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Sensitivity analysis to connect distributed generation

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ABSTRACT

One of the alternatives to reduce costs in a power system is the application of distributed generation (DG). Although inherent flexibilities of DG, the point of connection must be carefully chosen in order to avoid any hazardous impact. Normally, this choice is based on loss minimization, improvement of the voltage profile and reduction of the power flows through the lines. The search field of this problem is vast. In order to diminish it, this article assumes that only some buses of the network are candidates to the connection. Thus, one of the main objectives of this work is the proposition of a sensitivity analysis that indicates the best buses to realize the connection. Due to peculiarities of this proposed analysis, the voltage phasor is represented by the rectangular form. To test it, a conventional allocation's methodology is implemented and solved using genetic algorithms (GA) together with an optimal power flow (OPF). A purely radial feeder of one distribution company in Brazil, with 2678 buses and a typical network of 70 buses are chosen to present the results of the methodology.

1. Introduction

Throughout the world, there is great demand for energy to support the growth of diverse areas of the economy. Distributed Generation (DG) can be a salient option from among the alternatives available to meet these needs of demand.

DG includes generators based on biomass, photovoltaic systems, combustion turbines, fuel cells, microturbines, storage technologies, small central hydroelectric plants, and wind turbines.

Although these technologies are attractive, there is a need for in-depth studies on the impact of connecting them.

The literature presents many articles that define DG technologies, site and size them using artificial intelligence. For example, in [1], genetic algorithms (GA) were used to emphasize voltage profile, losses, intensity of the short circuit current and harmonics injected into the network after the insertion of DGs. Some other studies, such as [2–5], consider the losses of the primary system of distribution, emphasizing the effect of such loss on distribution system, depending on the size and place of the DG allocation.

The methodology presented in [6] allocated DGs at all the possible points of connection. The final choice of the size and place was obtained by determining the ones with the biggest dispatched values.

Recently, in [7,8], a review of the state-of-the-art of multi-objective planning of distributed energy resources was presented. In [9], it was formulated a methodology based on nodal pricing for optimally allocating distributed generation for profit, loss reduction, and voltage improvement including voltage rise phenomenon. This paper addressed voltage rise issue. Differently, the paper [10] presented an algorithm to radial distribution feeder, heavily overloaded with non-uniformly distributed load [11], an investigation into the effect of load models on the predicted energy losses in DG planning [12], presented a conventional multi-objective function to determine the optimal locations to place DGs based on dynamic programming, and [13] presented a novel that combined genetic algorithm (GA)/particle swarm optimization (PSO).

Considering the reliability improvement and loss reduction [14] analyzed, besides the allocation of DG, also remote controllable switches, using a multilevel yearly load model.

Taking into account the time-dependent evolution of generation and load, in [15] was presented a method to obtain the optimal size of DG sources in electrical distribution systems adopting two nested calculation stages. The external stage is carried out by selecting a set of candidate nodes through a clustering-based approach based on normalized loss sensitivity factors and normalized node voltages and the internal stage is an exhaustive search driven by the calculation of an objective function with energy losses and voltage profile components.

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In general, the cited articles seek to size the DG. However, when a DG's owner requests a connection with the electric network of a distribution company, the characteristics of that technology has already been sized. At this stage, it must be analyzed the best point of connection, in a way to reduce electric losses, improve voltage profile, overload through the handles, and others, because it is supposed that studies like costs and types of technology have been already done depending on the resources available of water, wind, gas, solar, etc.

This work studies exactly this stage: the choice of the best point of GD's connection in distribution networks, which emphasizes electrical analysis.

This kind of problem is observed by the side of the distribution's utility that receives a request to connect a new generation and has to operate it.

This question requires high computational effort, because it involves a vast search field. Thus, it is necessary to gather information from previous studies that showed particular points of the distribution network as being more favorable to the connection of the DGs.

There are a few studies that have focused on this issue. For example, in [16], a method based on the sensitivity between the total losses, L, and injection of power, $\mathbf{P}$, was established ($\partial L/\partial \mathbf{P}$). The biggest values of this sensitivity represent the best bus candidates of the system to allocate the DGs.

Based on this idea, one of the objectives of this study is the proposition of other sensitivities relations that can indicate the best buses to realize the GD allocation, as (i) buses with the biggest Lagrange multipliers related to the loss minimization problem; (ii) buses with the biggest incremental losses [16]; and (iii) buses with the biggest dispatches of generation when the GDs are virtually applied at all the possible points of connection.

This allocation problem involves, yet, the solution of a power flow analysis (PF). There are some efficient methods to find the solution of the load flow problem in radial distribution networks [17]. However, the majority of these methods are adjusted only for pure radial systems.

In order to resolve this restrictive question and besides to permit the dispatch of active and reactive power of the DGs (controlling the voltage profile, losses and restrictions), an optimal power flow (OPF) is modeled, based on the Interior Points Method, as presented in [6].

Differently of [6], this work models the voltage phasor using rectangular coordinates in order to skirt the problems of bad numerical conditioning in excessively long and radial networks.

