

Recent advances in solving economic dispatch problem using soft computing techniques – A review

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Abstract - In the modern world, electrical power plays a vital role in our life style. The development of various technology requires electricity which in turn increases the capacity and number of power generating stations. Since an engineer is always concerned with the cost of products and services, the efficient optimum economic operation and planning of electric power generation have always occupied an important position in the electric power industry. A saving in the operation of the system of a small percent represents a significant reduction in operating cost as well as in the quantities of fuel consumed. Among the different issues, in power system operation, economic dispatch plays major part. Economic dispatch (ED) is the process of allocating generation levels to the generating units in the mix, so that the system load may be supplied most economically. In the recent past, several soft computing has been developed to solve the issues in power generation industry. In this work, a review is made on solving economic dispatch problem using various soft computing techniques. Also four systems (6 unit, 13 unit, 20 unit and 20 unit) were taken for comparison of the results of various techniques.

Key Words: Economic dispatch, Soft computing techniques, Power, generation, Fuel cost

1. INTRODUCTION

Economic dispatch (ED) is an important optimization task in power system operation for allocating generation among the committed units such that the constraints imposed are satisfied and the energy requirements in terms of dollar per hour (\$/hr) are minimized. Improvements in scheduling the unit outputs can lead to significant cost savings. Traditional dispatch algorithms employ Lagrangian multipliers and require monotonically increasing incremental cost curves. The input-output characteristics of modern units are inherently highly nonlinear because of valve point loadings, ramp-rate limits, etc., and furthermore they may generate multiple local minimum points in the cost function. Classical dispatch algorithms require that these characteristics be approximated; however, such approximations are not desirable as they may lead to suboptimal operation and hence huge revenue loss over time [1]. In this work various soft computing techniques employed for solving the ED problems are compared.

2. PROBLEM FORMULATION

2.1 Objective Function

The objective of ED is the minimization of thermal unit fuel cost function and is:

$$\min F = \sum_{i=1}^{N_g} F_i(P_i) = \sum_{i=1}^{N_g} (a_i P_i^2 + b_i P_i + c_i)$$

where N_g is the total number of generating units in the system; $F_i(P_i)$ is the fuel cost of i^{th} generating unit in \$/hr; P_i is the power generated by the i^{th} generating unit in MW; a_i, b_i, c_i are the fuel cost coefficients of i^{th} generator

2.2 Economic Dispatch with Valve Point Effect

The real input - output cost curves for the generator units are non convex because of the valve point effect. Therefore objective function can be written as,

$$\min F = \sum_{i=1}^{N_g} F_i(P_i) = \sum_{j=1}^{N_g} (a_i P_i^2 + b_i P_i + c_i) + |e_i \sin(f_i (P_i^{\min} - P_i))|$$

where e_i and f_i are the fuel cost coefficients of valve point effect of generators

2.3 Constraints

For ED problem, real power balance criterion and real power generation limits are the equality and inequality constraints. They are represented by

$$\sum_{i=1}^{N_g} P_i = P_D + P_L$$

$$P_i^{\min} \leq P_i \leq P_i^{\max}$$

Where P_i is the generation of i^{th} generating unit in MW; P_D is the total power demand in MW; P_i^{\min} and P_i^{\max} are the minimum and maximum power generation limits of i^{th} generator; P_L is the total transmission losses in MW.

The Kron's formula (B-coefficients) is used to calculate the transmission loss:

$$P_L = \sum_{i=1}^{N_g} \sum_{j=1}^{N_g} P_i B_{ij} P_j + \sum_{j=1}^{N_g} B_{oj} P_j + B_{oo}$$

Where P_i and P_j are the real power injection at i^{th} and j^{th} generator respectively; B_{ij} is the loss coefficients which can be assumed to be constant under normal operating conditions.

2.4 Economic Dispatch with Consideration of Prohibited Operating Zones (POZ)

The prohibited zones are formed due to the vibrations in the shaft bearings and/or steam valve operation. The operating zones of unit i is:

$$P_i \in \begin{cases} P_i^{\min} \leq P_i \leq P_{i,1}^l \\ P_{i,k-1}^u \leq P_i \leq P_{i,k}^l, & k=2,3,\dots,n \\ P_{i,n_i}^u \leq P_i \leq P_i^{\max} \end{cases}$$

where n_i is the number of prohibited zones of unit j . k is the index of prohibited zones of a unit i . l and u denote the lower bound and upper bound of the prohibited zone of the generator.

