Firefly Algorithm based Optimal Power Flow for Sizing of Thyristor Controlled Series Capacitor to enhance line based voltage stability

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Abstract. *Reactive Power compensation in transmission systems improves the stability of the system and also reduces the transmission line losses. Installing Flexible AC Transmission System (FACTS) devices are the effective means to control reactive power compensation. However, due to the high cost of FACTS devices, it is important to optimally place these controllers in the system. Out of the different FACTS devices, TCSC is the most effective device for series compensation. This paper presents a Sensitivity analysis based Complex Power Flow Sensitivity Index (CPSI) proposed for placing the TCSC at an appropriate location. Once the location to install TCSC is identified, the optimal sizing of TCSC is determined through Firefly Algorithm based multi-criterion objective function comprising of four objectives minimize total real power loss, minimize total voltage magnitude deviations, minimize the fuel cost of total real power generation and minimize the branch loading to obtain the optimal power flow. Simulations have been carried out in MATLAB environment for the IEEE 14-bus system, the IEEE 30-bus system and IEEE57 bus system. The results have been taken for Firefly Algorithm based Optimal Power Flow without and with TCSC. The results obtained with Firefly Algorithm were compared with Genetic Algorithm (GA). The results indicate that FA is an easy to use and better optimization technique compared with GA.*

Keywords

Firefly Algorithm, Optimal placement, Sensitivity index, TCSC.

1. Introduction

Power systems are becoming increasingly more complex due to the interconnection of regional system and deregulation of the overall electricity market [1, 2]. It has become essential to better utilize the existing power networks to increase capacities by installing Flexible AC Transmission System (FACTS) controllers. The variables and parameter of the transmission line, which include line reactance, voltage magnitude, and phase angle are able to be controlled using FACTS controllers in a fast and effective way. The benefits derived from FACTS controllers include improvement of the stability of power system networks, such as voltage stability, line stability, small signal stability, transient stability, enhance power transfer capability and thus enhance system reliability. However, controlling power flows is the main function of FACTS [3-6].

Out of the several preventive and corrective measures suggested in literature to protect power system networks against voltage collapse, the placement of FACTS controllers has been established as an effective means. However, due to high cost of the FACTS devices, it is important to optimally place these controllers in the system. The Thyristor Controlled Series Capacitor (TCSC) is one of the most effective Flexible AC Transmission System devices [7-10]. It offers fast-acting reactive power compensation on high-voltage electricity transmission networks with much faster response compared to the traditional control devices [11].

This paper presents Sensitivity analysis based Complex Power Flow Sensitivity Index (CPSI) proposed for placing the TCSC at appropriate location. A new Meta heuristic optimization technique called Firefly Algorithm is introduced to find the optimal size of TCSC device to improve line stability. Its performance is compared with Genetic Algorithm (GA) [12-17] technique. The real and reactive power generation values and voltage limits for generator buses are taken as constraints, along with reactance limits of the TCSC, during the optimization. Computer simulations using MATLAB were done for the IEEE14 bus system, the IEEE 30 bus system and the IEEE57 bus system. In this paper, a new line-based voltage stability index is implemented to evaluate the line stability condition in a power system.

2. Problem Formulation

In this paper, the multi objective function is formulated to find optimal sizing of TCSC device by minimizing certain objective functions subject to satisfying some network constraints. The multi-objective problem can be written mathematically as follows.

2.1. Objective function

For a given system load, the best configuration of TCSC device is obtained by minimizing the objective function:

$$\mathrm{Min(F)} = \min(W_1 * FC + W_2 * F_{Ploss} + W_3 * F_{VD} + W_4 * F_S \quad (1)$$

Where W_1, W_2, W_3, W_4 are the weighting factors $W_1 + W_2 + W_3 + W_4 = 1$

$W_1 = W_2 = W_3 = W_4 = 0.25$

Reactance of TCSC has been added as a control variable along with real power generation of the generator buses for optimization problem. TCSC limits are given as:

$$X_{TCSC}^{min} \leq X_{TCSC} \leq X_{TCSC}^{max} \quad (2)$$

1) Fuel cost:

The objective function considering the minimization of total generation cost can be represented by following quadratic equation

$$FC = \min\left(\sum_{i=1}^{ng} a_i P_{Gi}^2 + b_i P_{Gi} + c_i\right) \quad (3)$$

Where ng = no. of generator buses

a, b, c are the fuel cost coefficients of a generator unit

2) Active Power Loss:

The objective of this function is to minimize real power losses in the transmission lines. It can be expressed as

$$F_{PLoss} = \min\left(\sum_{k=1}^{ntl} \mathrm{real}\,(S_{ij}^k + S_{ji}^k)\right) \quad (4)$$

Where ntl=no. Of transmission lines

S_{ij} is the total complex power flow of line i – j

3) Voltage Deviation:

To have a good voltage performance, the voltage deviation at each bus must be made as small as possible. The Voltage Deviation (VD) can be expressed as:

$$F_{VD} = \min\left(\sum_{k=1}^{Nbus} |V_k - V_k^{ref}|^2\right) \quad (5)$$

V_k is the voltage magnitude at bus k

V_k^{ref} is the reference voltage magnitude at bus k

4) Branch loading:

The objective of minimizing the branch loading in the transmission lines is to enhance the security level of the system. It can be expressed as

$$F_S = \min(S) = \min\left(\sum_{k=1}^{ntl} \left(\frac{|S_k|}{|S_k^{max}|}\right)^2\right) \quad (6)$$

S_k is the apparent power in line k and S_k^{max} is the maximum apparent power in line k.

