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Optimal reactive power flow using multi-objective mathematical programming

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Abstract This paper presents a multi-objective optimization methodology to solve the Optimal Reactive Power Flow (ORPF) problem. The ε-constraint approach is implemented for the Multi-objective Mathematical Programming (MMP) formulation. The solution procedure uses Mixed Integer Non-Linear Programming (MINLP) model due to discrete variables, such as the tap settings of transformers and the reactive power output of capacitor banks. The optimum tap settings of transformers are directly determined in terms of the admittance matrix of the network since the admittance matrix is constructed in the optimization framework as additional equality constraints. The optimization problem is modeled in General Algebraic Modeling System (GAMS) software and solved using DICOPT solver. Simulation results are implemented on the IEEE 14-, 30-, and 118-bus test systems to simultaneously optimize the total fuel cost, power losses and the system loadability as objective functions. The simulation results show that the proposed algorithm is suitable and effective for the reactive power planning.

1. Introduction

The multi-objective Optimal Reactive Power Flow (ORPF) is an optimization problem to help the operator to ensure the reactive power planning technically and economically as a subproblem of the Optimal Power Flow (OPF). The objective of the ORPF problem is to allocate reactive power compensation devices and optimize the objective functions while satisfying physical and technical constraints on the power system. The conventional reactive power compensation devices are tap changing transformers and shunt capacitors/reactors. The ORPF problem can be formulated as a Mixed Integer Non-Linear Programming (MINLP) model since tap ratios of transformers and outputs of shunt capacitors/reactors are inherently discrete [1].

Most of the previous researches on the OPF and ORPF have been focused on intelligent methods because they can resolve the defect of conventional optimization algorithms in global searching and handling discrete variables and the infeasibility problem [2]. For decades, conventional optimization techniques, such as Linear Programming (LP) [3], Non-Linear Programming (NLP) [4], Quadratic Programming (QP) [5], Sequential Quadratic Programming (SQP) [1], Newton method [6] and Interior Point Methods (IPMs) [7,8], have been developed for solving ORPF problem.

In recent years, global optimization techniques, such as Genetic Algorithms (GA) [9], Evolutionary Programming (EP) [10], hybrid EP [11], fuzzy [12], Evolutionary Strategies (ES) [13], Particle Swarm Optimization (PSO) [14] and Differential Evolution (DE) [2], have been suggested, which have greater or less success in solving different non-linear single-objective optimization problems. In [15] the Self-Adaptive Real Coded Genetic Algorithm (SARGA) has been applied as one of the techniques to solve Optimal Reactive Power Dispatch (ORPD) problem. The ORPF problem has been investigated using Hybrid GA and IPM (HGI) [16,17], EP [18], Reactive Tabu Search (RTS) [19,20] and PSO [21,22].

Recently, several multi-objective optimization methods as listed below have been investigated for solving the ORPF problem. In [23], multi-objective ORPF has been applied to

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minimize active power losses and payment for the provision of the reactive power service in the framework of the UK daily balancing market. OPF problem using Biogeography-Based Optimization (BBO) has been suggested to minimize three different objectives, i.e. the fuel cost, voltage profile and voltage stability improvement [24]. The multi-objective optimization has been investigated using PSO [25,26], Adaptive Immune Algorithm (AIA) [27] and GA [28–30] to solve ORPF problem.

In previous research works reported in the literature, the ORPF problem has been formulated as a MINLP with discrete and continuous variables; however, they have some serious problems. In some papers, the problem has been solved in two steps. In the first step, the continuous variables have been determined by the OPF algorithm, and in the second step, it has been tried to handle the discrete variables in the ORPF problem. Therefore, the results cannot converge to the optimal batch solution with such treatment and the authors do not have the ORPF program. In some other papers, the effect of tap changing transformers has been considered only on the objective functions while it has been influenced in the active and reactive power balance equations. Consequently, in this paper, it is implemented in the admittance matrix of the system. The Multi-objective Mathematical Programming (MMP) methods, such as generation methods, despite having significant advantages are less popular due to their computational complexity and the lack of widely available software [31]. Considering our present knowledge, no research work in this area has considered the MMP methods for solving ORPF problem. The main contribution of this paper is to propose the ε-constraint method for solving the multi-objective ORPF problem based on MINLP while the discrete and continuous variables are determined simultaneously.

