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Robust Multi-Area Economic Dispatch Using Coulomb's and Franklin's Laws Based Optimizer

Vadugapalayam Ponnuvel Sakthivel[1,*], Murugesan Suman[2], Palanigounder Duraisamy Sathya[3]

[1]Department of Electrical and Electronics Engineering, Government College of Engineering, Dharmapuri, India

[2]Department of Electrical Engineering, FEAT, Annamalai University, Chidambaram, India

[3]Department of Electronics and Communication Engineering, FEAT, Annamalai University, Chidambaram, India

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Abstract

The multi-area economic load dispatch (MAELD) can reduce running costs through making the areas with more cost-effective units produce more energy. The excess power is transferred to the areas with expensive units. This paper contributes a new physics inspired metaheuristic approach called the Coulomb's and Franklin's laws based optimizer (CFLBO) to solve the MAELD problem. The CFLBO approach is developed from Coulomb's and Franklin's theories, which comprise attraction/repulsion, probabilistic ionization, and contact stages. The effectiveness of the envisaged CFLBO approach has been examined on three standard test systems with various areas. Results obtained by the CFLBO approach are compared with the exchange market algorithm (EMA) and the existing state-of-the-art approaches to deal with MAELD. Numerical outcomes show the benefits of the quick convergence and better quality of the suggested approach compared to existing strategies. Consequently, the proposed approach is a helpful tool for generation planning in MAELD problems.

Keywords: CFLBO, metaheuristic approach, multi-area economic load dispatch, multi-fuel alternatives

1. Introduction

The objective of the MAELD problem is to assure the allocation of power generation by every generator in a power system, and power transfer between the zones to reduce the total production cost. For ongoing power system activity, economic load dispatch (ELD) must be considered with different types of requirements. To operate the power system efficiently, the ELD problem must be solved prior to power transfer for a multi-area system. The tie-line constraints that are associated with zones are considered as extra constraints in the MAELD problem. The power demand in every zone is prescribed in the MAELD problem.

Over the years, various classical multi-area power generation scheduling methods have been proposed. Shoults, Chang, Helmick, and Grady [1] applied an efficient approach for unit commitment and ELD problems with area import/export constraints. The proposed approach had been tested on the Texas utilities and Texas municipal power pool systems. Quintana, Lopez, Romano, and Valadez [2] suggested the use of the Dantzig-Wolfe decomposition principle regarding the revised simplex method and a fast decoupled power flow algorithm for the constrained MAELD of power systems. Ouyang and Shahidehpour [3] developed a model of the large-scale multi-area power generation system. They used a rule-based heuristic

* Corresponding author. E-mail address: vp.sakthivel@yahoo.com
Tel.: +918955912345

strategy to improve the generation schedule for every zone. Wang and Shahidehpour [4] suggested a decomposition approach which upgrades the scheduling process and accelerates the execution of a large-scale multi-area generation system in a real-time application.

Streiffert [5] expressed the MAELD problem as a capacitated nonlinear network flow problem and solved it through an incremental network flow programming (INFP) approach. Yalcinoz and Short [6] presented an improved hopfield neural network (IHNN) to solve MAELD problems with transmission capacity constraints. These strategies do not offer reasonable possibilities for dealing with the MAELD problem when prohibited operating zones (POZs), valve point loading (VPL), and multi-fuel alternatives (MFAs) are considered. To adapt to these challenges, numerous meta-heuristic methodologies have been used to take care of enhancement issues with complicated objectives [7].

In recent years, swarm intelligence algorithms have been broadly used to overcome the computational unpredictability issues in the MAELD problem. Jayabarathi, Sadasivam, and Ramachandran [8] proposed a proficient technique for MAELD problems by using an evolutionary programming (EP) approach. The performance of the various evolutionary algorithms on MAELD problems with Karush–Kuhn–Tucker optimality conditions was examined [9]. The performance of differential evolution (DE) strategies enhancedwith the time-varying mutation was investigated and analyzed to solve the reserve-constrained MAELD problem [10]. Somasundaram and Jothi Swaroopan [11] introduced another computationally efficient fuzzified particle swarm optimization algorithm to solve the security-constrained MAELD problem of an interconnected power system.

Basu proposed artificial bee colony (ABC) optimization [12] to solve a MAELD problem with tie-line constraints, transmission losses, multiple fuels, and valve point effects. Evolutionary approaches such as DE, EP, and real-coded genetic algorithm (RCGA) were applied to analyze the efficiency of the ABC approach. Teaching learning-based optimization (TLBO) [13] has been applied to solve the MAELD issue. The different MAELD models were solved by employing fast convergence evolutionary programming (FCEP) [14]. FCEP used Gaussian and Cauchy mutations to improve convergence speed and solution quality.These heuristic approaches involve complicated computation owing to the use of many control parameters.An efficient algorithm for solving MAELD problems to ascertain the optimum dispatch solutions must be developed and proposed.

Coulomb’s and Franklin’s laws based optimizer (CFLBO) is a new physics-motivated metaheuristic algorithm developed by Ghasemi, Ghavidel, Aghaei, Akbari, and Li in 2018 [15]. This algorithm is a population-based approach inspired by Coulomb’s and Franklin’s theories. The forces of attraction and repulsion among the point charges, probabilistic ionization, and probabilistic contact stages are considered in the algorithm. CFLBO has been beneficially used in ELD issues with various complexities and is superior to other heuristic methodologies.

The primary contributions of this paper are succinctly outlined as follows:

(1) This paper bestows a powerful physics-driven metaheuristic methodology, CFLBO, to tackle the MAELD problem of power systems.
(2) The envisaged research work considers three kinds of MAELD problems as follows: MAELD with transmission losses and POZs, MAELD with VPL impacts, and MAELD with VPL impacts and MFAs.
(3) To demonstrate the superiority of the recommended CFLBO approach, it has been tested on three different power systems and compared with EMA and some state-of-the-art approaches.

The structure of this paper is as follows. Section 2 presents the details of the MAELD model. The recommended CFLBO approach is explained in Section 3. Section 4 describes the constraints-handling mechanism adopted in the CFLBO approach. The implementation of the CFLBO approach for the MAELD problem is discussed in Section 5. In Section 6, the simulation results and the adequacy of the proposed CFLBO approach are demonstrated. Finally, Section 7 concludes the paper.

2. Assessment of MAELD Problem

The goal of the MAELD issue is to find the optimal set of generation values in every zone and power transfers among various areas to optimize the objective function subject to various constraints. The constraints of MAELD include the power balance constraints of each area, generator capacity limits, tie-line limits, and the POZ of generating units.

The following three distinct kinds of MAELD problems are addressed.

