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Intelligent Method based Optimal Reallocation of Generators for Enhancement of System Security for N-1 Contingency in Power Systems

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Abstract: Due to privatization of the power industry, proper utilization of the available resources has become a very important factor. Optimal power flow (OPF) is an ideal solution to the problem. At the same time, stable operation of the power systems in both normal and contingency condition is of vital importance. Use of Facts devices is a good method to stop further contingencies in the power system. In this paper, a combined index based strategy for the optimal placement of Thyristor Controlled Series Compensator (TCSC) and optimal tuning of generators using Krill Herd Algorithm has been proposed for contingency management. The TCSC has been placed on the basis of an index which is a combination of Line Utilization Factor (LUF) and Fast Voltage Stability Index (FVSI). A probability based approach has been adopted for the placement of the device. A multi objective function has been chosen for tuning the generators. The multi-objective function includes voltage deviation, active power generation cost and transmission line loss. The proposed method has been tested and implemented on an IEEE 30 bus system.

Keywords: Optimal Reallocation; TCSC; Krill Herd Algorithm; Voltage Stability.

1. INTRODUCTION

As a result of the increase in competition in the electrical industry, finest use of the obtainable power supplies has become mandatory. On the other hand, due to rise in power flow the transmission lines are continuously facing a problem of congestion because of carrying power at their extreme transmission limits and sometimes higher. Continuous overloading of the transmission lines can cause an excessive risk to power system security, reliability and stability.

Optimal power flow is a method of optimizing an objective function in the presence of operational constraints by the method of nonlinear programming. Many methods have been developed so far to solve the OPF problem [1]. Metaheuristic methods are one of the most recent methods used for the OPF problem. Nanda Kumar et al. [2] proposed optimal power flow method to determine the steady state operation point which minimizes multiple objectives and at the same time improves the system performance. Vijay kumar et al [3] demonstrated the effect of TCSC on congestion of transmission lines by optimal power flow method using Genetic algorithm. Rao et al [4] have used OPF technique in the presence of SVC for the improvement of network security under contingency condition. The performance of BAT and Firefly algorithm have been compared to determine the optimal location and size of Static VAR Compensator (SVC) in a power system to improve voltage stability for a multi objective function [5]. Mangaiyarkarasi [6] proposed a modified severity index and probability of severity based approach for the placement of

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Static VAR Compensator in order to improve the voltage stability. Prasad et al. [7] proposed Symbiotic Organisms Search (SOS) for the solution of optimal power flow of power systems with FACTS devices for a multi objective function. Several authors have used metaheuristic algorithms for obtaining the optimal location of FACTS devices for various objective functions [8, 9, 10].

Mishra et al [11] proposed the placement of Interline Power Flow Controller (IPFC) for the reduction of congestion of the transmission lines. The Line severity index used is found to a very efficient method of estimation of loading of the transmission lines. Ya-Chin et al. [12] have used multi-objective Particle Swarm optimization method for the installation of SVC to improve transmission system loading margin (LM) to a certain degree and reduce network expansion cost. Nam et al [13] have suggested optimal placement of SVC in power market that voltage stability is increased by PV curve as well as social welfare is increased by Locational Marginal Price (LMP). Shaheen et al [14] has used computational intelligence method namely DE has been used to find the optimal location and size of UPFC on the basis of performance index for N-1 contingency condition. Mishra et al. [15] proposed placement of IPFC using an index which is a combination of real power performance index and line stability index, for management of contingency. The IPFC was then tuned using Differential Evolution (DE). The proposed index is found to be a more accurate measure of severity in comparison to the individual indices. It is also found that use of line voltage stability index is a good option for the measurement of voltage stability for series devices. Optimal reallocation of generators is necessary for the optimal utilization of the available power system resources. The advantages of the method can be further improved by the placement of FACTS devices. Series FACTS devices are most suitable for enhancing the transmission capabilities. The FACTS device should be correctly placed in the system in order to enhance its effectiveness. Krill Herd Algorithm [16] was introduced in the year 2012. This recent algorithm has been implemented in different fields and has been found to be very successful [17, 18].

In this paper, optimal reallocation of generators has been proposed for the management of contingency condition in the power systems. Krill Herd Algorithm has been used for the optimal power flow in the presence of TCSC. The optimal reallocation of generators has been done for a multi-objective function, specifically, reduction in voltage deviation, reduction of fuel cost and reduction in transmission line loss. The real and reactive power generation values and voltage limits for buses are taken as constraints, during the optimization. The results of optimal tuning without and with TCSC have been compared to prove the effectiveness of the proposed method.

