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Chaotic artificial bee colony algorithm based solution of security and transient stability constrained optimal power flow

Kürşat Ayan [a], Ulaş Kılıç [b,*], Burhan Baraklı [c]

[a] Department of Computer Engineering, Sakarya University, Sakarya, Turkey
[b] Department of Mechatronics Engineering, Celal Bayar University, Manisa, Turkey
[c] Department of Electrical and Electronics Engineering, Sakarya University, Sakarya, Turkey

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ABSTRACT

Due to the increase rapidly of electricity demand and the deregulation of electricity markets, the energy networks are usually run close to their maximum capacity to transmit the needed power. Furthermore, the operators have to run the system to ensure its security and transient stability constraints under credible contingencies. Security and transient stability constrained optimal power flow (STSCOPF) problem can be illustrated as an extended OPF problem with additional line loading and rotor angle inequality constraints. This paper presents a new approach for STSCOPF solution by a chaotic artificial bee colony (CABC) algorithm based on chaos theory. The proposed algorithm is tested on IEEE 30-bus test system and New England 39-bus test system. The obtained results are compared to those obtained from previous studies in literature and the comparative results are given to show validity and effectiveness of proposed method.

Introduction

Optimal power flow (OPF) is an important tool for power system operators both in planning and operating stages. The OPF problem solution aims to optimize a selected objective function such as production cost via optimal adjustment of the power system control variables, while at the same time satisfying various equality and inequality constraints. The equality constraints are the power flow equations, while the inequality constraints are the limits on control variables and the operating limits of power system dependent variables [1]. The problem control variables include the generator active powers, the generator bus voltages, the transformer tap ratios, and the reactive power of switchable VAR sources, while the problem dependent variables include the load bus voltages, the generator reactive powers. Mathematically, the transient stability constrained OPF (TSCOPF) is OPF problem extended with additional rotor angle inequality constraints [2]. It means that after the disturbances the power system must be able to surviving and moving into an acceptable steady-state condition that meet all established limits [3]. Moreover, in Ref. [4] the authors indicate that TSCOPF is a nonlinear optimization problem with both algebraic and differential equations, which is difficult to be solved even for small power systems. The main difficulties of solving this problem include [4]: (1) how to deal with the differential equations that represent the dynamic behavior of the system; and (2) how to deal with the disruption of conventional optimization algorithms in highly nonlinear and non-convex solution landscapes.

In the past, classical optimization techniques such as interior point method [5], and linear programming (LP) [6] were employed for TSCOPF solution. These techniques have many limitations and some drawbacks. They need an acceptable starting point that is close to the solution in order not to be stuck in local optimum and have poor convergence. As the numbers of parameters in the problem increase, the quality of solutions substantially depends on the initial conditions. Additionally, as they have extremely limited capability to solve realistic power system problems, the mathematical relationships should be mostly simplified to obtain the solutions of the problem. They are also weak in processing qualitative constraints. [7,8]. In Ref. [6], a linear programming (LP) based computational procedure was developed to solve an algebraic NP problem. Therefore, many heuristic optimization techniques have recently become more and more attractive in OPF and TSCOPF solution for researchers. Some of them are particle swarm optimization (PSO) [9], genetic algorithm (GA) [10], and differential evolution (DE) [4].

In the literature, many different heuristic methods have been used together with the chaos theory so far. However, there are

* Corresponding author.
E-mail addresses: kayan@sakarya.edu.tr (K. Ayan), ulas.kilic@cbu.edu.tr (U. Kılıç), barakli@sakarya.edu.tr (B. Baraklı).

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no works in the literature on STSCOPF solution based on the ABC and the CABC algorithm. At first place, this paper represents an approach for solving STSCOPF problem of the power systems using the ABC algorithm that was originally proposed by Karaboga in 2005 [11] and then this approach is developed by using the chaos theory. The ABC algorithm is a new population based meta-heuristic approach inspired by the food pursuit behavior of honey bees.

After this introduction, the formulation of STSCOPF problem and the representation of security and transient stability constraints are reviewed in Section 'Formulation of STSCOPF problem'. The ABC and CABC algorithms are introduced in Section 'Illustration of the algorithms used in this study'. In Section 'Simulation results', the simulation results obtained from studies on IEEE 30-bus test system and the New England 39-bus test system are shown by comparing to those obtained by other methods in literature. Finally, the conclusions are discussed in last section.

