Thyristor Controlled Series Compensator based Optimal Reallocation of Generators for Contingency Management

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ABSTRACT

Privatization of the power industry has made proper utilization of the available resources a compulsory requirement. 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 contingency analysis has been done using a new method, namely, rapid contingency ranking technique (RCRT). 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 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: Reallocation, Rapid Contingency Ranking Technique, TCSC, Krill Herd Algorithm, Voltage Stability.

1. INTRODUCTION

Due to the increase in the competition in the electrical industry, optimum usage of the available power has become obligatory. Congestion is the problem faced by transmission lines continuously because of carrying power at their extreme transmission limits and sometimes higher. Continuous overloading of the transmission lines can risk the security, reliability and stability of the power systems. 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]. Meta-heuristic methods are one of the most recent methods used for the OPF problem.

Nanda Kumar and Dhanasekaran 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 [2]. Vijay Kumar demonstrated the effect of TCSC on congestion of transmission lines by optimal power flow method using Genetic algorithm [3]. Rao and Gundavarapu have improvise the security of network under contingency condition with SVC [4]. Further, the impact of BAT and Firefly algorithms to find the best position and size of Static VAR Compensator (SVC) in a power system to improve voltage stability for a multi objective function [5] are compared.

Mangaiyarkarasi and Raja proposed a modified severity index and probability of severity based approach for the placement of Static VAR Compensator in order to improve the voltage stability [6]. Prasad and Mukharjee obtained the solution of optimal power flow of power systems with FACTS devices using Symbiotic Organisms Search (SOS) for a multi objective function [7]. Several authors applied metaheuristic algorithms for obtaining the optimal location of FACTS devices[8 - 9]. Menniti et al. [10] placed SSSC for improvement of available transfer capability using a index which is found to be a very efficient method for the assignment of FACTS devices.

Ya-Chin improved transmission system loading margin (LM) with the installation of SVC to a certain degree and reduced network expansion cost [11]. Nam and Van have increased the locational Marginal Price (LMP) in power market with optimal placement of SVC [12]. Shaheen 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 [13]. Mozzammi et al [14] have stressed on the use of FACTS devices and to prevent blackouts in power systems along with optimal rescheduling. 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

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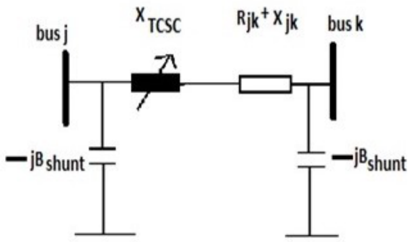

Fig.1: *Transmission line model with TCSC.*

be correctly placed in the system in order to enhance its effectiveness. Krill Herd Algorithm [15] is a latest algorithm and applied in different fields and is successful [16- 17].

In this paper, optimal reallocation of generators has been proposed for the management of contingency condition in the power systems. Sizing is carried using Krill Herd Algorithm and optimal power flow is obtained in the presence of TCSC. The contingency analysis has been performed using one of the latest methods, namely, rapid contingency ranking technique. The optimal reallocation of generators has been done with various objectives like reduction in voltage deviation, reduction in transmission line loss and reduction of fuel cost. The various limits taken as constraints during the optimization are real and reactive power generation values and voltage limits for buses. The results are presented and analysed with and without TCSC and compared to prove the effectiveness of the proposed method.

2. MODEL OF TCSC

Thyristor Controlled Series Compensator (TCSC) is connected in series in the transmission lines and operates 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, it is used for lead and lag compensation in the transmission lines. The following are the advantages of TCSC

- maintains balance in the reactive power,
- reduces the damped oscillations in the system,
- Improves the stability of the system post contingency.
- Improves the power transfer boundaries of the transmission corridors to some degree.

