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Real and Reactive Power Rescheduling for Congestion Management Based on Generator Sensitivity Index

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Abstract: *In a deregulated power system, the most critical issue is overloading of the transmission line beyond its thermal limits generally known as transmission congestion. Congestion is not an acceptable one hence it increases the congestion cost and also it poses threat to the system security and reliability. Transmission congestion can be removed by changing the pattern of power generation in the system. Power scheduling corresponding to the market clearing price needs to be changed for relieving congestion. Rescheduling of power generation is optimized for keeping the increased operating cost due to congestion. In this paper, black hole algorithm (BHA) is recommended for optimal active and reactive power re-dispatch for the congested system. Generators real and reactive power sensitivities are used to decide the range of change in real and reactive power generation. The validation of the suggested technique has been studied on the modified IEEE 30 bus system with two different congestion cases, and the obtained encouraging results are compared with other metaheuristic methods like particle swarm optimization (PSO) and big bang big crunch (BB-BC) reported in the recent literatures.*

Keywords: *Black hole algorithm, deregulated power system, generator power rescheduling, real and reactive power sensitivity.*

I. Introduction

Under the integrated utility system, the networks are governed by monopoly companies with objective functions as minimization of the transmission loss and generator fuel cost which satisfies the equality and inequality constraints of the system. During the last two decades, the power system environment has been deregulated as generating companies (GENCO), transmission companies (TRANSCO), distribution companies (DISCO), independent system operator (ISO), and retailer (RESCO). Now a days many market participants are permitted to play role in the competitive power market for their profit maximization. Transmission congestion occurs when participants try to extract the maximum utilization in the transmission line for the profit maximization will lead to overloads in the transmission line while crosses its thermal limits. The congestion is the major challenging issue for the independent system operator that gives serious threat to the systems reliability and security [1] to alleviate the transmission congestion, in the deregulated environment normally two approaches are implemented, they are cost free means and the non-cost free means. Some of the cost free means, like using FACTS devices, changing the tap settings in the transformers, phase shifters are utilized in the network to alleviate the congestion. Where as in the non-cost free means, the security considerations are taken into account by rescheduling the power generation, generators sensitivity factors [2].

The flexible AC transmission systems (FACTS) devices are installed to enhance the transmission capacity in the existing transmission networks. Also FACTS devices are connected in series for congestion management to ensure the system security by enhancing the voltage stability and transient stability. Relative electrical distance (RED) concept has been introduced for rescheduling of real power generations [3-7]. In the congestion management the importance of market flow policy has been reported [8-10]. Congestion is removed by rescheduling of the power generations from the generators with the objective of congestion cost minimization [11-13]. Sensitivity based rescheduling of optimal real powers in the participating generators in the congested state with minimum cost is addressed in [14-17]. In the literatures [18-19] it is reported that for the congested line, the active and reactive power generator sensitivity factors are calculated to manage the congestion by rescheduling the power generations

II. The Black Hole Phenomena

The concept of black hole was familiarized by John Michell and Pierre Laplace in the 18^{th} century, with the absence of stars in the space identified by integrating Newton’s law. On those days the absence of stars in the space is not known as a black hole. Later in the 20^{th} century, an American physicist, John Wheeler who first named the phenomenon that mass collapsing or absence of stars is known as black hole. At the space region, the black hole has a strong gravitational field that even light cannot escape from it once the light enters through it.

The radius of black hole is mathematically as defined as surface of event horizon also known as Schwarzschild radius [20].

