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A Combinatory Index based Optimal Reallocation of Generators in the presence of SVC using Krill Herd Algorithm

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Abstract: In the new competitive electric world, it is compulsory for the electrical industry to make effective utilization of the available resources. Optimal tuning of generators and implementation of FACTS devices has been found to be very effective in this regard. In this paper, a combination strategy of optimal tuning of generators using Krill herd (KH) algorithm in the presence of Static VAR Compensator (SVC) has been proposed.A combinatory index (CI), which is a combination of Vi/Vo index and L-index, has been formulated and verified for obtaining the optimal location of SVC. A multi objective function has been formulated for tuning the generators. The results obtained after performing Optimal Power Flow on an IEEE 30 bus system for normal loading and for severe system conditions due to line outage in the presence of SVC using KH has been verified with that of GA, to prove the effectiveness of the chosen methodology.

Keywords: Optimal Reallocation; Static VAR Compensator; Krill Herd Algorithm; Voltage Stability

Abbreviations

FACTS	Flexible AC Transmission System
OPF	Optimal Power Flow
SVC	Static VAR Compensators
KH	Krill Herd
GA	Genetic Algorithm
CI	Combinatory Index

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1 Introduction

There is a high increase in the complexity of power systems of today's times due to deregulation of the electric power market. Due to the pronounced increase in the competition, optimal utilization of the existing power supplies has become mandatory. On the other hand, due to increase in power flow the transmission lines are constantly facing a problem of congestion because of carrying power at their maximum transmission limits and sometimes higher. Continued congestion in the lines can pose a great risk to power system security, reliability and stability. FACTS devices have been suggested by researchers for various power system related issues [1]. Proper placement and tuning of the devices are necessary for utilizing the benefits of the devices to the utmost level. Various metaheuristic methods [2] have been used of late for placement and tuning of the FACTS devices for various purposes.

Several authors have used Genetic algorithm and its variants for obtaining the optimal location of FACTS devices and have applied OPF technique for various objective functions [3-5]. Ya-Chin et al. [6] implemented Particle Swarm optimization method for a multi-objective function using SVC to improve transmission system loading margin (LM) to a certain degree and reduce network expansion cost. Rao et al. [8] 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 find the optimal location and size of Static VAR Compensator (SVC) in a power system for a multi objective function to improve voltage stability. Khandani et al. [10] improved the voltage profile by optimal placement of Static VAR Compensator (SVC) using a novel hybrid Genetic Algorithm and Sequential Quadratic Programming (GA-SQP) method. Phadke et al. [10] have used a fuzzy based index for the effective location of SVC for a multi-objective function. Jirapong et al. [11] determined the optimal placement of multi-type FACTS devices with new hybrid evolutionary algorithm (HEA) for simultaneously maximizing the total transfer capability (TTC) and minimizing system real power losses of power transfers between different control areas. Roselyn et al. [12] has used multi-objective GA to solve the OPF problem to improve voltage stability of the system.

Mishra et al. [13] proposed the placement of IPFC based on Composite Severity Index (CSI). CSI is a combination of line stability index and real power performance index for management of contingency. The IPFC was then tuned using Differential Evolution (DE). CSI is found to be a more accurate measure of severity in comparison to the individual indices. Voltage instability has been quoted as the major indication of power system instability and insecurity. Parallel FACTS devices are apt at resolving the voltage related issues in the power systems. SVC is a parallel FACTS device; hence it is a suitable choice to overcome the voltage instability problem. Optimal placement and tuning of SVC is important for proper use of the device. Index-based method of placement of the FACTS device has been found to be a simple and effective method. L-index and Vi/Vo index can be a very effective combination to rank the vulnerable buses. Optimal tuning of the generators and FACTS devices is very well achieved with metaheuristic algorithm. Krill Herd algorithm [14] was introduced in the year 2012 and has been found to be very successful.

