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Optimal power flow using Teaching-Learning-Based Optimization technique

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ABSTRACT

Teaching-Learning-Based Optimization is a rising star among metaheuristic techniques with highly competitive performances. This technique is based on the influence of a teacher on learners. In this paper, the Teaching-Learning-Based Optimization technique is used to solve the optimal power flow problem. In order to show the effectiveness of the proposed method, it has been applied to the standard IEEE 30-bus and IEEE 118-bus test systems for different objectives that reflect the performances of the power system. Furthermore, the obtained results using the proposed technique have been compared to those obtained using other techniques reported in the literature. The obtained results and the comparison with other techniques indicate that the Teaching-Learning-Based Optimization technique provides effective and robust high-quality solution when solving the optimal power flow problem with different complexities.

1. Introduction

The optimal power flow (OPF) problem is the backbone tool for power system operation [1,2]. The objective of the OPF problem is to determine the optimal operating state of a power system by optimizing a particular objective while satisfying certain operating constraints [3].

The OPF has been studied for over half a century since the pioneering work of Carpentier [1,2]. Earlier, many traditional (deterministic) optimization techniques have been successfully used, the most popular were: gradient based methods, Newton-based method, simplex method, sequential linear programming, sequential quadratic programming, and interior point methods. A survey of the most commonly used conventional optimization algorithms applied to solve the OPF problem is given in [4,5]. Although, some of these deterministic techniques have excellent convergence characteristics and many of them are widely used in the industry however, they suffer from some shortcomings. Some of their drawbacks are: they cannot guarantee global optimality i.e. they may converge to local optima, they cannot readily handle binary or integer variables and finally they are developed with some theoretical assumptions, such as convexity, differentiability, and continuity, among other things, which may not be suitable for the actual OPF conditions [5,6].

Furthermore, the rapid development of recent computational intelligence tools have motivated significant research in the area of non-deterministic that is, heuristic, optimization methods to solve the OPF problem in the past two decades [6]. Some of these techniques are: Ant Colony Optimization (ACO), Artificial Neural Networks (ANN), Bacterial Foraging Algorithms (BFA), Biogeography-Based Optimization (BBO), Black-Hole-Based Optimization (BHBO), Chaos Optimization Algorithms (COA), Differential Evolution (DE), Evolutionary Algorithms (EAs), Electromagnetism-Like Mechanism (EM), Evolutionary Programming (EP), Evolutionary Strategies (ES), Fuzzy Set Theory (FST), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA), Tabu Search (TS), Gravitational Search Algorithm (GSA). These methods are known for: their capabilities of finding global solutions and avoid to be trapped with local ones, their ability of fast search of large solution spaces and their ability to account for uncertainty in some parts of the power system. A review of many of these optimization techniques applied to solve the OPF problem is given in [6,7].

One of the recently developed optimization techniques is the Teaching-Learning-Based Optimization (TLBO), which is a population based optimization technique inspired by passing on knowledge within a classroom environment, where learners first acquire knowledge from teacher and then from classmates [8,9].

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The main objective of this paper is to apply the TLBO to solve the OPF problem. The performance of the proposed technique is sought and tested on the standard IEEE 30-bus and IEEE 118-bus test systems where the objective functions are: minimization of generation fuel cost, voltage profile improvement, voltage stability enhancement, voltage stability enhancement during contingency condition, piecewise quadratic fuel cost curve and fuel cost minimization of generators with valve-point loading.

The remainder of the paper is organized as follows. First, the OPF is mathematically formulated. Then, the TLBO is presented. Next, we apply the proposed TLBO to solve the OPF problem in order to optimize the power system operating conditions. Finally, we conclude our paper with some remarks and points.

2. Optimal Power Flow formulation

As mentioned earlier, OPF is a power flow problem which gives the optimal settings of control variables for a given settings of load by minimizing a predefined objective function such as the cost of active power generation and under the consideration of operating limits of the system. The OPF problem can be formulated as a nonlinear constrained optimization problem as follows:

$$\text{Minimize} \quad J(\mathbf{x}, \mathbf{u}) \tag{1}$$

$$\text{Subject to} \quad g(\mathbf{x}, \mathbf{u}) = 0 \tag{2}$$

$$\text{and} \quad h(\mathbf{x}, \mathbf{u}) \leq 0 \tag{3}$$

where **u**, vector of independent variables or control variables; **x**, vector of dependent variables or state variables; $J(\mathbf{x},\mathbf{u})$, objective function; $g(\mathbf{x},\mathbf{u})$, set of equality constraints; $h(\mathbf{x},\mathbf{u})$, set of inequality constraints.

