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Evolutionary algorithm solution and KKT based optimality verification to multi-area economic dispatch

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ABSTRACT

This paper is aimed at exploring the performance of the various evolutionary algorithms on multi-area economic dispatch (MAED) problems. The evolutionary algorithms such as the Real-coded Genetic Algorithm (RGA), Particle Swarm Optimization (PSO), Differential Evolution (DE) and Covariance Matrix Adapted Evolution Strategy (CMAES) are considered. To determine the efficiency and effectiveness of various EAs, they are applied to three test systems; including 4, 10 and 120 unit power systems are considered. The optimal results obtained using various EAs are compared with Nelder–Mead simplex (NMS) method and other relevant methods reported in the literature. To compare the performances of various EAs, statistical measures like best, mean, worst, standard deviation and mean computation time over 20 independent runs are taken. The simulation experiments reveal that CMAES algorithm performs better in terms of solution quality and consistency. Karush–Kuhn–Tucker (KKT) conditions are applied to the solutions obtained using EAs to verify optimality. It is found that the obtained results are satisfying the KKT conditions and confirm the optimality. Also, the effectiveness of KKT error based stopping criterion is demonstrated.

1. Introduction

Economic dispatch (ED) is an important optimization task in power system operation for allocating generation to the committed units. Its objective is to minimize the total generation cost of units, while satisfying the various physical constraints in a single area. The generator units can be divided into several generation areas interconnected by tie-lines. The MAED determines the amount of power that can be economically generated in one area and transferred to another area. The objective of MAED is to achieve the most economical generation policy that could supply the local demands without violating tie-line capacity constraints.

The economic dispatch problem is frequently solved without accounting for transmission constraints. However, some researchers have taken transmission capacity constraints into account. Shoults et al. [1] considered import and export constraints between areas, and the economic dispatch problem was also carefully addressed. This study provides a complete formulation of multi-area generation scheduling, and was a framework for multi-area studies. Romano et al. [2] presented the Dantzig–Wolfe decomposition principle to the constrained economic dispatch of multi-area systems. Doty and McEntire [3] solved a multi-area economic dispatch problem by using spatial dynamic programming and the result obtained was a global optimum. In this paper, the authors considered transmission constraints with linear losses. Desell et al. [4] proposed an application of linear programming to transmission constrained production cost analysis. Multi-area economic dispatch with area control error was solved in Ref. [5] and the heuristic multi-area unit commitment with economic dispatch was solved in Ref. [6]. Wang and Shahidehpour [7] proposed a decomposition approach for solving multi-area generation scheduling with tie-line constraints using expert systems. They showed the efficiency of their approach by testing it on a four area system with each area consisting of 26 units. The same authors reported a decomposition and coordination method for short term generation scheduling of large-scale hydro-thermal power systems in Ref. [8]. Network flow models for solving the multi-area economic dispatch problem with transmission constraints have been presented by Streiffert [9]. An algorithm for multi-area economic dispatch and calculation of short range margin cost based prices has been proposed by Wernerus and Soder [10], where the multi-area economic dispatch problem was solved via Newton–Raphson's method. The direct search method for solving economic dispatch problem considering transmission capacity constraints was presented in Ref. [11]. Yalcinoz and Short [12] solved multi-area economic dispatch problems by using Hopfield neural network approach. Jayabarathi et al. [13] solved multi-area economic dispatch problems with tie-line constraints using evolutionary programming.

Additionally, the generating units supplied with multi-fuel sources (coal, nature gas, or oil), have the problem of selection of the most economic fuel to burn [14,15]. In all the previous works

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reported in literature for solving MAED problem, none of the studies consider both the multi-area and multi-fuel options. Recently, Covariance Matrix Adapted Evolution Strategy (CMAES) algorithm with the ability of learning of correlations between parameters and the use of the correlations to accelerate the convergence of the algorithm has been proposed to solve non-linear, multi-modal optimization problems. Owing to the learning process, the CMAES algorithm performs the search independent of the coordinate system, reliably adapts topologies of arbitrary functions, and significantly improves convergence rate especially on non-separable and/or badly scaled objective functions. CMAES algorithm has been successfully applied in varieties of engineering optimization problems [16]. This algorithm outperforms all other similar classes of learning algorithms on the benchmark multimodal functions [17].

The purpose of this paper is to apply various EAs such as RGA, PSO, DE and CMAES to MAED problem with multi-fuel options and verify the optimality. Deb et al. [18] proposed a verification method based on KKT conditions in order to validate the solutions obtained by EAs. To verify the optimality, KKT conditions are applied to the results obtained using PSO algorithm. Also, the performance of KKT error based stopping criterion is discussed.

The performance of EAs is tested on the following three cases of MAED problems with respect to the solution quality, consistency and computation time.

Case 1: 4-unit system with two areas
Case 2: 10-unit system including multi-fuel options with three areas
Case 3: 120-unit large scale system with two areas

The results are compared with the results of direct search method (DSM) and Hopfield neural network (HNN), evolutionary programming (EP) and Nelder–Mead simplex (NMS) method. To verify the optimality, KKT conditions are applied to the results obtained using PSO algorithm. Also, the performance of KKT error based stopping criterion is discussed.