In this paper, a metaheuristic method, namely, Krill herd algorithm has been used for the optimal power flow in the presence of SVC. A Combinatory Index (CI), composing of L-index and Vi/Vo has been formulated to obtain the optimal location of the SVC device. The optimal tuning of generators has been done for a multi-objective function. The multiple objectives are reduction in voltage deviation, reduction of fuel cost and reduction in transmission line loss. The constraints taken are real and reactive power generation values and voltage limits for buses during the optimization. The results obtained by OPF in the presence of Krill-herd algorithm has been compared with Genetic algorithm. The results of optimal tuning without and with SVC have been compared to prove the effectiveness of the proposed method.

2 Proposed Combinatory Index

A combinatory index is formulated using L-index and Vi/Vo index given in equation (1).

$$CI = Z_1 \times I_1 + Z_2 \times I_2 \tag{1}$$

Where, Z_1 and Z_2 are the weighting factors. The values of Z_1 and Z_2 are 0.5 respectively.

I_1 is the L-Index given by equation (2)

$$I_1 = \left| 1 - \sum_{i=1}^{g} F_{ji} \frac{V_i}{V_j} \right| \tag{2}$$

L-index I_1 has value between 0 to 1. Lower is the value of the index enhanced is the stability of the system.
F_{ji} which is one of elements in F-matrix is Load participation factor. F-matrix is the sub-array of partial inverse for node admittance matrix. F_{ji} represents complex elements. V_i represents voltage magnitude at bus I and V_j represents voltage magnitude at bus j.
Index I_2 is the V_i/V_o index given by equation (3) in whichV_i is the reference voltageand V_o is the output voltage.

$$I_2 = 1 - \frac{V_i}{V_o} \tag{3}$$

3 Problem Formulation

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

$$\text{Min } F = \text{Min } (w1 * F1 + w2 * F2 + w3 * F3) \tag{4}$$

Where, F1 is the Fuel cost given by

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

Ng is the number of generators in the power system and a, b, c are the fuel cost coefficients. The value for the coefficients for various generators has been mentioned in Table 1.

Table 1: Values of a, b, c for fuel cost

Generator bus No.	a (p.u.)	b (p.u.)	C (p.u.)
1	0.005	2.45	105
2	0.005	3.51	44.1
5	0.005	3.89	40.6
8	0.005	3.25	0
11	0.005	3	0
13	0.005	2.45	105

F2 is the Real power loss

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

Where number of transmission lines is ntl and the total complex power flows from bus j to bus k in line I is S_{jk}.

F3 is the Voltage deviation

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

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.

Power Balance Constraint

$$\sum_{i=1}^{N} P_{Gi} = \sum_{i=1}^{N} P_{Di} + P_L \tag{8}$$

Where i=1, 2, 3, ...N and N = no. of. Bus, P_L is the active power loss of the system.

Voltage balance constraint

$$V_{Gi}^{\min} \leqslant VGi \leqslant V_{Gi}^{\max} \tag{9}$$

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

Generation limit real power

$$P_{Gi}^{\min} \leqslant P_{Gi} \leqslant P_{Gi}^{\max} \tag{10}$$

Where, G_i=1, 2, 3, ...ng

P_{Gi} is the active power generated at bus i, P_{Di} is the power demand at bus i. The voltage limits of the generator buses are taken between 0.9 p.u and 1.1 pu.

4 Proposed Methodology

The steps involved for minimization of objective function using SVC are listed below in Fig. 1.

