

A Bald Eagle Search Optimization Approach for Congestion Alleviation in Power System Transmission Channels



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Abstract In the deregulated power system framework, congestion on transmission lines has become a significant concern. This study presents a congestion management strategy that focuses on efficiently adjusting the power output of generators. To determine the most effective generator for rescheduling, the generator sensitivity factor is used. The Bald Eagle Search (BES) optimization technique is employed to optimize the rescheduling of real power delivery from the generators, aiming to minimize congestion costs. The performance of this approach is analyzed using 39-bus New England test framework. A comparison with recent algorithms reveals that BES effectively minimizes congestion costs when contrasted to alternative optimization methods. Additionally, this approach improves the system voltage profile with reduction in the system losses thereby enhancing overall system stability.

Keywords Power rescheduling · Congestion management · Optimization techniques · Bald eagle search optimization · Sensitivity analysis

1 Introduction

Power system congestion occurs when the demand for electricity exceeds the transmission capacity of the power system, leading to potential power outages and blackouts. To mitigate this issue, power system operators use CM techniques to redistribute the power flows in the network and ensure reliable and efficient electricity delivery. CM involves a range of methods, including generation rescheduling, load shedding,

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and redispatching, as well as market-based approaches such as locational marginal pricing (LMP) and demand response programs. Effective CM by the system operator enhances the power transfer in the transmission channels while ensuring a consistent supply of electricity to customers.

The CM issues have been analyzed and evaluated by many power system researchers. Aditi et al. managed congestion in a wind-integrated power system by rescheduling the generation of wind and hydro units based on their combined cost bids. The approach uses hydro units with low operating costs and fast start-up times to help alleviate congestion costs and includes secured bilateral transactions [1]. Dehnavi et al. presented a new CM model that identifies candidate zones for congestion alleviation by analyzing a congestion index (CI) that measures the effectiveness of generators and loads in creating and alleviating congestion [2]. Pantos et al. proposed a market-based CM that involves minimum-cost redispatching which considered the combined influence of the generators, loads, and aggregators by the system operator to alleviate congested lines [3]. In [4], the researchers considered the power system risk in combination with the impact of renewable sources to manage congestion. In another research, locational marginal price (LMP) and transmission congestion cost (TCC) are used to manage congestion by identifying the optimal location of DG [5]. In [6] a decentralized approach for EV aggregators to collaborate with common clients for CM is proposed, which treats EVs as flexible loads and mobile distributed storage (MDS). The framework also suggests organizational support from the distribution system operator (DSO) to alleviate severe congestion.

Verma and Mukherjee proposed the use of the Firefly algorithm for CM in a deregulated environment. The algorithm aims to find optimal generation and load patterns to minimize congestion in a deregulated power system. Their study evaluates the effectiveness of the Firefly algorithm through simulation studies. Pandya and Joshi presented a CM approach that utilizes sensitivity analysis to identify critical lines and bus voltages affected by congestion. PSO has been applied to optimize the power generation and load shedding to alleviate congestion. Yesuratnam and Thukaram proposed a CM method based on relative electrical distances (RED) using voltage stability criteria that takes into account the RED between buses in a power system. The proposed method aims to optimize generation rescheduling to alleviate congestion [7]. Hazra et al. presented a CM approach that utilizes power rescheduling on the generation side in association to the scheduling of the loads at the most sensitive buses. The study investigates the effectiveness of the approach through case studies and provides insights into the optimal utilization of the generation and load shedding for congestion management [8]. Dutta and Singh proposed an optimal generator rescheduling method for CM based on PSO. The authors address CM by optimizing the generator schedules using the PSO algorithm. The proposed method aims to minimize the system operating cost while satisfying various operational constraints. Paul et al. proposed an optimal rescheduling method to mitigate congestion using the gravitational search algorithm (GSA). The authors address the issue of congestion in power systems by formulating it as an optimization problem and applying the GSA to find the optimal solution [9]. Zaeim et al. formulated a multi-objective transmission CM method that considers the management of the consumer electricity

patterns. They aimed to optimize the utilization of power consumption behavior to alleviate congestion and improve the overall performance of the power system [10]. In [11], Paul et al. proposed a CM that considered the power deliveries by the wind energy system. The work focused on the formulation of a modified whale optimization technique for congestion alleviation. The proposed technique aimed to find optimal generation patterns that minimize congestion and improve the overall performance. Deb and Goswami proposed a CM approach by generator rescheduling using the artificial bee colony (ABC) technique. The ABC algorithm is employed to find optimal generation schedules that minimize congestion [12].

