Generator Rescheduling Based Congestion Management in Power System Deregulation Using the Cheetah Optimization

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Abstract.

Transmission line congestion is more severe and persistent in deregulated power systems than it is in traditionally controlled power systems. In a deregulated power market (DPM) scenario, transmission line congestion is one of the most critical problems. To guarantee the electricity system framework runs consistently and securely, the independent system operator (ISO) controls congestion. Congestion management (CM), which takes into account the inherent uncertainties of the restructured power system, is essential to the functioning and security of DPM. This article demonstrates how to control congestion with generation rescheduling. The system is designed in such a way that it helps the traders to compete and trade using the bid prices. Network security is maintained by keeping all constraints within the allowed limits via the Newton-Raphson load flow. An innovative Cheetah Optimizer is employed to handle the congestion management challenge. The weighted sum approach is used instead of multi-objective optimization to simplify the problem as a single-objective optimization and solve the issue for multiple instances of congestion and tested in an IEEE 30 bus system. The MATLAB software serves as a tool for modelling the full process, and the results acquired with Cheetah optimiser give better results than the conventional optimisation technique.

***Keywords*: Congestion management; cheetah optimizer; deregulated power system.**

1. Introduction

The existing electrical system encountered its present form through an extensive process that included continuous alterations in the plan of action, including the implementation of numerous shifts. Economical and geographical restrictions promoted transformations and privatization of the power industry with the intent to achieve maximum utilization of resources within the existing framework [1]. An industry that was once vertically integrated has evolved into a diverse group of organizations that includes traders, buyers, transmission companies, distribution companies, and generation companies [2]. This encourages the efficient use of resources, which makes running businesses more reasonable and advantageous, and enables the entire framework to be more effective, secure, and trustworthy. Congestion in the transmission line is the largest obstacle to the continuing operation of the decentralised electrical system [3]. One of the main jobs done by system operators to guarantee that the transmission system operates within operating parameters is congestion control. Congestion control takes on greater significance in the developing electric power market and has the potential to obstruct the trade of electricity [4]. The fierce competition among diverse market players has culminated in major growth in power exchanges. However, that has had a significant impact on systems' profitability due to the hindering of transmission routes [5]. It has an impact on dispatch charges and bidding while also endangered the safety and soundness of the electricity network [6]. As a consequence, fast evaluation and immediate congestion diminution are essential for the flawless operation of the electricity sector [7]. The primary contributing factors to this threat are overload on currently operational lines, unbalanced generation and transmission, an unanticipated rise in demand, the failure of one or more generators, and malfunctioning system components [8]. Congestion control is a cost-effective alternative to network expansion in order to satisfy increased demand [9]. Congestion alleviation or mitigation refers to the diminution or distribution of the extra power flowing via stressed transmission cables [10]. Through regulating congestion, the power available could be transmitted optimally with no violation of system parameters [11]. In a deregulated context, power system congestion poses a serious threat to independent system operators due to its violation of system security and cost. Therefore, keeping the electrical system free of congestion is a crucial job for ISO [12]. There are generally two possible approaches to dealing with congestion, free or technical measures and paid or non-technical measures [13]. Rearranging the topology of the network, introducing transformer taps, and working with the transmission system operator (TSO) to use transmission system (FACTS) devices are all free options; in contrast, reallocating generation and reducing loads aren't available for free [14]. Several steps were taken to explore the congestion management markets in order for the producers and consumers of electrical energy to collaborate towards the shared objective of enhancing global welfare [15]. According to researchers in [16], congested lines can be cleared using the FACTS devices, and to mitigate congestion, an appropriate spot to install the thyristor controlled series capacitor (TCSC) was selected by employing flow sensitivity. Congestion is decreased without compromising cost issues with two newer FACTS devices, a static synchronous compensator (STATCOM) and an unified power flow controller. (UPFC) [17]. One competing multi-objective function was designed by the authors in [18] to discover the best place for deploying FACTS devices to obtain CM while lowering the generation and carbon emission rates. In a deregulated power market, authors in [19], present an easy, profitable, and dependable two-step optimization technique for resolving the congestion issue along with maximizing system profit, minimizing costs, and reducing emissions. This strategy makes optimal use of TCSC and wind generators as well.

The generator rescheduling methodology was widely employed by researchers to reduce congestion. Congestion mitigation techniques include the use of genetic algorithms [20], A real coded genetic algorithm [21], has been used to investigate the application of real-coding genetic algorithms in determining the best generation rescheduling for congestion relief and tested in an IEEE 30 bus system. Reference [22] uses the Firefly algorithm (FA), where there were two folds to the work. To find the generators taking part in output rescheduling for congestion management, the Generator Sensitivity Factor (GSF) is first determined. In order to determine the participating generators' ideal rescheduling cost, FA is added in the second place and tested in the IEEE 39 bus New England Test System. Rescheduling the real power output of the participating generators [23] provides a novel approach to congestion management based on the Ant Lion Optimisation (ALO) algorithm, where a sensitivity factor has been utilized to select the generators. The Satin Bowerbird optimization (SBO) algorithm efficiently reduces the cost of rescheduling changing generator actual power, efficiently relieves congestion in overloaded lines with varying contingency situations, and efficiently minimizes losses in varying contingencies of the test system cases. [24], Reference [25] discusses to find the best generators for the real power rescheduling process, a generator sensitivity factor-based generator selection technique has been presented. Hybrid optimization techniques are also employed in congestion relief by means of rescheduling [26]-[27]. Researchers in [28] proposed a method of congestion reduction using the particle swarm optimization approach with better time-dependent acceleration coefficients. The authors of Ref. [29] proposed a technique that uses the FFA to efficiently rearrange generator supply in order to reduce transmission congestion in the networks. A CM strategy based upon the optimal power flow (OPF) concept by applying an upgraded genetic algorithm was developed by researchers in [30], with the goal of lowering the overall MW of rescheduling. Researchers also utilize the moth swarm and the real-coded biography-based optimization in

OPF [31]-[32]. Applying the improved differential evolution method, authors in [33] investigated power system congestion mitigation with an emphasis on the use of wind energy sources. The authors in [34] employed the swarm intelligence techniques to address the congestion management issue by rescheduling the generators in the most effective way possible. Researchers in [35] implemented the artificial bee colony algorithm to alleviate congestion by varying the power output of generators that were chosen based on their sensitivity to the overloaded lines. In Ref. [36], a sensitivity method for distributing distributed generators (DGs) that concurrently takes voltage security and congestion alleviation into account is presented in this research. When ranking the load buses, the sensitivity of the overloaded lines to bus injections is taken into account. Next, using a genetic algorithm (GA), the new generation capacities for DGs linked at these load buses are calculated. The goal of this process is to improve system performance by lowering system losses and keeping the voltage profile of the different buses as close to its nominal value as possible. This study has taken into account the N-1 contingency requirement. A genetic algorithm, the multi-objective glowworm swarm optimization (MOGSO) algorithm, was used by the authors of [37] to address congestion problems on IEEE 30 and IEEE 118 bus test systems under a variety of congested scenarios. They were able to effectively demonstrate how the suggested method may calculate the transmission line loss and congestion cost at the lowest feasible expense level. Reference [38] discusses that when transmission lines in the electrical system are overloaded, the usual course of action is to reschedule generators, place FACTS devices on the lines, and reduce load. However, load curtailment is not usually carried out because the deregulated system promotes customer satisfaction. Generator rescheduling is therefore chosen as the problem solution because it doesn't require building additional infrastructure. One of the more modern optimisation methods, called Grey Wolf Optimiser (GWO), is predicated on the hunting strategy and leadership structure of grey wolves. The Nelder-Mead (NM) method conducts an efficient local search, and the output is utilised to initialise the population for GWO, which conducts a global best value search. Reference [39] discussed the quantitative examination of the generation companies' (GENCOs') market dominance and how congestion affects it in the market for deregulated energy. Using a new Market Revenue Share (MRS) index, the GENCOs' level of market power has been determined. The revenue received by a GENCO as a percentage of the total revenue of all the GENCOs involved in the deregulated electricity market during a given period of time is known as its MRS. In order to maximise the social welfare function while taking into account non-linear operational and congestion restrictions, an optimal power flow problem was solved, yielding the MRS of GENCOs. Manjulata et al. suggested the method that combines the Butterfly Optimisation Algorithm with Particle Swarm Optimisation and Grey Wolf Optimiser in a hybridised form to improve the ability to explore and exploit for reactive power management using new England 39 bus system to lower active power loss and system expenses [40].In reference [41] the authors used Sequentially Hybridized Differential Evolution with Particle Swarm Optimization to mitigate congestion using IEEE 14 bus system in two different scenarios: single point congestion and multipoint congestion where Cost analysis, stability analysis, complexity analysis, and strategy analysis are used in the performance inquiry on congestion mitigation. Second, by examining the quality of the solution dynamics and doing convergence analysis, the algorithm's properties are observed. A congestion management technique centred on effectively modifying generator power output is discussed in reference [42]. Using the generator sensitivity factor, the best generator for rescheduling is identified. In order to minimise congestion costs, the rescheduling of real power delivery from the generators is optimised using the Bald Eagle Search (BES) optimisation technique. The New England test framework for 39 buses has been used to analyse this approach's performance. Rescheduling the generating side of the power system network is one of the best ways to address the congestion problem. In order to minimise this congestion cost, reference [43] suggests a novel fuzzy-based hybrid optimisation technique that is based on the hybridisation of particle swarm optimisation and genetic algorithm optimisation. The effectiveness of the provided methodology is assessed using the modified IEEE 57 bus system.