2.1. MAELD with quadratic fuel cost function

The quadratic cost function of the submitted generation units in all zones can be expressed as [3]:

$$F_t = \sum_{i=1}^{n_g}\sum_{j=1}^{M_i} F_{ij}(P_{ij}) = \sum_{i=1}^{n_g}\sum_{j=1}^{M_i}(a_{ij} + b_{ij}P_{ij} + c_{ij}P_{ij}^2) \tag{1}$$

2.2. MAELD with VPL impacts

Thermal generators employ steam turbines which experience VPL effects because of the consecutive opening of steam valves. When these effects are considered, the fuel cost function of the generator reveals ripples of a rectified sinusoidal nature. To model the impact of valve-points, a common amended sinusoid participation is added to the quadratic function. The MAELD with VPL impacts is defined as [12]:

$$F_t = \sum_{i=1}^{n_g}\sum_{j=1}^{M_i} a_{ij} + b_{ij}P_{ij} + c_{ij}P_{ij}^2 + |\, e_{ij} \times sin\left\{ f_{ij} \times (P_{ij,min} - P_{ij})\right\}| \tag{2}$$

2.3. MAELD with VPL and MFA

The MAELD problem with MFA aims to find the amount of power that can be efficiently generated in one area and transferred to another to determine the economic fuel choice for each unit. Since generators are provided with multi-fuel sources, every generator ought to be defined with a few piecewise quadratic capacities superimposed by sine terms mirroring the impact of changes in the type of fuel. The MAELD problem with VPL and MFA impacts [12] can be modeled as:

$$F_{ij}(P_{ij}) = \begin{cases} \textit{Fuel type } 1;\ a_{ij1} + b_{ij1}P_{ij} + c_{ij1}P_{ij}^2 + |\, e_{ij1} \times \sin\left\{ f_{ij1} \times (P_{ij,\min} - P_{ij})\right\}|;\ P_{ij,\min} \le P_{ij} \le P_{ij1} \\ \textit{Fuel type } 2;\ a_{ij2} + b_{ij2}P_{ij} + c_{ij2}P_{ij}^2 + |\, e_{ij2} \times \sin\left\{ f_{ij2} \times (P_{ij,\min} - P_{ij})\right\}|;\ P_{ij1} < P_{ij} \le P_{ij2} \\ \vdots \\ \textit{Fuel type } k;\ a_{ijk} + b_{ijk}P_{ij} + c_{ijk}P_{ij}^2 + |\, e_{ijk} \times \sin\left\{ f_{ijk} \times (P_{ij,\min} - P_{ij})\right\}|;\ P_{ijk-1} < P_{ij} \le P_{ij,\max} \end{cases} \tag{3}$$

2.4. MAELD constraints

The MAELD problems are the constrained optimization problems, where the equality and inequality constraints are addressed. The total power generation must be equal to the transmission loss, tie-line power, and system demands. The following equality and inequality constraints are considered to deal with the MAELD problem.

2.5. Power balance constraint

The total power generated by a set of accessible units must satisfy the total load demand, tie-line power flow, and transmission losses [8] and can be obtained by:

$$\sum_{j=1}^{Mi} P_{ij} = P_{Di} + P_{Li} + \sum_{z,z\neq i} T_{iz},\ i \in n_g,\ j \in M_i \tag{4}$$

The transmission loss P_{Lj} of region j can be defined by using B-coefficients as follows:

$$P_{Li} = \sum_{l=1}^{M_i}\sum_{j=1}^{M_i} P_{ij} B_{ilj} P_{il} + \sum_{j=1}^{M_i} B_{0ij} P_{ij} + B_{00i} \tag{5}$$

2.5.1. Generator capacity limits

The real output power of the thermal units shouldbe in the range between minimum and maximum limits [8]:

$$P_{ij,min} \le P_{ij} \le P_{ij,max} \tag{6}$$

2.5.2. Tie-line limit

Because of the security basis, power shifted between various lines must not surpass their cutoff points [5]. The power transfer requirement between two unique regions is characterized by:

$$-T_{iz,max} \le T_{iz} \le T_{iz,max} \tag{7}$$

2.5.3. Prohibited operating zone

POZs are occured due to the functions of the steam valve or vibrations in the shaft bearings. This excessive vibration can damage the turbine shaft [8]. The viable operating sectors of the unit are defined as:

$$\begin{aligned} &P_{ij,min} \le P_{ij} \le P_{ij,1}^{\mathrm{L}} \\ &P_{ij,m-1}^{\mathrm{U}} \le P_{ij} \le P_{ij,m}^{\mathrm{L}},\ m = 2,\cdots,nz \\ &P_{ij,nz}^{\mathrm{U}} \le P_{ij} \le P_{ij,max} \end{aligned} \tag{8}$$

3. Synopsis of the CFLBO Approach

The CFLBO is a metaheuristic approach that was presented by Ghasemi, Ghavidel, Aghaei, Akbari, and Li [15]. This approach mimics Coulomb's and Franklin's hypotheses. The accompanying ideas are associated with the CFLBO approach.

Coulomb's Law: the connection between two distinctive point charges is controlled by the magnitude of electrostatic power of attraction (or) repulsion.

Franklin's Law: each object comprises equivalent positive and negative charges.

The CFLBO approach uses various objects (populations) of point charges (*X*) which move around various territories in an investigated space to find the global ideal solution. The initial objects are formed by different groups of point charges which are arbitrarily generated in the search space. Each point charge involves *D* quantized charges *x*, and each point charge is compared with a candidate solution of the problem.

The model of CFLBO is a monotonous procedure, which contains four stages: initialization stage, attraction/repulsion stage, probabilistic ionization stage, and probabilistic contact stage.

3.1. Initialization stage

Consider an object formed by a populace of m charges with dimension *D*. The objects, populaces, and each individual are represented as:

$$\mathrm{O} = [\mathrm{O}_1, \mathrm{O}_2, \cdots, \mathrm{O}_n] \tag{9}$$

$$\mathrm{X} = [\mathrm{X}_1, \mathrm{X}_2, \cdots, \mathrm{X}_q] \tag{10}$$

$$\mathrm{X}_{ij} = [\mathrm{X}_{i1}, \mathrm{X}_{i2}, \cdots \mathrm{X}_{iD}] \tag{11}$$

The initial populations of point charges are generated as follows:

$$x_{ij} = U(x_j^{\min},\ x_j^{\max}),\ for\ i = 1, 2, \cdots, m\ and\ j = 1, 2, \cdots, D \tag{12}$$

where U is a vector of consistently disseminated arbitrary numbers between x_j^{min} and x_j^{max}. Then, the initial population is arranged and disseminated into a few objects (O_1…….O_n).

