

Time-Series Based Maximization of Distributed Wind Power Generation Integration

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Abstract--Energy policies and technological progress in development of wind turbines have made wind power the fastest growing renewable power source worldwide. The inherent variability of this resource requires special attention when analyzing the impacts of high penetration on the distribution network. A time-series steady-state analysis is proposed that assesses technical issues such as energy export, losses and short-circuit levels. A multiobjective programming approach based on the Non-dominated Sorting Genetic Algorithm (NSGA) is applied in order to find configurations that maximize the integration of Distributed Wind Power Generation (DWPG) while satisfying voltage and thermal limits. The approach has been applied to a medium voltage distribution network considering hourly demand and wind profiles for part of the United Kingdom. The Pareto-optimal solutions obtained highlight the drawbacks of using a single demand and generation scenario, and indicate the importance of appropriate substation voltage settings for maximizing the connection of DWPG.

Index Terms--Wind power, distributed generation, multiobjective programming, Pareto's optimality, distribution networks.

I. INTRODUCTION

DISTRIBUTED GENERATION (DG) is playing an increasingly important role in the electric power system infrastructure and market. Environmental concerns and promotion of energy diversification have paved the way for increased deployment of renewable technologies, particularly wind power, which are presenting distribution networks with significant challenges [1]-[4].

In responding to these challenges DG placement has been investigated considering a range of impacts and objectives including power losses, voltage profile and regulation, short-circuit levels, environmental and economic concerns [5]-[15]. Exhaustive analysis and optimized placement approaches are found in the literature but consideration of the inherent time-varying behavior of loads and generation patterns of some DG technologies has been absent from all but a few analyses.

An analytical approach for optimizing the allocation of DG, considering the variability of demand and power generation by using daily average curves was proposed in [16]. Seasonal load curves were also used in [17]. The use of time-varying loads was introduced by [15] for analysis of reliability and

efficiency of distribution networks with DG. The variability of demand and various DG technologies, aimed at assessing energy losses for different penetration scenarios were considered in [18]. Through a deterministic and stochastic analysis, DG variability along with load curves, were taken into account in [19] aiming the maximum insertion within specific penetration limits.

With current renewable penetration targets currently being met by wind power a significant proportion of the installed capacity is, and will be, connected to distribution systems [20]. Considering only the critical scenarios of loading and generation, e.g., maximum generation and minimum demand, may mask the negative impacts or overestimate the advantages produced by the integration of non-dispatchable generation in distribution systems. As such, high levels of Distributed Wind Power Generation (DWPG) require analytical approaches that take into account the time-varying characteristics of this resource and that of network demand, in order to properly assess the benefits or otherwise for a given configuration.

Here, a time-series steady-state analysis of technical issues such as energy export to the grid, losses and short-circuit levels is presented that considers both load and generation patterns. The maximization of DWPG integration and the benefit it may bring to the electric utility is carried out using a multiobjective optimization approach based on the Non-dominated Sorting Genetic Algorithm (NSGA) [21]. Accommodation of DWPG is restricted by network statutory voltage and thermal limits which are relevant constraints in such developments [12], [22], [23]. The results of the analysis are a set of configurations known as the Pareto-optimal solutions which indicate the potential of a given distribution network to integrate DWPG.

This paper is structured as follows: Section II presents the time-series analysis using a medium voltage distribution network along with demand profiles and wind speed data applicable to the United Kingdom (UK). Section III lays out the multiobjective optimization algorithm and the considered objectives. In Section IV the application of the multiobjective technique is presented and discussed. Finally, the conclusions are drawn in section V.

II. TIME-SERIES ANALYSIS

A. Test Network

The IEEE 34-bus three-phase medium voltage radial feeder [24] will be used in order to perform the proposed analysis (Fig. 1). Its total demand is 1.7 MW with over two-thirds of

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the load concentrated in excess of 50 km from the substation (bus 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 base voltage of 24.9 kV. The automatic voltage regulators are also not represented due to the presence of DWPG units.