The Schwarzschild radius is mathematically formulated by the equation (1):

$$R=\frac{2GM}{C^2} \tag{1}$$

Where,

G is the gravitational constant
M is the mass of the black hole
C is the velocity of light

If any particle moves closer to the event horizon or crosses over surface of event horizon that will be absorbed by black hole and swallowed by it. The existence of black hole is distinguished by the effects of surrounding over it, like when light hits the horizon that will be absorbed completely without any reflection and vanish permanently. The schematic view of black hole in the space shown in figure (1)

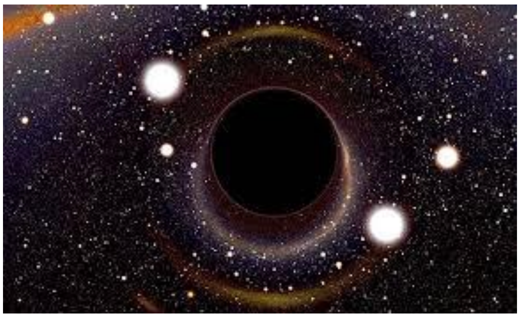

Fig. 1: Black Hole in the Space

2.1 Black Hole Algorithm

The BHA is a recently developed population based metaheuristic algorithm, which is used for optimization problems like genetic algorithm (GA) and particle swarm optimization (PSO) with some similar working mechanism. In BHA, the stars are used as a candidate solutions in a random search space. Where as in Genetic algorithm operators like cross cover, mutation, and reproduction are used for obtaining global best solution. Particle swarm optimization mimics the food foraging behaviour of birds, in which velocity and best positions are used to obtain gbest solutions. In the suggested algorithm, population of stars are randomly created in the search space with the help of objective functions. The candidate of stars are accelerated to move towards black hole as best solutions with random numbers based on current locations in every iterations. The absorbing power of stars is mathematically formulated for initializing of stars with objective functions is as follows:

$$x_i(t+1)=x_i(t)+rand(0,1)(x_{BH}-,x_i(t)) \tag{2}$$

Where

$x_i(t)$ location of the i^{th} star at iteration t ;

$x_i(t-1)$ location of the i^{th} star at iteration $t-1$;

x_{BH} location of the black hole in the search space;

rand random number in the interval [0, 1].

During the search process towards the black hole, a star can reach the black hole with lower cost, in that occasion the black hole should move to the locations of stars and vice versa. Thereafter, in BHA the black hole will start from its new location and searching will continue towards the new locations. In addition to the above said mechanism, there is a probability that stars will be moving towards the black hole that it may crosses the event of horizon. If the crossing stage happens, at that time stars will be sucked by the black hole, another new star will be created to maintain population size constant.

The radius for the event of horizon in black hole algorithm is determined by mathematically as