3.2. Attraction/repulsion stage

The relocation of point charges is impacted by attraction and repulsion forces acting on them. The net power acting on a point charge (X_i) is equivalent to its value (F_i). The CFLBO approach is used to limit the net force (cost) acting on them. For each object, the area of point charges is updated by:

$$x_j^{new} = x_{ij}^{old} + |cos\theta_j^{new}|^2 \times (x_j^{best} - x_j^{Worst}) + |sin\theta_j^{new}|^2 \times (mean(\sum_{n=1}^{amax} x_{jn}) - mean(\sum_{n=1}^{rmax} x_{jn})) \tag{13}$$

where

$$\theta_j^{initial} = U(0, 2\pi) \tag{14}$$

$$\theta_j^{mew} = \theta_j^{old} + U(0, \frac{3}{2}\pi) \tag{15}$$

The a_{max} and r_{max} can be expressed as:

$$a_{max} = a_0 \times (1 + cos\theta) \tag{16}$$

$$r_{max} = r_0 \times (1 - cos\theta) \tag{17}$$

3.3. Probabilistic ionization stage

Due to the influence of probabilistic ionization energy, there is a possibility of displacement of the location of the elementary charge x_j. This stage can be mathematically modeled by the following equation:

$$x_j^{new} = x_j^{Best} + x_j^{Worst} - x_j^{old}\ \ if\ \ rand\,(j) \le p_j \tag{18}$$

The control variable '*j*' is chosen as:

$$j = round\,(unifrnd(1, D)) \tag{19}$$

where rand (j) is the jth point charge of a uniform random number generated within the range [0, 1].

3.4. Probabilistic contact stage

If the objects are in contact with each other, each object passes its best and worst point charges to its neighbor. The probabilistic contact phase is expressed as:

If $rand_c \le p_c$, then

$$x_j^{Best_{Obj1}} = x_j^{Best_{Objn}}, \cdots, x_j^{Best_{Objn}} = x_j^{Best_{Objn-1}} \tag{20}$$

$$x_j^{Worst_{Obj1}} = x_j^{Worst_{Objn}}, \cdots, x_j^{Worst_{Objn}} = x_j^{Worst_{Objn-1}} \tag{21}$$

where $rand_c$ is uniform number generated within the range [0, 1].

4. Constraints-Handling Mechanism

The governing issue in solving the MAELD problem is constraints-handling. In this work, a renovating strategy is incorporated to handle the power balance constraints instead of using penalty-based approaches, as depicted in Fig. 1. In this strategy, a random generation unit is selected to perform the renovating process. The advantages of this strategy are easy implementation and fast renovation.

The prohibited zone constraint violation is renovated by updating the generation to the nearer bound of the corresponding prohibited zone and can be expressed as:

$$P_{ij} = \begin{cases} P_{ij,nz-1}^{L} + rand()\dfrac{(P_{ij,nz-1}^{U} - P_{ij,nz-1}^{U})}{P_{ij,nz-1}^{U}} & if\, P_{ij} \le P_{ij,nz}^{L} \\ P_{ij,nz+1}^{L} + rand()\dfrac{(P_{ij,nz+1}^{U} - P_{ij,nz+1}^{U})}{P_{ij,nz+1}^{U}} & if\, P_{ij} \ge P_{ij,nz}^{L} \\ P_{ij} & else \end{cases} \tag{22}$$

The fitness value of each point charge can be defined as:

$$Fit(P_{ij}) = \begin{cases} \sum_{i=1}^{ng} F(P_{ij}) \; if\, (P_{ij}) \;\; is\, feasible \\ \sum_{i=1}^{ng} F(P_{ij})_{max} + \Delta P_{ij} \;\; otherwise \end{cases} \tag{23}$$

All feasible solutions have no constraint infringement, and all the infeasible solutions are assessed based on constraint violations. Thus, there is no need to use a penalty coefficient for this approach. The following selection rules are enforced while selecting the individuals for the next generation:

(1) When the ΔP_{ij} values of the two individuals are positive, the one with the smaller fitness value is preferred.

(2) When the ΔP_{ij} values of the two individuals are both negative, the one with the smaller value is preferred.

(3) When the ΔP_{ij} value of one individual is positive and the other is negative, the one with a positive value is preferred.

While $\sum_{i=1}^{n_g}\sum_{j=1}^{M_i} P_{ij} - (P_{Di} + P_{Li} + \sum_{z,z\neq i} T_{iz}) = 0$

Randomly select a generator i of an individual

Find $\Delta P_{ij} = |\sum_{i=1}^{n_g}\sum_{j=1}^{M_i} P_{ij}| - (P_{Di} + P_{Li} + \sum_{z,z\neq i} T_{iz})$

If $\sum_{i=1}^{n_g}\sum_{j=1}^{M_i} P_{ij} - (P_{Di} + P_{Li} + \sum_{z,z\neq i} T_{iz}) \neq 0$

Update $P_{ij} = min(P_{ij} + \Delta P_{ij}, P_{ij,max})$

Else

Update $P_{ij} = max(P_{ij} - \Delta P_{ij}, P_{ij,min})$

End if

End while

Fig. 1 Renovate strategy for equality constraints handling

5. CFLBO Implementation to Solve MAELD

In this paper, the strategy to actualize the CFLBO approach to deal with the MAELD problem is depicted asa flow diagram in Fig. 2. Since the optimization variables for the MAELD problem are the real power outputs of the generators, they are represented by individual point charge. At the initialization stage, a population of *m* random feasible solutions is generated.

Then, the fitness value of each solution is evaluated in order to identify the best and the worst point charge. In each iteration of the CFLBO algorithm, each of the *m* point charges produces a new candidate solution by using attraction/repulsion, probabilistic ionization, and contact stages. The process is terminated when the specified stopping criterion is met.

6. Simulation Results and Analysis

To assess the efficacy of the envisaged CFLBO approach for solving the MAELD issue, a computational analysis is performed on three diverse test systems, namely a two-area system with six generating units, a three-area system with 10 generating units, and a four-area system with 40 generating units.

Also, to additionally check the adequacy of the envisaged CFLBO approach, the EMA approach is used to solve the MAELD problem and compared with recently published state-of-the-art approaches. The CFLBO and EMA approaches are implemented by using MATLAB 7.1 on an Intel core i3 processor with 4 GB of RAM, and is executed for 50 free runs for all the test systems. The accompanying three case studies are considered.

Case study 1: MAELD with transmission line losses and POZ impacts.
Case study 2: MAELD with transmission losses,and VPL and MFA impacts.
Case study 3: MAELD with VPL impacts.