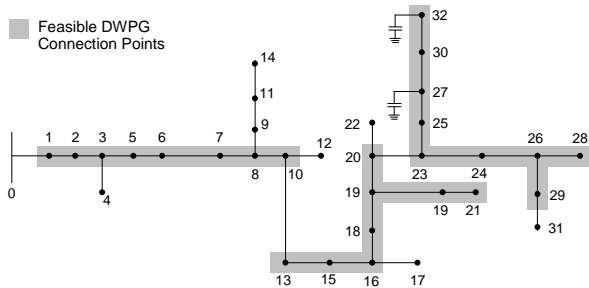


Fig. 1. IEEE-34 test feeder.

B. Load Demand and Wind Power Generation

The total feeder demand profiles are shown in Fig. 2a. The load at each bus is based on typical seasonal profiles reported for the UK [25] as normalized by the peak values of the IEEE-34 system [24].

Siting of new wind generation developments presents several real-life constraints related to geographical characteristics, natural areas, aviation zones and other forms of land utilization. Additionally, determining the density of zones with different wind characteristics will also depend on the topology and size of the system under analysis, as well as availability of historical data of wind speeds.

In illustrating the approach, this study makes the assumption that a single wind speed time series is appropriate for all feasible connection points. These points are defined by the need to be fed by a three-phase branch and are indicated by the grey area in Fig. 1. Given the inherent variability of wind speed the use of seasonal daily wind patterns may not provide an accurate picture. As such, wind speed data from hourly measurements carried out by the UK Meteorological Office for central Scotland for 2003 have been used. These have been applied to the power curve for a 500 kW wind turbine (50 m hub height) in Fig. 2b to derive corresponding hourly power output.

C. Example

With the above presented data and using the three-phase power flow algorithm from [26], the network's behavior due to a given DWPG configuration can be evaluated in terms of load demand, line losses, power exports and voltage levels. Fig. 3 and Fig. 4 illustrate hourly results for the seven-day period of maximum generation during winter and summer, respectively, considering one 500 kW DWPG unit (operating at unity power factor) sited at the remote node 28. Loads are modeled as constant power.

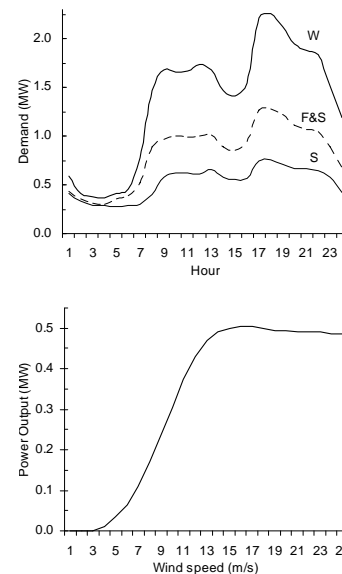


Fig. 2. (a) Seasonal daily load profiles (W: winter, F&S: fall and spring, S: summer); (b) 500 kW wind turbine power curve.

The variability of wind speeds and the derived wind power is evident. Moreover, while particular times of the year present more wind power potential, it is not possible to characterize wind speeds, thus the advantage of a time-series approach. Special attention should be given to those hours when wind power generation matches or exceeds the network total demand (including losses). In these cases, counter power flows are likely to occur, increasing voltage levels. As Fig. 3 and 4 show, the network maximum and minimum voltages are more affected during off-peak hours, and particularly summer time which presents the lowest power consumption.

It is clear from this example that through a time-series analysis it is possible to spot critical scenarios where operating constraints are being violated. Moreover, it can be observed that the maximization of DWPG integration would significantly rely on the appropriate control of voltage. One means to tackle this problem is by adopting different tap positions at the substation. Additionally, the electric utility may request the DWPG units to operate at a power factor that benefits overall network performance, thus increasing the penetration of new generation.

III. MULTIOBJECTIVE OPTIMIZATION ALGORITHM

Previous work considered the use of weighting factors for calculating a multiobjective performance index for a given distribution network with DG [5], whereas an approach for optimal placing of generation units used a similar multiobjective index as the objective function of an evolutionary algorithm [6]. The approach suffers as weighting factors inherently bias the outcome [5], [6], [8], [14]. However, this is not when Pareto-optimal solutions correspond to configurations are derived.