2.5 Economic Dispatch with Considerations of Ramp Rate Limits

The physical limitations of starting up and shutting down of generators impose ramp rate limits. The increase and decrease in generation is limited by:

$$P_i - P_i^0 \leq UR_i$$

$$P_i^0 - P_i \leq DR_i$$

where P_i^0 - Previous output power of the i^{th} thermal generating unit in MW; UR_i , DR_i - Upper ramp and down ramp limit respectively of i^{th} generator

Combining the equations,

$$\min F = \sum_{i=1}^{N_g} F_i(P_i) = \sum_{j=1}^{N_g} (a_j P_j^2 + b_j P_j + c_j) + |e_j \sin(f_j (P_j^{\min} - P_j))|$$

$$\text{Subject to } \sum_{i=1}^{N_g} P_i = P_D + P_L$$

$$\max(P_i^{\min}, P_i^0 - DR_i) \leq P_i \leq P_{i,1}^l$$

$$P_{i,k-1}^u \leq P_i \leq P_{i,k}^l, \quad k = 2, 3, \dots, n_i,$$

$$i = 1, 2, 3, \dots, N_g$$

$$P_{i,n_i}^u \leq P_i \leq \min(P_i^{\max}, P_i^0 + UR_i)$$

3. LITERATURES IN ECONOMIC DISPATCH PROBLEMS

Su and Lin [2] developed Hopfield model based approach for solving ED problem by defining an energy function composing power mismatch, total fuel cost and the transmission line losses. The weighting factors associated with the terms of the energy function can be either appropriately selected or directly estimated in the proposed model. To minimize the value of the energy function, the computational procedures including a series of adjusting the weighting factor associated with the transmission line losses and updating the unit generations and power losses are carried out. Because the weighting factors are governed by some relationships developed, adjustment of the weighting

factor is much simpler and more effective in steadily achieving solutions than adjustment of the multiplier in the lambda-iteration method for ED problems. In 2003, Sinha *et al* [1] made various modifications to the basic evolutionary method with a view to enhance speed and robustness for solving ED problem. The modifications to the basic technique were proposed, where adaptation is based on scaled cost and then, evolutionary programs were developed with adaptation based on an empirical learning rate. Absolute, as well as relative, performance of the algorithms are investigated on ED problems of different size and complexity having non-convex cost curves where conventional gradient-based methods are inapplicable.

In 2003, Gaing [3] proposed a particle swarm optimization (PSO) method for solving the non-convex ED problem. The feasibility of the method is demonstrated for three different systems, and it is compared with the GA method in terms of the solution quality and computation efficiency. The experimental results show that the proposed PSO method was indeed capable of obtaining higher quality solutions efficiently in ED problems. A new particle swarm optimization (NPSO), was proposed to solve non-convex economic dispatch (NCED) problems [4]. In NPSO, a split-up in the cognitive behaviour is proposed. That is, the particle is made to remember its worst position also. This modification helps to explore the search space very effectively. In order to well exploit the promising solution region, a simple local random search (LRS) procedure is integrated with NPSO. The resultant NPSO-LRS algorithm is very effective in solving the NCED problems. To validate the proposed NPSO-LRS method, it is applied to three test systems having non-convex solution spaces and better results were obtained when compared with previous approaches. Wang *et al* [5] presented a novel stochastic optimisation approach to find the feasible optimal solution of the ED problem considering various generator constraints. The proposed optimisation algorithm is called self-tuning hybrid differential evolution (SHDE). The self-tuning HDE utilises the concept of the 1/5 success rule of evolution strategies (ESS) in the original HDE to accelerate the search for the global optimum. Numerical results indicate that the entire performance of the proposed self-tuning HDE algorithm outperforms the other algorithms.