6.1. Parameter selection

In the CFLBO approach, five main parameters that have to be predetermined are the number of objects, population size of each object, maximum number of iterations, probabilistic ionization, and contact constants. These parameters can be easily fixed depending on the complexity and scale of the considered MAELD problems. The parameters selected for the suggested CFLBO approach are given in Table 1 [21]. The dimensional (*D*) sizes of the three case studies are set to 6, 10, and 40 respectively.

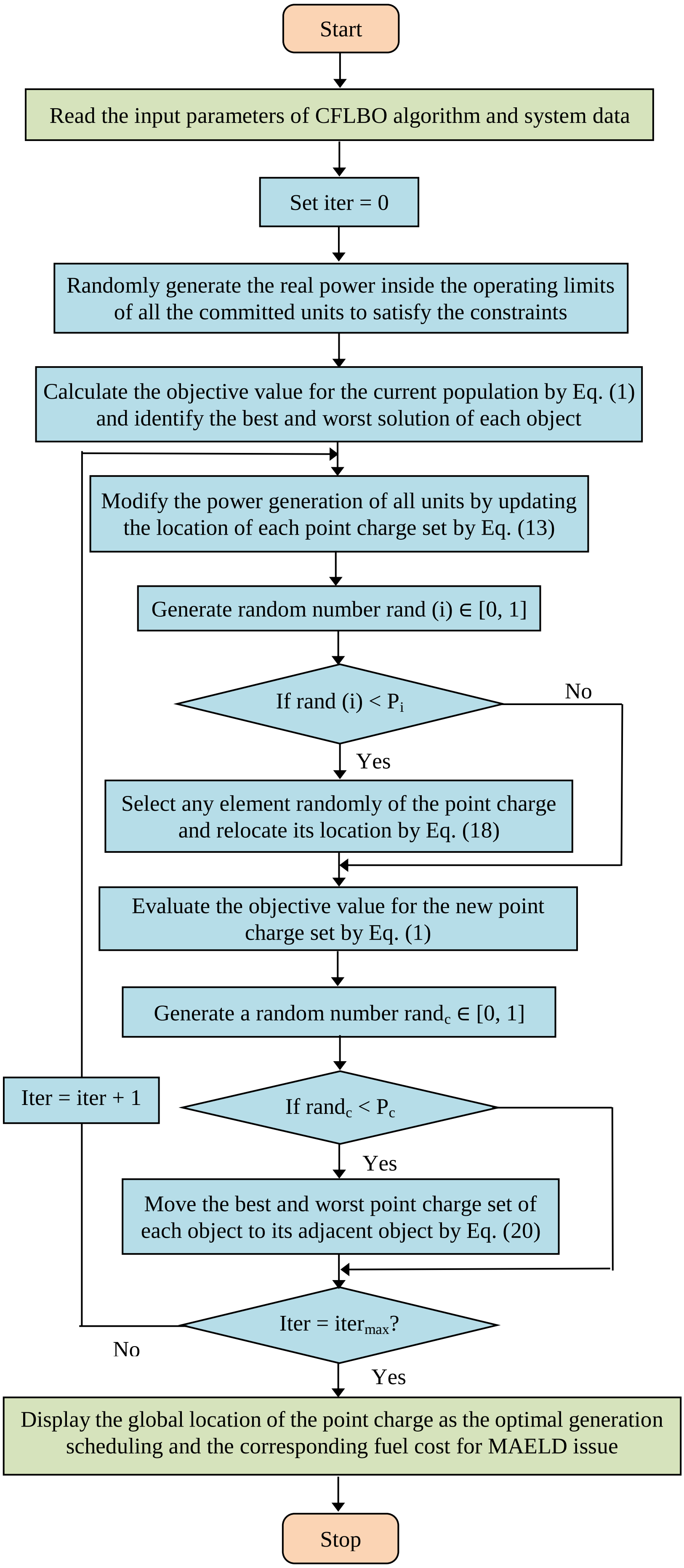


Fig. 2 Flow chart of CFLBO approach applied in MAELD issues

Table 1 Optimal CFLBO parameters

Parameter	Value
Maximum number of objects (n)	5
Population size of each object(q)	20
Maximum number of iterations($iter_{max}$)	200
Ionization probabilistic constant(p_i)	0.1
Contact phase probabilistic constant(P_c)	0.5

6.2. Case study 1

This case study uses a two-area test power system with six generating units. The total power load is 1263 MW. Nevertheless, the power balance, generation unit limits, tie-line limitations, transmission losses, and POZs are considered. In Ref. [12], the information on cost coefficients, emission coefficients, and POZs is given. The power demand shared by areas 1 and 2 are 60 % and 40 % of absolute load demand respectively.

The power stream from area 1 to area 2 is limited to 100 MW. The layout of this test system appears in Fig. 3. The generation plan compared to the lowest fuel cost obtained by the proposed CFLBO approach is reported in Table 2. Besides, area 1 imports power from area 2. Fig. 3 shows comparison among the fuel costs obtained by the CFLBO, EMA, and different techniques presented in previous research articles. In Fig. 4, the CFLBO approach has achieved the lowest generation cost among the fuel costs incurred by the other aforementioned approaches.

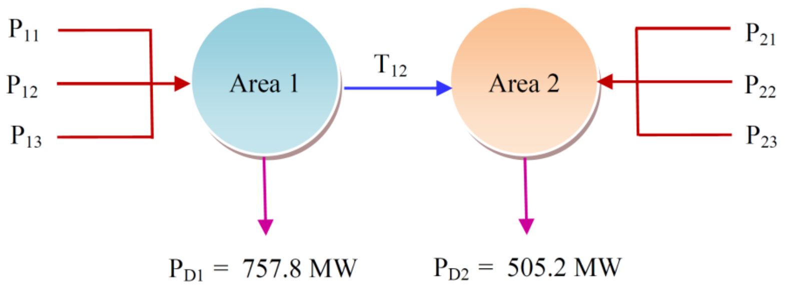


Fig. 3 Schematic diagram of two-area system

Table 2 Best dispatch solution incurred by the envisaged CFLBO approach for case study 1

Unit	$P_{ij,min}$ (MW)	$P_{ij,max}$ (MW)	POZ (MW)	Power generation (MW)
$P_{1,1}$	100	500	[210,240]; [350,380]	500
$P_{1,2}$	50	200	[90,110]; [140,160]	200
$P_{1,3}$	50	150	[80,90]; [110,120]	150
$P_{2,1}$	80	300	[150,170]; [210,240]	204.3186
$P_{2,2}$	50	200	[90,110]; [140,150]	154.6997
$P_{2,3}$	50	120	[75,85]; [100,105]	67.5976
T_{21}	82.7731			
P_{L1}	9.4269			
P_{L2}	4.1891			
Generation cost ($/h)	12255.3847			

