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Full Length Article

Water evaporation algorithm: A new metaheuristic algorithm towards the solution of optimal power flow

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ABSTRACT

A relatively new technique to solve the optimal power flow (OPF) problem inspired by the evaporation (vaporization) of small quantity water particles from dense surfaces is presented in this paper. IEEE 30 bus and IEEE 118 bus test systems are assessed for various objectives to determine water evaporation algorithm's (WEA) efficiency in handling the OPF problem after satisfying constraints. Comparative study with other established techniques demonstrate competitiveness of WEA in treating varied objectives. It achieved superior results for all the objectives considered. The algorithm is found to minimize its objective values by great margins even in case of large test system. Statistical analysis of all the cases using Wilcoxon's signed rank test resulted in p-values much lower than the required value of 0.05, thereby establishing the robustness of the applied technique. Best performance of the algorithm are obtained for voltage deviation minimization and voltage stability index minimization objectives in case of IEEE 30 and IEEE 118 bus test systems respectively.

1. Introduction

Power system networks are designed to deliver quality power to the end users in an efficient and economic manner. Increase in demands lead to frequent changes in the network parameters, thereby posing a challenge to the existing systems to deliver quality power. OPF helps to tune the existing network parameters to deliver optimum power after satisfying various constrains. It minimizes the selected objective function fulfilling simultaneously the equality and inequality constraints. Load flow equations form the equality constraints and limits of dependent and independent variables form the inequality constraints. Earlier, the sole aim of OPF used to be the minimization of fuel cost. But continuous rise in electricity demand poses various other threats to the power system like: lack of voltage stability, increased transmission losses etc. Hence, it becomes necessary to consider these factors apart from the fuel cost during formulation of the objective function for the OPF problem. Techniques to solve the OPF problem are abundant in literature. Few methods based on classical techniques are: reduced-gradient method, Newton-Raphson, Lagrangian relaxation, linear programming, interior point method [1–3]. But these techniques are not efficient for systems with complex, non-differentiable objective functions and constraints.

Many heuristic algorithms have also been projected in the literature to address non – linear OPF problems, such as evolutionary programming (EP) [4], genetic algorithm (GA) [5], hybrid evolutionary programming (HEP) [6], particle swarm optimization (PSO) [7], differential evolution (DE) [8], tabu search [9], chaotic ant swarm optimization (CASO) [10], biogeography based optimization (BBO) [11], bacteria foraging optimization (BFO) [12], harmony search algorithm (HSA) [13], gravitational search algorithm (GSA) [14], particle swarm optimization [15], teaching learning based algorithm (TLBO) [16],quasi-oppositional TLBO (QTLBO) [17], non-dominated sorting genetic algorithm (NSGA-II) [18] etc. A. Bhattacharya in [19] presented biogeography based optimization (BBO) to solve the optimal power flow. Multi-objective harmony search algorithm (MOHS) was applied by S. Sivasubramani and K. S Swarup, to solve the OPF problem [20]. Quasi-oppositional differential evolution was proposed by S. Rahnamayan et. al, in [21]. P.K Roy [22] implemented BBO to solve OPF for multiple objective functions in 9-bus, 26-bus, IEEE 118-bus systems. M.Y. Cheng in [23] proposed symbiotic organisms search algorithm (SOS) for solving constrained optimization problems. SOS exploits the different relations shared by organisms for their survival. In [24], S. Duman applied SOS to solve constrained OPF problem considering valve point loading effects and prohibited operating zones. W. Ongsakul in [25] and [26] proposed respectively a hybrid tabu

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search and simulated annealing (TS/SA) approach and improved evolutionary programming (IEP) to solve OPF. T. Niknam [27] applied a hybrid algorithm based on shuffle frog leaping algorithm (SFLA) and simulated annealing (SA) to the OPF problem. A. G. Bakirtzis, in [28] applied enhanced genetic algorithm for solving OPF. Another hybrid approach to solve OPF based on PSO-SFLA was proposed by M.R. Narimani et. al., in [29]. S. Wang in [30], studied the evaporation of small amount of water from solid surfaces having different wettabilities. This concept was applied by A. Kaveh [31], in the formulation of water evaporation algorithm (WEA) for solving global optimization problems. [32] presented the Wilcoxon's signed rank test for statistical analysis. [33] presented another hybrid approach based on genetic algorithm (GA) with active power optimization (APO). M. Basu [34], presented group search algorithm (GSO) for solving different OPF problems.

