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Enhancement of Power System Security through Security Constrained Optimal Power Flow using Binary Particle Swarm Optimization

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ABSTRACT

Power system security evaluation and control ensures that a power system is reliable, secure and operates uninterruptedly even at times of contingencies. To accomplish the above said aim, the operational engineer should be able to predict the possible credible contingencies and must be ready with the control action that are to be taken to keep the state of the power system in a secure manner. The objective of this paper is to perform contingency ranking to find out the possible credible contingencies. Contingency ranking is done by calculating the performance or severity indices for the N-1 line outages using Newton Raphson Load Flow (NRLF), Biogeography Based Optimization (BBO) and also using the BPSO algorithm. The list of credible contingencies is found out and the capture ratio is obtained by comparing the rankings. The remedial control action is taken by performing SCOPF and rescheduling the generators.

Index of Terms: Power system security enhancement, Contingency ranking, Security Constrained Optimal Power Flow (SCOPF), Binary Particle Swarm Optimization (BPSO)

1. INTRODUCTION

Modern power system faces several challenges due to increasing complexity of structure and operation .Power system security means keeping the system in the operating condition amidst the failure of any component. The power demand is raising in an enormous amount and it is important to check whether the operating state of the system is in secure state and is necessary to restore the system from insecure to secure state using appropriate controls, so that the system may not violate the limit in case of any contingency. The power equipment is designed to operate under certain limits. During contingencies, when the system is functioning in insecure state, this limit may be violated causing other power equipment to trip and leading to cascading equipment failures and blackout. The above said scenario was one of the reasons for the blackout that happened in India on July 2012 [1].

After performing the contingency analysis and ranking, Security Constrained Optimal power Flow (SCOPF) is undertaken as the corrective action under contingencies. OPF is implemented and the power is directed through different lines in such a way that the severity index decreases during contingencies [2]. Some of the classical methods used for solving the OPF are Newton method [3], Interior point method [5], Gradient method [4] etc. These classical techniques have some limitations such as poor convergence and time consuming behavior.

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Due to the limitations in the classical method, the OPF are solved using programming techniques derived from nature such as Genetic Algorithm (GA) and Evolutionary Programming (EP) [6], [7, 8], Particle Swarm Optimization (PSO) [9,10], Binary Particle Swarm Optimization (BPSO) [11] etc. These algorithms adopt a brilliant approach to search the feasible solution space but every algorithm will have some disadvantages such as premature convergence etc., but constant improvement to the algorithms and its parameters will make them suited for solving OPF problems efficiently. OPF based security using genetic algorithm was also conceived [12]. Similarly PSO, Evolutionary algorithm, and Cuckoo search algorithm are adopted for security constrained economic load dispatch purpose [13] [14] [26]. In the present paper, BPSO is used for the purposes of contingency ranking and SCOPF.

The present paper is organized as follows: the section on "Methodology" throws light on performance indices and problem formulation defining the severity indices and the objective function for the SCOPF. The section on "Optimization Technique" presents an overview of BPSO algorithm. The section named "Architecture of the Security Enhancement Technique" presents the problem as a flowchart. The section on "Test Case" describes the proposed system. The section on "Results and Discussion" discusses the outcome of the program and analysis. The last section named "Conclusion" provides the inferential remarks based on the study.

2. METHODOLOGY

2.1. Performance Indices

The performance index function penalizes a contingency for any violation in bus voltage constraints or transmission line constraint. The voltage constraints on the power system normally require the bus voltage to remain within the violation limits. The transmission line constraint is a thermal limit of each line which determines the maximum power flow allowed across each line.