2. MODEL OF TCSC

Thyristor Controlled Series Compensator (TCSC) is a series FACTS device. It can be used for both lead and lag compensation in the transmission lines. This is because of its operation in different modes like blocking mode in which inductive branch is opened, bypass mode in which it operates in parallel mode both as capacitor and inductor, and capacitive boost mode. The following are the advantages of TCSC

- ability to maintain balance in the reactive power,
- reducing the damped oscillations in the system,
- Improvement in the stability of the system at post contingency.
- Capability to improve the power transfer limits of the transmission lines to some extent.

The TCSC model between the buses j and k is shown as follows

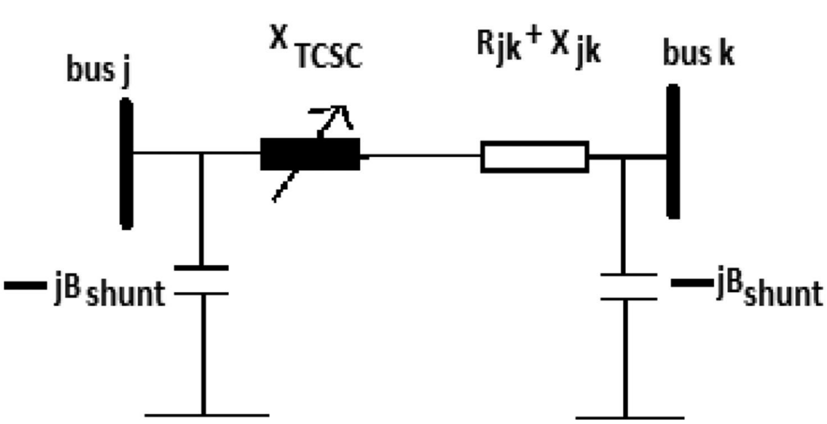


Fig. 1 Transmission line model with TCSC

The power flow equations of the transmission line would change as follows after adding the TCSC

$$\mathrm{P}_{\mathrm{jk}} = V_{\mathrm{j}}^2 G_{jk} - V_j V_k \left(G_{jk}\cos\delta_{jk} + B_{jk}\sin\delta_{jk}\right) \tag{1}$$

$$\mathrm{Q}_{\mathrm{jk}} = -V_{\mathrm{j}}^2 B_{jk} - V_j V_k (G_{jk}\sin\delta_{jk} - B_{jk}\cos\delta jk) \tag{2}$$

$$\mathrm{P}_{\mathrm{jk}} = V_{\mathrm{k}}^2 G_{jk} - V_j V_k (G_{jk}\cos\delta_{jk} - B_{jk}\sin\delta jk) \tag{3}$$

$$\mathrm{Q}_{\mathrm{jk}} = -V_{\mathrm{k}}^2 B_{jk} + V_j V_k (G_{jk}\sin\delta_{jk} - B_{jk}\cos\delta jk) \tag{4}$$

Where

$$\mathrm{G}_{\mathrm{jk}} = R_{jk} \Big/ {R_{jk}}^2 + X^2 \tag{5}$$

$$\mathrm{B}_{\mathrm{jk}} = X \Big/ {R_{jk}}^2 + X^2 \tag{6}$$

$$\mathrm{X}_{\mathrm{jk}} = \mathrm{X}_{\mathrm{jk}} - \mathrm{X}_{\mathrm{TCSC}} \tag{7}$$

δ_{jk} is the voltage angle between bus *j* and *k*.

The reactive constraint on the TCSC is given as $-0.8\ \mathrm{X}_{jk} \leq \mathrm{X}_{\mathrm{TCSC}} \leq 0.2\ \mathrm{X}_{jk}$.

3. PROPOSED COMBINATORY INDEX

A mbinatory index is formulated using LUF and FVSI index as given in equation 8.

$$CI = \mathrm{W}_1 \times I_1 + \mathrm{W}_1 \times I_2 \tag{8}$$

Where w_1 and w_2 are the weighting factors.

I_1 is the Line Utilization Factor is an index used for determining the congestion of the transmission lines.

LUF-Index given by equation (9)

$$I_1 = \frac{MVAij}{MVAij^{\max}} \tag{9}$$

$\mathrm{MVA}_{ij\,(max)}$: Maximum MVA rating of the line between bus *i* and bus *j*.

MVA_{ij} : Actual MVA rating of the line between bus *i* and bus *j*.

LUF gives an estimate of the percentage of line being utilized.