$$R = \frac{f_{BH}}{\sum_{i=1}^{N} f_i} \tag{3}$$

Where,

f_{BH} is the fitness for the black hole and f_i is the fitness value for the i^{th} star. N is the number of candidate solutions (stars). The stars will be collapsed, when the distance of stars and black hole is less than the radius R and at randomly new stars will generated in the search space. Based on the above explanation the key steps in the BH algorithm are given in pseudo code as follows:

```
Step1   Initialize a random population of stars at arbitrary locations in the search space.
Step2   Calculate the fitness value of every star as a candidate of solution.
Step2   Select the best star with lower cost as the fitness value.
Step3   Modify the position of every star  according to  Eq. (2).
Step4   if star reaches a position with lower cost than the black hole, then interchange their locations.
Step5   when star crosses the event horizon of the black hole, create a new star randomly in search space.
Step6   distance between black hole and star is less than the R, generate a new star in search space.
Step7   stop criterion with global best solution.
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III. Mathematical Formulation

3.1 Formulation of Generator Sensitivity Factors

All generators have their own sensitivity to the power flow through a congested line. A change in active power flow ΔP_{ij} in a transmission line connected between bus i and bus j due to unit change in active power injection. ΔP_{Gg} at bus n by generator 'g' can be defined as the active power generator sensitivity factor GS_{Pg}. Mathematically, it can be written for line as:

$$GS_{Pg} = \frac{\Delta P_{ij}}{\Delta P_{Gg}} \tag{4}$$

The detailed derivation for the Eq. (4) is given in [14].

Reactive power generator sensitivity factor, in the same way [18] for line can be written as:

$$GS_{Qg} = \frac{\Delta Q_{ij}}{\Delta Q_{Gg}} \tag{5}$$

The equation can be expanded as:

Neglecting $P-V$ coupling, Eq. (4) can be written as

$$GS_{Pg} = \frac{\partial P_{ij}}{\partial V_i} \cdot \frac{\partial V_i}{\partial P_g} + \frac{\partial P_{ij}}{\partial V_j} \cdot \frac{\partial V_j}{\partial P_g} \tag{6}$$

Neglecting $Q-\delta$ coupling, Eq. (5) can be written as

$$GS_{Qg} = \frac{\partial Q_{ij}}{\partial V_i} \cdot \frac{\partial V_i}{\partial Q_{Gg}} + \frac{\partial Q_{ij}}{\partial V_j} \cdot \frac{\partial V_j}{\partial Q_{Gg}} \tag{7}$$

Objective Function

The main objective of this present work is to minimize the total congestion cost due to rescheduling of real and reactive power generation. The function can be mathematically written as:

$$\text{Minimize} \sum_{g}^{ng} C_{Pg}(\Delta P_g)\Delta P_g + \sum_{g}^{ng} C_{Qg}(\Delta Q_g)\Delta Q_g \tag{8}$$

Subject to the following equality and inequality constraints.

Equality constraints:

The real power flow equality constraint is

$$P_{Gi} - P_{Di} - \sum_{n=1}^{nb} |V_i||V_j||Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij}) = 0 \tag{9}$$

The reactive power flow equality constraint is

$$Q_{Gi} - Q_{Di} - \sum_{n=1}^{nb} |V_i||V_j||Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) = 0 \tag{10}$$

Inequality constraints:

The real power generation limits are

$$P_g - P_g^{\min} = \Delta P_g^{\min} \le \Delta P_g \le \Delta P_g^{\max} = P_g^{\max} - P_g \qquad g \forall ng$$

The reactive power generation limits are