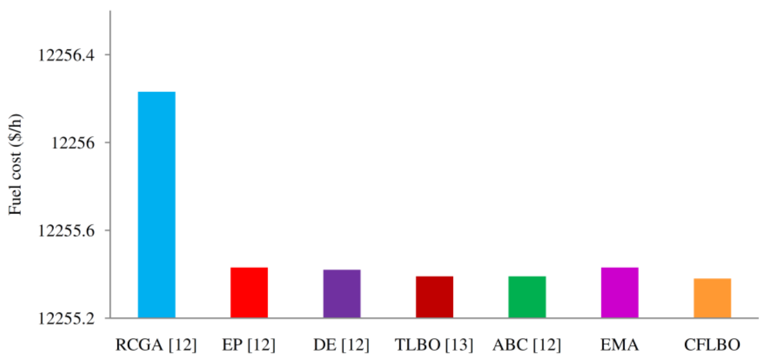


Fig. 4 Comparison of generation costs incurred by various approaches for case study 1

6.3. Case study 2

In this case, three areas, a 10-unit test system with transmission losses, and VPL and MFA impacts are taken into consideration. Areas 1, 2 , and 3 comprise four, three and three generating units, respectively as displayed in Fig. 5. The power demand of this system is 2700 MW. The power demand shares of areas 1, 2, and 3 are 50%, 25%, and 25% of total load demand respectively. The power stream from one area to another is restricted to 100 MW.

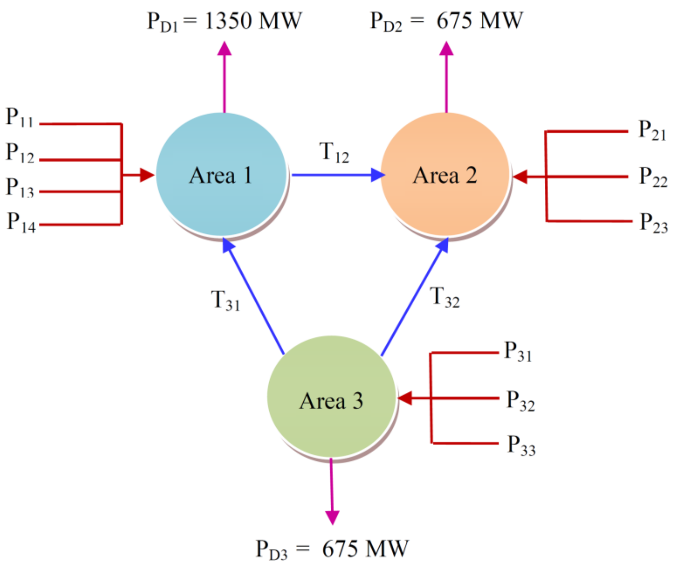


Fig. 5 Schematic diagram of three-area system

Table 3 Best dispatch solution incurred by the envisaged CFLBO approach for case study 2

Unit	$P_{ij,min}$ (MW)	$P_{ij,max}$ (MW)	Fuel types	Power generation (MW)
$P_{1,1}$	196	250	2	224.4524
$P_{1,2}$	157	230	1	212.1998
$P_{1,3}$	388	500	2	490.1287
$P_{1,4}$	200	265	3	240.5451
$P_{2,1}$	190	338	1	252.9731
$P_{2,2}$	200	265	3	234.5827
$P_{2,3}$	200	331	1	265.6763
$P_{3,1}$	200	265	3	234.9516
$P_{3,2}$	213	370	1	329.1937
$P_{3,3}$	200	362	1	251.0647
T_{21}	100	P_{L1}	17.2541	
T_{31}	99.9281	P_{L2}	9.8343	
T_{32}	31.6022	P_{L3}	8.6804	
Generation cost ($/h)			654.6016	

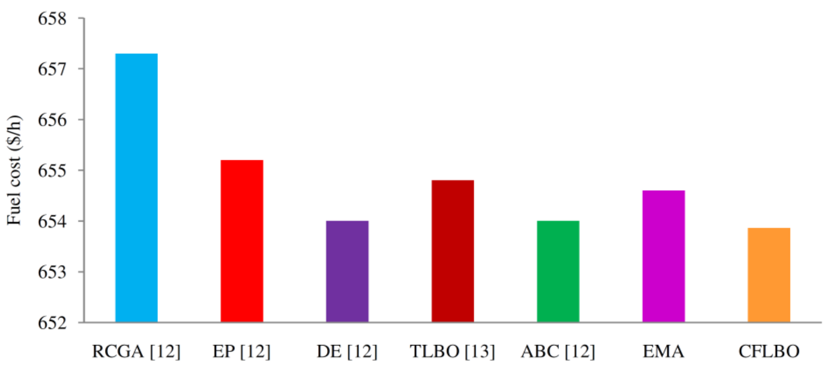


Fig. 6 Comparison of generation costs incurred by various approaches for case study 2

Table 3 presents the simulation results obtained by the proposed CFLBO approach. It can be easily seen that the optimal generation cost obtained by the CFLBO approach is 654.6016 $/h, which is the lowest among the compared approaches. Area

1 imports power from areas 2 and 3, and area 3 exports power to area 2. The comparison of the results of CFLBO approach with those of EMA, RCGA, EP, DE, TLBO, and ABC approaches is illustrated in Fig. 6. The outcomes show that the proposed strategy outperforms the other considered strategies with regard to finding the best generation schedule.

6.4. Case study 3

Four areas with a 40-unit system are considered in this case study. All the units have VPL impacts, and thus the cost functions are non-convex. The cost coefficients of this system are available in Ref. [12]. The system has a total load equivalent to 10500 MW. The schematic diagram of this four-area test system is shown in Fig. 7. Each area consists of 10 generation units. The shares of power demand for areas 1, 2, 3, and 4 are 15%, 40%, 30%,and 15 % of total load demand respectively.