An efficient hybrid genetic algorithm (HGA) approach for solving the ED problem with valve-point effect is presented [6]. The proposed method combines the GA algorithm with the differential evolution (DE) and sequential quadratic programming (SQP) technique to improve the performance of the algorithm. GA is the main optimizer, while the DE and SQP are used to fine tune in the solution of the GA run. To improve the performance of the SQP, the cost function of EDP is approximated by using a smooth and differentiable function based on the maximum entropy principle. An initial population obtained by using uniform design exerts optimal performance of the proposed hybrid algorithm. The combined algorithm is validated for two test systems

consisting of 13 and 40 thermal units whose incremental fuel cost function takes into account the valve-point loading effects. In 2008, Pothiya *et al* [7] developed an optimization technique based on a multiple tabu search algorithm (MTS) to solve the ED problem with generator constraints. The MTS algorithm introduces additional mechanisms such as initialization, adaptive searches, multiple searches, crossover and restarting process. To show its efficiency, the MTS algorithm is applied to solve ED problems of power systems with 6 and 15 units. The results obtained from the MTS algorithm are compared to those achieved from the conventional approaches. The experimental results show that the proposed MTS algorithm approach is able to obtain higher quality solutions efficiently and with less computational time than the conventional approaches.

Direct search (DS) methods are evolutionary algorithms used to solve constrained optimization problems. DS methods do not require information about the gradient of the objective function when searching for an optimum solution. One such method is a pattern search method (PSM). Sumait *et al* [8] employed a constrained PS algorithm to solve various types of power system ED problems. The effectiveness, convergence characteristics and robustness of the proposed method has been assessed and investigated through comparison with results reported in literature. The outcome is encouraging and suggests that PS methods may be very efficient when solving power system ED problems. Abdelaziz *et al* [9] studied the effect of the HNN parameters on the solution quality of the ED problem. By investigating the describing curves, the best values for the HNN parameters are tuned. To further improve the solution quality, an adaptive correction factor is introduced to the EDP solution obtained by the HNN. To investigate the effect of the modifications on the solution quality of the EDP, three case studies are selected and solved. Comparisons of results are then made with others to prove the validity and effectiveness of the proposed modifications. Balamurugan and Subramanian [10] presented an improved dynamic programming (IDP) approach to solve the economic power dispatch problem including transmission losses in power systems. They presented a detailed mathematical derivation of recursive dynamic programming approach for the economic power dispatch problem with transmission losses. The transmission losses are augmented with the objective function using price factor. The generalized expression for optimal scheduling of thermal generating units derived in this article can be implemented for the solution of the economic power dispatch problem of a large scale system. Six-unit, fifteen-unit, and forty-unit sample systems with non-linear characteristics of the generator, such as ramp-rate limits and prohibited operating zones are considered to illustrate the effectiveness of the IDP method. The IDP method results have been compared with the results of genetic algorithm and particle swarm optimization methods reported in the literature. Test results show that the

proposed IDP approach can obtain a higher quality solution with better performance.

Amjady and Nasiri Rad, [11] formulated an algorithm to solve ED problem considering more practical constraints and nonlinear characteristics than previous works in the area. To solve the non-convex ED formulation, an efficient real coded genetic algorithm (RCGA) with arithmetic average bound crossover and wavelet mutation is presented. To show the effectiveness of the solution method, it is applied to five test systems having non-convex solution spaces and compared with some of the most recently published approaches. The obtained results reveal the better performance of the RCGA. Hemamalini and Simon [12] utilized the Maclaurin series based Lagrangian method to solve complicated, non-convex and non-linear ED problems. In this method, the rectified sinusoid function is represented by Maclaurin sine series expansion and is solved using the Lagrangian method. The problem is solved iteratively using lambda iteration method. The effectiveness of the algorithm is demonstrated with 3, 13 and 40 generator test systems available in the literature. The results obtained substantiate the applicability of the proposed method for solving ED problems with non-smooth cost functions at par with stochastic search techniques generally used. Meng *et al* [13] proposed a quantum inspired particle swarm optimization (QPSO), which has stronger search ability and quicker convergence speed, not only because of the introduction of quantum computing theory, but also due to two special implementations: self-adaptive probability selection and chaotic sequences mutation. The proposed approach is tested with five standard benchmark functions and three power system cases consisting of 3, 13, and 40 thermal units. On comparisons it gives better results when compared to similar approaches.