Referring to the aforementioned research papers, transmission line restrictions possess a significant role in transferring electrical power from one point to the other. Furthermore, during the congested state, transmission line overflowing can result in a complete shutdown of the whole electrical system. As a result, CM is extremely important in preserving the safety and security of the system. The present study explores a generator rescheduling-based congestion management technique in the optimal power flow context. The main objectives for dealing with the CM issue are thought to be minimizing transmission line losses, fuel costs, and congestion costs. The following are the study's main contributions:

(1) In this work, the congestion mitigation problem is handled by the Cheetah Optimizer (CO) in the framework of OPF.

(2) To solve the CM problem and conduct a comparison with CO, the Whale Optimization Algorithm (WOA), Particle Swarm Optimization (PSO), Grey Wolf Optimization (GWO), and hybrid Grey Wolf Optimization and Particle Swarm Optimization (PSO-GWO) are also used.

(3) The whole study is divided into two studies: congestion control without taking the bid prices into account and congestion control taking the bid prices into account. Moreover, the issue is solved when there is no congestion in the system, along with three different scenarios of congestion.

(4) Minimization of total generation cost, congestion cost using bid rates, and active power loss are taken as objectives while solving the optimization problem.

(5) The weighted sum approach of multi-objective optimization is used in this paper to deal with both cost and loss simultaneously. Equal weights are considered to connect both the objectives into one.

(6) N-1 contingency analysis is used to detect critical line interruptions. An infraction or congestion on the network, results from a line outage combined with an increase in load on a specific bus.

(7) Congestion is alleviated using active power rescheduling of the generating units by the optimization methods while retaining the appropriate control measures to ensure that no grid constraints are breached.

(8) To meet the conditions for equality and inequality, Newton-Raphson load flow is used.

(9) Using standard IEEE 30 bus test systems, the recommended CM method is examined using the MATLAB 2019 program.

(10) The suggested CO algorithm's usefulness is demonstrated by the results obtained, which show that it can successfully mitigate congestion from the system and provide a better solution to the CM issue.

2. Problem Formulation

Rescheduling generators by satisfying all restrictions through the application of an optimization technique is an effective approach to eliminating network congestion. In the electricity market, the system operator takes appropriate measures to control congestion while retaining maximum profitability from the accepted contracts between the buyer and the seller. The buyer-seller pair is prepared to accept a compensation price for each market transaction in the bilateral power market model. Prioritizing transactions and accounting for the cost associated with violating constraints during times of congestion might help outline this market model. On the other hand, in a centralised market model, sellers, i.e., the GENCO's or the competing generators submit their bid rates for rescheduling the generators to clear the congestion. This market model is also incorporated in this study to determine the congestion cost utilising the increment or decrement in generations due to the rescheduling. Additionally, the CM problem is resolved utilising several optimisation strategies, with the objectives being the minimisation of active power loss, congestion cost, and overall generating cost. A weighted sum approach to handle both generation cost and power loss, or congestion cost and power loss simultaneously, is also utilised in this paper. The subsections that follow detail the mathematical formulation of all the objectives and constraints applied in the congestion alleviation challenge.

2.1 Objectives

2.1.1 Reduction of the overall cost of generation / cost of congestion

The goal of the proposed CM issue, without adjusting for market bidding prices, is to minimize the fuel cost (F_{fc}), which can be formulated as below [37]:

$$F_{fc} = min\left[\sum_{g=1}^{N_g}\{a_g(P_g)^2 + b_g(P_g) + c_g\}\right] \quad (1)$$

where, F_{fc} is the expanse of total generation, N_g is the number of total generators, P_g is the real power generation of g^{th} generator, a_g in \$/(MWhr)^2, b_g in \$/MWhr and c_g in \$/hr denotes the cost coefficient of generators. However, using the market bidding rates presented by GENCOs, the cost of congestion management becomes [35]:

$$F_{cc} = min\left[\left\{\sum_{g=1}^{N_g}\left(C_g^{bid^+} * \Delta P_g^{\ +}\right)\right\} + \left\{\sum_{g=1}^{N_g}\left(C_g^{bid^-} * \Delta P_g^{\ -}\right)\right\}\right] \quad (2)$$

Where, F_{cc} is the congestion cost, $\Delta P_g^{\ +}$ and $\Delta P_g^{\ -}$ are the incremented and decremented amount of generation, respectively, whereas $C_g^{bid^+}$ and $C_g^{bid^-}$ are respectively the incremented and decremented bid rates. Incorporating the bid prices not only helps to determine the congestion cost but also helps to gain more profitability with maximized social welfare by enabling the market players to trade and compete.

2.1.2 Minimization of Transmission Line Loss

Transferring power from generating companies to consumers incorporates losses, which should be reduced to attain more reliable and efficient power flow. Hence, the current research sought to minimize the following objective function in order to reduce the active power loss for each transmission line [37]:

$$F_{loss} = min\left[\frac{1}{2}\sum_{mn}[G_{mn}(V_m^2 + V_n^2 - 2V_mV_n\cos(\delta_m - \delta_n))]\right] \tag{3}$$

where, $m, n = 1, 2, 3 \ldots Nb$; $Nb =$ Number of bus, V_m and δ_m shows the voltage and angle at bus m respectively, whereas *G* denotes the conductance.

3.1.3 Simultaneous Cost and Line Loss Minimization

In this study, the weighted sum or scalarization approach [44] to multi-objective optimization is used. Fuel cost minimization and loss in transmission line are simultaneously achieved by applying Eq. (4), where the two objectives are combined by weights to form one primary goal. Similarly, minimizing congestion costs and line loss at the same time is carried out by utilizing Eq. (5).

$$F_{fcl} = w1 * F_{fc} + w2 * F_{loss} \tag{4}$$

$$F_{ccl} = w1 * F_{cc} + w2 * F_{loss} \tag{5}$$

where, $w1 + w2 = 1$ and $0 < w1, w2 < 1$.

2.2 Problem Constraints

Congestion control measures must comply with both equality and inequality requirements. Power balance constraints can be considered equality constraints, whereas inequality constraints are nothing else but the functional limits of the power system components.

2.2.1 Equality Constraints

Equality constraints, also referred to as power balance limitations, can be represented as follows [37]:

$$P_{gm} - P_{dm} - V_m\left[\sum_{n=1}^{Nb}\left[V_n * \left\{G_{m,n} * cos(\delta_m - \delta_n) + B_{m,n} * sin(\delta_m - \delta_n)\right\}\right]\right] = 0 \quad (6)$$

$$Q_{gm} - Q_{dm} - V_m\left[\sum_{n=1}^{Nb}\left[V_n * \left\{G_{m,n} * cos(\delta_m - \delta_n) - B_{m,n} * sin(\delta_m - \delta_n)\right\}\right]\right] = 0 \quad (7)$$

where, m, n = 1, 2…Nb, Nb is the total number of buses, $G_{m,n}$ and $B_{m,n}$ is the conductance and susceptance , respectively; V denotes the bus voltages; P_{gm} and P_{dm} are the active power injections and demand respectively, whereas Q_{gm} and Q_{dm} are respectively the reactive power injections and demand at bus m. The active power generated after congestion management is equal to the sum of active power generated before the congestion and the changes in active power due to the rescheduling of the generator.

$$P_g^r = (P_g + \Delta P_g) \quad (8)$$

where, P_g^r is the amount of active power of g^{th} generator unit after rescheduling during CM, P_g is the scheduled power at the ideal or no congestion state, and ΔP_g is the change in generation required to mitigate the congestion.

