Grey Wolf Optimization Algorithm for Generation Rescheduling In Deregulated Power System for Congestion Management

Pawan C. Tapre[1]
Department of Electrical Engineering
CVRU, Ph.D. Scholar Bilaspur (C.G.), India
pawan.tapre25@rediffmail.com
Dr. Dharmendra kumar Singh[2]
Department of Electronics Engineering Associate Professor,
CVRU, Bilaspur (C.G.),India
dmsingh2001@rediffmail.com
Dr. Sudhir Paraskar[3]
Department of Electrical Engineering, Professor,
SSGMCE, Shegaon(M.S.), India
srparaskar@gmail.com

Abstract—
The practitioners and researchers has received considerable attention solving complex optimization problems with metaheuristic algorithms during the past decade. Many of these algorithms are inspired by various phenomena of nature. One of the promising solutions for secure and continuous power flow in the transmission line is rescheduling based congestion management approach but the base problem is rescheduling cost.. To solve the congestion with minimized rescheduling cost , a new population based algorithm, the Grey Wolf Optimization (GWO) Algorithm, is introduced in this paper . The basic motivation for development of this optimization algorithm is based on special lifestyle of grey wolf and their cooperation characteristics. Based on some benchmark Grey Wolf Optimization(GWO) Algorithm is compared with the existing conventional algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Artificial Bee Colony (ABC), and Firefly (FF) by analyzing the convergence, cost, and congestion. In IEEE-14 and IEEE-30 bus system experimental investigation is carried out and the obtained results by the proposed algorithm GWO (Grey Wolf Optimization) Algorithm in comparison to the other algorithms used in this paper.

Keywords— *Rescheduling; Congestion Management; Optimization Algorithm; GWO, flexible AC transmission systems.*

1. Introduction

Restructuring of the electricity supply industries is a very complex exercise based on national energy strategies and policies, macroeconomic developments and national conditions, and its application varies from country to country . It is important to point out that there is no single solution applicable to all countries and there is a broad range of diverse trends. Liberalization, deregulation (or reregulation) and privatization are all processes under the general label of market reform. Reregulation is a more accurate term than deregulation. Privatization is the sale of government assets to the private sector, by itself, privatization is not sufficient to introduce competition into a reformed sector . Competition will be the result of careful regulation of the privatized entities to allow new entrants access to the market. Competition is fundamental to most market reforms and it is introduced in order to reduce costs and increase efficiency. There is considerable variation in the extent of the competition which is introduced.

The changes were initiated by:

" a realization that generation and distribution functions need not be monopolies;

" a feeling that public service obligations are no longer necessary ;

" the cost reduction potential of competition ;

" increased fuel availability and fuel supply stability; and

" the development of new technologies in power generation and information technology.

1.1 Previous Power System

In the past, power systems were developed to transmit large amounts of power at high voltage from remote generating stations and to distribute power at lower voltage down to millions of small consumers .

Deregulation has led the electricity industry to focus attention on the costs of generation and provides incentives for generators to reduce their costs and minimize their risks, e.g. by investing in smaller scale plants .

1.2 Congestion

The implementation of deregulation is further complicated by the presence of congestion. Congestion refers to the binding of thermal limits of the transmission network . Congestion can be relieved by re-dispatch of generators. In the traditional power system, the utility can achieve that by re-dispatching the cheapest generator(s) available while alleviating the constraints . In the deregulated environment, generation and transmission fall into different entities .

2 Challenges

Electricity markets throughout the world are undergoing major changes [1} . These changes are varied in their nature but the underlying trend is towards a more competitive and open environment and this results in electricity being traded as a commodity and in the creation of competitive markets to facilitate this trade. Political forces [2,3] are driving these changes . A competitive electricity market is one in which a number of suppliers (generators) are competing to sell their electricity to a number of competing customers (loads). Here we are concerned with competition in a wholesale electricity. Here some of these challenges are outlined.

2.1 Market Power Evaluation and Mitigation

Evaluation of market models can have many different viewpoints. The market must function in a reliable, efficient and fair manner. The generators will want to maximize their profits through the markets . The consumers will seek the best value for the service they receive which may conflict with the aims of the generators [4]. This will necessitate analysing the social benefit that the market offers and the prices that are charged . It will also be prudent to ensure that market power and gaming do not exist and that markets are not overly volatile.

2.2 System Capacity

The issue of planning in generation and transmission must be addressed with a view to maintenance and enhancements to meet increasing demand. On the generation side these functions are generally left to the market, the assumption being that energy prices will signal the best times to maintain units and when to build new plant. A market for generating capacity over a longer time frame (more than one year) may provide the necessary market signals to ensure that the system will expand according to the needs of the consumers [5].