5) Equality constraints:

$$\sum_{i=1}^{N} P_{Gi} = \sum_{i=1}^{N} P_{Di} + P_L \quad (7)$$

Where i=1,2,3,.......,N_{bus} and N_{bus} = no. of. Buses

$$\sum_{i=1}^{N} Q_{Gi} = \sum_{i=1}^{N} Q_{Di} + Q_L \quad (8)$$

Where i=1,2,3,.......,N_{bus} and N_{bus} = no. of. buses

P_L is total active power losses

Q_L is total reactive power losses

6) Inequality constraints:

Generator bus Voltage limits:

$$V_{Gi}^{min} \leq V_{Gi} \leq V_{Gi}^{max} \quad (9)$$

Where i=1,2,3,.......,N_{bus} and N_{bus} = no.of. buses

Real power generation limit:

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \quad (10)$$

Where i=1,2,3,......,ng and ng= no.of.generator buses

Reactive Powergeneration limits:

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \quad (11)$$

2.2. Fast Voltage Stability Index (FVSI)

Several techniques were proposed to analyse the static voltage stability condition in a system. Some of them were utilized the voltage stability indices referred either to a bus or to a line as an indicator to voltage collapse. In this paper, a new line-based voltage stability index is proposed to evaluate the line stability condition in a power system. This index is called as Fast Voltage Stability Index (FVSI). The system becomes unstable if FVSI is equal to or greater than unity.

FVSI can be expressed as

$$FVSI_{ij} = \frac{4\,Z^2 Q_j}{V_i^2\,X} \quad (12)$$

Where Z is the line impedance

X is the line reactance

Qj is the reactive power at bus j (receiving end bus)

Vi is the voltage magnitude at bus i (sending end bus)

Any line in the system that exhibits FVSI close to unity indicate that the line is may lead to system violation. Therefore, FVSI has to be maintained less than unity in order to maintain a stable system.

3. Thyristor controlled series capacitor (TCSC)

The basic Thyristor-controlled series capacitor scheme proposed in 1986 by Vithaythil with others is a method of “rapid adjustment of network impedance”. Apart from controlling the line power transfer capability, TCSC also enhances system stability [18-21]. The basic module of the TCSC is shown in Fig. 1. It consists of a series compensating capacitor shunted by thyristor controlled reactor [22-24]. Thyristor inclusion in the TCSC module enables it to have a smoother control of reactance against to system parameter variations. In view of a huge power system, TCSC implementation requires several such basic compensators to be connected in series to obtain the desired voltage rating and operating characteristics. It is modeled as a controllable reactance, inserted in series with the transmission line to adjust the line impedance and thereby control the power flow.

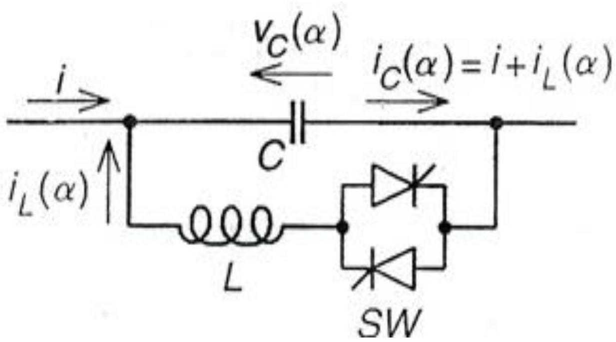

Fig. 1: Basic **TCSC model**

In this paper, the reactance of the transmission line is adjusted by TCSC directly. The TCSC is modeled as variable impedance [25, 26]. It is shown in Fig.2. The rating of TCSC depends on the reactance of the transmission line where the TCSC is located:

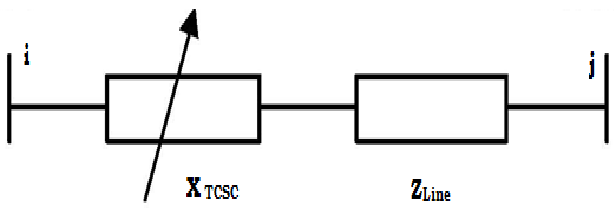

Fig. 2: Block diagram of TCSC

$$Z_{ij} = R_{ij} + X_{ij} \tag{13}$$

$$Z_{line} = R_{line} + X_{line} \tag{14}$$

$$X_{ij} = X_{line} + X_{TCSC} \tag{15}$$

Where X_{TCSC} is reactance of TCSC, to avoid over compensation, the working range of the TCSC is chosen between $-0.8X_{line}$ and $0.6X_{line}$.

The transfer admittance matrix of the TCSC is given by

$$\begin{bmatrix} I_i \\ I_j \end{bmatrix} = \begin{bmatrix} jB_{ii} & jB_{ij} \\ jB_{ji} & jB_{jj} \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix} \tag{16}$$

For capacitive operation, we have

$$B_{ii} = B_{jj} = \frac{1}{X_{TCSC}} \tag{17}$$

$$B_{ij} = B_{ji} = -\frac{1}{X_{TCSC}} \tag{18}$$

For inductive operation the signs are reversed

The active and reactive power equations at bus k are:

$$P_i = V_i V_j B_{ij} \sin(\theta_i - \theta_j) \tag{19}$$

$$Q_i = -V_i^2 B_{ii} - V_i V_j B_{ij} \cos(\theta_i - \theta_j) \tag{20}$$

The series reactance regulates the amount of active power flowing from bus i to bus j the change in reactance of TCSC is

$$\Delta X_{TCSC} = X_{TCSC}^{i} - X_{TCSC}^{(i-1)} \tag{21}$$

The state variable X_{TCSC} of the series controller is updated based on optimization rules.

4. Complex Power Flow Sensitivity Index for Optimal Placement of TCSC

A method based on the sensitivity of the sum of variations of complex power flow in all lines with respect to the change of reactance of a line is proposed. The TCSC has been modelled as a variable series capacitive reactance X_{TCSC}, resulting in a decrease of the total line reactance. The index is computed using Newton Raphson power flow. $CPSI_j$ at a line j is given as:

$$CPSI_j = \sum_{n=1}^{ntl} \left(\frac{\Delta S_n}{\Delta X_j} \right) \tag{22}$$

Where n=1, 2, 3,......., ntl and ntl = no.of transmission lines.

