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SOLUTION OF REACTIVE POWER DISPATCH OF POWER SYSTEMS USING BAT SEARCH ALGORITHM

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Abstract- This paper focuses on an echolocation based algorithm known as the BAT search algorithm inspired by the behavior of bats to optimal reactive power dispatch (ORPD) problem. The minimization of active power transmission losses through controlling a number of control variables is defined as the ORPD problem. The optimal reactive power dispatch is then developed as a non-linear optimization problem in regard to power transmission loss, voltage stability and voltage profile. The amount of reactive compensation devices to optimize a certain object, generator voltages as well as tap positions of tap changing transformers are some of the control variables to be properly acquired as the aim of proposed meta-historic technique. In addition, the penalty coefficients are employed to handle the inequality constraints. The IEEE 30-bus power system is used as a test system to verify the robustness of the propose scheme. The results acquired through the proposed BAT scheme is also compared with different optimization such as HSA, PSO to illustrate the effectiveness as well as the importance of employing a better constraint handling method for the proposed ORPD problem.

Keywords: ORPD, BAT Algorithm, Discrete Variables.

I. INTRODUCTION

One of the key concepts of power system operation and planning is the optimal power flow (OPF) [1]. The economic and secure operation of power systems is significantly influenced by a sub problem of OPF known as optimal reactive power dispatch (ORPD). The minimization of the real power transmission losses or the voltage deviation by means of allotting reactive power generation is the aim of an ORPD problem. In this regard, a number of constraints such as upper and lower voltage limits of the generators, restrictions in various reactive power sources such as generators, shunt capacitor banks, and transformer taps and the power flow equations should also be gratified.

The ORPD technique features a complex combinatorial optimization problem regarding nonlinear constraints, multiple local minima as well as both continuous and discrete variables. Numerous methods have been used to solve the OPF problem in general and the OPRD problem in particular since its introduction in the 1960s. A number of mathematical techniques are: Newton [2], gradient [3], linear programming [4], dynamic programming [5], nonlinear programming [6], quadratic programming [7], and interior point methods [8]. Among these methods, Newton and gradient schemes cannot be employed for problems with inequality constraints.

Owing to severe limitations in handling nonlinear discontinuous functions and constraints, linear programming requires the constraints to be linearized which can lead to loss of accuracy. One of the main difficulties in using the conventional techniques is their sensitivity to the initial guess of the search point in case of having multiple local minima. Furthermore, these methods are inefficient in dealing with discrete variables-based problems. Despite the fastness of gradient-based algorithms, these schemes have difficulties to escape from local minima in dealing with highly nonlinear and multimodal problems as well as discrete variables which results in their incapability for solving ORPD.

A number of classical gradient-based optimization algorithms have been employed to solve different ORPD problems of power systems [9-13]. The main feature of all these method is their fastness. Nevertheless, the conventional techniques depend on the convexity assumption of generators' cost functions. As a result, the cost function is monotonically increased by means of approximating these curves via quadratic or piecewise quadratic [9, 10]. Some of these classical methods are: iteration method, linear programming, interior point method, reduced gradient method and Newton method. The nonconvex or discontinuous landscape and discrete variables causes these methods to face with difficulties in handling problems. The further discussion on these techniques is addressed in ref. [14]. Therefore, the necessity of developing a robust technique to overcome these disadvantages seems inevitable.

The ORPD problem have been solved in the past using some meta-historic methods such as genetic algorithm (GA) [15], improved GA [16], real parameter GA [17], adaptive GA [18], evolutionary programming (EP) [19], particle swarm optimization (PSO) [20], hybrid PSO [22], bacterial foraging optimization (BFO) [23], differential evolution (DE) [24-26], seeker optimization algorithm (SOA) [27], gravitational search algorithm (GSA) [28] fast Newton-Raphson algorithm [29], linear programming [30] and etc. The drawbacks of classical algorithms are obviated by employing above-mentioned algorithms. Among these methods, PSO and DE have acquired more concentration by researchers owing to their fast searching ability.

A new metaheuristic method, the BAT search algorithm based on the echolocation behavior of bats is proposed in this paper for optimal reactive power dispatch (ORPD) problem. Optimal reactive power dispatch is defined as the minimization of active power transmission losses by controlling a number of control variables. ORPD is formulated as a non-linear constrained optimization problem with continuous and discrete variables. In this paper, the proposed algorithm is used to find the settings of control variables such as generator voltages, tap positions of tap changing transformers and the amount of reactive compensation devices to optimize a certain object.

