

OPTIMAL PLACEMENT OF TCSC AND TCPAR USING SENSITIVITY ANALYSIS

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Abstract : *Optimal placement of Flexible AC Transmission System (FACTS) devices are very important for maintaining proper power system performance. This article presents an optimal placement approach of two well-known FACTS devices, Thyristor controlled series capacitor (TCSC) and Thyristor controlled phase angle rectifier (TCPAR) based on sensitivity analysis. In this method, reduction of line losses and overloading are taken care of. Sensitivity indexes are used to find proper place of FACTS devices in the network. After placing FACTS devices the performance of the network is also analyzed. Which FACTS device is more suitable for the network is also analyzed with the impact of change of generation. Effectiveness of the method is tested on a WSCC-3-Machine-9 bus system and an IEEE 57 bus test system with various single and multiple contingency combinations. The results obtained are accurate and satisfactory. The whole simulation work is done by using Power World 12.0 commercial version.*

Keywords – Loss sensitivity indices, Optimal placement, Contingencies , TCSC, TCPAR

1.Introduction

The Flexible Alternating Current Transmission System(FACTS) devices are very important for the improvement of the power system security. The objectives of using these FACTS devices are to bring the system under control and increase the power transfer capability through the lines. However, these devices have to be located optimally to reduce the capital investment.

With the expansion of power network, several financial, social and technical problems are also increasing. Efforts have been made to utilize existing electric power systems optimally. Line flows and losses are increasing in power system due to consistent increase in energy demand. These issues lead to the system security and stability problems. All these problems can be solved by the use of FACTS devices [1]. FACTS devices are capable to control power flow both in steady state as well as in dynamic state [2]. Using controllable series capacitors, losses can be reduced and stability margin can be increased. Thus energy can be saved for proper utilization. FACTS devices such as TCSC, TCPAR, UPFC, IPFC and OUPFC can be used to change power flow in the lines by changing their parameters to achieve various objectives[3].FACTS devices are capable of controlling steady state power flow as well as system parameters in dynamic state [4-5]. Due to the advancements in power electronics industry, FACTS devices have become cost effective [6-7]. In order to get maximum economic benefits, FACTS devices should be placed at optimal locations.

Several approaches are proposed in the literature for optimizing location and parameter settings of the FACTS devices. The most popular technique used for FACTS placement problem is the heuristic types of procedures applied for optimal FACTS location. Examples of heuristic types of

procedures applied to the FACTs placement are found in reference [8-10].

S.N.Singh et al.[1] have developed models for optimal location of FACTS devices for congestion management. S.N.Singh et al.[2] suggested a sensitivity analysis for placing FACTS devices and reduction in real power flow performance index to enhance security of power system. R.Srinivasa Rao et al.[6] developed a generalized approach for optimal location of FACTS devices based on total system loss sensitivity indices and real power flow PI sensitivity indices. They have considered the effect of change of generation and comparison of various methods also in their work. But they did not consider the effect of *different contingency combinations* in the system while placement of TCSC, as well as which is the best suitable choice among FACTS devices to deal the problem.

S.C.Srivastava et al [7] suggested a novel approach to locate TCSC and UPFC for improving power system steady state operation. S.Parida et al. [3] developed a novel methodology for combined location of TCPAR and TCSC using a Mixed integer linear programming (MILP) approach in the deregulated electricity environment. The technique was based on DC load flow (DCLF) equations taking constraints on generation, line flow, TCPAR and TCSC parameters, power angle, and a number of FACTs controllers. The system loadability has been determined without and with combined optimal location of FACTs controllers. H.M.Ravi Kumar et al.[4] presented a three step procedure to decide number, location and optimal settings of TCSC to eliminate overloads on transmission lines under network contingencies. But *multiple contingency cases* are still untouched in this work also. H.I.Shaheen et al.[5] used GA and PSO for finding optimal location and settings of TCSC. In Reference [11] the authors propose a novel decomposition procedure for determining the optimal location of TCSC and their respective size for a network. In Reference [12] authors propose a multi-objective optimization based FACTs device placement approach. In Reference [13] authors propose a mixed-integer linear programming based approach for optimal placement of TCSC. In reference [14] authors suggested a technique which iteratively minimizes the operating points of the FACTs devices to enhance the security. In Reference [15] authors used line flow based (LFB)equations to find the

optimal locations and settings of a TCSC. However it shows that LFB equations are invalid for modelling meshed networks. Therefore application of LFB equations in FACTs location allocation problem is limited.