This research study focuses on addressing congestion management by considering the technique of generator rescheduling for real power. The rescheduling process involves adjusting the power output of generators based on their generation shift factors (GSFs). This research study introduces a BES optimization algorithm for solving CM problem. The proposed BES incorporates effective exploration and exploitation at two stages which are the search stage (Exploration phase), and swooping stage (Exploitation phase) respectively that generated appreciable results for the CM problem. The significant contribution of this work lies in the utilization of BES to effectively optimize the rescheduling of real power output from generators, with the objective of minimizing the associated cost.

2 Problem Formulation

GSF is termed as variation/modifications in actual state of power flow through a transmission line that connects between two buses due to slight variation in the injected power. Mathematically this can be represented as:

$$\text{GSF} = \frac{\Delta P_{ij}}{\Delta P_{G_g}} \quad (1)$$

where P_{ij} = active power flow in overloaded line, P_{G_g} = shift in actual power generation by g th generator. Power flow equation for an overloaded line is expressed as;

$$P_{ij} = V_i^2 G_{ij} + V_i V_j G_{ij} \cos(\theta_i - \theta_j) + V_i V_j B_{ij} \sin(\theta_i - \theta_j) \quad (2)$$

Here P_i is voltage amplitude and θ_i is phase angle of i th bus. Further detailed derivation for GSF is explained in [13]. More sensitive generating units for CM are selected for GR process based upon un-even GSF values. The required rescheduled cost is evaluated on the basis of the price to be paid from the participating generators by resolving the following optimization problem;

The total rescheduling cost is expressed as;

$$\text{Minimize } \sum_g^N C_g(\Delta P_g) \Delta P_g \quad (3)$$

Subjected to

$$F_k^0 + \sum_{g=1}^N (\Delta P_g (\text{GSF}_g)) \leq F_k^{\max} \quad k = 1, 2, \dots, n_1 \quad (4)$$

$$P_g - P_g^{\min} = \Delta P_g^{\min} \leq \Delta P_g \leq \Delta P_g^{\max}, \quad g = 1, 2, \dots, n_1 \quad (5)$$

$$\sum_{g=1}^N \Delta P_g = 0 \quad (6)$$

where ΔP_g is the power injection and C_g is the price bids. These are the bidding prices that the generators will incur/invite to alter their actual power outputs. F_k^0 is the power transfer that is carried through the entire contracts requesting for the transmitting operation. The line's limit is F_k^{\max} . N represents quantity of generating units involved for CM, n_1 represents entire system number of transmitting lines, P_g^{\min} and P_g^{\max} stands for upper and lower limits output parameters for generators, respectively. Here Eqs. (4) and (5) represents the inequality constraints, Eq. (6) represent equality limits that balance the power in CM process.

3 Bald Eagle Search Optimizer

Alsattar and colleagues developed a metaheuristic technique that imitates the hunting behavior of bald eagles, specifically their approach to catching fish. The technique, known as the Bald Eagle Search (BES), involves three stages: selection, exploring the designated area (exploration), and swooping down to attack (exploitation). Initially in the algorithm, the eagle chooses a designated region with the highest concentration of fish, and in the second stage, it navigates within that area to identify the optimal position. Finally, it moves from that position to attack its prey.

3.1 Selection Stage

During this particular stage, the bald eagles choose the area to search by evaluating the quantity of food available. This selection process greatly enhances their ability to capture fish:

$$Z_{\text{new},i} = Z_{\text{best}} + \alpha * r(Z_{\text{mean}} - Z_i) \quad (7)$$

The parameter α , which has a value between 1.5 and 2, is responsible for monitoring the changes in the eagle's position. Z_{best} is the current search area, while r varies within $[0,1]$.