The combinatorial nature of the DG insertion problem requires appropriate optimization tools and Genetic Algorithms (GAs) have presented suitable characteristic for

such a task [6], [8]. With multiple objectives to be analyzed, a multiobjective optimization algorithm based on the Non-Dominated Sorting Genetic Algorithm (NSGA) [21] is proposed. This algorithm varies from simple GAs in the way

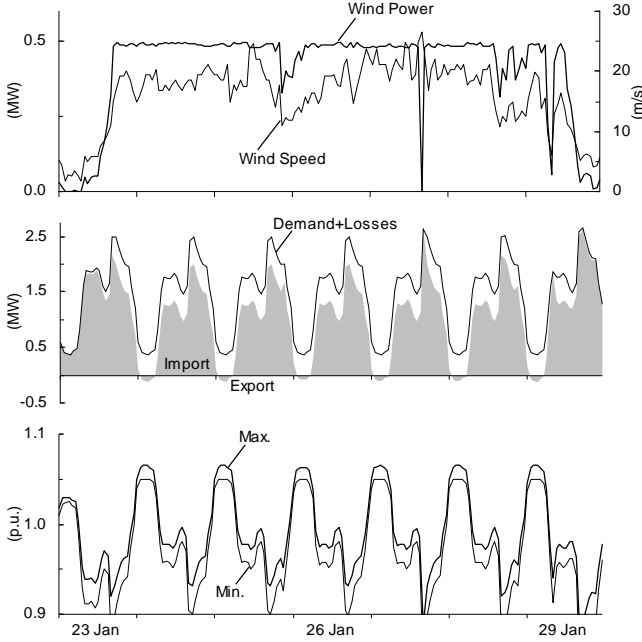


Fig. 3. Time-series analysis considering one DWPG unit (node 28) during maximum 7-day generation for the winter 2003.

- **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.

The procedure to be used for analyzing the dominance 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 solution list.

The characteristics of the GA which incorporates the Pareto optimality criterion include:

- **coding:** each configuration is described by a vector (chromosome) whose size is equal to the number of nodes. If a DWPG unit is inserted in a node, this element (gene) receives a number related to the nominal capacity of the generator (e.g. '1' for 500 kW), otherwise it is zero. Elements of the chromosome relating to the substation and unsuitable nodes (e.g. fed by non-three-phase branches, or land use constraints) are fixed to zero;
- **initial population:** is created by randomly inserting DWPG units using both a reduced set of nodes provided by the Zbus loss allocation method [27] (set of nodes that influence the most into the total network losses) and randomly selected feasible nodes;
- **genetic operators:** selection is performed by randomly

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:

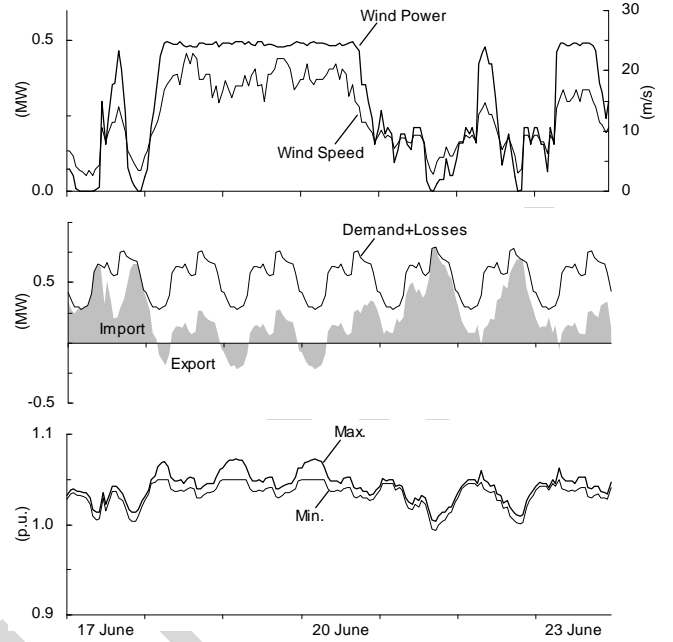


Fig. 4. Time-series analysis considering one DWPG unit (node 28) during maximum 7-day generation for the summer 2003.

