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Contingency Analysis and Improvement of Power System Security by locating Series FACTS Devices "TCSC and TCPAR" at Optimal Location

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ABSTRACT: *Stressed power system, either due to increased loading or due to severe contingencies, it will lead to situation where system no longer remains in the secure operating region. Under these situations, it is primary objective of the operator to apply control action to bring the power system again into the secure region. Any delay or unavailability of suitable control leads to the unstable system. In fact, contingencies results into voltage limit violations and leads to overloading of lines. The system overloading can be recover by two alternatives firstly by restructuring the power system and secondly by controlling the line parameters. The Power system restructuring requires expanding unused potentials of transmission systems but environmental, right-of-way, and cost problems are major hurdles for power transmission network expansion. Nowadays, FACTS devices are used as an alternative to reduce the flows in heavily loaded lines, it will results in an increased loading, low system loss, improved stability of the network, reduced cost of production. In this paper, first contingency conditions are analyzed after that according to severity of contingency a real power flow performance index (PI) sensitivity based approach and the line outage distribution factor has been used to decide optimal location of series FACTS devices ,Thyristor controlled series compensator(TCSC) and Thyristor controlled phase angle regulator(TCPAR) to restabilize the system. The effectiveness of the proposed controller has been tested on modified IEEE 14 bus system using Power world simulator 12.0 software.*

Keywords: *Optimal location of series FACTS device, Thyristor controlled series compensator (TCSC), Thyristor Controlled Phase Angle Regulator (TCPAR), Contingency analysis, Sensitivity (Severity) index method, Line outage distribution factor (LODF) , Power World Simulator Software version 12.0.*

I. INTRODUCTION

Electric utilities are forced to operate the system close to their thermal and stability limits due to major hurdles such as environmental, right-of-way and cost problems for power transmission network expansion. Controlling the power flow in an electric power system without generation rescheduling or topological changes can improve the performance considerably. Hence, there is an interest in better utilization of available capacities by installing Flexible AC Transmission System (FACTS) devices such as thyristor controlled series compensators, thyristor controlled phase angle regulators and unified power flow controllers etc. These devices, by controlling the power flows in the network, can help to reduce the flows in heavily loaded lines, resulting in an increased loadability, low system loss, improved stability of the network and reduced cost of production. The increased interest in these devices is essentially due to increased loading of power systems and deregulation of power industry.

In power system without violating specified power dispatch addition of controllable components such as controllable series FACTS devices can changed line flows in such a way that, losses minimized, thermal limits are not violated ,stability margin increased, contractual requirement fulfilled etc. FACTS devices have considerable high cost, so placement of FACTS devices at Optimal location is a very important concept, so as to recover the overloaded system economically and regain the system security as early as possible.

The purpose of this paper is to locate the FACTS devices at Optimal location for eliminating the insecurity of power system. A method to determine the optimal locations of thyristor controlled series compensators (TCSC) and thyristor controlled Phase Angle Regulator (TCPAR) has been suggested [1]. The proposed algorithm has been demonstrated on a modified IEEE 14 bus system.

II. MODELING OF FACTS DEVICES TCSC AND TCPAR

Here an injection model has been used to calculate the sensitivity of real power flow performance index with respect to control parameters [1]. The model of a transmission line with series impedance $z_{ij} = \left(r_{ij} + jx_{ij}\right)$ and a TCSC connected between bus-i and bus-j is shown in Fig. 1. Let complex voltages at bus-i and bus-j are $V_i\angle\delta_i$ and $V_j\angle\delta_j$ respectively. During the steady state the TCSC can be considered as a static reactance $-jX_c$.