Finally, a conventional allocation's methodology of GD (solved with GA) is described to validate the results obtained by the sensitivities analysis. The reason to use GA is the numerous articles that treat this problem of allocation with satisfactory results. However, the most important point of this work is not the intelligent technique used but the electrical analysis made by the OPF modeled with rectangular form and the sensitivity studies.

The article is organized as follows. Firstly, some considerations about the use of rectangular coordinates and the OPF formulation are presented. Next, the techniques use to select the sets of bus candidates to connect the DGs and the conventional allocation's methodology is described. Finally, results and conclusions are showed.

2. Power equations using rectangular coordinates

The search for optimum points to connect DGs requires solving of the power balance equations (PF problem). It is necessary to allow the evaluation of the network, losses, voltage profile and overload through the lines.

Some efficient methods to find the solution of a PF problem applied to distribution systems are available in the literature [17]. However, these methods are only adjusted for pure radial systems.

Moreover, depending on the type of the DGs under study, it can be necessary to control the voltage and value of reactive power generated. This kind of control cannot be decided by the usual power flow methods described in [17]. So, instead of them, it was chosen an OPF formulation to calculate the power balance equations that permits the optimal dispatch of active and reactive power generation of the DGs (controlling the voltage profile, losses, demand and restrictions) and more, not only to radial feeders as the commonly PFs applied to distribution systems.

On the other hand, the usual formulations of OPF (polar form) applied to transmission system are not suitable for radial distribution networks because this kind of network has a poor bus admittance matrix, proceedings of particular characteristics as low relation reactance/resistance (X/R) of the feeder and stretches with relatively low impedances (representation of keys, regulators, and small stretches of line) associated with others with relatively high value of impedance [17].

This bad conditioning can lead to the divergence of an OPF modeled in the polar form.

To skirt these numerical questions, the rectangular form is used to represent the power balance equations in order to better converge very extensive radial network.

The representation of complex bus voltages in rectangular form was employed by [18] got good results in terms of numerical stability and number of iterations.

The use of rectangular form has many advantageous properties described in [18] as: power balance equations and constraints are quadratic, thus the hessian is constant and needs to be calculated only once in the entire optimal process; the Taylor expansion terminates at the second-order term without truncation error; easy evaluation of higher order terms because it avoids trigonometric functions which are very time consuming [20] and the robustness of the solution process due to the structure of the hessian matrix which is diagonally dominant and is positive definite throughout the solution process [21]. So, with theses properties, the OPF retains the quadratic convergence characteristics and the solution time are reduced [19].

The voltage phasor, $\dot{V}_i$, represented by the rectangular form is:

$$\dot{V}_i = e_i + j \cdot f_i \quad i = 1, \ldots, nb \tag{1}$$

where e_i is the real component of $\dot{V}_i$, f_i is the imaginary component of $\dot{V}_i$ and nb is the number of buses. The elements that compose the real and imaginary components of the bus voltages are grouped as $\mathbf{e} = [\, e_1 \quad \cdots \quad e_{nb} \,]^T$ and $\mathbf{f} = [f_1 \quad \cdots \quad f_{nb}]^T$.

Therefore, the active and reactive power balance equations represented as a function of $\mathbf{e}$ and $\mathbf{f}$ [22] are:

$$\mathbf{P}(\mathbf{e},\mathbf{f}) = diag(\mathbf{e})[\mathbf{G} \cdot \mathbf{e} - \mathbf{B} \cdot \mathbf{f}] - diag(\mathbf{f}) \cdot [\mathbf{B} \cdot \mathbf{e} + \mathbf{G} \cdot \mathbf{f}] \tag{2}$$

$$\mathbf{Q}(\mathbf{e},\mathbf{f}) = diag(\mathbf{f})[\mathbf{G} \cdot \mathbf{e} - \mathbf{B} \cdot \mathbf{f}] - diag(\mathbf{e}) \cdot [\mathbf{B} \cdot \mathbf{e} + \mathbf{G} \cdot \mathbf{f}] \tag{3}$$

where $\mathbf{P}$ and $\mathbf{Q}$ are the active and reactive power injections, $\mathbf{G}$ is the real component of the bus admittance matrix $\dot{\mathbf{Y}}$, $\mathbf{B}$ is the imaginary component of $\dot{\mathbf{Y}}$ and $diag$ is an operator that transforms a vector into a diagonal matrix.

Considering the rectangular coordinates, let vector $\mathbf{x}$ be:

$$\mathbf{x} = [\mathbf{e}^T \quad \mathbf{f}^T] \tag{4}$$

Therefore, to obtain $\mathbf{e}$ and $\mathbf{f}$ through $\mathbf{x}$:

$$\mathbf{e} = [\boldsymbol{\Gamma} \quad \mathbf{N}] \cdot \mathbf{x} = \boldsymbol{\Gamma}_e \cdot \mathbf{x} \tag{5}$$

and

$$\mathbf{f} = [\mathbf{N} \quad \boldsymbol{\Gamma}] \cdot \mathbf{x} = \boldsymbol{\Gamma}_f \cdot \mathbf{x} \tag{6}$$