2.3 Reliability

While it is desirable to encourage competition in the electricity market to reduce the costs and improve the service quality for consumers, it is also vitally important to maintain the system reliability [6]. In an operational environment, an important reliability measure is system security. System security refers to a system's ability to withstand likely disturbances . A system is said to be in a secure state if it is able to meet the load demand without violating the operating constraints in case of a likely contingency, such as a line or generator outage [7]. In other words, security is defined with respect to a set of next contingencies that are likely to occur. Consequently, a system engineer at the ISO who studies system security may find it difficult to predict the future generation and load conditions for evaluation of system security .

2.4 Technical Issues

Regardless of wholesale electricity markets power system planning and operation has many technical challenges. The OPF algorithm which is at the heart of the marginal cost pricing paradigm [8] and of power system security analysis will have to meet ever-increasing challenges [9]. However, any actions need to allow market forces to push the industry towards possible long-term competitive solutions.

3. The Traditional Power Industry

The electricity supply industry in nearly every country for about the last hundred years has been a natural monopoly and as a monopoly attracted regulation by government. Without exception, the industry has been operated as a vertically integrated regulated monopoly that owned the generation, transmission and distribution facilities. It was also a local monopoly, in the sense that in any area one company or government agency sold electric power and services to all customers . In many countries, especially developing countries, the electric utility was owned by the state or local government, and in other countries, by an investor-owned private entity . The traditional power industry had several characteristics [10] :

(1) Monopoly franchise :

Only the national or local electric utility was permitted to produce, transmit, distribute and sell commercial electric power within its service territory.

(2) Obligation to serve:

The utility had to provide electricity for the needs of all consumers in its service area, not just those that were profitable.

(3) Regulatory oversight :

The utility's business and operating practices had to conform to guidelines and rules set down by government regulators.

(4) Regulated rates:

The electric utility's rates were either set or regulated in accordance with government regulatory rules and guidelines.

(5) Guaranteed rate of return:

The government guaranteed that regulated rates would provide the electric utility with a ‚reasonable' or `fair' profit margin above its cost.

(6) Least cost operation :

The electric utility was required to operate in a manner that minimized overall revenue requirements .

3.1 Motivations for Restructuring the Power Industry

Since the 1980s, the electricity supply industry has been undergoing rapid and irreversible change reshaping an industry that for a long time has been remarkably stable and had served the public well. A significant feature of these changes is to allow for competition among generators and to create market conditions in the industry, which are seen as necessary to reduce the costs of energy production and distribution, eliminate certain inefficiencies, shed labour and increase customer choice . This transition towards a competitive power market is commonly referred to as electricity supply industry restructuring or deregulation.

3.2 Components of Restructured Systems

The structural components representing various segments of the electricity market are generation companies (Gencos), distribution companies (Discos), scheduling coordinators (SCs), transmission owners (TOs), an independent system operator (ISO), and a power exchange (PX). Depending on the structure and the regulatory framework, some of these components may be consolidated together, or may be further unbundled.

3.2.1 Gencos

Gencos are responsible for operating and maintaining generating plant in the generation sector and in most of cases are the owners of the plant. Open transmission access allows Gencos to access the transmission network without distinction and to compete.

3.2.2 BOT Plant Operators and Contracted IPPs

Build, operate and transfer BOT; (or build, operate and own) plant or IPPs who have longterm contracts with surrounding, usually national, utilities play an important role in providing additional generation in many fast-growing systems . Take-or-pay power purchase agreements are often in force as an economic incentive to investors.

3.2.3 Discos and Retailers

Discos assume the same responsibility on the distribution side as in a traditional supply utility . However, a trend in deregulation is that Discos may now be restricted to maintaining the distribution network and providing facilities for electricity delivery while retailers are separated from Discos and provide electric energy sales to end consumers . Another trend in developing countries is to sell to an investor, or to corporatize, portions of the distribution system so that investment for reinforcement can be raised and better operating practices implemented.

3.2.4 Transmission Owners (TOs)

Where the transmission network was state owned before restructuring, obviously this integrity will be retained and a distinction between owner and operator is redundant. A basic premise of open transmission access is that transmission operators treat all users on a non-discriminatory basis in respect of access and use of services. This requirement cannot be ensured if transmission owners have financial interests in energy generation or supply. A requirement, therefore, is to designate an independent system operator to operate the transmission system.