The voltage Index (VI) function quantifies the contingency level based on the violation of voltage limit. This can be expressed as:

$$VI = \sum_{i=1}^{NB} \left(\frac{V_i}{V_i^{\max}} \right) 2m \tag{1}$$

Where,

V_i = Voltage in the bus i,

$V_i^{\max}$ = Maximum voltage in the bus i,

m = masking coefficient,

NB = total no. of buses in the system

The Power Index (PI) function quantifies the power flow in the line which is again constrained by thermal limit.

$$PI = \sum_{i=1}^{NB} \left(\frac{S_i}{S_i^{\max}} \right) 2m \tag{2}$$

Where,

S_i = Active power flow in line i,

$S_i^{\max}$ = Maximum active power in line i,

m = masking coefficient,

NL = the total no. of transmission lines present in the system

Line overloading causes larger performance indices during contingencies. Thus, contingency is ranked with the help of performance indices. Performance indices are applicable for the contingency selection for line contingency only.

2.2. Problem Formulation

This section presents the problem formulation for SCOPF using the description of a generalized OPF. When compared to objectives, variables, and constraints, the characteristics of the OPF differ significantly. It has both inequality and equality limits. Without considering the losses, the OPF can be represented as:

$$\text{Min } f\,(x, u)$$

Subject to

$$g\,(x, u) = 0$$

$$h\,(x, u) \le h^{max}$$

Here,

$g\,(x, u) = 0$ indicates power flow equations.

$H\,(x, u)\ h^{max}$ represents constraints on the branch flow.

h^{max} represents branch continuous ratings.

$f\,(x, u)$ is the objective function whose severity index has to be reduced. The variable ‘u’ denotes a set of independent system quantities like active power generation at PV buses, voltage magnitude at generation buses, etc. The variable ‘x’ is the set of dependable variables like voltage of the load buses, active power output of the slack bus, transmission line flow etc. [23] [24].

SCOPF differs from an OPF solution only when the contingency constraint is binding. It is formulated as:

$$\text{Min } f(x^0, u^0)$$

Subject to

$$g^k\,(x^k, u^k) = 0, \text{ for } k = 0, 1, 2, \ldots N_c$$

$$h^k\,(x^k, u^k) \le h^{max} \text{ for } k = 0, 1, 2, \ldots N_c$$

In the above equation, superscript “0” denotes the state prior to contingency that has to be optimized; superscript “k” (k > 0) represents the states after contingency for the contingency cases N_c. The post contingency state varies from pre contingency state. In the former, equality constraints g^0 to g^k and reflect the equipment outage and control variables u^0 respond by changing to u^k. [25]

3. OPTIMIZATION METHOD

3.1. Classical Particle Swarm Optimization

Particle Swarm Optimization is inspired by the behavior of birds that come in search of food as a swarm. At the end of every iteration, a particle updates its speed stochastically based on its best historical position and the better positions that are available nearby. Both positions are best according to the fitness function defined by the user. There are two different best solutions, one that occurs in local optima, and other that occurs in global optima. The particle motion develops an optimal or an almost optimal solution. The expression ‘swarm’ comes from the irregular movement of particles in the search space [10].

Particle Swarm Optimization Algorithm:

The algorithm for PSO has the following steps:

1. Assign location for the particle within a uniformly distributed search-space.
2. Evaluate the performance (fitness) or the objective function of every particle
3. Determine the maximum or minimum fitness for each particle according to its objective function, whether its maximization or minimization problem.
4. Initialize the best known local position of the particle with respect to its starting position.
5. Assign the optimal global position to the swarm's best known local position based on the minimum or maximum objective function value.
6. Assign the particle's velocity in such a way that it is within maximum and minimum limits of the search space.

   Repeat the steps until each particle meets the termination criterion.

The process and the formulae for PSO are given below,

1. Create uniform random vectors S1 and S2
2. Update the velocity of the particle using

$$v_i^{t+1} = v_i^t + c_1 * U_1^t * \left(pB_i^t - p_i^t \right) + c_2 * U_2^t * \left(gB_i^t - p_i^t \right) \tag{3}$$

Where,

v_i^{t+1} - Updated velocity.

v_i^t - Velocity at time 't'.

$c_1\ c_2$ - Inertia weight of local best.