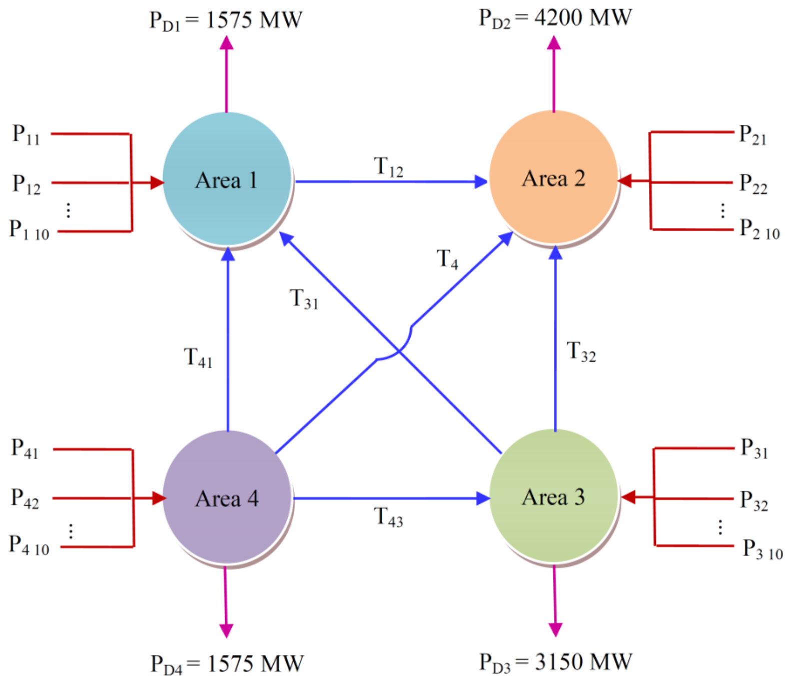


Fig. 7 Schematic diagram of four-area system

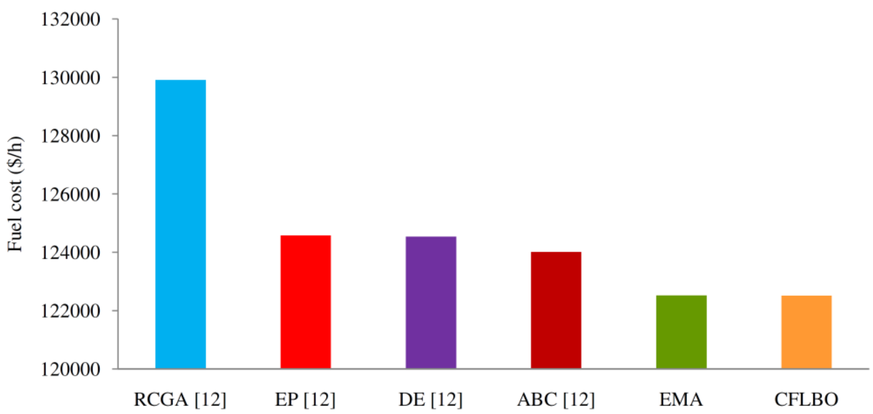


Fig. 8 Comparison of generation costs incurred by various approaches for case study 3

The power flow from area 1 to area 3, from area 2 to area 3, and from area 2 to area 4 are restricted to 200 MW. The tie-line limit for area 1 to area 4, area 2 to area 4, and area 3 to area 4 is 100 MW. The optimal generation dispatch obtained by the envisaged approach is given in Table 4. Area 2 imports power from areas 1, 3, and 4. Area 1 imports power from areas 3 and 4. Area 4 exports power to area 3. In this case study, the effectiveness of the CFBO approach is compared with those of the EMA, RCGA, EP, DE, and ABC approaches. Fig. 8 shows the results of this examination. Once more, the CFLBO demonstrated superior outcomes compared to the previously mentioned approaches.

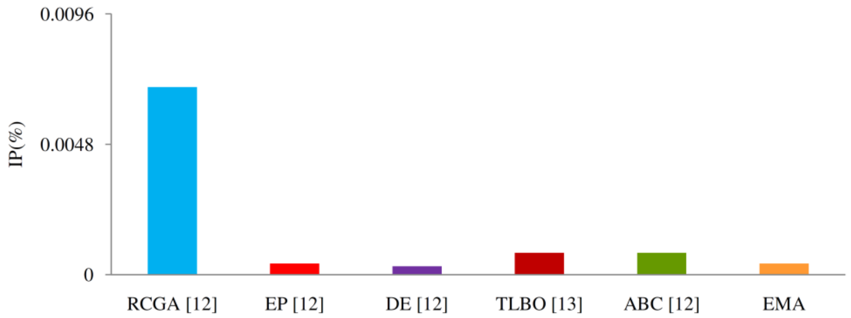
Table 4 Best dispatch solution incurred by the envisaged CFLBO approach for case study 3

Unit	$P_{ij,min}$ (MW)	$P_{ij,max}$ (MW)	Power generation (MW)	Unit	$P_{ij,min}$ (MW)	$P_{ij,max}$ (MW)	Power generation (MW)
$P_{1,1}$	36	114	109.6842	$P_{3,1}$	254	550	523.2769
$P_{1,2}$	36	114	110.3657	$P_{3,2}$	254	550	523.0318
$P_{1,3}$	60	120	92.1589	$P_{3,3}$	254	550	523.7060
$P_{1,4}$	80	190	178.2973	$P_{3,4}$	254	550	523.1712
$P_{1,5}$	47	97	90.8548	$P_{3,5}$	254	550	523.8235
$P_{1,6}$	68	140	139.8147	$P_{3,6}$	254	550	523.6948
$P_{1,7}$	110	300	259.9134	$P_{3,7}$	10	150	10.3171
$P_{1,8}$	135	300	284.6324	$P_{3,8}$	10	150	10.0000
$P_{1,9}$	135	300	284.2785	$P_{3,9}$	10	150	10.0000
$P_{1,10}$	130	300	130.5469	$P_{3,10}$	47	97	88.9502
$P_{2,1}$	94	375	164.1576	$P_{4,1}$	60	190	190
$P_{2,2}$	94	375	168.9706	$P_{4,2}$	60	190	189.7655
$P_{2,3}$	125	500	140.9572	$P_{4,3}$	60	190	189.1626
$P_{2,4}$	125	500	393.4854	$P_{4,4}$	90	200	164.3816
$P_{2,5}$	125	500	393.4218	$P_{4,5}$	90	200	165.6463
$P_{2,6}$	125	500	470.9157	$P_{4,6}$	90	200	164.4456
$P_{2,7}$	220	500	489.7922	$P_{4,7}$	25	110	90.1869
$P_{2,8}$	220	500	489.8491	$P_{4,8}$	25	110	90.6551
$P_{2\ 9}$	242	550	510.9340	$P_{4,9}$	25	110	109.2760
$P_{2,10}$	242	550	510.9887	$P_{4,10}$	242	550	472.4898
T_{12}		195.7255		T_{41}		79.4796	
T_{31}		10.6991		T_{42}		88.9691	
T_{32}		181.8331		T_{43}		82.5607	
Generation cost ($/h)		122516.2835					