Formulation of STSCOPF problem

OPF formulation

The power system is a complex network used for generating, transmitting, and distributing electric power. It is expected to operate by using minimum resources to satisfy maximum security and reliability. OPF problem is an important operator to try the implementation of these goals by optimizing whole controllable variables. Therefore, OPF is an optimization problem that has well known mathematical equations and is defined as follows [1,4–10]:

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

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

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

where the objective function $f(x, u)$ is taken as the total production cost, the equality constraints $g(x, u)$ are taken as the power flow equations and the inequality constraints $h(x, u)$ are taken as static and dynamic security constraints those are generation capacity constraints, security constraints (transmission line loading) and transient stability constraints. The vectors u and x what are the variables of the optimization problem are named as vector of control and state variables, respectively. The vector u is defined as follows:

$$u^T = [P_g, V_g, T, Q_c] \tag{4}$$

where the vector u consists of active power generation except the slack bus P_g, generator terminal voltage magnitude V_g, transformer tap ratio T and reactive power generation or absorption of compensation devices such as capacitor and reactor banks Q_c. Moreover, the vector x is defined as follows:

$$x^T = [P_{gslack}, V_L, Q_g] \tag{5}$$

where the vector x includes slack bus active power P_{gslack}, load bus voltage magnitude V_L and generator reactive power Q_g.

Objective function

The objective function can be described by the concepts such as production cost, social welfare, and fuel cost. In an interconnected energy system, the production cost is given by fuel cost curve approximated as a quadratic function of generator active power output. In this case, the total production cost minimization is taken into consideration as the objective of STSCOPF problem and it is expressed mathematically as follows [1,4–10]:

$$F_{cost} = \sum_{i=1}^{N_g} (a_i + b_i P_{gi} + c_i P_{gi}^2) \tag{6}$$

where F_{cost} is the total production cost, P_{gi} is the active power output of ith generator; N_g is the total number of generators; a_i, b_i and c_i are the production cost coefficients of ith generator.

Constraints in OPF problem with security and transient stability

Security and transient stability constrained OPF can be considered as a conventional OPF with additional inequality constraints imposed by the transmission line loading limits and the rotor angle limits. The power flow solution should meet the steady-state constraints related to solution of the conventional OPF problem and the dynamic constraints imposed on the rotor angles during the transient period under undesirable conditions.

Equality constraints (power flow constraints)

The power balance at ith bus can be expressed mathematically as follows [12,13]:

$$P_{gi} - P_{li} - P_i = 0 \qquad i = 1,\ldots,N \tag{7}$$

$$Q_{gi} + Q_{ci} - Q_{li} - Q_i = 0 \quad i = 1,\ldots,N \tag{8}$$

where N is the total number of system buses; P_{gi} and Q_{gi} are active and reactive power outputs of ith generator; P_{li} and Q_{li} are total active and reactive power loads of ith bus; P_i and Q_i are active and reactive power injections at bus i, Q_{ci} is shunt reactive source at ith bus. The active and reactive power injections at bus i can be also formulated as follows [14]:

$$P_i = V_i \sum_{\substack{j=1 \\ j\neq k}}^{N} V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) - V_i V_k T_i (g_{ik}\cos\theta_{ik} + b_{ik}\sin\theta_{ik}) + V_i^2 (G_{ii} + T_i^2 g_{ik}) \tag{9}$$

$$Q_i = V_i \sum_{\substack{j=1 \\ j\neq k}}^{N} V_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) - V_i V_k T_i (g_{ik}\sin\theta_{ik} - b_{ik}\cos\theta_{ik}) - V_i^2 (B_{ii} + T_i^2 b_{ik}) \tag{10}$$

where V_i, V_j and V_k are the voltage magnitudes of ith, jth and kth buses; G_{ij} and B_{ij} are transfer conductance and susceptance between buses i and j of the bus admittance matrix (Y_{bus}); G_{ii} and B_{ii} are self conductance and susceptance of bus i; θ_{ij} is the voltage angle difference between buses i and j; i T_i is transformer tap ratio at ith bus; g_{ik} is transformer conductance between buses i and k; b_{ik} is transformer susceptance between buses and k.

Inequality constraints (static and dynamic security constraints)

Generation capacity constraints: For stable operation, the generator active and reactive power outputs, bus voltage magnitudes, transformer tap ratios and shunt reactive sources are restricted by their lower and upper limits as follows [1–10]:

$$P_{gi}^{min} \leqslant P_{gi} \leqslant P_{gi}^{max} \quad i = 1,\ldots,N_g \tag{11}$$

$$Q_{gi}^{min} \leqslant Q_{gi} \leqslant Q_{gi}^{max} \quad i = 1,\ldots,N_g \tag{12}$$

$$V_i^{min} \leqslant V_i \leqslant V_i^{max} \quad i = 1,\ldots,N \tag{13}$$

$$T_i^{min} \leqslant T_i \leqslant T_i^{max} \quad i = 1,\ldots,N_T \tag{14}$$

$$Q_{ci}^{min} \leqslant Q_{ci} \leqslant Q_{ci}^{max} \quad i = 1,\ldots,N_c \tag{15}$$