- choosing two chromosomes: one from the current population and one from the Pareto-optimal solutions; single-point crossing-over and mutation;
- **unfeasible configurations:** configurations found not to have DWPG units after applying genetic operators will be penalized; and,
- **stop criterion:** when the Pareto-optimal solutions list is not being updated after a given number of generations.

A. Objective Functions

Here, three objectives are to be considered: energy export to the grid, real power losses and short-circuit levels. These objectives may be contradictory, i.e., minimization of one provokes degradation of the other and, since hourly load and generation vary, power losses and energy export are a function of time. Therefore, the latter objective functions will consider the total amount of energy "lost" and "exported", respectively, within a horizon of a year. Short-circuit levels, however, are more strongly related to the DWPG location than the demand and generation fluctuations which alter voltage levels. These differing requirements make analysis more complex. The objective functions considered are set out below.

1) Energy Export

Given the environmental benefits and the cost-effectiveness of wind power, its generation should not be constrained and energy export maximized:

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

where EE_i^k is the apparent power exported through the substation for the k -th distribution network configuration

during hour i and NH is the number of hours in the year.

2) Real Power Losses

Depending on the location of DWPG units and the instantaneous mismatch between power output and load demand, load downstream of the point of connection and even system total demand could be lower than the generator's output. Consequently, reverse power flows will occur as power is exported upstream. The changes in voltage profile induced by the reverse power flows will be broadly captured by the changes in losses. Although DWPG may unload lines and reduce losses, the reverse power flows from several units can give rise to excessive losses. As such, active power losses should be minimized:

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

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 DWPG the impact should ideally be minimized:

$$\text{Minimize } \max \left(\frac{I_{SCi}^k}{I_{SCi}^0} \right) \quad (3)$$

where I_{SCi}^k is the single-phase fault current value at node i for the k -th distribution network configuration and I_{SCi}^0 is the corresponding value where no DWPG unit is present.

In addition, quality of supply standards and reliable operation state that each configuration should satisfy voltage and thermal constraints:

$$V_{\min} \leq |\bar{V}_i| \leq V_{\max} ; i=1, NN \quad (4)$$

$$|\bar{I}_j| \leq I_{j\max} ; j=1, NS \quad (5)$$

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

IV. APPLICATION

The siting of wind generators depends on various technical and non-technical issues. Thus, an area with good wind speeds may not be suitable due to its orography (e.g., steep slopes) or other difficulties (e.g., natural areas, aviation zones, etc.) it could present for a viable, cost effective placement and interconnection to the distribution system. Nevertheless, real-life constraints will vary on a case-by-case basis. The following analyses were carried out considering all feasible connection points (Fig. 1) as candidates.

A. Single DWPG Unit Siting

To consider the sensitivity of the network to DWPG

location a single wind turbine (WT) was placed, in turn, at each potential connection point (Fig. 1). This allowed investigation of the influence of substation voltage and generator power factor on the deployment of DWPG. Two substation voltages (Vs/s), of 1.05 and 1.03 p.u. were considered along with power factors of unity, 0.9 lagging and leading.

The range of bus voltages gained from applying the time-series data for each configuration are presented in Fig. 5. Maximum and minimum voltages were obtained by averaging the daily maximum and minimum voltages taken at 4 a.m. (minimum load) and 6 p.m. (maximum load), respectively. Statutory voltage limits are $\pm 6\%$ of nominal. All thermal constraints were fulfilled. While no voltage surpasses the upper limit in any scenario, it is clear that by setting the substation to 1.03 p.u., single WTs located at nodes 1 to 3 will not satisfy the minimum voltage, whereas at node 5 it will depend on the power factor. Although not illustrated, reduction of substation voltage to 1.00 p.u. means that no configuration could keep the voltage above the lower limit. This analysis reveals the importance of adequately setting both the reference voltage and generator power factor, in allowing maximum accommodation of DWPG units.