The most severe line affected can be found by a voltage stability index called Fast Voltage Stability Index Factor (FVSI). It is introduced by Musirin and Rahman. It calculates the voltage stability of a given bus under any loading conditions. It is defined as follows

I_2 is the Fast Voltage Stability Index (FVSI) given by equation (10)

$$I_2 = 4\frac{Z^2 Qj}{Vi^2 X} \tag{10}$$

Where, Z is the impedance of line, X is the line reactance, is the voltage at the sending end and is the reactive power at the receiving end.

4. PROBLEM FORMULATION

A multi-objective function including of fuel cost, real power loss and voltage deviation is used for the optimal tuning of generators.

$$\text{Min } F = \text{Min } (w1*F1+w2*F2+w3*F3) \tag{11}$$

Where,

F1 is the Fuel cost given by-

$$F1 = \min(\sum_{i=1}^{ng} [a_i + b_i P_{Gi} + c_i P_{Gi}^2]) \tag{12}$$

Ng is the number of generators in the power system and a, b, c are the fuel cost coefficients.

F2 is the Real power loss

$$F2 = \min\left(\sum_{i=1}^{ntl} real(S_{jk}^{i} + S_{kj}^{i}\right) \tag{13}$$

Where n_{tl} is number of transmission lines, S_{jk} is the total complex power flows from bus *j* to bus *k* in line *i*.

F3 is the Voltage deviation

$$F3 = \min(VD) = \min(\sum_{k=1}^{Nbus} \left|V_k - V_k^{ref}\right|^2) \tag{14}$$

V*k* is the actual value of voltage magnitude at bus *k* and V_k^{ref} is the reference value of voltage magnitude at the bus.

Power Balance Constraint

$$\sum_{i=1}^{N} P_{Gi} = \sum_{i=1}^{N} P_{Di} + P_L \tag{15}$$

Where *i* = 1, 2, 3... N and N = no. of. Bus

Voltage balance constraint

$$V_{Gi}^{\min} \leq V_{Gi} \leq V_{Gi}^{\max} \tag{16}$$

Where G_i=1, 2, 3... ng and ng = number of Generator buses.

Generation limit real power

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \tag{17}$$

Where, Gi=1, 2, 3... *ng*

P_L is the active power loss of the system,

P_{Gi} is the active power generated at bus *i*,

P_{Di} is the power demand at bus *i*,

N is the number of buses and

n_g is number of generators.

The voltage limits of the generator buses are taken between 0.9 *pu* and 1.1 *pu*.

5 KRILL HERD ALGORITHM

Krill Herd (KH) algorithm is a Meta-heuristic algorithm inspired by nature, based on the herding behavior of the krill individuals, proposed by Gandomi and Alavi in 2012. The distance of each krill from the food source is the main objective of the krill movement.

The herding of krill is based on two main goals:

1. Increase the density and
2. Reach the food

The position of the krill individual is mainly influenced by three important factors:

3. Movement induced by the krill individuals
4. Foraging activity
5. Random diffusion

All individual krill, in this mechanism, move towards the finest probable solution when searching for highest density and food. By extending the algorithm to an n-dimensional, the fitness function of the algorithm (for i^{th}krill individual) is determined below:

$$\frac{dx_i}{dt} = N_i + F_i + D_i \tag{18}$$

Where, N_i is the motion induced on i^{th} krill individual due to the other krill individuals, Fi is the foraging motion and Di is the random diffusion. The procedure followed for Krill Herd is mentioned in Fig. 2

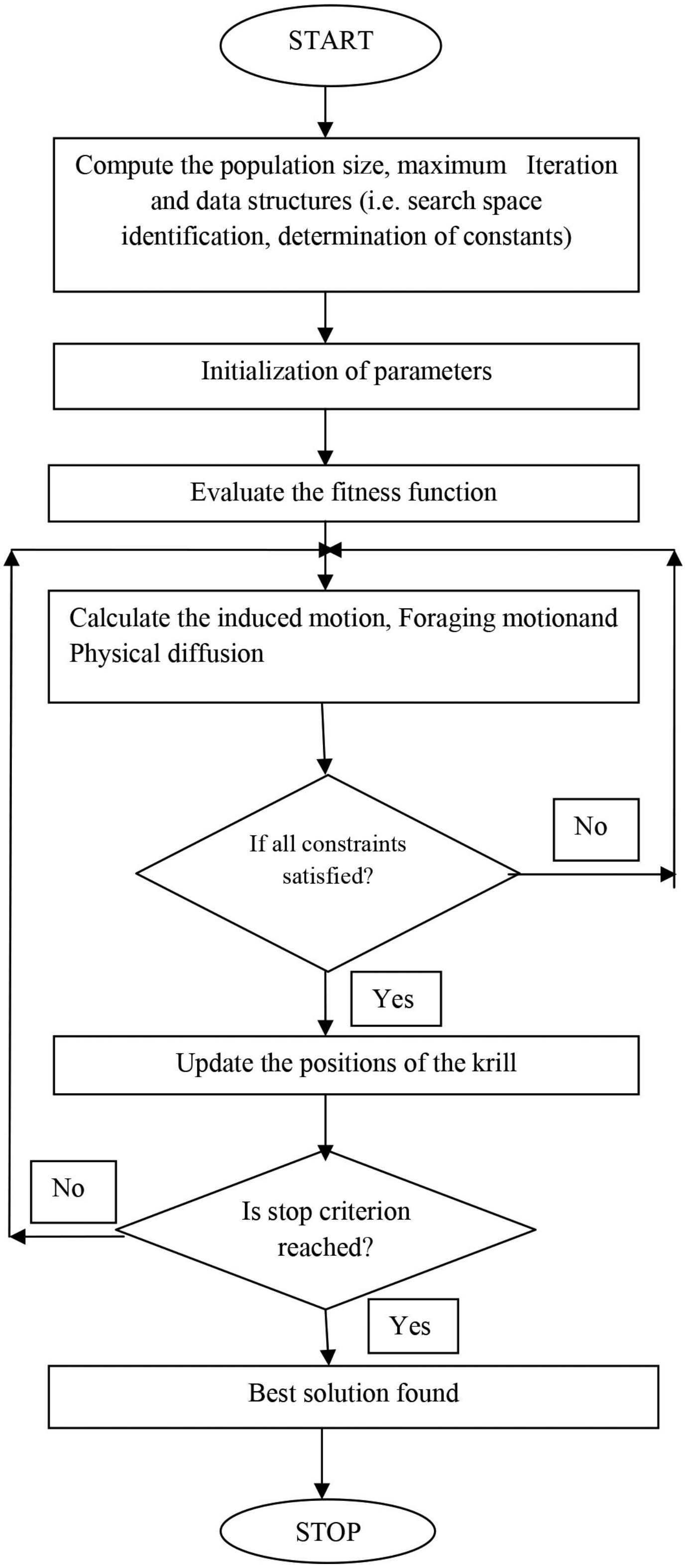


Fig. 2 Detailed Procedure for Krill Herd Algorithm

6. PROPOSED METHODOLOGY

The flowchart showing the steps followed to perform the optimal power flow in the presence of TCSC has been shown in Fig. 3