3.2.5 Independent System Operator (ISO)

The ISO is the supreme entity in the control of the transmission system. The basic requirement of an ISO is disassociation from all market participants and absence from any financial interest in the generation and distribution business . However, there is no requirement, in the context of open access, to separate transmission ownership and operation.

3.2.6 Power Exchange (PX)

The PX handles the electric power pool, which provides a forum to match electric energy supply and demand based on bid prices . The time horizon of the pool market may range from half an hour to a week or longer . The most usual is the day-ahead market to facilitate energy trading one day before each operating day. An hour-ahead market is also useful since it provides additional opportunities for energy trading to redress short-term imbalance .

3.2.7 Scheduling Coordinators (SCs)

SCs aggregate participants in the energy trade and are free to use protocols that may differ from pool rules. In other words, market participants may enter an SC's market under the SC's rules and this could give rise to different market strategies.

3.3 PX and ISO : Functions and Responsibilities

3.3.1 PX Functions and Responsibilities

A PX of some form is essential for efficient trading in electricity . The PX establishes an environment in which generators and consumers bid to sell and buy energy. Parties to bilateral contracts can operate their own separate energy trades and schedule their transactions outside the PX's market. The primary function of the PX is to provide a forum to match electric energy supply and demand in the current and forward energy markets . In its simplest form a PX provides a bulletin board type of environment for energy suppliers and energy customers to engage in bilateral forward contracts . However, the more usual function is to act as a pool for energy supply and demand bids, and to establish a market-clearing price (MCP).

Basically, the working process of the PX is:

(1) receive bids from power producers and customers ;

(2) match the bids, decide the MCP prepare scheduling plan; (3) provide schedules to the ISO or transmission system operators ;

(4) adjust the scheduling plan when the transmission system is congested.

3.3.2 ISO Functions and Responsibilities

The ISO has three objectives: security maintenance, service quality assurance and promotion of economic efficiency and equity[5].

To achieve these objectives the ISO performs one or more ofthe following functions :

(1) Power system operations function :
This fundamental function includes the operation-planning function and real-time control.

The operation-planning function includes :

" Perform power system scheduling.

" Co-ordinate with energy markets .

" Perform power system dispatch .

" Determine available transfer capabilities (ATCs).

" Determine real-time ATCs.

" Pre-calculate short-run costs and prices for transmission-related services.

" Calculate hourly prices for transmission-related services.

Real-time control includes :

" Monitor power system operation status .

" Monitor system security .

" Conduct physical network operations and network switching

" Deal with outages and emergencies .

" Coordinate real-time system operation .

(1) Power market administration function :
There are two types of energy markets : the pool market and the contract (bilateral and multilateral transactions) market. The former could be run by the PX or an ISO-PX combine while the latter may be coordinated by one or more SCs.

The pool market includes :

" Run a power pool where parties can bid to buy and sell energy.

" Develop a preferred schedule for the pool.

" Submit the supply and load schedule to the ISO according to pre-specified protocols

The contract market includes :

" Manage bilateral and multilateral transactions.

" Manage and coordinate submissions from SCs.

" Submit preferred schedules to the ISO according to pre-specified protocols .

(2) Ancillary services provision function :
" Own certain ancillary services for satisfactory grid operation

" Purchase ancillary services transactions from market participants according to prespecified protocols.

" Provide ancillary services to transmission users.

" Allocate costs of ancillary services among all users.

(3) Transmission facilities provision function :

" Maintain the transmission network.

" Provide transmission facilities for all supplies and loads.

" Plan transmission, reactive power and FACTS expansion and ensure that resources for future investment are generated.

" Plan and commission own ancillary services.

4. OPF Problem Formulation

OPF is a nonlinear optimization problem the objective functions (f (x, u)) optimized using equality constraints (g (x, u)) and inequality constraints (h(x, u)), that is used to find the best control variables (u) and state variables (x). The general form of OPF problem can be expressed as follows:

Minimize: f (x, u) (1)

Subject to: g (x, u) = 0 (2)

h(x, u) ≤ 0 (3)

4.1 Problem Objectives

Generation Cost Minimization

Minimization of generation cost (FG) in a power generation is expressed with the cost coefficients are ai, bi and ci,

$$FG = Min\ Gcost = \sum_{i=1}^{NG}(aiPgi^{2} + biPgi + ci) \quad (4)$$

4.1.1 Real Power Loss Minimization

Due to the transaction between generator node and demand node, the real power and reactive power losses produced in the transmission lines. Our aim is to minimize the losses in the power system network. The objective is to minimize the real power loss (FPL) in the transmission line is expressed as

$$FPL = Min\ Ploss = \sum_{i=1}^{nl} Gij\,(Vi^{2} + Vj^{2} - 2ViVj\cos(\delta i - \delta j)) \quad (5)$$