$$Q_g - Q_g^{\min} = \Delta Q_g^{\min} \le \Delta Q_g \le \Delta Q_g^{\max} = Q_g^{\max} - Q_g \qquad g \forall ng$$

IV. Numerical Results And Discussions

The BHA approach is implemented for congestion cost minimization in the test system. The performance of the suggested black hole algorithm is experimented in the modified IEEE-30 system with two cases of congestions. Case A: Outage of line number 1 and Case B- Load is increased with 20% at all the load buses. From the standard IEEE-30 bus system is modified so that the generator buses are first numbered serially then the load buses follow. The modified IEEE-30 bus system has six generators and 24 load bus with 283.4 MW real power and 126.2 MVAR reactive power respectively, and also with 41 transmission lines both bus data and line data of modified IEEE 30 bus is taken from [22].

4.1 Case A: Outage of line 1-2

In the modified IEEE-30 bus system the transmission line 1 is outage. The impact of this outage is the congestion created in two other lines. The power flow patterns in the congested line number 2 and line number 4 are beyond their rated thermal limits hence it is not a healthy situation to operate the system. The corrective measures are taken to alleviate the congestion by calculating the sensitivity of the generators and shown in table 1. The real and reactive power sensitivities are calculated to reschedule optimal real and reactive powers to eliminate the congestion observed in the transmission lines.

Table 1: Generator Sensitivity factors (case A)

Congested Lines		G_1	G_2	G_3	G_4	G_5	G_6
Line 1-7	P	0	-1.2089	-1.2647	-1.2032	-1.2040	-1.1821
	Q	-1.0194	-0.5836	-0.2343	-0.1440	-0.2190	-0.3258
Line 7-8	P	0	-1.0625	-1.1116	-1.0575	-1.0582	-1.0390
	Q	-0.9788	-1.2176	-0.6850	-0.4210	-1.7731	-3.2580

The algorithms are used to reschedule the powers with minimum congestion cost without violating the system constraints. The performances of the three algorithms are tabulated in table 2 that shows the real and reactive powers after reliving the congestion.

Table 2: Optimal rescheduling (case A)

Rescheduled power	**BBC Technique**		**PSO Technique**		**BHA Technique**	
	Real power	**Reactive power**	**Real power**	**Reactive power**	**Real power**	**Reactive power**
G_1	128.9054	89.729	129.9501	64.634	129.9214	63.3327
G_2	72.7149	52.7866	65.9089	0.0000	71.9518	32.4823
G_3	24.2072	0.6729	25.8077	56.8172	24.6240	18.0553
G_4	35.5572	20.3147	39.0586	0.1031	35.1864	45.4712
G_5	17.6479	69.9803	18.9724	71.0895	17.9315	10.7545
G_6	17.5338	39.7036	16.9306	71.7793	17.0769	51.8872

In table 3, it is shown that the minimum congestion cost obtained from three optimization algorithms with worst cost, average cost and best cost of the numerical values for comparison. Among the three algorithm the BHA approach has reported the minimum best cost as 475.8740 $/Day. Whereas BB-BC has reported best minimum cost as 565.3885 $/Day and PSO has reported 602.5971 as a minimum best cost

Table 3: Congestion cost (Case A)

Rescheduling cost $/Day	**WORST COST**	**AVERAGE COST**	**BEST COST**
BB-BC	580.2345	567.8734	565.3885
PSO	612.3476	605.2572	602.5971
BHA	480.6578	478.1952	475.8740

The calculated real and reactive power sensitivity factors of the generators for the congested lines are contributed a vital role to reschedule the real and reactive powers of power generations from the influencing generators. The change in powers are tabulated in the table 4 for all the three algorithm.