This paper presents a generalized approach to determine the optimal location of TCSC and TCPAR. The approach is based on sensitivity analysis which is subjected to reduction of line losses i.e. energy savings. The contributions of the paper are manifold. First of all we consider the network in single and multiple contingency combinations. We placed TCSC and TCPAR using sensitivity analysis keeping constraints as reduction of line losses i.e energy savings. In our proposed technique we consider a practical approach by taking the effect of change of generations. Secondly, it describes the procedure about how to handle the power network during overloading of any line of the system.

We utilized the WSCC-3-Machine-9-bus system and IEEE 57 Bus test systems to demonstrate the effectiveness of the proposed procedure and to develop new insights into the optimal placement problem of TCSC and TCPAR. The remainder of the paper is organized as follows :

Section2 and 3 describes the mathematical modelling of TCSC and TCPAR. Section 4 and 5 describes the optimal placement of TCSC and TCPAR with results. Section 6 describes the discussions. Finally in section-7, we made some conclusions and comments.

2. Modelling of TCSC

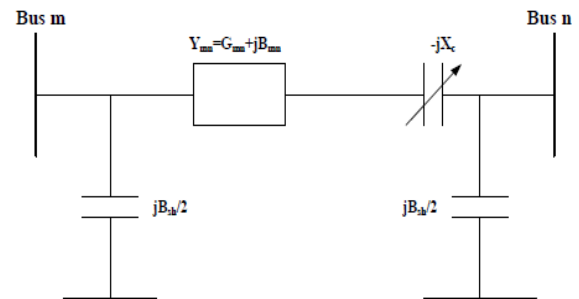


Fig.1 : Transmission line modelling with TCSC

The transmission line with TCSC modelled as static reactance ($-jx_c$) is shown in Fig 1. The power flow equations from bus m to bus n (P_{mn}

and Q_{mn}) and from bus n to bus m (P_{nm} and Q_{nm}) are given by following equations [16,24-26] :

$$P_{mn} = -V_m V_n [G_{mn} \cos \delta_{mn} + B_{mn} \sin \delta_{mn}] + V_m^2 G_{mn} \quad (1)$$

$$Q_{mn} = -V_m V_n [G_{mn} \sin \delta_{mn} - B_{mn} \cos \delta_{mn}] - V_m^2 (B_{mn} + B_{sh}) \quad (2)$$

$$P_{nm} = -V_n V_m [G_{mn} \cos \delta_{mn} - B_{mn} \sin \delta_{mn}] + V_n^2 G_{mn} \quad (3)$$

$$Q_{nm} = -V_n V_m [G_{mn} \sin \delta_{mn} + B_{mn} \cos \delta_{mn}] - V_n^2 (B_{mn} + B_{sh}) \quad (4)$$

The active power loss in the line is given by

$$P_{lk} = -2V_m V_n G_{mn} \cos \delta_{mn} + (V_m^2 + V_n^2) G_{mn} \quad (5)$$

$$\text{Here } G_{mn} = \frac{r_{mn}}{r_{mn}^2 + (x_{mn} - x_c)^2} \quad (6)$$

$$B_{mn} = \frac{-(x_{mn} - x_c)}{r_{mn}^2 + (x_{mn} - x_c)^2} \quad (7)$$

3. Modelling of TCPAR

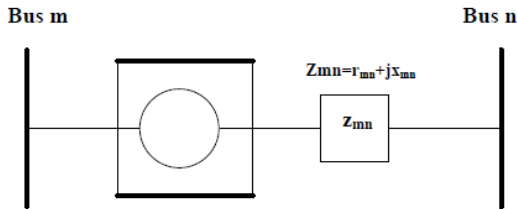


Fig. 2 : Modelling of TCPAR

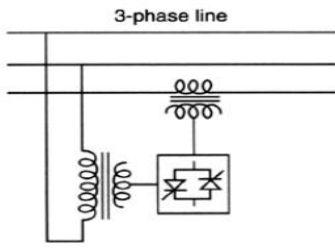


Fig. 3: Simple model of TCPAR /TCPST

TCPAR means Thyristor controlled phase angle regulators. With the phase shift of TCPAR, power flows and losses can be compensated. This device is also called TCPST (Thyristor controlled phase

shifting transformer). The device is required for power control damping of oscillations and transient stability. TCPAR/ TCPST can be modelled (ref. Fig 2 and Fig 3) by using following equations[16-21] :

$$P_{mn} = -V_i V_j A [G_{mn} \cos(\delta_{mn} + \Phi) + B_{mn} \sin(\delta_{mn} + \Phi)] + V_m^2 A^2 G_{mn} \quad (8)$$

