Electrical Power and Energy Systems 44 (2013) 832–843

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

An effective differential harmony search algorithm for the solving non-convex economic load dispatch problems

Ling Wang *, Ling-po Li

Tsinghua National Laboratory for Information Science and Technology (TNList), Department of Automation, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 27 April 2012
Received in revised form 12 June 2012
Accepted 9 August 2012
Available online 26 September 2012

Keywords:
Economic load dispatch problem
Harmony search
Differential evolution
Constraint handling

ABSTRACT

Solving the non-convex economic load dispatch (ELD) problem with evolutionary algorithms has gained increasing research in recent years. In this paper, a differential harmony search (DHS) algorithm is proposed by combining the mechanisms of both differential evolution and harmony search. In the DHS, the pitch adjustment operation is cooperated with the different mutation operation to enhance the exploitation ability of harmony search, and both the memory consideration and the pitch adjustment are used to enhance the exploration ability of evolution search. In addition, a repair procedure and three simple selection rules are proposed for constraint handling. Numerical simulations are carried out based on different kinds of testing problems with various constraints including valve point effects, multi-fuels, ramp rate limit and prohibited operation zones. Simulation results and comparisons with the some existing algorithms demonstrate the effectiveness, efficiency and robustness of the proposed DHS algorithm. Finally, the effect of parameter setting on the DHS is investigated as well.

1. Introduction

The economic load dispatch (ELD) problem is to find the optimal scheduling for the generating plants to meet the demand at minimum operating cost while satisfying all equality and inequality constraints [1–6]. So far, many classical methods, such as gradient-based method, linear programming, quadratic programming, and Lagrange relaxation [7] have been applied to solve the ELD problems by approximating the cost function of each generator by a single quadratic function. However, duo to the valve point effects, ramp rate limits, and multi-fuel optimization, the ELD problem is a nonlinear one with many local optima and multiple constraints in nature, which prevents the classical methods from obtaining the global optima. Although dynamic programming [8] can be used to solve the ELD problem, it suffers from the curse of dimensionality and thus it is not practical for many real-world applications.

Recently, evolutionary algorithms [9] have shown great potential in solving the nonlinear the ELD problems, such as genetic algorithm (GA) [10–14], simulated annealing (SA) [15], evolutionary programming (EP) [16,17], Tabu search (TS) [18,19], particle swarm optimization (PSO) [20–30], differential evolution (DE) [31–36], harmony search (HS) [6,37,38], cultural self-organizing migrating strategy [39], quantum-inspired evolutionary algorithm [40], clonal algorithm [41], neural network [42] and biogeography-based optimization [43–46]. Compared to other evolutionary algorithms, DE has been shown to be simple and effective. As for DE in particular for the ELD applications, a new algorithm by combining a chaotic differential evolution (CDE) and quadratic programming was proposed in [31] to solve the ELD problem with valve point effects; an adaptive hybrid DE (AHDE) was proposed in [32] for the dynamic ELD problems; a DE cooperating with estimation of distribution was proposed in [33] to solve large scale ELD problems; an algorithm coupling DE with a specially designed repair operation was proposed in [34] to solve the ELD problem with different constraints; an improved DE (IDE) based on cultural algorithm and diversity measure was proposed in [35] to solve two problems with valve point effects; and a modified DE was presented in [36] by introducing some mechanisms of the GA, PSO and SA.

Harmony search (HS) is a novel meta-heuristic algorithm [47] inspired by the musical improvisation process that occurs when a musician searches for a better harmony. It has been shown that the HS is faster than the GA [48]. So far, the HS has been successful used to solve a variety of optimization problems [49], such as scheduling problem [50], steel frame design [51], reliability optimization [52]. However, the research of the HS for the ELD problem is still rare. Inspired by the mechanism of PSO, an improved HS algorithm was proposed to solve the 13-unit ELD problem with valve point effects [37], and an improved HS was proposed by tuning one control parameter depending on the variance of the population for the 6-unit problem [38].

* Corresponding author. Tel.: +86 10 62783125; fax: +86 10 62786911.
E-mail addresses: wangling@tsinghua.edu.cn (L. Wang), llp03@mails.tsinghua.edu.cn (L.-p. Li).

0142-0615/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijepes.2012.08.021

In this paper, a differential harmony search (DHS) algorithm is proposed by combining the mechanisms of both harmony search and differential evolution. First, the pitch adjustment operation of the original HS is cooperated with the differential mutation operation to enhance exploitation ability. Second, the memory consideration and the enhanced pitch adjustment operation are both employed to strengthen the exploration ability. Compared with the pure HS, the use of differential mutation and crossover can enhance the exploitation in the DHS. Compared with the pure DE, the DHS may inherit elements from as many individuals as its number of dimensions when generating a new individual to enhance the exploration ability. Third, we present a repair procedure and three simple selection rules to handle the constraints of the ELD problem. Simulation results and comparisons to some existing algorithms based on some testing problems with various constraints including valve point effects, multi-fuels, ramp rate limit and prohibited operation zones demonstrate the effectiveness of the proposed DHS.

The remaining contents of the paper are organized as follows. Section 2 provides the formulation of the ELD problem. The brief introduction to DE and HS is given in Section 3. In Section 4, we present the differential harmony search to solve the ELD problem in detail. Simulation results and comparison are provided in Section 5. Finally, we end the paper with some conclusions and future work in Section 6.