2.2.2 Inequality Constraints

The following inequality constraints function as both operational and physical boundaries for all transformers, transmission lines, bus voltages, and generators:

A. Generator Constraints

The minimum and maximum limits of the generator's active and reactive powers (P_g and Q_g) are listed below [37]:

$$(P_g)_{min} \leq P_g \leq (P_g)_{max} \tag{9}$$

$$(Q_g)_{min} \leq Q_g \leq (Q_g)_{max} \tag{10}$$

The following restriction, given by Eq. (11), places a restriction on the generator's bus voltages (V_g) [37].

$$(V_g)_{min} \leq V_g \leq (V_g)_{max} \tag{11}$$

Incremented and decremented real power limits are as follows [23]:

$$(P_g)_{min} - P_g = (\Delta P_g)_{min} \leq \Delta P_g \leq (P_g)_{max} - P_g = (\Delta P_g)_{max} \tag{12}$$

where, $g = 1, 2, 3, \dots \dots, N_g$.

B. Transformer Constraints

Maximum and minimum constraints on transformer tapings (T_n) are represented in the following equation [37];

$$T_n^{min} \leq T_n \leq T_n^{max} \tag{13}$$

where, $n = 1, 2, 3, \ldots \ldots, N_{TF}$; N_{TF} = Number of transformer tapings.

C. Constraints of reactive power compensators

The following are the upper and lower limitations on reactive power compensations (Q_n) provided to the network [37]:

$$Q_n^{min} \leq Q_n \leq Q_n^{max} \tag{14}$$

where, $n = 1, 2, 3, \ldots \ldots, N_{sv}$; N_{sv} = Number of Compensators.

D. Constraints of Security

The security constraints, i.e., the load bus voltages (V_{ln}) and the transmission line power flow limits (S_{Ln}) are symbolized as below [37]:

$$(V_{ln})_{min} \leq V_{ln} \leq (V_{ln})_{max} \tag{15}$$

where, $n = 1, 2, 3, \ldots \ldots, N_l$; N_l = Number of Load buses.

$$S_{Ln} \leq S_{Ln}^{max} \tag{16}$$

where, $Ln = 1, 2, 3, \ldots \ldots, N_{line}$; N_{line} = Number of transmission lines in the system.

3. CHEETAH OPTIMIZATION

The cheetah optimizer is a novel optimization technique developed by researchers in [45] that takes into account the cheetahs' hunting techniques. During the optimization process, all three of a cheetah's primary hunting strategies—searching, waiting, and attacking—are used. In order to increase the population diversity and convergence efficacy of the optimization, the approach of leaving the prey and returning home is also used.

i. **Searching**: For the purpose of locating their prey, cheetahs must actively search, either by scanning or by moving about in their territories (search space). For updating the cheetah's new location, the random search equation shown below is suggested.

$$X_{i,j}^{t+1} = X_{i,j}^{t} + r_{i,j}^{-1} \times \alpha_{i,j}^{t} \quad (17)$$

where, $X_{i,j}^{t+1}$ and $X_{i,j}^{t}$ are the succeeding and present positions of Cheetah *i* in arrangement *j*, respectively. Index t denotes the current hunting time; $r_{i,j}^{-1}$ and $\alpha_{i,j}^{t}$ are the randomization parameter and step length, respectively.

ii. **Sitting-and-waiting:** Cheetahs may sit and wait for the prey to approach or change positions after it has been discovered, for a proper situation to attack. The following equation is used to simulate this behavior :

$$X_{i,j}^{t+1} = X_{i,j}^{t} \quad (18)$$

iii. **Attacking:** There are two critical steps in this strategy: rushing and capturing. In the former strategy, Cheetah will move as quickly as possible towards its target when it decides to attack; however, in the later strategy, Cheetah approached the target and then caught it by using its agility and speed. The CO uses the following mathematical definition to describe the cheetahs' attacking strategy:

$$X_{i,j}^{t+1} = X_{i,j}^{t} + \tau_{i,j} \times \beta_{i,j}^{t} \quad (19)$$

where, $X_{i,j}^{t+1}$ and $X_{i,j}^{t}$ are the updated and present positions of Cheetah *i* in arrangement *j*, respectively. Index t denotes the current hunting time; $\tau_{i,j}$ and $\beta_{i,j}^{t}$ are the turning factor and interaction factor, respectively.

iv. **Leave the prey and go back home:** This tactic is thought of in two scenarios: (1) The cheetah ought to shift locations or head back to its region if it is unable to get its prey. (2) In situations where there hasn't been a successful hunt for a while, it can move to the location of the most recent prey capture and search the area around it.

4. Result and Discussion

On a typical IEEE 30 bus, the suggested CM strategy is tested by using the MATLAB software. The IEEE 30 bus test system contains 30 buses, 21 loads, and 41 transmission lines [37]. There is a net load of 283.4 MW and 126.2 MVAr of active and reactive power on the test system. A total of 20 numbers of cheetahs are considered for solving the optimization problem for several cases with different objective functions. 200 is the assumed maximum number of iterations or generations and the algorithm will stop after it reaches maximum iteration i.e 200. The optimization technique terminates once the maximum number of iterations is reached, as can be seen from its flowchart shown in Fig. 1. In addition, the WOA, PSO, GWO, and hybrid PSO-GWO optimization technique are employed to mitigate all cases under the same conditions, i.e., system data, constraints, variables limits and population size.