Where

Vi, Vj → Voltage Magnitude at Bus i and Bus j

Gij → Conductance in the Line i-j

δi ,δj → Voltage Angle in the Bus i and Bus j

nl → Total Numbers of Transmission Lines

4.1.2 Voltage Deviation Minimization

The voltage gap between the reference voltage and load bus voltage is less means the voltage deviation get minimized. It can be mathematically expressed as.

$$FVD = Min\ VD = \sum_{i=1}^{NL}(Vi - Vi\ ref) \quad (6)$$

Where, Vi^{ref} is specified reference voltage at bus i, which is taken as 1.0 p.u.

NL- no. of load buses.

4.1.3 Problem Constraints

The list of equality constraints and inequality constraints are below.

Equality Constraints

Equality constraints of the given objective functions are

$$P_{Gi} - P_{Di} = Vi \sum_{j=1}^{NB} Vj[Gij\cos(\delta i - \delta\ NBj = 1\ j) + Bij\sin(\delta i - \delta j)] \quad (7)$$

$$QGi - QDi = Vi \sum_{j=1}^{NB} Vj[Gij\cos(\delta i - \delta\ NBj = 1\ j) + Bij\sin(\delta i - \delta j)] \quad (8)$$

P_{Gi}, Q_{Gi}→ real power & reactive power generations at bus i.

P_{Dj},Q_{Di}→ real power and reactive power demands at bus i.

Gij →Conductance in between the line i-j

Bij → Susceptance in between the line i-j

i → 1 to NB,

NB →total numbers of bus.

Inequality Constraints

Inequality constraints of the given objective functions are

$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max}$, i= 1,2,….,NG (9)

$V_{Gi}^{min} \leq V_{Gi} \leq V_{Gi}^{max}$, i= 1,2,….,NG (10)

$T_{i}^{min} \leq T_{i} \leq T_{i}^{max}$, i= 1,2,….,NT (11)

$Q_{ci}^{min} \leq Q_{ci} \leq Q_{ci}^{max}$, i= 1,2,….,NC (12)

$V_{PQi}^{min} \leq V_{PQi} \leq V_{PQi}^{max}$, i= 1,2,….,NPQ (13)

$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max}$, i= 1,2,….,NG (14)

$S_{LK}^{min} \leq S_{LK} \leq S_{LK}^{max}$, i= 1,2,….,NE (15)

The real power flow in a transmission lines is maintained below limit.

$P_{ij}^{min} \leq P_{ij}^{max}$; i=1,2,….NB; j=1,2,….NB; (18)

Where, Pij real power flow at branch i-j. , $P_{ij}{}^{max}$ maximum power flow limit(MW)

Pij = Vi [Gij(Vi – VjcosΘij) - BijVjsinΘij] (19)

Voltage Level at a load bus is maintained within a specific upper and lower limit (0.9-1.1)pu, determined by the operator.

$V_{i}^{min} \leq V_{i} \leq V_{i}^{max}$; i=1,2,….NPQ (20)

The control variables used in the OPF problem is generator real power settings (PGi) and voltage settings(VGi), transformer tap settings (Ti),reactive power compensation setting(Qci). $VPQii$ voltage at PQ bus, SLk is kth line apparent power. max and min represents maximum and minimum control variables value. Total Numbers of Generators (NG), Transformers (NT), Switchable VAR Sources (NC), and PQ Buses (NPQ).

4.1.4 Line Loading (LL)

Line loading minimization is to optimize the power flow of each line within a limit and minimize the line overloading objective function. It is used to minimize the power flow gap between actual values and limit value and expressed as:

Min LL = $\sum_{i=1}^{NL}(\mathrm{Pij(t)} - \mathrm{Pijmax})^2$ (21)

Here NL total number of lines

LL- Line loading

Pij Power flow in each lines

Pijmax Maximum power flow limit in each line

4.1.5 N-1 Contingency Analysis in Power System Using Severity Index (SI)

Severity Index used to find out the worst line outage based on the N-1contingency analysis, that can be expressed as

$$SI = \sum_{k=1}^{ovl} \left(\frac{Pk}{Pkmax} \right) \tag{22}$$

Where

Pk = Power flow in line k (MW)

Pk^{max} = Power flowmax limit in line k (MW)

Ovl is the set of overloaded lines, m as a weight coefficient.

5. Proposed Approach for Congestion Management

Here the two methods used to solve the CM problem that is conventional method and non-conventional method. The MATLAB used for conventional method and the intelligent technique like GWO used to optimize the OPF problem.