$U_1^t\ U_2^t$ - Random variable 1 & 2.

pB_i^t - Personal best

p_i^t - Particle position at time 't'.

gB_i^t - Global optimum

Update the particle's position by adding the velocity,

$$p_i^{t+1} = p_i^t + v_i^{t+1} \tag{4}$$

3. Find the performance (fitness) or objective function based on the updated position of the particles.
4. Suppose the new value of the objective function is lesser than the previous value then the positions of the new particle are updated based on the best known local position.
5. Assign the latest value of the objective function as the value of the local objective function and then determine the minimum or maximum from each of them.
6. Update global best position of the swarm based on the minimum or maximum value of the objective function. The new best positions provide us the optimum solution.

3.2. Binary Particle Swarm Optimization

The classical PSO concentrates primarily on the problem with continuous space applications and is unable to solve the combinational type of problems in discrete space application. This gave rise to the evolution of BPSO which has been employed in resolving different kinds of problems ranging from graphics [15], problem of knapsack [16], problems based on unit commitment [17], problems on lot sizing [18], scheduling type problems [19] [20] etc.

J. Kennedy and R. Eberhart have developed BPSO from the classical PSO. The difference in BPSO from the classical PSO is that each particle in BPSO consists of binary code for the search space and uses equation 3 to calculate and update velocity.

There is no position update formula in BPSO as in classical PSO. The value of velocity is between the interval 0 and 1 [22]. Scaling of velocities from 0 and 1 is performed using the sigmoid function. [21]

$$\text{Sigmoid } (V_{id}) = \frac{1}{1+\exp\left(-V_{id}\right)} \tag{5}$$

The particle will change the bit value by the equation

$X_{id} = 1$ uf rand $\leq$ sigmoid (V_{id})

$X_{id} = 0$ if otherwise

The rand is a variable consists of numbers sampled from an interval [0 1]. In order to prevent the value of Sigmoid (v_{id}) from being closer to 1 or 0, a parameter V_{max} is utilized to limit the value of V_{id} [27].

$V_{id}\,1[-V_{max}, V_{max}]$ which confines the value of V_{id}

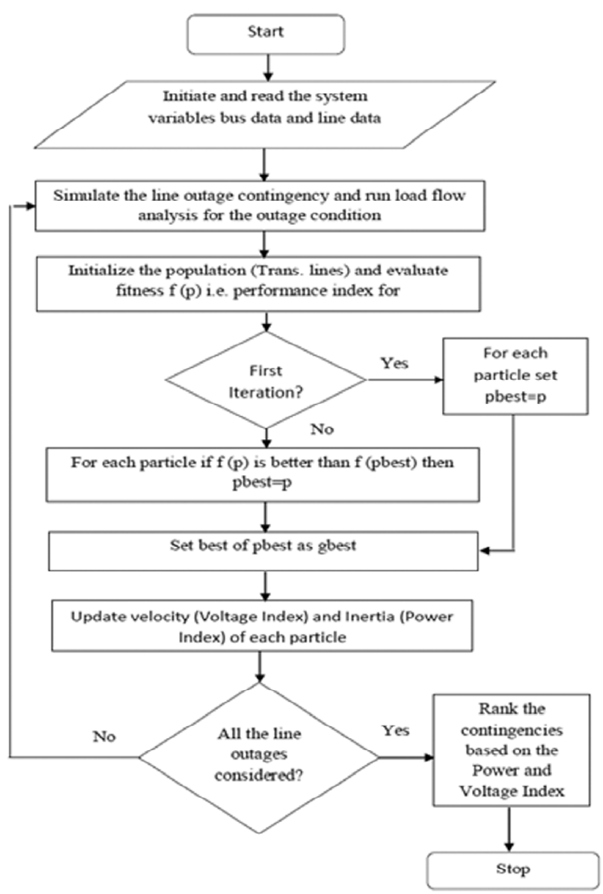

Figure 1: Flowchart for Contingency Ranking using BPSO

The contingency analysis is performed using NRLF method and the ranking is done using BPSO algorithm. Velocity of the individual particle is selected from values between 0 and 1. The objective function value for each particle is calculated and gbest and pbest values are selected.

