*-th distribution network configuration during hour *i*.

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. This objective function is expressed by:

$$\text{Minimize} \quad \sum_{i=1}^{NH} \mathrm{Re}\left\{Losses_i^k\right\} \qquad (2)$$

where, $Losses_i^k$ is the total complex power losses for the *k*-th distribution network configuration during hour *i*; and *NH* is the total of hours within the considered year.

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 gives the power engineer a notion of how the generation is impacting on the protection devices that were planned for a network without such generation units, hence it should be minimized.

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

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 single-phase fault current value in node *i* for the distribution network without DWPG.

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

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

$$\left|\bar{I}_j\right| \le I_{j\max} \qquad (5)$$

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] will be used in order to perform the proposed analysis (Fig. 1). Its total demand is 1770 kW, whereas 72% of the loads are concentrated 56 km far away from the root node. 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.

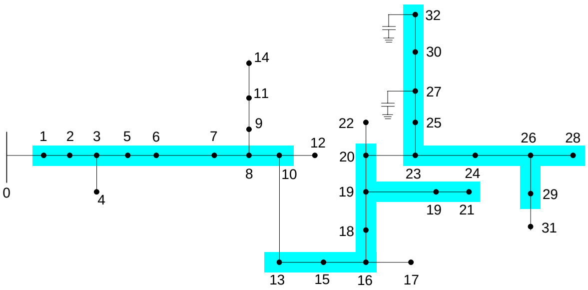

Fig. 1. IEEE-34 test feeder considering one wind speed zone.

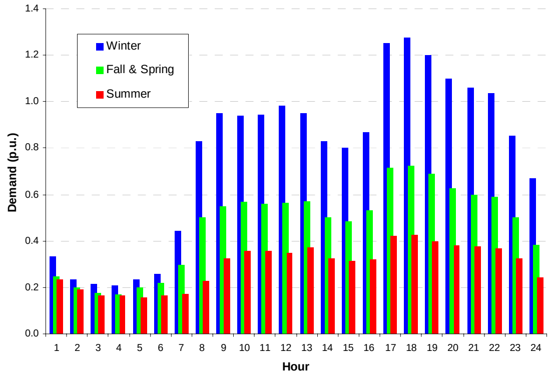

Fig. 2. Seasonal daily load profiles.

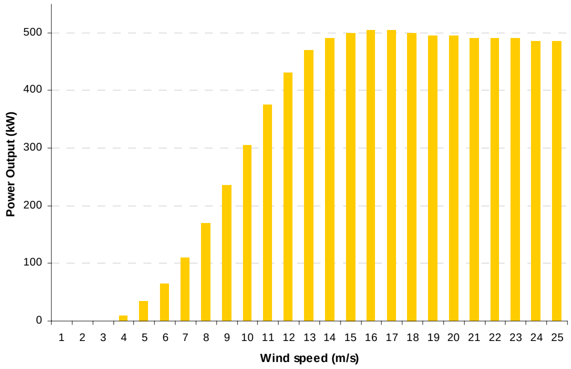

Fig. 3. 500 kW wind turbine power curve.

Typical load profiles are shown in Fig. 2 after adjustment from the design values of peak demand to the actual average value of peak winter demand and minimum summer demand as reported by the Electricity Association in the UK [10]. Moreover, 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) that was used to derive the hourly power output by combining it with relevant wind speed.

APPLICATION

The proposed algorithm is applied on the IEEE-34 distribution network considering the time-varying characteristics of both loads and wind power (500 kW nominal capacity wind turbines). In this way, each network configuration will be 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%, i.e., $V_{\min} = 0.94$p.u. and $V_{\max} = 1.06$p.u. 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, considering unity, 0.9 lagging and 0.9 leading power factors. Three reference voltages (*Vref*) are also analyzed: 1.05 (original network), 1.03 and 1.00p.u. Results are presented in Fig. 4 and Fig. 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.

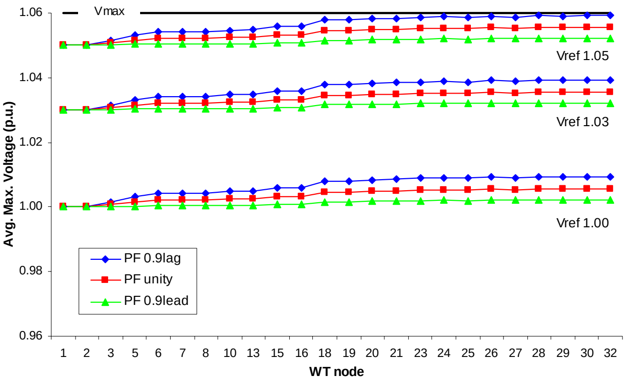

Fig. 4. Maximum voltage found in the IEEE-34 test feeder considering the insertion of a single 500 kW wind turbine.

The following simulations will be performed considering wind turbines' power factor equal to 0.9 lagging. Fig. 6, Fig. 7 and Fig. 8 present the sets of Pareto-optimal solutions considering a voltage of 1.05, 1.03 and 1.00p.u. at the substation, respectively. The regions indicate configurations with the same number of wind turbines.

