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Differential evolution based on truncated Lévy-type flights and population diversity measure to solve economic load dispatch problems

Leandro dos Santos Coelho [a,b,*], Teodoro Cardoso Bora [a], Viviana Cocco Mariani [c]

[a] Electrical Engineering Graduate Program (PPGEE), Department of Electrical Engineering, Federal University of Parana (UFPR), Polytechnic Center, CP 19011, 81531-980 Curitiba, PR, Brazil

[b] Industrial and Systems Engineering Graduate Program (PPGEPS), Pontifical Catholic University of Parana (PUCPR), Imaculada Conceição, 1155, 80215-901 Curitiba, PR, Brazil

[c] Department of Mechanical Engineering, Pontifical Catholic University of Parana (PUCPR), Imaculada Conceição, 1155, 80215-901 Curitiba, PR, Brazil

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ABSTRACT

Economic load dispatch (ELD) is an important constrained optimization task addressing this vital concern for power system operations. ELD problem is the process of allocating generation among available committed generating units such that cost of generation is optimum subject to several equality and inequality constraints. The conventional optimization methods are mainly classical mathematical methods, which include gradient method and Lagrange relaxation method. In recent years, different types of evolutionary algorithms have been used to solve ELD problems. Among the existing evolutionary algorithms, a well-known branch is the differential evolution (DE). The mutation operation of DE applies vector differentials between existing population members for determining both the degree and the direction applied to the individual subject of the mutation operation. With an eye to improve the performance of classical DE, in this paper, a DE algorithm combined with truncated Lévy flight random walks and a population diversity measure (DEL) to improve the crossover and mutation operations is designed to help avoiding premature convergence effectively. A Lévy flight random walks (a sequence of displacements) in which the increments are distributed according to a heavy-tailed probability distribution form the α-stable distribution family. The effectiveness of the proposed DEL is demonstrated for two benchmark ELD problems. In order to evaluate the performance of the proposed DEL, it is applied to benchmark systems consisting of 13 and 140 thermal units. Simulation results reveal that, compared with the classical DE and those other methods reported in literatures recently, the proposed DEL is capable of obtaining better quality solutions with higher efficiency.

1. Introduction

The economic load dispatch (ELD) problem plays a key role in operation planning of modern power systems. The main objective of ELD problem is to reduce the total generation cost, subject to load demand and other equality and inequality constraints.

Classical optimization algorithms such as lambda iteration, gradient method, Lagrange relaxation approximate, and Newton method can solve the ELD problems if the cost function is piecewise linear and monotonically increasing. However, ELD problem with constraints such as valve-point effects, multi-fuel cost, transmission losses, and prohibited zones are non-smooth optimization problems, in which finding the global optimum is a challenge [1–6]. As an alternative to the conventional optimization approaches, metaheuristics based on evolutionary algorithms [7–10] and swarm intelligence approaches [11–14] have received much attention by many researchers due to their ability to find potential solutions. However, although the metaheuristics do not always guarantee discovering globally optimal solutions in finite time, they often provide a fast and reasonable solution.

One of the evolutionary algorithms that have shown potential and good perspective for the solution of various optimization problems [15–19] is differential evolution (DE). DE was proposed by Storn and Price [15,16] and is now widely used by researchers in many scientific and engineering fields [17–19] as it is a robust and fast stochastic function optimizer. DE is particularly simple to work with, having only a few control parameters. However, their associated control parameters, namely the mutation factor (*MF*) and the crossover rate (*CR*) may significantly influence the searching accuracy and convergence speed of the DE. Choosing suitable

* Corresponding author at: Electrical Engineering Graduate Program (PPGEE), Department of Electrical Engineering, Federal University of Parana (UFPR), Polytechnic Center, CP 19011, 81531-980 Curitiba, PR, Brazil.

E-mail addresses: leandro.coelho@pucpr.br (L.S. Coelho), teodoro.bora@pucpr.br (T.C. Bora), viviana.mariani@pucpr.br (V.C. Mariani).

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control parameter values is, frequently, a problem dependent task and requires previous experience of the user. To successfully solve a specific optimization problem at hand, it is generally required to perform a time-consuming trial-and-error search to tune its associated control parameter values. Inappropriate choice of parameters may lead to premature convergence or stagnation. Adapting the DE's control parameters is one possible improvement. In this context, researchers are working on DE and further improving it through the application of adaptive or self-adaptive techniques to the control parameters [20–26].

In [20], a version of the DE with adaptive control parameters in which uses fuzzy systems to adapt the search parameters for the mutation operation and crossover operation was proposed. The control inputs incorporate the relative objective function values and individuals of the successive generations. Salman et al. [21] proposed a self-adaptive DE algorithm with the mutation factor tuning generated by normal distribution. This self-adaptive DE was tested on nine benchmark functions where it generally outperformed other well-known versions of DE. Nobakhti and Wang [22] proposed a self-adaptive approach called randomized adaptive DE with adaptation of the mutation factor. Das et al. [23] linearly reduced the mutation factor with increasing generation count from a maximum to a minimum value, or randomly varied in the range [0.5, 1]. They also employed a uniform distribution between 0.5 and 1.5 (with a mean value of 1) to obtain a hybrid DE approach. In [24], an improved self-adaptive DE algorithm with multiple strategies using a different search strategy and a parallel evolution mechanism was proposed and validated. Brest et al. [25] proposed a DE with a parameter control technique based on the self-adaptation of mutation factor and crossover rate. Zaharie [26] proposed to transform the mutation factor into a Gaussian random variable.

