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Optimal power flow solutions through multi-objective programming

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ABSTRACT

Despite the progress achieved in the development of optimal power flow (OPF) programs, most of the solution techniques reported in the literature suffer from the difficulty of dealing with objective functions of different natures at the same time. However, the need for alternative power network solutions during the planning of a power system operation requires the optimization of several performance indexes simultaneously. In this study, attention is focused on the modelling and solution of a parameterized multi-objective OPF problem. The proposed OPF model combines two classical multi-objective optimization approaches, the weighted sum and the constraint methods, through a parameterization scheme to manipulate the objective functions. This parameterization allows relaxation of the constraints imposed to handle the performance indexes, to facilitate the convergence of the iterative process. The resulting optimization problem, which ultimately is a mono-objective optimization problem, is solved through the nonlinear version of the predictor–corrector interior point method. The IEEE 24-bus test system was used to obtain the numerical results of the computational simulation.

1. Introduction

Since the early stages of work on power system operation, different strategies have been proposed to determine the best way to distribute the active and reactive powers among the generating units. The earliest approaches to solving this problem were based on the classical coordination equations. Later, improvements to these methodologies were achieved with the formulation of the optimal power flow (OPF) problem in the early 1960s, which was aimed at determining the power flow solution, optimizing a performance index (usually related to economy, power quality and security) and simultaneously satisfying a set of equality constraints (active and reactive power balance at each bus) and inequality constraints (generation capacity, operational limits of the power system variables and security). It also became impractical to diagnose the full extent of existing conditions and to determine appropriate operating strategies efficiently, without a number of computational tools developed for this purpose. These requirements emphasized the importance of the OPF program in the analysis of power system operation. Depending on the goal to be reached by the power system operation, different objective functions can be optimized. Conventional optimization algorithms usually solve OPF problems considering one performance index at a time. However, during the planning of the power system operation several performance indexes must be taken into account simultaneously, as shown in [1] for reactive power dispatch, which, in terms of optimization, leads to the use of multi-objective programming.

Several studies on multi-objective OPF can be found in the literature. Ref. [2] uses the active power cost function to optimize the reactive power generation. In this approach, the minimization of the active power transmission loss can be viewed as a by-product of the optimization of the reactive power distribution. In [3], the weighting sum method is applied to optimize two performance indexes, the active power cost and active power transmission loss. Each objective function is minimized individually in a mono-objective OPF, and the weighting factors are estimated in terms of the values of the performance indexes corresponding to these mono-objective solutions. In [4], an approach to the Var Planning multi-objective optimization problem is proposed, which is based on weighted deviation and simulated annealing. The main target of this methodology is to minimize the weighted norm of the deviation from an *ideal* or *utopic solution*, considering three objective functions: the active power generation cost, the deviation of the voltage magnitude from a pre-specified level and the security margin of the power system. Its main drawback is the use of equally distributed weighting factors, not taking into account the magnitude of the objective functions. Ref. [5] revisited the main aspects of two classical multi-objective optimization methods, illustrating

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their application in the simultaneous minimization of the active power generation cost and the active power transmission loss. In [6], the constraint method is applied to find a set of alternative OPF solutions, by changing systematically the bounds of the constraints corresponding to the objective functions. Three performance indexes are simultaneously optimized: the security associated with voltage collapse, the cost of the active power margin and the area interchange. It is possible to determine several compromise OPF solutions through the variation of these bounds, although this requires a considerable computational effort. In [7], the problem of determining the optimal feeder reconfiguration of a distribution network is solved through evolutionary algorithms and fuzzy logic. The former are used to deal with the integer variables involved in the optimization problem, such as the feasible configurations of active feeders. The latter is used to combine the technical objectives, that is, a reduction in the power loss, an increase in the power system security (load balancing) and improved power quality (minimization of voltage magnitude deviation) and it iterates with a decision maker to define bounds for the objective functions. Since this problem is treated as a mono-objective optimization problem, it is relatively simple to implement. In [8], attention is devoted to the problem of optimal allocation of reactive power compensation in distribution systems. Genetic algorithms are used to deal with discrete variables, such as location, type (fixed or switchable), operation rate and frequency of use of the compensation to be installed. The multi-objective OPF is solved through the so-called constraint method, and the performance indexes used in this work are the capacitor construction expenditures, the real power loss, and the security margins of feeders and transformers. More recently, [9] and [10] proposed the use of multi-objective optimization to find OPF solutions taking into account the voltage security of the power system. In the first approach, the social benefit and the distance to the critical loadability of the power network are simultaneously maximized. The second approach proposes the inclusion of the power system security, represented by the voltage stability criteria in the traditional OPF solution. The operation of deregulated power electricity markets is the main focus of this approach. The social benefit and the distance to a maximum loading condition are maximized at the same time. The Lagrange multipliers obtained as a by-product of the optimization process represent the so-called Locational Marginal Prices of each bus. In both cases, Interior Point methods are used to solve the nonlinear optimization problems. Particle Swarm Optimization, Genetic Algorithms and Bee Colony based methods have also been used to solve the OPF problem, with particular emphasis on the treatment of discrete variables, interface with continuous variables and the improvement of the exhaustive search in problems with a large number of solutions. Similarly, Evolutionary Programming has been applied to solve multi-objective optimization problems involving simultaneously economic and environmental objectives [11], and fuel cost, transmission loss and voltage stability performance indexes [12]. Although these approaches are interesting, in the present study these aspects are not dealt with.