$$Q_{mn} = -V_i V_j A [G_{mn} \sin(\delta_{mn} + \Phi) - B_{mn} \cos(\delta_{mn} + \Phi)] - V_m^2 A^2 B_{mn} \quad (9)$$

$$P_{nm} = -V_i V_j A [G_{mn} \cos(\delta_{mn} + \Phi) - B_{mn} \sin(\delta_{mn} + \Phi)] + V_m^2 A^2 G_{mn} \quad (10)$$

$$Q_{nm} = V_i V_j A [G_{mn} \sin(\delta_{mn} + \Phi) + B_{mn} \cos(\delta_{mn} + \Phi)] - V_m^2 A^2 B_{mn} \quad (11)$$

$$A = \sec(\Phi) \quad (12)$$

The real power loss

$$P_{lk} = -2V_m V_n A G_{mn} \cos(\delta_{mn} + \Phi) + V_m A^2 G_{mn} + V_n^2 G_{mn} \quad (13)$$

4. Optimal placement of TCSC/TCPAR

The optimal placement of TCSC/ TCPAR may be based on one of the following objectives described below :

- i) Reduction of real power loss of a particular line- k (P_{lk}).
- ii) Reduction of total system real or / and reactive power loss.
- iii) Reduction in real power flow performance index.
- iv) Minimization of total generation cost.
- v) Minimization of total system real power loss and total generation cost simultaneously .

The first three approaches are based on sensitivity analysis based approach .

4.1. Line loss sensitivity indices

Line loss sensitivity factor for calculation of optimal location of TCSC and TCPAR is based on differential approach. The factors are given by following equations :

$$a_1 = \frac{\Delta P_{lk}}{\Delta X_{ck}} \quad \text{for TCSC placement} \quad (14)$$

$$a_2 = \frac{\Delta P_{lk}}{\Delta \Phi_k} \quad \text{for TCPAR / TCPST placement} \quad (15)$$

X_{ck} is TCSC reactance and Φ_k is phase angle shift produced by TCPAR / TCPST

4.2. Criteria for optimal placement of TCSC/TCPAR

The criteria for optimal placement of TCSC / TCPAR are as follows :

- i) The device should be placed in a line which has least sensitivity with respect to the magnitude of static reactance.
- ii) The device should be placed in a line which has largest absolute value of the sensitivity with respect to the phase angle.
- iii) The device should not be placed in the line containing generation buses, even if the sensitivity is the highest.
- iv) The terminal end bus must not have a switched shunt connected to it.
- v) Multiple devices sending end on same bus are allowed.

4.3. The terms of sensitivity factors

From equation (1) to (13) following terms can be obtained:

$$\frac{\Delta P_m}{\Delta X_{ck}} = (V_m^2 - V_m V_n \cos \delta_{mn}) \frac{\Delta G_{mn}}{\Delta X_{ck}} - V_m V_n \sin \delta_{mn} \frac{\Delta B}{\Delta X_{ck}}$$

when $X_{ck} = 0$ (16)

$$\frac{\Delta P_n}{\Delta X_{ck}} = (V_m^2 - V_m V_n \cos \delta_{mn}) \frac{\Delta G_{mn}}{\Delta X_{ck}} + V_m V_n \sin \delta_{mn} \frac{\Delta B}{\Delta X_{ck}}$$

when $X_{ck} = 0$ (17)

$$\frac{\Delta P_m}{\Delta \Phi_k} = -V_m V_n (G_{mn} \sin \delta_{mn} - B_{mn} \cos \delta_{mn})$$

when $\Phi_k = 0$ (18)

$$\frac{\Delta P_n}{\Delta \Phi_k} = -V_m V_n (G_{mn} \sin \delta_{mn} + B_{mn} \cos \delta_{mn})$$

when $\Phi_k = 0$ (19)

5. Results

Various test cases are checked with single and multiple contingency conditions with WSCC-3-Machine-9 bus system (ref. Fig 4) and IEEE-57 bus test system. Various test cases results are listed in Table- 1, Table-2 ,Table -3, Table-4 and Table-5.