Table 4: Optimal change of real power (case A)

Technique	**UP/DOWN adjustment of participating generators (MW)**					
	ΔP_{G1}	ΔP_{G2}	ΔP_{G3}	ΔP_{G4}	ΔP_{G5}	ΔP_{G6}
BBC	-9.6846	15.1549	-0.3528	0.5572	-0.2821	0.6238
PSO	-8.6399	8.3489	1.2477	4.0586	1.0424	0.0206
BHA	-8.6686	14.3918	0.0640	0.1864	0.0015	0.1669

For the above case A, two lines lines are identifed as the congested lines that they are violted the thermal limits of the rated values . The line number 2 is conneted between bus number 1 and bus number 7 has the rated value as 130 MW but power flow is 147.6401 MW. Similarly the other line number 4, which is connected between bus number 7 and bus number 8 has the rated value as 130 MW but power flow at the congested duration is 140.8194 MW. The net power is 28.4595 MW which flows in the transmission lines leads a congestion shown in the figure 2. To relive the congestion optimization methods are implemented to reschedule the power flow patterns and to obtain the optimal values shown in the figure (2).

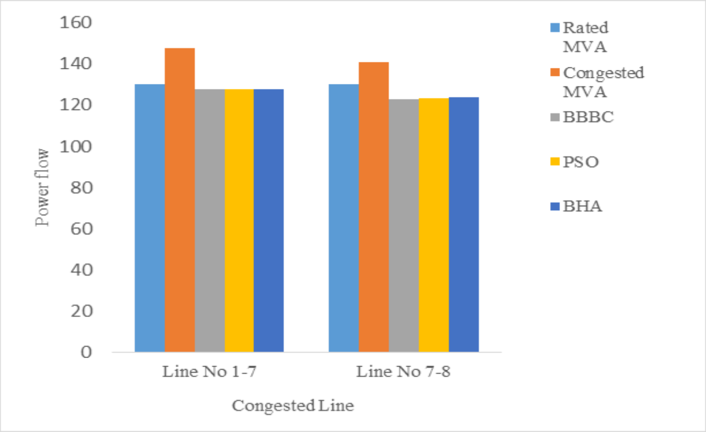

Fig. 2: Power flow through the lines (Case A)

Convergence characteristic of BHA method in case A is shown in figure 3 for active power and reactive power in rescheduling,

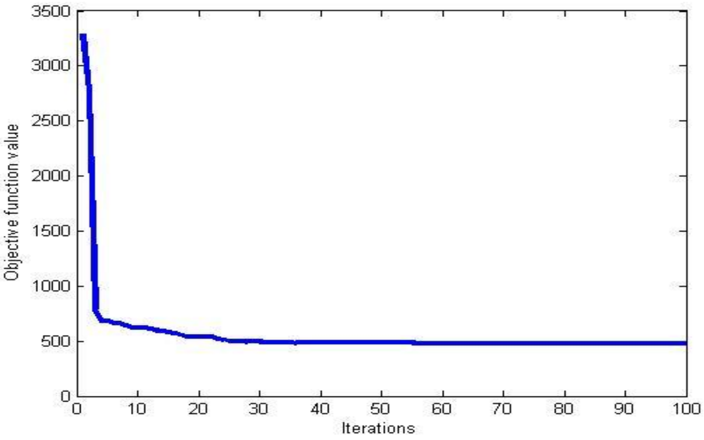

Fig. 3: Convergence characteristic of BHA (case A)

4.2 Case B: 20% overload at all load buses

In case B, Congestion is created by increasing 20% of load at all the load bus. As a result of increased, the total real and reactive power loads are increased to 340.08MW and 151.44MVAR respectively. It leads to congestion at line number 1 that is connected between bus numbers 1and bus number 2. For eliminating the congestion in the transmission line, sensitivity factors are calculated based on real and reactive power for the congested line as shown in the table 5. Based on the calculated sensitivity values the rescheduling process is carried out for the power generations at the influenced generator.

Table 5: Generator Sensitivity factors (Case B)

Congested lines		G_1	G_2	G_3	G_4	G_5	G_6
Line 1-2	P	0	-0.8805	-0.8552	-0.7302	-0.7202	-0.6832
	Q	-3.4871	-2.2153	-0.8456	-0.5200	-0.5375	-0.6632

Optimization methods are used for rescheduling of the optimal values of real and reactive powers as shown in table 6. The optimal powers are within the range of inequality constraints specified in the given data. The contributions in all generators are extended to relieve the congestion in the transmission line.

Table 6: Optimal rescheduling (Case B)

Rescheduled power	BBC Technique		PSO Technique		BHA Technique	
	Real power	**Reactive power**	**Real power**	**Reactive power**	**Real power**	**Reactive power**
G_1	169.8026	71.1431	192.3892	68.7265	192.868	63.5002
G_2	84.5876	13.8330	64.2465	0.7157	65.8229	54.0422
G_3	25.6461	48.4201	24.9250	46.7704	24.5534	84.2851
G_4	36.2497	60.7223	36.0380	0.0000	35.0121	33.8304
G_5	18.0050	19.8047	18.3149	70.8133	17.8360	-27.7726
G_6	17.6762	-4.0598	16.9431	71.7243	16.9923	52.7220

The congestion cost obtained from all the three mentioned optimization approaches are tabulated in Table 7 as worst cost, average cost and best cost. The minimum congestion cost obtained from the BHA approach is 1375.1000 $/day as the best cost, where as in the other algorithms BB-BC approach 1338.2000 $/day as best minimum congestion cost and in PSO approach 1401.0000 $/day as the best minimum congestion cost. From these results it is concluded that the recently develpoed BHA method is proved with its effeicency.

