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Simultaneous allocation of capacitors and voltage regulators at distribution networks using Genetic Algorithms and Optimal Power Flow

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ABSTRACT

The high reactive power level demanded by the distribution systems, the loads growth and consequent increase of system losses introduce variations at the buses voltage magnitudes, which compromise the quality of the supplied electric energy. To assure high quality, some devices such as voltage regulators – VRs and capacitors banks – CBs, are installed to allow effective control of voltage magnitude, reactive power and power factor. The present work proposes a methodology to allocate simultaneously these devices using both Genetic Algorithms – GAs and Optimal Power Flow – OPF. The strategy proposed involves the adoption of GA for the allocation of CBs with specification for the type of bank (fixed or automatic) and the reactive power (kvar), as well as the allocation of VRs with adjustment of their secondary voltage. The OPF is responsible for the solution of the power balance equations, tap adjustments of the VRs that assure the voltage level at their exits according to the voltage level specified by the GA for the diverse load curve and for the attainment of the nominal current of the VRs allocated.

1. Introduction

It is important for the distribution companies optimize their operation by diminishing the losses, obeying the demanded standards and following the necessary regulations. To assure adequate levels of voltage and losses at various points of the distribution network, the use of some devices that accomplish a voltage effective control, a reactive power control and a power factor control is essential. The usual equipments to carry through these controls are the voltage regulators (VRs), the transformers with changing taps (located at the substations) and parallel capacitors (capacitors banks – CBs). Some actions such as load transference from a more loaded feeder to a less loaded one, cross-section exchange, construction of new feeders, primary voltage change and construction of a new substation (SU) are necessary as well.

The supplied benefits of inserting regulating devices depend on how they are inserted into the system, that is, it depends on the localization, capacity and adjustments. These choices are complex because the distribution systems reach large areas. So, in order to help the allocation of these devices that make the voltage and the reactive compensation, this work intends to present a methodology established in terms of Genetic Algorithms (GA) and Optimal Power Flow (OPF) that allocates CBs and VRs simultaneously, minimizing, among other subjects, system losses and voltage deviations.

In terms of only CBs allocation, the first few methods [1–4] have been analytical, searching for economy of energy, reduction of losses and cost of banks' installation. However, they presented high computational efforts that gave birth to new approaches based on the application of heuristic techniques and relaxed versions of the problem. Searching for results that showed the reality of the problem in a more appropriate manner [5,6] considered the conductors of different sections and loads not uniformly distributed.

At the beginning of the nineties, the problem of CBs allocation was studied through the use of diverse techniques such as: Simulated Annealing [7,8], GA [9], Fuzzy Dynamic Programming [10], Fuzzy Systems [11–13] and other directed approaches through electric calculations and numerical methods [14,15], GA and Simulated Annealing [16], GA considering harmonic voltage distortion [17], GA considering an approach for complete distribution systems [18–20], Taboo Search [21] and other hybrid mathematical models [22,23] and heuristic algorithm [24].

In case of VR allocation, there are a few studies. For example, in [25], the optimal VR allocation for radial distribution systems was based on the minimization of an objective function (*OF*) that evaluates the cost of investment and maintenance of these equipments as well as the cost of losses of the network under analysis. In [26], a multi-objective function, focused on the losses and voltage drops, was taken into account using a micro-GA to find the solution.

In terms of simultaneous CBs and VRs allocation, there are only the studies [27,28]. These papers investigated the problem of con-

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temporaneously choosing optimal locations and sizes for both shunt capacitors and series voltage regulators in three-phase unbalanced distribution systems. The sizing and placement procedure not only minimized the power losses along distribution feeders but also made sure that both capacitors and series regulators had the minimum possible impact on the harmonic distortion of bus voltages in the system.

As this field is not enough considered, questions yet come up: which of these devices is the most adequate among so many other alternatives and objectives, besides the minimum cost of equipment and losses?

This study aims to answer this question, presenting a methodology to allocate CBs and VRs simultaneously, considering other objective functions related to the voltage profile. It uses, among the cited techniques, the GA, because of their easy applicability in combination problems. Differently of other studies, to evaluate the individuals supplied by the GA, the proposed methodology uses an OPF instead of the traditional load flows, previously accepted for radial distribution [29]. The OPF, solved by the Non-Linear Primal–Dual Interior Point Method [30], was chosen because it makes possible the optimization of tap regulators that assure the voltage level maintenance specified by the GA for different load platforms.