5.1 Grey Wolf Optimizer (GWO)

5.1.1 Source of Inspiration

GWO is a typical swarm-intelligence algorithm which is inspired from the leadership hierarchy and hunting mechanism of grey wolves in nature14. In the hierarchy of GWO, alpha ($\alpha\alpha$) is considered the most dominating member among the group leader and decision maker. The rest of the subordinates to $\alpha\alpha$are beta ($\beta\beta$) and delta ($\delta\delta$) which help to control the majority of wolves in the hierarchy that are considered as omega ($\omega\omega$). The $\omega\omega$wolves are of lowest ranking in the hierarchy.

The mathematical model of hunting mechanism of grey wolves consists of the following:

1. Tracking, chasing, and approaching the prey.

2. Pursuing, encircling, and harassing the prey until it stops moving.

3. Attacking the prey.

5.1.2 Social Hierarchy

While modeling the GWO social hierarchy, the fittest solution in the grey wolves is alpha (α). The second best solution is beta (β), the third best is delta (δ) and the rest is omega (ω) wolves. In the GWO algorithm the hunting mechanism is done by α, β, and δ wolves, the remaining ω wolves followed by these three wolves.

5.1.3 Encircling Prey

The position vector of prey Xp , position vector of grey wolf X and the coefficient vectors A and C and current iteration t now the mathematical model of grey wolves encircling prey during the hunt can be written as

$$D= | C.X_p (t)-X(t) | \tag{23}$$

$$X(t+1)=| X_p - A.D | \tag{24}$$

The A and C can be calculated as;

$$A = 2a.r_1-a \tag{25}$$

$$C = 2.r_2 \tag{26}$$

Where a values in the iterations are normally decreased from 2 to 0, random vectors r1 and r2 are in [0, 1].

5.1.4 Hunting

Grey wolfs hunting behavior is modeled with α, β, and δ wolves knows the knowledge about the prey position and updated their position, the equations are shown below.

$$D_\alpha = | C_1.X_\alpha - X | \tag{27}$$

$$D_\beta = | C_2.X_\beta - X | \tag{28}$$

$$D_\delta = | C_3.X_\delta - X | \tag{29}$$

$$X_1 = X_\alpha - A_1.(D_\alpha) \tag{30}$$

$$X_2 = X_\beta - A_2.(D_\beta) \tag{31}$$

$$X_3 = X_\delta - A_3.(D_\delta) \tag{32}$$

$$X (t+1) = \frac{(X1+X2+X3)}{3} \tag{33}$$

5.1.5 Attacking the Prey

In GWO algorithm when the hunting process finished by attack the prey. It is stated mathematically to decrease the vector value from 2 to 0. If |A| <1 the grey wolves force to attack the prey.

5.1.6 Search for the Prey (Exploration)

The grey wolves are search for a prey based on the position of α, β, and δ. They diverged from each other wolves to search for the prey and converged to attack the prey. If |A| >1 grey wolves force to search the better prey..

5.1.7 Grey Wolf Optimizer

In GWO the value of (a) decreases linearly from 2 to 0 .By update the value of (a) in a search space and update equation as follows:

a=2(1- t2 /T2) (34)

Where T indicates the maximum number of iterations and t is the current iteration. Using this exponential decay function, the numbers of iterations used for exploration and exploitation are 70% and 30%, respectively.

The GWO parameters taken in the problem is population size (N) 25, Maximum iteration (T) 100 and total number of runs 1.

6. The Pseudo Code of GWO Algorithm

1. Generate initial search agents Xi (i=1, 2,…., n)
2. Initialize the vector's a, A and C
3. Estimate the fitness value of each hunt agent
Xα =the best hunt agent
Xβ =the second best hunt agent
Xδ =the third best hunt agent
4. Iter=1
5. repeat
6. for i=1: Xs (grey wolf pack size)
Renew the location of the current hunt agent using Equation (7).
End for
7. Estimate the fitness value of all hunt agents
8. Update the value of Xα, Xβ, Xδ
9. Update the vectors a, A and C
10. Iter=Iter+1
11. until Iter>= maximum number of iterations {Stopping criteria}
12. output Xα, End