In the present paper, the problem formulation is different for different test cases. Hence the authors adopted a new meta-heuristic technique, WEA, which is flexible in nature and is not problem specific, to solve the OPF problem. Although some of the advanced classical techniques could be used to solve the problem, they are avoided as they require significant effort towards the problem formulation, which might affect the overall accuracy. Section 2 of this paper discusses the problem formulation of OPF. Section 3 briefly describes the proposed algorithm and its advantages over other meta-heuristic algorithms. Section 4 details the design of WEA to solve the OPF problem. Section 5 presents a comprehensive analysis of simulation results and Section 6 presents the statistical analysis of the test results. [35] proposed different statistical tests for comparing evolutionary and swarm intelligence techniques.

2. Problem formulation

The OPF problem can be mathematically represented as [17]:

$$\min A(p,q) \tag{1}$$

Subject to:

$$b(p,q) = 0 \tag{2}$$

and

$$c(p,q) \leqslant 0(3) \tag{3}$$

where, A represents the objective function and p and q represent the vectors of the dependent and control variables respectively.

Vector p contains slack bus power PG_1, load bus voltage VL_i, reactive power delivered by the generator QG_i, and transmission line loading SL_i and is expressed as:

$$p^T = [PG_1, VL_1, \dots VL_{PQ}, QG_1, \dots QG_{PV}, SL_1, \dots SL_{TL}] \tag{4}$$

Vector q contains real power outputs PG_i, except that of the slack bus, generator bus voltage VG_i, shunt VAR compensator output QC_i, transformer tap setting TCi and can be expressed as:

$$q^T = [PG_2, \dots PG_{PV}, VG_1, \dots VG_{PV}, QC_1, \dots QC_{NC}, TC_1, \dots TC_{NT}] \tag{5}$$

where, PQ, PV, TL, NC and NT represent the number of load bus, generator bus, transmission lines, shunt compensators and tap changing transformers respectively.b represents the set of equality constraints, and is expressed as follows:

$$PG_m - PL_m = V_m \sum_{n=1}^{NBUS} V_n (G_{mn} \cos\theta_{mn} + B_{mn} \cos\theta_{mn}) \tag{6}$$

where, m = 1,2,3,. . .. . ..NBUS.

$$QG_m - QL_m = V_m \sum_{n=1}^{NBUS} V_n (G_{mn} \sin\theta_{mn} + B_{mn} \cos\theta_{mn}) \tag{7}$$

where, m = 1,2,3,. . .. . ..NBUS.where, PG_m and QG_m represent the active and reactive power injected to network, PL_m and QL_m represent the active and reactive power demands at the mth bus, G_{mn} and B_{mn} are the conductance and susceptance, θ_{mn} is the difference between the phase voltage angles of the mth and nth buses respectively and $NBUS$ denotes the total number of buses in the system.

The set of inequality constraints c is represented by the following equations:

2.1. Generator Constraints

The generator constraints comprise the lower and upper bounds of all generator bus voltages and their active and reactive power outputs as follows:

$$VG_m^{\min} \le VG_m \le VG_m^{\max} \tag{8}$$

$$PG_m^{\min} \le PG_m \le PG_m^{\max} \quad m = 1,2,3,\dots.PV \tag{9}$$

$$QG_m^{\min} \le QG_m \le QG_m^{\max} \tag{10}$$

where, PV denotes the number of generator buses including the slack bus.

2.2. Transformer Constraints

The transformer constraints are represented by the lower and upper limits of the transformer tap settings as below:

$$TC_i^{\min} \leqslant TC_i \leqslant TC_i^{\max} \quad i = 1,2,3,\dots NT \tag{11}$$

2.3. Shunt VAR Compensator Constraints

Reactive power delivered by the compensators should be within their pre-specified limits as given below:

$$QC_j^{\min} \leqslant QC_j \leqslant QC_j^{\max} \quad j = 1,2,3,\dots NC \tag{12}$$

2.4. Security Constraints

These involve the lower and upper limits on the voltages of the PQ buses and the upper limits on line loadings and are represented as follows:

$$VL_i^{\min} \leqslant VL_i \leqslant VL_i^{\max} \quad i = 1,2,3,\dots.PQ \tag{13}$$

$$S_{Li} \leqslant S_{Li}^{\max} \quad i = 1,2,3,\dots\dots TL \tag{14}$$

where, PQ and TL represent the number of load buses and the number of transmission lines respectively.

3. Objective Functions

Case studies considering different objectives are analyzed to assess the efficiency of WEA in solving the OPF problem.

3.1. Formulation of single objective functions

3.1.1. Quadratic cost minimization

Generation cost or the total fuel cost can be expressed in terms of the real power output by the quadratic function as:

$$OBJ_1 = \min(F(P)) = \left(\sum_{m=1}^{NG} F_m(P_m)\right) = \left(\sum_{m=1}^{NG} (a_m + b_m P_m + c_m P_m^2)\right) \tag{15}$$

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