The exclusive allocation of VRs works mainly with voltage profile improvement and the exclusive allocation of CBs works mainly with supplement of reactive power. The simultaneous allocation of them presents a better combination of voltage profile and losses. So, this paper proposes a multi-objective problem that considers the costs of the equipment and losses (as majority of the works does) and considers the minimization of voltage limits and voltage drop violations along the feeder.

The study is organized as follows. First of all, some basic characteristics of voltage regulation, GA and mathematical formulation are shown. Then, some considerations about the OPF and the structure of algorithm are set. Finally, the results and conclusions are displayed for a 70-bus system [31].

2. Voltage regulation

To realize the allocation, initially, it is necessary to describe the limits of voltage as well as the equipments used for voltage control, focusing on the most relevant aspects.

For example, according to some countries, the magnitudes of voltage in steady state must be placed between 93% and 105% of nominal voltage of the system. There might be yet another cost for the distribution concessionaire, when there are voltage drops over 4% [32], beyond the costs with active power losses.

The imposition of these limits induces the concessionaires to raise the quality of service to their customers. But, to fulfill all these regulations, a detailed study of voltage correction alternatives must be carried out for it to be effective and inexpensive.

Among all the known possible alternatives of voltage control, two will be deeply analyzed in this study: the installation of CBs and VRs.

The CBs are used to make reactive compensation, minimize active losses and improve the voltage profile within acceptable limits. The amount of supplied compensation is related to the localization of capacitors at the distribution system, size, amount and the kind of capacitors to be installed [9].

The CBs available are either fixed or automatic, and their values are specified in terms of reactive power (kvar). The fixed banks are in operation permanently. The automatic banks can turn on and off depending on the load condition and adequate controls.

The VRs are equipments destined to maintain the voltage level at rural and urban distribution networks when they are submitted to voltage variations outside the specified limits.

A VR is basically an autotransformer that has taps and a control circuit responsible for commuting these taps whenever the voltage at the exit of the regulator violates the predetermined limits. Basically, there are three types of VRs: Autobooster, Line-Drop Compensation (LDC) and 32 steps.

This study used VRs of 32 steps because this regulation system is preferred by the concessionaires [33]. This kind of VR allows a constant and daily specified voltage at a pre-determined point of system. Each variation of the taps corresponds to 0.625%, for the 32 steps of voltage variation.

Some considerations about CBs and VRs allocation are still listed below:

(i) the methodology, described in the next section, determines the buses of the distribution network where the CBs must be installed, specifying the size (kvar) and the type (fixed or automatic);
(ii) the fixed CBs are used to make reactive compensation for all load levels; the automatic ones are used for middle and heavy load;
(iii) the VRs (32 steps, Type B) allow total voltage regulation of ±10%;
(iv) the methodology determines the lines of the network where the regulators must be installed, specifying the voltage levels to be adjusted at their exits.

3. Allocation's methodology

Next, the BC and VR allocation's methodology is formulated using GA.

The GA are evolutionary programs inspired by the Theory of Natural Selection. They act on a population of individuals based on the fact that the individuals with good genetic characteristics have greater survival possibilities and greater possibilities to produce more suitable individuals, while the less suitable individuals tend to disappear.

The GA are based, initially, on the generation of a population formed by a set of individuals that can be seen as possible solutions to the problem. During the evolutionary process, this population is evaluated. Fitness is calculated for each individual, reflecting its ability to adapt. A percentage of the most adapted individuals is retained, and others discarded. The members kept for the election can suffer modifications in their characteristics through recombination and mutations, generating descendents for the next generation that maintain the characteristics of the previous generation and make possible the variability of individuals in the population.

The genetic operators used are the selection via roulette with: mutation with tax of 10%, dispersed crossing with tax of 70% and elitism of two individuals. The creation of the initial population was random and the stopping criterion was a maximum number of generations equal to 10,000. The population includes 10 individuals.

In this study, the individual is a binary sequence that contains the localization, type and size of the CBs, and the localization and exit voltage of the VRs.

Fig. 1 presents this codification. It is formed by two parts. The first one indicates the line to receive a VR and the exit voltage of it. The second part indicates the bus to receive a CB, the type (fixed or automatic) and the size of it (kvar).

The fitness of each individual is obtained by the value *OF* that will be described in Eq. (1).

The *OF* prioritizes the reduction of electric losses, voltage profile improvement and cost of the devices.

If there are no economic limits of investment, as many CBs and VRs as are necessary in order to get satisfactory voltage profile may be placed. However, many companies have budget restrictions. So,