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A Comprehensive Review on Optimization Strategies for Combined Economic Emission Dispatch Problem

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***Abstract* - Power generation system largely depends on fossil fuels to generate electricity. Due to various reasons, the reserves of fossil fuels are declining and will become too expensive in near future. At the same time, generation of power from fossil fuels causes hazardous gases and particulates to emit, which pollutes the air and causes significant and long term damages on the environment. For this reason, extensive research works have been conducted for last few decades from different perspectives to reduce both the fuel cost as well as the emission of hazardous gases in power generation system. This power generation problem is commonly referred to as the combined economic emission dispatch (CEED) problem. This paper provides a comprehensive review on the uses of different optimization techniques to solve CEED problem. Authors have found advanced nature-inspired methods as the most suitable and successful, and have concluded combinational hybrid methods as the most prospective methods to solve CEED problem.**
***Keywords:* Combined economic emission dispatch; Economic dispatch; Emission dispatch; Optimization strategy**

I. INTRODUCTION

Electrical power generation system largely depends on fossil fuel powered thermal plants to generate electricity. The consumption of fossil fuels in the electrical power generation systems must be controlled and minimized. Fossil fuel reserves available in the nature are very much limited [1] and not always easily accessible to all as fuel reserves are concentrated into a small number of countries and those countries may influence or restrict the supply of fossil fuels. Environmental pollution due to the emission of large amount of pollutant gas-particulates is another fact that motivates researchers to work on minimizing the use of fossil fuel in the thermal plants during the process of electricity generation. Although various alter-natives including hydroelectric power generation, nuclear power generation and recent renewable energy technology have been developed and implemented to produce electricity, fossil fuel still remains to be the mostly used [2] ingredient to generate electricity. Thus, the major problems of using fossil fuel in power generation systems are to find an optimal solution to minimize both the use of fuel (fuel cost) and emission of hazardous gases simultaneously. Economic dispatch (ED) deals with the minimization of fuel cost by considering optimal power generation in each power generating unit of the power generation system, while emission dispatch deals with the minimization of the emission of hazardous gases and particulates from the system. Both the objectives are conflicting in nature and cannot be optimized simultaneously. This conflicting behavior of these objectives gives rise to a complex multi objective optimization [3] problem known as combined economic emission dispatch (CEED) problem, where both the objectives are considered and optimize simultaneously.

Over the past decades, many optimization methods have been used to solve CEED problem. These methods can be classified into three categories: (i) conventional methods, (ii) non-conventional methods and (iii) hybrid Methods as depicted in Fig. 1. Previously mathematical programming based conventional methods such as Lagrange relaxation [4, 5], lambda iteration [6, 7], Newton-Raphson [8], interior point method [9], weighted mini-max [10] and quadratic programming [11] had been used to solve ED and CEED problems. Classical methods have some advantages like they don't have any problem-specific parameters to specify [12], their optimality is mathematically proven [13] and some of them are computationally fast [14]. They have some major disadvantages like they can immaturely converge into local optimum, sensitivity to the initial starting points, many of the them are not applicable to some types of cost function i.e. non-smooth, non-convex, non-monotonically increasing cost functions etc. [15,16].

Artificial intelligence-based non-conventional methods have been frequently used to solve CEED problems which include artificial intelligence (AI) based artificial neural network (ANN) [17] and computational intelligence [18] (CI) based methods like genetic algorithm [19], particle swarm optimization (PSO) [20], harmony search (HS) [21], simulated annealing (SA) [22], differential evolution (DE) [23], gravitational search algorithm (GSA) [24], biogeography based optimization (BBO) [25] and some nature inspired advanced CI methods like bacterial foraging algorithm (BFA) [25], ant colony optimization (ACO) [26], cuckoo search (CS) [27], bat algorithm (BA) [28], artificial bee colony (ABC) [29], firefly algorithm (FFA) [30], flower pollination algorithm (FPA) [31] etc. These advanced optimization methods play a pivotal role in alleviating the problems found in the classical approaches in solving CEED problem, for example, they can enable us to solve nonlinear and non-convex cost functions and can achieve nearly global/global solutions. However, some of these methods are suffer from many problems specific parameter selections and high computational time.

