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ASOC-2488; No. of Pages 10
ARTICLE IN PRESS
Applied Soft Computing xxx (2014) xxx–xxx
Contents lists available at ScienceDirect
Applied Soft Computing
journal homepage: www.elsevier.com/locate/asoc

Optimal power flow using black-hole-based optimization approach

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ARTICLE INFO

Article history:
Received 12 January 2013
Received in revised form 14 August 2014
Accepted 22 August 2014
Available online xxx

Keywords:
Optimal power flow
Black-hole-based optimization
Power system optimization
Metaheuristic

ABSTRACT

In this paper a new nature-inspired metaheuristic algorithm is proposed to solve the optimal power flow problem in a power system. This algorithm is inspired by the black hole phenomenon. A black hole is a region of space-time whose gravitational field is so strong that nothing which enters it, not even light, can escape. The developed approach is called black-hole-based optimization approach. In order to show the effectiveness of the proposed approach, it has been demonstrated on the standard IEEE 30-bus test system for different objectives. Furthermore, in order to demonstrate the scalability and suitability of the proposed approach for large-scale and real power systems, it has been tested on the real Algerian 59-bus power system network. The results obtained are compared with those of other methods reported in the literature. Considering the simplicity of the proposed approach and the quality of the obtained results, this approach seems to be a promising alternative for solving optimal power flow problems.

1. Introduction

Since it has been introduced by Dommel and Tinney in the early 1960s, the concept of Optimal Power Flow (OPF) has received an immense attention [1,2]. The OPF can be defined as a nonlinear optimization problem, where a specific objective function has to be optimized while satisfying operational and physical constraints of the electric power system [3].

A large variety of optimization techniques have been employed to solve OPF problems. Earlier, many traditional (deterministic) optimization techniques have been successfully used, the most popular were: gradient based methods, Newton-based method, the simplex method, sequential linear programming, sequential quadratic programming, and interior point methods. A survey of the most commonly used traditional 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].

In additions to the abovementioned drawbacks, there was a rapid development of recent computational intelligence tools such as genetic algorithm, ant colony algorithm, artificial immune algorithm, particle swarm optimization algorithm, harmony search algorithm, differential evolution algorithm, cuckoo search algorithm, which have been widely used in many applications instead of the conventional techniques like in [7–12]. Moreover, hybrid evolutionary optimization algorithms have received significant interest for fast convergence and robustness in finding the global minimum at the same time as illustrated and demonstrated in [13–21]. Hence, all these new developments, have motivated significant research in the area of non-deterministic that is, metaheuristic, optimization methods to solve the OPF problem in the past two decades [6]. 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 optimization techniques applied to solve the OPF problem is given in [6,22].

However, it is noteworthy to mention that, most of the existing metaheuristics are dependent of some internal parameters. For example, the performance of the PSO technique depends on the inertia weight and the acceleration factors that have to be selected carefully. Hence, many simulations have to be done in order to select these internal parameters. In the OPF problem, simulations are time costly and any changes in the configuration of the network or in its characteristics, like the load for instance, require a new tuning of the internal parameters.

The main contribution of this paper is to apply a new metaheuristic approach based on the black hole phenomenon to solve the OPF problem. The basic idea of a black hole is simply a region of space that has so much mass concentrated in it that there is no way

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http://dx.doi.org/10.1016/j.asoc.2014.08.056
1568-4946/

Please cite this article in press as: H.R.E.H. Bouchekara, Optimal power flow using black-hole-based optimization approach, Appl. Soft Comput. J. (2014), http://dx.doi.org/10.1016/j.asoc.2014.08.056

for a nearby object to escape its gravitational pull. In other words, anything falling into a black hole, including light, is forever gone from our universe. Its advantage over other well-known optimization algorithms is simplicity and it is a parameter-less optimization algorithm (i.e. it has no internal parameter to tune).

This paper is organized as follows. After this first section which is the introduction, the second section focuses on the formulation of the OPF problem. The third section of this paper presents the concept and main steps of the developed BHBO approach. Next, we apply the BHBO approach to solve the OPF problem in order to optimize the power system operating conditions. Finally, the conclusions are drawn in the fifth section.

2. Optimal power flow formulation

As aforesaid, OPF is a power flow problem which gives the optimal settings of the control variables for a given settings of load by minimizing a predefined objective function such as the cost of active power generation or transmission losses. The majority of OPF formulations may be represented using the following standard form [5]:

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

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

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

where $\mathbf{u}$ represents the vector of independent variables or control variables. $\mathbf{x}$ represents the vector of dependent variables or state variables. $J(\mathbf{x},\mathbf{u})$ represents the system's optimization goal or the objective function. $g(\mathbf{x},\mathbf{u})$ represents the set of equality constraints. $h(\mathbf{x},\mathbf{u})$ represents the set of inequality constraints.

The control variables $\mathbf{u}$ and the state variables $\mathbf{x}$ 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: represents the active power generation at the PV buses except at the slack bus.
- V_G: represents the voltage magnitude at PV buses.
- T: represents the tap settings of transformer.
- Q_C: represents the shunt VAR compensation.

Hence, $\mathbf{u}$ 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

All OPF formulations require variables to represent the electrical state of the system [5]. Most often, the state variables for the OPF problem formulation are:

- P_{G1}: represents the active power output at slack bus.
- V_L: represents the voltage magnitude at PQ buses; load buses.
- Q_G: represents the reactive power output of all generator units.
- S_l: represents the transmission line loading (or line flow).

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

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

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

2.3. Constraints

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

2.3.1. Equality constraints

The equality constraints of the OPF reflect the physics of the power system. These equality constraints are as follows.

2.3.1.1. Real power constraints.

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

2.3.1.2. Reactive power constraints.

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

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.

2.3.2.1. 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:

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

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

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

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

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

2.3.2.3. Shunt VAR compensator constraints. Shunt VAR compensators must be restricted by their lower and upper limits as follows:

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

2.3.2.4. 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:

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