The control specifications (velocity and position) of the particles are initialized. The velocity and inertia values are updated. The objective function value is again evaluated for the updated position, pbest and gbest are obtained. This procedure is carried on until the convergence criterion is fulfilled.

Table 1
Algorithm Parameters vs Problem Parameters

Algorithm Parameters	*Problem Parameters*
Population	Transmission line
Inertia	Power Index
Velocity	Voltage Index
Personal best (*pbest*)	Performance Indices of each transmission line outage.
Global best (*gbest*)	Highest indices among 41 transmission lines.
Probability of population	Chooses exact random population matching with the fitness function.

4. ARCHITECTURE OF SECURITY ENHANCEMENT TECHNIQUE

The main aim of the enhancement of the security is to perform SCOPF and minimize the severity indices under contingency scenarios. The SCOPF problem should be approached in an orderly manner and this section gives us the flow of the problem.

Contingency Analysis Phase: The line data and the bus data are inputted in to the system. Then a contingency analysis is performed using Newton Raphson Load Flow method. Critical contingencies are identified using the contingency ranking based on the severity indices.

SCOPF Phase: Then the system is fed with the generator data and values of line flows and voltages taken from the previous phase. After the rescheduling of the generators, the severity indices are calculated again. The severity indices are feedback to the previous phase until the minimum severity indices are achieved. The SCOPF architecture is performed using a standard IEEE 30-bus system and the BPSO algorithm is applied.