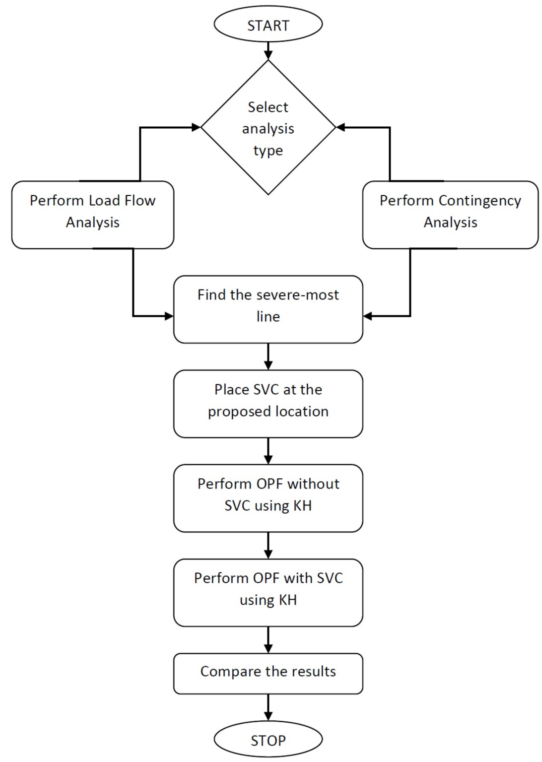

Figure 1: Proposed methodology for multi-objective optimization using KH

5 Results and Discussion

The proposed methodology has been tested on an IEEE 30 bus system shown in Fig. 2. 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 SVC used are Q_{SVC}= 0.06789 p.u. and B = 0.06789 p.u.The CI value at each bus is calculated and the results have been presented in Fig. 3. It is observed that Bus no. 30 has maximum CI of 0.10495 p.u. Hence, Bus 30 is the weakest bus of the system. Different combinations of NR and NK have been used and the value of the objective function has been presented in Fig. 4. 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.

5.1 OPF for Normal Condition

Different combinations of weights of the objective function have been used and the objective function values have been observed and tabulated in Table 2. It is observed that w1 = 0.7, w2 = 0.15, w3 = 0.15 gives the minimum value of the objective function and hence has been chosen for the study.

The voltage profile for OPF without and with SVC has been compared in Fig. 5. OPF in the presence of SVC improves the voltage at the buses. The real power generation of the system and at individual generators, real and reac-

Table 2: Non dominant solutions for Cost, Losses and Voltage deviation objectives krill

SOLUTION NUMBER	WEIGHT			
	W1	W2	W3	F1
1	0.7	0.15	0.15	209.7
2	0.55	0.3	0.15	420.4
3	0.4	0.45	0.15	618.5
4	0.25	0.6	0.15	846.4
5	0.3	0.4	0.3	550

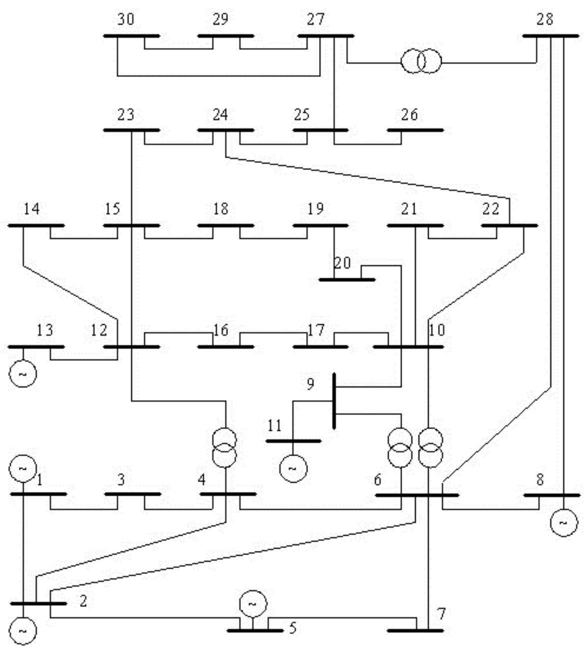

Figure 2: Typical IEEE 30 bus system

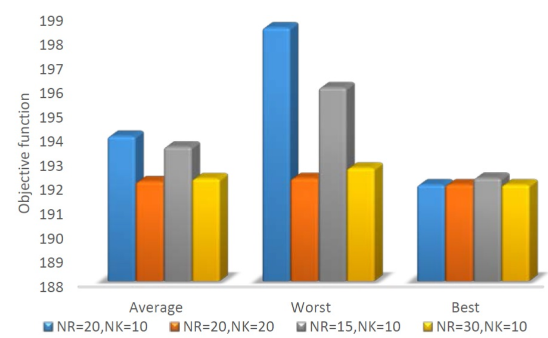

Figure 4: Objective Function value with the Variation of Krill Herd Parameters
*NR= NO OF RUNS NK=NO OF KRILLS