Table 7: Congestion cost (Case B)

Rescheduling cost $/day	WORST COST	AVERAGE COST	BEST COST
BB-BC	1401.4587	1390.2953	1388.2000
PSO	1412.1834	1403.8725	1401.0000
BHA	1382.2873	1380.1854	1375.1000

Change in real power generations in the influencing generator for the case B is shown in the table 8. The values show that all the generators have contributed the optimal real power and reactive power. To eliminate the congestion in the transmission line due to load at all the load buses are overloaded with 20% from their base loads, the three algorithms are used and the explored optimal values are table 8.

Table 8: Optimal change of real power (Case B)

Technique	UP/DOWN adjustment of participating(MW)					
	P_{G1}	ΔP_{G2}	ΔP_{G3}	ΔP_{G4}	P_{G5}	ΔP_{G6}
BBC Technique	31.2126	27.0276	1.0861	1.2497	0.075	0.7662
PSO Technique	53.7992	6.6865	0.365	1.038	0.3849	0.0331
BHA Technique	54.278	8.2629	-0.0066	0.0121	-0.094	0.0823

By experimental procedure the case B in the modified IEEE 30 bus system, congestion is observed at line number 1 hence power flow in the line number 1 exceeds the rated value. The Figure 4 shows that power flow pattern for the congested line, under the congested state the power flow in the line is 137.1241MW but the rated value is 130 MW therefore 37.1241 MW of power flows in line makes the congestion by violating the line constraints . To regulate the normal power flow with its range, the optimization techniques are implemented for their best power flow pattern shown in the figure 4.

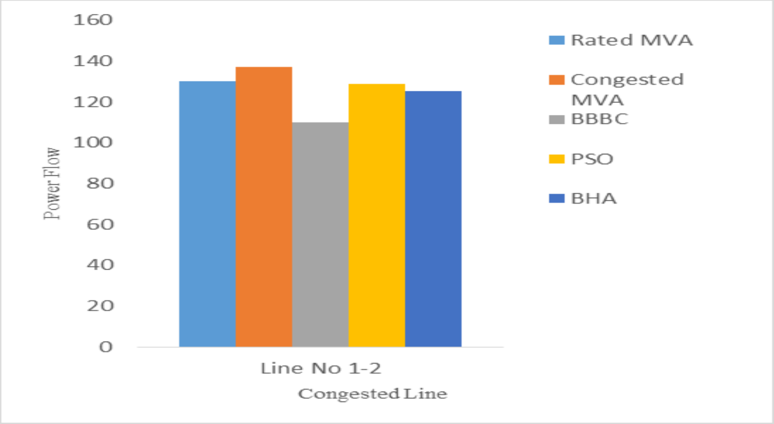

Fig 4: Power flow through the lines (Case B)

Convergence characteristic of BHA for case B is shown in the Figure 5. It clear from the plot that the algorithm takes about 20 iterations to converge to the best results.

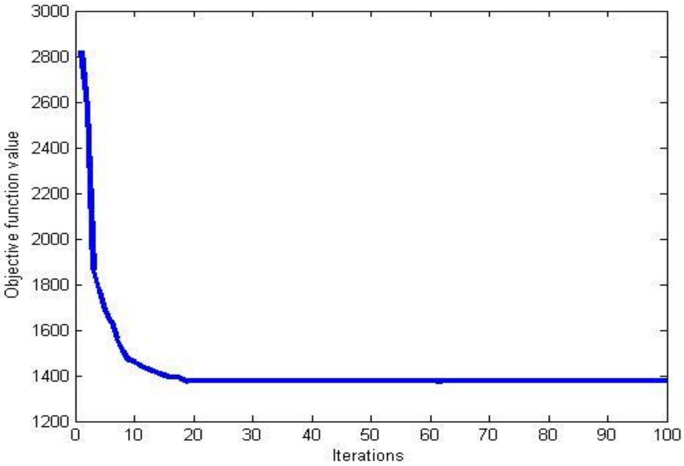

Fig. 5: Convergence characteristic of BHA (case B)

V. Conclusions

In this work, the BHA approach has been recommended to relieve the transmission congestion in the modified IEEE 30 bus test system. The cases of congestion taken are: line outage and 20% overloaded in the system. Minimum congestion cost is achieved by rescheduling the real and reactive power using generator sensitivity factors. The proposed work contributes to handle the congestion management problem by giving more priority to reschedule the generators which have more sensitivity index than the other generators instead of rescheduling all the generator powers. This ensures that the total cost due to rescheduling is not high. The effect of reactive power is also considered along with real power for congestion management. The contributions of reactive power sensitivity index has also a played a vital part to alleviate the congestion in the transmission line. The recommended algorithm proved its performance on the test system with the help of generator sensitivity based rescheduling of real and reactive power generation in the generators. The obtained numerical results are efficiently capable with higher quality of solutions and also the suggested results are compared with PSO method and BB-BC method. The recommended approach can be implemented to other power system optimization problems and also in dynamic congestion management too.

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