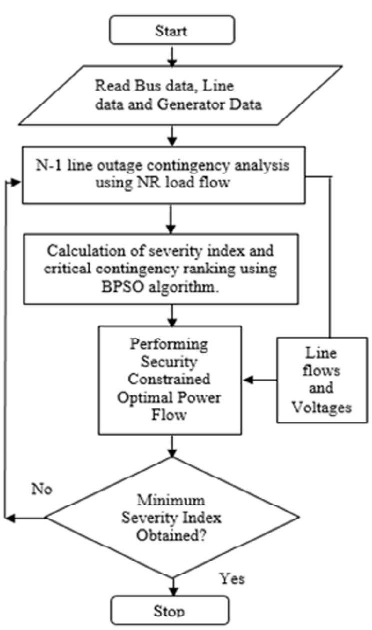

Figure 2: Flow chart of Security Enhancement Architecture

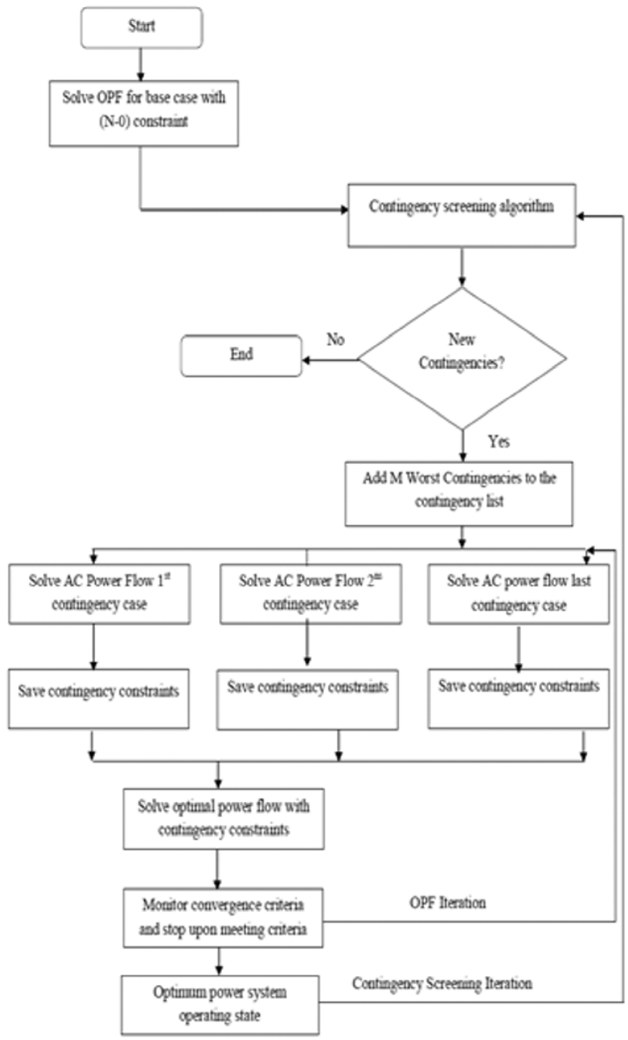

Figure 3: SCOPF Flowchart

5. TEST SYSTEM

In the present paper, a standard IEEE 30-bus test system is considered. The test case comes under the American Electric Power System (December, 1961). It comprises of six generators and forty one transmission lines. The data for the transmission line and the generator are obtained from [28]. The maximum and minimum voltage values are 1.05 p.u and 0.95 p.u. The slack bus voltage is assumed to be 1.06 p.u. The base MVA of the system is 100 and the system frequency is 60Hz.

6. RESULTS AND DISCUSSION

The IEEE 30-bus system which is taken for security enhancement is programmed using the software MATLAB R2009b. The N-1 line outage contingency analysis is performed for the IEEE 30-bus test system having forty one transmission lines. So there will be forty one line outage contingencies. Contingency analysis is performed for all the lines using NRLF method.

6.1. Test Cases

The programming for contingency ranking is carried out the first 15 contingency cases are ranked. The three different cases as given below.

Case 1: This case presents contingency ranking using the Newton Raphson Load Flow method.

Case 2: This case presents contingency ranking based on the Biogeography Based Optimization (BBO) algorithm.

Case 3: This case presents the contingency ranking on the basis of BPSO algorithm.

Case 4: This case presents the results of SCOPF and the contingency ranking done after SCOPF. All the Ranking is done on the basis of power index and voltage index..

Case 1: Contingency Ranking Using NRLF Method

Table 2
Contingency Ranking using NRLF on the Basis of Voltage Index

Outage Line Number	*From Bus*	*To Bus*	*Voltage Index*	*Contingency Ranking*
36	28	27	194.1804	1
38	27	30	18.7727	2
4	3	4	17.8879	3
11	6	9	17.8706	4
18	12	15	17.8547	5
19	12	16	17.7335	6
7	4	6	17.5250	7
30	15	23	17.5189	8
21	16	17	17.4825	9
9	6	7	17.4569	10
22	15	18	17.4161	11
34	25	26	17.3602	12
33	24	25	17.3391	13
32	23	24	17.3243	14
23	18	19	17.2921	15

Table 3
Contingency Ranking using NRLF on the Basis of Power Index

Outage Line Number	*From Bus*	*To Bus*	*Power Index*	*Contingency Ranking*
10	6	8	5.1725	1
36	28	27	3.4914	2
1	1	2	3.1360	3
7	4	6	2.9303	4
5	2	5	2.8036	5
41	6	28	2.7076	6
9	6	7	2.5431	7
8	5	7	2.3937	8
2	1	3	2.3759	9
4	3	4	2.3428	10
18	12	15	2.3297	11
38	27	30	2.3209	12
19	12	16	2.3201	13
37	27	29	2.3190	14
16	12	13	2.3190	15

Case 2: Contingency Ranking by BBO Algorithm

Table 4
Contingency Ranking using BBO on the Basis of Voltage Index

Outage Line number	*From Bus*	*To Bus*	*Voltage Index*	*Contingency Ranking*
36	28	27	177.5304	1
38	27	30	2.1227	2
4	3	4	1.2379	3
11	6	9	1.2206	4
19	12	16	1.0835	5
7	4	6	0.8750	6
30	15	23	0.8689	7
21	16	17	0.8325	8
9	6	7	0.8069	9
22	15	18	0.7661	10
33	24	25	0.6891	11
32	23	24	0.6743	12
23	18	19	0.6421	13
37	27	29	0.6274	14
14	9	10	0.5807	15