The TCSC model between the buses j and k is shown in Figure 1. The reactive constraint on the TCSC is given as $-0.8X_{jk} \leq X_{TCSC} \leq 0.2X_{jk}$

3. PROPOSED COMBINED INDEX

Line contingency analysis consists of removal of a line from the network and analyzing the stability of the system. The above type of analysis is a typical case of n-1 contingency analysis. Various methods are available for analyzing a system in contingency condition. Most of the methods available in literature are either very complicated or cumbersome. The method used for contingency analysis in this study is known as Rapid Contingency Ranking technique suggested by Mishra and Gundavarapu [18]. The authors, in their study, have shown that all contingencies do not cause severity in the system, hence may be discarded from the contingency analysis study. The method comprises analyzing only a few selective lines for contingency. On the basis of this method lines connected to only slack bus, generator buses, load bus with maximum number of lines are selected for the analysis of line contingency.

A combinatory index (CI) formulated by of two different indexes (by taking one index of each category) for the optimal location of FACTS devices. Since TCSC is a series device, only line indices have been considered in the study. A combined index is formulated using LUF and FVSI indices as given in equation (1).

$$CI = w_1 \times I_1 + w_2 \times I_2 \tag{1}$$

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 and given by equation (2)

$$I_1 = \frac{MVA_{ij}}{MVA_{ij}^{\max}} \tag{2}$$

Maximum MVA rating of the line (i-j) is $MVA_{ij(max)}$ and the actual MVA rating is MVA_{ij}. The estimate of the percentage of line being utilized is given by LUF. The voltage stability of a given bus under any loading conditions is given by Fast Voltage Stability Index Factor (FVSI) and given by equation (3)

$$I_2 = 4\frac{Z^2Qj}{Vi^2X} \tag{3}$$

Where, Z is the impedance of line, X is the line reactance, V_i is the voltage at the sending end. Q_j is the reactive power at the receiving end. Both LUF and FVSI have stable region, when the value of the index is less than 1. Using the functions fuel cost, real power loss and voltage deviation a multi-objective function is formulated for optimal tuning of generators.
Objective function

$$\min F = \min \left(w1 * F1 + w2 * F2 + w3 * F3\right) \tag{4}$$

Where, F1 is the Fuel cost given by

$$F1 = \min\left(\sum_{i=1}^{ng}\left[a_i + b_iP_{Gi} + C_iP_{Gi}^2\right]\right) \tag{5}$$

Parameters	Quantity
Number of krill's(NK)	20
Number of runs(NR)	20
Number of iterations	50
Foraging speed (Vf)	0.02
Maximum Diffusion Speed Dmax	0.005
Maximum Induced Speed Nmax	0.01

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

$$F2 = \min\left(\sum_{i=1}^{ntl} real\left(S_{jk}^{i} + S_{kj}^{i}\right)\right) \quad (6)$$

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

$$F3 = \min(VD) = \min\left(\sum_{k=1}^{Nbus}\left|V_k - V_k^{ref}\right|^2\right) \quad (7)$$

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

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

Motion induced by other krill individuals: The movement of a krill individual is mainly dependent on the neighbouring krill individuals and the mutual effects between them.

Foraging Motion: The foraging motion mainly depend upon two main factors:

The food location.

The previous experience about the food location.

Physical Diffusion: it is basically, the random diffusion of the krill individuals in the solution space. This motion includes two components: a maximum diffusion speed and oriented vector.

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 ithkrill individual) is determined below:

$$\frac{dX_i}{dt} = N_i + F_i + D_i \quad (8)$$

Where, N_i is the motion induced on ithkrill individual due to the other krill individuals, F_i is the foraging motion and D_i is the random diffusion. The procedure followed for Krill Herd is mentioned in Figure 2. The flowchart showing the steps followed to perform the optimal power flow in the presence of TCSC has been shown in Figure 3.

5. RESULTS AND DISCUSSION

The proposed methodology has been implemented on an IEEE 30 bus system as shown in Figure. 4. A line contingency is considered to test the effectiveness of the proposed method for in adverse condition. The parameters of TCSC used are $P_{TCSC} = 0.482149$ p.u. and $Q_{TCSC} = 0.01123$p.u. and $X = 0.002$ p.u. Contingency analysis by traditional method is performed for the IEEE 30 bus system 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. In Table 2 the contingency analysis by RCRT technique is performed. The most severe line detected by this technique is line 4-12 for line 9-10 contingency, which is the same as that obtained by the traditional method. It is observed that the number of lines required to be analysed by this method is much less in comparison to the traditional method.