The present work proposes a methodology to determine multi-objective OPF solutions based on a parameterized optimization model. The parameterization is used to combine the weighted sum and the constraint multi-objective optimization methods. One performance index is elected as the main objective function and the others are converted into parameterized inequality constraints with variable limits. Weighting factors are used to penalize the limits of these constraints. This imparts flexibility to the multi-objective optimization problem, reducing the risk of infeasibility. Three performance indexes related to the squared deviation of a pre-specified magnitude of selected optimization variables (voltage magnitude, active power generation, and reactive power generation) are considered. These objective functions are used to find OPF solutions avoiding large changes in the control variables, as required during the power system operation, when the controls are adjusted to track load variations. The resulting problem is solved through the nonlinear version of the predictor–corrector interior point method. The IEEE 24-bus test system was used to obtain the numerical results of the MatLab simulation.

The remainder of this paper is organized as follows. The rationale concerning the basic multi-objective optimization concepts is stated in Section 2. Section 3 describes the multi-objective OPF model proposed herein and Section 4 presents the numerical results of its application. Section 5 summarizes the main conclusions of the proposed approach. A description of the main aspects of both the mono-objective OPF and its solution through the nonlinear version of the predictor–corrector interior point method is presented in Appendix A.

2. Preliminary aspects of the multi-objective OPF

2.1. Analytical formulation

A multi-objective optimization problem can be analytically represented as

$$\begin{aligned} \text{Minimize} \quad & \mathbf{f}(\mathbf{x}) \\ \text{subject to} \quad & \mathbf{g}(\mathbf{x}) = 0, \\ & \mathbf{h}(\mathbf{x}) \geq 0 \end{aligned} \tag{1}$$

where $\mathbf{x}$ is the vector of the optimization variable,

$$\mathbf{f}(\mathbf{x}) = \left[f_1(\mathbf{x}), f_2(\mathbf{x}) \cdots f_j(\mathbf{x}) \cdots f_k(\mathbf{x})\right]^t \tag{2}$$

is a vector of the functions that represent the performance indexes. The components of the vectors $\mathbf{g}(\mathbf{x})$ and $\mathbf{h}(\mathbf{x})$ are nonlinear functions representing the equality and the inequality constraints.

The mono-objective OPF seeks the feasible power flow solution that provides the best value for the performance index. Even in the case of alternative local optimal solutions, the value of the objective function is unique. The solution of the problem stated by Eq. (1) must be optimal with respect to the objective functions that compose vector $\mathbf{f}(\mathbf{x})$. multi-objective optimization strategies usually generate several solutions, which reflect the compromise between the distinct objective functions. These solutions belong to a large set, referred to as the *Pareto Set* or *Set of Non-inferior Solutions*, which has the following feature: *improving an objective function implies degradation of at least one of the other objectives*. Since it is not trivial to determine an exact description of the Pareto set, given that it is normally too large, it is useful to obtain at least a partial description of this set. Observe that, the optimality conditions of mono-objective OPF problems play an important role in the iterative process applied to find the optimal solution, because they allow reduction in the large set of feasible solutions which are candidates for the optimum. Although the concept of non-inferiority is less limiting, it has a purpose similar to that of the optimality conditions in a mono-objective optimization problem.

2.2. Basic solution methods

The common goal of multi-objective optimization methods used to solve the problem stated by Eq. (1) is to identify solution with the best compromise between the distinct objectives. These methods rely on explicit statements or preferences, which can be articulated in at least two ways, that is, by using a weighting scheme or by including additional constraints in the optimization problem. Two