ΔS_n is change in complex power flow in line n

ΔX_j is the reactance of the line j

This index is calculated for all the lines. The minimum and maximum values of CPSI are obtained. Normalized complex power flow sensitivity index is defined as:

$$CPSI_{nj} = \frac{CPSI_j - CPSI_{min}}{CPSI_{max - CPSI_{min}}} \tag{23}$$

Where $CPSI_{nj}$ is the normalized complex power flow sensitivity index at line j.

Highest positive normalized complex power flow sensitivity index is the best location for placement of TCSC.

From the Tab. 1 it is observed that highest positive value for CPSIn(j) is 1 for line no 7. So it is the best location for placement of TCSC in the IEEE 14 bus system. From the Tab. 2 it is observed that highest positive value for CPSIn(j) is 1 for line no 9. So it is the best location for placement of TCSC in the IEEE 30 bus system.

Tab.1: Complex power flow sensitivity indexes for all lines in the IEEE 14 bus system.

Line .No	Line	CPSIn(j)	S. No	Line	CPSIn(j)
1	1-2	0.8331	11	4-9	0.4319
2	2-3	0	12	7-9	0.5345
3	2-4	0.4189	13	9-10	0.482
4	1-5	0.2641	14	6-11	0.4657
5	2-5	0.8747	15	6-12	0.4977
6	3-4	0.6675	16	6-13	0.4155
7	4-5	1	17	9-14	0.4727
8	5-6	0.3855	18	10-11	0.4722
9	4-7	0.5619	19	12-13	0.4832
10	7-8	0.4829	20	13-14	0.4759

Tab.2: Complex power flow sensitivity indexes for all lines in the IEEE 30 bus system.

Line .No	Line	CPSIn(j)	S. No	Line	CPSIn(j)
1	1-2	0.4232	21	16-17	0.7326
2	1-3	0.7943	22	15-18	0.7082
3	2-4	0.7952	23	18-19	0.7266
4	3-4	0.8800	24	19-20	0.7576
5	2-5	0	25	10-20	0.6973
6	2-6	0.6968	26	10-17	0.7564
7	4-6	0.8331	27	10-21	0.7547
8	5-7	0.8282	28	10-22	0.5547
9	6-7	1.0000	29	21-22	0.9930
10	6-8	0.8254	30	15-23	0.5485
11	6-9	0.6773	31	22-24	0.4224
12	6-10	0.5921	32	23-24	0.5465
13	9-11	0.6805	33	24-25	0.6404
14	9-10	0.4868	34	25-26	0.6914
15	4-12	0.6793	35	25-27	0.6360
16	12-13	0.7023	36	28-27	0.5564
17	12-14	0.7236	37	27-29	0.6963
18	12-15	0.4829	38	27-30	0.6745
19	12-16	0.7365	39	29-30	0.6954
20	14-15	0.7215	40	8-28	0.7008
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5. Optimal sizing of TCSC using the Firefly Algorithm

The Firefly algorithm has been used to find the optimum sizing of *TCSC*. It was developed by Dr Xin-She Yang at Cambridge University in 2007. FA is based on natural behaviour of the firefly, developed for solving the multimodal optimization problem [27, 28]. Fireflies called as lighting bugs, are one of the most special and fascinating creatures in nature. For simplicity, the following three ideal rules are introduced in FA development those are 1) All the fireflies are gender-free that is every firefly will attract the other firefly substantive of their sex, 2) Attractiveness depend on their brightness. The less bright one will move towards the brighter one, 3) the landscape of the objective function affects the firefly brightness. Let us consider the continuous constrained optimization problem where the task is to minimize multi objective function f(x). Firefly algorithm is a dynamic converging algorithm. The solution for the algorithm depends on the selection of swarm size, maximum attractiveness value, the absorption coefficient value and the iteration limit. The basic steps of the FA can be summarized by the pseudo code [29, 30].

Firefly Algorithm

……………………………………………….

Objective function $f(\mathbf{x})$, $\mathbf{x} = (x1,\ldots,xd)T$
Generate initial population of fireflies $\mathbf{x}_{ii}$ ($i=1, 2\ldots, n$)
Light intensity I_{ii} *at* x_{ii} *is determined by* $f(\mathbf{x}_{ii})$
Define light absorption coefficient γ
while (t < *MaxGeneration*)
for $ii = 1$*: n all n fireflies*
for $jj = 1$*: ii all n fireflies*
if ($I_{jj} > I_{ii}$), *More firefly ii towards jj in d-dimension;* **end if**
Attractiveness varies with distance r
Evaluate new solutions and modify the light intensity
end for *jj*
end for *ii*
Rank all the fireflies and find the current best firefly
end while
Post process results and visualization
………………………………..

Pseudo code of the FA.

6. Results and Discussion

In order to find the effectiveness of the proposed Firefly Algorithm for Optimal Power Flow with TCSC, the IEEE14, IEEE30 and IEEE 57 bus systems are taken. An OPF program using Firefly algorithm is implemented in MATLAB software without and with TCSC. The results are presented and analysed. The input parameters of Firefly Algorithm for the test system are given in the Tab. 3.

Tab.3: Input parameters of FA Algorithm

S.No	Parameters	Quantity
1	Number of fireflies	20
2	Max Generation	50
3	Alpha (random movement factor)	0.5
4	Beta (attractiveness parameter)	0.5
5	Gama (absorption parameter)	1

6.1. For 14 bus system

In the IEEE 14 bus system bus no 1 is considered as a slack bus and bus numbers 2,3,6,8 are considered as a PV buses all other buses are considered as load buses. This system has 20 interconnected lines. A MATLAB program is written for the test system and the results have been presented and analysed. Table. 4 indicates the generators coefficients, minimum and maximum limit of real power generation for generator buses.

Table. 5 indicates the voltage magnitudes in FA-OPF without TCSC and FA-OPF with TCSC (By placing TCSC at line No 7). The results indicate that there is a good improvement in voltage profile with TCSC in Firefly Algorithm based OPF.

