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Multiobjective Optimization Model for the Connection of Wind Power Generation to Distribution Networks

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SUMMARY

Current energy policies are encouraging the connection of renewable energy generation to both transmission and distribution networks, mainly due to environmental concerns but also to promote energy diversification. In the last decade, several initiatives from industry and governments were taken to accelerate wind power projects resulting in successful commercial development of the technology. Consequently, wind power is expected to play an increasingly important role in the electric power system infrastructure and market. On the other hand, given that distribution networks were not planned to support insertion of power generation units (Distributed Generation), various studies have reported that such integration may create technical and safety problems. The main issues include where to locate and how to operate distributed generation to minimize the impact on distribution management. Moreover, special attention should be paid to wind power generation since its impact are time-variant given the nature of the renewable source.

In this work a steady-state analysis considering the assessment of technical impacts such as losses and reverse power flows for time-variant loads and generation is proposed, aimed at finding a set of optimal connection points for wind power generation in medium voltage distribution networks. Depending on the network size and on the number of generators to be connected to the network, the problem presents a combinatorial nature, requiring an optimization tool able to handle multiple objectives. When using weighting factors for the multiobjective approach, the main advantage is the controllability of the emphasis of one impact (objective) over the other, giving flexibility to the distribution engineer (decision maker). Nevertheless, this approach needs a complete knowledge of the priority of each objective. Therefore, distribution engineers require different alternatives in decision making so they can be able to choose the most appropriate solution for the current situation without biasing any objective. Here, the impacts will be analyzed simultaneously based on the non-dominated sorting genetic algorithm (NSGA) leading to a more realistic and diversified set of solutions.

With current legislation generally disallowing utility-owned generation, in practice, distribution engineers are limited in their ability to specify the connection point of a generation unit. Nevertheless,

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a multiobjective optimization analysis based on technical impacts permits knowing where this generation could be more beneficial for the studied distribution network, helping distribution engineers take decisions and even shape the nature of the contract that might be established between the utility and the distributed generator owner.

A medium voltage distribution network considering its one-year basis demand profile is analyzed. Wind power generation is calculated based on wind speed measurements performed by the UK Meteorological Office for the central Scotland during 2003. Results are presented and discussed remarking the time-variant benefits and drawbacks of wind power generation.

KEYWORDS

Multiobjective optimization, distribution networks, wind power generation.

1. Introduction

CIGRE defines distributed generation (DG) as electric power generation within distribution networks or on the consumer side of the meter [1]. Recently, the Brazilian Electricity Regulatory Agency (ANEEL) have included in the preliminary version of Distribution Procedures [2] a more specific definition where DG is the electric power generation provided by concessionary or authorized agents connected to the distribution electric system of the buyer, except those hydroelectric plants larger than 30 MW and thermal plants with efficiencies of less than 75% (excluding thermal plant using biomass or process waste). Hydroelectric plants less than 1 MW and thermoelectric plants less than 5 MW are also included as DG and exempted of concession or authorization. DG is not centrally dispatched by the system operator (ISO).

In this way, new rules and incentives are being granted in many countries to DG technologies, whose penetration is expected to play an increasingly important role in the electric power system infrastructure and market. Nevertheless, since various studies have demonstrated that integration of DG in distribution networks may create technical and safety problems [3]-[6], it is critical to assess technical impacts of DG in power systems, in order to apply generators in a manner that avoids causing degradation of power quality and reliability. Thus, DG placement has been investigated considering several impacts (objectives) such power losses, voltage profile, voltage regulation, short-circuit levels, environmental concerns and economical aspects [7]-[17]. Both exhaustive analysis and optimized placement approaches are found in the literature. Nonetheless, the inherent time-variant behavior of loads and power generation patterns of some DG technologies were not taken into account, leading to results that may be masked or solely applicable to the considered scenarios.

Currently, the most ambitious penetration targets have been for wind power where a significant proportion of the installed capacity is and, will be, connected to distribution systems [18]. Integration of such non-dispatchable generation into distribution systems presents several problems for planners and operators. Hence, in order to accurately analyze wind power generation impacts, it is critical to consider wind variations along with load variations [19].

In this work, a time-variant approach is applied to both load and generation. Moreover, the DG placement problem is analyzed by means of multiobjective optimization based on the non-dominated sorting genetic algorithm (NSGA) [20], resulting in a set of configurations known as the Pareto-optimal solutions. Previous work considered the use of weighting factors for calculating a multiobjective performance index for a given distribution network with DG [7], whereas an approach for optimal placing of generation units used a similar multiobjective index as objective function of an evolutionary algorithm [8]. However, the Pareto-optimal solutions correspond to configurations where considered objectives are treated independently, i.e., no objective is biasing another as it happens when weighting factors are utilized [7], [8], [10], [16]. Thus, the Pareto-optimal solutions allows the decision maker to choose among various possibilities the configuration that suits the most utility's current concerns.