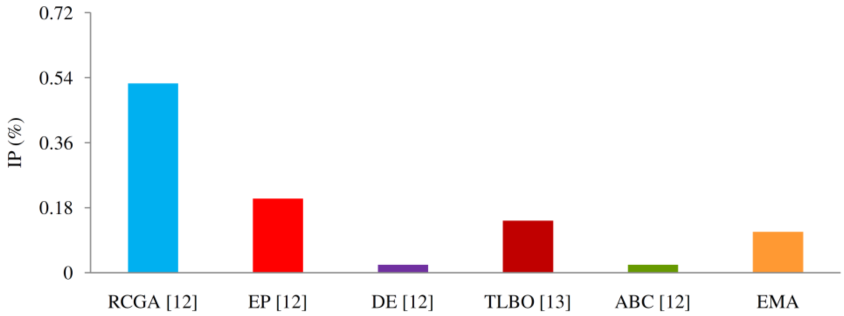
6.5. Fuel cost improvement percentage

Fuel cost improvement percentage (IP) is the ratio of obtained fuel cost difference between two approaches to get the higher value of obtained fuel cost expressed as a percentage, and is defined as [16]:

$$IP=\frac{\text{fuel cost of the compared approach - fuel cost of the suggested approach}}{\text{fuel cost of the compared approach}}\times 100 \tag{24}$$

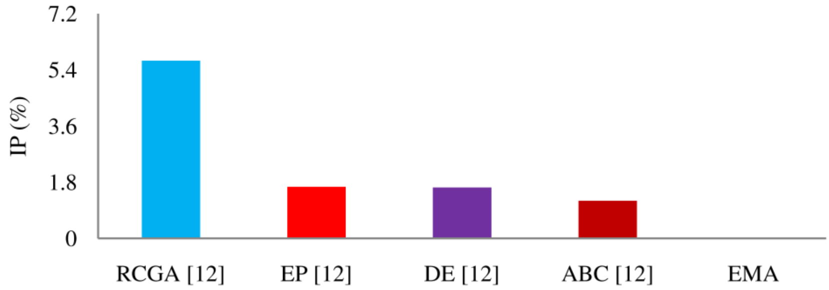


(a) case study 1



(b) case study 2

Fig. 9 Comparison of obtained Fuel cost IP by various approaches for case study 3



(C) case study 3

Fig. 9 Comparison of obtained Fuel cost IP by various approaches for case study 3 (continued)

The IPs obtained by the CFLBO approach in the comparison with the existing heuristic approaches for the case studies are shown in Fig. 9. The fuel cost IP of the CFLBO approach is compared to other approaches ranges from 0.0004% to 0.0069%, from 0.113% to 0.5234%, and from 0.0077% to 5.69% for case studies 1, 2, and 3 respectively. It is noteworthy that the IP of the CFLBO approach is high for case study 2 and case study 3. Therefore, the CFLBO approach provides better results than the other compared approaches.

6.6. *Convergence graph*

The convergence comparison of the CFLBO and EMA approaches is shown in Fig. 10. It can well be construed that the CFLBO approach requires a smaller number of iterations to converge to the globally optimal solution.

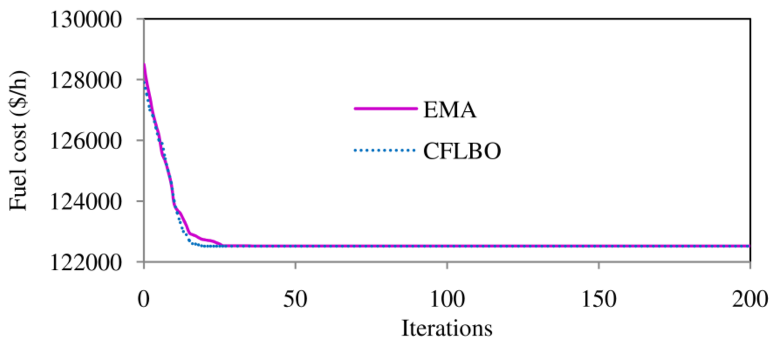
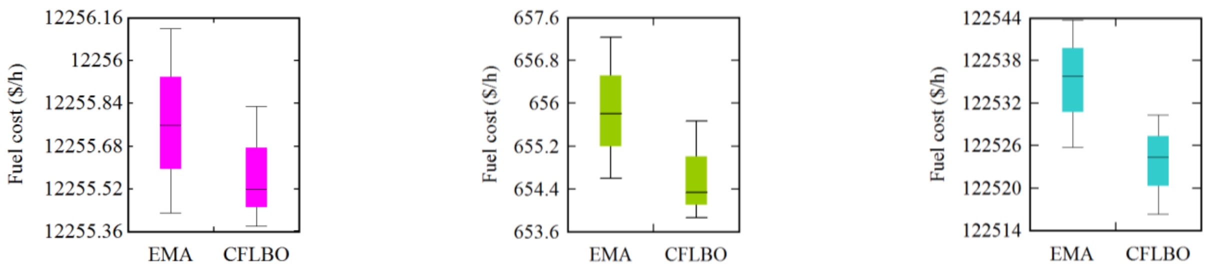


Fig. 10 Schematic diagram of four-area system

6.7. *Box-whisker plot*



(a) case study 1 (b) case study 2 (c) case study 3

Fig. 11 Box-Whisker plot for the obtained fuel costs in 50 runs

The fuels costs obtained in 50 independent trials by the CFLBO approach are depicted in the box-whisker plot in Fig. 11. The box-whisker plot is a graph which gives statistics from a five number (lowest fuel cost, lower quartile, median, upper quartile, and highest fuel cost) epitome [17]. The vertical line inside the box represents the median of obtained fuel cost in 50 runs. It is obvious from Fig. 11 that the CFLBO approach obtains fuel costs below the mean cost more often than the other approaches. Thus, the CFLBO approach is robust and more stable in achieving feasible solutions for all the case studies.

6.8. Wilcoxon rank-sum test

In this test, H_0 and H_1 indicate the null hypothesis that $\mu_{cov}(CFLBO, EMA) = \mu_{cov}(EMA, CFLBO)$ and the alternate hypothesis that $\mu_{cov}(CFLBO, EMA) \neq \mu_{cov}(EMA, CFLBO)$respectively. Ap-value less than 0.05is statistically significant, and indicates the strong evidence against the null hypothesis. Fig. 12 illustrates the p-values obtained by CFLBO versus EMA by using the Wilcoxon rank-sum test. For each case study, $\mu_{cov}(CFLBO, EMA)$is greater than $\mu_{cov}(EMA, CFLBO)$. Besides, the p-value is lower than the ideal estimate of 0.05. Both the p-value and h = 1indicate that the null hypothesis can be rejected for all the case studies. Consequently, the CFLBO approach produces statistically significant results.

