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An intelligent θ-Modified Bat Algorithm to solve the non-convex economic dispatch problem considering practical constraints

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ABSTRACT

This paper proposes a practical formulation for the non-convex economic dispatch problem to consider multi-fuel options, ramp rate limits, valve loading effect, prohibited operating zones and spinning reserve. A new optimization algorithm based on the θ-bat algorithm (θ-BA) is suggested to solve the problem. The θ-BA converts the Cartesian search space into the polar coordinates such that more search ability would be achieved. According to the complex, nonlinear, and constrained nature of the problem, a new self-adaptive modification method is proposed. The proposed modified θ-BA (θ-MBA) is constructed based on the roulette wheel mechanism to effectively increase the convergence of the algorithm. The high ability and satisfying performance of the proposed optimization method is examined on IEEE 15-unit, 40-unit and 100-unit test systems.

Introduction

In recent years, optimization methods have become major parts of engineering problems particularly the power engineering [1]. This condition shows the necessity of doing more struggles to generate new powerful algorithms. The key incentive is to uncover the most optimal solutions for the electric system operation or planning. In this way, economic dispatch (ED) is a popular and well-timed issue that aims to minimize the total system costs while meeting different constraints [2,3]. In the simple interpretation, ED is an optimization problem with two constraints of generation capacity and power and demand balance. Nonetheless, the realistic ED contains more nonlinear and complex constraints such as the valve loading effects, ramp rate limits, prohibited operating zones (POZs), spinning reserve and multi-fuel options. The valve loading effect modifies the ED cost function to a more complete nonlinear non-smooth objective function incorporating a sinusoidal term [4]. Some of the methods that have considered valve loading effect cane be named as dynamic programming (DP) [5], evolutionary programming (EP) [6], improved fast EP (IFEP) [7], tabu search (TS) [8] and sequential quadratic programming (SQP) [9]. The other practical constraint is POZ that alter the continuous formulation into discontinuous problem [10]. Some methods such as decomposition technique (DT) [11], dynamic programming [12], genetic algorithm (GA) [13] and particle swarm optimization (PSO) [14] have addressed POZ effect. The next constraint is reserve that supplies extra power more than the demand. Bender's decomposition (BD) [15], HNN [16] and sequential quadratic programming (SQP) [17] have considered reserve constraint. The other constraint is multi-fuel option that determines different cost function coefficients for different generators. Heuristic techniques, evolutionary programming (EP) [18], hierarchical method (HM) [19] and HNN [20] have considered multi-fuel option. These works have provided useful and timely results in the ED problem, but ignoring some of the practical limitations reduces their quality. Some of the works which have considered all these constraints new PSO (NPSO) with local random search (NPSO–LRS) [21], GA with multiplier updating method (IGAMUM) [22] and real-coded genetic algorithm (RCGA) [23]. However, due to the high nonlinearity and complexity of the problem, most of the above methods could not find the optimal solution. This situation clearly shows the lack of a sufficient powerful optimization tool to inspect the practical ED problem.

This paper addresses a new optimization algorithm to solve the practical ED problem. According to the complexity and nonlinearity of the optimization problem, a powerful optimization method is presented to search the problem space suitably and escape from premature convergence. Therefore, a new modified optimization algorithm based on bat algorithm (BA) [24] is proposed to solve the problem. Original BA imitates the behavior of the bats to catch their prey. BA has many features such as a straightforward concept, few adjusting parameters, and implementation ease that make it a

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Nomenclature

Symbol	Description
A_i	loudness of frequency f_i
$Acum_\tau$	accumulated probability of τth *sub-modification method*
B_{ij}	susceptance between the busses i and j
e_i and f_i	costs associated with valve loading effect
$F_i^{\max}/F_i^{\min}$	maximum/minimum frequency of ith bat
N_{bat}	number of bats in the population
NP_i	number of POZs of unit i
n_f	number of fuel types
$P_i^{\min}/P_i^{\max}$	minimum/maximum power capacity of the ith unit
$P_{i,j}^{LB}/P_{i,j}^{UB}$	lower/upper boundary of POZ$_j$ of unit i
P_i^t	amount of power produced by the ith unit at time t
r_i	frequency rate of f_i
$S_i^{\max}$	maximum spinning reserve of unit i
S_R^t	system required spinning reserve at time t
UR_i^t/DR_i^t	ramp-up/ramp-down rate limits of ith unit at time t
X_G/θ_G	global solution
Θ	set of all in service units which have POZ
φ_1 to φ_4	random values in the range $[0,1]$
β	random values in the range $[0,1]$
ε	random number between $[-1,1]$
A_{mean}^{old}	mean value of loudness of all bats
a_i, b_i, c_i	cost coefficients
D	total power demand of the system
F_i	frequency of the signal produced by bat i
N_{GP}	number of generators with POZ
N_{Mod_τ} $\tau = 1,2,3$	number of bats which have chosen the τth sub-modification
n	number of generators in the network
N_t	number of time intervals
P_{Ploss}^t	network power losses at time t
P_{0i}^{t-1}	active power output of unit i in the previous time
Prb_τ	probability of τth sub-modification method
$rand_i$	random value in the range $[0,1]$
$S_{r,i}^t$	spinning reserve for unit i at time t
$Iter$	number of the iteration in the algorithm
V_i	velocity of ith bat
$\theta_{i,\min}/\theta_{i,\max}$	minimum/maximum values of phase angle
θ_i	phase angle vector corresponding to X_i
Ω	set of all units which are in service
α and γ	constant parameters of BA
Γ	balancing constant set to 0.25 experimentally

