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Full Length Article

Firefly algorithm for congestion management in deregulated environment

Sumit Verma, V. Mukherjee *

Department of Electrical Engineering, Indian School of Mines, Dhanbad, Jharkhand, India

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ABSTRACT

In competitive electricity market, congestion is a serious economic and reliability concern. Congestion is a common problem that an independent system operator faces in open access electricity market. This paper presents a reliable and efficient meta-heuristic based approach to solve congestion problem. The proposed approach of the present work employs firefly algorithm (FFA) for alleviation of transmission network congestion in a pool based electricity market via active power rescheduling of generators. FFA is a new meta-heuristic approach based on flashing patterns and behavior of fireflies. Various important security constraints such as load bus voltage and line loading have been taken into account while dealing with congestion problem. The proposed methodology may help in removing the congestion of line with minimum rescheduling cost. The numerical results of modified IEEE 30- and 57-bus test power systems are illustrated.

1. Introduction

1.1. General

Before restructuring of the power system, the power grids were, usually, used to be operated by vertically integrated utilities. These utilities had common control over both generation and transmission facilities. With unbundling: generating, transmitting and distributing companies are working as independent entities and, thus, it has become a challenge for independent system operators (ISO) to operate the system in synchronism [1]. In deregulated market, all the market players are free to interact with each other. Buying and selling of electricity is done by the participants in such a way that only aims to maximize the profit, causing transmission networks to operate beyond their operational limits.

Congestion is the difference in the megawatts of the power scheduled to flow on a transmission line and the actual transfer that is allowed on the line without violating any constraints. Congestion occurs whenever one or more constraints are violated under which the system operates in the normal operating condition or in any of the specified contingencies. The constraints can be either physical limits like thermal or voltage limits or specified limits to ensure system security and reliability [2]. Increase in power demand, unexpected outage of generation, restriction on the construction of new lines, unscheduled power flow in lines, tripping of transmission lines or failures of other equipment are some of the potential causes for congestion. In a deregulated environment, congestion is a primary challenge to an ISO who is responsible in managing congestion in the transmission line and ensuring security as congestion may cause serious menace to stability of the power networks and may also result in market inefficiency and electricity price hike [3]. Rescheduling of generator outputs, supplying reactive power support or curtailment of transactions are, physically, the usual methods adopted for congestion management (CM).

1.2. Literature review

The literature survey reveals that various techniques have been used to address the serious issues related to CM. CM in open access electricity market has been discussed in References [4–6]. A detailed analysis of different CM techniques, used in different electricity markets throughout the world, may be found in Reference [4]. A minimum distance re-dispatch has been proposed in Reference [5] ignoring the economic value of the transaction adjustment. In Reference [6], the congestion is managed by using the marginal cost signals for the generators. Thukaram and Parthasarathy [7] have proposed an expert system based approach for the alleviation of network overloads using phase shifting transformers and generation rescheduling. A physical flow based CM allocation mechanism for multiple transaction networks has been discussed by Shu and Gross in Reference [8], which enables the independent grid operator to

* Corresponding author. Tel.: +91 0326 2235644; fax: +91 0326 2296563.
E-mail address: vivek_agamani@yahoo.com (V. Mukherjee).
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acquire the congestion relief services for each transaction to remove its congestion contribution at the least cost. Kumar et al. [9] have proposed a zonal model based on ac load flow in which the calculation of sensitivity values for all the buses in the system is required and, therefore, a large amount of computational effort is required to be spent. Dutta and Singh [10] have demonstrated a technique for the optimum selection of generators based on generator sensitivities to the power flow using particle swarm optimization (PSO) algorithm with an aim to solve CM problem. A method for selection of participating generators based on sensitivity to current flow on congested line as well as the generation bids has been presented by Talukdar et al. in Reference [11]. Conejo et al. [12] has addressed the CM problem by disregarding the off line transmission capacity limits related to stability which results in economical and secure operating conditions. Kumar and Chaturvedi [13] have presented integration of fuzzy systems with genetic algorithm and PSO to solve the optimal power flow (OPF) problem for optimal setting of control parameters. An approach for CM with flexible ac transmission systems in deregulated electricity market with voltage stability constraint, taking loadability parameter into consideration along with the line security limits using rescheduling of generators, is proposed by Kumar and Sekhar in Reference [14]. In Reference [15], an efficient PSO method has been used for real power rescheduling of generator for transmission CM in deregulated environment. The proper placement and sizing of proper flexible ac transmission systems (FACTs) devices based on PSO in deregulated environment has been studied in References [16,17]. The utilization of distributed generation units for CM by improving the voltage profile using PSO has been studied in Reference [18]. The application of PSO to maximize total system social welfare in a double-sided auction market by the proper allocation of FACTs devices is proposed in Reference [19]. The application of fuzzy-based genetic algorithm (GA) to maximize total system social welfare in a double-sided auction market by the best placement and sizing of FACTs devices has been proposed in References [20,21].

A methodology based on improved harmony search is proposed in Reference [22] to solve transmission expansion planning problem with adequacy-security considerations in deregulated power system. Simulated annealing (SA) has been applied on unit commitment problem by Zhuang and Galiana [23]. Jang et al. [24] have discussed a computationally simple random search method (RSM) that can be utilized to solve various optimization problems.

Firefly algorithm (FFA) is a meta-heuristic approach inspired from the flashing behavior of fireflies [25] and its prevalence is increasing rapidly in almost all branches of science and technology for the purpose of optimization. FFA has been used to solve non-linear design problem in Reference [25]. FFA has been utilized in Reference [26] to optimize the control variables for simultaneous optimization of real power loss and voltage stability limit of the transmission system. The modified FFA is used in Reference [27] to design a Smith predictor controller for integration and unstable delay processes. FFA [28] has been proposed in the current work for the rescheduling purpose to alleviate congestion in the power networks.

1.3. Motivation

Literature survey reveals that numerous techniques have been implemented by researchers in the past to solve the CM problem. A major force behind the present work is to design a novel technique to solve the CM problem. Most traditional optimization techniques do not function admirably for the issues with nonlinearity and multimodality. Current pattern is to utilize nature-propelled metaheuristic algorithms to handle such difficulties, and it has been demonstrated that metaheuristics are exceptionally productive. FFA is inspired from natural behavior of fireflies. Unlike other algorithms, a firefly works individually and tries to find the best position for itself in consideration with its current position as well as the position of other fireflies. Hence, it moves from the local minima and finds the global minima in less number of iterations. Apart from the self improving process within the current space, the FFA also includes the improvement among its own space from the previous stages. Robustness and high convergence rate make this algorithm most suitable to use for such kind of optimization problems [25].

FFA is proposed in this paper to solve CM problem. The main motivation of the present work is to aid ISO to remove congestion of lines in an optimal manner. In this paper FFA is applied on modified IEEE 30-bus and 57-bus test power systems to solve congestion problem under various considered contingencies.

1.4. Contribution

The main contributions of this work are to:

(a) project FFA as an effective optimizing tool to minimize the rescheduling cost under different contingencies for the two IEEE standard power systems: IEEE 30-bus system and IEEE 57-bus system,
(b) effectively remove the overload in the lines caused by various considered contingencies with smallest shift in generation schedule,
(c) minimize the total amount of rescheduling and losses for various considered cases and
(d) demonstrate the effectiveness of the proposed FFA over the others for this specific application.

1.5. Paper layout

The remaining portion of this paper is structured as follows. Section 2 provides the mathematical formulation of the CM problem. Section 3 explains the FFA. Section 4 deals with FFA for CM problem. Simulation results are presented and discussed in Section 5. Finally, conclusions are drawn and scope of future work is presented in Section 6.