2. Multiobjective Optimization Algorithm

The combinatorial nature of the DG insertion problem requires optimization tools. Since genetic algorithms have presented suitable characteristic for such a task [8], [10] and considering the multiple objectives to be analyzed, here the multiobjective optimization algorithm will be based on the NSGA [20]. This algorithm varies from simple genetic algorithm in the way the selection operator works: two subsets of the population are considered, the Pareto-list and the remaining configurations. The former is composed by the Pareto-optimal solutions based on the following concepts:

1) *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 $j,i=1,2,\ldots,k$ and $j \neq i$.

2) *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 main characteristics of the Evolutionary Algorithm (EA) with the incorporated Pareto optimality criterion include:

1) *coding*: each configuration is described by a vector (chromosome) whose size is equal to the number of nodes. If a DG unit is inserted in a node, this element (gene) receives a "1", otherwise it is zero. Elements of the chromosome for the substation and nodes fed by single- or two-phase branches are fixed to zero;

2) *initial population*: is created by randomly inserting DG units using both a reduced set of buses provided by the Zbus loss allocation method [21] (set of buses that influence the most into the total network losses) and randomly selected feasible buses;

3) *genetic operators*: selection is performed by randomly choosing two chromosomes one from the current population and one from the Pareto-optimal solutions; single-point crossing-over and mutation with probabilities 0.75 and 0.008, respectively, are used;

4) *unfeasible configurations*: configurations found not to have DG after applying genetic operators will be penalised; and,

5) *stop criterion*: when the Pareto-optimal solutions list is not being updated after a given number of generations.

2.1. Objective Functions

When addressing DG impacts several technical and non-technical issues can be considered. Here, two objectives are to be taken into account: real power losses and reverse power flow. Both objectives will be minimized, nonetheless, they may be contradictory, i.e., minimization of one provokes degradation of the other. Moreover, since load and generation patterns are being considered, power losses and reverse power flow will vary as a function of time. Therefore, each objective function will consider the total amount of energy "lost" and "exported", respectively, within a horizon of a year divided by hourly periods. 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 considering DG the objectives functions considered are set out in Sections 2.2 and 2.3:

2.2. Real Power Losses

While DG may unload lines and reduce losses, the reverse power flows from several DG units can give rise to excessive losses. This objective function is expressed by.

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

where,

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

NH : total of hours within the considered year.

2.3. Reverse Power Flow

Depending on the location of DG and the mismatch between its power output and load demand at a given instant, load downstream of the point of connection and even system total demand could be lower than DG power output. Consequently, reverse power flows will occur as power is exported upstream. While the changes in voltage profile induced by the reverse power flows will be captured by the first objective function, there potential negative impacts remain. In particular, these relate to transformer capability to control voltage under reverse power flow conditions as well as interference with the discrimination of network protection schemes. To this effect, the following expresses the corresponding objective function:

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

where,

RPF_i^k : total complex power exported through the substation for the *k*-th distribution network configuration during hour *i*.

3. Case Study

3.1. Test Network

The IEEE 34-bus three-phase medium voltage radial feeder [22] will be used in order to perform the proposed analysis (Fig. 1). Its total demand is 1770 kW, and 72% of the loads are concentrated 56 km far away from the root node (the most distant node is 59 km from the substation). X/R ranges from 0.91 to 2.25. Line-to-line base voltage, V_b, is 24.9 kV. This feeder presents ACSR 1/0, 2 and 4 conductors. The network is simplified by replacing the 24.9 kV /4.16 kV in-line transformer in the original IEEE 34 test feeder with a line and modeling the entire feeder at a single voltage level. The automatic voltage regulator is also not represented due to the presence of DG units.

Wind speed data corresponds to hourly measurements carried out by the UK Meteorological Office for central Scotland for 2003. Given the strong dependence between wind speed and geographical position, three anemometers were chosen in order to create different wind speed zones for the IEEE-34 test feeder. Possible connection points (three-phase connection available) for wind turbines are those within the shadowed areas (wind speed zones) presented in Fig. 1.

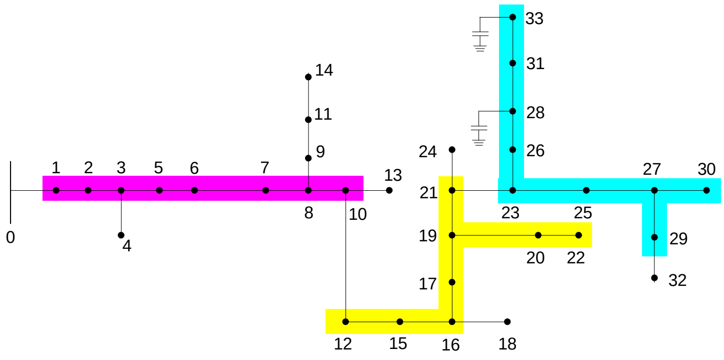

Fig. 1. IEEE-34 test feeder considering three wind speed zones.