good candidate for the problem in hand. But, the use of Cartesian coordinates reduce the ability of BA while reducing its convergence capability. This paper proposes the polar version of BA called θ-BA which will makes use of phasor vectors to update the position of bats in the polar search space. Also, a new self-adaptive modification method including three sub-modification techniques is proposed to increase the variety of the bat population, effectively. We call this new algorithm as modified θ-BA or shortly θ-MBA. The feasibility and satisfying performance of the proposed method are examined using three IEEE standard test systems.

The rest of this paper is structured as follows. Section 'Practical ED formulation' describes the formulation of the ED problem. The proposed θ-MBA is introduced in Section 'θ-Modified Bat Algorithm (θ-MBA)'. Section 'Solution procedure' details the procedure for using the modified BA method to solve the ED problem. Simulation results are presented and discussed in Section 'Simulation results'. Section 'Conclusion' concludes the paper with some remarks.

Practical ED formulation

In this section, the practical formulation for the ED problem including the objective function and the constraints are described.

Classical ED

The classical ED objective function is as below [2]:

$$\text{Min } fun(X) = Cost(X) = \sum_{i=1}^{n} F_i(P_i) = \sum_{i=1}^{n}(a_i + b_i P_i + c_i P_i^2) \qquad (1)$$
$$X = [P_1, P_2, P_3, \ldots, P_n]$$

Subject to the power and demand balance as well as the production capacity as follows:

$$\sum_{i=1}^{n} P_i = D + P_{Loss}$$
$$P_i^{\min} \leqslant P_i \leqslant P_i^{\max} \qquad (2)$$

The network active losses may be neglected or approximated using B loss matrix [21]:

$$P_{Loss} = \sum_{i=1}^{n}\sum_{j=1}^{n} P_i B_{ij} P_i + \sum_{i=1}^{n} B_{0i} P_i + B_{00} \qquad (3)$$

Practical ED problem

The practical ED with valve loading effects contains a sinusoidal term as shown at the following [5–9]:

$$Cost(X) = \sum_{t=}^{N_t}\sum_{i=1}^{n} F_i(P_i^t)$$
$$= \sum_{t=}^{N_t}\sum_{i=1}^{n}(a_i + b_i P_i^t + c_i P_i^{t2} + |e_i \sin(f_i(P_i^{\min} - P_i^t)|)) \qquad (4)$$

The idea of multi-fuel option is as follows [18–20]:

$$F_i(P_i^t) = \begin{cases} a_{i1} + b_{i1} P_i^t + c_{i1} P_i^{t2}; & \text{Fuel1} : P_i^{min} \leqslant P_i^t \leqslant P_{i1}^{max} \\ a_{i2} + b_{i2} P_i^t + c_{i2} P_i^{t2}; & \text{Fuel2} : P_{i2}^{min} \leqslant P_i^t \leqslant P_{i2}^{max} \\ & \ldots \\ a_{ij} + b_{ij} P_i^t + c_{ij} P_i^{t2}; & \text{Fuel j} : P_{ij}^{min} \leqslant P_i^t \leqslant P_{ij}^{max} \end{cases} \qquad (5)$$

Considering valve loading effect, the objective function including valve-loading effect and multi-fuel option is as follows:

$$F_i(P_i^t) = a_{ij} + b_{ij} P_i^t + c_{ij} P_i^{t2} + |e_{ij} \sin(f_{ij}(P_{ij}^{\min} - P_i^t))|$$
$$Fuel\ j : P_{ij}^{min} \leqslant P_i^t \leqslant P_i^{max}; \quad j = 1, 2, \ldots, n_f \qquad (6)$$

The ED constraints that are considered as limitations are described at below.

Ramp Rate limits [22–23]:

$$\begin{cases} P_i^t - P_{0i}^t \leqslant UR_i^t; & \text{If generation increases} \\ P_{0i}^t - P_i^t \leqslant DR_i^t; & \text{If generation decreases} \end{cases} \qquad (7)$$

Using the ramp rate limit, the generating capacity of each power unit is amended:

$$\max(P_i^{\min}, P_{0i}^t - DR_i^t) \leqslant P_i^t \leqslant \min(P_i^{\max}, P_{0i}^t + UR_i^t)$$
$$i = 1, 2, \ldots, n; \quad t = 1, 2, \ldots, N_t \qquad (8)$$