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Minimization of voltage deviation and power losses in power networks using Pareto optimization methods

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ABSTRACT

Voltage regulation is an important task in electrical engineering for controlling node voltages in a power network. A widely used solution for the problem of voltage regulation is based on adjusting the taps in under load tap changers (ULTCs) power transformers and, in some cases, turning on Flexible Alternating Current Transmission Systems (FACTS), synchronous machines or capacitor banks in the substations. Most papers found in the literature dealing with this problem aim to avoid voltage drops in radial networks, but few of them consider power losses or meshed networks. The aim of this paper is to present and evaluate the performance of several multi-objective algorithms, including hybrid approaches, in order to minimize both voltage deviation and power losses by operating ULTCs located in high voltage substations. In particular, a well-known multi-objective algorithm, PAES, is used for this purpose. PAES finds a set of solutions according to Pareto-optimization concepts. Furthermore, this algorithm is hybridized with simulated annealing and tabu search to improve the quality of the solutions. The implemented algorithms are evaluated using two test networks, and the numerical results are analyzed with two metrics often used in the multi-objective field. The results obtained demonstrate the good performance of these algorithms.

1. Introduction

The operation of power networks has undergone considerable change in recent times. Several factors have influenced this change. For example, the interest in saving energy, the use of cheaper and more universal measuring devices, the growing demand from consumers for improved quality of the power supply, or even the appearance of new tools for monitoring power networks. New technologies are constantly appearing in all fields of science and engineering, including electrical engineering and power systems. Specifically, there are many elements in power distribution networks that could be automated and coordinated, such as tap changers in power transformers or tap changers in bank capacitors. The present paper deals with new computational optimization algorithms which allow a better operation of the system, achieving a better voltage profile and reduced power losses. The general problem of voltage control and optimization of power flow occurs because of the need to act on the voltage at the network nodes to ensure that it remains within acceptable limits. One of the main elements allowing this adjustment is the under load tap changer (ULTC), which can adjust the voltage ratio in discrete steps. Taking into account the combinatorial nature of this problem, different methodologies based on artificial intelligence have been applied. Some authors have proposed the use of techniques such as dynamic programming (Lu and Hsu, 1995) to control tap changers and capacitor banks in substations for 24-hour-planning. This aims to improve the efficiency of the algorithm by limiting the search space in the vicinity of an analytical solution calculated using the hourly load forecasting. This technique has even been extended to small networks with radial capacitor banks at the heads of the lines (Ruey-Hsun and Chen-Kuo, 2001). Fuzzy logic techniques have also been used (Liu et al., 2002). Other authors have used neural network techniques for voltage and power regulation in radially operated networks during one-day periods, making use of the tap changers of transformers and capacitor banks (Saric et al., 1997). Other techniques such as genetic algorithms (Haida and Akimoto, 1991) have also been implemented for voltage optimization. On the other hand, the typical problem of voltage and reactive power

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compensation (known as the Volt/Var problem) has been widely studied in power networks (Begovic et al., 2004).

Moreover, the variation of voltage at the system nodes due to ULTCs could involve a change in the power flow through the system lines, which must be minimized in order to avoid the power losses that occur due to the Joule effect. In this way, optimal operation of ULTCs allows voltage and power flow to be under control. Thus, this problem can be treated from a multi-objective perspective (Augugliaro et al., 2004). The traditional way of dealing with multi-objective optimization problems consists of introducing weights in a simple aggregating function (weighted sum), where weights reflect the relative significance of the different objectives. However, the main drawback of this linear combination is the difficulty to establish accurate values for the weights, especially when the objectives to be considered have different scales or represent different magnitudes. An interesting, and possibly the best way of overcoming this drawback is the use of Pareto optimization (Deb, 2001), which is a method that includes multiple criteria without using weights. This paper addresses the problem of optimizing the control of an automated power distribution network under normal operation using Pareto-optimization, where the objectives to minimize are: a voltage deviation index that gives information about the voltage profile in the network (Montoya et al., 2006), and the power loss of electrical lines due to the Joule effect.