2. Mathematical problem formulation

The main objective of the CM is to minimize the congestion cost while satisfying the network constraints. In the present work, the CM problem is solved by rescheduling (increasing or decreasing) the active power output of generators. But change in active power output is associated with cost which, in turn, depends upon the price bids submitted by generating companies (GENCOs). The problem may be stated as in Eq. (1) [15]:

Minimize

$$C_c = \sum_{j \in N_g} \left(C_k \Delta P_{Gj}^{+} + D_k \Delta P_{Gj}^{-} \right) \$/h \tag{1}$$

where $C_c, C_k, D_k, \Delta P_{Gj}^{+}$ and ΔP_{Gj}^{-} represent the total cost incurred for changing active power output (\$/h), incremental price bids submitted by GENCOs (\$/MWh), decremental price bids submitted by GENCOs (\$/MWh), active power increment of generator (MW) and active power decrement of generator (MW), respectively.

The present optimization problem is subjected to the equality and inequality constraints as stated in the next two sub-sections.

2.1. Equality constraints

The equality constraints of CM represent the power flow equations as stated in Eqs. (2) to (5) [29]:

$$P_{Gk} - P_{Dk} = \sum_{j} |V_j||V_k||Y_{kj}| \cos(\delta_k - \delta_j - \theta_{kj}); \quad j = 1, 2, \ldots, N_b \tag{2}$$

$$Q_{Gk} - Q_{Dk} = \sum_j |V_j||V_k||Y_{kj}|\sin(\delta_k - \delta_j - \theta_{kj}); \quad j = 1, 2, \ldots, N_b \tag{3}$$

$$P_{Gk} = P_{Gk}^C + \Delta P_{Gk}^+ - \Delta P_{Gk}^-; \quad k = 1, 2, \ldots, N_g \tag{4}$$

$$P_{Dj} = P_{Dj}^C; \quad j = 1, 2, \ldots, N_d \tag{5}$$

where P_{Gk} and Q_{Gk} are the generated active and reactive power at bus k, respectively; P_{Dk} and Q_{Dk} are the active and reactive load power at bus k, respectively; V_j and V_k are voltages at bus j and k, respectively; δ_j and δ_k are bus voltage angles of bus j and k, respectively; θ_{kj} is admittance angle of line connected between k and j; N_b, N_g, and N_d are number of buses, generators and loads, respectively; P_{Gk}^C and P_{Dj}^C are the active power produced by generator k and active power consumed by load bus j, respectively, as obtained by the market clearing value.

It is to be noted here that Eqs. (2) and (3) show active and reactive power balance at each node while Eqs. (4) and (5) represent final power as a function of market clearing price.

2.2. Inequality constraints

The inequality constraints represent the operating and physical limit of all the transmission lines, transformers and generators and are stated in Eqs. (6) to (10) [29]:

$$P_{Gk}^{\min} \le P_{Gk} \le P_{Gk}^{\max}, \quad \forall k \in Ng \tag{6}$$

$$Q_{Gk}^{\min} \le Q_{Gk} \le Q_{Gk}^{\max}, \quad \forall k \in Ng \tag{7}$$

$$(P_{Gk} - P_{Gk}^{\min}) = \Delta P_{Gk}^{\min} \le \Delta P_{Gk} \le \Delta P_{Gk}^{\max} = (P_{Gk}^{\max} - P_{Gk}) \tag{8}$$

$$V_n^{\min} \le V_n \le V_n^{\max}, \quad \forall n \in N_l \tag{9}$$

$$P_{ij} \le P_{ij}^{\max} \tag{10}$$

where the superscripts *min* and *max* represent the minimum and maximum values of the respected variables and N_l represents the number of lines.

3. FFA

FFA is inspired by the flashing characteristics of fireflies to attract their mating partners and is developed by Yang [25]. A brief overview of this algorithm is provided in the next two sub-sections.

3.1. FFA: features

The pattern of flashes produced by bioluminescence is unique for a particular species of fireflies. FFA, based on the nature of fireflies, follows three idealized rules as mentioned below [28].

(a) Each and every firefly is unisex and, hence, one firefly is attracted to the other regardless of its sex.
(b) Attraction is proportional to the brightness of the fireflies. For any two fireflies, the one having less brightness moves toward the other having more brightness. The intensity of flashes is inversely proportional to the distance between the two fireflies. So, as the distance increases, brightness and, hence, attraction between the two fireflies, decreases. The brightest firefly moves randomly in the population.
(c) The brightness of a firefly is determined by the objective function value.

3.2. Light intensity and attractiveness

Two important things that should be considered in FFA are the variation of the light intensity and formulation of attractiveness. The attractiveness of a particular firefly is determined by its brightness which, in turn, is associated with the objective function value. The attractiveness (termed as β) is relative, as it is seen and judged by the other fireflies and it increases as the distance between the two fireflies decreases. Also, light intensity decreases with the increase in distance from the source and light is also absorbed in the medium of its propagation. So, a degree of attractiveness is to be set in order to vary β. The light intensity, $(I(r))$, varies monotonically and exponentially with the distance (r) between the two fireflies and it is expressed as in Eq. (11):

$$I(r) = I_0 \exp(-\gamma r) \tag{11}$$

where I_0 and γ are the original light intensity and light absorption co-efficient, respectively.

As a firefly's attractiveness is proportional to the light intensity seen by other fireflies, the attractiveness β can be defined as in Eq. (12):

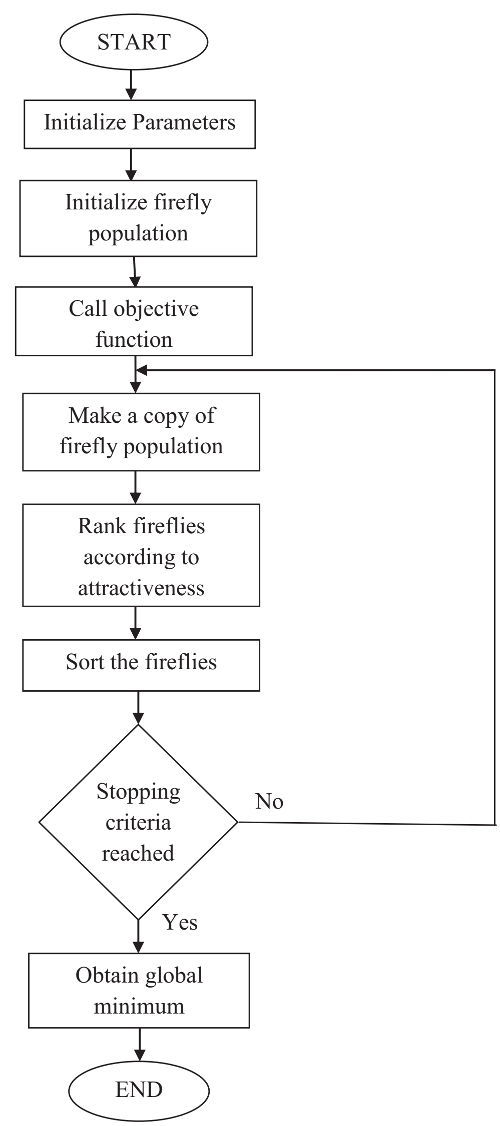

Fig. 1. Flowchart of the FFA.

$$\beta(r) = \beta_0 \exp(-\gamma r^2) \tag{12}$$

where β_0 is the attractiveness at $r = 0$.

The distance between any two fireflies *i* and *j*, located at positions x_i and x_j, respectively, is the Cartesian distance given by Eq. (13):

$$r_{ij} = \|x_i - x_j\| = \sqrt{\sum_{k=1}^{d}(x_{i,k} - x_{j,k})^2} \tag{13}$$

where $x_{i,k}$ and $x_{j,k}$ are the components of the spatial co-ordinates x_i and x_j of i^{th} and j^{th} firefly, respectively and *d* is the dimension of the problem.

