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Artificial bee colony algorithm for solving multi-objective optimal power flow problem

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ABSTRACT

This paper presents a new and efficient method for solving optimal power flow (OPF) problem in electric power systems. In the proposed approach, artificial bee colony (ABC) algorithm is employed as the main optimizer for optimal adjustments of the power system control variables of the OPF problem. The control variables involve both continuous and discrete variables. Different objective functions such as convex and non-convex fuel costs, total active power loss, voltage profile improvement, voltage stability enhancement and total emission cost are chosen for this highly constrained nonlinear non-convex optimization problem. The validity and effectiveness of the proposed method is tested with the IEEE 9-bus system, IEEE 30-bus system and IEEE 57-bus system, and the test results are compared with the results found by other heuristic methods reported in the literature recently. The simulation results obtained show that the proposed ABC algorithm provides accurate solutions for any type of the objective functions.

1. Introduction

Optimal power flow (OPF) is one of the most important problems for power system planners and operators. The main goal of OPF is to find the optimal settings of a given power system network that optimize a selected objective function such as total generation cost, system loss, bus voltage deviation or social welfare while satisfying its power flow equations, system security, and equipment operating limits [1,2].

The literature on OPF is vast and [3–5] present the major contributions in this field. Many traditional optimization techniques such as linear programming (LP) [6], nonlinear programming (NLP) [7,8], quadratic programming (QP) [9], Newton method and interior point method (IPM) [10–12] have already been employed to solve the OPF problem. Some of these techniques have excellent convergence characteristics and are widely used in the industry; however, they are developed with some theoretical assumptions and fail to deal with systems having non-smooth, non-convex and non-differentiable objective functions and constraints. Therefore, in the past few years many researches have focused on efficient optimization methods, which can be employed to overcome the above-mentioned drawbacks. For this purpose, heuristic algorithms such as genetic algorithm (GA) [13,14], enhanced genetic algorithm (EGA) [15], evolutionary programming (EP) [16,17], tabu search (TS) [18], simulated annealing (SA) [19], particle swarm optimization (PSO) [20,21], differential evolution (DE) [22,23], modified differential evolution (MDE) [24], biogeography-based optimization (BBO) [25], gravitational search algorithm (GSA) [26], modified shuffle frog leaping algorithm (MSFLA) [27], and harmony search (HS) algorithm [28] have been proposed to tackle the OPF problem.

In [13], Lai and Ma employed the GA with dynamical hierarchy of coding system for the OPF problem. In [14] Bakirtzis et al. proposed an enhanced GA to solve the OPF problem with both continuous and discrete control variables. The authors tested their approach on the IEEE 30-bus and 73-bus IEEE RTS-96 systems. In [16] Yuryevich and Wong used EP to solve OPF problems in order to increase the convergence speed. Abido employed TS [18] and PSO [20] for solving OPF problems with different objective functions. Also, Abido and co-workers [23] developed DE for solving the OPF problem. The MDE algorithm was used in [24] to solve the OPF problem with non-smooth cost function. Bhattacharya and Chattopadhyay in [25] employed BBO algorithm, which was based on two fundamental mechanisms namely migration and mutation to solve the OPF problem. They tested their method on two different versions of IEEE 30-bus system. The GSA which is based on the Newton's law of gravity and mass interactions was employed for solving the OPF problem, and was applied on the IEEE 30-bus and IEEE 57-bus test systems in [26]. In [28] a multi-objective harmony search algorithm was proposed for the OPF. The authors tested their approach on the IEEE 30-bus test system and compared their results with fast non-dominated sorting GA.

One of the recently proposed heuristic algorithms is the artificial bee colony (ABC) algorithm, which is based on the intelligent

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behavior of honeybees. It was developed by Karaboga in 2005 [29]. Each cycle of the ABC algorithm consists of three phases: employed bees phase, onlooker bees phase, and scout bees phase [29–33]. Comparative studies have shown that ABC is faster and more efficient than other heuristic algorithms in benchmark problems. Due to its advantages, ABC algorithm have been successfully used in several power systems problems, including reactive power optimization [34], real and reactive power tracing in deregulated power systems [35], fault section estimation [36], automatic generation control [37], distributed generation allocation and sizing [38] and so on.

In this paper, the newly proposed heuristic optimization algorithm, the ABC method, is employed to solve the OPF problem considering both equality and inequality constraints in an electric power system. Different objective functions such as convex and non-convex fuel costs, total active power loss, voltage profile improvement, enhancement of voltage stability in both normal and contingency situations, and total emission cost are chosen for this optimization problem, and the proposed ABC-based method is applied to the IEEE 9-bus system, IEEE 30-bus system and IEEE 57-bus system. It should be noted that due to the flexibility of the proposed method, the fuel cost curve is not limited to the quadratic type (form) only, and other fuel cost curves including piecewise quadratic or quadratic with sine component that show the effect of valve point loading of thermal units, can be used in the proposed ABC-based method. Simulation results obtained demonstrate that the proposed ABC method provides effective and remarkable results for OPF problem.