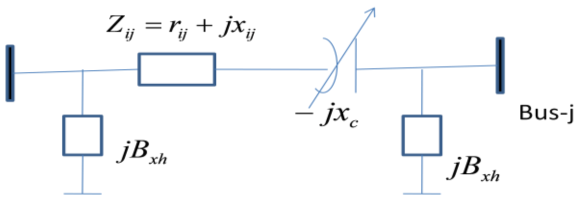

Fig.1. Model of TCSC

The change in the line flow due to series capacitance can be represented as a line without series capacitance with power injected at the receiving and sending ends of the line as shown in Fig. 2. The real power injections at bus-i (P_{ic}) and bus-j (P_{jc}) can be expressed as [3],

$$P_{ic} = V_i^2\Delta G_{ij} - V_iV_j[\Delta G_{ij}\cos\delta_{ij} + \Delta B_{ij}\sin\delta_{ij}] \tag{1}$$

$$P_{jc} = V_j^2\Delta G_{ij} - V_iV_j[\Delta G_{ij}\cos\delta_{ij} - \Delta B_{ij}\sin\delta_{ij}] \tag{2}$$

Where $\Delta G_{ij} = \dfrac{x_c r_{ij}(x_c - 2x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)}$ and $\Delta B_{ij} = \dfrac{-x_c(r_{ij}^2 - x_{ij}^2 + x_c x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)}$

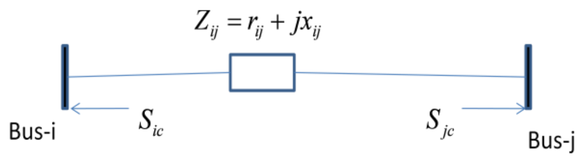

Fig. 2. Injection model of TCSC

In TCPAR , the phase shift is accomplished by adding or subtracting a variable voltage component in perpendicular to the phase voltage of the line. The static model of a TCPAR in a transmission line between bus-i and bus-j is shown in Fig. 3. From the basic circuit theory, the injected equivalent circuit of Fig. 4 can be obtained. The injected active power at bus-i (P_{is}) and bus-j (P_{js}) of a line having a phase shifter can be written as [1]. Here $K = \tan\phi$

$$P_{is} = -V_i^2K^2G_{ij} - V_iV_jK[G_{ij}Sin\delta_{ij} - B_{ij}Cos\delta_{ij}] \tag{3}$$

$$P_{js} = -V_iV_jK[G_{ij}Sin\delta_{ij} + B_{ij}Cos\delta_{ij}] \tag{4}$$

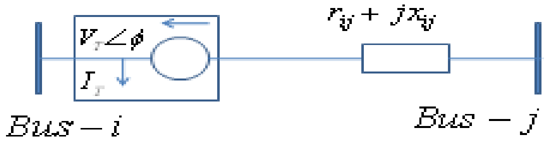

Fig.3. Equivalent circuit of TCPAR

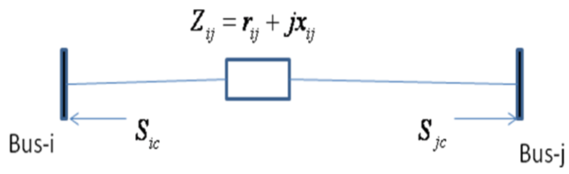

Fig .4. Injection model of a TCPAR

III. METHODOLOGY AND SOLUTION TECHNIQUE

Energy control centre mainly performs three functions for system security are - System monitoring, Contingency analysis and Corrective action plan. From the above discussion it is observed that there are several methods for finding the optimal location of FACTS devices like Sensitivity Approach, Line Outage Distribution Factor, Genetic Algorithm, Particle Swarm Optimization method. In this paper the whole procedure divided into two parts. First the contingency analysis will be perform by line outage distribution factor after that for removing the effect of contingency conditions from the system optimal location of FACTS devices are done by Sensitivity index method.

IV. LINE OUTAGE DISTRIBUTION FACTOR

Line outage distribution factors gives the effect of lost of any line in a system which results into overloading of a particular line. It is defined as, the change in flow on a line as a percentage of the pre outage flow on another line. Using LODF's it is possible to efficiently determine how line outage of one line will affects other line in the system.

$$d_{l,i} = \frac{\Delta f_l}{f_i^\circ} \tag{5}$$

Where, $d_{l,i}$ = line outage distribution factor when monitoring lth line after an outage of ith line, Δf_l = change in MW flow on lth line and f_i° = precontingency line flow on ith line.