ALGORITHM 1: GWO based mutation process
Initialize L Population size, parameter a , Z and X , $Max^{iteration}$
Set $t := 0$ (counter initialization)
for $(j = 1 : j \leq b)$ do
Develop an arbitrary initial population $X_j(v)$
Evaluate the fitness function $f(X_j)$
End for
Assign $X_{(\alpha)}, X_{(\beta)}$, the first and second best solutions
repeat
for $(j = 1 : j \leq L)$ do
Updating the search agent in population
Minimize the parameter a from 2 to 0
Update Z and X
Calculate the fitness function of each search agent $f(X_j)$
End for
Update the vectors $X_{(\alpha)}$ and $X_{(\beta)}$
set $t = t + 1$
until $(t < Max^{iteration})$
Generate the best solution $X_{(\alpha)}$

7. Results and Discussion

7.1 Experimental Setup

The implementation of the proposed congestion management system, which is based on rescheduling strategy, is established in the operational platform of MATLAB. The investigation takes place in IEEE benchmark test bus systems like IEEE 14 bus system and IEEE 30 bus system. The system comprises loads, capacitor banks, transmission lines, and generators. Three GENCOs are connected in IEEE 14 bus system, and six GENCOs are connected in IEEE 30 bus system. Consequently, Table I and II summarize the generation limits as well as cost coefficients of both IEEE 14 bus system and IEEE 30 bus system. Further, the performance of proposed GWO rescheduling approach is compared to other existing approaches like PSO [32], GA [33], ABC [34], FF [35], and Proposed GWO [36] respectively in terms of various analysis such as cost analysis, congestion analysis and convergence analysis.

Methods	Congestion cost ($)	Compensation cost ($)	Final cost ($)
PSO[32]	14.49477	809.0968	22.58574
GA [33]	14.47597	824.9463	22.72544
ABC[34]	9.395873	1119.105	20.58692
FF[35]	9.396742	1116.117	20.55791
GWO[36]	2.548434	1206.484	14.61327

Table-I Generation limits and cost coefficients of IEEE-14 bus system

Methods	Congestion cost ($)	Compensation cost ($)	Final cost ($)
PSO[32]	33	365.8715	36.65871
GA [33]	33	578.7387	38.78739
ABC[34]	33	285.8715	35.85871
FF[35]	33	327.8771	36.27877
GWO[36]	33	376.504	34.76504

7.2 Cost Analysis

The related relationship among each rescheduling costs like congestion cost, compensation cost and final cost under the performance of proposed GWO rescheduling strategy over the other conventional strategies are summarized in Table III and IV, respectively. Table III specifies the attained congestion cost, compensation cost and final cost of proposed GWO rescheduling strategy over other existing methods of IEEE 14 bus system. From the analysis, it is observed that the proposed GWO strategy has drastically minimized the final rescheduling cost when compared to other models, which is showing its performance level over other models. It is reviewed that the proposed GWO rescheduling strategy is 35.71%, 35.31% 28.93% and 29.03%, better than FF based rescheduling strategy, ABC based rescheduling strategy, GA based rescheduling strategy and PSO based rescheduling strategy, respectively.

In the same way, Table IV reviews the congestion cost, compensation cost and final cost that sustained by proposed GWO rescheduling strategy over other conventional algorithms of IEEE 30 bus system. It is observed that the proposed GWO rescheduling strategy is 2.18%, 1.46%, 4.15%, and 2.20% superior to FF-based rescheduling strategy, GA-based rescheduling strategy and PSO-based rescheduling strategy respectively.

Generator number	P_i^{min} (MW)	P_i^{max} (MW)	a_i ($/MWhr)	b_i ($/MWhr)	c_i ($/hr)
1	10	160	0.005	2.450	105.00
2	20	80	0.005	3.510	44.100
3	20	50	0.005	3.890	40.600

Table-III Cost analysis of Proposed GWO based rescheduling strategy over existing models of IEEE-14 bus system

Generator number	P_i^{min} (MW)	P_i^{max} (MW)	a_i ($/MWhr)	b_i ($/MWhr)	c_i ($/hr)
1	50	200	0.00375	2.00	0
2	20	80	0.01750	1.75	0
3	15	50	0.06250	1.00	0
4	10	35	0.00834	3.25	0
5	10	30	0.02500	3.00	0
6	12	40	0.02500	3.00	0

Table-IV Cost analysis of Proposed GWO based rescheduling strategy over existing models