For this application, General Algebraic Modeling System (GAMS) is used to solve the optimal model, and Matlab is used to feed parameters to the GAMS routine. The MINLP optimization problem is modeled in GAMS software and solved by using DICOPT solver [32]. In order to select the "best" compromised solution among the Pareto optimal solutions of multi-objective optimization problem, a fuzzy decision-making tool is adopted. In addition, the admittance matrix is formed as additional equality constraints to involve the tap ratios of transformers in the optimization problem. The total fuel cost, the active power losses and the system loadability are simultaneously optimized as objective functions in the power system while satisfying several constraints. The proposed algorithm is implemented on the IEEE 14-, 30-, and 118-bus test systems. The single- and multi-objective optimization results show that the proposed algorithm is outperformed by the other methods.

The paper is organized as follows. The ORPF problem formulation is developed in Section 2. Section 3 describes the MINLP formulation and its solution methods briefly. The multi-objective ORPF solution procedure is explained in Section 4. Section 5 contains simulation results followed by conclusions.

2. Problem formulation

The multi-objective ORPF problem seeks to optimize one or more objective functions to improve the steady state performance of the power system while satisfying several equality and inequality constraints. The objective functions, constraints, and the multi-objective optimization framework of the problem are explained in the following subsections.

2.1. The objective functions

In this paper, three objective functions are considered which are the total fuel cost, the active power losses and the system loadability. These objective functions are formulated as follows:

(1) *The total fuel cost:* The first objective function is to minimize the total fuel cost that can be expressed as:

$$F_1 = \sum_{i=1}^{NG} a_i + b_i P_{Gi} + c_i P_{Gi}^2 \quad (\$/\mathrm{h}), \tag{1}$$

where P_{Gi} is the active power output of ith generator; NG is the total number of generators; a_i, b_i, and c_i are the fuel cost coefficients of ith generator [33].

(2) *The real power losses:* The second objective function is to minimize the real power losses in transmission lines that can be defined as:

$$F_2 = \sum_{k=1}^{Nl} g_k (V_i^2 + V_j^2 - 2V_i V_j \cos\theta_{ij}), \tag{2}$$

where g_k is the conductance of branch k between buses i and j; Nl is the number of branches; V_i is the voltage magnitude at bus i; θ_{ij} is the voltage angle difference between buses i and j [34].

(3) *The system loadability:* The third objective function is to maximize the system loadability that can be described as [35]:

$$F_3 = \rho(x, u), \tag{3}$$

and ρ can be obtained by assuming constant power factor at each load in the both real and reactive power balance equations as follows:

$$P_G - \rho P_D = f_p(x, u), \tag{4}$$

$$Q_G - \rho Q_D = f_q(x, y), \tag{5}$$

where P_G and Q_G are the vectors of generators real and reactive power, respectively; P_D and Q_D are the vectors of loads real and reactive power, respectively; f_p and f_q are the vectors of real and reactive power flow equations, respectively.

2.2. Constraints

The multi-objective ORPF problem has two sets of constraints including equality and inequality constraints. These constraints can be described in the following compact form:

$$g(x, u) = 0, \tag{6}$$

$$h(x, u) \le 0, \tag{7}$$

where u is a set of control variables which includes active power and voltage magnitude of generator buses, voltage angle and magnitude of the swing bus, tap of transformers and the reactive power sources; x is a set of dependent variables which includes active and reactive power of the swing bus, voltage angle and reactive power of generator buses, voltage angle and magnitude of load buses, and the admittance matrix of the power system; $g(x, u)$ is the set of equality constraints which are usually the power flow constraints for a specified operating condition; $h(x, u)$ is the set of inequality constraints which represents the limits on the control variables and the operating limits of the power system [36]. The equality and inequality constraints are explained in the following subsections.