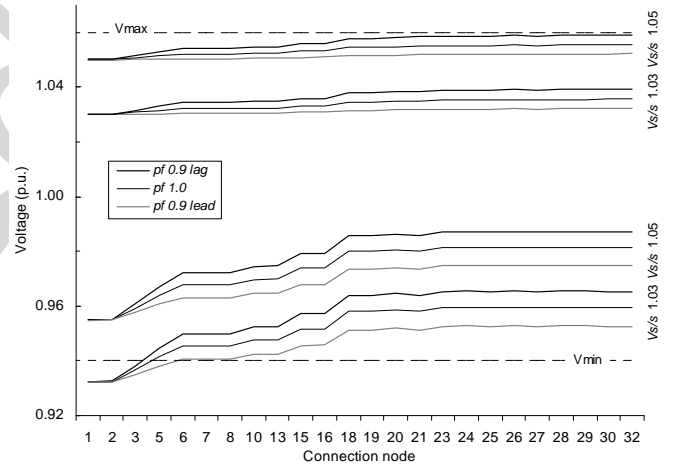


Fig. 5. Maximum and minimum nodal voltages found for a single wind turbine per node.

B. DWPG Siting Maximization – Multiobjective Approach

Using the multiobjective programming technique proposed in Section III, it is possible to explore configurations of 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 power losses and short-circuit levels, while simultaneously maintaining statutory voltage and thermal limits. Short-circuit analysis was carried out based on symmetrical components and using sequence impedances presented in [5]. Simulations were performed assuming 0.9 lagging power factor for DWPG units since the major sensitivity was found to be the Vs/s setting.

Two separate analyses were performed to illustrate the differences in outcome between the use of time-series and snapshot approaches. Fig. 6 shows the Pareto-optimal solutions from the time-series approach for three different

substation voltages of 1.00, 1.03 and 1.05 p.u. Fig. 7 presents the same information using a snapshot with annual average demand of 881 kW and each DWPG unit producing an

average of 240 kW. In both cases the horizontal set of points corresponds to configurations with the same number of WTs.

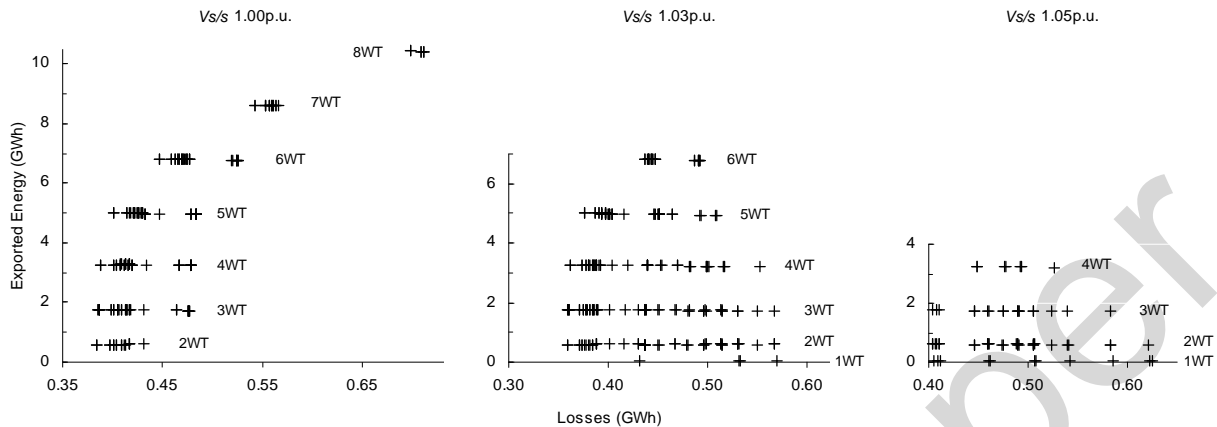


Fig. 6. Pareto-optimal solutions using time-series demand and generation – maximization of export, minimization of losses and short-circuit levels for three different substation voltages (V_s/s).