3.2 Search Stage (Exploration Phase)

In this scenario, the exploration behavior is conducted by the eagles to locate fish. They move in a spiral pattern to increase their search efficiency. The optimal location for swooping down to catch the fish can be determined by:

$$Z_{i,\text{new}} = Z_i + h(k) * (Z_i + Z_{i+1}) + m(k) * (Z_i - Z_{\text{mean}}) \quad (8)$$

$$m(k) = \frac{mr(i)}{\max(|mr|)}, \quad h(i) = \frac{hr(i)}{\max(|hr|)} \quad (9)$$

$$hr(k) = r(k) * \cos(\theta(k)); \quad mr(k) = r(k) * \sin(\theta(k)) \quad (10)$$

$$r(k) = \theta(k) + R * \text{rand} \quad (11)$$

$$\theta(k) = a * \pi * \text{rand} \quad (12)$$

The location of the bald eagle is decided using $m(k)$ and $h(k)$, which have values ranging from 0 to 1 and are used to calculate the eagle's polar coordinates. The parameters $r(i)$ and $\theta(k)$ represent spiral flight, respectively. β ranges between 5 and 10. R ranges from 0.2 to 2. The random number, rand , falls between 0 and 1.

3.3 Swooping Stage (Exploitation Phase)

In this case, the eagle traverses toward the prey identified from the best location. Additionally, all the solutions make its movement toward the best location as well. This process can be described as follows:

$$Z_{i,\text{new}} = \text{rand} * Z_{\text{best}} + m1(k) * (Z_i - c1 * Z_{\text{mean}}) + h1(k) * (Z_i - c2 * Z_{\text{best}}) \quad (13)$$

$$m1(k) = \frac{mr(k)}{\max(|mr|)}, \quad h1(k) = \frac{hr(k)}{\max(|hr|)} \quad (14)$$

$$hr(k) = r(k) * \cosh[\cos^{-1} \theta(k)] \quad (15)$$

$$mr(k) = r(k) * \cosh[\theta(k)], mr(k) = r(k) * \sinh[\theta(k)] \quad (16)$$

$$\theta(k) = a * \pi * \text{rand} \quad \text{and} \quad r(k) = \theta(k)$$

where $c1, c2 \in [1, 2]$.

The movement concentration of the eagles toward the central locations is increased by the parameters $c1$ and $c2$, which have values between 1 and 2. A flowchart of the BES optimizer is presented in Fig. 1.

4 Results and Discussion

The application of BES to manage congestion by rescheduling the generators has been demonstrated on 39 bus New England Test System which includes 10 generators and 29 load buses [14] and is shown in Fig. 2

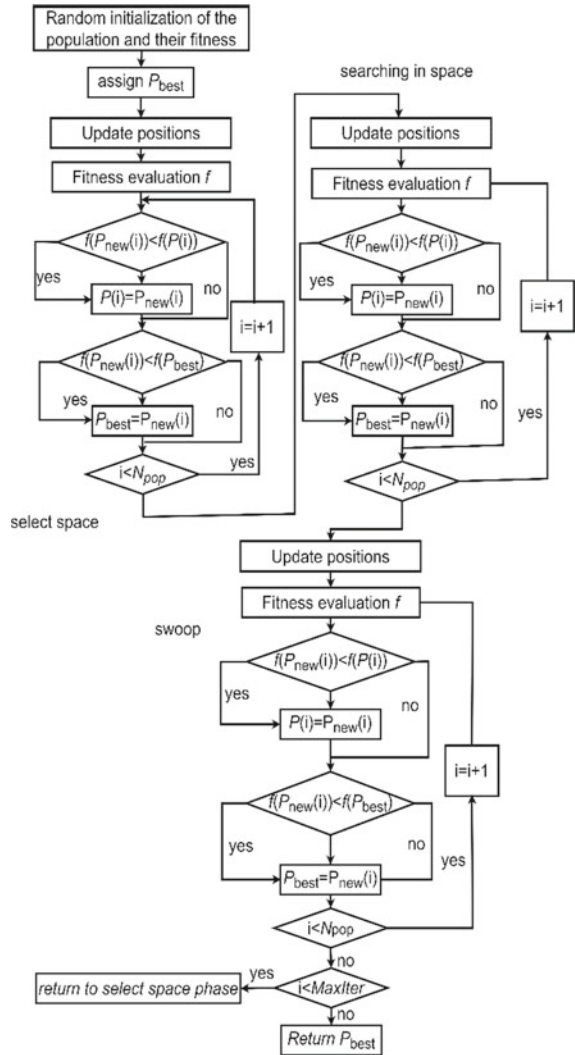
The line L14-34 has a power flow of 262.3 MVA, which is well below its flow limit of 600 MVA. The congestion in the system is created when the L14-34 has been tripped, the flow on line L15-16 between buses 16 and 15 exceeds its limit, reaching 628.6 MVA compared to the limit of 500 MVA. Load flow analysis has been used to detect this issue of overloading.