2. Material and methods

2.1. Voltage regulation in electrical power networks

Currently, voltage regulation in traditional power substations for HV/MV (high/medium voltage) or MV/MV transformers is performed by under load tap changers (ULTC), whose input variables are essentially the voltage and current values measured at the outlet of the secondary circuit of the transformer, while regulation in the MV/LV (medium/low voltage) is carried out manually using vacuum tap changers. In an automated network, this process can be approached from a different, more holistic perspective that takes into account other elements in the network. A typical power network consists of:

- N power substations with HV/MV transformers of a nominal power S_{Ni};
- N ULTCs for N transformers in the substations. In our test cases, 21 positions (-10% to $+10\%$ with a step size of 1%) have been used;
- N_{LV} nodes with MV/LV transformers to service the LV network;
- N_L power lines connecting different nodes;
- N_C capacitor banks, synchronous compensators, etc.

For a given load scheme in the system, the objectives to minimize are:

- Voltage deviation index, which indicates the deviation of the nodal voltages from their nominal value;
- power losses in the network.

While the reduction of power losses is clearly a goal in terms of cost savings, the optimization of voltages, and more specifically their adjustment to a flat profile, have not received sufficient consideration from either system operators or national legislation. For instance, the Spanish Royal Decree on the Regulation of the Distribution and Transmission of Electricity (R.D. 1955/2000) only stipulates that the maximum variation in voltage supplied to end consumers must be within $\pm 7\%$ of the supply voltage declared. The cost associated with the quality of service (operation of electrical and electronic systems, product quality, disturbances in the system, etc.) has not been clearly and appropriately estimated to date. It is also important to remark that the two objectives are contradictory, i.e. lower voltage deviation implies higher losses in the network and vice versa. This is dealt with in greater detail below.

2.2. Problem formulation

As commented above, the main problem is to find the optimum of two objectives subject to certain constraints (maximum deviation of $\pm 7\%$ with respect to the nominal voltage at system nodes). The first objective is modelled using the voltage deviation index (VDI), which determines the difference between the voltage in nodes with respect to the nominal voltage. The following equation describes how VDI is calculated:

$$VDI = \sum_{i=1}^{N_T} \frac{(V_i - V_{Ni})^2}{V_{Ni}^2} \quad (1)$$

where VDI is the voltage deviation index, V_i is the voltage at node i, V_{Ni} is the nominal voltage at node i; and N_T is the number of network nodes. From the power systems perspective, unit quantities are used, i.e. V_{Ni}=1 and V_i will always be close to one.

The second objective to minimize is the power loss (P_{loss}) in the power system, which is associated with the well-known Joule effect in power lines and power transformers. Both lines and transformers have an inherent resistive component, which causes warming when current flows through them. In this work a simplistic assumption is used, which obviates the power losses associated with insulators of the different equipment (lines, capacitors, etc.). These losses are much lower than those produced by the Joule effect and can therefore be neglected. Under these assumptions, the power loss of the system is displayed as

$$P_{loss} = \sum_{i=1}^{N_T} R_i I_i^2 \quad (2)$$

where P_{loss} is the power loss in watts, R_i is the resistance in ohms of element i (either line or transformer), and I is the current in amperes.

Bearing in mind that the optimization process consists of the simultaneous minimization of the voltage deviation index (VDI) and power losses, multi-objective optimization techniques should be applied. In this case, the solutions are evaluated according to Pareto-dominance relationships, where the result of the algorithm is not a single solution, but rather several non-dominated solutions as an approximation to the (unknown) Pareto-optimal front (Goldberg, 1989; Deb, 2001). Thus, solution s is said to dominate another solution s' when it is better in at least one objective, and not worse in the others (i.e. s has a lower value of VDI/P_{loss} than s' and its value of P_{loss}/VDI is not higher than that of s'). Two solutions are called indifferent if neither one dominates the other (i.e. s has a lower value of VDI/P_{loss} but higher P_{loss}/VDI than s'). It should be pointed out that when engineering tasks involve multiple criteria of similar importance, there may be solutions that are equivalent (indifferent) considering all criteria, in which case the set of non-dominated solutions will contain many indifferent solutions. Thus, this strategy gives a diversity of solutions to be chosen by a high-level decision-maker, who will undertake the appropriate actions depending on the circumstances of the moment and/or future interests. The constraints of the problem are the statutory limits on voltage ($\pm 7\%$ of the nominal voltage), and the operational limits of network elements (maximum and minimum power, maximum and minimum limits