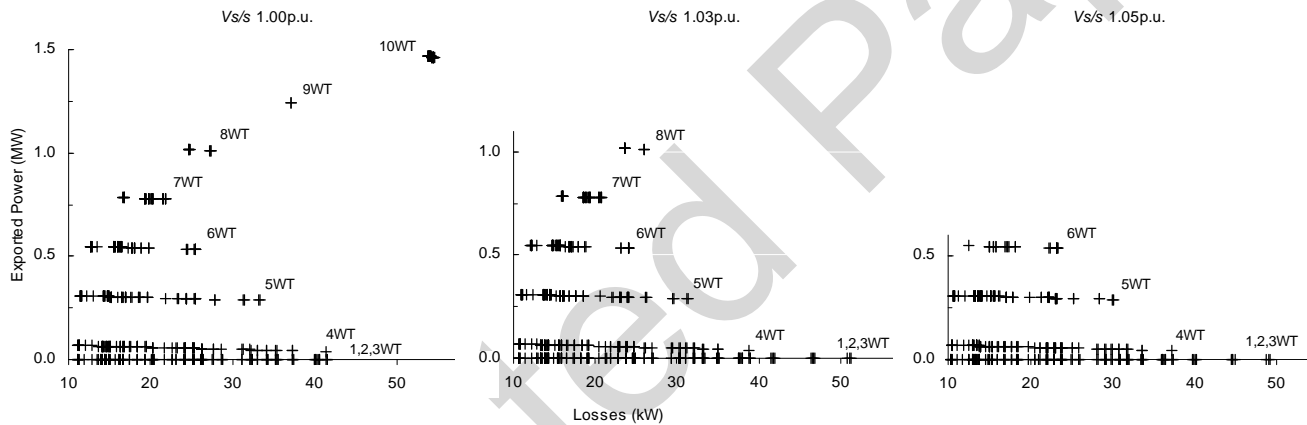


Fig. 7. Pareto-optimal solutions using a snapshot of average demand and generation – maximization of export, minimization of losses and short-circuit levels for three different substation voltages (V_s/s).

Fig. 6 for the time-series approach shows that the substation voltage has a major impact on the number of feasible solutions: 1.00 p.u. led to 169 configurations, with 209 and 65 for 1.03 and 1.05 p.u., respectively as well as the number of turbines accommodated. No thermal limits were exceeded in any case. In terms of connectable capacity the pattern is clear: lower substation voltage allows greater headroom and larger numbers of generators (8 in the case of 1.00 pu and 4 for 1.05). The pattern for the number of configurations is less clear but can be explained by reference to the previous subsection where using a substation voltage of 1.00 p.u. no configuration of single WT could satisfy the lower voltage limit. The limited connectable capacity available at the highest substation voltage explains the small number of configurations

The snapshot approach considering the annual average demand and generation (Fig. 7) produced 413, 397 and 324 Pareto-optimal solutions for substation voltages of 1.00, 1.03 and 1.05 p.u., respectively. The number of solutions increased significantly relative to the time-series approach as the average values of demand and generation do not reflect the actual interaction of these parameters and therefore

overestimate the potential of the network to absorb wind power. Indeed, for the three voltage settings, configurations with more wind turbines were allowed to be inserted since for the considered single scenario of demand and generation the voltage constraints were satisfied.

Table I summarizes the characteristics of those configurations that produced the maximum exported energy for each substation voltage setting considering the time-series approach (Fig. 6). It is observed that, while the minimum voltages are distant from the lower limit (0.94 p.u.), the maximum voltages are very close to the upper limit which highlights the importance of careful substation voltage. In the original network annual losses amounted to 628 MWh; only two of the three maximum-exported-energy cases reduced that value. However, energy export may potentially represent another revenue source for the utility, which justifies its maximization despite no significant decrease (or even increase) of power losses. In addition Table I shows that larger number of DWPG units leads to greater short-circuit levels, thus impacting on the protection scheme. Consequently, the required extra costs for upgrading the network's protection to cope with significant exported energy should also be taken

into account.

It can be observed in Table I that due to the compromise that Pareto's optimality criterion tries to keep between the three objectives, certain nodes were preferred. These were either close to the substation or close to the load concentration. Generation located at nodes near the grid supply point and those feeding large loads are likely to produce fewer counter power flows, reducing the impact on voltage rise and allowing more penetration. At the same time, short-circuit levels are less affected if generation is close to the substation.