The active power generation and power loss for the IEEE 14 bus test system without and with TCSC is shown in Tab.6 and it is observed that active power losses are reduced to 5.0631 MW from 5.4104 MW by placing TCSC in Firefly Algorithm based Optimal Power Flow. TCSC value was tuned to 0.0220 ohms using Firefly Algorithm. In case of Genetic Algorithm based Optimal Power Flow the TCSC value has been tuned to 0.031 ohms. Table. 7 represents the voltage deviation, TCSC reactance value, total active power generation cost, branch loading, FVSI for all lines, Objective function value and active power losses for the IEEE 14 bus system without TCSC and with TCSC using GA-OPF and FA-OPF. The results clearly indicate the effectiveness of Firefly Algorithm over Genetic Algorithm.

Table 8 & 9 indicates the FVSI values for Firefly Algorithm based Optimal Power Flow without and with TCSC with different reactive load conditions at bus number 14. From these tables it can be inferred that increase in reactive load would result in FVSI value to unity leading to less line stability. By installing the TCSC in Firefly Algorithm based Optimal Power Flow can improve the FVSI that means line stability has been improved.

Tab.4: GENERATOR CHARACTERISTICS OF IEEE 14 BUS SYSTEM

Generator BUS NO	a ($/MW^2/hr)	b ($/MW /hr)	c ($/hr)	P_G^{min} (MW)	P_G^{max} (MW)
1	0.005	2.45	105	10	400
2	0.005	3.51	44.1	20	80
3	0.005	3.89	40.6	20	50
6	0.005	3.25	0	10	35
8	0.005	3	0	10	30

Tab.5: Comparison of bus voltages for 14 bus system using GA-OPF and FA-OPF without and with TCSC

BUS No	GA-OPF without TCSC	GA-OPF with TCSC connected at Line No 7	FA-OPF without TCSC	FA-OPF with TCSC connected at Line No 7
	Voltage (p.u)	Voltage (p.u)	Voltage (p.u)	Voltage (p.u)
1	1.06	1.06	1.06	1.06
2	1.045	1.045	1.045	1.045
3	0.9872	1.01	0.9925	1.01
4	1.0015	1.0287	1.0022	1.0267
5	1.0114	1.0378	1.0118	1.038
6	0.9813	1.07	0.9819	1.07
7	0.9817	1.0372	0.9829	1.0363
8	1.0218	1.09	1.0232	1.09
9	0.948	1.01	0.949	1.0089
10	0.9454	1.01	0.9464	1.0118
11	0.9591	1.032	0.9599	1.0367
12	0.9578	1.043	0.9584	1.0463
13	0.9458	1.0333	0.9465	1.0331
14	0.883	0.96	0.8839	0.9606
TCSC node voltage		1.0372		1.0347

Tab.6: Comparison of Real power loss for 14 bus system without and with TCSC (TCSC placed at line number 7)

Parameter	GA-OPF with out TCSC	GA-OPF with TCSC	FA –OPF without TCSC	FA-OPF with TCSC
Active Power Generation in MW	265.925 1	265.43 39	264.4104	264.0631
Reactive Power Generation in MVAR	120.672 8	117.97 50	115.2766	113.3547
Active Losses in MW	6.9251	6.4339	5.4104	5.0631
Reactive Losses in MVAR	14.2728	11.468 5	8.8766	6.6128
TCSC size	---	0.031	----	0.0220

Tab.7: Comparison of objective function parameters before and after installation of TCSC

Objective function parameters	GA-OPF with out TCSC	GA-OPF with TCSC	FA –OPF without TCSC	FA-OPF with TCSC
Total Real Power Losses	6.9251	6.4339	5.4104	5.0631
Total Voltage Deviation(p.u)	0.5718	0.2819	0.5593	0.2773
Branch loading	2.6532	2.6199	2.3502	2.3280
Fuel cost	1280.32 10	1278.4 76	1206.3879	1105.2432
FVSI for all lines	2.1963	1.7489	1.9871	1.6300
Objective function value	367.037 9	336.20 11	364.2483	333.6814

Tab.8: Comparison of FVSI by changing the reactive load at bus 14 before and after installation of TCSC

	FVSI (Q14=30 MVAR)		FVSI (Q14=40 MVAR)	
Line NO	FA-OPF with out TCSC	FA-OPF with TCSC	FA –OPF without TCSC	FA-OPF with TCSC
1	0.0257	0.0254	0.0249	0.0251
2	0.1277	0.06	0.1443	0.0599
3	0.0918	0.013	0.1242	0.0073
4	0.1176	0.0202	0.1455	0.0223
5	0.0772	0.0247	0.1074	0.0222
6	0.0071	0.0429	0.0101	0.0367
7	0.0204	0.0171	0.0235	0.0186
8	0.1116	0.1309	0.1686	0.1343
9	0.0751	0.038	0.1184	0.0274
10	0.175	0.2213	0.1821	0.2395
11	0.1965	0.0651	0.2576	0.0888
12	0.1307	0.1011	0.1551	0.1144
13	0.0083	0.0144	0.0063	0.0214
14	0.0586	0.0998	0.0672	0.1152
15	0.0604	0.0589	0.0765	0.0712
16	0.1086	0.1091	0.1406	0.1339
17	0.2602	0.1847	0.3671	0.2572
18	0.0404	0.0879	0.0483	0.1051
19	0.0578	0.0603	0.0804	0.0785
20	0.2363	0.2551	0.3343	0.335
Total	1.98	1.6299	2.5824	1.914

Tab.9: Comparison of FVSI by changing the reactive load at bus 14 before and after installation of TCSC