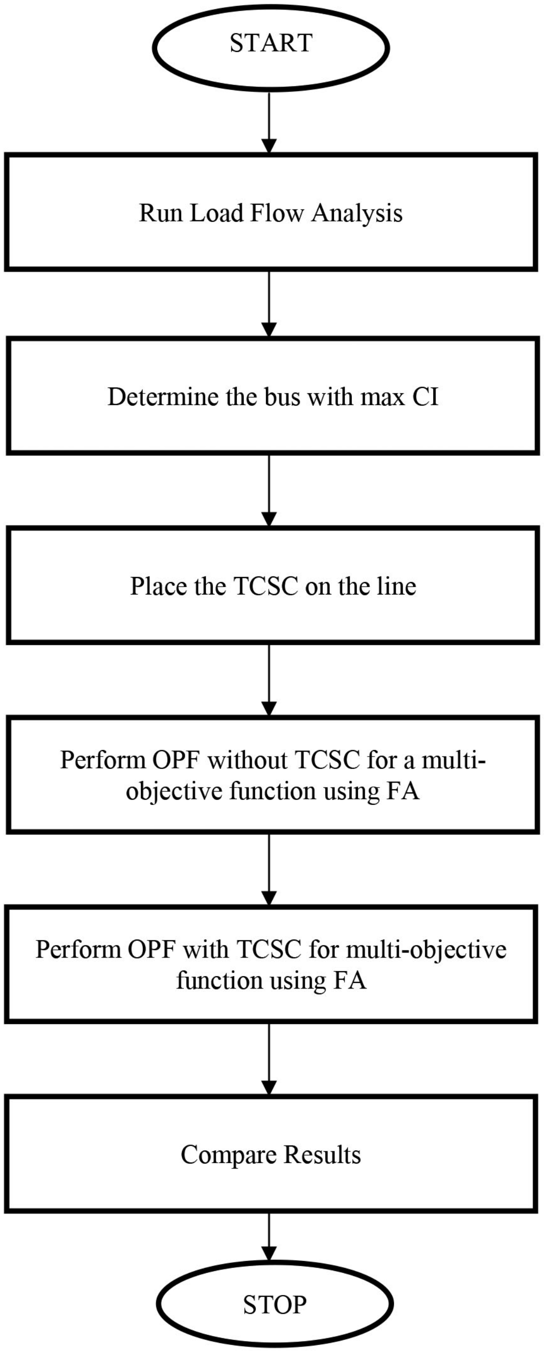


Fig. 3 Flowchart for illustration of the proposed methodology

7. RESULTS AND DISCUSSION

The proposed methodology has been implemented on an IEEE 30 bus system shown in Fig.4. Initially the proposed methodology has been tested for normal condition. A line outage condition has then been taken into consideration to test the proposed method under adverse conditions. The parameters of TCSC used are PTCSC = 0.482149p.u. and QTCSC = 0.01123p.u. & X = 0.002p.u.

Contingency analysis for the IEEE 30 bus system is performed and the details of the indices after every contingency are mentioned in Table 1.CI gives an estimate of the overall stress on the lines as a result of various contingencies. Fig, 5 shows the probability of severity of lines due to various line outages. It is observed from Fig. 5 that line 9-10 has the maximum probability of severity due to various contingencies.

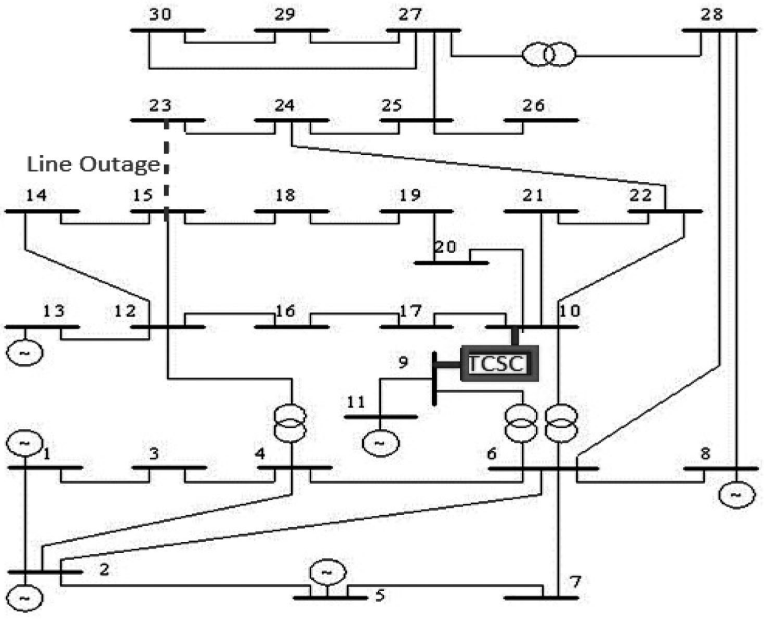


Fig.4 IEEE 30 bus system with15-23 contingency

Table 1.
Severity of lines for various line outages in decending order of CI

Line Outage		Severe line		LUF (p.u.) Value	Severe Line		FVSI (p.u.)	Severe line		CI (p.u.)
FB	TB	FB	TB		FB	TB		FB	TB	
15	23	3	4	0.3024	4	12	0.1497	9	10	0.2828
4	12	4	6	0.4236	9	10	0.1964	9	10	0.2569
28	27	3	4	0.3208	4	12	0.207	9	10	0.2326
4	6	4	12	0.2365	4	12	0.2202	4	12	0.2283
6	10	3	4	0.3055	4	12	0.168	9	10	0.2102
3	4	9	10	0.2397	4	12	0.1784	9	10	0.2047
12	15	4	6	0.3107	9	10	0.1492	9	10	0.1988
25	27	3	4	0.304	9	10	0.1658	9	10	0.1966
6	28	3	4	0.3105	4	12	0.164	9	10	0.1925
12	16	3	4	0.3025	4	12	0.1446	9	10	0.1922
15	18	3	4	0.303	4	12	0.1488	9	10	0.1896
12	14	3	4	0.3034	4	12	0.1503	9	10	0.1885
16	17	3	4	0.3024	4	12	0.1546	9	10	0.1877
24	25	3	4	0.3027	9	10	0.3589	9	10	0.1876
18	19	3	4	0.3026	4	12	0.152	9	10	0.187
27	30	3	4	0.3052	4	12	0.1548	9	10	0.1869
6	7	3	4	0.2666	4	12	0.144	9	10	0.1867
27	29	3	4	0.3046	4	12	0.1541	9	10	0.1866
14	15	3	4	0.3027	4	12	0.1521	9	10	0.1861
29	30	3	4	0.3033	4	12	0.153	9	10	0.1861
10	21	3	4	0.3089	4	12	0.1995	4	12	0.1853
23	24	4	6	0.2492	4	12	0.1495	9	10	0.1849
21	23	3	4	0.3028	4	12	0.1591	9	10	0.1833
6	9	3	4	0.3057	9	10	0.1596	9	10	0.1832
19	20	3	4	0.3044	4	12	0.1706	9	10	0.1818
10	22	3	4	0.3035	4	12	0.1534	9	10	0.1818
22	24	3	4	0.3035	4	12	0.1534	9	10	0.1818
10	20	3	4	0.3055	4	12	0.1764	9	10	0.1813
10	17	3	4	0.3044	4	12	0.1934	4	12	0.1783

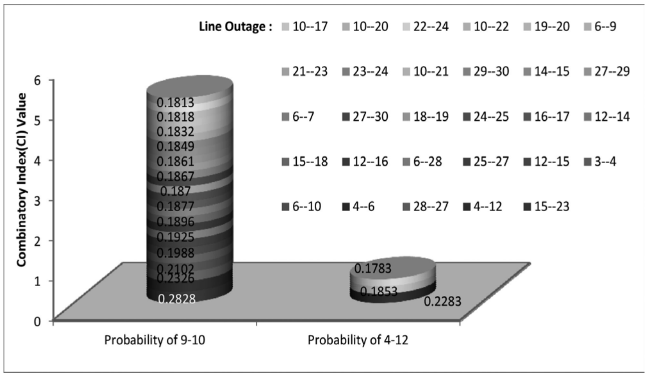
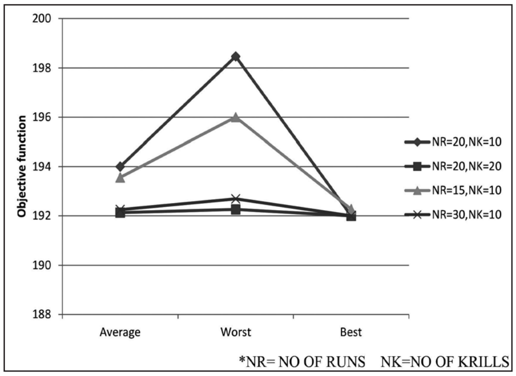


Fig. 5. CI values for various line outage of IEEE 30 bus system



*NR= NO OF RUNS NK=NO OF KRILLS

Fig. 6. Objective Function value with the Variation of Krill Herd Parameters

Different combinations of NR and NK have been used and the value of the objective function has been presented in Fig. 6. It is observed that NR = 20 = NK, which has been used for the study, gives the minimum average and best value of the objective function. Different combinations of weights have been compared in Table 2. It is observed that w1 = 0.7, w2 = 0.15, w3 = 0.15 gives the minimum value of the objective function equal to 192 p.u. Hence, the above values of the weights have been used for the study.

Table 2.
Different Combinations of Weights vs. objective function

solution number	*weight*			
	w1	w2	w3	f1
1	0.7	0.15	0.15	192
2	0.55	0.3	0.15	379.52
3	0.4	0.45	0.15	567
4	0.25	0.6	0.15	773.56
5	0.1	0.75	0.15	958.9
6	0.3	0.4	0.3	509.2

Table 3.
Comparison of Real and Reactive power losses with placement of TCSC in different locations under 15-23 contingency

S.No	*TCSC placement*		*Real power losses (MW)*	*Reactive power losses (MVAR)*
	From bus	*To bus*		
1	9	10	5.12	6.46
2	4	12	5.64	7.71
3	3	4	5.68	8.61
4	6	10	5.34	6.51

The real and reactive power losses for different placement locations of the TCSC device have been compared in Table 3. It is observed that line 9-10 is the best suitable location for the placement of TCSC. In table 4 different parameters of the system have been compared for different system conditions. It is observed that the severity of the system is increased due to the outage of line 15-23. Optimal placement and sizing of the TCSC using KH reduces the severity to a great extent.