IV.I. CRITERIA FOR OPTIMAL LOCATION OF SERIES FACTS DEVICE BY LODF METHOD

The series FACTS device should be placed on the most sensitive lines. The device should be placed in a line having most negative line outage distribution factor.

IV.II. TEST CASE AND RESULTS BY LODF METHODS

The proposed method for optimal location of series FACTS device has been tested on modified IEEE-14 bus system by using Power world simulator software 12.0. In modified IEEE-14 bus system, line 3-4 is a outaged line. The critical line outages were computed by line outage distribution factor for a single line outage case.

Table 1. % LODF on modified IEEE 14-bus system when line 3-4 is outage

Line	From bus i to j	%LODF	Ranking
1	1-5	0.2283	1
2	2-5	0.3582	2
3	2-4	0.484	3

From above Table 1 , it is found that placement of series FACTS device in line 1-5 is suitable for removing overloading present in line 1-2 , which is the most negative line outage distribution factor . Placement of series FACTS device in lines 2-5 and 2-4 will be less effective than line 1-5 .

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V. REAL POWER FLOW PERFORMANCE INDEX

The severity of the system loading under normal and ,contingency cases can be described by a real power line flow performance index [1] as given below.

$$PI = \sum_{m=1}^{N_l} \frac{w_m}{2n} \left(\frac{P_{lm}}{P_{lm}^{\max}} \right)^{2n} \tag{6}$$

Where , P_{lm} is the real power flow , $P_{lm}^{\max}$ is the rated capacity of line-m, n is the exponent and W_m is a real nonnegative weighting coefficient which may be used to reflect the importance of lines.

PI will be small when all the lines are within their limits and reach a high value when there are overloads. Thus, it provides a good measure of severity of the line overloads for a given state of the power system. Most of the work on contingency selection algorithms utilize the second order performance indices which in general, suffers from masking effects. The lack of discrimination, in which the performance index for a case with many small violations may be comparable in value to the index for a case with one huge violation, is known as Masking effect. By most of the operational standards, the system with one huge violation is much more severe than that with many small violations. Masking effect to some extent can be avoided by using higher order performance indices, that is n > 1. However, in this study, the value of exponent has been taken as 2 and W_m = 1.0.

VI. SENSITIVITY ANALYSIS

Since the number of contingencies in a power system is very large, it is not possible to run the OPF for checking the suitability of the FACTS devices in both planning and operational studies. A sensitivity approach has been used to see the suitability of the FACTS devices in the line.[1] . The real power flow PI sensitivity factors with respect to the parameters of TCSC can be defined as,

$$\alpha_k^c = \frac{\partial PI}{\partial X_{ck}} \Big|_{X_{ck}=0}$$ = PI sensitivity w.r.t. TCSC placed in line-k

Using equation (6), the sensitivity of PI with respect to FACTS device parameter X_k (X_{ck} for TCSC) connected between bus-i and bus-j, sensitivity factors α_k^c can be written and calculated as

$$\frac{\partial PI}{\partial X_k} = \sum_{m=1}^{NL} w_m P_{lm}^{\ 3} \left(\frac{1}{P_{lm}^{\max}} \right)^4 \frac{\partial P_{lm}}{\partial X_k} \tag{7}$$

The real power flow PI sensitivity factors with respect to the parameters of TCPAR can be defined as, Using equation (6), the sensitivity of PI with respect to FACTS device parameter X_k (ϕ_k for TCPAR) connected between bus-i and bus-j, can be written as

$$\alpha_k^s = \frac{\partial PI}{\partial \phi_k} = \sum_{m=1}^{Nl} w_m P_{lm}^{\ 3} \left(\frac{1}{P_{lm}^{\max}} \right)^4 \frac{\partial P_{lm}}{\partial \phi_k}$$ = PI sensitivity with respect to TCPAR placed in line-k

(8)

Here transformer is inserted, the reactance is 0.1j has been considered. Putting all above values in equation (8) will give us the new sensitivity factor when TCPAR is employed in the system i.e. α_k^s. From this factors first sensitivity has been calculated manually and then it is being verified by simulation results.