Different combinations of number of runs (NR) and Number of Krills (NK) have been used and the value of the objective function has been presented in Figure 5. It is observed that NR = 20 = NK, gives the least average and best value of the objective function.

Different combinations of weights are compared in Table 3. $w_1 = 0.7$, $w_2 = 0.15$, $w_3 = 0.15$ gives the least objective function value equal to 192 p.u. Hence, the above values of the weights have been used for the study. The real and reactive power losses for different placement locations of the TCSC device have been compared in Table 4. It is observed that line 4-12 is the best suitable location for the placement of TCSC. In Table 5 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 9-10. Optimal placement and sizing of the TCSC using KH reduces the severity to a great extent. Various system parameters, namely, real power loss (OF1), generation cost (OF2), voltage deviation (OF3), and real power generation at each generator bus for individual objectives and multi-objective function (OF4) have been compared

Table 1: *Severe lines for various line outages in descending order of CI by traditional method.*

Line Outage		Severe line		LUF Value	Severe Line		FVSI	Severe line		CI
FB	TB	FB	TB		FB	TB		FB	TB	
9	10	3	4	0.3289	6	10	0.4292	4	12	0.2992
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
FB - From Bus, TB - To Bus, LUF - Line Utilisation Factor, FVSI - Fast Voltage Stability Index, CI - Combinatory Index										

Table 2: *Contingency Analysis by RCRT Technique*

Line Outage		Severe line		LUF Value	Severe Line		FVSI	Severe line		CI
FB	TB	FB	TB		FB	TB		FB	TB	
9	10	3	4	0.3289	6	10	0.4292	4	12	0.2992
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
6	28	3	4	0.3105	4	12	0.164	9	10	0.1925
6	7	3	4	0.2666	4	12	0.144	9	10	0.1867
10	21	3	4	0.3089	4	12	0.1995	4	12	0.1853
6	9	3	4	0.3057	9	10	0.1596	9	10	0.1832
10	22	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

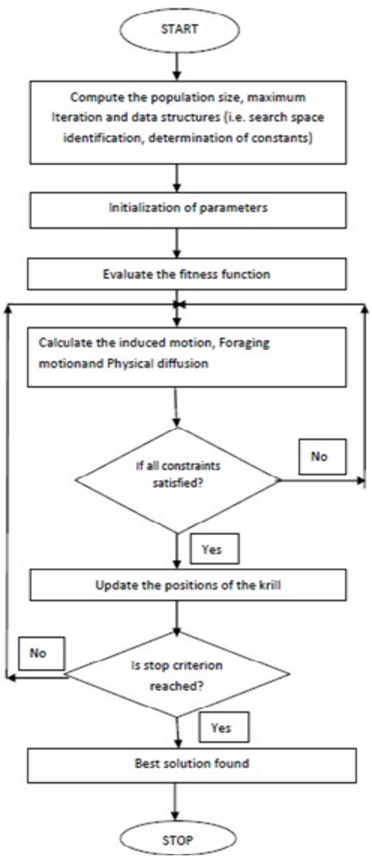

Fig.2: *Procedure for optimization using Krill Herd Algorithm.*

Table 3: *Analysis for the determination of weights*

SOLUTION NUMBER	WEIGHT			OBJECTIVE FUNCTION
	W_1	W_2	W_3	F_1
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

in Figures 6, 7, 8 and 9 respectively. It is observed that for a single objective function only one aspect of the system is reduced. When a multi-objective function is chosen, a good solution is observed for all the objectives in comparison to the single-objective function. Thus, a multi objective function is observed to be more suitable for catering to multiple aspects of the power system parameters.