5.1. WSCC-3-Machine-9 Bus System Cases

The test system is constructed by using Power World 12.0 Commercial version. The Newton Raphson load flow (NRLF) is run in the test system in base case (without change of compensation and without contingency) condition. Then the different types of single and multiple contingencies are created in the system and then again NRLF is run in the system. Then the different indexes are calculated as per formula from the available data in two different run cases. eg: For showing one calculation, we are choosing the example of line 7-8 arbitrarily. As per Table-1, the base case real power loss in case of line 7-8 was 0.26 p.u and at contingency was 0 p.u. So,

$$\Delta P_{lk} = (0 - 0.26) \text{ p.u}$$

= -0.26 p.u. In the said case, change in line reactance is 0.0288 p.u (decrease). So,

$\Delta X_{ck} = -0.0288$ p.u .So, for line 7-8 as per Table1

$$a_1 = \frac{\Delta P_{lk}}{\Delta X_{ck}} = \frac{-0.26}{-0.0288} = 9.0278$$

Here one thing is needed to be mentioned that before placement of TCSC , while calculating the a_1 index, we will consider the line reactance change to produce the change of real power loss. i.e- ΔP_{lk} is the change of real power loss in the line(lk) while the line reactance is varied by ΔX_{ck} and after placement of TCSC , the ΔX_{ck} term can be calculated from TCSC reactance. In case of TCPAR , the calculation of a_2 can be done from change of real power loss (ΔP_{lk}) in the line with respect to change in difference in bus angle magnitudes ($\Delta \Phi_k$) before placement of TCPAR

and after the placement of TCPAR the change of angle values can be obtained from TCPAR itself.

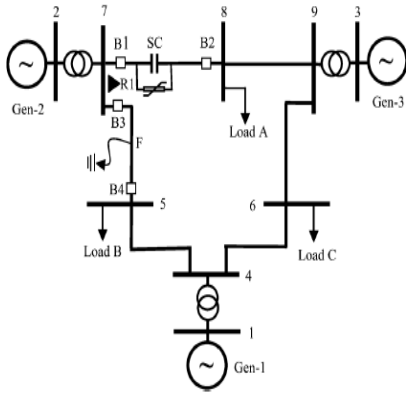


Fig. 4: Single line diagram of a WSCC-3-Machine-9-bus system

For showing one calculation of a_2 , we are choosing the example of line 7-8 arbitrarily. As per Table-3, the base case real power loss in case of line 7-8 was 0.26 unit and at contingency was 0.2 unit. So,

$$\Delta P_{lk} = (0.2 - 0.26) p.u$$

$$= -0.06 p.u$$

And in the said case change in phase angle shift obtained from TCPAR is 0.39 p.u (increase). So, $\Phi_k = 0.39 p.u$ So, for line 7-8 as per Table3

$$a_2 = \frac{\Delta P_{lk}}{\Delta \Phi_k} = \frac{-0.06}{0.39} = -0.1538$$

Fig 5 to Fig 8 show some graphical plots (bus voltage profile and real power loss) to see the effect of FACTs devices (TCSC) with and without on a WSCC-3-Machine-9bus system. Fig 9 to Fig 12 show the same in case of an IEEE 57 bus system. In both the cases we are observing the voltage profile smoothens and real power loss decreases in the presence of FACTs device (TCSC). Table- 1 shows FACTs (TCSC) placement under single contingency condition and Table-2 (TCSC) , Table-3 (TCPAR) show under multiple contingency condition in case of 9 Bus system.

Table-4 and Table-5 shows IEEE 57 bus applications . Table-4 listed the results of TCSC placement and Table-5 shows the results of TCPAR placement.

5.1.1. TCSC Placement

Table-1 : Line 8-9 under contingency (single contingency case)

Line	Base case real power loss(p.u) (P _{base})	Real power loss at contingency (p.u) (P _{contingency})	ΔP_{lk} (p.u) = (P _{contingency} - P _{base})	Change in line reactance (p.u) (ΔX_{ck})	$a_1 = \frac{\Delta P_{lk}}{\Delta X_{ck}}$	Remarks
2-7	-	-	-	-	not required	Connected to generation bus . So, violating the criteria .
7-8	0.26	0	-0.26	-0.0288	9.0278	
5-7	2.11	8.99	6.88	-0.0644	-106.832	
8-9	-	-	-	-	-	Under contingency
3-9	-	-	-	-	not required.	Connected with generation bus. So, violating the criteria.
6-9	0.14	23.24	23.10	-0.068	-339.706	Proper place for TCSC Placement. Run NRLF after placement of TCSC .In case of any violations,% compensation to be adjusted.
4-5	0.06	8.86	8.8	-0.0386	-227.647	
4-6	0.04	10.83	10.79	-0.0392	-275.815	
4-1	-	-	-		not required.	Connected to generation bus. So, violating the criteria