Table 1 presents the GSF values. The GSF of generators G4 to G7 are uniformly set to -0.35 , indicating that these four generators do not contribute to congestion management thus the contributing generators for the CM are the G2, G3, G8, G9, G10.

Table 2 highlights the outcomes achieved with the application of BES for the CM problem. The outcomes of BES are then compared to the findings with RED [7], GSA [9], ABC [12], PSO [15]. The congestion cost achieved with BES is 7943.91 \$/h and is minimum when compared to RED, PSO, ABC, and GSA. The congestion cost comparison is shown in Fig. 3. The rescheduling quantities for generators 3, 8, and 10 have been compared with different methods, as illustrated in Fig. 4. The convergence characteristics for the congestion cost minimization with BES has been shown in Fig. 5.

Table 3 reveals that rescheduling using BES leads to enhancements in the minimum voltage of the system and reductions in active power losses. The voltage profile of the system after BES-based rescheduling is comparatively better than the results reported in RED, ABC, PSO. It is also observed that the system losses have been reduced. The system loss achieved with BES post CM is 57.96 MW and it is noted that the system losses achieved with BES is comparatively lower than the other techniques. The voltage at the buses after CM with BES is represented in Fig. 6.

Fig. 1 BES optimizer flowchart for CM



5 Conclusion

In this study, an approach of rescheduling generator’s active power is considered for CM. The generators for CM are selected based on GSF. The selected generators are rescheduled using BES to mitigate congestion. The utilization of the GSF helps to minimize the number of participating generators. The BES-based solution yields superior results, and the solution demonstrates system stability with reduced redispatch costs. The BES algorithm requires tuning of very few parameters, namely the

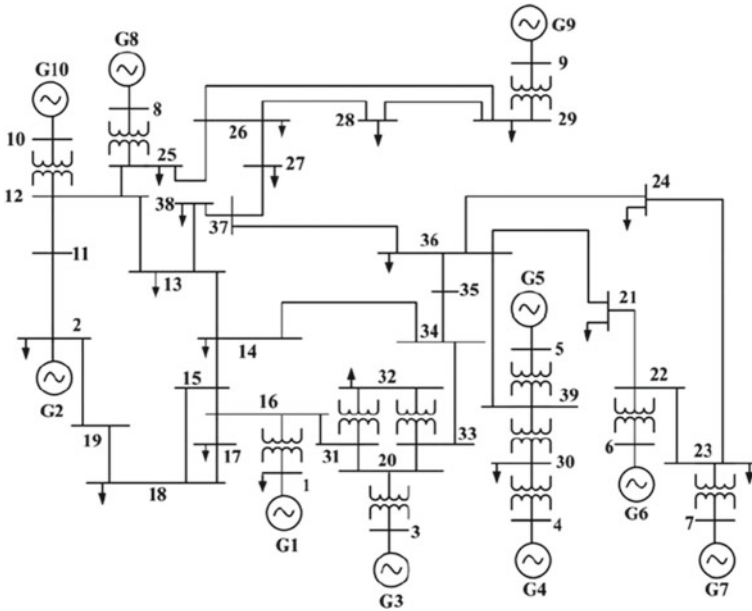


Fig. 2 Representation of 39 bus system

Table 1 GSF data for 39-bus New England system

Gen. No	01	02	03	04	05
GSF	0.00	- 0.47	- 0.04	- 0.35	- 0.035
Gen. No	06	07	08	09	10
GSF	- 0.35	- 0.35	- 0.49	- 0.44	- 0.51

colony and this simplicity in parameter tuning increases the likelihood of finding the most effective values compared to other metaheuristic algorithms.