	FVSI (Q14=60 MVAR)		FVSI (Q14=70 MVAR)	
Line NO	FA-OPF with out TCSC	FA-OPF with TCSC	FA –OPF without TCSC	FA-OPF with TCSC
1	0.1017	0.0228	0.2463	0.0194
2	0.1899	0.0673	77824.08	0.0247
3	0.207	0.0073	9758.097	0.0019
4	0.2769	0.028	79.3714	0.0051
5	0.1777	0.0146	4265.893	0.0119
6	0.0532	0.0309	0.3591	0.0143
7	0.0413	0.0235	2.6996	0.0196
8	0.3341	0.1467	4.5429	0.1834
9	0.2482	0.0046	0.686	0.0037
10	0.2145	0.2797	0.3403	0.3069
11	0.4383	0.141	0.23	0.1571
12	0.2409	0.1461	0.5752	0.1646
13	0.0019	0.0357	0.8769	0.0455
14	0.0951	0.1459	0.7784	0.1661
15	0.13	0.097	0.0418	0.1119
16	0.2462	0.1866	4.8691	0.2168
17	0.6884	0.4137	23.1054	0.4961
18	0.0747	0.1414	2.6273	0.1663
19	0.1561	0.1173	7586.467	0.1399
20	0.6324	0.4974	2.9831	0.5862
Total	4.5485	2.5475	99558.87	2.8414

From fig 3 it can be observed that by increasing the reactive load at bus number 14, total FVSI value also increases. Incorporating the TCSC in Firefly Algorithm based Optimal Power Flow total FVSI value has been reduced that indicates that line stability has been improved.

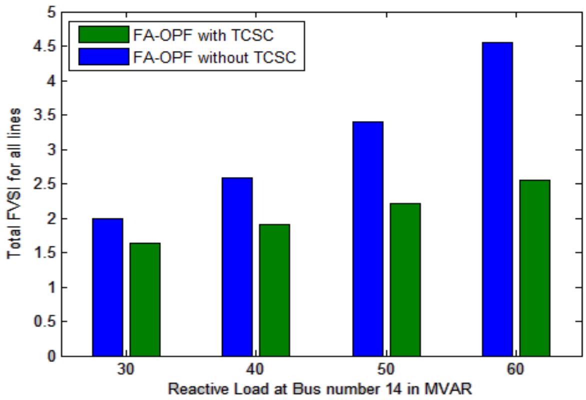

Fig. 3: Fig: 3 FVSI values for different reactive load conditions

6.2. For 30 Bus System

In IEEE 30 bus system bus no 1 is considered as a slack bus and bus no's 2,5,8,11,13 are considered as a PV buses all other buses are considered as load buses. This system has 41 interconnected lines. A MATLAB program is coded for the test system and the results have been tabulated. Table.10 represents the generators a coefficient, minimum and maximum limits of real power generation for generator buses.

Table.2 indicates that the optimal location for TCSC is line no 9. By placing the TCSC at line no 9 in both Genetic Algorithm and Firefly Algorithm based Optimal Power Flows and the results have been presented. Table.11 indicates the voltage magnitudes in FA-OPF without TCSC and FA-OPF with TCSC (By placing TCSC at line No 9). The results indicate that there is a good improvement in voltage profile with TCSC in Firefly Algorithm based OPF. The active power generation and power loss for IEEE 30 bus test system without and with TCSC is shown in Tab.12 and it is observed that active power losses are reduced to 11.5926 MW from 12.5466 MW by placing TCSC in Firefly Algorithm based Optimal Power Flow. TCSC value was tuned to 0.0400 using Firefly Algorithm and for the same the TCSC value has been tuned to 0.0468 using Genetic Algorithm based Optimal Power Flow.

Tab.10: GENERATOR CHARACTERISTICS OF IEEE 30 BUS SYSTEM

Generator BUS NO	a ($/MW^2/hr)	b ($/MW/hr)	c ($/hr)	P_G^{min} (MW)	P_G^{max} (MW)
1	0.00375	2	0	50	300
2	0.0175	1.75	0	20	80
5	0.0625	1	0	15	50
8	0.00834	3.25	0	10	35
11	0.025	3	0	10	30
13	0.025	3	0	12	40

Tab.11: Comparison of bus voltages for 30 bus system using GA-OPF and FA-OPF without and with TCSC

BUS No	GA-OPF without TCSC	GA-OPF with TCSC connected at Line No 9	FA-OPF without TCSC	FA-OPF with TCSC connected at Line No 9
	Voltage (p.u)	Voltage (p.u)	Voltage (p.u)	Voltage (p.u)
1	1.06	1.06	1.06	1.06
2	1.045	1.045	1.045	1.045
3	1.0145	1.0196	1.0196	1.0219
4	1.0044	1.0106	1.0107	1.0135
5	1.01	1.01	1.01	1.01
6	0.9981	1.0043	0.999	1.0056
7	0.9946	0.9988	0.995	0.9988
8	1.01	1.01	1.01	1.01
9	0.9647	0.991	0.9663	0.9912
10	0.908	0.9379	0.9093	0.9371
11	1.0427	1.082	1.0446	1.082
12	0.9461	0.9853	0.9532	0.9884
13	1.0085	1.071	1.0142	1.071
14	0.8874	0.9273	0.8944	0.9303
15	0.8917	0.9302	0.8974	0.9322
16	0.9218	0.9576	0.9262	0.9587
17	0.906	0.938	0.9082	0.9377
18	0.8832	0.9193	0.8873	0.9202
19	0.8819	0.9164	0.8851	0.9167
20	0.8875	0.9209	0.8902	0.9209
21	0.8735	0.9047	0.8751	0.904
22	0.8679	0.8993	0.8696	0.8986
23	0.8371	0.8741	0.8417	0.8754
24	0.7748	0.8095	0.7777	0.8097
25	0.8374	0.8624	0.8388	0.8621
26	0.8157	0.8414	0.8172	0.841
27	0.8883	0.9066	0.889	0.9062
28	0.9865	0.9928	0.9873	0.9938
29	0.865	0.8839	0.8657	0.8834
30	0.8516	0.8708	0.8523	0.8703
	TCSC node Voltage	0.9976		0.9989