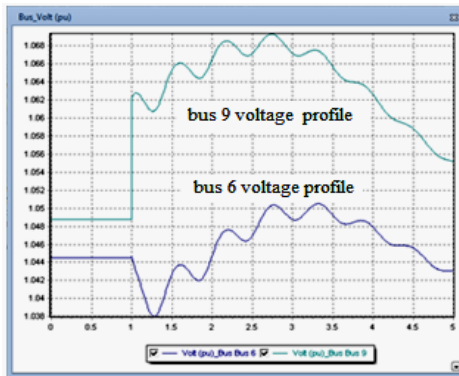


Fig.5: Voltage profile before placement of TCSC

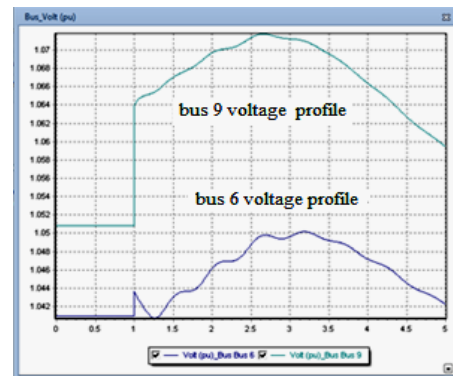


Fig.6 : Voltage profile after placement of TCSC

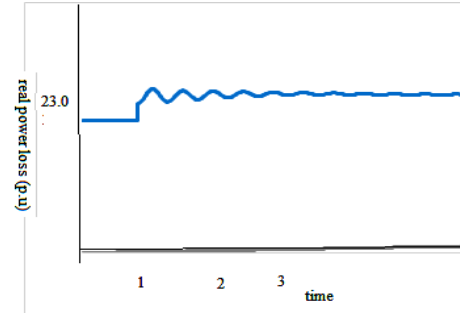
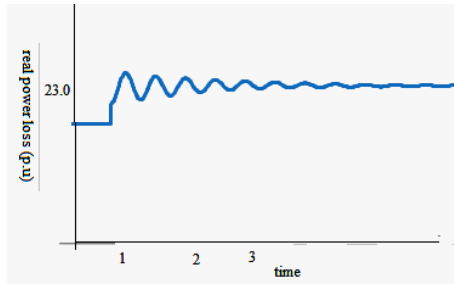


Fig.7: real power loss in line 6-9 before placement of TCSC Fig.8: real power loss in line 6-9 after placement of TCSC

Table-2 : Line 8-9 and Line 3-9 under contingency (Multiple contingency case)

Line	Base case real power loss(p.u) (P_{base})	Real power loss at contingency (p.u) ($P_{contingency}$)	ΔP_{lk} (p.u) = ($P_{contingency} - P_{base}$)	Change in line reactance (p.u) (ΔX_{ck})	$a_1 = \frac{\Delta P_{lk}}{\Delta X_{ck}}$	Remarks
2-7	-	-	-	-	Calculation not required .	Connected to generation bus . So, violating the criteria of optimal placement of TCSC.
7-8	0.26	0	-0.26	-0.0288	9.0278	
5-7	2.11	19.16	17.05	-0.0644	-264.75	Proper place for TCSC Placement. Run NRLF after placement of TCSC .In case of any violations,% compensation to be adjusted .
8-9	-	-	-	-	-	Under contingency
3-9	-	-	-	-	-	Connected with generation bus and it is under contingency
6-9	0.14	17.98	17.84	-0.068	-262.5	.
4-5	0.06	2.36	2.3	-0.034	-67.647	
4-6	0.04	6.94	6.9	-0.0368	-187.5	
4-1	-	-	-	-	Calculation not required	Connected to generation bus . So, violating the criteria of optimal placement of TCSC.

5.1.2. TCPAR / TCPST Placement

Table-3 : Line 4-6 and Line 4-5 under contingency (Multiple contingency case)

Line	Base case real power loss(p.u) (P_{base})	Real power loss at contingency (p.u) ($P_{contingency}$)	ΔP_{lk} (p.u) = ($P_{contingency} - P_{base}$)	Change in phase angle shift(p.u) $\Delta \Phi_k$	$a_2 = \frac{\Delta P_{lk}}{\Delta \Phi_k}$	Remarks
2-7	-	-	-	-	Calculation not required.	Connected to generation bus . So, violating the criteria of optimal placement of TCPAR.
7-8	0.26	0.2	-0.06	0.39	-0.1538	
5-7	2.11	3.35	1.24	-3.31	-0.3746	Proper place for TCPAR Placement. Run NRLF after placement of TCPAR .In case of any violations,% compensation(or proper angle) to be adjusted
8-9	0.32	0.21	-0.11	-5.34	0.0206	
3-9	-	-	-	-	Calculation not required.	Connected to generation bus . So, violating the criteria of optimal placement of TCPAR.
6-9	0.14	0.13	-0.01	-1.11	0.009	
4-5	-	-	-	-	-	Under contingency
4-6	-	-	-	-	-	Under contingency
4-1	-	-	-	-	Calculation not required.	Connected to generation bus . So, violating the criteria of optimal placement of TCPAR.