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VII. SIMULATION RESULTS

The proposed method has been tested on modified IEEE 14 bus system, which consists of 5 generators and 20 transmission lines. The generator and transmission –line data relevant to the system are taken from IEEE standard 14 bus system. The slack bus bar voltage was fixed to its specified value of 1.06 p.u.. Fig (5) shows the modified IEEE 14 bus system and Fig (6) shows contingency effect when line 3-4 is outaged it will overload line 1-2 from 103% to 107%.

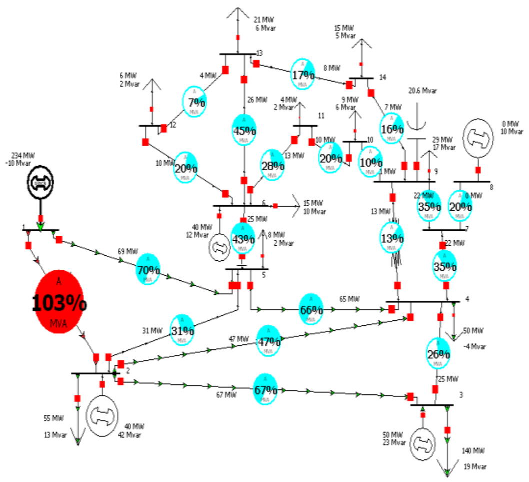

Fig. 5. Modified IEEE 14 bus system

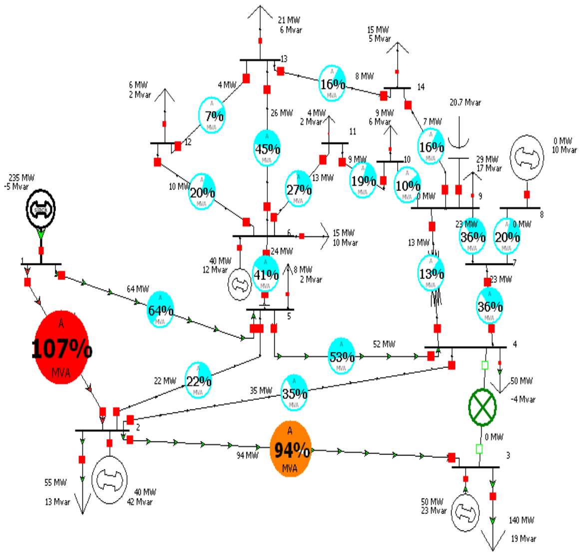

Fig. 6. Modified IEEE 14 bus in which line 1-2 is overloaded when 3-4 line is outaged

VII.I. CRITERIA FOR OPTIMAL LOCATION OF TCSC(By Real Power Flow Performance Index Method)
The FACTS device should be placed on the most sensitive lines. The Criteria for Optimal Location of TCSC device is based on sensitivity index computed by equation (7). The TCSC should be placed in a line k having most negative sensitivity index.

VII.I.I. TEST CASE AND RESULTS FOR TCSC (By Real Power Flow Performance Index method)
The Placement of TCSC is obtained on the basis of real Power flow Performance index method. It is assumed that the limits of the compensation of series reactance is assumed as $\pm 37\%$ The results of the sensitivity factor of modified IEEE 14 bus system are as shown in Table (2).

Table.2. Sensitivity Factor of Modified IEEE 14 bus system for TCSC (when line 3-4 outaged)

Line K	From bus i to bus j	Sensitivity factor α_k^c	Ranking
1	1-5	20.050	1
2	2-5	21.4055	2
3	2-4	22.3782	3

Sensitivity Factor for heavily loaded lines are presented in Table (2). Table (2) shows that the placement of TCSC in line 1-5 is most sensitive as compare to other lines. The Placement of TCSC in line 1-5 will reduce the loading of line 1-2. The best location of TCSC is line 1-5.

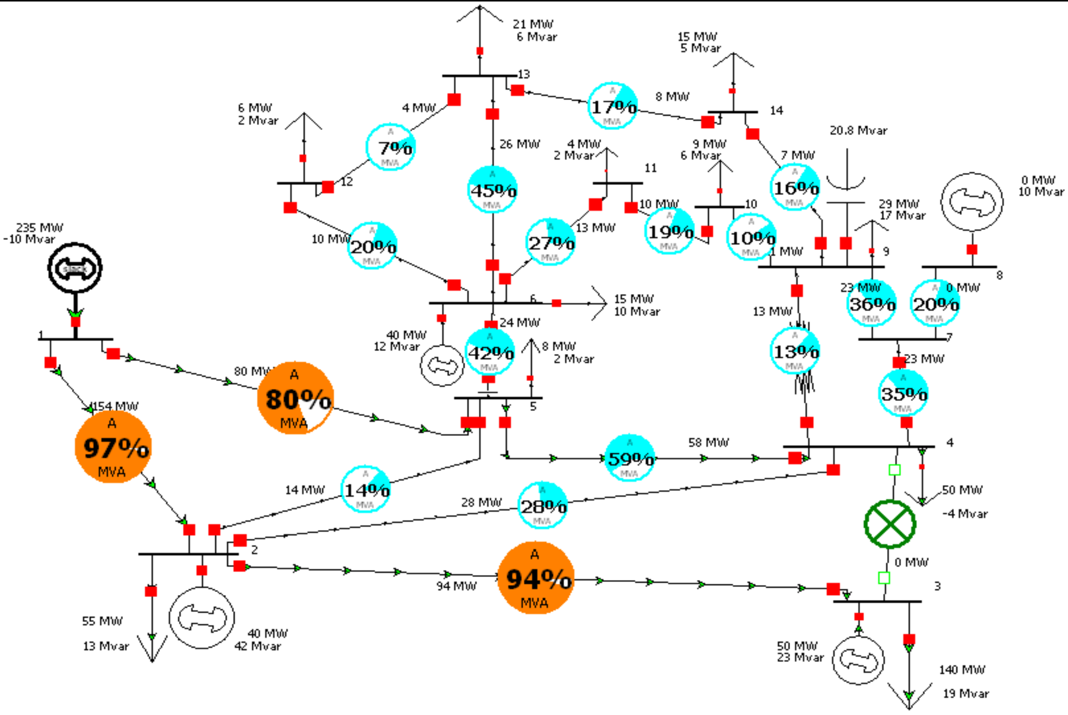

Fig .7. Modified IEEE 14 bus system with TCSC is placed in line 1-5

Initially line 1-2 is most sensitive having overloading 107% but when TCSC is placed in line 1-5 with -37% reactance compensation , it decreases to 97% as shown in Fig.(7). Fig (8) and (9) shows when TCSC is placed in line 2-5 and 2-4 overloading of line 1-2 will be decreases from 107% to 106%.