In this paper, in order to solve the ELD problem of units with valve-point effects effectively, a solution methodology integrating DE, a population diversity measure and Lévy flights random walks (DEL) to improve the crossover and mutation rates tuning has been proposed. Lévy flights are Markov processes and have infinite variance, and their increments are distributed by the α-stable Levy laws of index $0 < \alpha < 2$ (Levy distributions). The probability distribution of truncated Lévy flight increments is a slightly deformed Lévy distribution. Details about the Levy flights implementation can be found in [27–30]. Mantegna and Stantely [27] introduced a class of stochastic process called truncated Lévy flight in which the arbitrarily large steps of a Lévy flight are eliminated. The proposed method is useful to solve the problem of infinite variance, in which the probability of taking a step is abruptly cut to zero at a certain critical step size. Gupta and Campanha [28] extended the gradually truncated Lévy flight combining statistical distribution factor and a controlling mechanism. The authors discussed also the variation of controlling parameters with the increase of time difference between successive observations. This allows us to generate a number of theoretical curves for the same system by varying the time difference between successive observations. In [29], a version of an exponentially damped Lévy flight is evaluated. Grothe and Schmidt [30] described the scaling behavior of such Lévy-Student processes and the parameters of its marginal distributions by a simple analytical scaling law.

This deformation must change the variance of the resulting distribution from the infinite to the finite, and consequently, according to the generalized central limit theorem, the resulting distribution belongs to the Gaussian basin of attraction.

In this paper, to show the advantages of the proposed DEL algorithm, it has been applied for solving two benchmark ELD problems with 13 and 140 generators with valve-point loading are adopted to demonstrate the performance of the proposed DEL algorithm. Simulation results obtained through the DEL approach are analyzed and compared with the classical DE method and those reported in the recent literature.

The next section of this paper contains the description of ELD problem, while Section 3 explains the classical DE and the proposed DEL algorithm. Section 4 briefly describes the procedure of constraint handling in DE and DEL algorithms. Section 5 presents and discusses the optimization results. Finally, the conclusion is drawn in Section 6.

2. Description of the ELD problem

The increasing energy demand and decreasing energy resources have requested the optimum use of available resources. The basic objective of the ELD is to determine the allocation of output powers of generators so as to meet the power demand at minimum operating cost under various system and operating constraints. Improvements in scheduling of the unit power outputs can lead to significant cost savings. The ELD can be formulated mathematically as an optimization problem (minimization) with an objective function and constraints. The equality constraint given by the power balance equation is expressed as:

$$\sum_{i=1}^{n} P_i - P_L - P_D = 0. \tag{1}$$

The inequality constraints related to real power operating limits are represented by Eq. (2) given by

$$P_i^{\min} \leqslant P_i \leqslant P_i^{\max}. \tag{2}$$

In the power balance criterion, an equality constraint must be satisfied, as shown in Eq. (1). The generated power should be the same as the total load demand plus total line losses. The generating power of each generator should lie between maximum and minimum limits represented by Eq. (2), where P_i is the power of generator i (in MW); n is the number of generators in the system; P_D is the system load demand (in MW); P_L represents the total line losses (in MW) and $P_i^{\min}$ and $P_i^{\max}$ are, respectively, the minimum and maximum power outputs of the ith generating unit (in MW). The total fuel cost function OF is formulated as follows:

$$\min \; OF = \sum_{i=1}^{n} F_i(P_i) \tag{3}$$

where F_i is the total fuel cost for the generator unity i (in \$/h). To simplify the optimization problem and facilitate the application of classical techniques, cost functions of generation units are typically modeled by smooth quadratic function form given as

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i \tag{4}$$

where a_i, b_i and c_i are cost coefficients of generator i. Generally, the input–output characteristics of modern power generating units are inherently high nonlinear because of valve-point loading effects, multi-fuel effects, among others. To take these effects into consideration, the ELD problem can be represented as a non-smooth optimization problem. The incremental fuel cost function of the generators in this paper including valve-point loading effects can be represented as follows

$$\widetilde{F}_i(P_i) = F(P_i) + |e_i \sin(f_i(P_i^{\min} - P_i))| \quad \text{or} \tag{5}$$

$$\widetilde{F}_i(P_i) = a_i P_i^2 + b_i P_i + c_i + |e_i \sin(f_i(P_i^{\min} - P_i))| \tag{6}$$

where e_i and f_i are non-smooth fuel cost coefficients of generator i. In other words, to take account for the valve-point effects in the ELD problem, sinusoidal functions are added to the quadratic cost functions given by Eq. (4).

Hence, the total fuel cost that must be minimized, according to Eq. (3), is modified to: