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ORIGINAL PAPER

Bat Algorithm for Congestion Alleviation in Power System Network

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Abstract

Congestion in power transmission lines is designated as one of the critical issues in the deregulated power system scenario. The System Operator (SO) bears the responsibility to manage the congestion in order to ensure a secure and reliable operation of the power system framework. This article proposes a Congestion Management (CM) strategy based on the generator rescheduling approach using Bat Algorithm (BA). BA is one of the recent nature inspired optimization approaches based on the echolocation strategy adopted by the bats in search of prey. In the proposed CM scheme the BA is used to minimize the congestion cost with the optimal rescheduling of the active power output of the generators. The participation of the generators in the CM is accomplished considering the generator sensitivity values. The potency of the proposed method is tested on 39-bus New England framework, IEEE 30 bus system, IEEE 118 bus system and a comparative analysis is established with other recent optimization approaches. The outcomes obtained with the proposed BA for CM outperforms the outcomes achieved with other algorithms. The proposed approach ensures a better convergence profile avoiding the traps into local minima and also aids the SO to manage congestion efficiently.

Keywords Bat algorithm · Congestion management · Cost optimization · Generator rescheduling · Generator sensitivity factor · Optimal power flow

Introduction

In the modern restructured framework of power system, the transmission system is treated as an integral channel for achieving the transactions between the generators and the loads. The increase in the load is met by the increase in the generation. The transfer limits may be compromised due to the overburdening of the transmission lines and hence creating a state of congestion [1].The violation of any one of the transfer limits, which are entitled as the voltage limit, stability limit and thermal limit, may lead to the congestion in the power system framework. The practices adopted by the SO to relive the overburden of transmission channels preserving the transfer limits is termed as CM. The rescheduling of the generators, application of Flexible Alternating Current Transmission System (FACTS) devices, integration of renewable sources and load curtailment are some of the measures that are adopted for the CM process [2, 3].

The various methods of CM are discussed in [4, 5]. The role of CM subjected to various electricity markets are stated in [6]. Nesamlar et al. proposed an efficient Hybrid Nelder-Mead-Fuzzy Adaptive Particle Swarm Optimization (HNM-FAPSO) technique to curtail the congestion service cost [7]. Reddy proposed a new CM technique collaborating the generator rescheduling and load shedding considering the voltage dependent loads [8]. Eshfani and Yousefi utilized the concept of the congestion clearing time and formulated a real time optimization problem for CM considering the quasi-dynamic thermal rates of the transmission lines [9]. Hemati et al. utilized the Energy Storage Systems (ESS) to manage congestion. Their work dealt with the optimal capacity and the time of charging and discharging of the EES based on the uncertainty of the wind or solar units [10]. The CM considering the voltage stability is addressed in [11]. In another research Mohammadi and

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Zheng analyzed the stability of the system by combining the effect of generation and load based on the continuous power flow [12]. The effect of power flow and the power management in the electrical system maintaining the system stability can be found in [13–15]. In [16] Mishra and Gundavarapu utilized the disparity line utilization factor to sort a better position for the placement of Interline Power Flow Controller (IPFC) using Fire Fly Algorithm (FFA) to diminish the effect of congestion in the transmission lines. Murphy et al. [17] considered the uncertainty and the variability of the renewable energy for CM. The utilization of the FACTS devices for CM are studied in [18, 19]. The implementation of distributed generation to manage congestion using Particle Swarm Optimization (PSO) has been presented in [20]. Chellam and Kalyani determined the congestion cost by adopting power flow tracing methodology for CM [21]. The CM by rescheduling of the real power using Bacterial Forging Algorithm (BFA) is discussed in [22]. Kumar et al. formulated a zonal CM based approach. The approach stated that the generators corresponding to the most sensitive zones are determined to reschedule their active and reactive power output [23].

The rescheduling of the power delivery by the generators is one of the primary procedures to treat the congestion in the transmission lines. Several research strategies have been adopted by the researchers in the field of real power rescheduling to mitigate the problem of congestion. Hazra et al. combined generator rescheduling with load reduction to mitigate the over burden of the transmission framework [24]. Khemani and Patel in their work identified the most sensitive zone and rescheduled the generators associated with that zone to manage the congestion without involving the generators located in other zones [25]. In another research a mixed integer non-linear programming method was adopted to designate the optimal position of the Sen transformer and Unified Power Flow Controller (UPFC) and rescheduling of the active power of the generators is done to relieve congestion [18]. In [26] a combined approach of real and reactive power rescheduling approach was implemented to mitigate the congestion. Verma and Sharma concentrated their work towards the rescheduling the hydro-thermal units in hybrid market scenario to minimize the rescheduling cost for CM [27]. In [28] the active power delivery of the generators was monitored to control congestion based on the positioning of the wind farm. The rescheduling of the power output of the wind farm based on the Generator Sensitivity Factor (GSF) can be found in [29, 30]. A CM approach based on GSF and real power management to mitigate have been discussed in [31, 32].

The recent trend of the research revolves round the proper selection and implementation of heuristic optimization approaches in the engineering problems to obtain the optimal results [33, 34]. In the power system research, the implementation of heuristic algorithms has been adopted by several researchers to address the CM problem. Yesuratnam and Thukaram introduced the Relative Electrical Distance (RED) concept for CM by rescheduling the generators to achieve a better voltage profile and minimum losses [35]. Dutta and Singh used the Generator Sensitivity Factor (GSF) values to sort out the best responsive generators for CM. The optimization of the congestion cost was performed with PSO [36]. Deb et al. have introduced Artificial Bee Colony (ABC) algorithm to optimize the real power output of the generators to manage the overloading of the transmission lines [37]. Verma et al. mollified congestion using FFA [38].

It is noticed that there is a substantial scope in application of the heuristic techniques in this proposed area. Hence, a new algorithm, formulated by Xin-She Yang in 2010 [39] based on the echo location strategy of the bats has been incorporated in this research work. The characteristic of Bat Algorithm (BA) states that it has a brisk convergence rate in the initial phase by swapping from exploration to exploitation. It also has the feature of auto-control and monitor the search space by adjusting the loudness and pulse emission. In addition to these, it is simple, flexible and can be easily incorporated that makes it one of the best choice for obtaining optimal solution for the engineering problem.

The performance of BA has been validated by many of the researchers in the power system engineering area. Murali et al. have adopted spot pricing technique based on the DC optimal power flow to minimize the fuel cost using BA. The results obtained with BA are found to be better when compared to the results obtained with Genetic Algorithm (GA) and Linear Programming (LP) [40]. Biswal et al. have optimized the fuel cost for the economic load dispatch problem using the BA. The results achieved with BA were proved to be better when compared to PSO and Intelligent Water Droplet (IWD) algorithm [41]. Rashidi et al. have combined BA with Differential Evolution (DE) algorithm to formulate a hybrid algorithm to optimize the estimation of power system model parameters [42]. Furthermore Niknam et al. have addressed the unit commitment issue and concentrated their research in formulating a self adaptive BA. The results achieved were much more improved when compared with GA, PSO and Shuffled Frog Leaping Algorithm (SFLA) [43]. Again Niknam et al. have extended their research to design a multi-objective BA to solve the constrained dynamic economic load dispatch problem [44]. The above literature survey states that the application of BA has yielded adequate results for all the considered cases and it can be appreciated that the BA will also accord better and efficient results for the proposed CM philosophy.

The integral motivation following the proposed work in this manuscript is to develop a latest and efficient technique for solving the CM problem for the transmission framework. It may be observed from the literature survey that numerous techniques have been adopted to minimize congestion cost for the CM problem. The performance and efficiency of these optimization algorithms are based on the use of the control parameters, like the performance of GA is influenced by the crossover rates and mutation, in the same way the PSO is also influenced by the inertia weights and strategy parameters [45]. In order to achieve a better convergence profile and optimal value of fitness function, proper adjustment of its parameters are required. In this scenario there is always a possibility to achieve a compromised outcome due to the inappropriate setting of parameters. In order to overcome these circumstances, a new heuristic algorithm (based on the echo location of bats) has been adopted in this work. The BA approach is robust and simple due to its auto-control and monitoring the search space from exploration to exploitation. In view of this, the BA approach has been implemented in this CM problem to obtain the best results. The primary intent of this research approach is to minimize the cost along with the optimal adjustment on the real power delivery of the generators.

The CM problem in this article is codified in terms of optimal power flow problem which includes several constraints and necessitates the implementation of heuristic method. The GSF values are used to select the most sensitive generators. The generators having large magnitude and non uniform GSF values are engaged for the rescheduling purposes. The potency of the proposed approach is analyzed by establishing a comparative study with other optimization algorithms. The proposed method aids the SO to manage congestion efficiently. With this above discussion the *contributions* of this paper are as follows:

- The research approach adopted in this work aims to solve the congestion management issue in the power system framework. The concept of rescheduling of the generators has been incorporated with the implementation of the BA search technique to obtain the optimal congestion cost. The integral contribution of this work is to develop a mathematical model based on the rescheduling of the generators to minimize the congestion cost.
- Extend BA as an adept optimizing approach for the congestion cost minimization involving the rescheduling of the generators participating in the CM based on the GSF values.
- The potency of the BA for the proposed CM is analyzed based on its application on different test system like 39 bus New England System, IEEE 30 bus system and 118 bus framework.
- The optimum outcomes offered by BA are analyzed and contrasted with the other recent algorithms like RED [35], PSO [36], ABC [37], FFA [38], Grey Wolf Optimization (GWO) [46], $\epsilon-$constraint [47] and Dragonfly Algorithm (DA) [48], which is done in order to sort out the best algorithm for the proposed work.
- The comparative analysis has been established based on the congestion cost, convergence profile and system losses between BA and other algorithms to provide an efficient CM approach.

The remaining structure of the research article is organized in the following sections. The problem formulation and the implementation of the BA for the proposed research philosophy are demonstrated in Sections “Problem formulation” and “Bat Algorithm” respectively. The results and discussions are stated in Section “Results and Discussions” followed by conclusion in Section “Conclusion”.

Problem Formulation

The concept of GSF can be stated as the ratio of alteration in the flow of real power in the line $'k'$ which connects the buses $'i'$ and $'j'$ to the small shift in the real power generated by the generator $'g'$ [36]. The mathematical interpretation of the GSF_g for the g^{th} generator can be expressed as:

$$GSF_g = \frac{\Delta P_{ij}}{\Delta P_g} \tag{1}$$

Here ΔP_{ij} is designated as the alteration in the amount of the active power flow for the overburdened k^{th} line connecting the buses $'i'$ and $'j'$. The shift in the real power yield by the generator $'g'$ is denoted as ΔP_g. The generators with the non-uniform or high GSF values exhibit higher influence on the power flow in the congested lines so these generators are sorted to take part in the CM process. The detail derivation of GSF has been portrayed in [36].

The total amount of cost involved in real power rescheduling for the CM process can be stated as:

$$Minimize = \sum_{g=1}^{N_g} C_g(\Delta P_g)\Delta P_g \tag{2}$$

Here ΔP_g=shift in the active power of the generator $'g'$ in MW. C_g= price bids submitted by the generators involved in the CM (\$/MWh).

The optimization problem is subjected to the following constraints.

$$\sum_{g=1}^{N_g}((GSF_g) * \Delta P_g) + PF_k^0 \le PF_k^{\max} \tag{3}$$

$$\Delta P_g^{\min} \le \Delta P_g \le \Delta P_g^{\max} \tag{4}$$

$$\Delta P_g^{\min} = P_g - P_g^{\min} \tag{5}$$

$$\Delta P_g^{\max} = P_g^{\max} - P_g \tag{6}$$

$$\sum_{g=1}^{N_g} \Delta P_g = 0 \tag{7}$$

ΔP_g= active power adjusted by the participating generators.
$P_g^{\max}$= maximum limit of generator output.
$P_g^{\min}$= minimum limit of generator output.
PF_k^0= power flow in the line ‘k’ requesting all the contracts.
$PF_k^{\max}$= maximum power flow of the line ‘k’ (line limit).
N_g= generator count involve in CM.

The formulation of the fitness function is framed by transforming the constraints into penalty function and associating those to the objective function which is represented as:

$$\begin{aligned}&\sum_{g=1}^{N_g} C_g(\Delta P_g)\Delta P_g + penalty\ multiplier * [(\sum_{g=1}^{N_g}((GSF_g) * \Delta P_g) + \\ &PF_k^0 \leq PF_k^{\max}) + P_g - P_g^{\min} + \sum_{g=1}^{N_g} \Delta P_g = 0)]\end{aligned} \tag{8}$$

In order to restrict the search space for the masses penalty function is used. This is done to ensure that the masses do not traverse to an unacceptable region. Again, the multiplier used here must be taken carefully for a proper limitation. If it is too large, it cannot search several regions productively and converges early and for too small value of it there is a chance to escape search area and convergence to an undesired point. The value of penalty multiplier in this paper is taken as 1000 for simulation [38].

Bat Algorithm

Xin-She Yang in the year 2010 formulated the Bat Algorithm (BA) [49]. Like other prevailing meta heuristic algorithm, the BA is also a meta heuristic algorithm inspired from the echolocation strategy adopted by the group of bats in search of prey. The bats are considered as the fascinating mammals with wings and the power to use echolocation. The phenomenon of echolocation is broadly used by the micro bats. These bats produce very large sound pulses and detect the echo that returns back after hitting the object in their surroundings. The variations in the pulses are observed based on their hunting strategies and differ from species to species. Most of the bats prefer short frequency modulated signals during echolocation where as the others use constant frequency signals. A higher frequency up to 150 kHz are emitted by some of the species but most of the species emit frequency between 50 kHz to 100 kHz. The fundamental structure of the BA is based on the following idealized rules.

- The echolocation is used by all the bats to feel the distance and they also bear a marvelous ability to measure the distinctness between the prey and background barrier.
- A position x_i corresponding to it a velocity component v_i is accredited to each of the bats among the group with a certain wavelength λ, fixed frequency $f_{\min}$ and loudness A_0. They also have the ability to modulate the pulse emission rate r_i, from a range of [0-1] depending upon the vicinity of the prey.
- The variation of the loudness is done from a large positive A_0 to a minimum constant $A_{\min}$.

Bat Motion

The velocity and the position of the bats are designated as v_i and x_i in dimension $'d'$ respectively. At time step $'t'$ the new solution for v_i^t and x_i^t are given by:

$$f_i = f_{\min} + (f_{\max} - f_{\min})\beta \tag{9}$$

$$v_i^{t+1} = v_i^t + (x_i^t - x_*) f_i \tag{10}$$

$$x_i^{t+1} = x_i^t + v_i^t \tag{11}$$

Here $\beta \in [0, 1]$ is designated as a random vector of uniform distribution. The entire group of n bats are considered to establish a comparison for all the solutions achieved at every iteration so as to procure the global best solution x_*. The velocity increment is defined as the product of $\lambda_i \times f_i$. The velocity can be altered by modulating the value of f_i or (λ_i) keeping the other factor constant. The $f_{\min}$ and $f_{\max}$ are assigned as 0 and 1 respectively in this article. So the frequency that is initially assigned to the bats is selected evenly from the values of $[f_{\min}, f_{\max}]$. The development of the new solution is performed locally for all the number of bats and is represented as:

$$x_{new} = x_{old} + \varepsilon A^t \tag{12}$$

here ε is denoted as the random number fetched from [-1,1], the average loudness of all bats at time step $'t'$ is designated as $A^t =< A_i^t >$.

Loudness and Pulse Emission

The loudness is designated as A_i and the rate of the pulse emission is represented as r_i and the values of both the component are updated with the execution of each iteration. It is to be noted that as the bat approaches its target there is a decrement in the loudness value and an increment in the rate of pulse emission. The choice for the loudness value depends as per user accessibility. Now to make it simple the value of the loudness can be taken as $A_0 = 1$ and $A_{\min} = 0$

which means that at $A_{\min} = 0$, the bat has found its prey and it eventually stops emitting sound. Now we have:

$$A_i^{t+1} = \alpha A_i^t, r_i^t = r_i^0[1 - \exp(-\gamma t)] \tag{13}$$

here α and γ are treated as constants. It is to be noted that corresponding to any value existing from $0 < \alpha < 1$ and $\gamma > 0$, we have:

$$A_i^t \rightarrow 0, r_i^t \rightarrow r_i^0, t \rightarrow \infty \tag{14}$$

Here, r_i^0 is defined as initial emission rate.

The parameters for the BA used are: Population $Size = 25$, Pulse Rate=0.5, $A_0 = 2$, $A_{\min} = 1$, $f_{\min} = 0$, $f_{\max} = 1$, $\alpha = 0.9$, $\gamma = 0.9$. The pseudocode of BA for CM is stated in Algorithm 1 and the flowchart representation for the same is depicted in Fig. 1.

Algorithm 1 Bat algorithm pseudocode for CM.

```
Objective function $g(x) = (x_1, x_2 .....x_j)^T$
Initialization of the bat population $x_i$ and velocity $v_i$
Define the pulse frequency $f_i$ at $x_i$
while ($t < maximum\ iteration\ numbers$) do
    Generate the new solution with frequency adjustment and update the velocities and the positions
    if ($rand < r_i$) then
        Select a solution from the best solutions
        Generate a local solution around the best solution
    end if
    Generate new solution by randomly flying
    if ($rand < A_i$ and $f(x_1) < f(x_*)$) then
        Accept the new solutions
        Increase $r_i$ and reduce $A_i$
    end if
    Rank the bats and obtain the best $x_*$
end while
```

Results and Discussions

The BA approach for the CM has been implemented using MATLAB 2016(b) in Windows platform of personal computer with 3.10 GHz processor speed and 8GB memory. The results and computations are evaluated under same running environment. The efficacy of the proposed approach is investigated considering the test case systems like 39 bus New England, IEEE 30 and 118 bus framework. A comparative analysis is presented with other algorithms to put forward the efficiency of the proposed CM approach. The comparison has been established with RED [35], PSO [36], ABC [37], FFA [38]. The CM problem has also been analyzed with some latest techniques GWO, $\epsilon-$ constraints, and DA and the results of these approaches are also included in this research article for comparative analysis purpose.

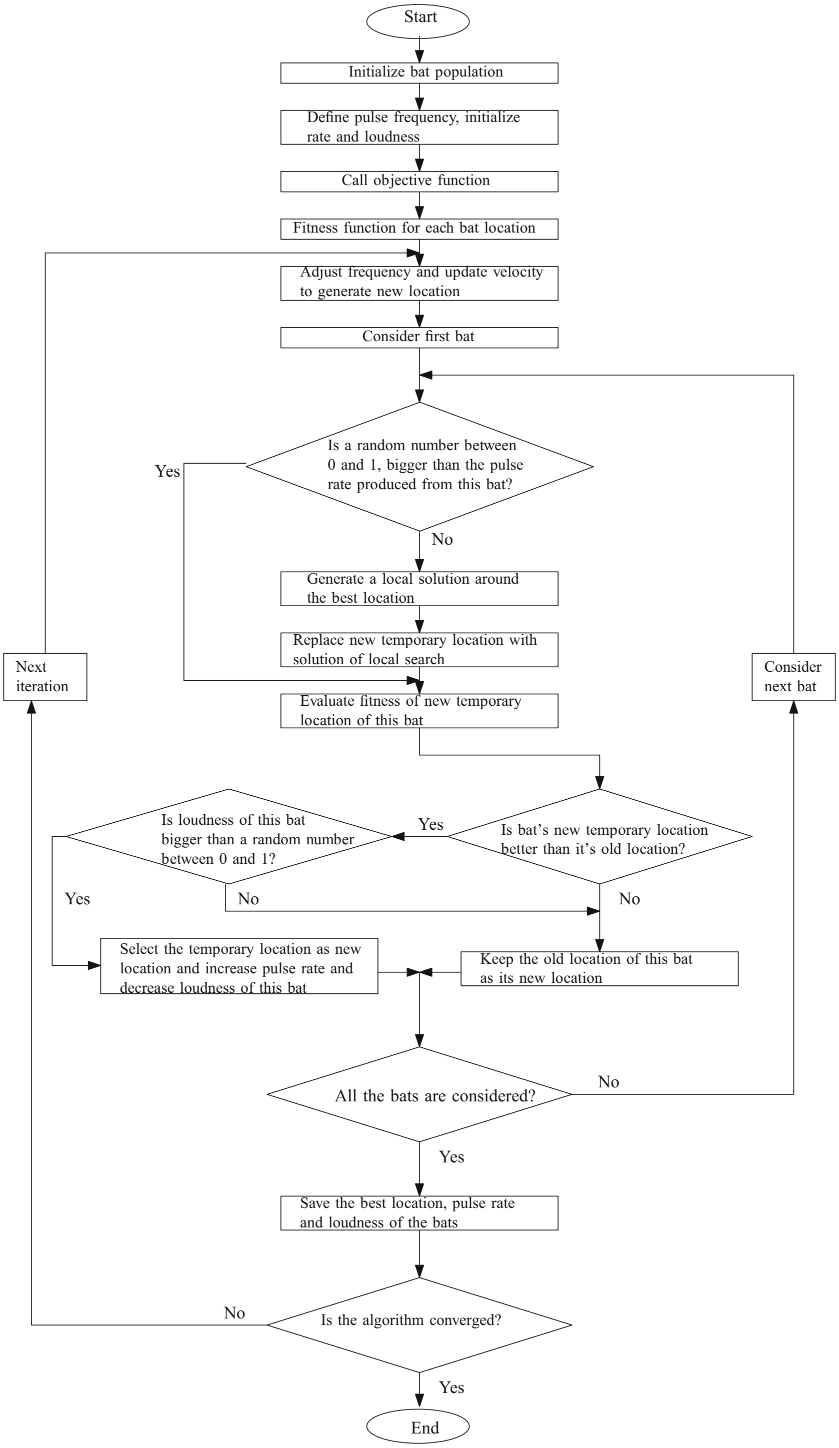
Modified 39-bus New England System

The 39 bus New England framework is configured with 10 generators and 29 load buses. The representation of 39 bus New England framework is shown in Fig. 2 and the complete details of the system data, parameters, and the power limits of the generators can be found in [50]. The line connected between the buses 14-34 is subjected to an outage. The outage resulted in the overloading of the line joining the buses 15-16 and its power flow is raised to 628.2 MW and resulted in the overburden of the line. The details of the over loaded line is given in Table 1.

The strong and the non-uniform values of the GSF are considered to sort out the generators participating in the CM procedure. The GSFs are given in Table 2 and it is observed that the generator numbers 4, 5, 6 and 7 exhibit uniform GSF values and will not take part in the rescheduling process for the CM problem while the generator numbers 2, 3, 8, 9 and 10 will take part in the CM problem as they exhibit non-uniform GSF values. The generator's bids are represented in Table 3.

The overloading of the congested lines must be relieved to maintain a healthy power system. The incorporation of the proposed BA technique for CM is done to attenuate the congestion with the minimization of the congestion cost. Table 4 represents the outcomes brought about with the incorporation of proposed BA technique for the CM problem. The results reported in the literature [35–37]

Fig. 1 Flowchart of Bat Algorithm for congestion management



and the results of GWO, $\epsilon-$ constraints, and DA are also included in Table 4 for a comparative analysis. The congestion cost of 7751.36 \$/h is obtained with the proposed BA method and is minimum amongst the congestion costs achieved with the other existing techniques. It is also observed that the power flow of the congested lines are within the line limits after CM.

The pictorial comparison of the congestion costs achieved with BA and other algorithms are shown in Fig. 3. It is noted from Fig. 3 that the congestion cost achieved with RED [35], PSO [36] and ABC [37], GWO [46], $\epsilon-$ constraints [47], and DA [48] are 8639.1 $\$/h$, 8872.9 $\$/h$, 8451.8 $\$/h$, 8295.52 $\$/h$, 8104.11 $\$/h$ and 7964.58 $\$/h$ respectively. Figure 3 also shows the optimal congestion

Fig. 2 Topology of 39 bus New England system

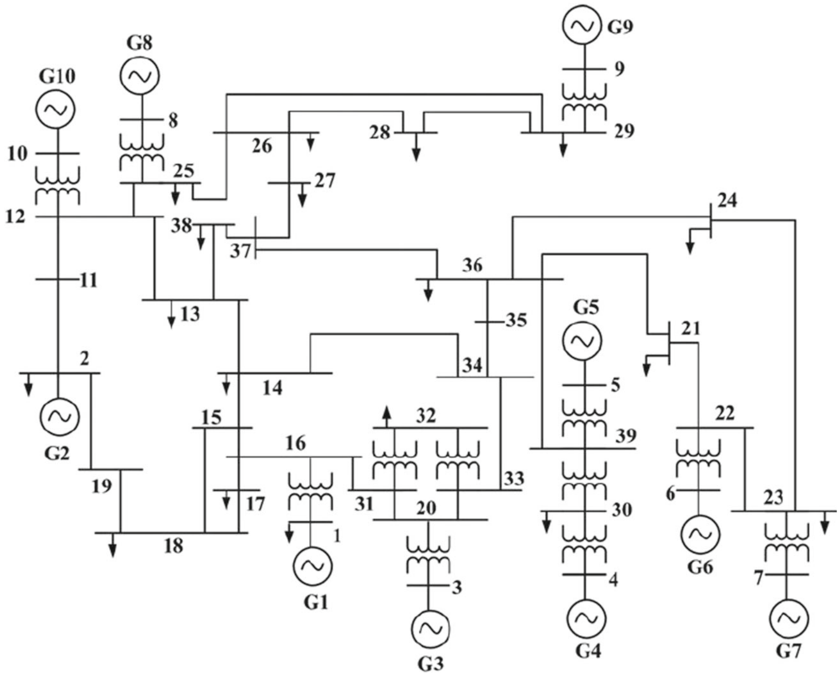


Table 1 Power flow in congested line (line 15-16)

Congested Line	Power Flow (MW)	Line Limit (MW)
15-16	628.2	500

Table 2 Generator sensitivity factor (39 bus new England)

Gen No.	1	2	3	4	5	6	7	8	9	10
GSF	0.00	−0.49	−0.12	−0.35	−0.35	−0.35	−0.35	−0.53	−0.46	−0.58

Table 3 Price bids for 39 bus new England framework

Gen No.	1	2	3	4	5	6	7	8	9	10
Bids($/MWh)	15	20	17	16	12	17	13	11	14	19

Table 4 Comparative analysis of results with BA for 39 bus New England framework

	RED [35]	PSO [36]	ABC [37]	GWO [46]	ϵ-constraint [47]	DA [48]	BA [Proposed]
Approx. Cost of generator rescheduling ($/h)	8639.1	8872.9	8451.8	8295.52	8104.11	7964.58	7751.36
Power flow post CM. Line 15-16 (MW)	510	490	499.50	499.00	496.90	496.98	496.90
ΔP_1 (MW)	-99.59	-149.1	-131.0	-141.62	-132.63	-160.79	-142.89
ΔP_2 (MW)	98.75	65.6	63.2	68.54	46.12	67.30	60.72
ΔP_3 (MW)	-159.64	-129	-132.0	-115.57	-125.32	-90.20	-100.06
ΔP_4 (MW)	12.34	Not Involve	Not Involve	Not Involve	Not Involve	Not Involve	Not Involve
ΔP_5 (MW)	24.69	Not Involve	Not Involve	Not Involve	Not Involve	Not Involve	Not Involve
ΔP_6 (MW)	24.69	Not Involve	Not Involve	Not Involve	Not Involve	Not Involve	Not Involve
ΔP_7 (MW)	12.34	Not Involve	Not Involve	Not Involve	Not Involve	Not Involve	Not Involve
ΔP_8 (MW)	24.69	75.4	72.2	65.44	90.78	63.43	70.75
ΔP_9 (MW)	12.34	52.1	49.1	45.02	47.95	53.39	40.68
ΔP_{10} (MW)	49.38	83.0	78.8	73.26 78.19		71.06	70.78
Total Amount (MW)	518.45	554.2	526.3	514.38	516.06	503.17	485.88

Fig. 3 Comparison of congestion cost with different algorithm for 39 bus New England system

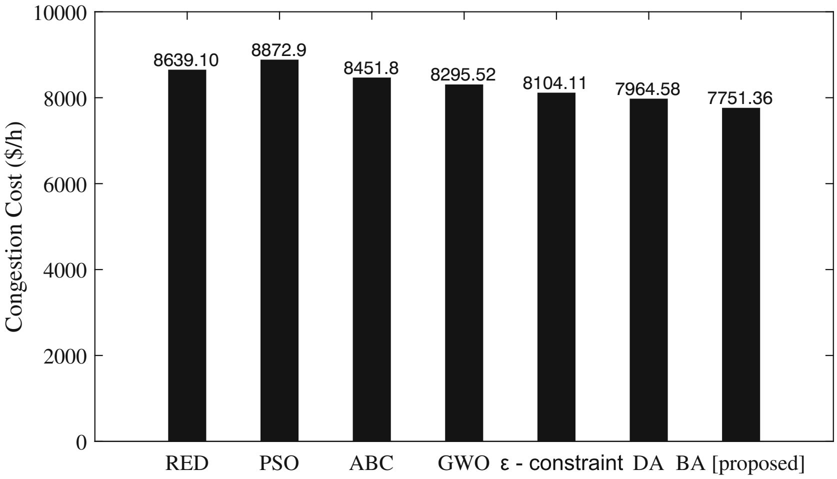


Fig. 4 Comparison of real power rescheduled for 39 bus New England system

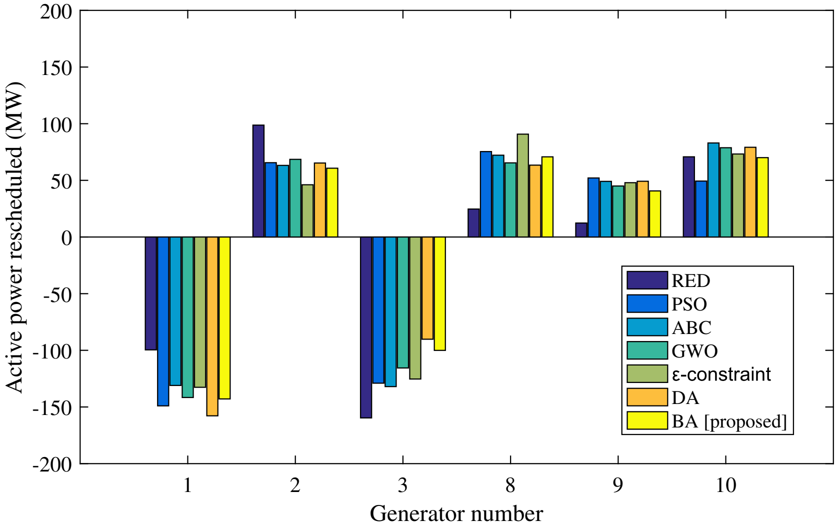
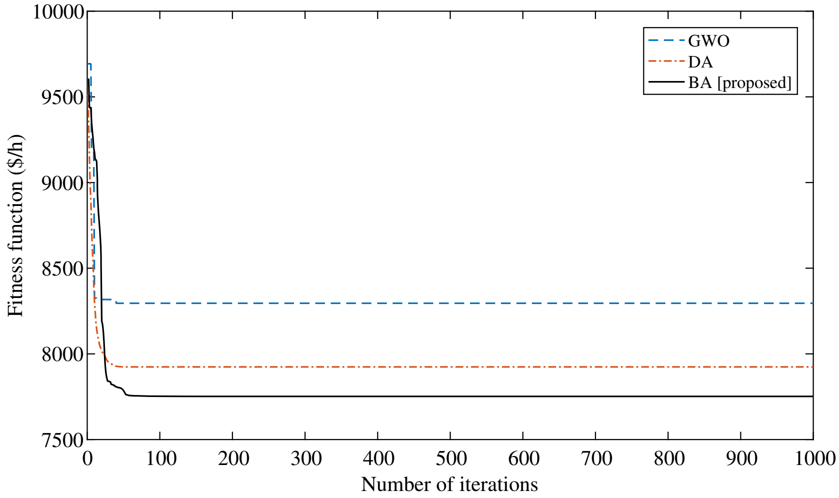


Fig. 5 Convergence characteristics with BA for 39 bus New England system



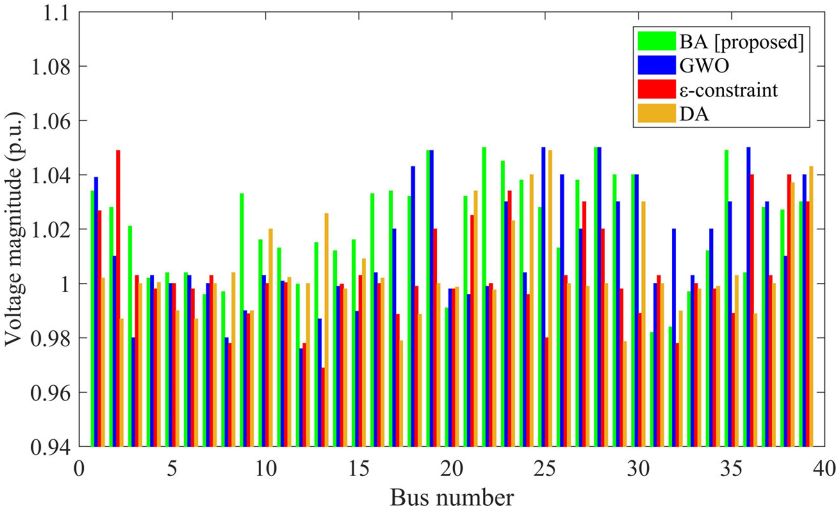


Fig. 6 Bus voltage representation after CM for 39 bus New England system

cost achieved with BA for the CM problem is 7751.36 $\$/h$. It is observed that the congestion cost with the BA approach for congestion management delivers the minimum cost among all the other cost represented in Fig. 3. The comparative analysis of the of the real power adjusted by the BA and the real power rescheduled by the referred optimization algorithms for the considered CM problem are represented in Fig. 4.

The adjusted real power with BA is appreciable to achieve the optimal cost of rescheduling than the other algorithms. Figure 5 shows the converging characteristic of BA along with the convergence profile of GWO and DA. The convergence profile of BA provides a better minimization of the congestion cost with the increment in the number of iterations. The system loss has also decreased from its initial value of 59.39 MW before CM to 57.01 MW after CM. The voltage profile obtained with the implantation of BA after CM is depicted in Fig. 6. The voltage at each of the buses represents that the voltage limits are well maintained after the BA approach is used for CM. The convergency time for the adopted optimization approaches for the CM problem are given in Table 5.

Modified IEEE 30 Bus System

The topological framework of the modified IEEE 30 bus structure includes 6 buses that are entitled as generator buses and the rest 24 buses are entitled as the load buses. The pictorial representation of IEEE 30 bus system has been given in Fig. 7. The detail system data, parameters and the power limits of the generators can be found in [45]. The numbering of the slack, generator and load buses are done with the slack bus marked as number 1 and then the generator buses are numbered which are followed by the load buses [36]. The contingency is created with the outage of the line existing between the buses 1-3, leading to the overloading of the lines existing between the buses 2-1 and 9-2. The contingency condition has lead to the flow to be 170 MW and 66 MW for the lines connected between the buses 2-1 and 9-2 respectively. The power flow data for the overloaded lines are represented in Table 6.

Table 7, represents the GSFs computed for the overburdened lines. It is observed that no significant deviation is prevailing between the GSF values. This portrays that the framework of 30 bus system is compact and intimately connected. Hence each of the generators will contribute towards the CM scheme. The influence of the proposed approach on a larger framework is studied by adopting the framework of IEEE 118 bus in the later section of this research article. Table 8, represents the bidding cost submitted by the generators.

The optimal rescheduling of the generators is preformed with BA to mitigate the overloading of the lines and the outcomes are represented in Table 9. Results reported in [36, 38] and those achieved with GWO, $\epsilon-$ constraints and DA are also tabulated in Table 9 to establish a contrast with the outcomes obtained with the proposed BA approach. The cost of rescheduling obtained with BA is 1425.7 \$/h which is economical when contrasted with the other reported results. The change in the power flow post CM in the congested lines are also reported in Table 9. The line power flows are within its permissible limits.

Table 5 Representation of convergency time (39 bus system)

	DA	ϵ-constraint	GWO	BA [proposed]
Time (Sec.)	0.30454	0.56506	0.36857	0.44786

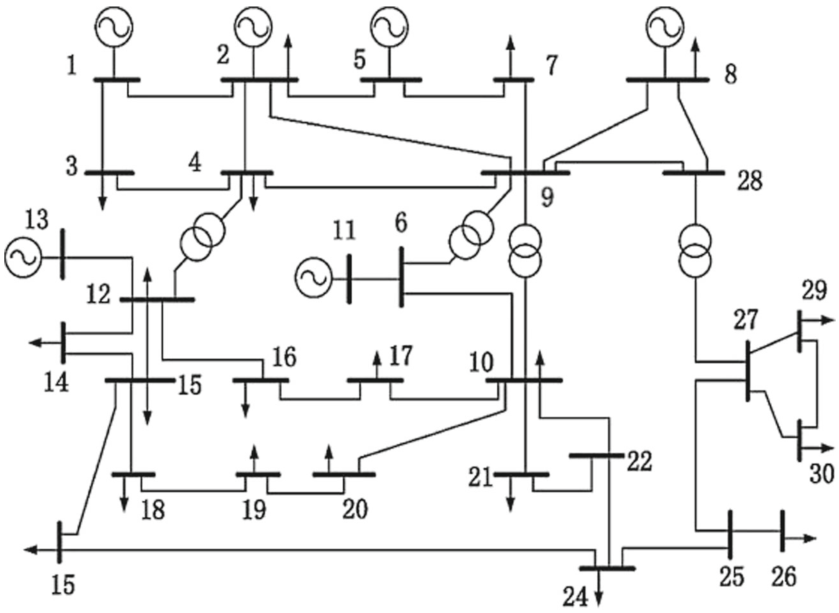


Fig. 7 Topology of IEEE 30 bus system

Table 6 Power flow in congested lines (30 bus system)

Congested Line	Power Flow (MW)	Line Limit (MW)
2-1	170	130
9-2	66	65

Table 7 Generator sensitivity factor (30 bus system)

Gen No.	1	2	3	4	5	6
GSF	0.00	−0.85	−0.78	−0.68	−0.66	−0.64

Table 8 Price bids for 30 bus system

Gen No.	1	2	3	4	5	6
Bids($/MWh)	11	17	19	20	15	10

Table 9 Comparative analysis of results with BA for 30 bus framework

	PSO [36]	FFA [38]	GWO [46]	ϵ-constraint [47]	DA [48]	BA [Proposed]
Approx. Cost of generator rescheduling ($/h)	1521.8	2769.53	1526.59	1468.73	1429.91	1425.7
Power flow post CM. Line 2-1 (MW)	129	129.7	129.28	129.55	129.6	129.68
Power flow post CM. Line 9-2 (MW)	60.00	64.97	62.00	60.72	60.50	60.25
ΔP_1 (MW)	-59.00	-8.57	-54.01	-53.92	-51.20	-51.63
ΔP_2 (MW)	19.9	75.99	20.01	21.02	17.10	19.79
ΔP_3 (MW)	13	0.057	14.84	14.08	15.29	14.59
ΔP_4 (MW)	6	42.99	7.60	3.60	6.77	3.95
ΔP_5 (MW)	6.5	23.83	8.55	7.63	6.30	6.20
ΔP_6 (MW)	7	16.51	3.01	6.43	5.56	7.21
Total Amount (MW)	111.4	167.97	108.02	106.66	102.22	103.37

Fig. 8 Comparison of congestion cost with different algorithm for 30 bus system

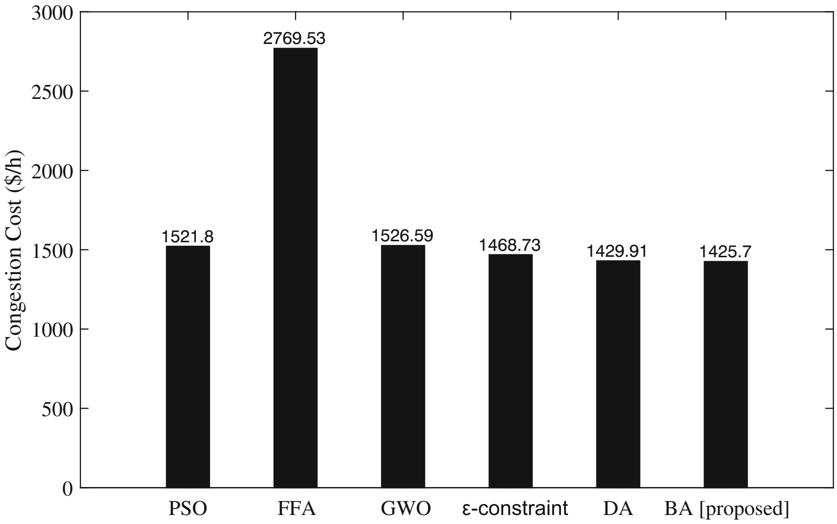


Fig. 9 Comparison of real power rescheduled for 30 bus system

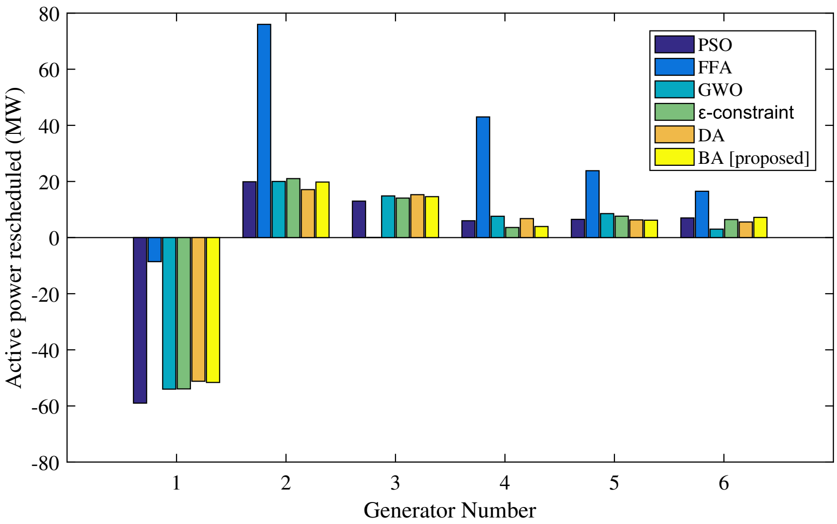


Fig. 10 Convergence characteristics with BA for 30 bus system

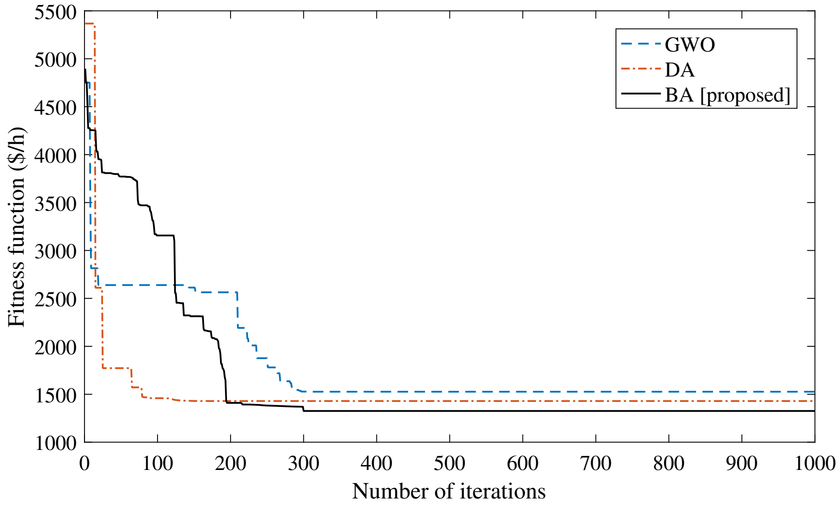


Fig. 11 Bus voltage representation after CM for 30 bus system

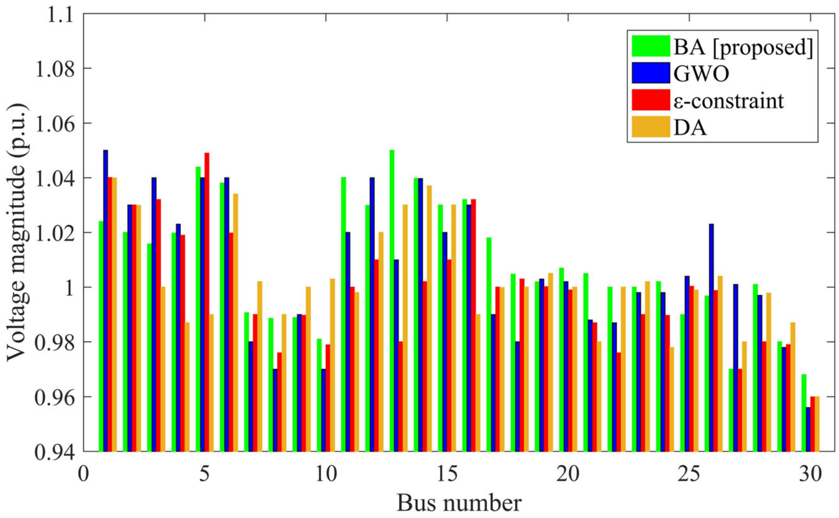


Table 10 Representation of convergency time (30 bus system)

	DA	ϵ-constraint	GWO	BA [proposed]
Time (Sec.)	0.39528	0.66506	0.56857	0.50086

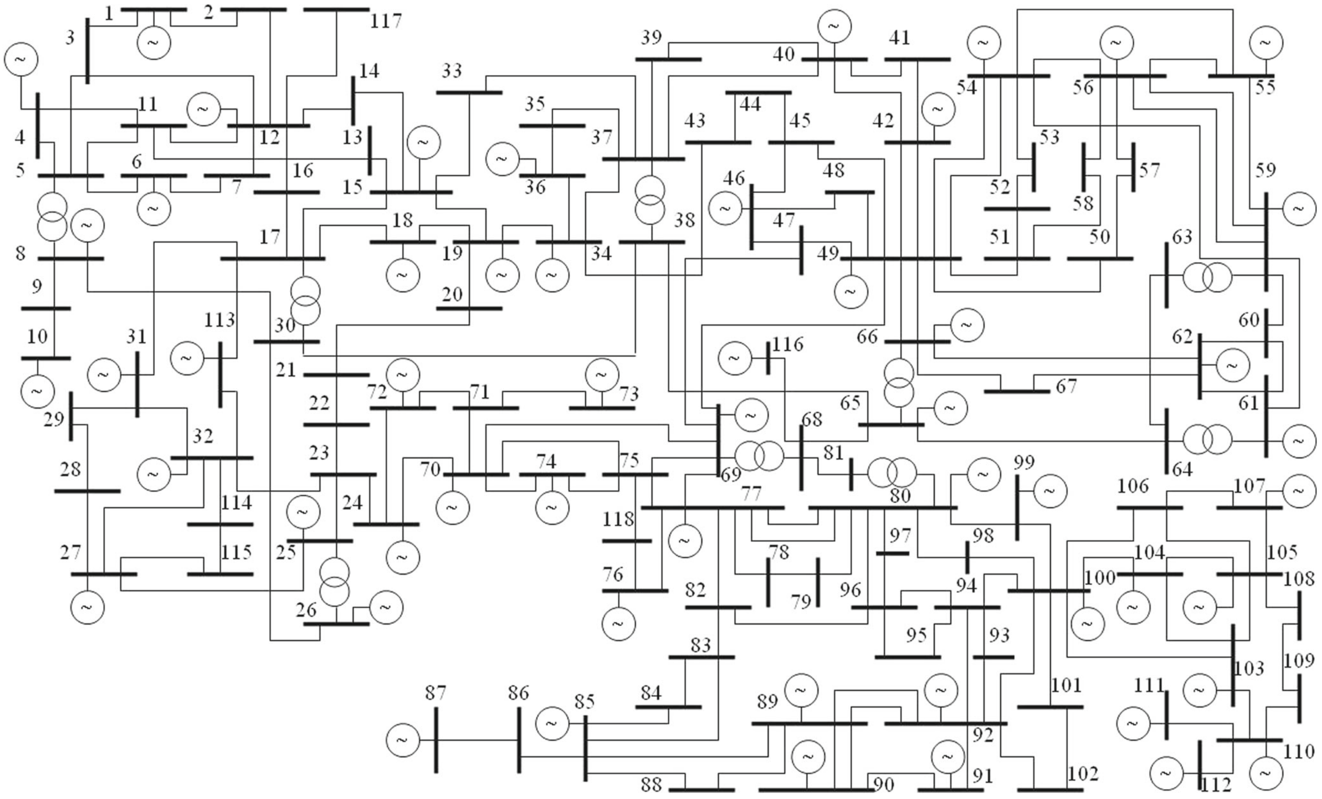


Fig. 12 Topology of IEEE 118 bus system

Table 11 Power flow in congested line

Congested Line	Power Flow (MW)	Line Limit (MW)
13-16	262	200

Table 12 Generator sensitivity factor (118 bus system)

Gen No.	GSF	Gen No	GSF	Gen No	GSF
1	0.00	19	0.01	37	−0.004
2	0.001	20	0.03	38	−0.003
3	−0.001	21	0.02	39	−0.002
4	−0.04	22	0.009	40	−0.002
5	−0.04	23	0.004	41	−0.0002
6	−0.04	24	0.003	42	−0.0005
7	−0.04	25	0.005	43	−0.0003
8	−0.04	26	−0.001	44	−0.0004
9	−0.04	27	−0.004	45	−0.0002
10	−0.04	28	−0.002	46	0.001
11	−0.05	29	−0.006	47	−0.001
12	−0.05	30	−0.006	48	−0.001
13	−0.16	31	−0.09	49	−0.001
14	−0.24	32	−0.014	50	−0.001
15	0.45	33	−0.014	51	−0.001
16	0.63	34	−0.014	52	−0.001
17	0.38	35	−0.006	53	−0.001
18	0.51	36	−0.005	54	−0.001

A comparison of the congestion costs is represented in Fig. 8. It is observed from Fig. 8 that the congestion cost with PSO, FFA, GWO, $\epsilon-$constraints, DA, and BA for the proposed CM problem are 1521.8 $\$/h$, 2769.53 $\$/h$, 1526.59 $\$/h$, 1468.73 $/h, 1429.91 $\$/h$, and 1425.70 $/h respectively. The bar graph comparative analysis in Fig. 8 portrays that the optimal congestion cost achieved with BA is minimum than the other reported cost with the referred optimization algorithm. The comparative results of the active power rescheduled is shown in Fig. 9. It is noticed that the optimal rescheduled of real power with BA resulted in achieving the minimum congestion cost. The comparative representation of the convergence profile with other existing methods is shown in Fig. 10. The convergence characteristics with BA portrays that the optimal congestion cost is achieved with the increased in the iterations. The total system loss has curtailed to 13.6 MW after the CM drive, which was 21 MW during the congested scenario.

Table 13 Generator price bids (118 bus system)

Gen No.	Bids ($/MWh)	Gen No	Bids ($/MWh)	Gen No	Bids ($/MWh)
1	60	19	14	37	18
2	25	20	10	38	17
3	19	21	20	39	16
4	16	22	21	40	15
5	21	23	13	41	11
6	12	24	18	42	9
7	13	25	16	43	10
8	14	26	15	44	21
9	17	27	17	45	30
10	19	28	19	46	15
11	70	29	25	47	14
12	15	30	27	48	11
13	17	31	15	49	20
14	19	32	14	50	21
15	20	33	17	51	22
16	15	34	9	52	23
17	10	35	6	53	19
18	18	36	20	54	25

Table 14 Comparative analysis of results with BA for 118 bus framework

	PSO [36]	GWO [46]	ϵ-constraint [47]	DA [48]	BA [Proposed]
Approx. Cost of generator rescheduling ($/h)	3479.7	3404.97	3364.1	3180.02	3116.18
Power flow post CM. Line 13-16 (MW)	199	198.98	198.9	198.9	198.89
ΔP_1 (MW)	-3.79	-2.99	-3.17	-2.18	-1.00
ΔP_{13} (MW)	81.9	81.51	76.52	77.01	70.64
ΔP_{14} (MW)	16.4	14.94	20.62	13.02	18.71
ΔP_{15} (MW)	-17	-7.54	-2.36	-11.56	-1.02
ΔP_{16} (MW)	-55	-29.84	-32.02	-5.09	-32.24
ΔP_{17} (MW)	-9	-2.80	-2.17	-12.06	-1.68
ΔP_{18} (MW)	-16.3	-53.7	-51.78	-59.14	-54.39
Total Amount (MW)	199.4	183	188.64	190.5	179.68

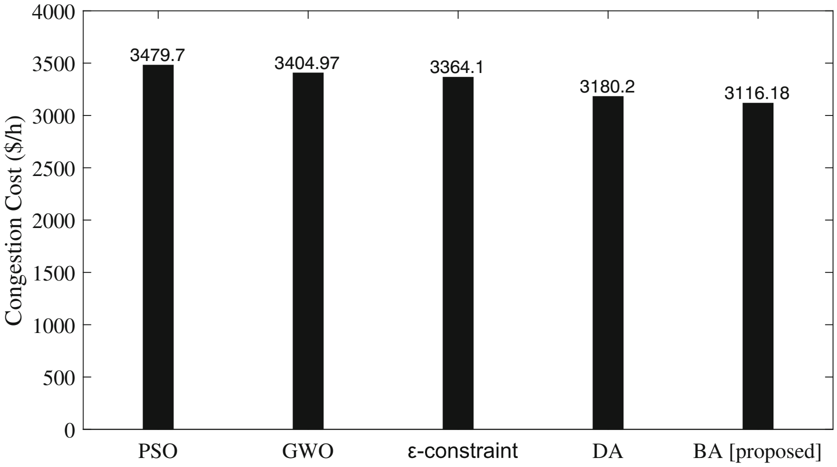


Fig. 13 Comparison of congestion cost with different algorithm for 118 bus system

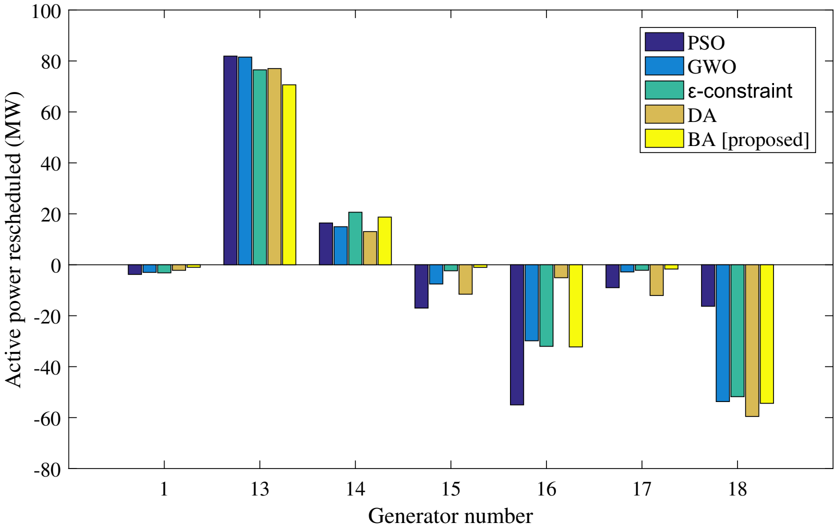
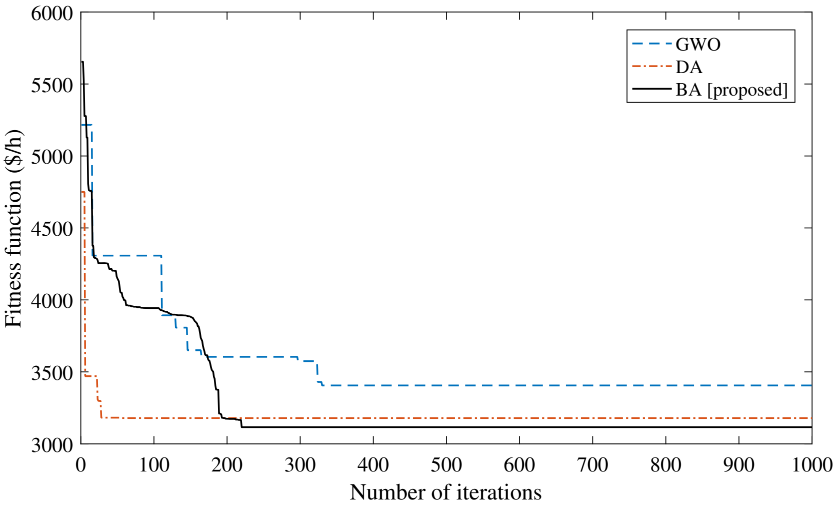


Fig. 14 Comparison of real power rescheduled for 118 bus system

Fig. 15 Convergence characteristics with BA for 118 bus system



The bus voltages after CM with BA are displayed in Fig. 11. It is observed that the voltages at each of the buses are well maintained within its acceptable limits and thus ensure a better system adequacy. The convergency time for the proposed CM approach has been represented in Table 10.

Modified IEEE 118 Bus System

The number of generator buses and load buses are 54 and 64 respectively that constitutes the complete framework of 118 bus system. The framework of IEEE 118 bus system is represented in Fig. 12. The system data, parameters and the power limits of the generators for the case be found in [36, 51]. The buses are marked consecutively with number 1 assigned to the slack bus and then the sequence is followed by the generator buses and the load buses. Line connecting the buses 13-16 is found to be over burdened. The detail of the overburdened line is given in Table 11. The power flow of the overburdened line has increased to 262 MW.

The GSF values are represented in Table 12. It is observed that the GSF values corresponding to the generators 13-18 are non uniform in nature. Thus the generators corresponding to these GSF values are chosen to take part in the CM process. The slack bus generator is also rescheduled to take care of the losses. It is also noticed that the involvement of the generators for the CM process has been drastically reduced in number, as out of 54 generators only 7 generators are taking part in the CM process. The GSF values may be either positive or negative. The positive GSFs indicate that the participating generators in the CM will reduce their power output whereas the generators with negative GSFs will increase their power output. Table 13 represents the price bids for the generators.

The CM process is carried out by rescheduling the generators using the BA to completely mitigate the overloading of 62 MW. The details of the results achieved with the proposed BA for CM are tabulated in Table 14. The results depicted in other literature are also placed in

Fig. 16 Bus voltage representation after CM for 118 bus system

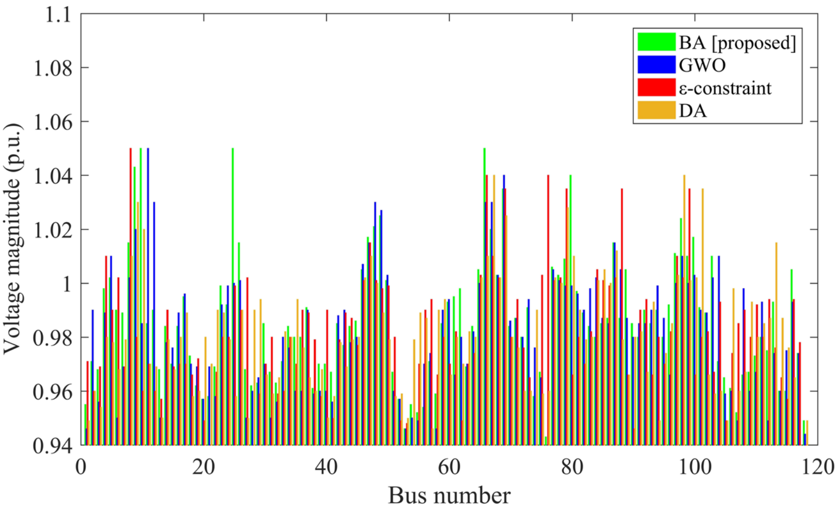


Table 15 Representation of convergency time (118 bus system)

	DA	ϵ-constraint	GWO	BA [proposed]
Time (Sec.)	0.29086	0.79865	0.68857	0.59784

Table 14, in order to put forward a detailed comparative analysis with the proposed scheme of CM. The congestion cost comes out to be 3116.19 \$/h with the proposed CM scheme and is also the best among the other outcomes represented in Table 14.

The pictorial representation of the congestion costs is shown in Fig. 13. The Fig. 13 represents the congestion cost delivered by PSO [36], GWO [46], $\epsilon-$constraints [47], DA [48], and BA for the CM problem proposed in this work. It is seen that the congestion cost achieved are 3479.7 $\$/h$, 3404.97 $\$/h$, 3364.1$\$/h$, 3180.02 $\$/h$, and 3116.19 $\$/h$ for PSO [36], GWO [46], $\epsilon-$constraints [47], DA [48] and BA respectively. In case of the BA approach it is observed from bar graph representation in Fig. 13 that the BA approach provided the optimal cost among all the other cost delivered by optimization approaches in the referred literature. The comparisons of the active power rescheduling amounts are portrayed in Fig. 14. It is observed from Fig. 14 that the BA approach has optimally rescheduled the real power output in comparison to PSO [36], GWO [46], $\epsilon-$constraints, and DA [48]. Thus, the optimal rescheduled of the real power enabled to achieve the minimum congestion cost.

The convergence profile for the fitness function with the BA and GWO and DA is shown in Fig. 15. The BA convergence characteristic seems to a promising one for the congestion cost minimization. The BA convergence profile portrays that the optimal cost is achieved with the increase in the iterations and is efficient than the other referred algorithms. The losses are also curtailed to 134.68 MW post CM which was 140.63 MW during the state of congestion. The post CM bus voltages with BA are shown in Fig. 16. It is observed that the voltages at each of the buses are within its desired values. This enhances the system stability. The convergency time for the optimization approached adopted for CM are represented in Table 15.

Conclusion

The work portrayed in this manuscript exhibit the formulation of CM approach for the power system transmission network. The generator rescheduling technique and the GSF values are considered for the formulation of the CM problem. The generators having most deviated GSF values are selected to reschedule the power output. This contributes an effective impact on the rate of power flow through the congested line. The generators price bids and amount of the real power adjusted are taken into account to model the CM problem. The line outage is considered as the contingency for research work. The proposed BA for the CM problem exhibits that it is an efficient optimization approach with fast convergence that aids in searching the global optima more effectively. The achieved results also suggest that BA can perform adeptly to provide solutions for non-linear and multimodal problems. The comparative analysis established with other optimization approaches like RED, PSO, ABC FFA, GWO, DA, and $\epsilon-$constraints portrays that BA is capable to provide random reduction and minimum time to sort the optimum value.

The optimization of the congestion cost has been performed by implementing BA technique and have also successfully relieved the overburden of the congested line. Test cases like 39-bus New England, modified IEEE 30, and 118 bus cases are considered to analyze the efficacy of the proposed research philosophy. A comparative analysis is also established between BA and other algorithms like RED, PSO, ABC, FFA, GWO, $\epsilon-$constraint, and DA. It can be observed that in case of 39 bus New England system the reduction in the congestion cost with BA is 10.27%, 12.64%, 8.28%, 6.55%, 4.55% and 2.67% when compared with the congestion cost achieved with RED, PSO, ABC, GWO, $\epsilon-$constraint, and DA respectively. The real power loss is also reduced by 2.38 MW in comparison to the congested state. In case of 30 bus system the congestion cost is also reduced by 6.31%, 8.52%, 6.60%, 3.01% and 0.29% in comparison to the congestion cost achieved with PSO, ABC, GWO, $\epsilon-$constraint, and DA respectively. The real power loss is also curtailed by 7.4 MW for the same test case system. The BA approach for CM when incorporated on 118 bus system a reduction of 10.44%, 8.48%, 7.95% and 2.00% congestion cost is achieved in comparison to PSO, GWO, $\epsilon-$constraint, and DA. The real power loss is reduced by 5.95 MW with BA compared to the congested state of the framework. The comparative analysis portrays that the adopted BA proves to be potent for the congestion cost minimization considering the generator rescheduling procedure. It is also noticed that the system losses have been reduced using the adopted approach and the voltages at each of the buses are also within its desired limits. This ensures the overall stability of the system.

The future scope of this research work can be extended considering the application of renewable energy sources and Distribution Generation (DG). The optimal location for the placement of the DGs can be identified based on the heuristic approaches to mitigate the congestion by rescheduling its power output. The proposed philosophy can also be extended considering the reactive power dispatch to control congestion.

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