3.2. Load Demand and Wind Power Generation

The 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 UK [23]. Due to the inherent variability of wind speed measurements it is not accurate to characterize seasonal daily profiles for wind speeds. In this way, as stated in the previous subsection, hourly measurements are to be used in order to compute the corresponding wind power generation. Fig. 3 presents the power curve for a 500 kW wind turbine (50 m high) that was used along with the wind speed measurements corresponding to the zone of the node where a DG unit is to be allocated to derive the hourly power output.

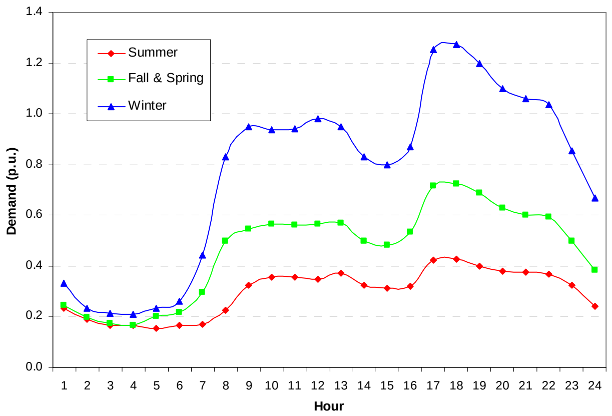

Fig. 2. Seasonal daily load profiles [23].

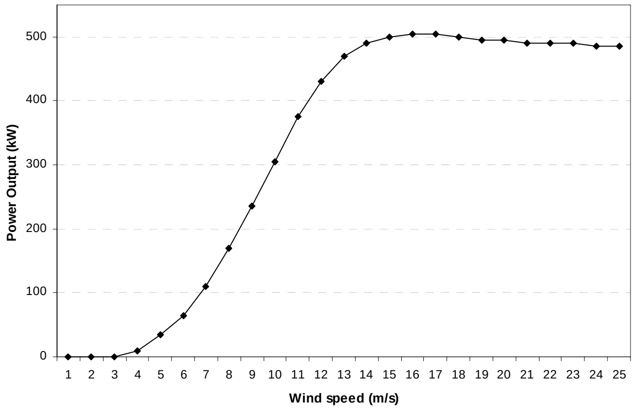

Fig. 3. 500 kW wind turbine power curve.

3.3. Results

Since distribution networks are inherently unbalanced due to load characteristics and topology, here the indices will, explicitly, consider phases *a*, *b* and *c* and the neutral wire (*n*). Moreover, taking in to account the hourly approach for loads and wind power generation, each network configuration (chromosome) is used for 8760 hourly power flows. Thus, the three-phase four-wire power flow algorithm from [24] will be utilized due to its robustness and swiftness. This approach is also applicable to balanced systems.

Application of the proposed multiobjective optimization algorithm on the IEEE-34 distribution network considering the time-variant characteristics of both loads and 500 kW wind turbines while analyzing two objectives functions, real power losses and reverse power flow, resulted in a set of Pareto-optimal solutions (non-dominated front) composed by 41 configurations, as shown in Fig. 4.

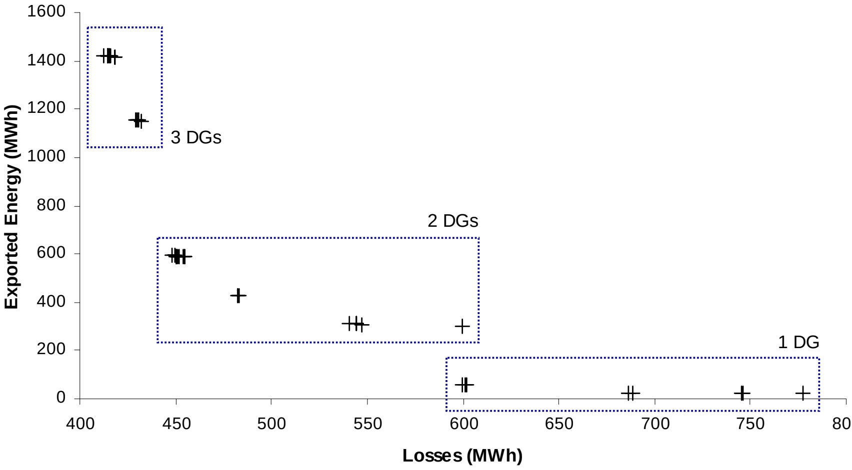

Fig. 4. Pareto-optimal solutions (non-dominated front) – Losses × Exported Energy (Reverse Power Flow)