The objects are power transmission loss, voltage stability and voltage profile which are optimized separately. In the presented method, the inequality constraints are handled by penalty coefficients. The proposed methods have been tested on IEEE 30-bus power system. Simulation results clearly demonstrate the importance of employing an efficient constraint handling method to solve the ORPD problem effectively.

II. MATHEMATICAL PROBLEM FORMULATION

The proposed algorithm is tested and compared with other conventional algorithms on optimal performance in terms of minimization of:

- Power losses in transmission lines.
- Sum of voltage deviations on load busses.
- Voltage stability. The function is optimized while satisfying equality and inequality constraints.

The first objective is to minimize the real power losses that can be expressed as:

$$F_1 = P_{loss}(x,u) = \sum_{l=1}^{NL} P_L \tag{1}$$

where x is the vector of dependent variables, u is the vector of control variables, P_L is the real power losses at line-L and NL is the number of transmission lines.

The second object is the voltage deviation at load buses and can be expressed as [31]:

$$F_2 = VD(x,u) = \sum_{i=1}^{ND} \left| V_i - V_i^{sp} \right| \tag{2}$$

where V_i is the voltage at load bus-i, which is usually set to 1.0 pu and ND is the number of load buses.

The third objective which is minimized is the L voltage stability index. This index is calculated for all load buses and the maximum amount of all buses is the objective [32]. It can be expressed as:

$$F_3 = VL(x,u) = L_{\max} \tag{3}$$

In all of the problems the dependent vector is considered as:

$$x^T = [[V_L]^T, [Q_G]^T, [S_L]^T] \tag{4}$$

where x is the vector of dependent variables, $[V_L]$ is the vector of load bus voltages, $[Q_G]$ is the vector of generator reactive power outputs and $[S_L]$ is the transmission line loadings. The vector of control variables is presented as below.

$$u^T = [[V_G]^T, [T]^T, [Q_C]^T] \tag{5}$$

where $[V_G]$ is the vector of generator bus voltages, $[T]$ is the vector of transformer taps and $[Q_C]$ is the vector of reactive compensation devices.

The equality constraints are the load flow equations as:

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

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

where NB is the number of buses, P_{Gi} is the active power generation, Q_{Gi} is the reactive power generation, P_{Di} is the active load demand, Q_{Di} is the reactive load demand, G_{ij} and B_{ij} are the conductance and susceptance, respectively.

The inequality constraints in all of the problems represent the system operating constraints:

- Generator constraints: Generator voltages VG and reactive power outputs are restricted by their limits as the below relations:

$$V_{Gi}^{\min} \le V_{Gi} \le V_{Gi}^{\max} i = 1......, NG \tag{8}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \tag{9}$$

where NG is the number of generators.

- Reactive compensation sources: These devices are limited as follows:

$$Q_{Ci}^{\min} \le Q_{Ci} \le Q_{Ci}^{\max}, i = 1,...., NC \tag{10}$$

where NC is the number of reactive compensation devices.

- Transformer constraints: Tap settings are restricted as:

$$T_i^{\min} \le T_i \le T_i^{\max}, i = 1....NT \tag{11}$$

where NT is the number of transformers.

- Operating constraints: Which are the constraints of voltage load buses and line loadings.

$$V_{Li}^{\min} \le V_{Li} \le V_{Li}^{\max} i = 1......, NPQ \tag{12}$$

$$S_{li} \le S_{li}^{\max}, i = 1,..., NTL \tag{13}$$

The inequality constraints are considered in the objective function by penalty coefficients.

III. OVERVIEW OF BAT ALGORITHM

BAT search algorithm is an optimization algorithm inspired by the echolocation behavior of natural bats in locating their foods. It is introduced by Yang [33–34] and is used for solving various optimization problems. Each virtual bat in the initial population employs a homologous manner by performing echolocation way for updating its position. Bat echolocation is a perceptual system in which a series of loud ultrasound waves are released to create echoes. These waves are returned with delays and various sound levels which qualify bats to discover a specific prey. Some rules are investigated to extend the structure of BAT algorithm and use the echolocation characteristics of bats [35-36].