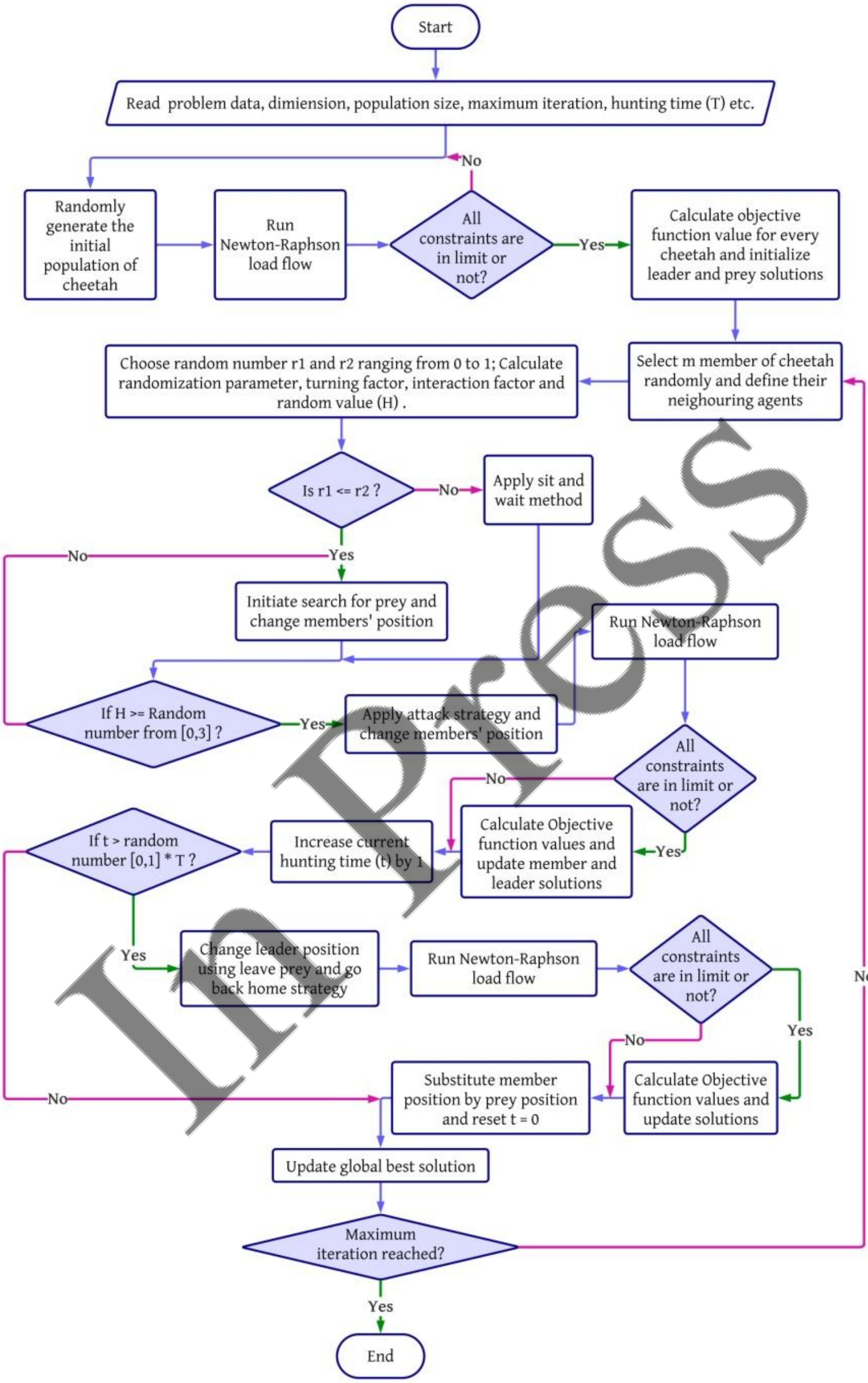


Fig. 1: Flowchart of Cheetah Optimizer as utilized in solving the CM issues

4.1 Study 1: Congestion Mitigation without Prices of Bidding

Without taking the bidding prices into account during the market clearing process, the CM problem is handled in this study. The major goal is to reduce the system's overall fuel and generation costs. Transmission line loss minimization as a single objective optimization problem and fuel cost and loss minimization as a multi objective optimization via the weighted sum approach are both taken into consideration. Equal weights are considered to connect both the objectives, and hence the value of both $w1$ and $w2$ is taken as 0.5. In Study 1, generation scheduling is performed in two different cases, which are as follows [37]:

Case A: Generation scheduling in the absence of system congestion (Base case).

Case B: Congestion control based on generation scheduling by causing congestion in the network.

4.1.1 Case A: Generation scheduling in the absence of system congestion (Base case).

When there is no network congestion, generating scheduling is done to minimize fuel costs and transmission line loss. Results of generator scheduling using the cheetah optimization in this case are shown in Table 1 and taken as base values of Case B and Study II. The same objectives are then solved by using WOA, GWO, PSO , and hybrid PSO-GWO algorithms for comparison with the CO. Minimization of fuel cost by the CO, WOA, PSO, GWO, and hybrid PSO-GWO results 799.0156 \$/h, 801.0511 \$/h, 799.3393 \$/h, 802.6162 \$/h , and 799.763 \$/h, respectively. From which it is clear that the CO algorithm shows the best cost compared to the other algorithms. Minimization of transmission line loss in this case shows the amount of loss as 2.8514 MW, 2.8873 MW, 3.1102 MW, 3.9218 MW and 2.9346 MW when using the CO, WOA, PSO, GWO, and the hybrid PSO-GWO, respectively. The lowest amount of loss is obtained using the CO only. Fuel cost minimisation and loss simultaneously by using the CO results 799.1813 \$/h and 8.2986 MW, respectively, which provides the lowest value as compared to the other optimisation methods. Fig. 2 depicts the convergence characteristics in this scenario. Visualising the characteristics of convergence of all the methods in different situations, it is confirmed that the Cheetah optimiser outperforms all the other methods used for solving the problem.

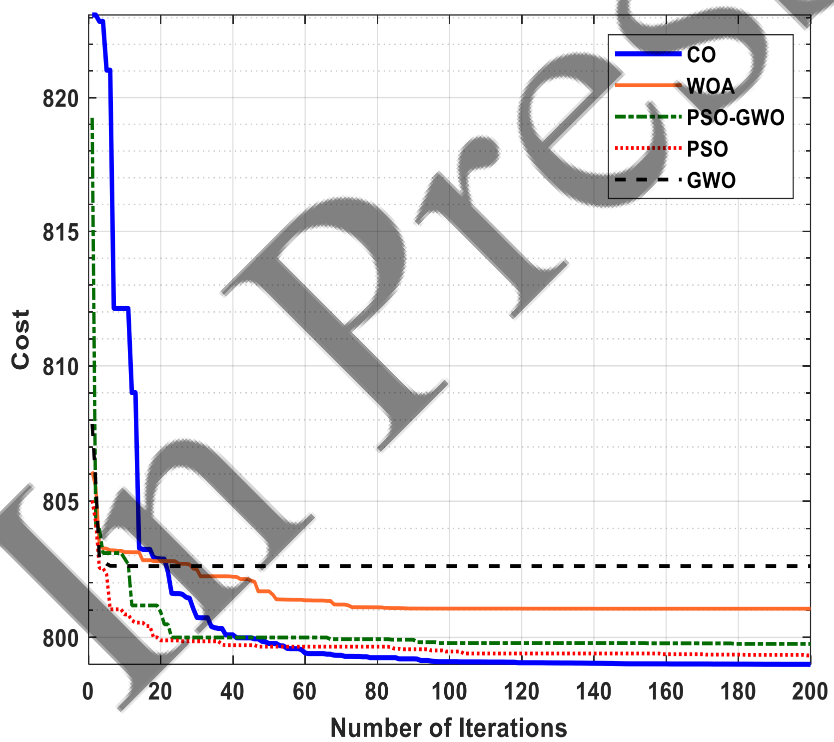
Table 1: *Result of CO considering different objectives when there is no congestion in the system*

Parameters	Fuel Cost Minimization	Loss Minimization	Fuel Cost and Loss Minimization
PG1 (MW)	177.123	51.362	172.921
PG2 (MW)	48.681	79.933	48.823
PG5 (MW)	21.270	49.998	21.838
PG8 (MW)	21.067	34.979	23.456
PG11 (MW)	11.867	29.990	12.655
PG13 (MW)	12.006	39.990	12.005
Total Generation (MW)	292.014	286.251	291.699
Fuel cost ($/h)	799.0156	966.8362	799.1813
PLoss(MW)	8.6141	2.8514	8.2986

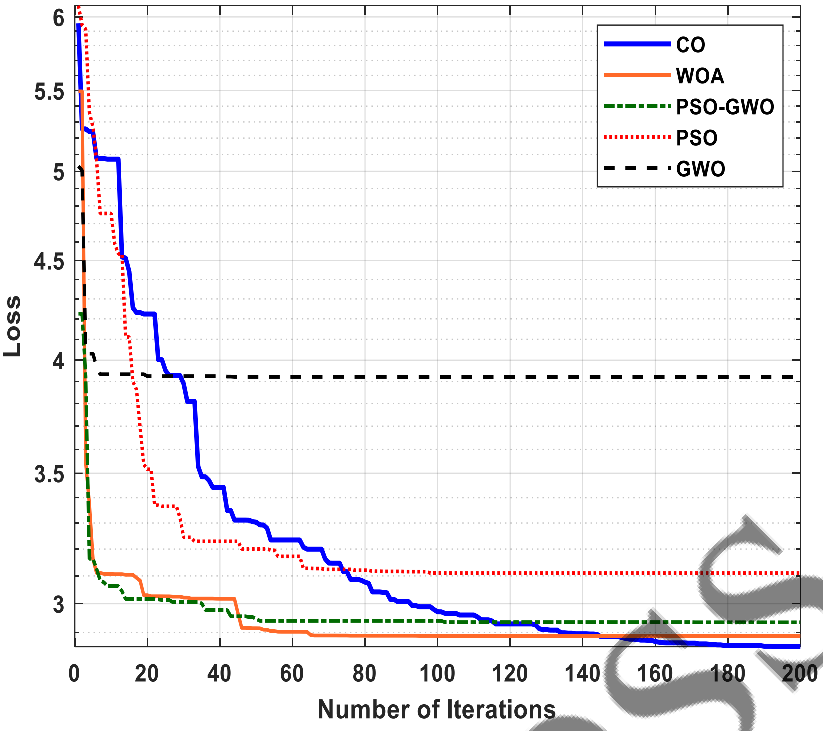
Table 2: *Comparison of CO with WOA, GWO, PSO and hybrid PSO-GWO for Case A*