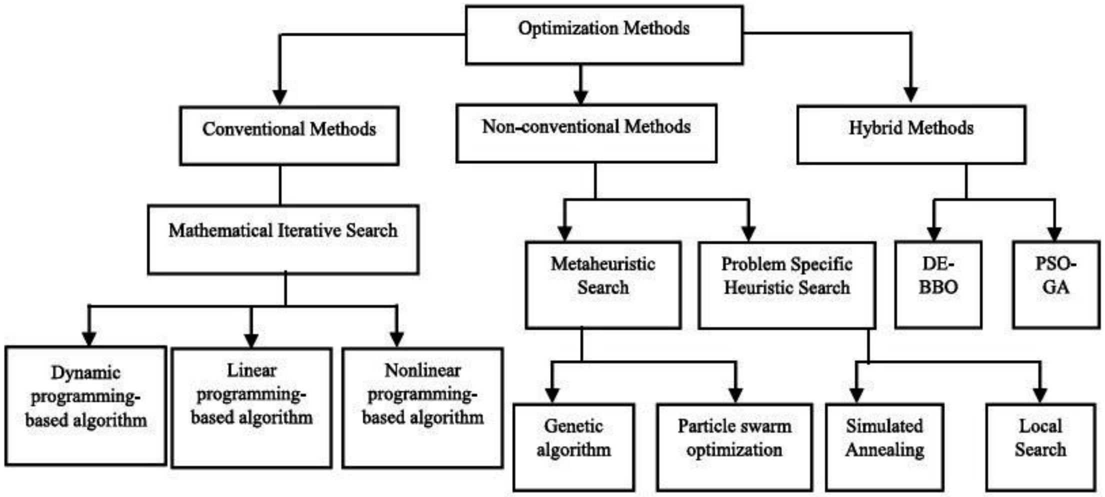

Fig. 1 Different optimization methods and their subsections.

In order to combine the best features of different algorithm and thereby achieve superior performance than the stand-alone methods researchers have developed many hybrid methods [32–35] by combining two or more algorithms to solve CEED problems. Sometimes researchers integrate classical method with non-conventional method to solve CEED problems [36] and in some cases two or more non-conventional methods are combined to create hybrid algorithm to solve CEED problems [37]. But, hybrid algorithm usually suffers from long computational time as two or more algorithms operate (either in parallel) to solve CEED problem, where each of the algorithms perform individually into the problem.

The paper is organized as follows: (ii) CEED formulation section describe different aspects and form of functions to define CEED problems with many practical equal and unequal constraints. (iii) Non-conventional algorithms section reviews some of the most renowned algorithms (iv) Hybrid methods section elaborates the hybrid algorithms used for CEED problems with their pros and cons. (v) Fuzzy compromised solution for CEED problems section discusses about fuzzy approaches to get compromised solution from set of Pareto-optimal solution (vi) Conclusion section summarizes the paper by providing overall gist of the paper and finishing remarks.

II. PROBLEM FORMULATION

A. Economic Dispatch

In large scale power system may consists of many number of generating units, it is difficult to choose the active unit for a particular demand; this difficulty is termed as Economic Dispatch Problem which is the one of the important issue in modern cost minimization algorithms. For economic feasibility the fuel cost of base load power plants are considered as a crucial criterion. The fuel cost curves of generators are approximated as quadratic function as shown in Eq. (1). This equation consisting of sin components which represents ripples produced at valve openings due to steam admission.

$$C_t = \sum_{i=1}^{Ng} \alpha_i + \beta_i P_{Gi} + \gamma_i P_{Gi}^2 + \left|\zeta_i \sin\left[\lambda_i \left(P_{Gi}^{\min} - P_{Gi}\right)\right]\right| \quad (1)$$

where N_g represents number of generating units, α_i, β_i, γ_i, ζ_i, λ_i are the fuel cost coefficients of i_{th} generation unit, P_{Gi} is the power output of i_{th} generating unit (MW), C_t is the fuel cost in the system ($/hr).
The total cost C_t is function of active power generation of generating units as shown in Eq. (2) & (3).