- Each bat utilizes echolocation characteristics to classify between prey and barrier.
- Each bat flies randomly with velocity v_i at position x_i with a fixed frequency $f_{\min}$, varying wavelength λ and loudness A_0 to seek for prey. It regulates the frequency of its released pulse and adjust the rate of pulse release r in the range of [0, 1], relying on the closeness of its aim.
- Frequency, loudness and pulse released rate of each bat are varied.
- The loudness A_m^{iter} changes from a large value L_0 to a minimum constant value $L_{\min}$.

where β is a random variable drawn from a uniform distribution. Here x^* is the current global best location in which, it's selected after comparing all the solutions among all the n bats. As the product $\lambda_i f_i$ is the velocity increment, one can consider either f_i (or λ_i) to set the velocity change while fixing the other factor. For implementation, every bat is randomly assigned a frequency which is drawn uniformly from ($f_{\min}$, $f_{\max}$). For the local search, once a solution is chosen among the current best solutions, a new solution for each bat is generated locally using random walk:

$$x_{new} = x_{old} + \varepsilon' A^t \tag{14}$$

where ε' is a scaling factor which drawn randomly from [0,1]. Also $A_t = \langle A_i^t \rangle$ is the average loudness of all the bats at time step t. Once a bat has found its prey, loudness usually decreases, while the rate of pulse emission increases, the loudness can be set to arbitrary value.

Furthermore, the loudness A_i and the rate r_i of pulse emission update iteratively as follows:

$$\begin{cases} A_i^{t+1} = \alpha A_i^t \\ r_i^{t+1} = r_i^0[1 - \exp(-\gamma t)] \end{cases} \tag{15}$$

where α is constant in the range of [0, 1] and γ is positive constant. In steady state case (i.e. t goes to infinite) loudness goes to zero, and γ_i^t will be γ_i^t. The flow chart of BAT algorithm is shown in Figure 1.

IV. SIMULATION RESULTS

The BAT has been implemented to IEEE 30-bus and the results are compared with HSA and PSO algorithms. the standard IEEE 30-bus test system was used as shown in Figure 2. All of the three algorithms are used to minimize three object functions separately which are: (1) Real power losses in transmission lines, (2) voltage stability index, and (3) sum of voltage deviations. The IEEE 30-bus network used in this study consists of six generators, 41 lines, four transformers which are placed in lines 6-9, 4-12, 9-12 and 27-28.

The network also includes three reactive compensation devices which are placed in buses 3, 10 and 24. Tap settings are in the range of [0.95, 1.05]. The reactive compensation devices are considered within the interval MVAR also generator voltages are limited to [0.9, 1.1] pu [12, 36]. In this case the optimization problem has 13 control variables.

