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Differential evolutionary algorithm for optimal reactive power dispatch

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ABSTRACT

This paper presents differential evolutionary algorithm for optimal dispatch for reactive power and voltage control in power system operation studies. The problem is formulated as a mixed integer, nonlinear optimization problem taking into account both continuous and discrete control variables. The optimal setting of control variables such as generator voltages, tap positions of tap changing transformers and the number of shunt reactive compensation devices to be switched for real power loss minimization in the transmission system are determined. In the proposed method, the inequality operational constraints were handled by "penalty parameterless" approach. This helps in avoiding the time-consuming trial and error process for fixing the penalty parameter and makes the process system independent. The algorithm was tested on standard IEEE 14,30,57 and 118-Bus systems and the results compared with conventional method.

1. Introduction

Global optimization of a non-continuous, nonlinear function, arising from large-scale complex engineering problems, which may have a large number of local minima and maxima, is quite challenging. A number of deterministic approaches based on branch and bound and real algebraic geometry are found to be successful in solving these problems to some extend. Of late, stochastic and heuristic optimization techniques such as evolutionary algorithms (EA) have emerged as efficient tools for global optimization and have been applied to a number of engineering problems in diverse fields. For the secure and economic operation of large-scale power systems, a variety of optimization problems have to be solved. The optimal power flow (OPF) problem, which was introduced in 1960s by Carpentier, [1] is an important and powerful tool for power system operation and planning. Reactive power optimization is a sub-problem of OPF calculation, which determines all the controllable variables, such as tap ratio of transformers, output of shunt capacitors/reactors, reactive power output of generators and static reactive power compensators etc., and minimizes transmission losses or other appropriate objective functions, while satisfying a given set of physical and operational constraints. Since transformer tap ratios and outputs of shunt capacitor/reactors have a discrete nature, while reactive power outputs generators, bus voltage magnitudes and angles are, on the other hand, continuous variables, the reactive power optimization problem is formulated as mixed-integer, nonlinear problem.

A number of mathematical programming based techniques have been proposed to solve the OPF problem. For decades, conventional gradient-based optimization algorithms have been used for the solving optimal reactive power dispatch problem [2,3]. The gradient and Newton methods suffer from the difficulty in handling inequality constraints. Linear programming requires objective function and constraints have linear relationship, which may lead to loss of accuracy. Conventional methods are not efficient in handling problems with discrete variables. The combinatorial-search approaches, branch-and-bound and cutting plane algorithms, which are usually used to solve the mixed integer programming model, are 'non-polynomial and all suffer from the problem of "curse of dimensionality" making them unsuitable for large-scale OPF problems.

Wu and Ma [4] applied Evolutionary Programming (EP) for global optimization problems of large-scale power systems to achieve optimal reactive power dispatch and voltage control of power systems. Lai and Ma [5] showed that in optimization of non-continuous and non-smooth function, EP is much better than nonlinear programming and has applied it for reactive power planning. Lee et al. [6] solved the reactive power operational and investment-planning problem by using a Simple Genetic Algorithm (SGA) combined with the successive linear programming method. The Benders' cut is constructed during the SGA procedure to enhance the robustness and reliability of the algorithm. Chebbo and Irving [7] proposed a linear programming based conventional approach for combined active and reactive power dispatch. Yoshida et al. [8] proposed a Particle Swarm Optimization (PSO) for reactive power and voltage control considering voltage security assessment. Zhao et al. [9] proposed a

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solution to the reactive power dispatch problem with a PSO approach based on multi-agent systems.

Differential evolutionary algorithm (DEA) is a technically simple; population based evolutionary algorithm (EA), which is highly efficient in constrained parameter optimization problems [10]. DEA employs a greedy selection process with implicit elitist features. It has demonstrated its robustness and effectiveness in a variety of applications, such as neural network learning and infinite impulse response filter design [11,12]. It presents no difficulty in solving mixed integer problems [13] and hence is highly suitable for reactive power optimization where the generator voltage is a real valued parameter while tap position and the number of shunt devices to be switched is integer parameters. DE differs from other EA's in the mutation and recombination phase. Unlike stochastic techniques such as Genetic Algorithms (GA) and Evolutionary Strategies (ES), where perturbation occurs in accordance with a random quantity, DE uses weighted differences between solution vectors to perturb the population. Authors in [14–17] used differential evolution to solve problems in power systems.

Method of constraint handling is extremely important in power system optimization problems. In all the previous works reported in literature, inequality constraints were handled by use of a penalty function approach, i.e., the constraint violation is multiplied by a penalty coefficient or parameter and added to the objective function. Deb [18] proposed a penalty parameterless scheme to overcome the difficulty of choosing penalty coefficients for GA based constrained optimization problems. It is important to realize that such a penalty parameterless strategy is only applicable to population based approach. This is because it requires the population to be divided into two sets: feasible and infeasible sets. The fitness function depends on the feasible and infeasible population members. Since in a point-by-point optimization approach, there is only one member in each iteration, such a penalty parameterless scheme cannot be applied. Although a penalty term is added to the objective function to penalize infeasible solutions, the method differs from the way the penalty term is defined in conventional methods and in earlier evolutionary algorithm implementations. In this paper an optimal reactive power dispatch using differential evolutionary algorithm with an efficient penalty parameterless scheme of constraint handling is employed. A performance comparison with conventional interior point technique is provided to highlight the efficiency of the differential evolutionary algorithm based optimization.