Table 4.
Comparison of Results for without & with 15- 23 contingency, with optimal placement of TCSC at 9-10 and optimal sizing of TCSC using Krill Herd

S. No.	*Parameter*	*Values in different system state*			
		Without contingency	*With Contingency At 15-23*	*With optimal placement of TCSC*	*With optimal sizing of TCSC using KH*
1.	Active Power Loss(MW)	10.78	10.82	8.61	5.12
2.	Reactive Power Loss(MVAR)	29.98	30.21	16.16	6.46
3.	Voltage Deviation (p.u.)	2.3176	2.3295	0.5761	0.46593
4.	Overall LUF (p.u.)	4.5163	4.5319	4.1612	3.586
5.	Overall FVSI (p.u.)	2.5638	2.5672	1.6983	1.7847
6.	Overall CSI (p.u.)	3.54	3.5496	2.9297	2.6853

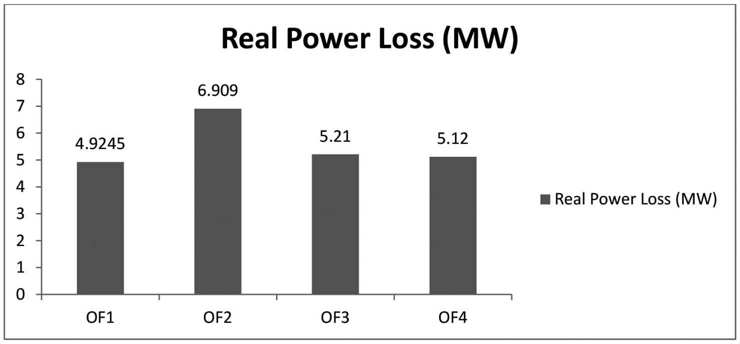


Fig.7 Real power loss vs. objective function

Various system parameters, namely, real power loss, generation cost, voltage deviation, and real power generation at each generator bus for individual objectives and multi-objective function have been compared in Fig. 7, 8, 9, and 10 respectively. It is observed that for a single objective function only one aspect of the system is reduced. A multi objective function is observed to be more suitable for catering to multiple aspects of the power system parameters.

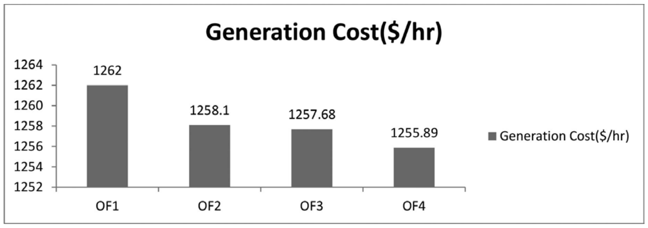


Fig. 8 Generation cost vs. objective function

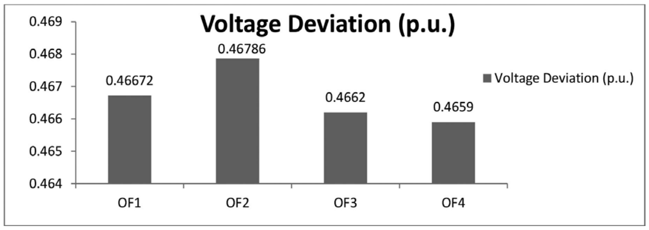


Fig. 9 Voltage deviation vs. objective function

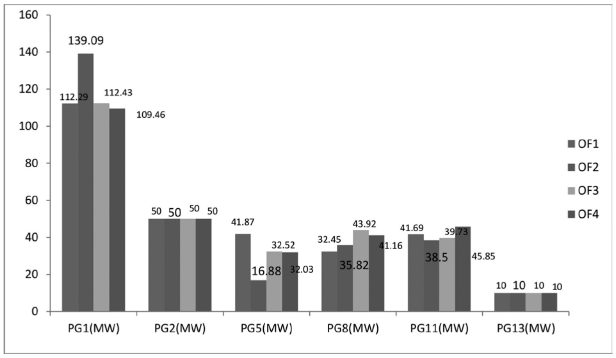


Fig. 10 Real power generation vs. objective function

*OF: Objective Function

OF1: only losses

OF2: only cost

OF3: only voltage deviation

OF4: multi objective function

Table 5.
Comparison of Real power losses, Cost & Voltage deviation for different line outages with TCSC placed at 9-10