Case no.	Objectives	CO	WOA	GWO	PSO	PSOGWO
Fuel Cost Minimization	**Fuel cost ($/h)**	**799.0156**	**801.0511**	**802.6162**	**799.3393**	**799.763**
	PLoss(MW)	8.6141	9.0973	9.4765	8.6514	8.6127
	Total Generation (MW)	292.014	292.497	292.876	292.051	292.013
Loss	Fuel cost ($/h)	966.8362	967.155	911.4188	967.6867	967.2677

Minimization	**PLoss(MW)**	**2.8514**	**2.8873**	**3.9218**	**3.1102**	**2.9346**
	Total Generation (MW)	286.251	286.287	287.322	286.510	286.335
Fuel Cost and Loss Minimization	**Fuel cost ($/h)**	**799.1813**	**801.2973**	**815.6229**	**805.6269**	**800.3754**
	PLoss(MW)	**8.2986**	**8.7123**	**7.4628**	**7.7479**	**8.6969**
	Total Generation (MW)	291.699	292.112	290.863	291.148	292.097
	F_{fcl}	403.740	405.005	411.543	406.687	404.536

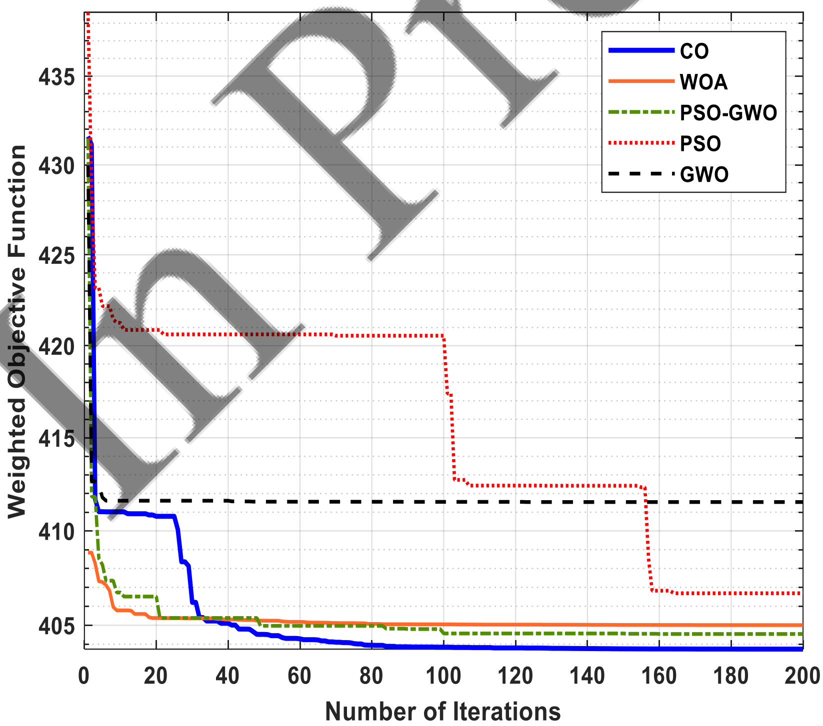


(a)



Loss
Number of Iterations
CO
WOA
PSO-GWO
PSO
GWO

(b)



Weighted Objective Function
Number of Iterations
CO
WOA
PSO-GWO
PSO
GWO

(c)

Fig. 2: Convergence Characteristics of Different Optimization Techniques for: (a) Fuel Cost Minimization; (b) Transmission line loss minimization; (c) Minimization of fuel cost and transmission line loss simultaneously.

4.1.2 Case B: Generation Scheduling Based Congestion Management by Creating Congestion in the System

In this case, congestion is created in the system for three different scenarios, and the problem is solved by generation scheduling. In all the scenarios, multiobjective optimisation using the weighted sum approach is considered, and hence minimisation is done by using the different optimisation methods. The three different scenarios of creating congestion to solve the CM problem include:

Scenario 1: Solving the CM problem for congestion in the system created by reducing capacity of the line 1-2 from 130 MVA to 100 MVA.

Scenario 2: Solving the CM problem for congestion in the system created by outage of line 1-2, with 30% load increase in all buses.

Scenario 3: Solving the CM problem for outage of generating unit 3 at bus number 5 and by reducing the capacity of the line 2–5 from 130 to 80 MVA.

4.1.2.1 Scenario 1: Solving the CM Problem for Congestion in the System Created by Reducing Capacity of the Line 1-2 from 130 MVA to 100 MVA.

In this scenario, congestion is created in the system by reducing the maximum power flow capacity of line 1-2 from 130 MVA to 100 MVA. Consequently, violation or congestion appears in line 1-2 as the power flow on that line in the base case or non-congested situation was greater than its reduced maximum limit as shown in Table 3. Congestion occurs in this scenario and is mitigated by generation scheduling using the optimization techniques. The amount of power flow in the congested line after generation scheduling is provided in Table 3 for different optimisations, and from the results it can be observed that the violation occurring previously is now alleviated as the power flow in the congested line becomes lower or equal to its maximum limit. Hence, it is confirmed that the CM problem is solved successfully by the utilisation of optimisation methods. The amount of active power generation, fuel cost, and transmission line loss in this scenario by using the CO are presented in Table 6. The amount of fuel cost obtained by CO is 803.4445 $/h and the amount of loss is 6.9856 MW. Comparison of CO with WOA, PSO, GWO, and hybrid PSO-GWO is presented in Table 7, from where it can be seen that the lowest value of 405.215 is obtained by using the CO. Convergence characteristics obtained by solving the problem are shown in Fig. 3(a).

Table 3: *Congestion created by reducing capacity of the line 1-2 from 130 MVA to 100 MVA*

Congested Line	Maximum Line Capacity (MVA)	Power Flow After Creating Congestion (MVA)	Amount of Violation (MVA)	Power Flow After Congestion Management in Scenario 1 (MVA)	
1 - 2	100	116.383	16.383	By CO	99.975
				By WOA	100.000
				By PSO-GWO	100.000
				By GWO	99.988
				By PSO	84.482

4.1.2.2 Scenario 2: Solving the CM Problem for Congestion in the System Created by Outage of line 1-2, with 30% Load Increase in all Buses.

In Scenario 2, congestion is created in the IEEE 30 bus test system by the outage of line 1-2 with an increase of 30% load in all the buses. Outage on the mentioned line is performed as an N-1 contingency, and load increase is done by multiplying all the loads with a factor of 1.3. As shown in Table 4, lines 1-3, 3-4, 4-6, and 6-8 become congested due to the outage and show violations of 180.285 MVA, 157.480 MVA, 89.165 MVA, and 13.887 MVA, respectively. Generation scheduling in this state using the optimization techniques results in power flow less than the maximum bounds in the congested lines and thus alleviates congestion from the network successfully. Fuel cost and line loss in scenario 2 as mentioned in Table 6 are 1209.7806 $/h and 13.5461 MW, respectively, can be observed using the CO. Values for different methods are mentioned in Table 7, and it shows that the amount obtained by the CO is better than the other methods. Convergence of the applied methods can be observed from Fig. 3(b).

Table 4: *Congestion created by outage of line 1-2, with 30% load increase in all buses*

Congested Line	Maximum Line Capacity (MVA)	Power Flow After Creating Congestion (MVA)	Amount of Violation (MVA)	Power Flow After Congestion Management in Study 1 – Case B (MVA)	
1 - 3	130	310.285	180.285	By CO	129.999
				By WOA	130.000
				By PSO-GWO	129.999
				By GWO	129.959
				By PSO	130.000
3 - 4	130	287.480	157.480	By CO	123.698
				By WOA	123.716
				By PSO-GWO	117.119
				By GWO	123.749
				By PSO	123.661
4 - 6	90	179.165	89.165	By CO	70.984
				By WOA	79.613

				By PSO-GWO	70.033
				By GWO	75.688
				By PSO	70.849
6 - 8	32	45.887	13.887	By CO	30.033
				By WOA	22.495
				By PSO-GWO	29.503
				By GWO	26.743
				By PSO	30.342

4.1.2.3 Scenario 3: Solving the CM problem for Outage of Generating Unit 3 at Bus Number 5 and by Reducing the Capacity of the Line 2–5 from 130 to 80 MVA.