2. Problem formulation

The objective of MAED is to determine the generation levels and the interchange power between areas which minimize fuel costs in all areas while satisfying power balance and generating limit constraint. The objective of the MAED problem with multi-fuel options is to determine the amount of power that can be economically generated in one area and transferred to another area and to determine economic fuel for each unit. The piecewise quadratic function for this problem is represented in Eq. (1) as,

$$\begin{aligned} C(P_{mn}) &= a_{mnk}P_{mn}^2 + b_{mnk}P_{mn} + c_{mnk}; \quad k = F_1 \quad \text{if} \quad P_{mn(\min)} \leqslant P_{mn} \leqslant P_{L1} \\ &= a_{mnk}P_{mn}^2 + b_{mnk}P_{mn} + c_{mnk}; \quad k = F_2 \quad \text{if} \quad P_{L1} < P_{mn} \leqslant P_{L2} \\ &= a_{mnk}P_{mn}^2 + b_{mnk}P_{mn} + c_{mnk}; \quad k = F_3 \quad \text{if} \quad P_{L2} < P_{mn} \leqslant P_{mn(\max)} \end{aligned} \tag{1}$$

where a, b, c are the cost coefficients; $m = 1, 2,\ldots, M$ (areas); $n = 1, 2,\ldots, N$ (generating units); $k = 1, 2,\ldots, K_n$ (fuels).

If an area with excess power is not adjacent to a power deficient area, or the tie-line between the two areas is at transmission limit, it is necessary to find an alternative path between these two areas in order to transmit additional power. Taking into consideration the cost of transmission though each tie-line, the objective function of multi-area economic dispatch with multi-fuel options problem is given in Eq. (2).

$$\text{Minimize } C = \sum_{m=1}^{M} C_m + \sum_{J=1}^{M-1}\sum_{K=J+1}^{M} f_{JK}T_{JK} \tag{2}$$

where $C_m = \sum_{n=1}^{N} C(P_{mn})$, T_{JK} is the tie-line flow from area J to area K, and f_{JK} is the cost coefficient associated with tie-line flow T_{JK}. N is the number of units in mth area. The objective function is minimized subjected to the following constraints:

(i) Area power balance constraints

The power balance equation without considering losses of the system is given in Eq. (3).

$$\sum_{n=1}^{N} P_{mn} = D_m + \sum\nolimits_{k \neq m}^{k=1} T_{mk} \quad \text{for } m = 1, 2, \ldots, M \tag{3}$$

where D_m is the load demand in area m.

(ii) Generating limit constraint

The MW output of a unit must be allocated within the range bounded by its lower and upper limits of real power generation as given in Eq. (4).

$$P_{mn(\min)} \leqslant P_{mn} \leqslant P_{mn(\max)} \quad n = 1, 2, 3 \ldots, N \tag{4}$$

where $P_{mn(\min)}$ and $P_{mn(\max)}$ are the minimum and maximum power outputs of the nth unit in mth area.

(iii) Tie-line limits constraint

The tie-line power transfer from area J to area K should be between limits of minimum and maximum capacity.

$$T_{JK(\min)} \leqslant T_{JK} \leqslant T_{JK(\max)} \tag{5}$$

where $T_{JK(\min)}$ and $T_{JK(\max)}$ are the minimum and maximum tie-line power flow from area J to area K.

2.1. Representation of solution

The initial population comprises a combination of only the candidate dispatch solutions and tie-line flows which satisfy all the constraints. Elements of an individual parent are:

a. Power outputs of the generating units, randomly chosen over the range $[P_{mn(\min)}, P_{mn(\max)}]$ and
b. Tie-line flows, randomly selected over the range $[T_{JK(\min)}, T_{JK(\max)}]$. This range covers the minimum and maximum flow in either direction.

$$T_{JK} = \begin{cases} \text{positive when line flows from } J \text{ to } K \\ \text{negative when line flows from } K \text{ to } J \end{cases} \tag{6}$$

The number of elements in a parent is equal to N on-line generating units in M areas, plus the total tie-lines interconnecting M areas.

Each individual of population represents a candidate of the generation scheduling solution. They can be represented as array of vectors as Eq. (7).

$$\begin{aligned} p_i = [&(P_{11}, P_{12}, \ldots P_{1N_1}), (P_{21}, P_{22}, \ldots P_{2N_2}), \ldots\ldots (P_{M1}, P_{M2}, \ldots P_{MN}), \\ &(T_{12}, T_{13}, \ldots T_{1M}), (T_{23}, T_{24}, \ldots T_{2M}), \ldots\ldots T_{M-1,M}] \end{aligned} \tag{7}$$

where $i = 1, 2, \ldots, I$ (population number). For example, an individual for three area systems with three tie-lines is represented as follows:

$$p_i = [P_{11}\ P_{12}\ P_{13}\ P_{14}\ P_{21}\ P_{22}\ P_{23}\ P_{31}\ P_{32}\ P_{33}\ T_{12}\ T_{13}\ T_{23}]$$