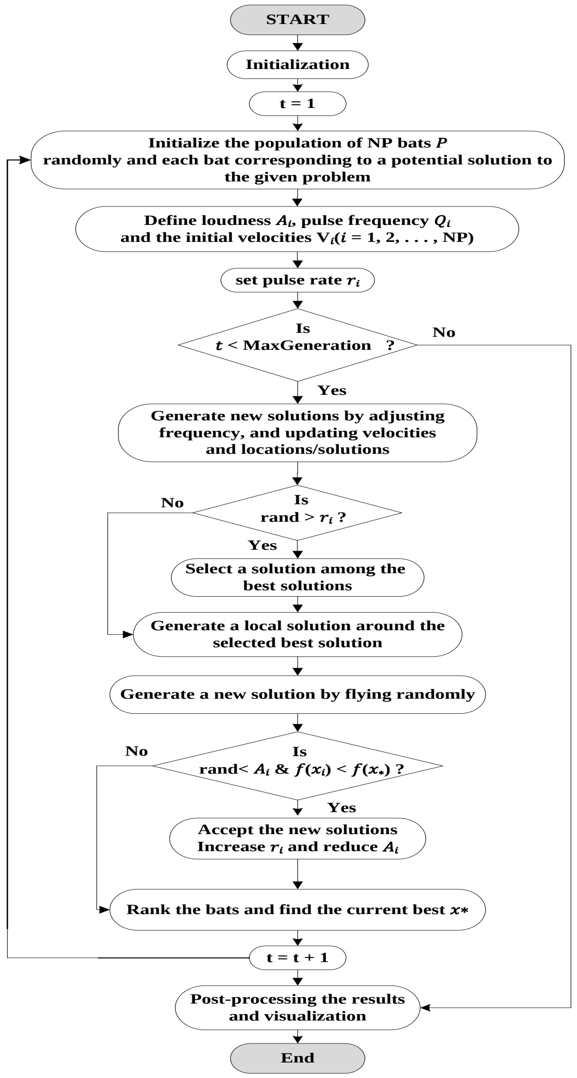

Figure 1. BAT search algorithm flow chart

The variable limits are presented in Table 1. Transformer taps and reactive compensation devices are discrete variables with the changes step of 0.01 p.u. To expose the profit of BAT, simulation results have been compared other techniques such as harmony search algorithm (HSA) and PSO method. The initial conditions for all the methods are same and are given as:

$P_{load} = 2.832$ pu and $Q_{load} = 1.262$ pu

$\sum PG = 2.893$ pu , $\sum QG = 0.980199$ pu

$P_{load} = 0.059879$ pu

The bus which there voltages are outside the specified range are:

$V_{26} = 0.932$ pu, $V_{29} = 0.940$ pu, $V_{30} = 0.928$ pu

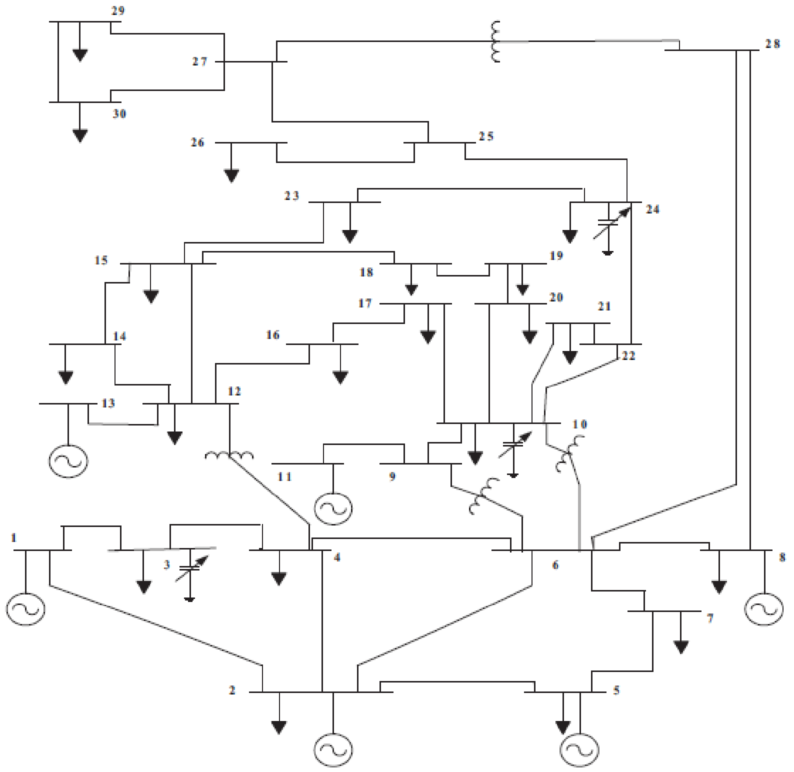

Figure 2. Single line diagram of IEEE 30-bus test system

Table 1. Variable limits (pu)

Reactive power generation limits						
Bus	1	2	5	8	11	13
$Q_G^{\max}$	0.596	0.48	0.6	0.53	0.15	0.155
$Q_G^{\min}$	-0.298	-0.24	-0.3	-0.265	-0.075	-0.078
Voltage and tap setting limits						
$V_G^{\max}$	$V_G^{\min}$	$V_{load}^{\max}$	$V_{load}^{\min}$	$T^{\max}$	$T^{\min}$	--------
1.1	0.9	1.05	0.95	1.05	0.95	--------
Reactive compensation devices and voltage limits						
$Q_C^{\max}$	$Q_C^{\min}$	$V_C^{\max}$	$V_C^{\min}$	--------	--------	--------
0.36	-0.12	1.05	0.95	--------	--------	--------

Table 2. Comparison of transmission loss for different methods in the IEEE 30-bus system

Compared item	PSO	HSA	BAT
Best P_{loss} (MW)	4.9239	4.9059	4.8213
Worst P_{loss} (MW)	5.0576	4.9653	4.7653
Average P_{loss} (MW)	4.9720	4.9240	4.8108

After implementing the HSA to the ORPD problem for different objective functions the results are presented. Table 2 compares optimal transmission loss for the 30-bus IEEE network for different methods after ten runs for each method. The table also shows percentage of power loss decrease with respect to the case that all generator voltages and transformer taps are set to 1 p.u. and reactive compensation devices are set to zero. These results show that the BAT leads to a better solution than the other two solutions. Also the proposed method keeps all of the dependent variables within their limits. The transmission loss is reduced from 0.05934 p.u (In the base case) to 0.05001 by the BAT in the best case.