In this scenario, a generator outage is performed along with a reduction in the power flow limit of line 2-5 from 130 MVA to 80 MVA to create congestion in the network. The third generator unit, which is connected to bus number 5 of the IEEE 30 bus system, is removed from the dataset, and consequently line 1-2 become congested with a power flow violation of 5.749 MVA. Now scheduling the active power of the rest of the five generators of the IEEE 30 bus system using the optimization techniques successfully mitigates the congestion. Less amount of power flow in line 1-2 than its maximum limit can be observed from Table 5 for different optimization techniques. 829.2901 $/h of fuel cost, 9.8447 MW of active power loss is obtained using CO in Scenario 3. Comparison of CO with WOA, PSO, GWO, and hybrid PSO-GWO is presented in Table 7, and the convergence characteristics for this scenario are presented in Fig. 3(c). Results obtained in this scenario also show the supremacy of CO over the other algorithms.

Table 5: *Congestion created by outage of generating unit 3 at bus number 5 and by reducing the capacity of the line 2–5 from 130 to 80 MVA*

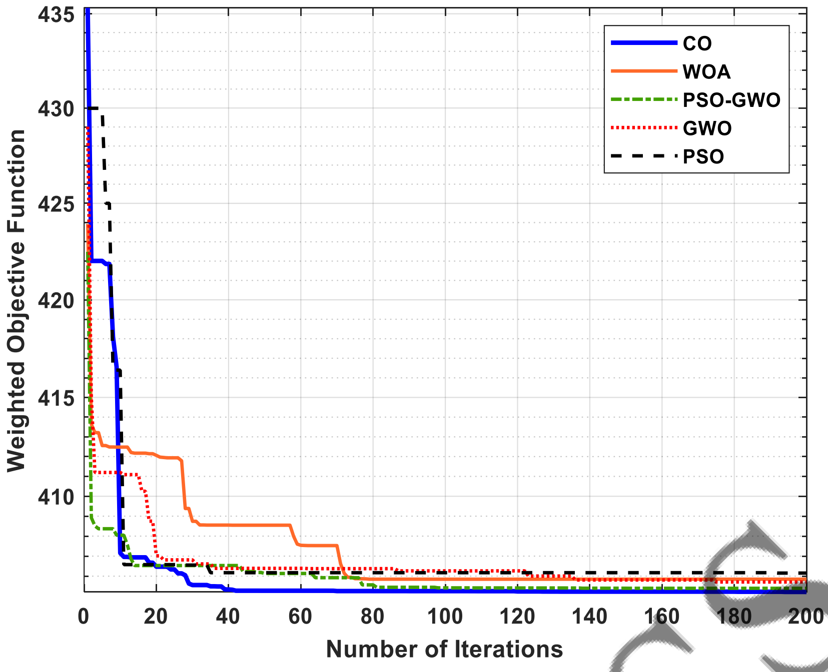
Congested Line	**Maximum Line Capacity (MVA)**	**Power Flow After Creating Congestion (MVA)**	**Amount of Violation (MVA)**	**Power Flow After Congestion Management in Study 1 – Case B (MVA)**	
1 - 2	130	135.749	5.749	By CO	126.284
				By WOA	126.741
				By PSO-GWO	126.735
				By GWO	128.278
				By PSO	121.948

Table 6: *Results of CO for congestion management without considering the bidding prices*

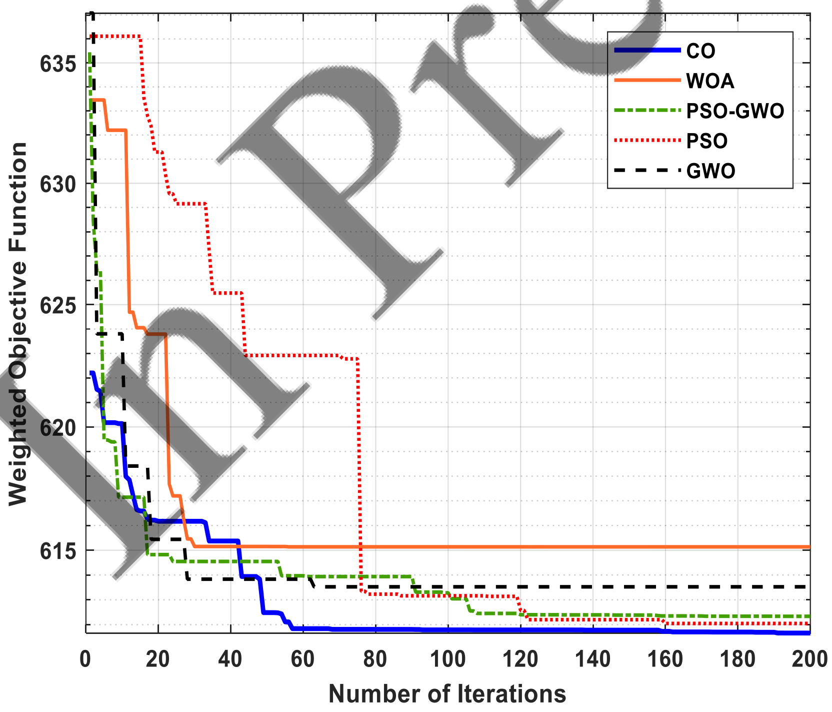
Parameters	**Scenario 1**	**Scenario 2**	**Scenario 3**
PG1 (MW)	150.074	129.857	184.075
PG2 (MW)	55.255	82.380	51.710
PG5 (MW)	23.754	31.693	0
PG8 (MW)	30.960	75.674	29.210
PG11 (MW)	15.486	31.988	14.713
PG13 (MW)	14.857	30.374	13.536
Total Generation (MW)	290.386	381.966	293.245
Fuel cost ($/h)	803.4445	1209.7806	829.2901
PLoss(MW)	6.9856	13.5461	9.8447

Table 7: *Comparison of the CO with WOA, GWO, PSO and hybrid PSO-GWO for Study 1 – Case B*

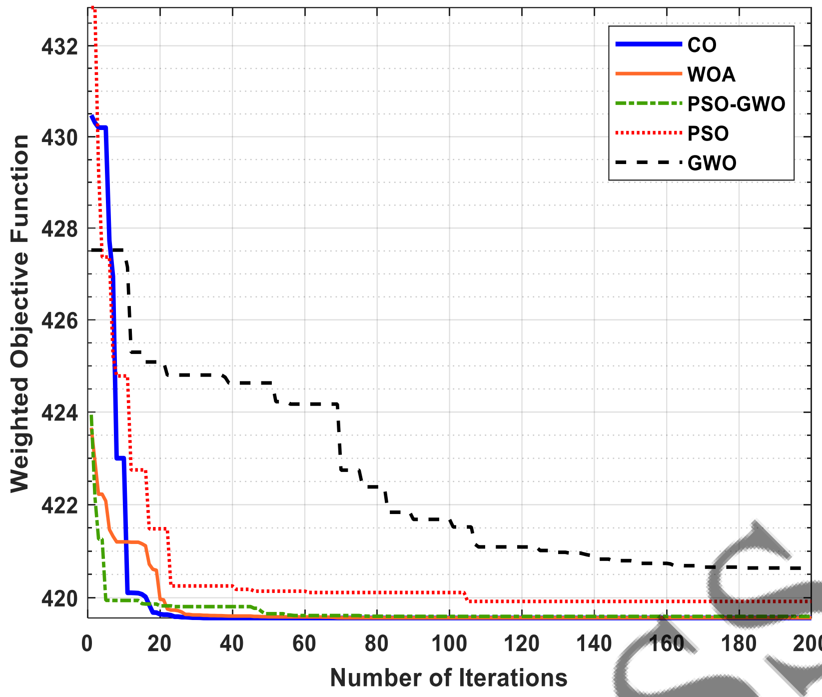
Case no.	Objectives	CO	WOA	GWO	PSO	PSO-GWO
Scenario 1	**Fuel cost ($/h)**	**803.4445**	**804.9893**	**805.2276**	**804.3456**	**803.8116**
	PLoss(MW)	**6.9856**	**6.7086**	**7.0806**	**7.0766**	**6.9799**
	Total Generation (MW)	290.386	290.109	290.801	290.477	290.380
	F_{fcl}	**405.215**	**405.849**	**406.154**	**405.711**	**405.396**
Scenario 2	**Fuel cost ($/h)**	**1209.7806**	**1216.4842**	**1213.72**	**1210.5815**	**1210.9956**
	PLoss(MW)	**13.5461**	**13.7875**	**13.3286**	**13.5169**	**13.6774**
	Total Generation (MW)	381.966	382.208	381.749	381.937	382.097
	F_{fcl}	**611.663**	**615.136**	**613.524**	**612.049**	**612.337**
Scenario 3	**Fuel cost ($/h)**	**829.2901**	**829.306**	**831.7135**	**830.5499**	**829.3082**
	PLoss(MW)	**9.8447**	**9.8359**	**9.5567**	**9.2944**	**9.8934**
	Total Generation (MW)	293.245	293.236	292.957	292.694	293.293
	F_{fcl}	**419.567**	**419.571**	**420.635**	**419.922**	**419.601**