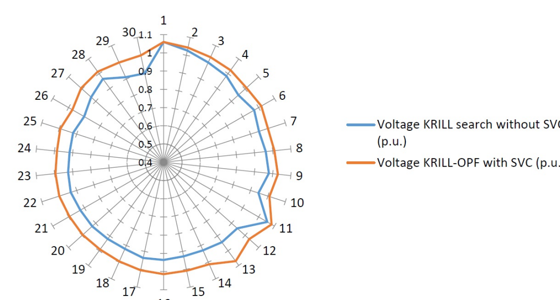

Figure 5: Comparison of voltage magnitude of optimal power flow without and with SVC

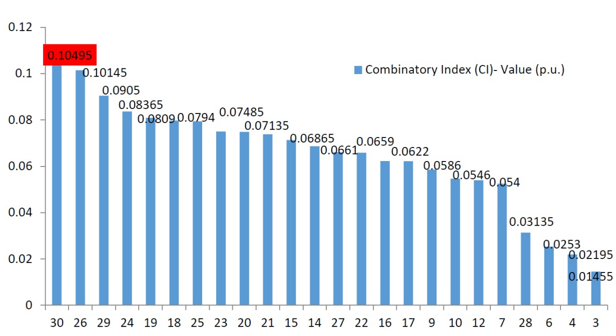

Figure 3: Weak bus in IEEE 30 bus System

tive power loss, voltage deviation and real power generation cost for KH-OPF without SVC, GA-OPF without SVC, KH-OPF with SVC and GA-OPF with SVC have been compared in Table 3. It is observed that krill herd is much more suitable for the multi-objective optimization problem chosen in comparison to GA. Also, it is observed that OPF in the presence of SVC is much more effective in comparison to without SVC. Thus, the device proves to be highly effective for the optimization of the generators. The performance of a single objective function has been compared with multi-objective function in Table 4. A multi-objective function is found to be more suitable for improvement multiple parameters of the power system.

Table 3: Comparison of OPF solution for 30 bus system without and with SVC using Krill-OPF

S.No	Parameter		Krill-OPF without SVC	GA-OPF without SVC	Krill-OPF with SVC	GA-OPF with SVC
1	Real power generation (MW)	PG1	122	126.6562	119.62	165.9437
		PG2	50	27.3374	50	45.707
		PG5	26.47	27.3348	32.7	28.1988
		PG8	40.22	21.3279	37.45	10.1949
		PG11	42	84.8224	39	34.5105
		PG13	10	3.9926	10	6.6718
2	Total real power generation (MW)		290.69	291.4713	288.8	291.2267
3	Total real power loss (MW)		6.618	8.0713	5.42	7.8267
4	Total reactive power loss (MVAR)		19.16	35.35	8.632	15.55
5	Voltage Deviation (p.u.)		1.8355	2.5	0.2852	0.2853
6	Total real power generation cost ($/h)		1355.33	1366.9	1258.37	1283.2

Table 4: Comparison of different objective using different objective functions using Krill Algorithm without SVC