Tab.12: Comparison of Real power loss for 30 bus test system without and with TCSC (TCSC placed at line number 9)

Parameter	GA-OPF with out TCSC	GA-OPF with TCSC	FA –OPF without TCSC	FA-OPF with TCSC
Active Power Generation in MW	300.1323	298.9865	295.9466	294.9926
Reactive Power Generation in MVAR	256.8372	253.2349	239.7242	237.0999
Active Losses in MW	16.7323	15.5865	12.5466	11.5926
Reactive Losses in MVAR	51.9372	47.8382	34.8242	31.9679
TCSC size	------	0.0468	------	0.0400

Tab.13: Comparison of objective function parameters before and after installation of TCSC

Objective function parameters	GA-OPF with out TCSC	GA-OPF with TCSC	FA –OPF without TCSC	FA-OPF with TCSC
Total Real Power Losses	16.7323	15.5865	12.5466	11.5926
Total Voltage Deviation(p.u)	2.4521	1.7663	2.3984	1.7642
Branch loading	5.4414	5.4378	4.6713	4.6066
Fuel cost	1122.2283	1118.196	1023.9815	1021.4473
FVSI for all lines	5.8644	5.243	5.6015	5.1077
Objective function value	324.0970	322.32	312.9326	311.6005

Tab.14: Comparison of FVSI by changing the reactive load at bus 14 before and after installation of TCSC in IEEE 30 bus system

	FVSI (Q14=20 MVAR)		FVSI (Q14=30 MVAR)	
Line NO	FA-OPF with out TCSC	FA-OPF with TCSC	FA –OPF without TCSC	FA-OPF with TCSC
1	0.0196	0.0234	0.0164	0.0208
2	0.1094	0.0934	0.1258	0.0949
3	0.1038	0.0783	0.126	0.0813
4	0.0238	0.0199	0.0278	0.0202
5	0.0451	0.0492	0.037	0.042
6	0.0958	0.0929	0.0977	0.0914
7	0.039	0.0198	0.0215	0.0157
8	0.0719	0.058	0.0792	0.0617
9	0.0101	0.0005	0.0152	0.002
10	0.0488	0.0192	0.0609	0.0252
11	0.1268	0.0567	0.1543	0.0614
12	0.3215	0.2484	0.3596	0.2599
13	0.3564	0.4066	0.3642	0.4204
14	0.2178	0.2025	0.2372	0.2121
15	0.2096	0.0929	0.2704	0.1163
16	0.2774	0.3667	0.2927	0.4148
17	0.2317	0.2234	0.3244	0.303
18	0.1943	0.1962	0.2154	0.2169
19	0.0757	0.0945	0.0599	0.0907
20	0.0741	0.0556	0.1965	0.154
21	0.0537	0.0738	0.0372	0.0699
22	0.0004	0.0166	0.0219	0.0053
23	0.0074	0.0031	0.0213	0.004
24	0.0188	0.0122	0.027	0.0163
25	0.0612	0.0426	0.0831	0.0537
26	0.0035	0.0073	0.0119	0.0051
27	0.1399	0.131	0.1477	0.1346
28	0.1679	0.1572	0.1776	0.1617
29	0.0313	0.0291	0.0335	0.0301
30	0.2451	0.2458	0.2401	0.2425
31	0.4728	0.4429	0.5016	0.4565
32	0.3157	0.3182	0.3068	0.3126
33	0.4662	0.381	0.5201	0.3961
34	0.0719	0.0681	0.0744	0.069
35	0.2959	0.2504	0.3228	0.258
36	0.3497	0.3135	0.3687	0.3192
37	0.0412	0.0396	0.0422	0.0399
38	0.0529	0.051	0.054	0.0513
39	0.0169	0.0162	0.0173	0.0164
40	0.0953	0.0683	0.107	0.0737
41	0.0412	0.0416	0.0421	0.0415
Total	5.6015	5.1076	6.2404	5.4621

Tab.15: Comparison of FVSI by changing the reactive load at bus 14 before and after installation of TCSC

	FVSI (Q14=40 MVAR)		FVSI (Q14=50 MVAR)	
Line NO	FA-OPF with out TCSC	FA-OPF with TCSC	FA –OPF without TCSC	FA-OPF with TCSC
1	0.0247	0.0314	3.5638	0.0599
2	0.1824	0.1074	0.0039	0.0495
3	0.1912	0.0892	0.2326	0.0897
4	0.0422	0.0233	59484.73	0.0081
5	0.0396	0.0486	5.0783	0.0108
6	0.2091	0.1001	0.8509	0.0728
7	0.0736	0.0163	33.8875	0.0076
8	0.149	0.0626	0.8762	0.0818
9	0.0674	0.0027	19.3619	0.0154
10	0.0236	0.0276	0.0487	0.0538
11	0.2022	0.0731	0.032	0.0728
12	0.4291	0.2824	9.5571	0.2903
13	0.3963	0.4384	529.776	0.4597
14	0.2731	0.2243	1210.433	0.2374
15	0.3885	0.1492	0.082	0.1631
16	0.3257	0.4612	899.0658	0.5289
17	0.4516	0.3815	6297.134	0.4707
18	0.2579	0.2339	12763.23	0.2598
19	0.0501	0.0798	44823.85	0.0767
20	0.3748	0.2718	12.5555	0.407
21	0.0244	0.0585	0.2975	0.0552
22	0.0491	0.0123	1.216	0.0256
23	0.0389	0.0149	0.0648	0.023
24	0.0385	0.0224	3.0378	0.0271
25	0.1136	0.0705	0.8907	0.083