CO
WOA
PSO-GWO
GWO
PSO
Weighted Objective Function
Number of Iterations
435
430
425
420
415
410
0
20
40
60
80
100
120
140
160
180
200

(a)


CO
WOA
PSO-GWO
PSO
GWO
Weighted Objective Function
Number of Iterations
635
630
625
620
615
0
20
40
60
80
100
120
140
160
180
200

(b)



(c)

Fig. 3: Convergence Characteristics of Different Optimization Techniques for: (a) Scenario 1; (b) Scenario 2; (c) Scenario 3.

4.2 Study 2: Congestion Management while Considering the Bidding Prices

In this study, the congestion management problem is solved by utilising the bidding prices of market clearing. Bidding prices are provided by GENCO's to determine the congestion cost while clearing congestion from the network. Utilising the change in active power generation and bidding price, the cost of congestion can be determined as given in Eq. 3. In this study, congestion is mitigated by generator rescheduling while considering the minimization of congestion cost and transmission line loss simultaneously using Eq. 5 as the main objective. Bid price values used for congestion cost calculation are taken from [21]. Congestion is created in the network for the same scenarios discussed in Study 1 Case B and hence the violated lines and the amount of violation in the three scenarios also remain the same.

4.2.1 Scenario 1: Solving the CM Problem for Congestion in the System Created by Reducing Capacity of the Line 1-2 from 130 MVA to 100 MVA.

Solving the CM problem for this scenario while considering the bid prices results in active power flow in line 1-2 as 99.999 MVA, 100 MVA, 95.998 MVA, 97.998 MVA, and 98.662 MVA using the CO, WOA, PSO, GWO, and hybrid PSO-GWO, respectively. Since the power flow in line 1-2 as mentioned in Table 8, is lower than its maximum limit, it can be said that the congestion is mitigated successfully. Congestion cost and the amount of active power loss obtained using the CO are 750.7557 $/h and 7.6714 MW. Change in active power generation due to generation rescheduling is shown in Table 11. A total of 37.823 MW change in power generation can be observed while using CO. Comparisons of CO with the other algorithms in this study are shown in Table 12. The convergence characteristics as obtained in this scenario are shown in Fig. 4(a). Results of CO as observed again confirm its better performance over the other algorithms.

Table 8: *Congestion created by reducing capacity of the line 1-2 from 130 to 100 MVA*

Congested Line	**Maximum Line Capacity (MVA)**	**Power Flow After Creating Congestion (MVA)**	**Amount of Violation (MVA)**	**Power Flow After Congestion Management in Study 2 (MVA)**	
1 - 2	100	116.383	16.383	By CO	99.999
				By WOA	100.000
				By PSO-GWO	95.998
				By GWO	97.988
				By PSO	98.662

4.2.2 Scenario 2: Solving the CM Problem for Congestion in the System Created by Outage of Line 1-2, with 30% Load Increase in all Buses.

Solving the CM problem for Scenario 2 considering the bid prices shows congestion costs of 4440.3334 \$/h, 4476.2751 \$/h, 4841.8254 \$/h, 4470.6697 \$/h, and 4444.3542 \$/h using the CO, WOA, PSO, GWO, and hybrid PSO-GWO, respectively, whereas the amount of active power loss becomes 13.0665 MW, 13.3617 MW, 14.0843 MW, 13.2201 MW, and 13.0776 MW, respectively. Changes in active power generation while using CO are shown in Table 11. Values are mentioned in Table 12. Moreover, the amount of power flow in the congested lines, as mentioned in Table 9, shows the successful mitigation of congestion from the network. Convergence graphs, as shown in Fig. 4(b), represent that the cheetah optimiser performs better in Scenario 2.

Table 9: *Congestion created by outage of line 1-2, with 30% load increase in all buses*

Congested Line	Maximum Line Capacity (MVA)	Power Flow After Creating Congestion (MVA)	Amount of Violation (MVA)	Power Flow After Congestion Management in Study 2 (MVA)	
1 - 3	130	310.285	180.285	By CO	129.994
				By WOA	130.000
				By PSO-GWO	129.999
				By GWO	129.637
				By PSO	129.795

3 - 4	130	287.480	157.480	By CO	123.403
				By WOA	123.468
				By PSO-GWO	123.389
				By GWO	123.354
				By PSO	123.224
4 - 6	90	179.165	89.165	By CO	87.299
				By WOA	85.121
				By PSO-GWO	85.102
				By GWO	88.708
				By PSO	84.321
6 - 8	32	45.887	13.887	By CO	23.051
				By WOA	18.905
				By PSO-GWO	18.118
				By GWO	10.887
				By PSO	15.286

4.2.3 Scenario 3: Solving the CM Problem for Outage of Generating Unit 3 at Bus Number 5 and by Reducing the Capacity of the Line 2–5 from 130 to 80 MVA.

Outage of generator unit 3 with reduction of capacity of line 2-5 from 130 to 80 MVA creates congestion in line 1-2 which is then mitigated by using the optimization techniques. 491.0486 \$/h of congestion cost and 9.7928 MW of power loss is obtained while solving the problem using CO, and the values are provided in Table 11. Comparisons of CO with the other algorithms for this scenario are mentioned in Table 12, and the convergence characteristics of the applied methods are shown in Fig. 4(c). Value obtained in Scenario 3 confirms that the performance of CO is better than the other algorithms. Moreover, the power flow in line 1-2 obtained using the optimization techniques is less than its maximum limit and thus shows the successful alleviation of congestion from the network.

Table 10: *Congestion created by outage of generating unit 3 at bus number 5 and by reducing the capacity of the line 2–5 from 130 to 80 MVA*

Congested Line	Maximum Line Capacity (MVA)	Power Flow After Creating Congestion (MVA)	Amount of Violation (MVA)	Power Flow After Congestion Management in Study 2 (MVA)	
1 - 2	130	135.749	5.749	By CO	114.760
				By WOA	126.741
				By PSO-GWO	126.735
				By GWO	128.278
				By PSO	121.948