2. Problem formulation

2.1. Objective function

The objective of the ELD problem is to minimize the total fuel cost of power generation while satisfying all the equality and inequality constraints. The cost function of the power system is the following sum of the fuel cost of each generating unit:

$$F = \sum_{i=1}^{n} F_i(p_i) \tag{1}$$

where $F_i(p_i)$ denotes the fuel cost of the ith generating unit with output p_i, and n is the number of the generating units in the system.

Usually, the cost of a generating unit can be modeled as the following smooth quadratic function:

$$F_i(p_i) = a_i p_i^2 + b_i p_i + c_i \tag{2}$$

where a_i, b_i and c_i are the cost coefficients of the ith generating unit.

In reality, the generating units with multi-valve stream turbine have valve-point loading effect. Thus, the cost function contains the following higher-order nonlinearity:

$$F_i(p_i) = a_i p_i^2 + b_i p_i + c_i + |d_i \sin(e_i(p_i^{\min} - p_i))| \tag{3}$$

where d_i and e_i are valve loading coefficients of the ith generating unit.

Another realistic representation of generating unit is the multiple fuels. In such a case, the fuel cost function is expressed as the following piecewise quadratic function:

$$F_i(p_i) = \begin{cases} a_{i,1} p_i^2 + b_{i,1} p_i + c_{i,1} & i p_i^{\min} \leqslant p_i < p_{i,1} \\ a_{i,2} p_i^2 + b_{i,2} p_i + c_{i,2} & \text{if } p_{i,1} \leqslant p_i < p_{i,2} \\ \vdots & \vdots \\ a_{i,k} p_i^2 + b_{i,k} p_i + c_{i,k} & \text{if } p_{i,k-1} \leqslant p_i \leqslant p_i^{\max} \end{cases} \tag{4}$$

where $a_{i,j}$, $b_{i,j}$ and $c_{i,j}$ are the cost coefficients of the ith generating unit for type j, $p_{i,j}$ is the upper bound of the output for type j ($j = 1, 2, \ldots, k$), and $p_i^{\min}$ and $p_i^{\max}$ are the lower bound and upper bound of the output of the ith generating unit, respectively.

The more accurate and practical ELD problem may consider both valve point loading and multiple fuels. Thus, the cost function can be described as follows:

$$F_i(p_i) = \begin{cases} a_{i,1} p_i^2 + b_{i,1} p_i + c_{i,1} + |d_{i,1} \sin(e_{i,1}(p_i^{\min} - p_i))| & \text{if } p_i^{\min} \leqslant p_i < p_{i,1} \\ a_{i,2} p_i^2 + b_{i,2} p_i + c_{i,2} + |d_{i,2} \sin(e_{i,2}(p_i^{\min} - p_i))| & \text{if } p_{i,1} \leqslant p_i < p_{i,2} \\ \vdots & \vdots \\ a_{i,k} p_i^2 + b_{i,k} p_i + c_{i,k} + |d_{i,k} \sin(e_{i,k}(p_i^{\min} - p_i))| & \text{if } p_{i,k-1} \leqslant p_i \leqslant p_i^{\max} \end{cases} \tag{5}$$

2.2. Constraints

The ELD problem should satisfy some equality or inequality constraints, including generating capacity, power balance, ramp rate limit, and prohibited operating zones.

(1) *Generating capacity*: the power output of each unit must satisfy the generating capacity. That is,

$$p_i^{\min} \leqslant p_i \leqslant p_i^{\max} \tag{6}$$

(2) *Power balance*: the total generated power should be the same as the sum of the power demanded and the total transmission loss. That is,

$$\sum_{i=1}^{n} p_i = P_D + P_L \tag{7}$$

where P_D is the total power demanded, and P_L is the transmission loss as follows:

$$P_L = \sum_{i=1}^{n}\sum_{i=1}^{n} p_i B_{i,j} p_j + \sum_{i=1}^{n} B_{0,j} p_i + B_{00} \tag{8}$$

where $B_{i,j}$, $B_{0,j}$ and B_{00} are the loss coefficients that can be assumed to be constant under a normal operating condition.

(3) *Ramp rate limit*: the operating ranges of all the online units are restricted by their corresponding ramp rate limits. The up-ramp and down-ramp constraints can be written as follows:

$$p_i - P_i^0 \leqslant UR_i \text{ and } P_i^0 - p_i \leqslant DR_i \tag{9}$$

where P_i^0 is the previous power output of the ith generating unit, and UR_i and DR_i are the up-ramp and down-ramp limits of the ith generating unit, respectively.

(4) *Prohibited operating zone*: the prohibited operating zones are the range of output power of a generating unit where the operation may cause damage to the turbine. Thus, operation is avoided in such regions. This constraint can be described as follows:

$$\begin{aligned} & p_i^{\min} \leqslant p_i \leqslant p_{i,1}^l \\ & p_{i,j-1}^u \leqslant p_i \leqslant p_{i,j}^l \quad j = 2, 3, \ldots, m_i \\ & p_{i,m_i}^u \leqslant p_i \leqslant p_i^{\max} \end{aligned} \tag{10}$$

where m_i denotes the number of prohibited operating zones of the ith generating unit, and $p_{i,j}^l$ and $p_{i,j}^u$ are the lower and the upper bounds of the jth prohibited operating zone.

3. Introduction to DE and HS

3.1. Differential evolution

Differential evolution [53] is a population-based evolutionary algorithm originally proposed for unconstrained continuous problem. So far, many variants of the classic DE have been proposed [54]. In this paper, *DE/rand/bin* with three main operations