5.2 IEEE-57 Bus Application

5.2.1 TCSC Placement

Table –4 : Line 1-2 under contingency(Single contingency case)

Line	Base case real power loss(p.u) (P_{base})	Real power loss at contingency (p.u) ($P_{contingency}$)	ΔP_{lk} (p.u) = ($P_{contingency} - P_{base}$)	Change in line reactance (p.u) (ΔX_{ck})	$a_1 = \frac{\Delta P_{lk}}{\Delta X_{ck}}$	Remarks
1-2	-	-	-	-	-	Under contingency
4-18	0.18	0.11	-0.07	-0.02564	2.73	
6-7	-	-	-	-	not required.	Connected to generation bus. So, violating the criteria of optimal placement of TCSC
7-29	0.14	0.13	-0.01	-0.03392	0.295	
11-43	0	0		-0.0612	0	
13-49	7.89	8.4	0.51	-0.01736	-29.38	Proper place for TCSC Placement. Run NRLF after placement of TCSC. In case of any violations,% compensation to be adjusted.

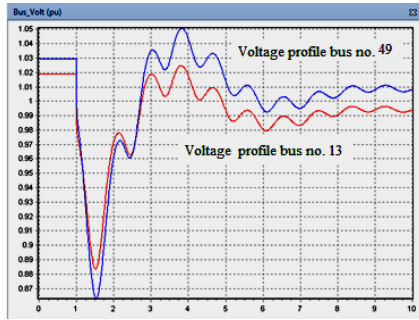


Fig.9 : Voltage profile before placement of TCSC

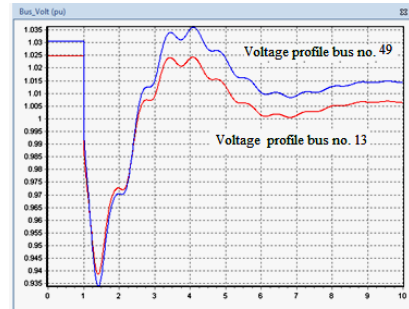


Fig.10 : Voltage profile after placement of TCSC

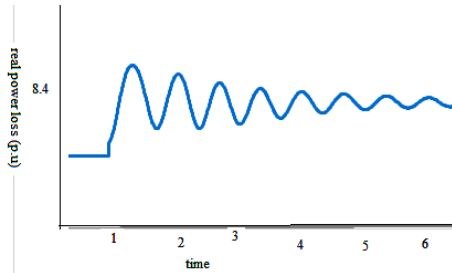


Fig.11: real power loss in line 13-49 before placement of TCSC

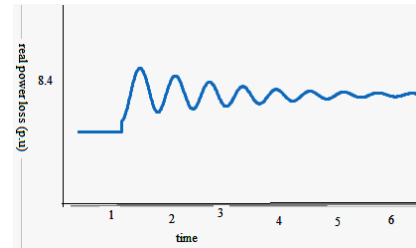


Fig.12: real power loss in line 13-49 after placement of TCSC

5.2.2 TCPAR Placement

Table –5: Line 24-26 and Line 37-38 under contingency (Multiple contingency case)

Line	Base case real power loss(p.u) (P_{base})	Real power loss at contingency (p.u) ($P_{contingency}$)	ΔP_{lk} (p.u) = $(P_{contingency} - P_{base})$	Change in phase angle shift(p.u) $\Delta \Phi_k$	$a_2 = \frac{\Delta P_{lk}}{\Delta \Phi_k}$	Remarks
1-2	-	-	-	-	Calculation not required.	Connected to generation bus . So, violating the criteria of optimal placement of TCPAR.
4-5	0.17	0.16	-0.01	-0.08628	0.1159	
6-7	-	-	-	-	Calculation not required.	Connected to generation bus. So, violating the criteria of optimal placement of TCPAR.
10-12	0.27	0.3	0.03	-0.013	-2.308	
13-49	7.89	7.57	-0.32	-0.010145	31.542	Proper place for TCPAR Placement. Run NRLF after placement of TCPAR.In case of any violations,% compensation to be adjusted.
14-15	1.07	1.14	0.07	0.14112	0.496	
24-26	-	-	-	-	-	Under contingency
26-27	0.04	0.34	0.3	2.0027	0.1498	
37-38	-	-	-	-	-	Under contingency
46-47	0.06	1.12	1.06	2.0076	0.528	
56-57	0.05	0.13	0.08	-1.4286	-0.056	