Table 2 Comparison evaluation result with proposed method for 39-bus New England system

Parameters	Method				
	RED [16]	PSO [17]	ABC [12]	GSA [9]	BES [proposed]
Rescheduling cost(\$/h)	8639.17	8872.9	8456	8033	7944.28
Power flow of L 15–16 (MW) after CM	510	490	499.50	499.10	498.32
ΔP_1 (MW)	– 99.59	– 149.1	– 131.0	– 130.82	– 137.68
ΔP_2 (MW)	98.75	65.6	63.2	46.43	72.34
ΔP_3 (MW)	– 159.64	– 129	– 132.0	– 124.69	– 115.60
ΔP_4 (MW)	12.34	NP	NP	NP	NP
ΔP_5 (MW)	24.69	NP	NP	NP	NP
ΔP_6 (MW)	24.69	NP	NP	NP	NP
ΔP_7 (MW)	12.34	NP	NP	NP	NP
ΔP_8 (MW)	24.69	75.4	72.2	88.90	46.18
ΔP_9 (MW)	12.34	52.1	49.1	47.95	93.78
ΔP_{10} (MW)	49.38	83.0	78.8	72.26	36.54
Total cost (MW)	518.45	554.2	526.3	518.45	502.1

Fig. 3 Congestion cost comparison with BES

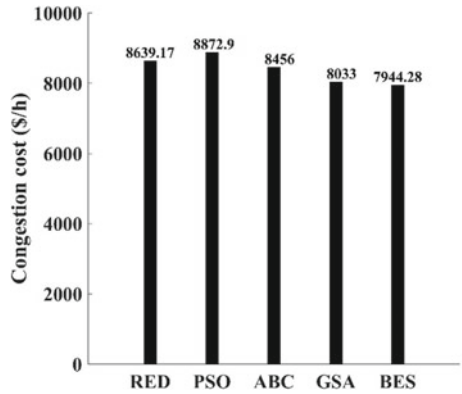


Fig. 4 Rescheduled power comparison with BES

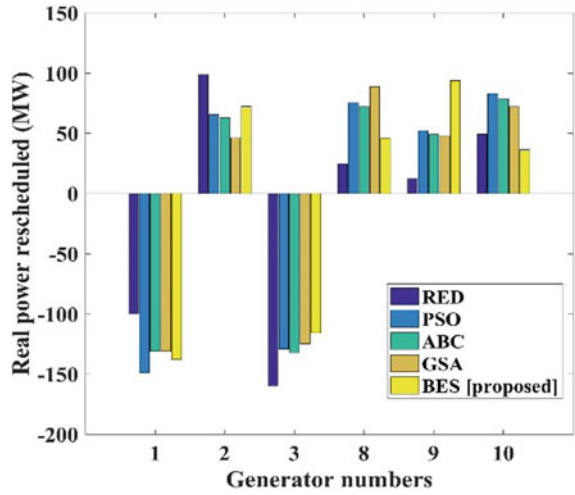


Fig. 5 Convergence profile of BES for CM

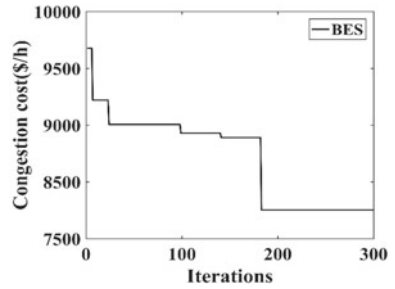
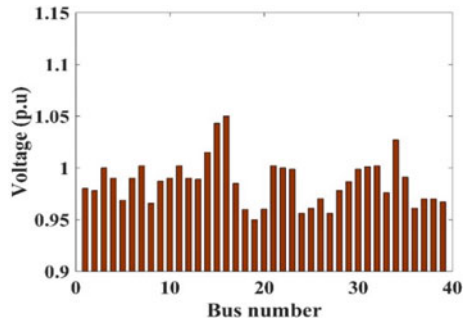


Table 3 Representation of system voltage and losses

	Congested state	RED [7]	PSO [8]	ABC [9]	BES [Proposed]
V_{min} (p.u.)	0.941	0.945	0.932	0.940	0.955
P_{loss} (MW)	59.64	57.31	58.00	59.00	57.96

Fig. 6 Voltage at the buses post CM with BES



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