Table 5
Contingency Ranking using BBO on the Basis of Power Index

Outage Line number	*From Bus*	*To Bus*	*Power Index*	*Contingency Ranking*
21	16	17	11.0353	1
33	24	25	9.4474	2
10	6	8	9.239	3
37	27	29	6.7332	4
14	9	10	5.76	5
31	22	24	5.1626	6
7	4	6	4.1212	7
28	10	22	4.1212	8
8	5	7	3.897	9
25	10	20	2.8611	10
26	10	17	2.8569	11
13	9	11	2.8292	12
12	6	10	1.8937	13
19	12	16	1.8209	14
5	2	5	1.8209	15

Case 3: Contingency Ranking by BPSO Algorithm

Table 6
Contingency Ranking using BPSO on the Basis of Voltage Index

Outage Line Number	*From bus*	*To bus*	*Voltage Index*	*Contingency Ranking*
36	28	27	177.5304	1
38	27	30	2.1227	2
4	3	4	1.2379	3
11	6	9	1.2206	4
18	12	15	1.2047	5
19	12	16	1.0835	6
7	4	6	0.8750	7
30	15	23	0.8689	8
21	16	17	0.8325	9
9	6	7	0.8069	10
22	15	18	0.7661	11
34	25	26	0.7102	12
33	24	25	0.6891	13
32	23	24	0.6743	14
23	18	19	0.6421	15

Table 7
Contingency Ranking using BPSO on the Basis of Power Index

Outage Line Number	*From Bus*	*To Bus*	*Power Index*	*Contingency Ranking*
36	28	27	5.6725	1
38	27	30	3.9914	2
4	3	4	3.6360	3
11	6	9	3.4303	4
18	12	15	3.3036	5
19	12	16	3.3036	6
7	4	6	3.2076	7
30	15	23	3.0431	8
21	16	17	3.0431	9
9	6	7	2.8937	10
22	15	18	2.8759	11
34	25	26	2.8428	12
33	24	25	2.8297	13
32	23	24	2.8209	14

Case 4: Contingency Ranking after SCOPF

Table 8
Contingency Ranking after SCOPF on the Basis of Voltage Index

Outage Line Number	*From Bus*	*To Bus*	*Power Index*	*Contingency Ranking*
36	28	27	5.6725	1
38	27	30	3.9914	2
4	3	4	3.6360	3
11	6	9	3.4303	4
18	12	15	3.3036	5
19	12	16	3.3036	6
7	4	6	3.2076	7
30	15	23	3.0431	8
21	16	17	3.0431	9
9	6	7	2.8937	10
22	15	18	2.8759	11
34	25	26	2.8428	12
33	24	25	2.8297	13
32	23	24	2.8209	14
23	18	19	2.8201	15

6.2. Interpretation from the Test Cases

Capture Ratio: The capture ratio indicates the effectiveness of a method by giving the desired results (contingencies). It compares the severe contingencies returned by the assessed method with the list returned by the exhaustive method. Capture ratio can be shown as:

$$Capture\ Ratio = \frac{k(p)}{N} \times 100 \tag{6}$$

Where,

N – No. of severe contingencies captured

P – List of severe contingencies and their positions in the assessed method

K (p) – severe contingencies in the initial positions of the list (‘p’)

Table 9
Capture ratio between NRLF and BPSO on the Basis of Voltage Index

N	*k(p)*	*Capture Ratio in %*
5	5	100
10	10	100

Table 10
Capture ratio between NRLF and BPSO on the Basis of Power Index

N	*k(p)*	*Capture Ratio in %*
5	1	20
10	4	40

Table 11 and 12 below show the capture of voltage and power index between BBO and BPSO respectively

Table 11
Capture ratio between BBO and BPSO on the Basis of Voltage Index

N	*k(p)*	*Capture Ratio in %*
5	4	80
10	9	90

Table 12
Capture ratio between BBO and BPSO on the Basis of Power Index

N	*k(p)*	*Capture Ratio in %*
5	1	20
10	2	20

Security Enhancement: Enhancement of Security can be witnessed in table 13 and figure 4 by comparing the top 5 critical contingencies in the table 6 and table 8 and the reduction in the voltage index can be observed.