Variables	OF1	OF2	OF3	OF4
PG1(MW)	184.76	147.4329	154.81	122
PG2(MW)	50	50	29.25	50
PG5(MW)	17.36347	24.44	44.66	26.47
PG8(MW)	12.86	22.79	23.78	40.22
PG11(MW)	14.5	37.67	29.03	42
PG13(MW)	10	10	10	10
Total real power generation (MW)	289.4	292.34	291.5443	290.69
Total real power generation cost($/h)	1407	1360	1380.9	1365.33
Active power Loss (MW)	6	8.9451	8.145	6.618
Voltage deviation (p.u.)	2.5156	2.1545	1.8125	1.8355
Objective function	6 (MW)	1360($/h)	1.8125(p.u.)	209

*OF- Objective Function OF1 – only losses OF2- only cost OF3- only voltage deviation OF4 – multi objective function

5.2 OPF for Contingency Condition

Contingency analysis for the IEEE 30 bus system is performed and it is observed that removal of line 27-28 causes maximum stress to the system indicated by the maximum CI value of 0.3998 p.u as shown in Table **??**. It is also observed that for the above considered contingency, bus number 30 is the weakest bus. In order to verify whether the bus indicated by CI is actually the best location for the placement of SVC, the device has been placed at various other locations and the results have been presented in Table 6. It is observed that the real and reactive power loss is reduced to the maximum extent by the placement of SVC at the location indicated by CI. Hence, $n-1$ contingency for line 27-28 and SVC at bus 30 has been considered for the study.

Table 7 compares the value of various parameters without contingency and with contingency, with SVC placement and sizing. It is observed that, the CI value after OPF is reduced to the maximum extent when optimal placement and sizing of the SVC has been performed. The system parameters for individual objectives and multi-objective function have been observed in Table 8. A multi objective function is observed to be more suitable for catering to the various aspects of the power system parameters.

Various parameters of the power system have been compared for without contingency and with contingency condition for OPF without and with SVC in Table 9. The OPF with SVC is observed to be the optimal solution in both normal and contingency condition. KH shows a better performance in comparison to GA for the multi-objective function. In Fig. 6, the multi-objective function values have been compared; KH seems to give a lower value of 193.923

Table 5: Lj,Vi/v0 and CSI values of for some line outage of IEEE 30 Bus Test System

Line outage FB-TB	Bus no with max. (Lj)	Lj Value (p.u.)	Bus no. with max. (1-Vi/V0)	(1-Vi/V0) (p.u.)	Bus no with max (CI)	CI (p.u.)
2 to 5	30	0.1209	30	0.2483	30	0.1766
27 to 28	30	0.4522	30	0.3474	30	0.3998
27 to 29	29	0.1613	29	0.1761	29	0.1687
27 to 30	30	0.1793	30	0.189	30	0.1841
29 to 30	30	0.1163	30	0.142	30	0.1291
8 to 28	30	0.0891	30	0.1223	30	0.1057
6 to 28	30	0.1298	30	0.1583	30	0.1440

Table 6: Comparison of real and reactive power losses with placement of SVC in different locations under 36th line (27-28) Contingency

SVC placement Bus no.	Real power losses (MW)	Reactive power losses(MVAR)
30	6.119	7.960
29	7.431	8.806
27	6.501	9.233
25	7.046	11.781

Table 7: Comparison of results without contingency, with contingency at line (27-28)

Parameter	Values in different system state			
	Without contingency	With Contingency At 27-28	With optimal placement of SVC	With optimal sizing of SVC using Krill Algorithm
Active Power Loss(MW)	10.78	15.36	10.64	6.596068
Reactive Power Loss(MVAR)	29.98	46.5	22.69	6.6361
Lj of Severe bus (p.u.)	0.0895	0.4522	0.0721	0.058468
(1-Vi/V0) of Severe bus (p.u.)	0.1204	0.3474	0.0496	0.030961
CI of Severe bus (p.u.)	0.10495	0.3998	0.06085	0.043747
Voltage Deviation (p.u.)	2.3176	4.0516	0.4252	0.29268
Overall Lj (p.u.)	1.2089	3.1974	0.6179	0.500657
Overall (1-Vi/V0) (p.u.)	1.8984	3.5476	0.3801	0.280652
Overall CI (p.u.)	1.55365	3.3725	0.499	0.390655

p.u. in comparison to that of GA which is 199.7049 p.u. The voltage profile in the presence of KH-OPF SVC improves to a great extent.