The voltage profile of the 30 bus system for OPF without and with TCSC has been compared in Figure 10. The voltage profile of the system improves greatly when Krill OPF is performed in the presence

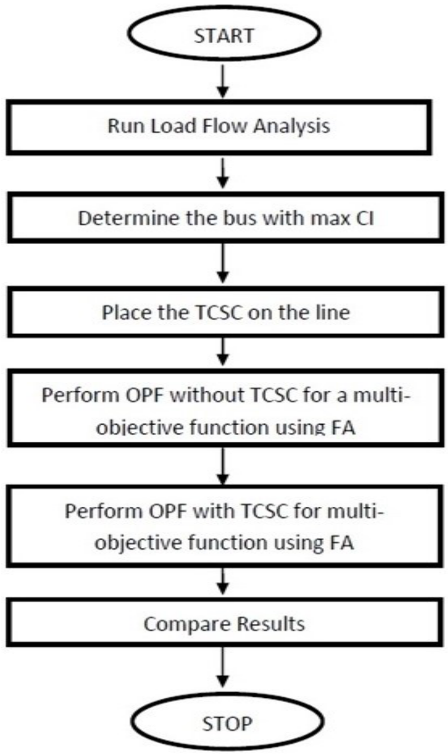

Fig.3: *Flowchart showing the steps followed for the implementation of the proposed methodology.*

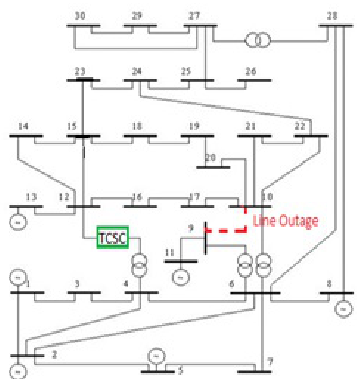

Fig.4: *IEEE 30 bus system with 9-10 contingency.*

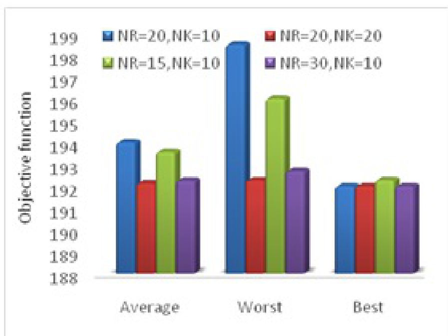

Fig.5: *Krill Herd parameters vs. objective function.*

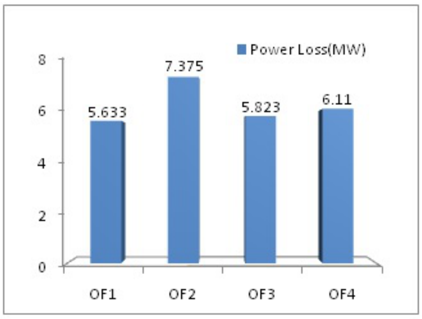

Fig.6: *Real power loss vs. objective function.*

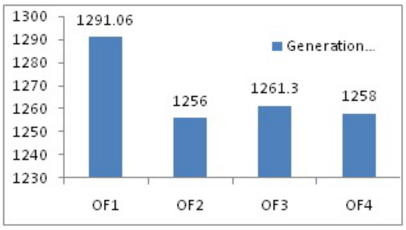

Fig.7: *Generation cost vs. objective function.*

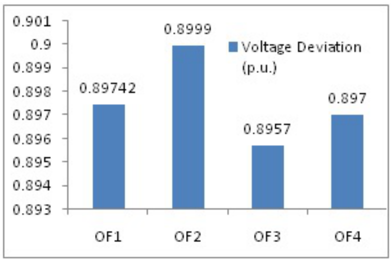

Fig.8: *Voltage deviation vs. objective function.*

Table 4: *Placement of TCSC in different locations for line 9-10 contingency*

TCSC placement		Real power	Real power
From bus	To bus	losses (MW)	(MVAR)
4	12	6.1	18.7
6	10	6.1	19.51
3	4	6.788	19.95
4	6	6.71	21.93

of TCSC. The values of real power loss and reactive power loss for line 9-10 contingency for different conditions have been shown in Figure 11 and 12 respectively.

The system parameters are also studied for some other contingencies and the result has been compared in Table 6. It is observed that the values of real power generation, real power loss, and total generation cost and voltage deviation are highest for line 9-10 contingency. Thus it is found that the composite index used gives an accurate result. The real power generation of the system and at individual generators, real and reactive power loss, voltage deviation and real power generation cost for KH-OPF without TCSC, GA-OPF without TCSC, KH-OPF with TCSC and GA-OPF with TCSC have been compared in Table 7. It is observed that Krill Herd Algorithm is much more suitable for the multi-objective optimization problem chosen in comparison to GA.

6. CONCLUSION

Contingency in power system is one of the most hazardous problems of power systems. Optimal power flow is a crucial need for effective exploitation of the resources of power system. Effective use of FACTS devices can prove very beneficial in this respect. Optimal generation reallocation with Optimal placement of TCSC using combined index and Optimal tuning of TCSC using Krill Herd Algorithm is the reason behind the success of the proposed method. In this paper,

- The RCRT technique for contingency analysis has been verified and compared with the traditional method.
- Optimal power flow method in the presence of TCSC is proposed to overcome the instability issues in the power systems due to line outages and reduction of losses.
- OPF in the presence of TCSC is found to be a very effective method of reducing the severity of the power system.

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Table 5: *Placement of TCSC in different locations for line 9-10 contingency*

Parameter	Values in different system state			
	Without contingency	With Contingency At 9-10	With optimal placement of TCSC	With optimal sizing of TCSC using KH
Active Power Loss (MW)	10.78	13.22	9.39	6.1163
Reactive Power Loss (MVAR)	29.98	51.21	23.82	18.706
Voltage Deviation (p.u.)	2.317	4.0573	0.90	0.89
Overall LUF	4.516	4.904	4.382	3.9215
Overall FVSI	2.563	3.8843	2.0534	2.2075
Overall CI	3.54	4.3942	3.2177	3.0645

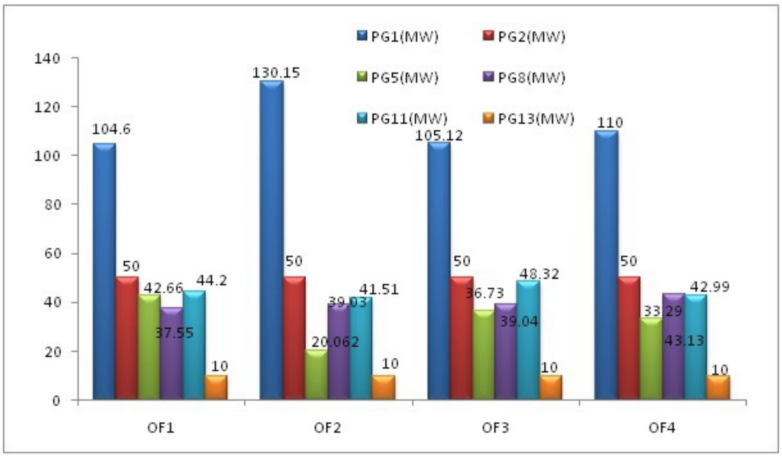

Fig.9: *Real power generation vs. objective function.*

Table 6: *Comparison of objective functions for different contingencies with TCSC placed at 4-12*

Loading Condition		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 ($/hr.)	1365.33	1254.32
	Voltage Deviation (p.u.)	1.835553	0.410978
With Contingency 9-10	TCSC Rating (p.u.)	-	0.002
	Total Real power generation(MW)	292.6	289.41
	Real power losses (MW)	9.221813	6.11634
	Total generation cost ($/hr.)	1376.7	1258
	Voltage Deviation (p.u.)	3.715624	0.897987
15-23	TCSC Rating (p.u.)	-	0.002
	Total Real power generation(MW)	290.1	288.85
	Real power losses (MW)	6.719	5.4640
	Total generation cost ($/hr.)	1365.78	1255
	Voltage Deviation (p.u.)	1.8292	0.46420
27-28	TCSC Rating (p.u.)	-	0.002
	Total Real power generation(MW)	292.26	291.04
	Real power losses (MW)	8.874	7.66
	Total generation cost ($/hr.)	1366.51	1255.18
	Voltage Deviation (p.u.)	4.3264	1.174

Table 7: *Comparison of objective functions for different contingencies with TCSC placed at 4-12*

System condition	Parameter		KH-OPF without TCSC	GA-OPF without TCSC	KH-OPF with TCSC	GA-OPF with TCSC
With 9-10 line contingency	Real power generation (MW)	PG1	122.26	130.2206	110	167.0161
		PG2	50	27.3374	50	45.707
		PG5	39.56	27.3348	33.29	28.1988
		PG8	31.75	21.3279	43.13	10.1949
		PG11	39.03	84.8224	42.99	34.5105
		PG13	10	3.9926	10	6.6718
	Total Real power generation (MW)		292.6	295.0357	289.41	292.2991
	Real power losses (MW)		9.221813	11.6357	6.11634	8.8992
	Reactive power loss (MVAR)		41.89	79.76	18.7	27.84
	Total generation cost ($/hr.)		1376.7	1380	1258	1267.6
	Voltage Deviation (p.u.)		3.715624	4.6428	0.897987	0.9089

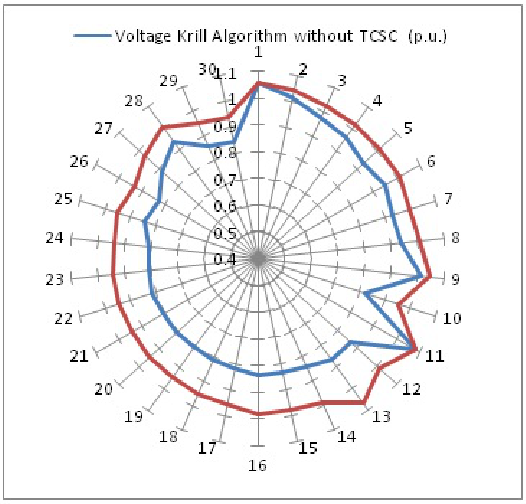

Fig.10: *Comparison of bus voltages for 30 bus system using Krill Herd OPF without and with TCSC.*

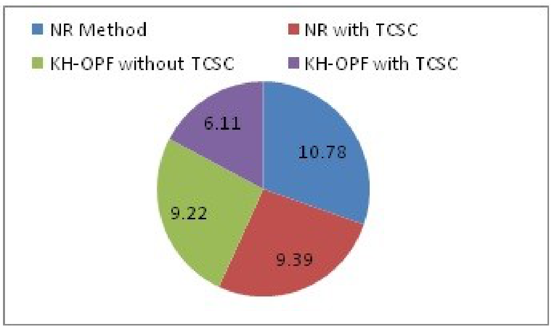

Fig.11: *Comparison of Active Power Losses for Different Methods under 9-10 contingency.*

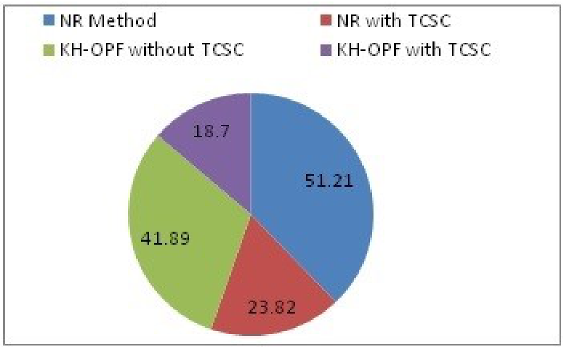

Fig.12: *Comparison of Reactive Power Losses for Different Methods under contingency.*

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