26	0.0207	0.0004	0.5833	0.0024
27	0.169	0.1383	0.0412	0.1436
28	0.2036	0.1664	0.0635	0.173
29	0.0393	0.0313	11.2937	0.0329
30	0.256	0.2325	3.196	0.2314
31	0.5752	0.4708	34.7376	0.491
32	0.3265	0.2979	0.2951	0.295
33	0.6558	0.4295	326.7163	0.4417
34	0.0846	0.0701	0.0046	0.0713
35	0.3939	0.2762	0.0093	0.2814
36	0.4197	0.3342	0.3417	0.3371
37	0.0472	0.0404	16.7764	0.0409
38	0.0599	0.0519	4835.505	0.0525
39	0.0194	0.0166	689.0327	0.0168
40	0.0896	0.0778	189.5542	0.098
41	0.0591	0.0432	1.0708	0.0384
Total	7.8361	5.9609	132209.1	6.3771

From Fig 4 it has been observed that by incorporating the TCSC in Firefly Algorithm based Optimal Power Flow Real power losses were minimized. Table.13 represents the voltage deviation, TCSC reactance value, total active power generation cost and active power losses for IEEE 30 bus system without TCSC and with TCSC using GA-OPF and FA-OPF. Table.14 & 15 indicates the FVSI values for Firefly Algorithm based Optimal Power Flow without and with TCSC at different reactive load conditions at bus number 14. From this table it can be observed that by increasing the reactive load FVSI values reach towords one that indicates less line stability. By installing the TCSC in Firefly Algorithm based Optimal Power Flow can improve the FVSI that means line stability has been improved.

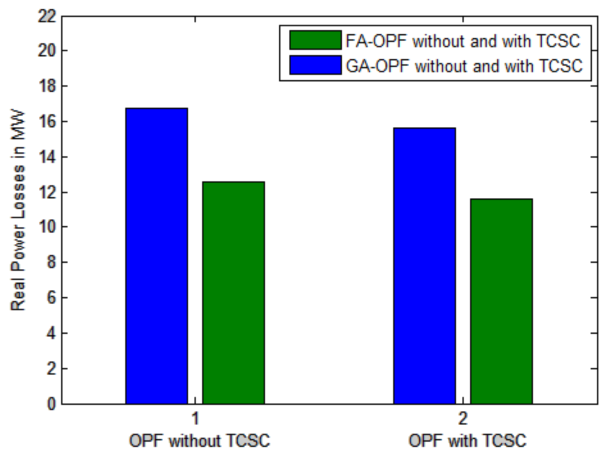

Fig. 4: Fig: 4 comparisons of Real Power Losses

6.3. For 57 Bus System

In IEEE 57 bus system, bus 1 is considered as slack bus and buses 2,3,6,8,9,12 are considered as generator buses. It consists of 50 load buses and 80 transmission lines. From the Tab. 16 it is observed that highest positive value for CPSIn(j) is 1 for line no76. So it is the best location for placement of TCSC in the IEEE 57 bus system. After placing the TCSC consider all the parameters of the system, generation reallocation is carried out with a multi objective function which is formed by considering the cost of the real power generation, active power losses, voltage deviation and branch loading. Results are presented in Tab. 17 to 19.

Tab.16: Complex power flow sensitivity Index values for all lines in the IEEE 57 bus system

S .No	Line No	$CPSI_n(j)$	S. No	Line No	$CPSI_n(j)$
1	**76**	**1**	41	80	0.8837
2	36	0.9987	42	32	0.88
3	73	0.9986	43	17	0.8666
4	35	0.9982	44	58	0.863
5	46	0.9951	45	6	0.8616
6	31	0.9915	46	50	0.8593
7	44	0.991	47	68	0.8551
8	54	0.99	48	39	0.8506
9	29	0.9889	49	15	0.8426
10	19	0.9836	50	10	0.8324
11	74	0.9833	51	14	0.832
12	43	0.9804	52	2	0.8316
13	30	0.9759	53	26	0.8217
14	20	0.9755	54	47	0.8142
15	56	0.9733	55	59	0.8055
16	75	0.9679	56	24	0.8032
17	55	0.9675	57	65	0.7947
18	11	0.9582	58	22	0.794
19	77	0.9523	59	60	0.7883
20	34	0.9514	60	41	0.7746
21	38	0.951	61	21	0.7716
22	69	0.945	62	25	0.7583
23	70	0.9434	63	40	0.7499
24	64	0.9412	64	57	0.7478
25	42	0.9351	65	28	0.7311
26	16	0.9348	66	48	0.7248
27	67	0.9291	67	18	0.7194
28	66	0.9283	68	8	0.7106
29	27	0.9244	69	79	0.6948
30	78	0.9241	70	37	0.6865
31	7	0.9219	71	52	0.6816
32	9	0.9195	72	13	0.6612

33	12	0.9141	73	51	0.6058
34	71	0.9101	74	3	0.5956
35	5	0.9079	75	49	0.5916
36	4	0.8954	76	45	0.5844
37	62	0.8922	77	53	0.4902
38	63	0.8914	78	1	0.4612
39	23	0.8909	79	61	0.353
40	72	0.8868	80	33	0

The results from Tab. 17 show that , for minimization of the multi objective function, Firefly algorithm with TCSC, the generation cost of the best solution is 46412.3565$/hr with 44.8432 MW line loss, 4.8530 voltage deviation and 12.7971 branch loading. The results in Tab.17 indicate the values of the different parameters of the multi objective function using Firefly algorithm and genetic algorithm considering without & with TCSC. From this table it is observed that Firefly algorithm gives better results compared to genetic algorithm. Tab.18 shows that after placing the TCSC in the system voltage profile has been improved. Tab. 19 shows the comparison of FVSI before and after installation of TCSC in IEEE 57 bus system. From this table it is observed that by incorporating the TCSC in the system improves the line based stability.