It is important to highlight that, considering that metaheuristic techniques do not ensure finding the global optimal solution, the multiobjective approach based on the NSGA neither guarantees obtaining all non-dominated solutions. Nevertheless, as exhibited in Fig. 4, one can notice that obtained Pareto-optimal solutions are diversified. Moreover, the non-dominated front can be separated in three different regions according to the number of allocated wind turbines (DG units). As expected, the more wind turbines, the smaller the total power losses and the larger exported energy. On the other hand, when the penetration of wind power exceeds the network demand power losses may increase. This effect can be verified in the results where no configuration with four wind turbines was found to be non-dominated, mainly due to the high amount of exported energy and power losses greater than those configurations with three DG units.

Detailed results of those configurations at the boundaries of each of the three regions marked in Fig. 4 (3 DGs, 2 DGs and 1 DG) are presented in Table. I. Considering that in the original configuration (no DG) total power losses accounted for 974 MWh, the non-dominated solution with 3 wind turbines at nodes 10, 23 and 28, achieved 42% of that amount. On the other hand, the solution found to the extreme right of the non-dominated front (one DG unit at node 12) accounted for almost 80% of the original power losses. Nevertheless, the latter exhibits 25 MWh of exported energy while the former is almost 57 times that value. From Table. I it can be concluded that, given the original characteristics of the network, the voltage profile faced an improvement when more generators were allocated. Opposed to this was the impact of the number of generators and their insertion points to the three-phase short circuit levels.

Table. I. Boundary configurations of each region from Fig. 4.

No. of DG units	Insertion Points	Losses (MWh)	Exported Energy (MWh)	Voltage Drop[1] (%)	Three-phase Short Circuit[2]
3	10, 23, 28	412.75	1420.36	5.73	26.02
	10, 21, 30	431.93	1151.68	6.26	21.84
2	23, 28	448.28	592.81	6.79	24.15
	10, 16	599.39	299.56	9.12	12.05
1	28	599.69	57.46	9.24	12.03
	12	777.20	25.07	11.26	7.43

[1] Average of the maximum voltage drop calculated daily at peak hour (6pm).

[2] Maximum ratio between a three-phase short circuit considering a given configuration and the original configuration (no GD). Parameters for short circuit calculation taken from [7].

From a financial point of view, and valuing losses at US$ 0.10/kWh, the loss reductions from the solution with least exported energy, i.e. one wind turbine at node 12, would represent savings of US$ 19,700/year. On the other hand, the insertion of three wind turbines at nodes 10, 23 and 28 would save the utility up to US$ 56,100/year. Nonetheless, besides the protection scheme investments required in both cases, the latter scenario would necessitate additional costs associated with upgrading the protection to cope with significant reverse power flows. Moreover, with increasing penetration levels of DG, the transmission system operator will lose its overview of the generation assets, requiring cooperation between with the distribution system operator regarding generation developments [18].

4. Conclusions

Due to the particular characteristics of wind power generation and its increasing role in distribution networks worldwide, a multiobjective optimization algorithm was proposed in this work aimed at finding a set of network configurations with DG where each of them represents a unique compromise (Pareto-optimal solutions) between its two objectives, power losses and reverse power flow, while taking into account the complexity of including the variability of both load and generation. More objectives, such as short circuit levels, reliability, economical aspects, environmental concerns, etc., can be included in the procedure, nonetheless, adding complexity to the problem requires a detailed observation of each objective since none of them should exhibit the same behavior of the others.

Despite the limitations of distribution engineers determining the connection point of a generation unit, the multiobjective optimization analysis presented in this work permits knowledge of where generation could be beneficial for the distribution network considering the critical aspect of load and generation patterns. The set of Pareto-optimal solutions can help the decision maker to choose the configuration that suits the utility’s current concerns and even shape the nature of the contract that might be established between the utility and the distributed generator owner.

Reliability, considered most of the time as the main concern of electric utilities, has been the focus of various DG studies [10], [17]. In order to increase network reliability, islanding should be an option for DG, however, due to power quality issues in most countries such an option does not exist. In Brazil, the Distribution Procedures [2] grants utilities the right to decide whether they allow islanded operation of DG units. If so, a deep analysis should be performed considering both load and power generation variability.

This analysis was based on wind speed measurements. In practice, in order to investigate the impacts of wind turbines insertion in distribution networks it is critical the availability of wind speed forecasting for a given horizon. State-of-the-art methodologies for performing this task are already in use but still include a certain level of uncertainty [25]. Wind power generation variability also raises system operating costs but recent studies have pointed out that in most cases these are relatively modest (less than 10% of wholesale energy value) [19].

5. Acknowledgement

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