The movement of i^{th} firefly, attracted to any brighter firefly *j* is given by Eq. (14).

$$x_i = x_i + \beta_0 \exp(-\gamma r_{ij}^2) \times (x_j - x_i) + \alpha \times (rand - 0.5) \tag{14}$$

In Eq. (14), the first term represents the current position of i^{th} firefly, the second term represents the attractiveness to other brighter fireflies and the third term represents a random walk associated with a randomization parameter α. *rand* is a uniformly distributed random number generated in the range [0,1] and the range of α is, usually, taken as [0,1]. The parameter γ characterizes the variation of attractiveness and its value is, significantly, important as it determines the behavior and convergence of FFA and it has the range $[0, \infty]$.

The operation of FFA may be summarized to the pseudo-code [28], presented in Algorithm 1. The flowchart of the FFA is presented in Fig. 1.

The inequality constraints are converted to the penalty functions and these penalty functions are added to the objective function. In this paper, the equality constraints are handled effectively during Newton–Raphson power flow [30] and the active power inequality constraints are handled during the execution of iteration. Reactive power inequality constraints are handled during the load flow solution. Other inequality constraints such as load bus voltage and line power flow are considered as quadratic penalty functions. The fitness function of CM problem may be described as in Eq. (15) [15]:

$$\text{Minimize} \quad F_f = C_c + PF_1 \times \sum_{i=1}^{ovl}(P_{ij} - P_{ij}^{\max})^2 + PF_2 \times \sum_{j=1}^{VB}(\Delta V_j)^2 + PF_3 \times (\Delta P_G)^2 \tag{15}$$

where

$$\Delta V_j = \begin{cases} (V_j^{\min} - V_j); & \text{if } V_j \le V_j^{\min} \\ (V_j - V_j^{\max}); & \text{if } V_j \ge V_j^{\max} \end{cases} \tag{16}$$

$$\Delta P_G = \begin{cases} (P_G^{\min} - P_G); & \text{if } P_G \le P_G^{\min} \\ (P_G - P_G^{\max}); & \text{if } P_G \ge P_G^{\max} \end{cases} \tag{17}$$

Here, F_f is fitness function which is required to be minimized in order to get minimum rescheduling cost; *ovl* and *VB* represent set of the overloaded lines and voltage violated load buses, respectively, and PF_i $(i = 1, 2, 3)$ represent penalty factors which has been taken as 10,000 throughout the simulation process [15]. Moreover, the second, third and fourth terms are added to the fitness function, keeping in mind the possibilities of violations.

Algorithm 1: Pseudo-code of FFA

```
Define objective function f(X); X = (x_1, x_2, ..., x_d)^T
Initialize a population of fireflies X_i; i = (1,2,3,...,n)     % n be the total number of fireflies
Define light absorption co-efficient γ
Determine light intensity I_i at X_i via f(X_i)
while (t < MaxGeneration)
    for i = 1: n
        for j = 1: n
            if (I_j > I_i)
                Move i^th firefly towards j^th firefly in all d-dimensions using (14)
                                                   % d is the dimension of the problem
            end if
            Obtain attractiveness, which varies with distance r according to (12)
            Find new solutions and update light intensity
        end for
    end for
    Rank the fireflies and find the current global best solution
end while
```

4. FFA for CM problem

In this work, each population has *N* number of design variables where *N* is the number of generators taking part in the CM problem. Usually, the objective function is considered as the fitness function. In this work, penalty approach [15] is adopted, which penalizes the constraints and builds a single objective function which, in turn, is minimized by using an optimization algorithm.

4.1. Computational procedure of FFA for CM

Based on the above discussions, the procedure in applying the proposed FFA algorithm for the solution of CM problem is given below.

Step 1 Read the bus data, the line data, the price bids and the generator information.
Step 2 Create contingency by either line outage or increase in load.
Step 3 Run load flow while satisfying equality constraints stated in Eqs. (2) to (5). Hence, find the excess power flow and bus voltage violation, if any.
Step 4 Initial population of fireflies is generated using Eq. (6), which is the amount of rescheduling required by the generators to manage congestion (randomly within the limits).
Step 5 For each generated population of fireflies, load flow is performed and, hence, the fitness function is evaluated by using Eq. (15) and the best solution is identified. During the execution of iteration, Eqs. (9), (10), (16), and (17) are checked.
Step 6 The positions of all the fireflies are modified with reference to their attractiveness using Eqs. (12) to (14).
Step 7 The fitness function, defined in Eq. (15), is evaluated with modified fireflies. Any two fireflies are randomly selected and their fitness values are compared. The firefly with better fitness value is accepted while the other is rejected.
Step 8 If maximum number of iteration is reached then the program is stopped; otherwise, it goes back to Step 6.

5. Simulation results and discussion

In the present work, FFA for CM is implemented using MATLAB (version 7.6.0) software on an Intel Core i3 Processor based system with 2.4 GHz clock speed and supported by 4 GB of RAM. To verify the effectiveness of the proposed FFA in solving CM problem, simulations are carried out on modified IEEE 30-bus and 57-bus test systems. The bus data and line data may be found in the Appendix section (Tables A1 and A2 for modified IEEE 30-bus test system and Tables A3 and A4 for modified IEEE 57-bus test system). The price bids offered by the GENCOs to ISO for modified IEEE 30- and IEEE 57-bus test systems are given in Tables A5 and A6, respectively. Generation rescheduling cost is calculated for the simulated cases and is compared with results reported in Reference [15].

Details of simulated cases carried out on the two test systems are given in Table 1. Congestion is created in lines for the simulation purpose by overloading the lines. In this paper, line overloads are created either by reducing the capacity of lines as to the compared standard limits or by considering generator or line outage.

The proposed FFA has been executed for 100 independent trial runs, out of which the best solution set is presented here. The values of α and γ are taken in the range of 0 to 1, while the value of β_0 is kept constant at 10. It has been found that population of 40 fireflies is sufficient in solving the CM problem of the present work. The maximum number of iteration is set to 150 for all the test cases. The major observations of the present work are documented below. Results of interest are **bold faced** in the respective tables.

5.1. Example 1: modified IEEE 30-bus test system

The modified IEEE 30-bus test system is taken for consideration as Example 1. It has forty-one transmission lines, twenty-four load buses and six generator buses. The total active and reactive power of load for this test system is 283.4 MW and 126.2 MVAR, respectively. Generation and load values (provided in the Appendix section), are taken as the initial market clearing values for P_G and P_D, respectively. Contingencies like unexpected line outage and increase in system load are considered for the simulation purpose. Two different cases of this example viz. case 1A and case 1B (Table 1) are considered for this example.

Table 1
Simulated cases.

Test system	Test case	Contingency considered
Modified IEEE 30-bus	1A	Outage of line 1–2
	1B	Outage of line 1–7 with increase in load at all buses by 50%
Modified IEEE 57-bus	2A	Reduction in capacity of lines 5–6 and 6–12 from 200 MW to 175 MW and from 50 MW to 35 MW, respectively
	2B	Reduction in capacity of line 2–3 from 85 MW to 20 MW.

5.1.1. Case 1A

In this case, congestion is created by considering outage of line number-1 connected between bus-1 and bus-2. Due to outage of line 1, congestion occurs in lines number-2 and -4, connected between buses 1–7 and 7–8, respectively. OPF [29] results reveal that power flows in those lines become 147.463 MW and 136.292 MW, respectively, against the line flow limit of 130 MW for both lines. Details of the congested lines are presented in Table 2. Hence, the congestion has to be alleviated by the optimal rescheduling of active power generation of generators. The results, obtained by employing the proposed FFA for the solution of CM problem for case 1A of Example 1, are tabulated in Table 3. For comparison purpose, the results obtained from RSM, SA and PSO techniques reported in Reference [15] are also included in the same table. From Table 3 it may be concluded that the results obtained by proposed FFA is the best, providing minimum rescheduling cost compared to other methods reported in the literature, without overloading the other lines. The proposed FFA gives the best solution as **511.8737 $/h** (Table 3). The total system loss before CM was 16.023 MW while the same is decreased to **13.10 MW** after CM. A comparative pictorial representation of active power rescheduling and congestion cost offered by different methods like PSO [15], RSM [15] and SA [15] are shown in Figs. 2 and 3, in order. The convergence profile of fitness function for this test case, as yielded by the proposed FFA, is shown in Fig. 4.

5.1.2. Case 1B

For this case, congestion is created by considering outage of line number-2 connected between bus-1 and bus-7 accompanied by

Table 2
Details of congested lines for modified IEEE 30-bus test system corresponding to Case 1A.

Test case	Congested lines	Actual flow (MW)	Line limit (MW)
1A	1–7	147.463	130
	7–8	136.292	130

Table 3
Comparison of results obtained from different algorithms for modified IEEE 30-bus test system corresponding to Case 1A.

Parameters	Techniques			
	FFA [Proposed]	PSO [15]	RSM [15]	SA [15]
Total congestion cost ($/h)	**511.8737**	538.95	716.25	719.861
Power flow (MW) on previously congested line 1–7	**129.812**	129.97	129.78	129.51
Power flow (MW) on previously congested line 7–8	**120.617**	120.78	120.60	120.35
ΔP_{G1} (MW)	**−8.7783**	−8.6123	−8.8086	−9.0763
ΔP_{G2} (MW)	**+15.0008**	+10.4059	+2.6473	+3.1332
ΔP_{G3} (MW)	**+0.1068**	+3.0344	+2.9537	+3.2345
ΔP_{G4} (MW)	**+0.0653**	+0.0170	+3.0632	+2.9681
ΔP_{G5} (MW)	**+0.1734**	+0.8547	+2.9136	+2.9540
ΔP_{G6} (MW)	**−0.6180**	−0.0122	+2.9522	+2.4437
Total generation rescheduled (MW)	**24.7425**	22.936	23.339	23.809

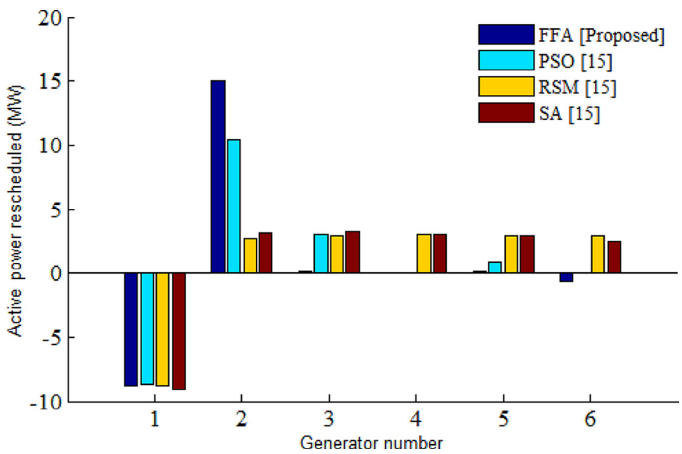

Fig. 2. Comparative active power rescheduling of generators for modified IEEE 30-bus test system corresponding to Case 1A.

increase of load at all the buses by 50%. This considered contingency causes overloading of lines connected between buses 1–2, 2–8 and 2–9 with power flow of 310.917 MW, 97.353 MW and 103.524 MW, respectively, which are beyond the limits of their maximum power flow limits (130 MW for line 1–2 and 65 MW each for both the lines 2–8 and 2–9). Table 4 shows the list of overloaded lines for this case. In this case, total power violation due to congestion in the transmission lines is found to be 251.794 MW. To alleviate this overloading, the optimum rescheduling of generators are carried out by using FFA and the obtained results are presented in Table 5. The results yielded by proposed FFA are compared with the results reported in Reference [15] while adopting PSO, RSM and SA. The cost for CM is visibly less for the proposed FFA method than for other methods reported in Reference [15]. Also, the total system loss is decreased to **16.264 MW** after CM, which was initially 37.8 MW during congestion. The up/down adjustment of active power generated by the generators, as offered by the proposed FFA method, is shown in Fig. 5. The comparative total cost incurred while removing congestion for this case is plotted in Fig. 6. The convergence of fitness function, as offered by the proposed FFA with the number of iterations, for this test case is plotted in Fig. 7.

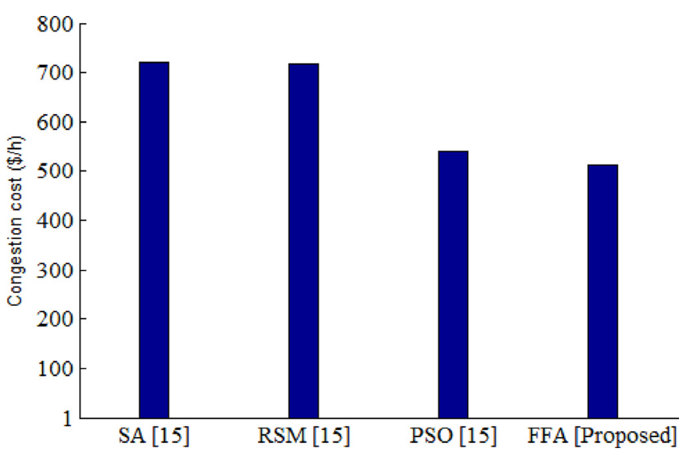

Fig. 3. Congestion cost offered by different algorithms for modified IEEE 30-bus test system corresponding to Case 1A.

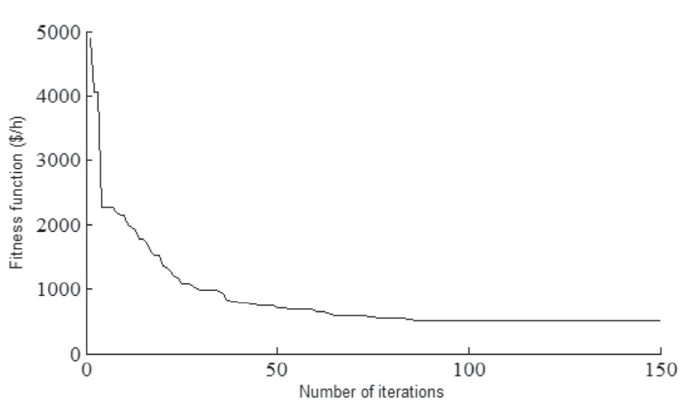

Fig. 4. FFA based convergence profile of fitness function value for modified IEEE 30-bus test system corresponding to Case 1A.

Table 4
Details of congested lines for modified IEEE 30-bus test system corresponding to Case 1B.

Test case	Congested lines	Actual flow (MW)	Line limit (MW)
1B	1–2	310.917	130
	2–8	97.353	65
	2–9	103.524	65

Table 5
Comparison of results obtained from different algorithms for modified IEEE 30-bus test system corresponding to Case 1B.

Parameters	Techniques			
	FFA [Proposed]	PSO [15]	RSM [15]	SA [15]
Total congestion cost ($/h)	**5304.40**	5335.5	5988.05	6068.7
Power flow (MW) on previously congested line 1–2	**130**	129.7	129.91	129.78
Power flow (MW) on previously congested line 2–8	**62.713**	61.1	52.36	51.47
Power flow (MW) on previously congested line 2–9	**64.979**	64.67	55.43	54.04
ΔP_{G1} (MW)	**–8.5798**	NR	NR	NR
ΔP_{G2} (MW)	**+75.9954**	NR	NR	NR
ΔP_{G3} (MW)	**+0.0575**	NR	NR	NR
ΔP_{G4} (MW)	**+42.9944**	NR	NR	NR
ΔP_{G5} (MW)	**+23.8325**	NR	NR	NR
ΔP_{G6} (MW)	**+16.5144**	NR	NR	NR
Total generation rescheduled (MW)	**167.974**	168.03	164.55	164.53

NR means not reported in the referred literature.

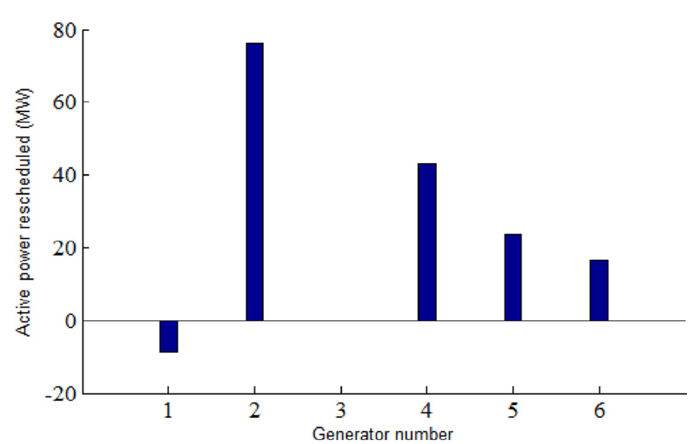

Fig. 5. FFA based active power rescheduling of generators for modified IEEE 30-bus test system corresponding to Case 1B.

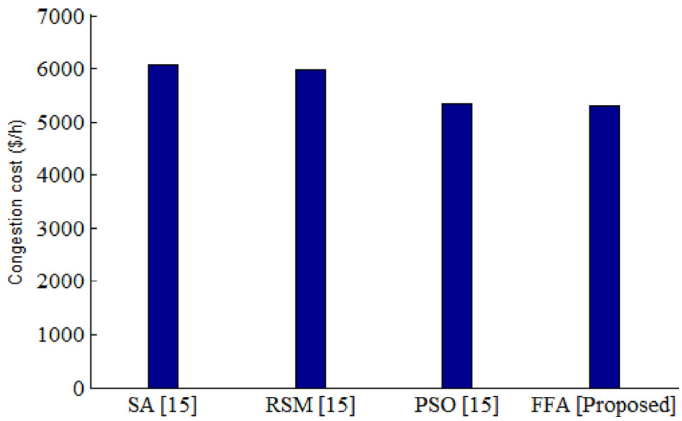

Fig. 6. Congestion cost offered by different algorithms for modified IEEE 30-bus test system corresponding to Case 1B.

5.2. Example 2: IEEE 57-bus test system

Modified IEEE 57-bus test system consists of seven generator buses, fifty load buses and eighty transmission lines and is chosen as Example 2. The total active and reactive power loads are 1250.8 MW and 336 MVAR, respectively. The two different simulation cases considered for this example are case 2A and 2B, as presented in Table 1.

5.2.1. Case 2A

In this case, the line limits are taken as 175 MW for the line 5–6 and 35 MW for the line 6–12, instead of their original power flow limit of 200 MW and 50 MW, respectively, to create congestion (Table 1). The details of congested lines are provided in Table 6. Due to this congestion, the lines 5–6 and 6–12 get overloaded and total power violation becomes 35.322 MW. Optimum generator rescheduling is performed using the proposed FFA to completely alleviate this overloading of 35.322 MW. The details of the results obtained are listed in Table 7 and these results are compared with those yielded by PSO [15], RSM [15] and SA [15]. A comparison of the amount of active power rescheduling required for CM, as offered by PSO, RSM and SA is presented in Fig. 8. Fig. 9 exhibits the comparative congestion cost offered by SA, RSM, PSO and the proposed FFA method. It may be noted from Table 8 and Fig. 9 that the total cost of CM, obtained from proposed FFA method, is only **6050.1 $/h**, which is the lowest among the costs obtained from the other three methods, SA, RSM and PSO. The total system loss before CM

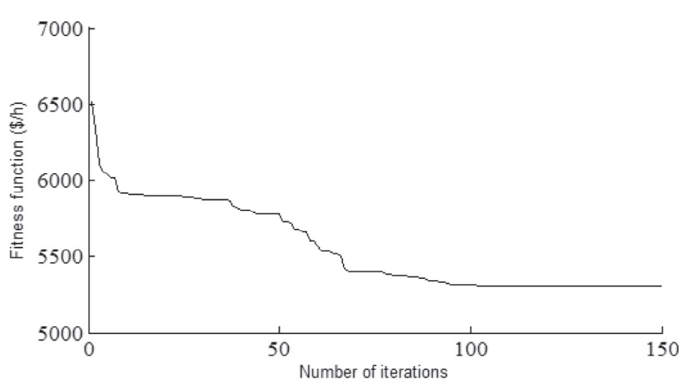

Fig. 7. FFA based convergence profile of fitness function value for modified IEEE 30-bus test system corresponding to Case 1B.

Table 6
Details of congested lines for modified IEEE 57-bus test system corresponding to Case 2A.

Test case	Congested lines	Actual flow (MW)	Line limit (MW)
2A	5–6	195.971	175
	6–12	49.351	35

Table 7
Comparison of results obtained from different algorithms for modified IEEE 57-bus test system corresponding to Case 2A.

Parameters	Techniques			
	FFA [Proposed]	PSO [15]	RSM [15]	SA [15]
Total congestion cost ($/h)	**6050.1**	6951.9	7967.1	7114.3
Power flow (MW) on previously congested line 5–6	**174.318**	141	148.4	146.60
Power flow (MW) on previously congested line 6–12	**34.993**	34.67	35	34.84
ΔP_{G1} (MW)	**+5.6351**	+23.135	+59.268	+74.499
ΔP_{G2} (MW)	**+2.5230**	+12.447	0	0
ΔP_{G3} (MW)	**+0.5098**	+7.493	+37.452	−1.515
ΔP_{G4} (MW)	**+0.107**	−5.385	−47.391	+9.952
ΔP_{G5} (MW)	**−39.1514**	−81.216	−52.125	−85.920
ΔP_{G6} (MW)	**−35.1122**	0	0	0
ΔP_{G7} (MW)	**+62.1938**	+39.03	0	0
Total generation rescheduled (MW)	**145.227**	168.70	196.23	171.87

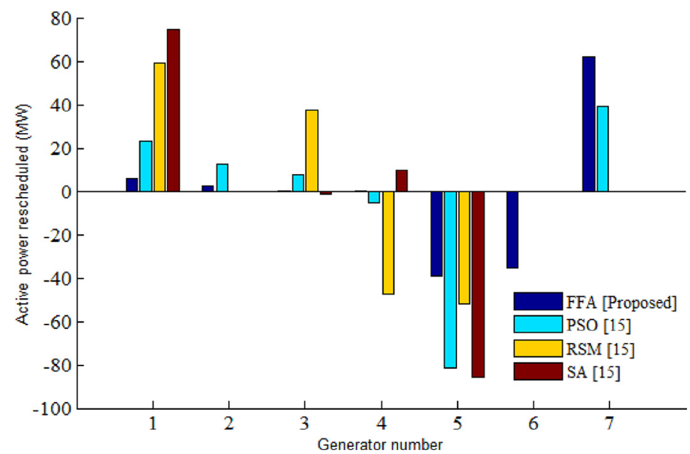

Fig. 8. Comparative active power rescheduling of generators for modified IEEE 57-bus test system corresponding to Case 2A.

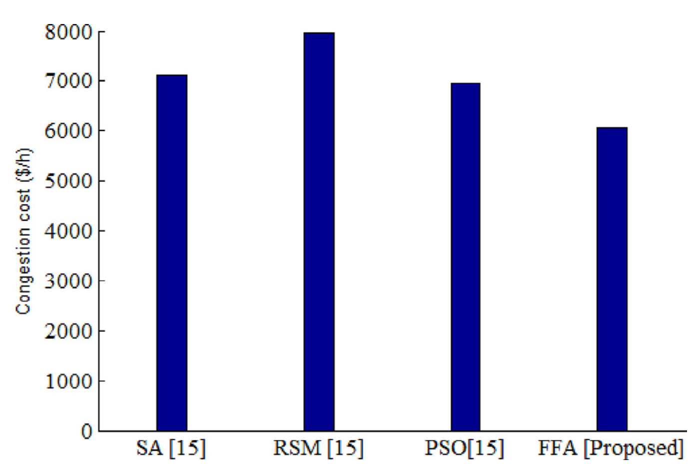

Fig. 9. Congestion cost offered by different algorithms for modified IEEE 57-bus test system corresponding to Case 2A.

Table 8
Details of congested lines for modified IEEE 57-bus test system corresponding to Case 2B.

Test case	Congested lines	Actual flow (MW)	Line limit (MW)
2B	2–3	37.048	20

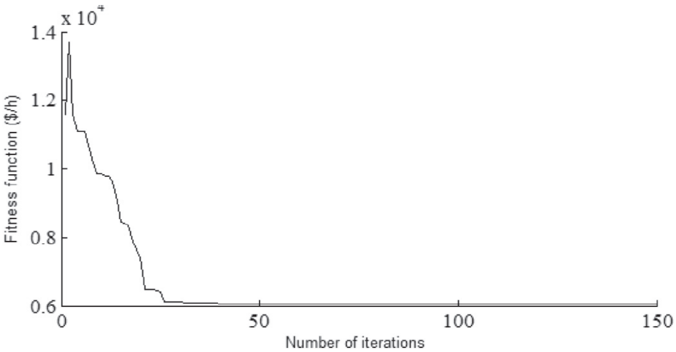

Fig. 10. FFA based convergence profile of fitness function value for modified IEEE 57-bus test system corresponding to Case 2A.

was 21.458 MW and it is decreased to 17.64 MW after CM while adopting proposed FFA (Table 7). Fig. 10 portrays the convergence profile of fitness function, as obtained by the proposed FFA.

5.2.2. Case 2B

In this case, line 2–3 is made to be overloaded by reducing its capacity to 20 MW from the original value of 85 MW. Under base load condition, the power flow in this line is 37.048 MW and, hence, it gets overloaded and the total power violation becomes 17.048 MW (Table 8). To relieve this amount of power overloading, active power rescheduling of the generators are carried out by using the proposed FFA method. The details of the results obtained while adopting the proposed FFA and the other methods reported in the literature like PSO [15], RSM [15] and SA [15] are listed in Table 9. From Table 9, it is clear that the cost incurred for CM is only **2618.1 $/h** for the proposed FFA method, which is the lowest one among all the costs, obtained from different reported methods. The total system loss is decreased to 21.062 MW after CM, which was 21.458 MW initially. The optimal rescheduling of active power generation required for this case is shown in Fig. 11. It is evident from Fig. 11 that incremental change in active power generation is required for generators 1, 3 and 4, and for all the remaining generators, a decremental change is required. Comparative congestion cost offered by different algorithms like SA [15], RSM [15] and PSO [15] and the proposed FFA are displayed in Fig. 12. The convergence of the fitness function value for this test case, based on the proposed FFA method, is shown in Fig. 13.

Table 9
Comparison of results obtained from different algorithms for modified IEEE 57-bus test system corresponding to Case 2B.

Parameters	Techniques			
	FFA [Proposed]	PSO [15]	RSM [15]	SA [15]
Total congestion cost ($/h)	**2618.1**	3117.6	3717.9	4072.9
Power flow (MW) on previously congested line 2–3	**19.79**	19.88	20	18.43
ΔP_{G1} (MW)	**+0.3704**	NR	NR	NR
ΔP_{G2} (MW)	**–27.5084**	NR	NR	NR
ΔP_{G3} (MW)	**+31.6294**	NR	NR	NR
ΔP_{G4} (MW)	**+0.3308**	NR	NR	NR
ΔP_{G5} (MW)	**–2.2549**	NR	NR	NR
ΔP_{G6} (MW)	**–1.9354**	NR	NR	NR
ΔP_{G7} (MW)	**–0.5101**	NR	NR	NR
Total generation rescheduled (MW)	**64.5393**	76.314	89.320	97.887

NR means not reported in the referred literature.

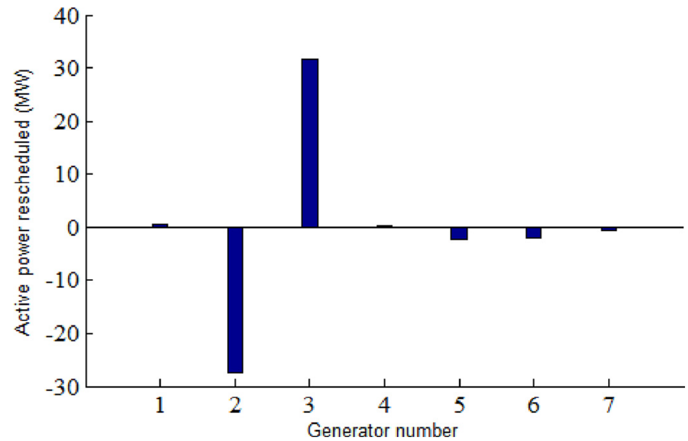

Fig. 11. FFA based active power rescheduling of generators for modified IEEE 57-bus test system corresponding to Case 2B.

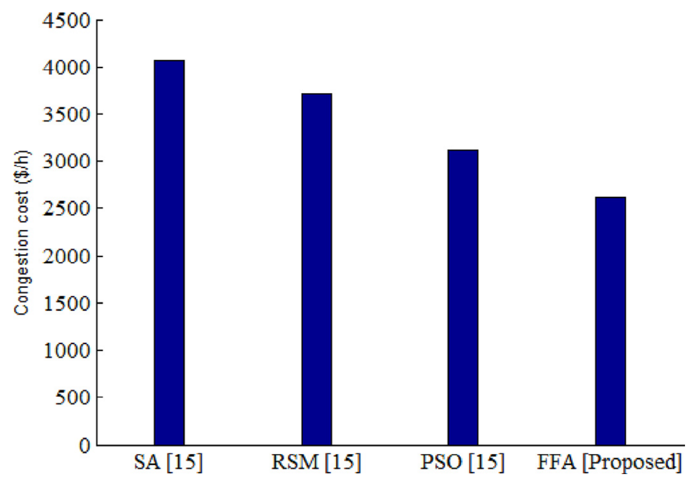

Fig. 12. Comparative congestion cost for modified IEEE 57-bus test system corresponding to Case 2B.

6. Conclusion and scope of future work

This paper demonstrates a novel optimization technique for solution of the CM problem in open access electricity market. FFA is,

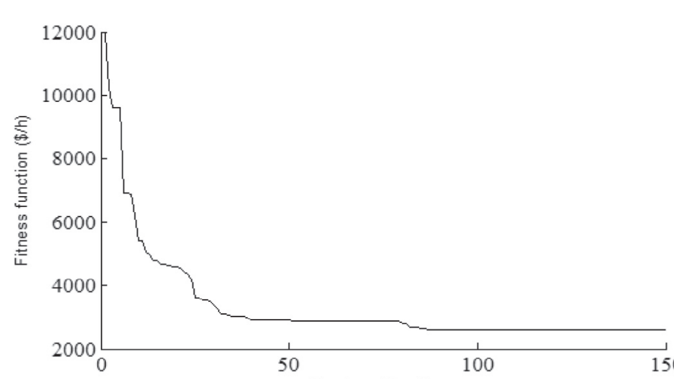

Fig. 13. FFA based convergence profile of fitness function value for modified IEEE 57-bus test system corresponding to Case 2B.

successfully, implemented to minimize the rescheduling cost for alleviating congestion completely. Contingencies like line outage and sudden load variation are considered in this work. The proposed method is implemented on modified IEEE 30- and IEEE 57-bus systems and the results are compared with random search method, simulated annealing and PSO. It is observed that the proposed FFA effectively relieves congestion, and rescheduling cost obtained is much lower than the costs reported by the other approaches. Moreover, total amount of rescheduling and losses are also found to be lower.

From all the considered simulated cases, it may be observed that FFA is a potential tool to solve a non-linear, multimodal problem. Compared to other optimization algorithms like PSO, SA and RSM, FFA has added advantage of random reduction, lesser time to produce optimum value and automatic subdivision among the fireflies. Apart from the self improving process within the current space, the FFA also includes the improvement among its own space from the previous stages. Thus, it may be concluded that FFA is a powerful and strong approach to solve optimization problems, providing most economical, reliable and secure operating conditions. Use of sensitivity analysis for selection of participating generators along with rescheduling may be the direction of future research work. FFA may be recommended as an effective optimization tool for some other power engineering optimization applications.

Appendix

Bus data and line data for modified IEEE 30-bus system are presented in Tables A1 and A2, respectively, while those for modified IEEE 57-bus system are given in Tables A3 and A4, respectively. Price bids submitted by GENCOs for modified IEEE 30- and 57-bus systems are given by Tables A5 and A6, respectively.

Table A1
Bus data for modified IEEE 30-bus test system.

Bus no.	Bus code	Voltage (V)	Angle (°)	Generation		Load		Generation	
				MW	MVAR	MW	MVAR	Q_{min}	Q_{max}
1	1	1.06	0.0	138.59	0.0	0.0	0.0	−30	100
2	2	1.043	0.0	57.56	50.0	21.7	12.7	−30	100
3	2	1.01	0.0	24.56	37.0	94.2	19.0	−30	100
4	2	1.01	0.0	35.0	37.3	30.0	30.0	−30	100
5	2	1.082	0.0	17.91	16.2	0.0	0.0	−30	100
6	2	1.071	0.0	16.93	10.6	0.0	0.0	−30	100
7	0	1.0	0.0	0.0	0.0	2.4	1.2	0.0	0.0
8	0	1.01	0.0	0.0	0.0	7.6	1.6	0.0	0.0
9	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0	1.0	0.0	0.0	0.0	22.8	10.9	0.0	0.0
11	0	1.802	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0	1.0	0.0	0.0	0.0	5.8	2.0	0.0	0.0
13	0	1.071	0.0	0.0	0.0	11.2	7.5	0.0	0.0
14	0	1.0	0.0	0.0	0.0	6.2	6.2	0.0	0.0
15	0	1.0	0.0	0.0	0.0	8.2	2.5	0.0	0.0
16	0	1.0	0.0	0.0	0.0	3.5	1.8	0.0	0.0
17	0	1.0	0.0	0.0	0.0	9.0	5.8	0.0	0.0
18	0	1.0	0.0	0.0	0.0	3.2	0.9	0.0	0.0
19	0	1.0	0.0	0.0	0.0	9.5	3.4	0.0	0.0
20	0	1.0	0.0	0.0	0.0	2.2	0.7	0.0	0.0
21	0	1.0	0.0	0.0	0.0	17.5	11.2	0.0	0.0
22	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	0	1.0	0.0	0.0	0.0	3.2	1.6	0.0	0.0
24	0	1.0	0.0	0.0	0.0	8.7	6.7	0.0	0.0
25	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	0	1.0	0.0	0.0	0.0	3.5	2.3	0.0	0.0
27	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	0	1.0	0.0	0.0	0.0	2.4	0.9	0.0	0.0
30	0	1.0	0.0	0.0	0.0	10.6	1.9	0.0	0.0

Table A2
Line data for modified IEEE 30-bus test system.

Start bus	End bus	R (p.u.)	X (p.u.)	B/2 (p.u.)	Line limit (MW)	Start bus	End bus	R (p.u.)	X (p.u.)	B/2 (p.u.)	Line limit (MW)
1	2	0.0192	0.0575	0.0264	130	15	18	0.1073	0.2185	0.0	16
1	7	0.0452	0.1652	0.0204	130	18	19	0.0639	0.1292	0.0	16
2	8	0.0570	0.1737	0.0184	65	19	20	0.0340	0.0680	0.0	32
7	8	0.0132	0.0379	0.0042	130	12	20	0.0936	0.2090	0.0	32
2	3	0.0472	0.1983	0.0209	130	12	17	0.0324	0.0845	0.0	32
2	9	0.0581	0.1763	0.0187	65	12	21	0.0348	0.0749	0.0	32
8	9	0.0119	0.0414	0.0045	90	12	22	0.0727	0.1499	0.0	32
3	10	0.0460	0.1160	0.0102	70	21	22	0.0116	0.0236	0.0	32
9	10	0.0267	0.0820	0.0085	130	15	23	0.1000	0.2020	0.0	16
9	4	0.0120	0.0420	0.0045	32	22	24	0.1150	0.1790	0.0	16
9	11	0.0	0.2080	0.0	65	23	24	0.1320	0.2700	0.0	16
9	12	0.0	0.5560	0.0	32	24	25	0.1885	0.3292	0.0	16
11	5	0.0	0.2080	0.0	65	25	26	0.2544	0.3800	0.0	16
11	12	0.0	0.1100	0.0	65	25	27	0.1093	0.2087	0.0	16
8	13	0.0	0.2560	0.0	65	28	27	0.0	0.3960	0.0	65
13	6	0.0	0.1400	0.0	65	27	29	0.2198	0.4153	0.0	16
13	14	0.1231	0.2559	0.0	32	27	30	0.3202	0.6027	0.0	16
13	15	0.0662	0.1304	0.0	32	29	30	0.2399	0.4533	0.0	16
13	16	0.0945	0.1987	0.0	32	4	28	0.0636	0.2000	0.0214	32
14	15	0.2210	0.1997	0.0	16	9	28	0.0169	0.0599	0.065	32
16	17	0.0824	0.1923	0.0	16						

Table A3
Bus data for modified IEEE 57-bus test system.