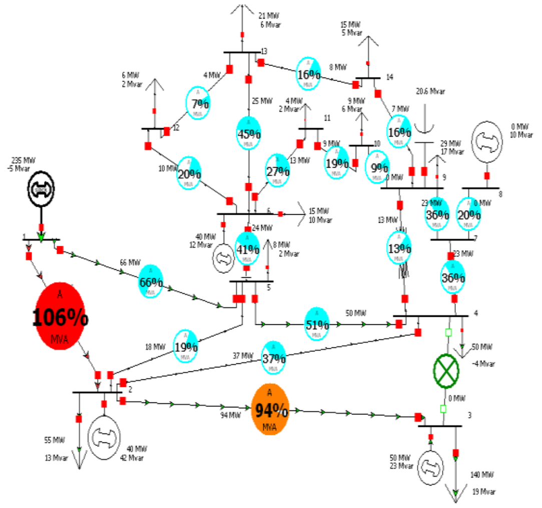

Fig. 8. Modified IEEE 14 bus system with TSCS placed in line 2-5

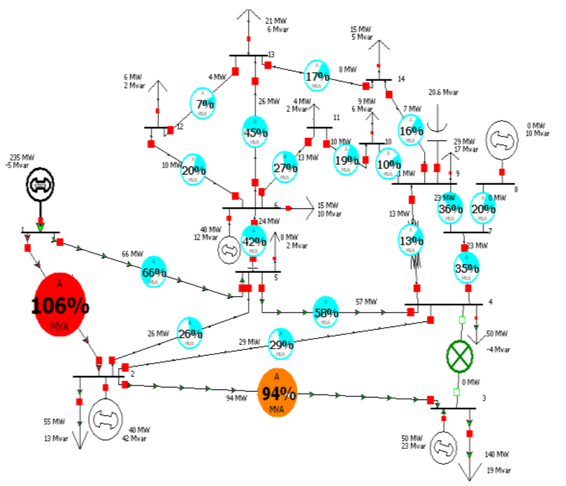

Fig .9. Modified IEEE 14 bus system with TCSC is placed in line 2-4

VI.II. CRITERIA FOR OPTIMAL LOCATION OF TCPAR (By Real Power Flow Performance Index Method)

The FACTS device should be placed on the most sensitive lines. The Criteria for Optimal Location of TCPAR device is based on sensitivity index computed by equation (8). The TCPAR should be placed in a line k having highest value of the sensitivity index.

VI.II.I. TEST CASE AND RESULTS FOR TCPAR (By Real Power Flow Performance Index method)

The Placement of TCPAR is obtained on the basis of real Power flow Performance index method. It is assumed that the limits of the phase shifting angles of TCPARs were taken as $\pm 30^\circ$. The results of the sensitivity factor of modified IEEE 14 bus system are as shown in Table (3).

Table.3. Sensitivity Factor of Modified IEEE 14 bus system for TCPAR (when line 3-4 outaged)

Line K	**From bus i to bus j**	**Phase Shift (ϕ)**	**Sensitivity factor (α_k^s)**	**Ranking**
1	1-5	-10	-326.87	1
2	2-5	11.5	-329.78	2
3	2-4	10	-330.03	3

Sensitivity Factor for heavily loaded lines are presented in Table (3). Table (3) shows that the placement of TCPAR in line 1-5 is most sensitive as compare to other lines. The Placement of TCPAR in line 1-5 will reduce the loading of line 1-2. The best location of TCPAR is line 1-5.

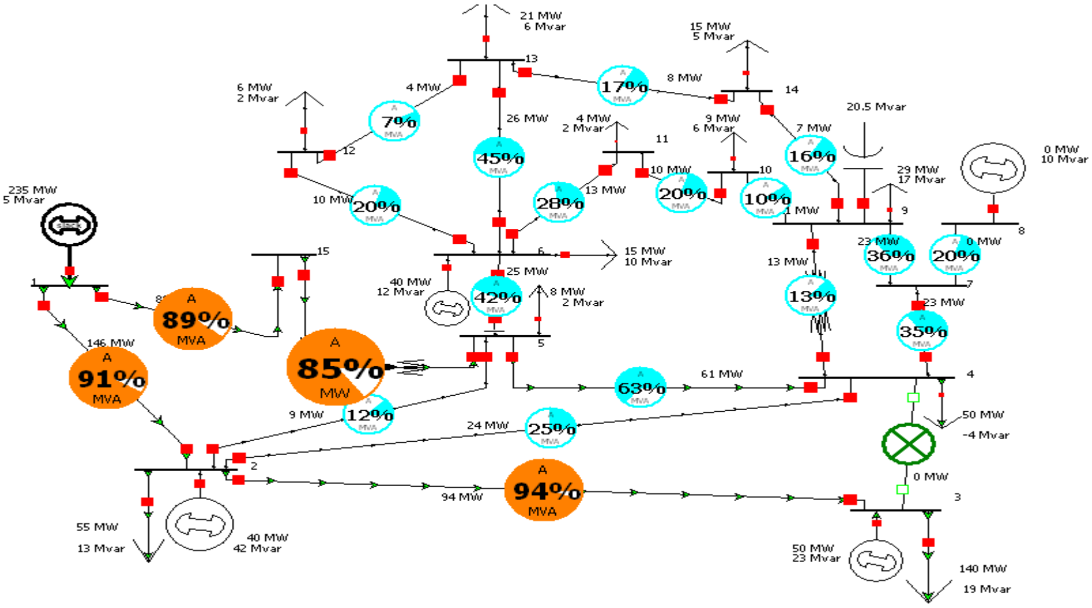

Fig .10. Modified IEEE 14 bus system with TCPAR is placed in line 1-5

Fig.10. shows the TCPAR placed in line 1-5 removes the overloading. Here one new bus i.e. bus no. 15 has been added in the system and for phase shifting a transformer is connected between new added bus and bus no.5. It will change the phase shift between line 1-5. The Fig. 10. shows that, the power flow is within range and hence we will get back the system to its stable state . TCPAR placement in line 1-5 will reduce the overloading from 107% to 91%, which shows that the system came back to its stable condition. Here, -10° phase shift compensation has been used. Similarly, Fig.11. shows that the TCPAR is placed in line 2-5. It will reduce the congestion present in line 1-2 from 107% to 92% . Here, 11.5° phase shift compensation has been used. Fig.12. shows that the TCPAR is placed in line 2-4. It will reduce the congestion present in line 1-2 from 107% to 96%. Here, 10° phase shift compensation has been used.

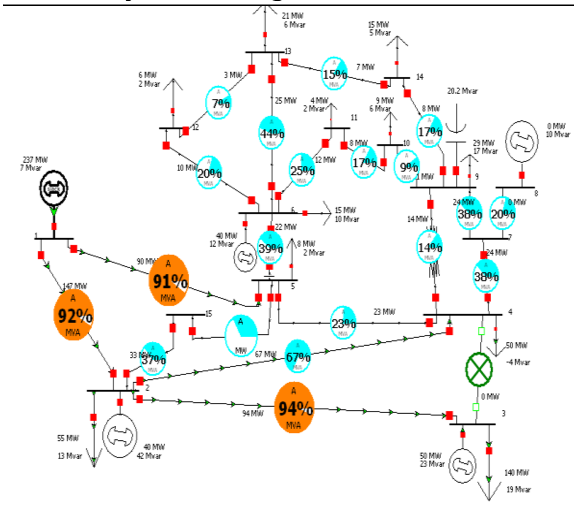

Fig.11. Modified IEEE 14 bus system with TCPAR placed in line 2-5

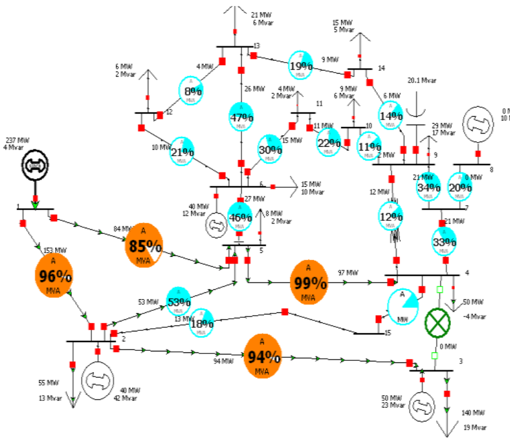

Fig .12. Modified IEEE 14 bus system with TCPAR is placed in line 2-4

VIII. CONCLUSION

In this paper , a sensitivity based approach has been used for determining the optimal placement of TCSC and TCPAR. In a congested system, the optimal locations of TCSC & TCPAR can be effectively decided based on the real power flow Performance index. Sensitivity factors which indicates the reduction of the total system real power loss and will also improve the system voltage profile. In this paper first line outage distribution factor has been calculated after that sensitivity index is being calculated and on comparing both the results we get the same ranking for TCSC and TCPAR and from that it is concluded that the best suitable Optimal location of TCSC and TCPAR is on line 1-5. The effectiveness of the sensitivity method has been tested on Modified IEEE 14 bus system by using Power world Simulator Software Version 12.0. From both the methods and from Power world simulator results, it is concluded that TCPAR device is more appropriate than TCSC and in the assumed modified IEEE 14-bus system, 1-5 line is the best Optimal location for both the devices.

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