Amjady and Sharifzadeh [14] presented solution for ED problem considering valve point loading effect by a new Modified Differential Evolution (MDE) algorithm. The proposed MDE is in the framework of differential evolution owning new mutation operator and selection mechanism inspired from GA, PSO and Simulated Annealing (SA), respectively. In other words, positive characteristics of DE, GA, PSO and SA are combined to create a new efficient stochastic search technique. In the solution of the non-convex ED by the proposed stochastic search technique, an effective constraint handling method is also presented. The proposed MDE is examined on three ED test systems and compared with some of the most recently published ED solution methods. Bhattacharya and Chattopadhyay [15] employed biogeography based optimization (BBO) algorithm to solve convex and non-convex ED problems. Biogeography deals with the geographical distribution of biological species. Mathematical models of biogeography describe how a species arises, migrates from one habitat to another and gets wiped out. BBO has some features that are in common with other biology based optimization methods, like genetic

algorithms (GAs) and particle swarm optimization (PSO). This algorithm searches for the global optimum mainly through two steps: migration and mutation. The effectiveness of the proposed algorithm has been verified on four different test systems, both small and large, involving varying degree of complexity. Compared with the other existing techniques, the proposed algorithm has been found to perform better in a number of cases. Bhattacharya and Chattopadhyay [16] presented an algorithm, biogeography based optimization (BBO), to solve both convex and non-convex ED problems of thermal generators of a power system. This algorithm searches the global optimum mainly through two steps: migration and mutation. To show the advantages of the proposed algorithm, it has been applied to four different test systems for solving ED problems. Comparing with the other existing techniques, the current proposal is found better than, or at least comparable to them considering the quality of the solution obtained.

Kumar *et al* [17] presented a multi agent based hybrid particle swarm optimization technique (HMAPSO) for ED problem. The earlier PSO suffers from tuning of variables, randomness and uniqueness of solution. The algorithm integrates the deterministic search, the Multi-agent system (MAS), the particle swarm optimization (PSO) algorithm and the bee decision-making process. Thus making use of deterministic search, multi-agent and bee PSO, the HMAPSO realizes the purpose of optimization. To test the capability of the proposed algorithm, it is applied to two cases 13 and 40 generators, respectively. The results show that this algorithm is more accurate and robust in finding the global optimum than its counterparts. Niknam *et al* [18] developed a hybrid method to solve the ED problem with valve point loading effect by integrating the variable DE with the fuzzy adaptive PSO called FAPSO-VDE. DE is the main optimizer and the PSO is used to maintain the population diversity and prevent leading to misleading local optima for every improvement in the solution of the DE run. The parameters of proposed hybrid algorithm such as inertia weight, mutation and crossover factors are adaptively adjusted. The feasibility and effectiveness of the proposed hybrid algorithm is demonstrated for two case studies and results are compared with those of other methods. It is shown that FAPSO-VDE has high quality solution, superior convergence characteristics and shorter computation time. Moradi Dalvand *et al* [19] applied an optimization algorithm for the solution of non-convex and large scale ED problems. A continuous version of quick group search optimizer (QGSO) algorithm is proposed. A more realistic ED formulation with considering valve points effect, prohibited operating zones, transmission losses and ramp-rate limits is utilized. The performance of the proposed method is verified by implementation on five test systems. Case studies and numerical examples show that the proposed continuous QGSO algorithm has better solution quality comparing with the most of the latest reported algorithms in the literature. Ciornei and Kyriakides [20] designed a heuristic hybrid

optimization method to solve the non-convex ED problem. Due to the fast computational capabilities of the proposed algorithm, it is envisioned that it becomes an operations tool for the generation companies. The methodology improves the overall search capability of two powerful heuristic optimization algorithms: a special class of ant colony optimization called API and a real coded genetic algorithm (RCGA). The proposed algorithm, entitled GA-API, is a relatively simple but robust algorithm, which combines the downhill behavior of API and a good spreading in the solution space of the GA search strategy. The feasibility of the proposed method is first tested on a number of well known complex test functions, as well as on four different power test systems having different sizes and complexities. The results are analyzed in terms of both quality of the solution and the computational efficiency; it is shown that the proposed GA-API algorithm is capable of obtaining highly robust, quality solutions in a reasonable computational time, compared to a number of similar algorithms proposed in the literature.