$$C_t = F(P_G) \quad (2)$$

$$P_G = \left[P_{G1}, P_{G2}, P_{G3}, \ldots, P_{GNg}\right] \quad (3)$$

B. Emission Dispatch

Considering the environment conditions, the dangerous and harmful emission of pollutants produced has to be minimized. The emission function can be presented is the sum of all the types of emissions considered, with suitable weighting on each pollutant emitted. In this paper, only one type of emission (NOx) is taken into account without loss of generality [10]. The amount of NOx emission is given as a function of generator output, i.e., the sum of a quadratic and exponential function. Many possible solutions are proposed to solve this problem such as installation of cleaning equipment and change of fuels with less pollutant etc. The emission dispatch power problem is represented in Eq. (4).

$$E(P_G)=\sum_{i=1}^{ng}10^{-2}\left(a_i+b_iP_{Gi}+c_iP_{Gi}^2\right)+d_i.\exp\left(e_iP_{Gi}\right) \quad (4)$$

where E (P_G) is the total NOx emission (ton/hr), P_{Gi} is the power output of the i_{th} generator (MW), a_i, b_i, c_i, d_i and e_i are the NOx emission coefficients of i_{th} unit and N is the number of thermal units. The total emission depends on power generation.

C. Combined Economic Dispatch and Emission Dispatch Problem

The economic and emission dispatch problems are of two different criteria's. Former deals with minimizing the fuel cost of generating unit by considering the optimal power generation, while other one deals with minimization of NOx emission from the system. Therefore, to reduce the complexity of calculation above multi-objective ECED problem, it can be converted in to a single optimization problem by introducing modified price penalty factor from Eq. (5) represented as follows.

$$Min\ F(P_G)=C_t+h\times E(P_G)\ \$/\text{hr} \quad (5)$$

where h is the price penalty factor ($/ton) which is the cost incurred to reduce 1Kg of NOx emission output. This is subjected to the generating unit constraint.

The price penalty factor can be defined as the ratio between maximum fuel cost and emission of the generator which is represented in Eq. (6).

$$\text{Where } h_i=\frac{C_t\left(P_G^{max}\right)}{E\left(P_G^{max}\right)} \quad (6)$$

III. NON-CONVENTIONAL METHODS

A. Genetic algorithm (GA)

Genetic algorithm (GA), one of the most used optimization algorithms, was developed by John Holland in 1970 [38]. This algorithm was inspired by the theory adopted by some evolutionist, which stated that only strong and fit species survive in the nature. GA algorithm operates with a set of chromosomes, known as population. It is randomly initialized and then it searches for the fitter and fitter solution, and ultimately converges to a single best solution. Some well-known advantages of GA [39] are it is comparatively less susceptible to the complex problem than other non-evolutionary methods, in the presence of many parameters it can achieve solutions rapidly by dealing with multiple solutions in a single run, can explore to a number of local optima etc. GA has some termination criteria by which it decides whether to continue or terminate search.

Different versions of GA like non-dominated sorting genetic algorithm-II (NSGA-II) [40], epsilon-dominance-based genetic algorithm [41], and genetic algorithm based on similarity crossover [105] have been used to solve CEED problems. Basu *et al.*, implemented his proposed NSGA-II in 10-unit system and compared it with real coded GA (RCGA) to demonstrate its performance. Later, he claimed that NSGA-II can obtain better solution with less computational time than the classical techniques [40]. Osman et al. compared their proposed method with non-dominated sorting genetic algorithm (NSGA), Niched Pareto Genetic Algorithm (NPGA) and strength Pareto evolutionary algorithm (SPEA) to demonstrate the performance of their proposed method. These recent versions of GA showed better performance than classical GA in terms of quality solutions, avoiding local optima and computational time. Apart from these techniques some hybrid methods like lambda based hybrid genetic algorithm and tabu search integrated genetic algorithm have also been used to solve this multi-objective problem.

B. Particle swarm optimization (PSO)

Inspired by the social behavior of the animals and organism like fish schooling, herd of elephants, bird flocking etc., particle swarm optimization (PSO) technique was developed by Kennedy and Eberhart [42] in 1995. PSO provides a population-based search approach, where individuals called particles, can be deemed as bird, fly and change their position with time to find the optimum solution in a multidimensional search space [43]. These individuals or particles initialized randomly by their position and velocity at the beginning of the search and are the probable solutions of the fitness function [44-45]. Each particle iteratively evaluates the fitness of the probable solutions and adjusts its position.