Tab.17: Comparison of objective function parameters using GA and FA-OPF considering without and with TCSC in IEEE 57 bus system

Variables	GA-OPF without TCSC	FA-OPF without TCSC	GA OPF with TCSC at line no 76	FA- OPF with TCSC at line no 76
Total real power generation (MW)	1245.255	1241.847	1244.255	1240.643
Total real power generation cost ($/hr)	47701.16	46977.18	47689.09	46412.35
Active power Loss (MW)	49.4550	46.0472	49.2455	44.8432
Voltage deviation (p.u)	5.9295	5.7421	4.9056	4.8530
Branch loading (p.u)	13.8480	13.3127	14.1600	12.7971
FVSI value for all lines (p.u)	7.9431	7.6171	7.5205	7.3326
Reactance of TCSC (p.u)	----	----	0.4201	0.3111
Objective function value	11942.59	11760.57	11939.35	11618.96

Tab.18: Comparison of bus voltages for 57 bus system using FA-OPF without and with TCSC

BUS No	FA-OPF without TCSC	FA-OPF with TCSC at Line No 76	BUS No	FA-OPF without TCSC	FA-OPF with TCSC at Line No 76
	Voltage (p.u)	Voltage (p.u)		Voltage (p.u)	Voltage (p.u)
1	1.04	1.04	31	0.7224	0.8143
2	1.0334	1.01	32	0.7406	0.8589
3	1.0115	1	33	0.7376	0.8563
4	1.0017	0.9941	34	0.7888	0.9255
5	0.997	0.9945	35	0.7978	0.9362
6	1	1	36	0.8099	0.9485
7	0.985	0.9879	37	0.8201	0.9605
8	1.005	1.005	38	0.852	1
9	0.9902	1	39	0.8177	0.9569
10	0.9801	0.9979	40	0.8075	0.9443
11	0.9591	0.9831	41	0.8186	0.877
12	1.015	1.015	42	0.7778	0.8535
13	0.9706	0.9974	43	0.9191	0.9526
14	0.9445	0.9907	44	0.884	1.0033
15	1.0073	1.0167	45	0.964	1.023
16	1.0136	1.0142	46	0.9149	0.993
17	1.0186	1.0193	47	0.8797	0.9882
18	0.9625	0.9594	48	0.8732	0.9916
19	0.9005	0.9109	49	0.8943	0.9879
20	0.8754	0.8943	50	0.8982	0.9696
21	0.8542	0.8884	51	0.9633	0.9922
22	0.8508	0.8872	52	0.9244	0.9321
23	0.8498	0.8862	53	0.909	0.9171
24	0.85	0.8854	54	0.9385	0.947
25	0.7826	0.8419	55	0.9775	0.9864
26	0.8554	0.8885	56	0.7745	0.8645
27	0.9143	0.9312	57	0.7693	0.8698
28	0.9435	0.9542			
29	0.9662	0.973			
30	0.757	0.8264			

Tab.19: Comparison of FVSI before and after installation of TCSC in IEEE 57 bus system

Line No	FVSI without TCSC	FVSI with TCSC at Line No 76	Line No	FVSI without TCSC	FVSI with TCSC at Line No 76
1	0.0432	0.1334	41	0.0715	0.0573
2	0.0756	0.0256	42	0.0828	0.0718
3	0.0247	0.0156	43	0.1156	0.095
4	0.0134	0.0059	44	0.052	0.0653
5	0.0145	0.0047	45	0.0109	0.0099
6	0.0696	0.0556	46	0.204	0.1991
7	0.0335	0.0276	47	0.0312	0.0292
8	0.0097	0.039	48	0.0409	0.0378

9	0.0299	0.0122	49	0.036	0.036
10	0.081	0.0757	50	0.1163	0.1184
11	0.1591	0.1115	51	0.0096	0.0107
12	0.0152	0.016	52	0.0093	0.0115
13	0.0882	0.0702	53	0.0002	0.0106
14	0.0826	0.0371	54	0.4858	0.4548
15	0.1165	0.1133	55	0.1007	0.0782
16	0.0247	0.0259	56	0.562	0.5083
17	0.0072	0.0067	57	0.13	0.0778
18	0.01	0.0595	58	0.1596	0.1094
19	0.1369	0.121	59	0.12	0.0914
20	0.1395	0.1236	60	0.1249	0.0933
21	0.0023	0.0063	61	0.0441	0.0279
22	0.0467	0.0388	62	0.119	0.0467
23	0.1517	0.1232	63	0.0432	0.0251
24	0.074	0.0676	64	0.2567	0.2195
25	0.2172	0.1782	65	0.0657	0.0589
26	0.0202	0.0207	66	0.2823	0.1699
27	0.0458	0.0466	67	0.1017	0.089
28	0.0878	0.0837	68	0.041	0.0338
29	0.1755	0.101	69	0.0874	0.1025
30	0.1032	0.0501	70	0.1082	0.1204
31	0.1014	0.0268	71	0.1587	0.1475
32	0.0207	0.0056	72	0.3095	0.1987
33	0.0026	0.0062	73	0.1506	0.1911
34	0.0144	0.0759	74	0.0272	0.0267
35	0.261	0.2361	75	0.0141	0.0329
36	0.261	0.2361	76	0.2117	0.24
37	0.026	0.0147	77	0.0144	0.028
38	0.2183	0.129	78	0.2596	0.1194
39	0.0805	0.0517	79	0.1328	0.0721
40	0.0615	0.0437	80	0.0493	0.0526

7. Conclusion

In this paper, Sensitivity Analysis based Complex Power Flow Sensitivity Index (CPSI) has been implemented for optimal location of TCSC. After placing the TCSC in best location, a new swarm based Firefly Algorithm has been presented to solve the optimal sizing of TCSC. The effectiveness of Firefly Algorithm was presented. The results show that incorporating the TCSC in the IEEE 14, IEEE 30 and IEEE57 bus systems can reduce the total active power losses, improve the voltage profile of the system and enhance the line stability. For finding the best size of a TCSC, Firefly Algorithm based optimization technique, with the objective of reducing total generation cost, voltage deviation, active power losses and branch loading were implemented. The comparative study of the Firefly Algorithm based Optimal Power Flow with GA based Optimal Power Flow in solving the optimal tuning problem also reflected the effectiveness of the proposed approach. The obtained results show that TCSC is the most effective series compensation device that can significantly increase the line stability of the power system.

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