2. Optimal power flow

The optimal power flow (OPF) is a static, nonlinear optimization problem, which calculates a set of optimum variables from the network state, load data and system parameters. Optimal values are computed in order to achieve a certain goal such as generation cost or line transmission power loss minimization subject to equality and inequality constraints. The OPF problem can be presented as

$$\begin{aligned} &\min \quad f(\mathbf{x},\mathbf{u}) \\ &\text{s.t} \quad \mathbf{g}(\mathbf{x},\mathbf{u}) = 0 \\ &\mathbf{h}(\mathbf{x},\mathbf{u}) \leqslant 0 \end{aligned} \tag{1}$$

where, f is the objective function that typically includes total generation cost, losses in transmission system etc. Generally, $\mathbf{g}(\mathbf{x},\mathbf{u})$ represents the load flow equations and $\mathbf{h}(\mathbf{x},\mathbf{u})$ represents transmission line limits and other security limits. The vector of dependent and control variables are denoted by $\mathbf{x}$ and $\mathbf{u}$ respectively. In general, the dependent vector includes bus voltage angles θ, bus voltage magnitudes V_L and generator reactive power Q_g , i.e., $\mathbf{x} = [\theta, V_L, Q_g]^T$. The control variable vector consists of real power generation P_g, generator terminal voltage V_g, transformer tap ratio t and reactive power generation or absorption Q_c of compensation devices such as capacitor and reactor banks, i.e., $\mathbf{u} = [P_g, V_g, t, Q_c]^T$. Of the control variable mentioned P_g and V_g are continuous variables, while tap ratio, t, of tap changing transformers and reactive power output of compensation devices, Q_c, are discrete in nature. Loss minimization is usually required when cost minimization is the main goal with generator active power generation as the control variable. When all control variables are utilized in a cost minimization, a subsequent loss minimization will not yield further improvements. Therefore in reactive power dispatch problem, such as loss minimization, active power generation of all generators, except slack generator, is fixed during the optimization procedure.

3. Problem formulation

The solution of the optimal reactive power dispatch problem involves the optimization of the nonlinear objective function with nonlinear system constraints.

3.1. Objective function

The objective function here is to minimize the active power loss (P_{loss}) in the transmission system. Network losses either for the whole network or for certain sections are non-separable functions of dependent and independent variables. It is given as

$$P_{loss} = \sum_{k=1}^{N_l} g_k[(t_k V_i)^2 + V_j^2 - 2t_k V_i V_j \cos\theta_{ij}] \tag{2}$$

where, N_l is the number of transmission lines; g_k is conductance of branch k between buses i and j; t_k the tap ratio of transformer k; V_i is the voltage magnitude at bus i; θ_{ij} the voltage angle difference between buses i and j.

3.2. Constraints

The minimization of the above function is subjected to a number of equality and inequality constraints. The equality constraints are the power flow equations given by

$$P_{g_i} - P_{d_i} - V_i \sum_{j=1}^{N_b} V_j(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) = 0 \quad \text{for} \quad i = 1,\ldots,N_{PV}+N_{PQ} \tag{3}$$

$$Q_{g_i} - Q_{d_i} + Q_{c_i} - V_i \sum_{j=1}^{N_b} V_j(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) = 0 \quad for i = 1,\ldots,N_{PQ} \tag{4}$$

where, N_b, N_{PV} and N_{PQ} are the number of buses, PV buses and PQ buses respectively; G_{ij}, B_{ij} are real and imaginary part of (i,j)th element of bus admittance matrix; P_{g_i}, Q_{g_i} are active and reactive power generation at bus i ; P_{d_i}, Q_{d_i} are active and reactive power demand at bus i ; Q_{c_i} the reactive power compensation source at bus i. The inequality constraints on security limits are given by

$$P_{g,slack}^{min} \leqslant P_{g,slack} \leqslant P_{g,slack}^{max} \tag{5}$$

$$V_{L_i}^{min} \leqslant V_{L_i} \leqslant V_{L_i}^{max} \quad \text{for} \quad i = 1,\ldots,N_{PQ} \tag{6}$$

$$Q_{g_i}^{min} \leqslant Q_{g_i} \leqslant Q_{g_i}^{max} \quad \text{for} \quad i = 1,\ldots,N_g \tag{7}$$

$$|S_l| \leqslant S_l^{max} \quad \text{for} \quad l = 1,\ldots,N_l \tag{8}$$

The inequality constraints on control variable limits are given by

$$V_{g_i}^{min} \leqslant V_{g_i} \leqslant V_{g_i}^{max} \quad \text{for} \quad i = 1,\ldots,N_{PV} \tag{9}$$

$$t_k^{min} \leqslant t_k \leqslant t_k^{max} \quad \text{for} \quad k = 1,\ldots,N_t \tag{10}$$

$$Q_{c_i}^{min} \leqslant Q_{c_i} \leqslant Q_{c_i}^{max} \quad \text{for} \quad i = 1,\ldots,N_c \tag{11}$$

where, N_g, N_c and N_t are the number of generators, compensator devices and transformers; S_l the apparent power flow in line l ; S_l^{max}