PSO and its different variants are one of the most used optimization techniques to solve combined economic emission dispatch problem [46]. As per the investigations performed by the authors, Kumar *et al.*,[42] at first proposed PSO to solve combined economic emission problem. They obtained results for a test system of six generating units and compared them with conventional methods, RCGA and hybrid genetic algorithm, which showed that PSO gave better global optimal solution then the above mentioned methods. Basu et al. presented goal attainment based PSO to solve CEED problems, where fuel cost and emission are treated as competing objectives. Goal attainment method was used to convert this multi objective problem into a single objective optimization and then the problem was handled by PSO. Later, other versions of PSO like modified PSO, local search integrated PSO, quantum behaved PSO , refined PSO, fuzzy adaptive modified theta PSO, bare-bones multi-objective PSO, improved PSO, modulated PSO, enhanced PSO, gravitational enhanced PSO and self-adaptive PSO have been used to solve CEED problems. S Lu and C Sun proposed two versions of quantum behaved PSO (QPSO) in their papers, where they introduced quantum computing idea into PSO to solve CEED problems. Zhang et al. developed a new variation of PSO named bare-bones multi-objective PSO to solve CEED problems [46-52]. This algorithm has three distinctive features like it has such a particle updating strategy that does not require control parameters tuning, a mutation operator that has time variable action range which expand the search capability and a particle diversity based approach in order to update the global particle leaders. The developed method was tested with several trials on the IEEE 30-bus test system and compared with total ten multi-objective optimization algorithms including three well known versions of PSO which validated it's capability to generate excellent results with certain superior characteristics.

C. Cuckoo search algorithm (CSA)

Inspired by the brood parasitism of some cuckoo species and Levy flight behavior of some birds and insects, Yang and Deb [53-54] developed cuckoo search algorithm in 2009. It's relatively a new nature inspired efficient algorithm with few controlling parameters and successfully used in solving many global optimization problems [55]. Recent literature reveals that CSA performs better than both particle swarm optimization (PSO) and GA by providing higher success rate of finding optimal solutions [54]. The inclusion of Levy flights in global search process makes it more efficient than other algorithms that uses standard random walks [56]. Cuckoo are wonder birds, they have mysterious and aggressive reproduction strategy. Cuckoo engages the obligate brood parasitism by laying their eggs in the nests of other host birds. However, if a host bird discovers the eggs in her nest are not of her own, it will either throw these intruder's eggs away from her nest or simply abandon its nest and build a new nest elsewhere. The three idealized rules that CSA follows are: (i) each cuckoo lays only one egg in randomly chosen nest at a time, 2) the best nests that contain high quality eggs (solution) will carry over to the next generations, 3) the total number of host nests is fixed, and pa $\in [0, 1]$ is the probability that an egg laid by cuckoo will be discovered by the host bird.

D. Bat algorithm (BA)

Bat algorithm was pioneered by Xin-she Yang [57] in 2010. This algorithm was inspired by the echolocation or bio-sonar characteristics of bats and based on three idealized rules, (i) echolocation technique of bats to sense distance and to calculate difference between their prey (food) and background barriers, (ii) bats vary their wavelength (λ_0) and loudness (A_0) to search for their prey.

Almost at the same time Ramesh et al. [28], Nikman *et al.*, [58] and Azizipanah-Abarghooee [59] proposed bat algorithm for solving CEED problems. Ramesh et al. [28] tested proposed bat algorithm in two different system consisting of three and six units respectively and separately compared with Refined GA (RGA), NSGA-II, ABC and hybrid GA-TS. Compared result showed that bat algorithm is efficient, easy to implement and performs better in minimizing both the objectives simultaneously. Nikman [58] in his paper compared each objectives of CEED separately with a wide range of previously used methods from the literature which justified bat algorithms supremacy over other algorithms. However, authors don't find any comparison with other methods considering both the objectives simultaneously. Azizipanah-Abarghooee [59] proposed an improved bat algorithm with a new mutation strategy to avoid local optima and improve convergence characteristics. An interactive fuzzy based technique had also been exploited to deal with this multi objective problem.