Loading Condition	Parameters	KH	
		KH OPF without TCSC	KH OPF with TCSC
Without Contingency	TCSC Rating (p.u.)	-	0.002
	Total Real power generation(MW)	290.011	288.77
	Real power losses (MW)	6.618261	5.472154
	Total generation cost ($/hr)	1365.33	1254.32
	Voltage Deviation (p.u.)	1.835553	0.410978
With Contingency 15-23	TCSC Rating (p.u)	-	0.002
	Total Real power generation (MW)	289.23	288.5
	Real power losses (MW)	5.863573	5.121716
	Total generation cost($/hr)	1367.25	1255.89
	Voltage Deviation(p.u.)	1.724115	0.46593
4-12	TCSC Rating(p.u.)	-	0.002
	Total Real power generation (MW)	292.56	290.54
	Real power losses (MW)	9.173	7.157
	Total generation cost($/hr)	1373.39	1258.25
	Voltage Deviation(p.u.)	3.4644	0.36164
27-28	TCSC Rating(p.u.)	-	0.002
	Total Real power generation (MW)	293.385	291.69
	Real power losses (MW)	9.99	8.298
	Total generation cost($/hr)	1374.29	1364.62
	Voltage Deviation(p.u.)	3.3258	1.182
6-10	TCSC Rating(p.u.)	-	0.002
	Total Real power generation (MW)	294.08	288.86
	Real power losses (MW)	10.7	5.482
	Total generation cost($/hr)	1392.22	1258.19
	Voltage Deviation (p.u.)	2.5379	0.4229

The system parameters are also studied for some other contingencies and the result has been compared in Table 5.The voltage profile of the 30 bus system for OPF without and with TCSC has been compared in Fig.11. The voltage profile of the system improves greatly when Krill OPF is performed in the presence of TCSC.

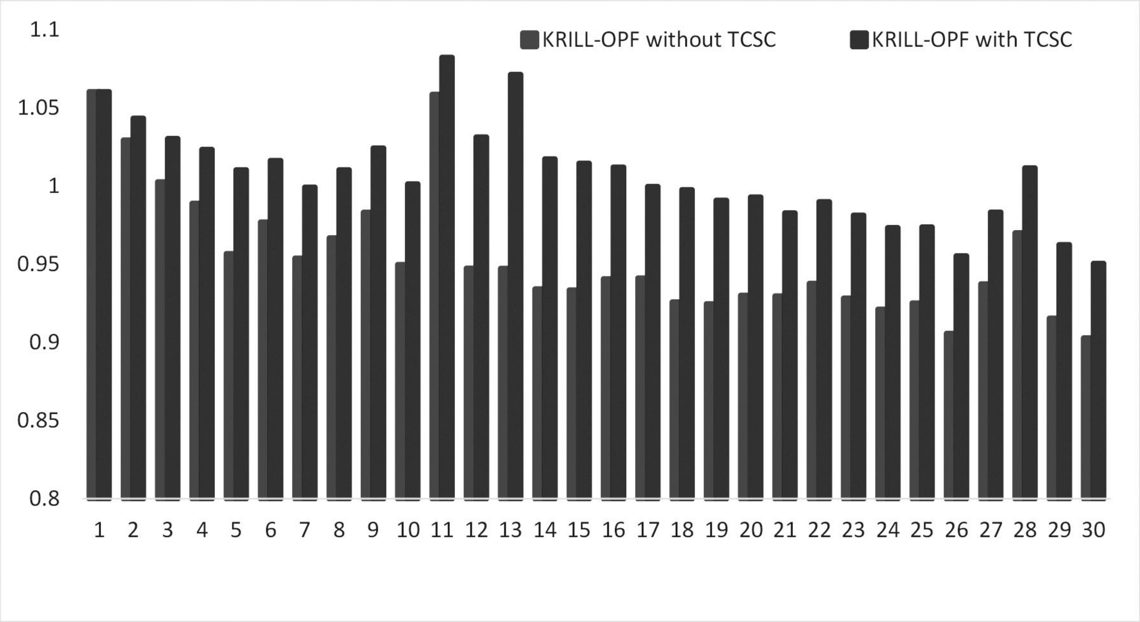


Fig. 11 Comparison of bus voltages for 30 bus system using Krill Herd OPF without & with TCSC

8. CONCLUSION

Contingency in power system is one of the most hazardous problems of power systems. Optimal power flow is an essential requirement for effective utilization of the power system resources. Effective use of FACTS devices can prove very beneficial in this respect. In this paper,

- Optimal power flow method in the presence of TCSC has been suggested for overcoming the instability issues of the power systems due to line outages and reduction of losses.
- A multi-objective function has been considered for the purpose. The multi-objective function consists of - voltage deviation, active power generation cost and transmission line loss.
- OPF in the presence of TCSC is found to be a very effective method of reducing the severity of the power system.
- Although TCSC is basically a series device the voltage profile of the system improves considerably.
- The proposed methodology has been tested for an IEEE 30 bus system.

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