Provas Kumar Roy *et al* [21] developed an efficient optimization technique by hybridizing chemical reaction optimization (CRO) and differential evolution (DE) to solve the ED problem. To show the priority of the proposed algorithm, it is implemented on six different test systems for solving ED problems. Comparative studies are carried out to examine the effectiveness of the proposed HCRO-DE approach with conventional DE, CRO and the other algorithms. The simulation results show that the proposed HCRO-DE method is capable of obtaining better quality solutions than DE, CRO and the other well popular optimization techniques. Delshad and Rahim [22] presented backtracking search algorithm (BSA) for solving of ED problems. BSA uses a single control parameter and two crossover and mutation strategies for powerful exploration of the problem's search space. Four test systems are the case studies verifying the method's robustness and effectiveness. The results confirm that compared with existing well known methods and especially in large scale test systems, the proposed algorithm is the better approach to solving ED problems.

Subathra *et al* [23] presented a hybrid approach integrating the cross-entropy (CE) algorithm and the sequential quadratic programming (SQP) technique to solve the non-convex ED problems. CE approach is employed to constructs a random sequence of solutions probabilistically converging to a near-optimal solution and, thus, facilitating the exploration capability. Additionally, to fine tune the solution in promising basins of attraction, the SQP algorithm is invoked, which performs a local search. Despite its reliance on a global heuristic scheme, CE-SQP is vested with fast convergence capability, which may entail its use for online power dispatch. Elsayed and El-Saadany [24] proposed a new decentralized approach for solving the ED problem. This approach consists of either two or three stages. In the first

stage, a flooding based consensus algorithm is proposed in order to achieve consensus among the agents with respect to the units and system data. In the second stage, a suitable algorithm is used for solving the economic dispatch problem in parallel. For cases in which a nondeterministic method is used in the second stage, a third stage is applied to achieve consensus about the final solution of the problem, with a flooding based consensus algorithm for sharing the information required during this stage. The proposed approach is highly effective for solving the non-convex formulation of the economic dispatch problem and for incorporating transmission losses accurately in a fully decentralized manner. Three case studies that were examined for validation purposes are described. The results obtained demonstrate that the proposed approach aggregates many of the advantages of both centralized and fully decentralized mechanisms for solving the ED problem.

Secui [25] developed a modified artificial bee colony algorithm (MABC) to solve the ED problem. The MABC algorithm introduces a new relation to update the solutions within the search space, in order to increase the algorithm ability to avoid premature convergence and to find stable and high quality solutions. Moreover, to strengthen the MABC algorithm performance, it is endowed with a chaotic sequence generated by both a cat map and a logistic map. The MABC algorithm behavior is investigated for several combinations resulting from three generating modalities of the chaotic sequences and two selection schemes of the solutions. The performance of the MABC variants is tested on four systems. The comparison of the results shows that the MABC variants have a better performance than the classical ABC algorithm and other optimization techniques. Junpeng Zhan *et al* [26] proposed the dimensional steepest decline method (DSD) for the ED with non-smooth objectives. The fuel cost's decline rate between each two adjacent singular points is utilized to find the optimal solutions in a serial sequence. The computational complexity of the DSD is analyzed. The DSD has been applied to solve different types of ED problems on different test systems, including large-scale systems. The simulation results show that DSD can obtain more accurate solutions and consume much less time and its advantage is more obvious on large scale systems.

Four case studies (6 unit, 13 unit, 20 unit, 40 unit) were considered in this work and they were compared in terms of total fuel cost. The total cost (TC) for power demands of 1263 MW for the six generating units system using different techniques are given in Fig.1. A comparison has been made with the results obtained by various algorithms viz. PSO, GA [3], NPSO-LRS, PSO-LRS, NPSO [4], IDP [10], MTS, TS, SA [7], RCGA [11], MDE [14], GA-Binary, GA-API, LM [20], DE [24], MABC [25].

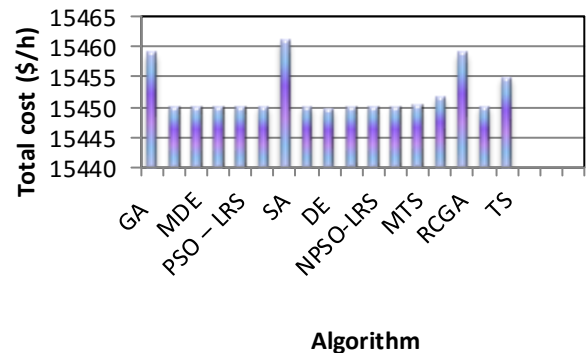


Fig.1 Comparison of Total Cost for 6 Unit Systems with Various Algorithms

Figure 2 shows comparison of the system consists of 13 generating units meeting a load demand of 1800 MW. It includes valve point loading, which has the effect of introducing several local minima [23], thereby making the cost curve multimodal. It also shows the comparison of the results of the RMO and other algorithms viz. DSD [26], CE-SQP [23], QPSO [13], HMAPSO [17], PSO-TVAC, HGA [6], FAPSO-VDE [18], SHDE [5], MSL [12], PSM [8], DE, CRO, HCRO-DE [21].