TABLE I. PARETO-OPTIMAL CONFIGURATIONS WITH MAXIMUM EXPORTED ENERGY

Vs/s (p.u.)	No. of WT	Connection Points	Exported Energy (MWh)	Losses (MWh)	Short Circuit Level	Min. Voltage (p.u.)	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

V. DISCUSSION

Although inherently more straightforward, analyses based on critical scenarios or typical wind speeds/power generation patterns, could neglect some effects and under- or overestimate the actual DWPG integration potential. An additional benefit offered by the time-series approach is the further detailed analysis of simulations [28]. As an example, Fig. 8 presents the total network power import and export for the original configuration without wind turbines and the three maximum exported energy scenarios presented in Table I. While the original distribution network is a natural importer from the grid, this scenario changes dramatically with the insertion of DWPG placed according to the method. The first arrangement presented in Table I results in the network exporting energy for almost 50% of the time a figure that increases to more than 67% when the substation voltage is lowered to 1.00 p.u.

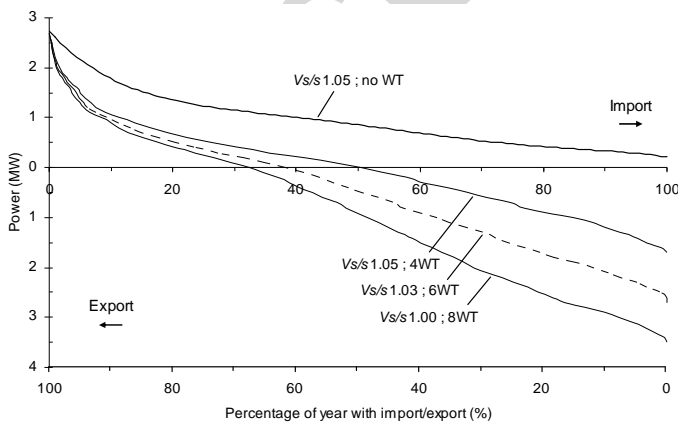


Fig. 8. Import and Export for the original configuration without wind turbines (WT) and the three maximum exported energy scenarios presented in Table I.

It is clear from the analysis that adjusting the voltage setting at the substation may boost network capacity for

absorbing DWPG while satisfying its technical constraints. One consideration is that by lowering substation voltage to allow greater DWPG penetration there is potential for voltages to fall below limits should the generator trip at high demand levels. The analysis presented here tends to account for this as the variability of wind means that there are occasions when zero wind output coincides with peak demand.

Selecting the most suitable configuration from among the Pareto optimal solutions set will rely on the utility's interests. At first glance it would seem feasible to draw the Pareto front to the left edge of each of the plots in Fig. 6 and Fig. 7. In this case, however, it should be remembered that an additional objective, that of short-circuit level is also a factor and, as such, the front is a three dimensional feature and cannot directly be drawn by inspection. However, a range of solution methods exist to help decision-making in this case, ranging from direct methods such as min-max to more interactive approaches using concepts such as significant dominance.

It is important to highlight that as metaheuristic techniques do not ensure finding the global optimal solution, the multiobjective approach based on the NSGA does not guarantee to obtain all non-dominated solutions. Nevertheless, as exhibited by the analysis carried out, Pareto-optimal solutions are diversified.

VI. CONCLUSIONS

Restricting the analysis of Distributed Wind Power Generation integration to scenarios where demand and power production are considered to be static rather than taken into account the inherent variability of such parameters may under- or overestimate the benefits it might bring to the network.

The proposed multiobjective optimization algorithm was able to find sets of DWPG arrangements (Pareto-optimal solutions) that were a 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 satisfying voltage and thermal constraints.

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 substation voltages is a more direct procedure for maximizing integration of DWPG.

The proposed technique can help assess the potential of distribution networks to connect DWPG as well as identifying those constraints that may restrict a larger integration.

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VIII. BIOGRAPHIES

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