IV. HYBRID METHODS

Hybrid methods make use of two or more algorithms in order to utilize their strengths and mitigate their weakness in solving complex problems and thus are found to be effective to find global optimal solution for complex combined economic emission dispatch problems with different constraints. Gong et al. [60] presented a hybrid method combining PSO with DE and integrating several techniques such as time variant acceleration coefficients, crowing distance-based technique etc. to get global optimal result for CEED problems. Obtained results were found to be well distributed, efficient and superior to many other algorithms like linear programming (LP), NSGA, SPEA and fuzzy clustering PSO (FCPSO). A. Bhattacharya et al. [61] exploited hybrid DE-BBO method to solve complex economic emission dispatch problem considering power demand and operating limit constraints. This method was pioneered by Gong et al. [62] in order to utilize the exploration and exploitation capability of DE and BBO methods respectively and previously used for economic dispatch (ED) problem [63]. Three different test systems with different degree of complexities were considered to test the performance of this method. The important findings of the paper are DE-BBO method effectively eliminates premature convergence and offers robust solution with high level of computational efficiency.

Two of the most well-known optimization methods i.e. GA and PSO were incorporated with each other by Roselyn *et al.*, [43] to tackle CEED problems. GA was combined with PSO to enhance the effectiveness of this method. Elitism technique was utilized before updating population in the algorithm, while position of the particles and velocity were updated by GA based mutation strategy to attain the global best position (solution). PSO has the ability to converge quickly and has found not to be affected much by initial population, whereas GA is more efficient in fine tuning although it is affected much by initial population. Thus, to overcome each other's drawbacks and take benefits from their advantages, PSO is usually utilized at the early stages, while GA is utilized at later stages [64] in PSO-GA hybrid algorithm. This proposed hybrid method was found to give better results with faster convergence and took less memory space. However, authors don't find any comparison with other well established stand-alone or hybrid methods except PSO to assert claim in its superior performance.