6. Discussion

6.1. Treatment of Network after placing TCSC/ TCPAR

After placing FACTS device in proper place, we will run the NRLF and observe any line is violating the limit or not. In case any line is violating any limit, then we need to adjust the percentage compensation of the overloaded line. Here one thing need to be mentioned that the line is provided with up to 30% overload backup support. So, our objective will be to bring the line within 30% overload. Refer to Table-2 multiple contingency case after placing TCSC in line 5-7 and then running load flow we get the result same as Fig13. Here we can see line 2-7 is congested with 45% overload and line 6-9 is congested with 43% overload. We are neglecting line 5-7 (1% overload < 30%). Then we can vary percentage compensation to adjust the network within limit like shown in Fig14 and Fig15. First we compensated line 2-7 by 40% and run the load flow again. Still line 2-7 is showing 40% overload and line 6-9 is showing 44% overload (ref. Fig14). Now we compensate line 2-7 and line 6-9 both by 50% and run the load flow again. Now we can see both the lines (line 2-7 and line 6-9) are within limit (within 30% overload) (ref. Fig 15).

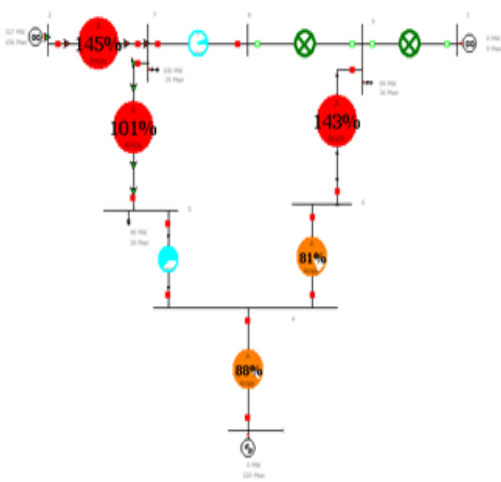


Fig.13 : NRLF result after placing TCSC in line 5-7

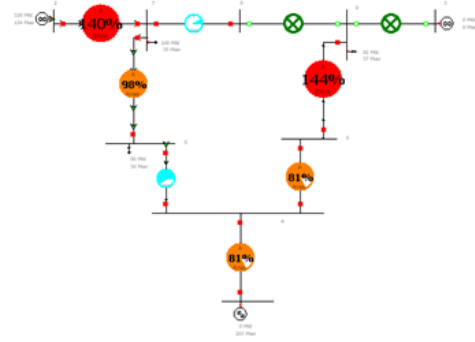


Fig.14: NRLF result after 40% compensation in line 2-7

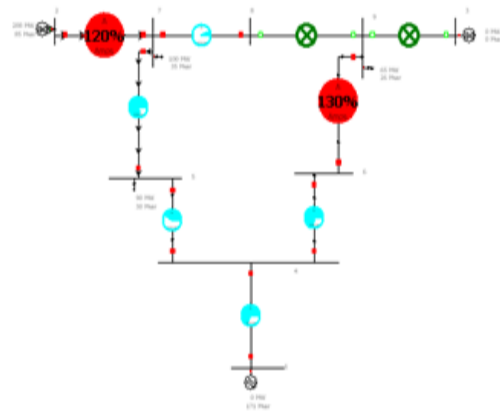


Fig.15: NRLF result after 50% compensation in line 2-7 and Line 6-9

6.2. TCSC or TCPAR Which FACT device is more appropriate for network and Impact of Generation

Both TCSC and TCPAR are useful for power system to maintain proper performance of the network. TCSC varies its percentage compensation and firing angle to maintain network performance and TCPAR usually gives negative phase shift to a line in a network to minimize losses etc and maintaining proper power system performance. But TCPAR is very sensitive to the phase angle shift. If phase shift exceeds certain limits, it can produce even black out of the whole system. But such conditions does not occur in case of TCSC. So, it can be said TCPAR is more vulnerable than TCSC. So, TCSC is more appropriate FACT device than TCPAR. Fig 16 shows the screen shot of the simulation when TCPAR exceeds -58 degree phase shifts in line 6-9. Here it is showing complete black out of the system.