The results obtained from BAT for power loss reduction are compared with other algorithms such as [16] which a DE method is used to solve the optimization problem or CLPSO in [17]. In all of these references some of the constraints and initial settings of the problem are different with the assumed values and constraints. So, to coincide the ORPD solved by BAT in this paper with the introduced algorithms and obtaining a reasonable comparison the constraints and initial values are changed according to the constraints used in each of these papers. Table 3 indicates solving the ORPD problem when four reactive compensation devices are installed at buses 6, 17, 18 and 27.

It seems if the BAT procedure is modified (such as changing the parameters of the algorithm proportional to the search process or combining it with other algorithms) reaching better answers than the mentioned algorithms is possible. Table 5 represents the results for the voltage stability objective function. The results show that BAT improves the voltage stability better than the other two methods. By the BAT maximum value of the L index has reduced from 0.1579 to 0.1179 and as a consequence the voltage stability margin has increased. Also the results for voltage deviation as the objective function are exposed in Table 6.

The results show that the BAT decreases the voltage deviation more than HSA and PSO. Using the BAT voltage deviation has decreased from 0.694 in the base case to 0.1349 in the optimization case. Values of control variables for transmission loss minimization problem come in Table 7 which all of them are restricted in there specified limits.

Table 3. Comparison of the proposed method with the results exposed in [37]

Solving with constraints according to [37]				
Method	PSO [37]	CLPSO [37]	HAS	BAT
Power Loss(MW)	4.8136	4.7208	4.7624	4.6764

Table 4. Comparison of voltage stability for different methods for the IEEE 30-bus system

Compared item	PSO	HSA	BAT
Best L_{max}	0.1217	0.1212	0.1197
Worst L_{max}	0.1327	0.1221	0.1201
Average L_{max}	0.1264	0.1216	0.1211

Table 4. Comparison of voltage stability for different methods for the IEEE 30-bus system

Compared item	PSO	HSA	BAT
Best deviation	0.1424	0.1349	0.1287
Worst deviation	0.1639	0.1589	0.1302
Average deviation	0.1496	0.1443	0.1394

Table 4. Values of control variables after optimization by HSA, PSO and BAT

Variable	PSO	HSA	BAT
V_1	1.0313	1.0726	1.0678
V_2	1.0114	1.0625	1.0597
V_5	1.0221	1.0399	1.0301
V_8	1.0031	1.0422	1.0411
V_{11}	0.9744	1.0318	1.0431
V_{13}	0.9987	1.0681	1.0543
T_1	0.97	1.01	1.000
T_2	1.02	1.00	1.031
T_3	1.01	0.99	0.913
T_4	0.99	-0.05	0.965
Q_1	0.17	0.34	0.401
Q_2	0.13	0.12	0.134
Q_3	0.23	0.10	0.154

V. CONCLUSIONS

ORPD is an important problem in power engineering which has discrete variables, nonlinear objective function, and nonlinear constraints. In ORPD, to handle constraints, penalty functions are most commonly used, due to their simplicity. In this paper, one recently developed meta-heuristic like BAT has been, successfully, implemented to solve the ORPD problem of power systems. From the simulation work, it is observed that the proposed BAT yields optimal settings of the control variables of the test power system. The simulation results also indicate the robustness and superiority of the proposed approach to solve the ORPD problem of power systems.

Also in this paper the results obtained by BAT have been compared with other algorithms that have been developed in the recent years such as HSA and PSO. Although a number of these algorithms represent better answers, but by modifying BAT better results can be attained this is recommended for the future works. The ability of proposed scheme compared with other algorithms can be summarized as follow:

- The faster convergence and less time consuming.
- The ability to jump out the local optima.
- Providing the correct answers with high accuracy in the initial iterations.
- Superiority in computational simplicity, success rate and solution quality.

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