6 Conclusion

Optimal power flow is an essential requirement for effective utilization of the various components of the power system. Optimal power flow method in the presence of SVC has been proposed in this paper for overcoming the voltage instability issues of the power systems and reduction

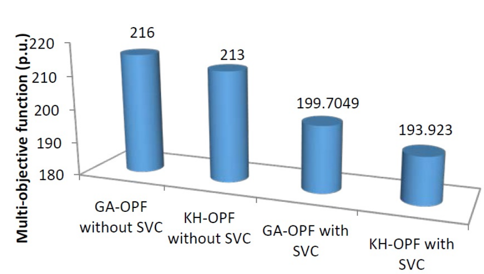

Figure 6: Comparison of objective function values with contingency for different methods

Table 8: Comparison of different objective using different objective functions using Krill Algorithm with SVC (SVC located at Bus no 30)

Variables	OF1	OF2	OF3	OF4
PG1(MW)	99.064	103.748	108.856	133.935
PG2(MW)	50.0	50	50	50
PG5(MW)	43.713	29.6528	37.461	26.79
PG8(MW)	40.988	47.098	43.029	34.4
PG11(MW)	44.354	48.234	39.287	34.85
PG13(MW)	10	10	10	10
Total real power generation (MW)	288.119	288.7328	288.633	289.975
Total real power generation cost($/hr)	1263.59	1255.94	1261.07	1261.7
Active power Loss (MW)	4.7213	5.3343	5.2353	6.596
Voltage deviation (p.u.)	0.29206	0.2920	0.29215	0.2926
Objective function value	4.7213(MW)	1255.9($/hr)	0.29215(p.u.)	193.923

*OF- Objective Function OF1 – only losses OF2- only cost OF3- only voltage deviation OF4 – multi objective function

Table 9: Comparison of Real power losses, Cost and Voltage deviation for normal & line outage with SVC placed at bus number 30

Condition	Parameters	KH OPF without SVC	GA OPF without SVC	KH OPF with SVC	GA OPF with SVC
Without Contingency	SVC Rating (p.u.)	–	–	0.06789	0.0682
	Total Real power generation (MW)	290	291.4713	288.8	291.2267
	Real power losses (MW)	6.61	8.0713	5.42	7.8267
	Total generation cost ($/hr)	1355.3	1366.9	1258.3	1283.2
	Voltage Deviation (p.u.)	1.835553	2.5013	0.285292	0.2853
27 to 28 Line outage	SVC Rating (p.u.)	–	–	0.087	0.1527
	Total Real power generation (MW)	293.17	297.5454	289.97	293.493
	Real power losses (MW)	9.79	14.1453	6.596	10
	Total generation cost ($/hr)	1374.06	1390.5	1261.74	1283.9
	Voltage Deviation (p.u.)	3.291027	4.9205	0.29268	0.3835

of losses. A Combinatory Index has been formulated for obtaining the location for the SVC. The results obtained by CI have been verified, in order to confirm that the index gives the optimal position for the FACTS device. A multi-objective function has been considered, viz., reduction in voltage deviation, fuel cost and transmission line loss. Krill Herd algorithm has been used to optimize the generators for the multi-objective function that was considered.It is found from the results that SVC is very efficient in improving the voltage profile of the system. Optimal reallocation of the generators and tuning of the device with Krill Herd algorithm further improves the voltage profile. The combinatory index indicates an improvement in voltage stability after optimal power flow has been performed in the presence of SVC. It has been proven from the results that KH gives superior results in comparison to GA for the chosen problem.OPF in the presence of SVC has been found to be an optimal solution for improvement of the power system performance as depicted by the improvement in the values of the power system parameters.

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