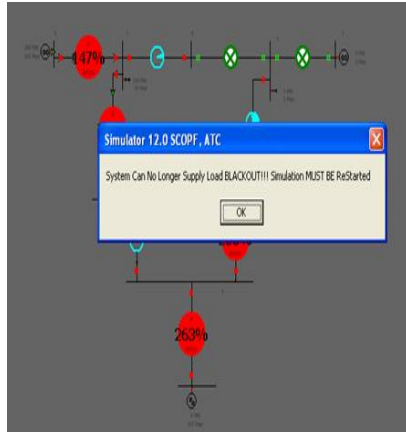


Fig. 16 : NRLF result after TCPAR phase shift exceeds -58degree in line 6-9

Now, to study the effect of variation of generation in this method to determine the optimal location of the FACTS device, the generation has been rescheduled to 45 MW from 85 MW at bus 3 and 130 MW from 163 MW at bus 2. Results are listed in Table-6. Comparing with Table-3, we can say line 8-9 and line 6-9 are not much affected with respect to change in sensitivity index. In case of line 7-8 and line 5-7, sensitivity index increased but optimal place for TCPAR placement remains same(line 5-7) (refer to Table-6)

Table-6 : Line 4-6 and Line 4-5 under contingency (Multiple contingency case)

Line	Base case real power loss(p.u) (P_{base})	Real power loss at contingency (p.u) ($P_{contingency}$)	ΔP_{lk} (p.u) $= (P_{contingency} - P_{base})$	Change in phase angle shift(p.u) $\Delta \Phi_k$	$a_2 = \frac{\Delta P_{lk}}{\Delta \Phi_k}$	Remarks
2-7	-	-	-	-	not required.	Connected to generation bus. So, violating the criteria .
7-8	0.62	0.65	0.03	0.161	0.1863	
5-7	2.73	3.4	0.67	0.161	4.1615	Proper place for TCPAR Placement. Run NRLF after placement of TCPAR. In case of any violations,% compensation(or proper angle) to be adjusted
8-9	0.82	0.83	0.01	0.161	0.0621	
3-9	-	-	-	-	Calculation not required.	Connected to generation bus . So, violating the criteria of optimal placement of TCPAR.
6-9	0.001	0.001	0	0.0001	0	
4-5	-	-	-	-	-	Under contingency
4-6	-	-	-	-	-	Under contingency
4-1	-	-	-	-	not required.	Connected to generation bus. So, violating the criteria.

6.3 Advantages of using the technique

This method is very useful as it is developed on consideration of reduction of real power loss

(P_{lk}) of lines. It is very simple and useful in case of both single and multiple contingency conditions. This method explains how to treat the network after the placement of the FACTS devices

and also works fine with respect to change of generation. It is transparent with both heavy and light loads. So, the technique is very useful and advantageous compare to other contemporary techniques .

To prove the efficacy of our work, we are comparing the method with ref. [16] method. The comparison is listed in Table-7:

Table-7 : Comparison of the methods

Reference [16]Method	Proposed Method
This method is used for only small test systems. e.g- 5 bus and IEEE 14bus system.	Our work extends for larger test systems. e.g- WSCC-3-machine-9 bus and IEEE 57 bus test system
This method is used for only single contingency case studies.	This work extends for even multiple contingency case studies.
This method is unable to handle overloading cases of lines after FACTs placement through single method.	This method can handle overloading cases of lines through single approach.

7.Conclusions

An optimal FACTs device placement method based on sensitivity analysis is developed in this paper. The differential of real power loss is taken with respect to FACTs device control parameters (TCSC reactance and TCPAR phase angle). Calculation of indexes are also shown in this paper with examples. After placing TCSC or TCPAR, the NRLF is run using Power World simulator. If there is no overload condition observed, then the result is correct. But in case, if any violation of limit is taken place, then how to treat the condition that is also discussed in this paper. Apart from that a rigorous analysis is done about the more suitable FACTs device between TCSC and TCPAR for the power network in this paper. The effect of changes in generation and advantages of using the proposed technique are also discussed in the paper. A comparison with other method is also discussed in this context. Analysis using multiple contingency cases is novel in this paper and in future extension of the work can be, to be implemented on larger wide area systems(e.g-IEEE 118 bus , IEEE 300 bus systems or practical systems like Northern Regional Power Grid or Southern Regional Power Grid etc.) with more number of contingency combinations(e.g- different lines, generators and buses etc.). It is expected that this analysis will be helpful for industry practitioners, for choosing appropriate FACTs device for their work.

Appendix

All the test system data are obtained from Ref.[22] and Ref.[23].

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