The rest of the paper is organized as follows: the mathematical formulation of the optimal power flow problem is reviewed in Section 2. The proposed ABC approach for solving OPF problem is presented in Section 3. Section 4 represents the simulation results obtained on the three test power systems. Finally, conclusion is drawn in Section 5.

2. OPF problem formulation

The optimal power flow (OPF) is a nonlinear optimization problem. The main goal of OPF is to optimize the settings of control variables in terms of one or more objective functions while satisfying several equality and inequality constraints. In general, the OPF problem can be mathematically formulated as follows:

$$\text{Minimize } f(x,u) \tag{1}$$

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

$$h(x,u) \leqslant 0 \tag{3}$$

where f is the objective function to be optimized, g is the equality constraints representing nonlinear power flow equations, and h is the system operating constraints. Also, $\boldsymbol{u}$ is the vector of independent control variables including:

1. Generator active power output P_G except at slack bus P_{G1}.
2. Generator bus voltage V_G.
3. Transformer tap setting T.
4. Shunt VAR compensation Q_C.

Hence, $\boldsymbol{u}$ can be expressed as:

$$u^T = [P_{G2} \cdots P_{GN_g}, V_{G1} \cdots V_{GN_g}, T_1 \cdots T_{N_t}, Q_{C1} \cdots Q_{CN_c}] \tag{4}$$

where N_g, N_t and N_C denote the number of generating units, number of regulating transformers and number of shunt compensators, respectively. Generators active powers (except slack bus) and generators bus voltages are continuous variables, while the tap settings of the tap changing transformers and VAR injections of the shunt capacitors are discrete variables. Also, $\boldsymbol{x}$ is the vector of dependent variables including:

1. Slack bus generated active power P_{G1}.
2. Load (PQ) bus voltage V_L.
3. Generator reactive power output Q_G.
4. Transmission line loading (line flow) S_L.

Hence, $\boldsymbol{x}$ can be expressed as:

$$x^T = [P_{G1}, V_{L1} \cdots V_{LN_{pq}}, Q_{G1} \cdots Q_{GN_g}, S_{L1} \cdots S_{LN_l}] \tag{5}$$

where N_{pq} is the number of PQ buses, and N_l is the total number of transmission lines.

2.1. Objective function

In this paper, five different objective functions are considered. The objective functions are as follows:

2.1.1. Minimization of total fuel cost

This objective function represents the total fuel cost, and it can be expressed as follows:

$$fc = \sum_{i=1}^{N_g} f_i(P_{Gi}) \tag{6}$$

Three different types of fuel cost curves (functions), namely, quadratic cost curve, piecewise quadratic cost curve and quadratic cost with valve point loading are considered here. These fuel cost characteristics are expressed in (7)–(9), respectively [24–26].

$$f_i(P_{Gi}) = a_i + b_i P_{Gi} + c_i P_{Gi}^2 \tag{7}$$

$$f_i(P_{Gi}) = \begin{cases} a_{i1} + b_{i1}P_{Gi} + c_{i1}P_{Gi}^2 & P_{Gi,\min} \leqslant P_{Gi} \leqslant P_{Gi1} \\ a_{i2} + b_{i2}P_{Gi} + c_{i2}P_{Gi}^2 & P_{Gi1} \leqslant P_{Gi} \leqslant P_{Gi2} \\ \cdots & \cdots \\ a_{ik} + b_{ik}P_{Gi} + c_{ik}P_{Gi}^2 & P_{Gik-1} \leqslant P_{Gi} \leqslant P_{Gi,\max} \end{cases} \tag{8}$$

$$f_i(P_{Gi}) = a_i + b_i P_{Gi} + c_i P_{Gi}^2 + |d_i \sin(e_i(P_{Gi,\min} - P_{Gi}))| \tag{9}$$

where a_i, b_i, c_i, d_i, and e_i are the fuel cost coefficients of the ith generating unit, and a_{ik}, b_{ik}, and c_{ik} are the fuel cost coefficients of the ith unit for fuel type k.

2.1.2. Voltage profile improvement

The aim of this objective function is to minimize all PQ bus voltage deviations from 1.0 per unit [20,23,25,26]. This objective function can be described as follows:

$$VD = \sum_{i=1}^{N_{pq}} |V_i - 1.0| \tag{10}$$

Combining both the fuel cost-based objective function and the voltage profile improvement objective function leads to the following twofold objective function:

$$f_1 = fc + w_1 VD = \sum_{i=1}^{N_g} f_i(P_{Gi}) + w_1 \sum_{i=1}^{N_{pq}} |V_i - 1.0| \tag{11}$$

where w_1 is a suitable weighting factor, to be selected by the user.

2.1.3. Voltage stability enhancement

Voltage stability is one of the important issues in power system planning and operation. The static approach for voltage stability analysis involves determination of an index known as voltage collapse proximity indicator. This index is an approximate measure of closeness of the system operating point to voltage collapse. There