For a larger test system consisting of twenty thermal units with a load demand of 2500 MW, a comparison has been made. Transmission losses are included in this system. The Fig. 3 shows the comparison of results of the various algorithms viz. BBO [15], λ -Method, HM [2], NR, EHNN [9], GSO, CQGSO [19], BSA [22] for the best fuel cost. A forty generators supplying a demand of 10,500 MW, which includes valve point loading effects, due to which a number of local minima are introduced, thereby making the problem more complex. The results are compared with recently reported efficient techniques like QPSO [13], HGA [6], FAPSO-VDE [18], BBO [15], DE/BBO [16], DE, CRO, HCRO-DE [21], CE-SQP [23], BSA [22]. The comparison of the results is shown in Fig.4.

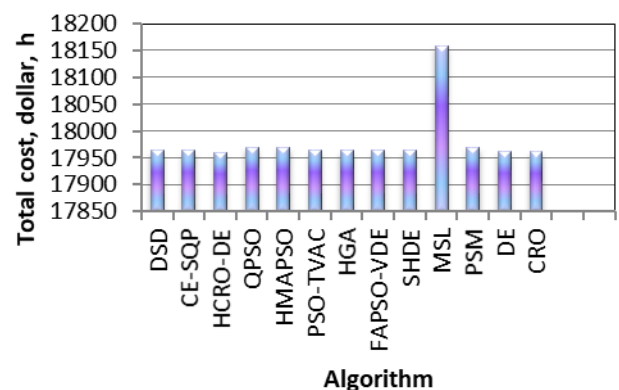


Fig.2. Comparison of Total Cost for 13 Unit System with Various Algorithms

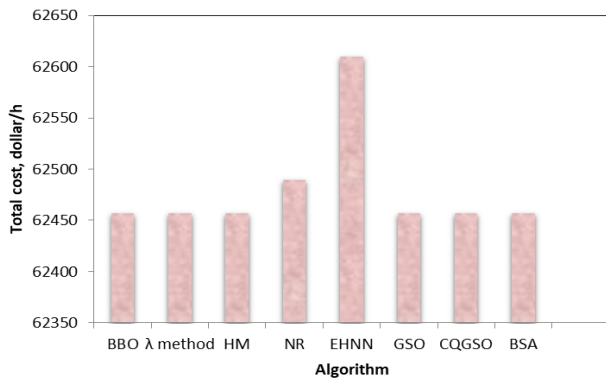


Fig.3. Comparison of Total Cost for 20 Unit System with Various Algorithms

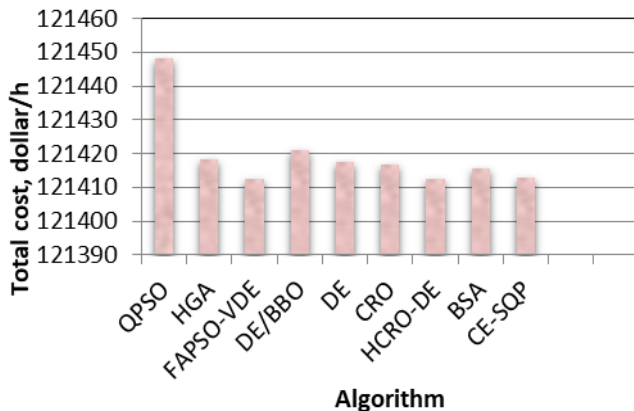


Fig.4. Comparison of Total Cost for 40 Unit System with Various Algorithms

4. CONCLUSION

In this work, the solution of different types of ED problems on different test systems, including large scale systems has been reviewed. Unlike the traditional algorithms and dynamic programming, the stochastic algorithms may prove to be very effective in solving nonlinear ED problems without any restrictions on the shape of the cost curves.

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