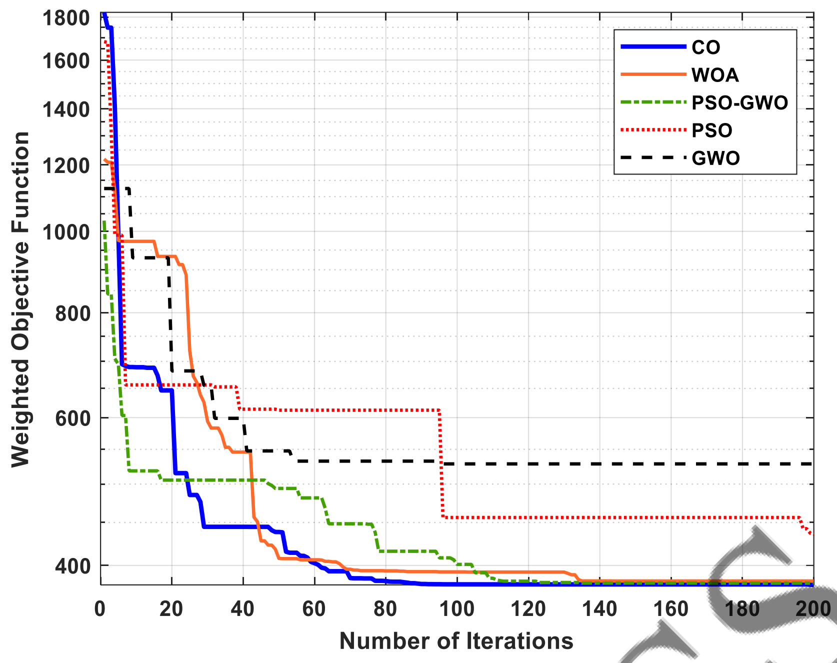
Table 11: *Results of CO for congestion management while considering the bidding prices*

Parameters	Scenario 1	Scenario 2	Scenario 3
ΔPG1 (MW)	-18.909	-42.372	+0.0006
ΔPG2 (MW)	+18.821	+90.841	+23.2970
ΔPG5 (MW)	+0.049	+38.153	0
ΔPG8 (MW)	+0.001	+0.023	+0.0004
ΔPG11 (MW)	+0.004	+0.254	+0.0382
ΔPG13 (MW)	+0.039	+3.518	-0.0035
Total Change in Generation (MW)	37.823	175.161	23.3397
Congestion cost ($/h)	754.4381	4440.3334	491.0486

PLoss(MW)	7.6789	13.0665	9.7928

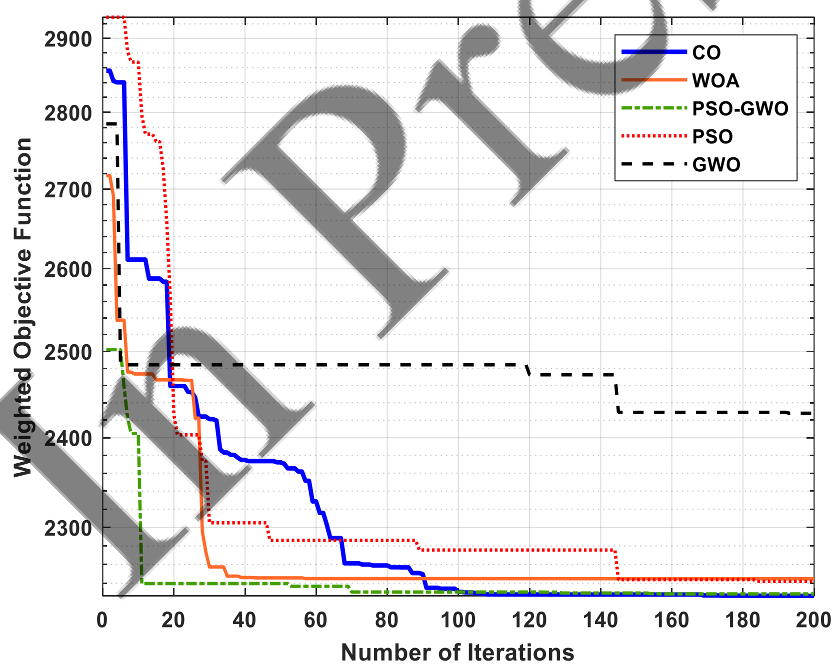
Table 12: *Comparison of the CO with WOA, GWO, PSO and hybrid PSO-GWO for Study 2*

Case no.	Objectives	CO	WOA	GWO	PSO	PSO-GWO
Scenario 1	**Congestion cost ($/h)**	**750.7557**	**758.8617**	**1049.7785**	**864.2632**	**754.4381**
	PLoss(MW)	**7.6714**	**7.6843**	**7.1126**	**7.5067**	**7.6789**
	Total Change in Generation (MW)	37.823	38.735	41.959	40.470	38.241
	F_{ccl}	**379.213**	**383.273**	**528.445**	**435.885**	**381.058**
Scenario 2	**Congestion cost ($/h)**	**4440.3334**	**4476.2751**	**4841.8254**	**4470.6697**	**4444.3542**
	PLoss(MW)	**13.0665**	**13.3617**	**14.0843**	**13.2201**	**13.0776**
	Total Change in Generation (MW)	175.161	179.182	185.364	176.620	175.861
	F_{ccl}	**2226.7**	**2244.818**	**2427.955**	**2241.945**	**2228.716**
Scenario 3	**Congestion cost ($/h)**	**491.0486**	**493.7832**	**628.1213**	**519.8499**	**491.7295**
	PLoss(MW)	**9.7928**	**9.7916**	**10.227**	**9.932**	**9.7913**
	Total Change in Generation (MW)	23.3397	23.3957	23.9045	24.2389	23.3365
	F_{ccl}	**250.421**	**251.787**	**319.174**	**264.891**	**250.760**



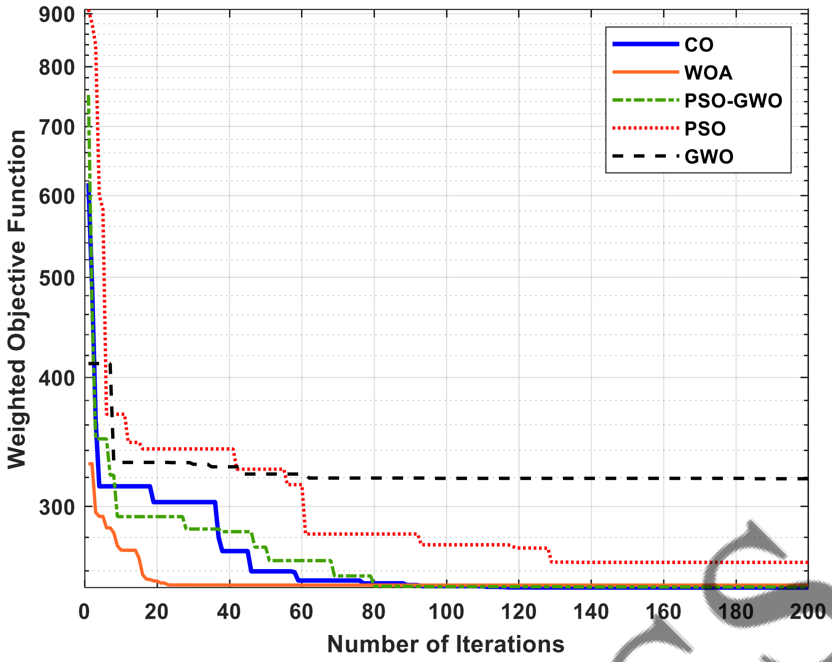
Weighted Objective Function
Number of Iterations
CO
WOA
PSO-GWO
PSO
GWO

(a)



Weighted Objective Function
Number of Iterations
CO
WOA
PSO-GWO
PSO
GWO

(b)



(c)

Fig. 4: Convergence Characteristics of Different Optimization Techniques for: (a) Scenario 1; (b) Scenario 2; (c) Scenario 3.

5. CONCLUSION

This paper represents the application of a novel Cheetah optimiser for solving the congestion management problem. To reduce congestion on the IEEE 30 bus network, it uses optimal generation rescheduling at a low cost. The challenge of managing congestion has been overcome without considering the bid prices and also by considering the bid prices. Minimisation of fuel cost and transmission line loss is observed when bid prices are not considered, whereas minimisation of congestion cost and line loss is done by using the bid prices. Multi objective optimization of cost and power loss simultaneously using the weighted sum approach is applied in this paper. Along with the cheetah optimizer WOA, PSO, GWO, and hybrid PSO-GWO are also used to solve the CM problem. Violations observed in each of the scenarios of creating congestion are eliminated successfully with the application of generation scheduling using different optimization techniques. Moreover, results obtained in different cases and scenarios show that the Cheetah optimiser outperforms all the other algorithms applied in this paper. The CO algorithm not only produces secure working conditions while solving the CM problem but also effectively reduces the expenses, and hence the algorithm is proven to be an effective tool for handling congestion in deregulated power systems.

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