Electrical Power and Energy Systems 104 (2019) 880–897

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Deterministic approach for solving multi-objective non-smooth Environmental and Economic dispatch problem

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ARTICLE INFO

Keywords:
Economic/environmental dispatch
Multi-objective programming
Modified logarithmic barrier function
Interior/exterior-point
Smoothing functions methods

ABSTRACT

The Environmental and Economic Dispatch Problem with Valve-Point loading effect representation (EEDP-VP) is a multi-objective, nonconvex and non-differentiable optimization problem. Due to these difficulties, it has been solved in the literature mainly by heuristic approaches, while deterministic approaches are scarce. Therefore, the main objectives of this paper are to propose a deterministic approach for solving this problem and compare its solutions with the ones obtained by some heuristic and deterministic approaches. The deterministic approach proposed has the following features: the multi-objective nature of the problem is handled by the Progressive Bounded Constraints (PBC) strategy, while the modified logarithmic barrier function method is used to solve the subproblems resulting from the PBC strategy; a smoothing technique is used to handle non-differentiability issues, while the inertia correction strategy is used so that only descent directions are generated. The methodology is applied to five generation systems and the results show that the Pareto-curve is obtained more efficiently when compared to other heuristic and deterministic optimization approaches.

1. Introduction

The multi-objective economic and environmental dispatch problem (EEDP) is concerned with the minimization of generation costs and the emission of pollutants while representing systems operational constraints. When valve-point loading effect (VPLE) is introduced in the generation costs, EEDP results in an Environmental and Economic dispatch problem with valve-point loading effect (EEDP-VP). The EEDP-VP is a multi-objective, nonlinear, and non-differentiable problem, which poses some difficulties for deterministic optimization techniques.

Due to such difficulties, the multi-objective EEDP-VP problem has been traditionally solved in the literature only by Heuristic Optimization (HO) methods, which are inherently able to handle such difficulties. Numerous HO methods have been proposed for solving the problem, such as: non-dominated sorting genetic algorithm (NSGA-II), Pareto-niched genetic algorithms and strength-Pareto evolutionary algorithms [2], differential evolution algorithms [4,3], quasi-oppositional teaching learning based optimization [36], multi-objective adaptive clonal selection algorithm [34], flower pollination algorithm [1], a combination of Continuous Greedy Randomized Adaptive Search Procedure (c-GRASP) algorithm and differential evolution [26]; a combination of ant colony, artificial bee colony and harmonic search [38]; tribe-modified differential evolution [27]; gravitational acceleration enhanced particle swarm [20]; kinetic gas molecule optimization [7]; fuzzified multi-objective iterative honey-bee mating optimization [15]; bat algorithms [22], exchange market algorithms [32]; modified particle swarm optimization [6], backtracking-search optimization [9], real coded chemical reaction algorithm [8], teaching learning based optimization [33] and many others.

All such HO methods share a common feature: they do not rely on the calculation of derivatives (gradient vectors or Jacobian/Hessian matrices). Therefore, issues such as non-convexity and non-differentiability do not pose any additional difficulty for such approaches. On the other hand, deterministic approaches need to iteratively calculate the derivatives of the functions involved in the optimization problem, which is not directly possible for the multi-objective EEDP-VP problem. This is probably the main reason why no deterministic approach has been previously proposed for solving the problem. The only works describing a deterministic approach for solving this problems are given in [39,37]. In [39] the authors use a predictor-corrector primal-dual

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https://doi.org/10.1016/j.ijepes.2018.07.056
Received 15 June 2017; Received in revised form 14 June 2018; Accepted 24 July 2018
0142-0615/

interior-point method for solving the problem, but disregarding VPLE. In [37] a deterministic solution framework is described which is similar to the one adopted in this paper. However, alternative optimization approaches are used here in each phase of the solution framework as further discussed.

Despite the numerous applications of HO methods for solving the EEDP-VP problem, these methods have some potential drawbacks when compared to deterministic approaches. Since HO methods generally operate over populations of solution candidates and depend on the evolution of these populations over a large number of generations, they generally demand higher computation times. Another drawback of HO methods is their inability to iteratively verify optimality of their solution candidates, which would involve evaluating the Karush–Kuhn–Tucker (KKT) conditions for each candidate. On the other hand, deterministic approaches generally operate over a single solution candidate, therefore, they tend to be potentially faster for solving most optimization problems. Another advantage of deterministic approaches is their robustness for obtaining the solution under previously established assumptions and their ability to evaluate iteratively the optimality of their solution candidates. However, deterministic approaches are generally designed to perform local search only. Therefore, their iterative solution candidates may become trapped in local optimal solutions when solving multi-modal optimization problems.

The numerical advantages and disadvantages of deterministic and heuristic optimization methods for solving the multi-objective EEDP-VP problem have not yet been put into perspective in the literature. Therefore, the main objectives of this paper are twofold: i) propose a deterministic solution methodology for solving the multi-objective EEDP-VP problem and ii) compare the solutions obtained by the proposed deterministic approach with the ones obtained by an HO method. For multi-objective problems this comparison is performed by comparing qualitatively and quantitatively the Pareto curves obtained by the methods. For a quantitative comparison, we propose the utilization of a hypervolume metric, which is further detailed in the paper.