Table 13
Comparison of voltage index before and after SCOPF

Outage Line Number	*From Bus*	*To Bus*	*Voltage Index Before SCOPF*	*Voltage Index After SCOPF*
36	28	27	177.5304	168.8873
38	27	30	2.1227	2.0976
4	3	4	1.2379	1.1836
11	6	9	1.2206	1.1966
18	12	15	1.2047	1.1986

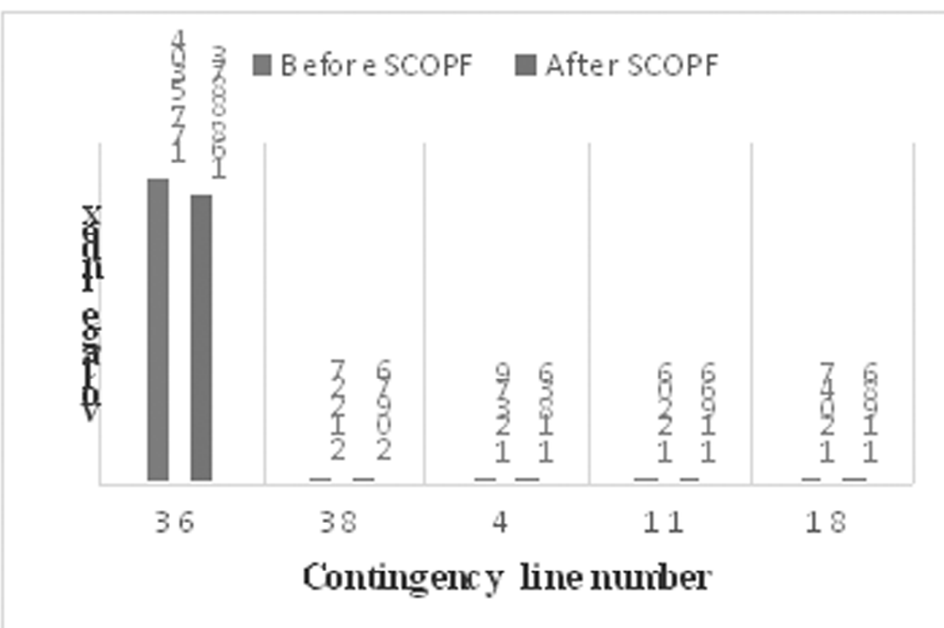

Figure 4: Graphical Representation of Security Enhancement

7. CONCLUSION

This paper presents a method for enhancement of security using SCOPF. In the present paper, contingency analysis on N-1 line outage is performed using NRLF method. The contingencies are ranked using the traditional sorting methods like Biogeography Based Optimization (BBO) and Binary Particle Swarm Optimization (BPSO). The contingency ranking identifies the critical contingencies present in the system and prepares the system to act defensively. The capture ratio obtained in this project, presents the effectiveness of the BPSO contingency ranking. Further from the results obtained after performing SCOPF, it can be concluded that the security has been enhanced with the reduction in the voltage index. On comparing the voltage indices before and after performing SCOPF, the latter has decreased voltage indices. The outcome of this paper shows that the overload in the lines is considerably alleviated and the security of the system under contingency is enhanced. The IEEE 30-bus test system considered for the present study was programmed using MATLAB programming.

The future scope of this work can be extended by testing the proposed method with different algorithms and obtaining the best optimal results further enhancing the system security.

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