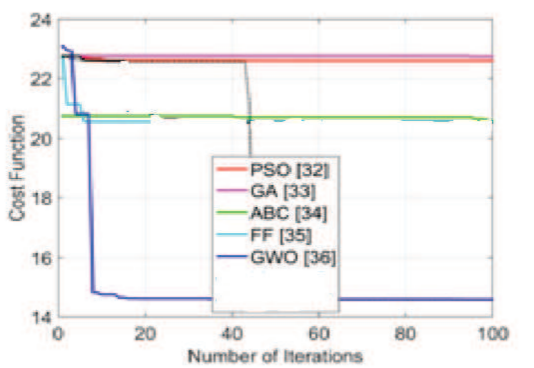
7.3 Convergence Analysis

Fig.1 illustrates the convergence analysis of offered finest congestion management system over other existing models of both IEEE bus systems. All approaches are analyzed by specifying the capability of reducing cost function in correspondence with count of iterations. In IEEE 14 bus system, the rescheduling cost incurred by proposed GWO is tremendously lower than the conventional algorithms such as PSO, GA, ABC, FF respectively. Primarily, the cost function is identified to be at the topmost level, and then it gets minimized as the number of iterations increases.

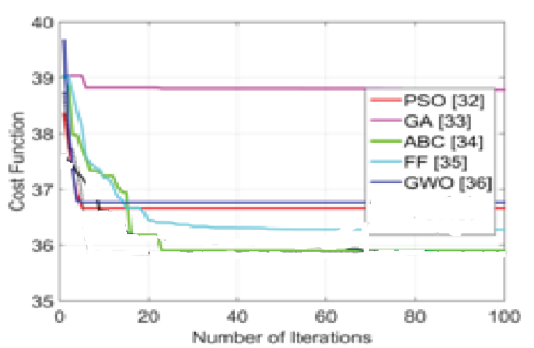
The same minimization of cost is also observed in IEEE 30 bus system, which shows the betterment of the offered model over other models in terms of minimized rescheduling cost. More particularly, the rescheduling strategy with diminished cost is witnessed at the final iteration (100th iteration). From the analysis on IEEE 14 bus system, it is observed that the proposed GWO recognition system is 38.36%, 30.24%, 29.20%, 27.92%, better than FF, ABC, GA, and PSO, respectively. While analyzing the IEEE 30 bus system, it is reviewed that the recognition cost incurred by GWO algorithm is 0.81%, 1.08%, 0.27%, and 1.83% better than other existing approaches like conventional FF, ABC, GA, and PSO respectively. From the overall analysis, the effectiveness of the proposed GWO is abundantly surpassing the other conventional algorithms in terms of minimum rescheduling cost.

7.4 Congestion Analysis

Fig.2 illustrates the congestion analysis of the developed congestion management system as well as existing systems of both IEEE 14 bus system and IEEE 30 bus system. This analysis reviews how the congestion management techniques work in terms of minimizing congestion.

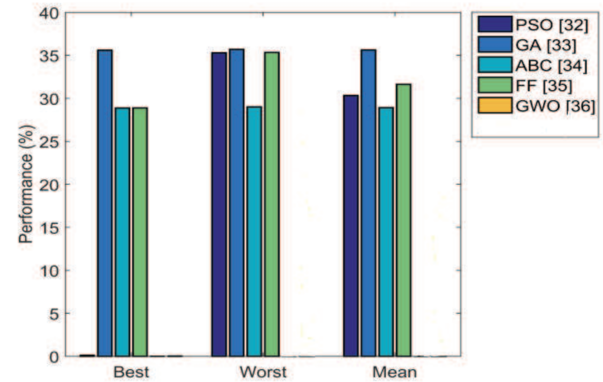


(a) IEEE 14 bus system

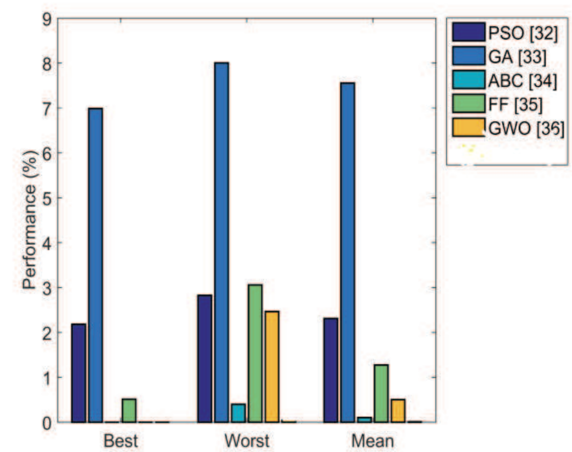


(b) IEEE 30 bus system

Fig.1 Convergence Analysis Demonstration of Grey Wolf Optimization with other Conventional Methods