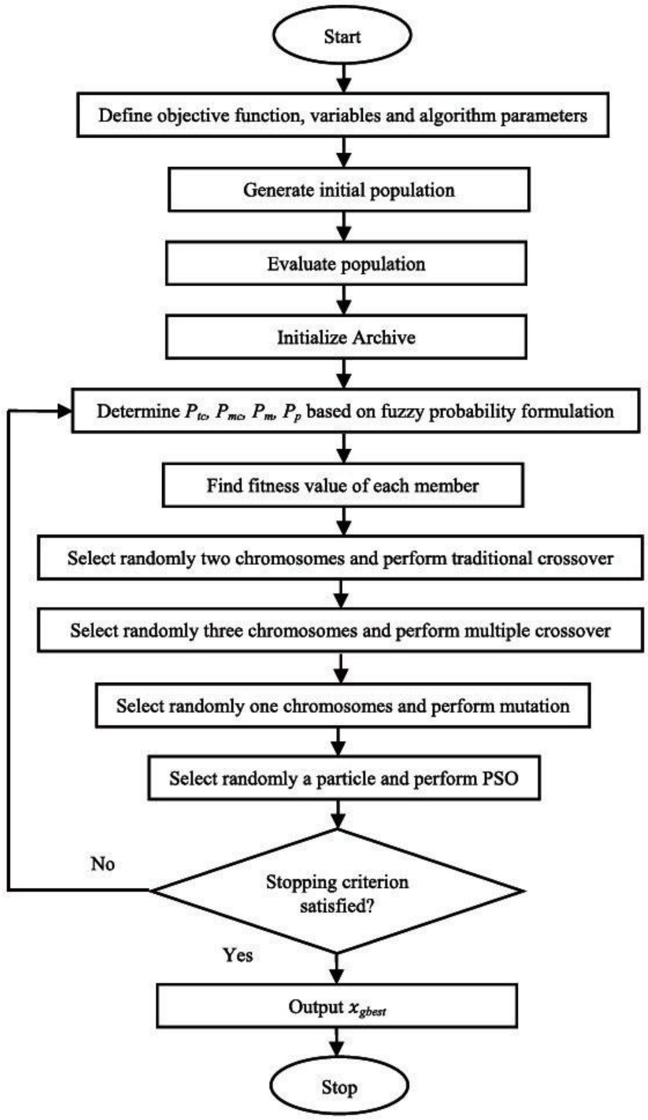

Fig. 2 Flowchart of PSO-GA hybrid algorithm

Fig. 2 describes the flowchart of PSO-GA hybrid method. Hooshmand and his men [36] proposed a new hybrid bacterial foraging-Nelder–Mead (BF-NM) algorithm to solve tri-objective power generation, spinning reserve and emission load dispatch problem (ERELD) considering a wide range of constraints such as power balance constraint, power generation limits, ramp rate limits, prohibited operating zones constraint, spinning reserve constraint, frequency deviation limit etc. Authors have found this paper as one of the most organized and well developed power generation system models to represent actual power generation system. The precision of Nelder-Mead method and the power of BF method to cover a wide search area were simultaneously utilized to solve this many-objective problem. Hooshmand *et al.*, [36] found that consideration of frequency constraint in the problem allowed them to solve the problem by controlling the frequency within its permissible limit, which ultimately increase the social welfare for consumers. The superiority of this proposed hybrid method had also been verified after comparing with other stand-alone methods like GA, BFA and PSO.

V. FUZZY COMPROMISED SOLUTION FOR CEED PROBLEM

In multi objective combined economic emission dispatch problem, there are two objective functions i.e. economic and emission dispatch functions to be considered in the same time and therefore it is difficult to compare two solutions. If solution vectors X_1 and X_2 are Pareto-optimal, then neither set of vectors should be better than the other. It is because if X_1 provides better result for one objective then X_2 would provide better result for another objective. Both of the solution sets are competing or non-dominating solutions in nature. In multi objective economic emission problem, it is difficult to find the best solution from many non-dominated solutions. In order to compare these solutions and get the best compromised solution some mechanism is needed to combine both the objectives in accordance with the decision maker's preference. Fuzzy set theory is often used by the researchers to get the best compromised solution from many non-dominated solutions. As both the objectives of fuel cost and emission are conflicting in nature, it is not possible to get the least fuel cost and at the same time least emission. But, it is desirable to get a dispatch option that can reduce both fuel cost and emission as much as possible. Degree of satisfaction (DoS) to each objective is assigned by fuzzy membership functions, where DoS reflects the merit of their objective in a linear scale of 0–1 (worst-best). If F_i is a solution in the Pareto-optimal set in the i^{th} objective function and is represented by a membership function μ_i, which can be defined as

$$\mu_i = \begin{cases} 1, F_i \le F_{i,\min} \\ \dfrac{F_{i,\max} - F_i}{F_{i,\max} - F_{i,\min}}, F_{i,\min} \le F_i \le F_{i,\max} \\ 0, F_i \ge F_{i,\max} \end{cases} \quad (7)$$

VI. CONCLUSION

This paper presents a comprehensive review on recent advanced optimization strategies to solve CEED problems. Classification of different optimization methods have been shown with their advantages and disadvantages. Different formulation criteria of CEED problem such as quadratic and cubic function along with their major equality and inequality constraints have been presented to give a clear idea to the readers about actual CEED problem. This paper mainly focuses on nature-inspired advanced optimization methods for solving multi objective CEED problem. Description of some well-known and promising methods have been given along with their flowcharts and working principle. Again, authors have discussed fuzzy set theory to find comprised solution from a set of Pareto-optimal solutions of CEED problems. Later, some graphical data has been shown to figure out the recent trends of using different nature-inspired optimization algorithm to solve this multi objective CEED problem. It is clear from the previous discussion that research on solving CEED problem is high in recent years and researchers are increasingly motivated to use hybrid algorithm to solve CEED problem. This comprehensive study will guide and benefit to implement more economic and environmental friendly real-world power generation system. From this study, it can be concluded that stand-alone nature-inspired meta heuristic techniques are most successful, while hybrid techniques are found to be most prospective to optimize CEED problem.

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