Bus no.	Bus code	Voltage (V)	Angle (°)	Generation		Load		Generation	
				MW	MVAR	MW	MVAR	Q_{min}	Q_{max}
1	1	1.04	0.0	146.39	0.0	55.0	17.0	–140	200.0
2	2	1.01	0.0	87.55	0.0	3.0	88.0	–40	50.0
3	2	0.99	0.0	41.97	0.0	41.0	21.0	–40	60.0
4	2	0.98	0.0	89.67	0.0	75.0	2.0	–30	25
5	2	1.01	0.0	461.21	0.0	150.0	22.0	–140	200
6	2	0.98	0.0	100.0	0.0	121.0	26.0	–30	9
7	2	1.02	0.0	344.95	0.0	377.0	24.0	–150	155
8	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0	1.0	0.0	0.0	0.0	13.0	4.0	0.0	0.0
10	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0	1.0	0.0	0.0	0.0	5.0	2.0	0.0	0.0
12	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	0	1.0	0.0	0.0	0.0	18.0	2.3	0.0	0.0
14	0	1.0	0.0	0.0	0.0	10.5	5.3	0.0	0.0
15	0	1.0	0.0	0.0	0.0	22.0	5.0	0.0	0.0
16	0	1.0	0.0	0.0	0.0	43.0	3.0	0.0	0.0
17	0	1.0	0.0	0.0	0.0	42.0	8.0	0.0	0.0
18	0	1.0	0.0	0.0	0.0	27.2	9.8	0.0	0.0
19	0	1.0	0.0	0.0	0.0	3.3	0.6	0.0	0.0
20	0	1.0	0.0	0.0	0.0	2.3	1.0	0.0	0.0
21	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	0	1.0	0.0	0.0	0.0	6.3	2.1	0.0	0.0
24	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	0	1.0	0.0	0.0	0.0	6.3	3.2	0.0	0.0
26	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	0	1.0	0.0	0.0	0.0	9.3	0.5	0.0	0.0
28	0	1.0	0.0	0.0	0.0	4.6	2.3	0.0	0.0
29	0	1.0	0.0	0.0	0.0	17.0	2.6	0.0	0.0
30	0	1.0	0.0	0.0	0.0	3.6	1.8	0.0	0.0
31	0	1.0	0.0	0.0	0.0	5.8	2.9	0.0	0.0
32	0	1.0	0.0	0.0	0.0	1.6	0.8	0.0	0.0
33	0	1.0	0.0	0.0	0.0	3.8	1.9	0.0	0.0
34	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
35	0	1.0	0.0	0.0	0.0	6.0	3.0	0.0	0.0
36	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
37	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
38	0	1.0	0.0	0.0	0.0	14.0	7.0	0.0	0.0
39	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
40	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
41	0	1.0	0.0	0.0	0.0	6.3	3.0	0.0	0.0
42	0	1.0	0.0	0.0	0.0	7.1	4.0	0.0	0.0
43	0	1.0	0.0	0.0	0.0	2.0	1.0	0.0	0.0
44	0	1.0	0.0	0.0	0.0	12.0	1.8	0.0	0.0
45	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
46	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
47	0	1.0	0.0	0.0	0.0	29.7	11.6	0.0	0.0
48	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
49	0	1.0	0.0	0.0	0.0	18.0	8.5	0.0	0.0
50	0	1.0	0.0	0.0	0.0	21.0	10.5	0.0	0.0
51	0	1.0	0.0	0.0	0.0	18.0	5.3	0.0	0.0
52	0	1.0	0.0	0.0	0.0	4.9	2.2	0.0	0.0
53	0	1.0	0.0	0.0	0.0	20.0	10.0	0.0	0.0
54	0	1.0	0.0	0.0	0.0	4.1	1.4	0.0	0.0
55	0	1.0	0.0	0.0	0.0	6.8	3.4	0.0	0.0
56	0	1.0	0.0	0.0	0.0	7.6	2.2	0.0	0.0
57	0	1.0	0.0	0.0	0.0	6.7	2.0	0.0	0.0

Table A4
Line data for modified IEEE 57-bus test system.

Start bus	End bus	R (p.u)	X (p.u)	B/2 (p.u)	Line limit (MW)	Start bus	End bus	R (p.u)	X (p.u)	B/2 (p.u)	Line limit (MW)
1	2	0.0083	0.0280	0.0645	150	10	29	0.0	0.0648	0.0	100
2	3	0.0298	0.0850	0.0409	85	25	30	0.1350	0.2020	0.0	100
3	8	0.0112	0.0366	0.0190	100	30	31	0.3260	0.4970	0.0	100
8	9	0.0625	0.132	0.0129	100	31	32	0.5070	0.7550	0.0	100
8	4	0.0430	0.148	0.0174	50	32	33	0.0392	0.0360	0.0	100
4	10	0.0200	0.102	0.0138	40	34	32	0.0	0.9530	0.0	100
4	5	0.0339	0.173	0.0235	100	34	35	0.0520	0.0780	0.0016	100
5	6	0.0099	0.050	0.0274	200	35	36	0.0430	0.0537	0.0008	100
6	11	0.0369	0.167	0.0220	50	36	37	0.0290	0.0366	0.0	100
6	12	0.0258	0.0848	0.0109	50	37	38	0.0300	0.1009	0.0010	100
6	7	0.0648	0.0295	0.0386	50	37	39	0.0192	0.0379	0.0	100
6	13	0.0481	0.158	0.0203	50	36	40	0.0	0.0466	0.0	100
13	14	0.0132	0.0434	0.0055	50	22	38	0.2070	0.0295	0.0	100
13	15	0.0269	0.0869	0.0115	100	12	41	0.0	0.7490	0.0	100
1	15	0.0178	0.0910	0.0494	200	41	42	0.0289	0.3520	0.0	100
1	16	0.0454	0.2060	0.0273	100	41	43	0.0	0.4120	0.0	100
1	17	0.0238	0.1080	0.0143	100	38	44	0.0	0.0585	0.0010	100
3	15	0.0162	0.0530	0.0272	100	15	45	0.0230	0.1042	0.0	100
8	18	0.0	0.5550	0.0	100	14	46	0.0182	0.0735	0.0	100
8	18	0.0	0.4300	0.0	100	46	47	0.0834	0.0680	0.0016	100
9	4	0.0302	0.0641	0.0062	100	47	48	0.0801	0.0233	0.0	100
10	5	0.0139	0.0712	0.0097	100	48	49	0.1386	0.1290	0.0024	100
11	7	0.0277	0.1262	0.0164	100	49	50	0.0	0.1280	0.0	100
12	13	0.0223	0.0732	0.0094	100	50	51	0.0	0.2200	0.0	100
7	13	0.0178	0.0580	0.0302	100	11	51	0.1442	0.0712	0.0	100
7	16	0.0180	0.0813	0.0108	100	13	49	0.0762	0.1910	0.0	100
7	17	0.0397	0.1790	0.0238	100	29	52	0.1878	0.1870	0.0	100
14	15	0.0171	0.0547	0.0074	100	52	53	0.1732	0.0984	0.0	100
18	19	0.4610	0.6850	0.0	100	53	54	0.0	0.2320	0.0	100
19	20	0.2830	0.4340	0.0	100	54	55	0.0624	0.2265	0.0	100
21	20	0.0	0.7767	0.0	100	12	43	0.0	0.1530	0.0	100
21	22	0.0736	0.1170	0.0	100	44	45	0.5530	0.1242	0.0020	100
22	23	0.0099	0.0152	0.0	100	40	56	0.2125	1.1950	0.0	100
23	24	0.1660	0.2560	0.0042	100	56	41	0.0	0.5490	0.0	100
24	25	0.0	1.1820	0.0	100	56	42	0.1740	0.3540	0.0	100
24	25	0.0	1.23	0.0	100	39	57	0.1150	1.3550	0.0	100
24	26	0.0	0.0473	0.0	100	57	56	0.0312	0.2600	0.0	100
26	27	0.1650	0.2540	0.0	100	38	49	0.0	0.1770	0.003	100
27	28	0.0618	0.0954	0.0	100	38	48	0.0	0.0482	0.0	100
28	29	0.0418	0.0587	0.0	100	6	55	0.0	0.1205	0.0	100

Table A5
Price bids submitted by GENCOs for modified IEEE 30-bus test system.

Bus number	Increment ($/MWh)	Decrement ($/MWh)
1	22	18
2	21	19
3	42	38
4	43	37
5	43	35
6	41	39

Table A6
Price bids submitted by GENCOs for modified IEEE 57-bus test system.

Bus number	Increment ($/MWh)	Decrement ($/MWh)
1	44	41
2	43	39
3	42	38
4	43	37
5	42	39
6	44	40
7	44	41

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