The control variables **u** and the state variables **x** of the OPF problem are stated in (4) and (5), respectively.

2.1. Control variables

These are the set of variables which can be modified to satisfy the load flow equations. The set of control variables in the OPF problem formulation are:

P_G, active power generation at the PV buses except at the slack bus; V_G, voltage magnitude at PV buses; T, tap settings of transformer; Q_C, shunt VAR compensation.

Hence, **u** can be expressed as:

$$\mathbf{u}^T = [P_{G_2} \cdots P_{G_{NG}}, V_{G_1} \cdots V_{G_{NG}}, Q_{C_1} \cdots Q_{C_{NC}}, T_1 \cdots T_{NT}] \tag{4}$$

where NG, NT and NC are the number of generators, the number of regulating transformers and the number of VAR compensators, respectively.

2.2. State variables

These are the set of variables which describe any unique state of the system. The set of state variables for the OPF problem formulation are:

P_{G_1}, active power output at slack bus; V_L, voltage magnitude at PQ buses, load buses; Q_G, reactive power output of all generator units; S_l, transmission line loading (or line flow).

Hence, **x** can be expressed as:

$$\mathbf{x}^T = [P_{G_1}, V_{L_1} \cdots V_{L_{NL}}, Q_{G_1} \cdots Q_{G_{NC}}, S_{l_1} \cdots S_{l_{nl}}] \tag{5}$$

where, NL, and nl are the number of load buses, and the number of transmission lines, respectively.

2.3. Objective constraints

OPF constraints can be classified into equality and inequality constraints, as detailed in the following sections.

2.3.1. Equality constraints

The equality constraints of the OPF reflect the physics of the power system. The physics of the power system are represented by the typical power flow equations. These equality constraints are as follows.

(a) Real power constraints

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{NB} V_j [G_{ij} \cos(\theta_{ij}) + B_{ij} \sin(\theta_{ij})] = 0 \tag{6}$$

(b) Reactive power constraints

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{NB} V_j [G_{ij} \sin(\theta_{ij}) + B_{ij} \cos(\theta_{ij})] = 0 \tag{7}$$

where $\theta_{ij} = \theta_i - \theta_j$, NB is the number of buses, P_G is the active power generation, Q_G is the reactive power generation, P_D is the active load demand, Q_D is the reactive load demand, G_{ij} and B_{ij} are the elements of the admittance matrix ($Y_{ij} - G_{ij} + jB_{ij}$) representing the conductance and susceptance between bus i and bus j, respectively.

2.3.2. Inequality constraints

The inequality constraints of the OPF reflect the limits on physical devices present in the power system as well as the limits created to guarantee system security. These inequality constraints are as follows.

(c) Generator constraints

For all generators including the slack: voltage, active and reactive outputs ought to be restricted by their lower and upper limits as follows:

$$V_{G_i}^{\min} \leq V_{G_i} \leq V_{G_i}^{\max}, \quad i = 1, \ldots, NG \tag{8}$$

$$P_{G_i}^{\min} \leq P_{G_i} \leq P_{G_i}^{\max}, \quad i = 1, \ldots, NG \tag{9}$$

$$Q_{G_i}^{\min} \leq Q_{G_i} \leq Q_{G_i}^{\max}, \quad i = 1, \ldots, NG \tag{10}$$

(d) Transformer constraints

Transformer tap settings ought to be restricted within their specified lower and upper limits as follows:

$$T_i^{\min} \leq T_i \leq T_i^{\max}, \quad i = 1, \ldots, NT \tag{11}$$

(e) Shunt VAR compensator constraints

Shunt VAR compensators must be restricted by their lower and upper limits as follows:

$$Q_{C_i}^{\min} \leq Q_{GC_i} \leq Q_{C_i}^{\max}, \quad i = 1, \ldots, NG \tag{12}$$

(f) Security constraints

These contain the constraints of voltage magnitude at load buses and transmission line loadings. Voltage of each load bus must be restricted within its lower and upper operating limits. Line flow through each transmission line ought to be restricted by its capacity limits. These constraints can be mathematically formulated as follows:

$$V_{L_i}^{\min} \leq V_{L_i} \leq V_{L_i}^{\max}, \quad i = 1, \ldots, NL \tag{13}$$

$$S_{l_i} \leq S_{l_i}^{\max}, \quad i = 1, \ldots, nl \tag{14}$$