This analysis reveals the importance of adequately setting both the reference voltage and the generators' power factor, so the maximum number of wind turbines can be placed.

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.

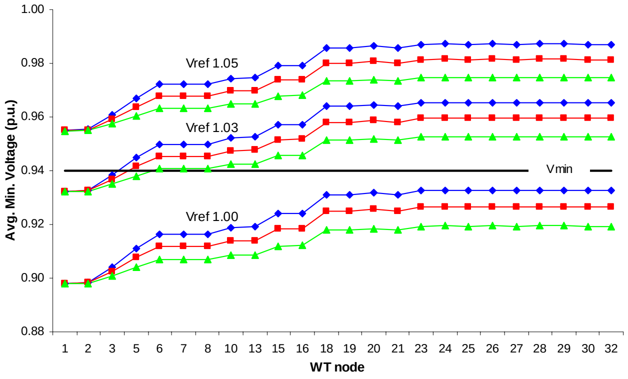

Fig. 5. Minimum voltage found in the IEEE-34 test feeder considering the insertion of a single 500 kW wind turbine.

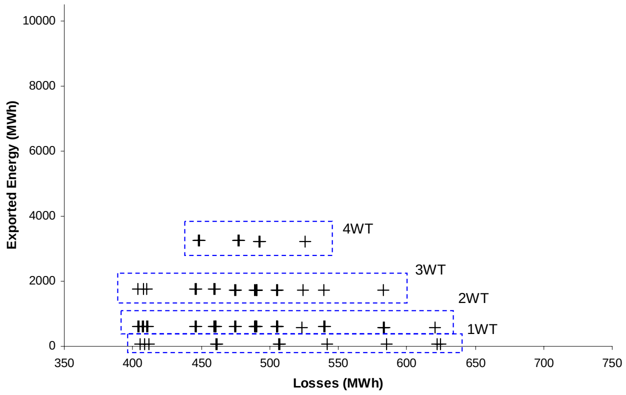

Fig. 6. Pareto-optimal solutions – maximization of energy export, minimization of losses, and minimization of short-circuit levels. *Vref*=1.05p.u. ; WT power factor 0.9 lagging.

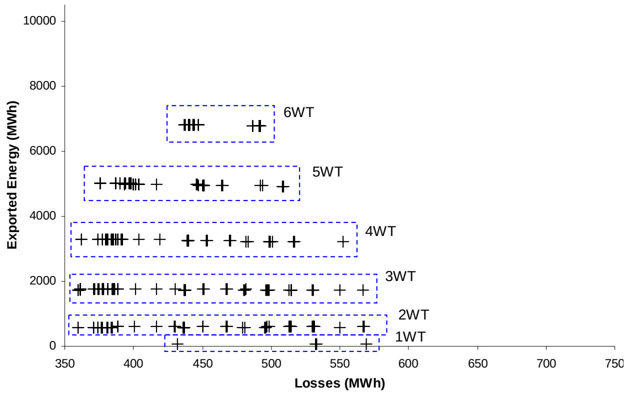

Fig. 7. Pareto-optimal solutions – maximization of energy export, minimization of losses, and minimization of short-circuit levels. *Vref*=1.03p.u. ; WT power factor 0.9 lagging.

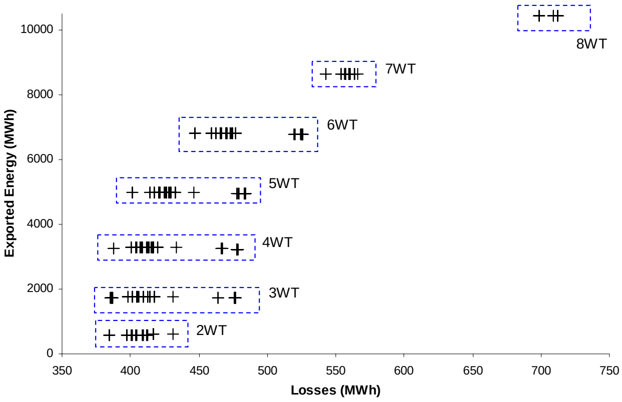

Fig. 8. Pareto-optimal solutions – maximization of energy export, minimization of losses, and minimization of short-circuit levels. *Vref*=1.00p.u. ; WT power factor 0.9 lagging.

Using *Vref*=1.05p.u. led to 65 configurations, whereas for 1.03 and 1.00p.u. 209 and 169 arrangements were found, 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 was found to be 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. Hence, the importance of properly setting the reference voltage. Moreover, considering that the original network (no DWPG) losses accounted for 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 no reduction –or even increase- of losses, taken 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 compromise (Pareto-optimal solutions) 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 being constrained by voltage and thermal limits.

While the capability of wind power generators to adopt power factors beneficial for the network will depend on the technology used, as well as on the incentives or regulations involved, setting reference 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 considering the technical issues adopted.

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