The deterministic solution methodology proposed for solving the EEDP-VP problem involves three main aspects: i) the handling of the multi-objective nature of EEDP-VP problem, which, for *a posteriori* methods (methods for generating the optimal Pareto curve), generally involves converting such problems into a set of single-objective subproblems; ii) the handling of non-differentiability of the objective functions in the single-objective subproblems by using a smoothing technique, which results in a set of smoothed single-objective subproblems; iii) the solution of the smoothed single-objective subproblems using a nonlinear optimization method that is able to avoid multiple local maxima and find only minima. Each one of these aspects required the choice for specific optimization techniques which are discussed below.

Two *a posteriori* strategies are generally used for handling the multi-objective nature of the EEDP-VP problem: the weighted sum strategy and the ε-constraint strategy [25]. Both of them may fail to obtain Pareto curves for nonconvex problems [12,25]. In general, the weighted-sum strategy is ineffective for finding points in the non-convex parts of the Pareto-set, while the ε-constraint strategy tends to obtain many inefficient solutions. For the EEDP-VP problem, both weighted-sum and ε-constraint strategies tend to produce poorly spaced points in the Pareto curve. In [19], the authors propose the orthogonal ε-constraint (OEC) strategy, which introduces additional constraints that enforce upper and lower bounds for both objective functions in the single-objective subproblems. These constraints reduce the objective-space to a smaller subregion defined by the upper and lower bounds (band constraints) for the objective functions involved, aiming at reducing the spacing of the points in the Pareto curves. In this paper we adopt a variation of the approach proposed in [19] in which additional bands are defined only for one of the objective functions: the emission function. We named it after Progressive Bounded Constraints (PBC) strategy, since the single-objective subproblems associated with the bands are progressively solved using the solution of the previous band as a warm-start. We proposed the PBC strategy because adding band constraints also for cost functions would introduce non-differentiability in the feasible set, resulting in a very difficult problem to be solved by a deterministic approach.

The handling of non-differentiability generally involves the definition of a smoothing function, which is a parameterized function $\vartheta(x, \eta)$ that tends toward the original non-differentiable function when $\eta \to 0$. We adopted a Hyperbolic Smoothing (HS) function for smoothing the absolute value function in the single-objective subproblems. Numerical results associated with this function have shown efficient approximation to the absolute value function. However, any other good smoothing function could be used in the solution methodology proposed. In [37], an arctangent function is also successfully used for such a purpose. The authors in [37] compare the solution of hyperbolic and arctangent functions in terms of their capability to represent the original absolute value function in the solution points of the methods. An interesting feature of the arctangent function is its exact representation in the origin, while the hyperbolic function tends infinitely to this point but never reaches it exactly.

The solution of the smoothed single-objective subproblems could be performed by various nonlinear optimization methods. Since the solution of a single-objective subproblem tends to become an infeasible warm start to the next subproblem, it is important for the solution method to be capable of working over both interior and exterior points of the feasible region of the subproblems. Therefore, we opted for the modified logarithmic barrier function method, which is able to work both in the interior and exterior portions of the feasible region, and is a state-of-the-art method for nonlinear programming. Another important feature of the single-objective subproblems is multi-modality, since these problems tend to present various maxima and minima. Therefore, their solution approach must be adapted to avoid local maxima and search for minima, only. In order to cope with this issue, we propose a variation of the modified logarithmic barrier function method by introducing a global convergence strategy based on the inertia correction strategy described in [40]. The resulting method is called Modified Logarithmic Barrier function method with Inertia Correction (MLBIC).

Therefore, the deterministic approach proposed for solving the multi-objective EEDP-VP problem integrates the following methods: the Progressive Bounded Constraints (PBC) strategy for handling the multi-objective nature of the problem, the hyperbolic smoothing (HS) strategy for handling non-differentiability in the objective function, and the modified logarithmic barrier function method with inertia correction (MLBIC) for solving the subproblems generated by the PBC. We use the acronym PBC-HS-MLBIC to identify the approach hereinafter. In order to put deterministic and heuristic approaches into perspective for solving the EEDP-VP problem, we compare the Pareto curves obtained by the PBC-HS-MLBIC approach with the ones obtained by the heuristic NSGA-II. Results have shown that the proposed approach has solved the EEDP-VP problem in a faster and more accurate fashion when compared to the heuristic approach tested. We also evaluate the solutions calculated by the MLBIC method for the single-objective subproblems by comparing their solutions with the ones obtained by the solvers COUENNE, IPOPT, KNITRO, which are available at the GAMS platform [14].

Various formulations have been proposed in the literature for multi-objective dispatch problems which aims at representing enhanced modeling aspects of generation systems. The classical EEDP-VP formulation is concerned with the minimization of both fuel and environmental costs while enforcing demand supply as well as upper and lower bounds for power outputs. However, the classical formulation has been continuously improved to introduce new modeling aspects. In [1–3], transmission network losses are represented by means of quadratic approximation. In [15,32] the transmission network is explicitly represented by means of load flow equations. In [6,7,20,22] prohibited operating zones related to the power outputs are included. In [22]