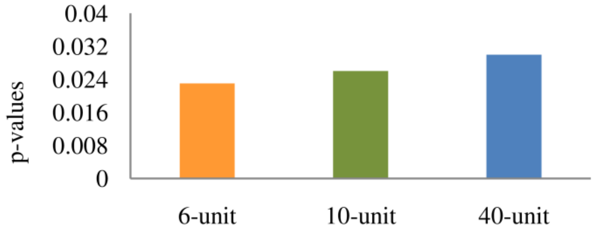


Fig. 12 Comparison of Wilcoxon test results for all the Case studies

6.9. Computational efficiency

Tables 2, 3, and 4 show that the minimum fuel costs achieved by the CFLBO approach are 12255.3847 \$/h, 654.6016 \$/h, and 122516.2835 \$/h for the case studies 1, 2, and 3 respectively. These costs are lower than the ones presented in recent literature. The CFLBO approach is definitely effective. Fig. 13 shows the number of function evaluation adopted by the CFLBO and EMA strategies for the various case studies. It is significant that the time requirement is shorter and better than those of other referenced techniques. So, in general, it tends to be noted that the CFLBO technique is more computationally effective than recently referenced strategies.

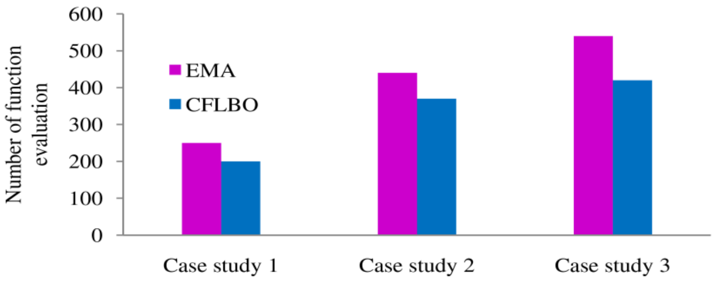


Fig. 13 Comparison of function evaluation adopted by various case studies

6.10.Confidence interval measure

A confidence interval (CI) indicates the degree of uncertainty associated with the mean of a true population. It is the sample mean plus or minus the margin of error. Typically, the CI refers to the confidence levels of 95 or 99%. The CI value depends on the sample mean, standard deviation, and z statistic. It is expressed as:

$$\mu = M \pm Z(S_M) \tag{25}$$

$$S_M = \sqrt{\frac{SD^2}{N}} \tag{26}$$

The CI values obtained by the CFLBO and EMA approaches for the various studies are shown in Fig. 14. The CFLBO approach obtains a smaller margin of error than the EMA approach. Thus, the robustness and effectiveness of the proposed approach are demonstrated.

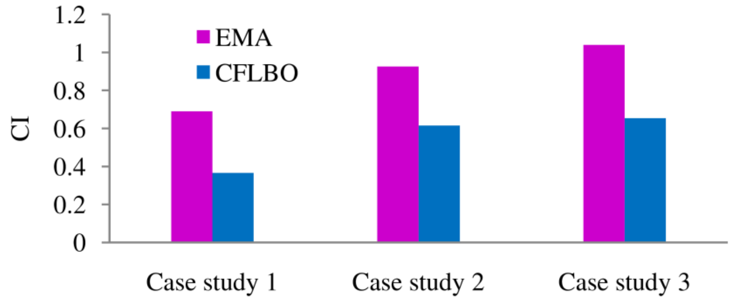


Fig. 14 Comparison of CI measure obtained by various case studies

7. Conclusions

In this paper, a new physics-inspired metaheuristic approach named Coulomb's and Franklin's Laws Based Optimizer (CFLBO) has been presented to solve the MAELD problem. Three different case studies are addressed: MAELD with transmission losses and POZs, MAELD with transmission losses, VPL and MFA impacts, and MAELD with VPL impacts for a large scale system. The viability of the envisaged approach has been tested on a two-area system with six generating units, a three-area system with 10 generating units, and a four-area system with 40 generating units. A comparative study of the envisaged CFLBO, EMA, RCGA, EP, DE, TLBO, and ABC approaches indicates that the CFLBO approach essentially outflanks other approaches in dealing with the MAELD problem.

In order to demonstrate the robustness of the suggested CFLBO approach, Wilcoxon's rank-sum test and confidence interval measures are used for statistical analysis. The results indicated that the CFLBO algorithm has better performance with statistical significance. Therefore, it can be concluded that the CFLBO algorithm is an efficient method of solving the MAELD problem.

This research work offers an optimizer that provides an amazing advance for the MAELD issue. Moreover, it advances the use of the evolutionary approaches in the energy optimization domain. For future work, it will be intriguing to implement this compelling approach to solve other economic operation problems of power systems.

Nomenclature

a_{ij}, b_{ij}, c_{ij}	Cost coefficients of generator j in area i
$a_{max}$and r_{max}	Maximum number of positive and negative charges respectively
a_0 and r_0	Initial values for positive and negative charges respectively
B_{ij}	Line loss coefficients
e_{ij}, f_{ij}	Cost coefficients of the VPL effect of generator j in area i
$F_{ij}(P_{ij})$	Fuel cost of the generator j in area i
k	Number of fuel alternatives
m	Index of prohibited zone
M	Sample mean
M_i	Number of participated generators in area i
n	Maximum number of objects
ng	Total number of generating units
nz	Total number of POZs
N	Sample size
P_{ij}	Real power generation of generator j in area i
$P^L_{ij,m}$, $P^U_{ij,m}$	Lower and upper power outputs of the m^{th} prohibited zone of the j^{th} generator in area i
P_{Di}	Power demand in area i
P_{Li}	Power losses in area i
$P_{ij,min}$, $P_{ij,max}$	Minimum and maximum generation j in area i
p_i	Ionization probabilistic constant

P_c	Contact phase probabilistic constant
q	Population size of each object
SD	Standard deviation of a sample
S_M	Standard error
T_{iz}	Tie line power stream from area *i* to area *z*
$T_{iz,max}$	Maximum tie line power stream from area *i* to area *z*
$-T_{iz,max}$	Maximum tie line power stream from area *z* to area *i*
x_{ij}	j^{th} elementary charge of the i^{th}point charge
x_j^{min} and x_j^{max}	Lower and upper limits of variable *j*
x_j^{new}	Current location of j^{th} elementary charge
x_{ij}^{old}	Previous location of j^{th} elementary charge of the i^{th}point charge
Z	Z statistic estimated by confidence level
θ_j^{new}	Current electric angle of j^{th} elementary charge in radians
θ_j^{old}	Previous electric angle of j^{th} elementary charge in radians
$\mu_{cov}(CFLBO, EMA)$	Population mean of the CFLBO solutions covering the EMA solutions
$\mu_{cov}(EMA, CFLBO)$	Population mean of the EMA solutions covering the CFLBO solutions

Conflicts of Interest

The authors declare no conflict of interest.

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