(a) IEEE 14 bus system



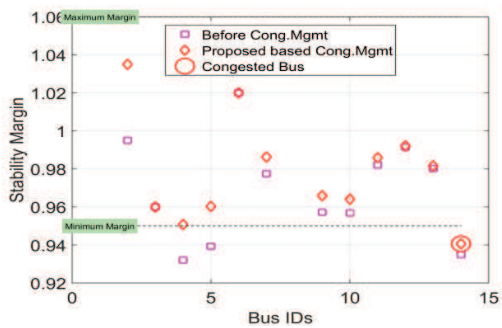
(b) IEEE 30 bus system

Fig.2 Congestion analysis of Grey Wolf Optimization with other Conventional Methods

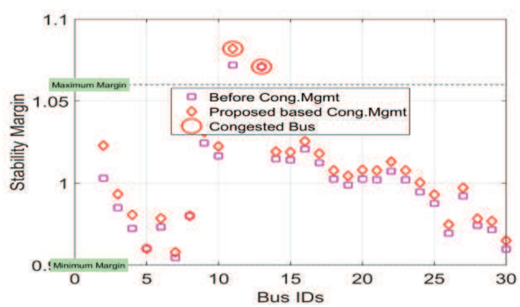
Fig.2(a) illustrates the performance of PSO, GA, ABC, FF and proposed GWO technique performed on IEEE 14 bus system to lessen the congestion that happened in buses. At first, there are two congested buses available below the minimum margin. From the illustration, the performance of PSO and GA are not so effective in decreasing congestion. In contrast to this, the proposed strategy performed the congestion management in an effective way, by which it minimizes the congested bus from two to one. Correspondingly, the capability of decreasing congestion by PSO, GA, ABC, FF, and proposed GWO technique in IEEE 30 bus system is illustrated in Fig. 2(b) respectively. The efficiency of the proposed strategy is proved over other techniques in correspondence with reduced congestion in bus.

7.5 Statistical analysis

In this section, the performance of proposed GWO is compared to other stochastic algorithms like PSO, GA, ABC, and FF. Usually, the performance of such algorithms depends on initialization, and hence it is more difficult to finalize the efficiency of the algorithms. A common way to analyze the algorithms is utilizing statistical tests on the gained results.



(a) IEEE 14 bus system



(b) IEEE 30 bus system

Fig.3 Performance percentage from statistical analysis (best case, worst case and mean) of

Fig.3 shows the statistical information on the diminished rescheduling cost attained from proposed GWO-based rescheduling approach over other existing rescheduling algorithms of both IEEE 14 bus system and IEEE 30 bus system respectively, and the graphical representation of the performance of the rescheduling strategies are illustrated in Fig. . For the purpose of analysis, certain parameters are concerned, and they include best case, worst case, mean performance, median performance as well as standard deviation among the mean and distinct performances.

7.6 Best Solution Generation

The best solution generation of both IEEE 14 bus system and IEEE 30 bus system by all the algorithms like PSO, GA, ABC, FF and proposed GWO is summarized in Table II and Table-V respectively. From Table II, it is observed that the proposed approach has attained the three optimal best generators like 160, 80 and 44.73 respectively. Similarly, From Table VI , the approach has attained six optimal generators of IEEE 30 bus system like 50, 20, 15, 35, 10 and 12 respectively.

PSO [32]	GA [33]	ABC [34]	FF [35]	GWO [36]
118.5098	119.4853	159.2605	156.0871	160
37.6382	40.23428	64.90504	69.56678	80
29.62553	30.14488	39.98064	37.71193	44.72549

Table –V Best solution generation of proposed generator rescheduling strategy of IEEE 14 bus system

PSO [32]	GA [33]	ABC [34]	FF [35]	GWO [36]
50	77.57261	50	50	50
20	28.24541	20	20	20
15	41.28962	15	15.00109	15
10	19.84808	10	17.60708	35
30	13.43874	10	11.67345	10
12	21.77339	12	14.61927	12

Table-VI Best solution generation of proposed generator rescheduling strategy of IEEE 30 bus system

8. Conclusion and Future Work

In a deregulated power systems congestion management is one of the major technical issue. The OPF based congestion management is considered here and the results are compared with both conventional and nonconventional methods (GWO algorithm). Conventional methods not provide the optimized results. The GWO algorithm (non-conventional method) give the good results on the basis of cost analysis, convergence analysis, congestion analysis, statistical analysis, best solution generation. Thus, it is concluded that the performance of the GWO-based rescheduling strategy is superior to the existing conventional methods by minimized rescheduling cost in computation. By removing congestion from deregulated power system by minimizing cost of rescheduling of generator the society get constant voltage, stable system and continuous interrupted power. The efficiency of the system is increases, so the production of product also increases. In future the congestion management will be done with different recent intelligent techniques in a higher order IEEE test bus systems.

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