Sensitivity Based Allocation of FACTS Devices in a Transmission System Considering Differential Analysis

V. Srinivasa Rao[1,2], M. Ravindra[2,3(✉)], A. S. Veerendra[2,3], R. Srinivasa Rao[2,4], A. Ramesh[2,3], and K. Manoz Kumar Reddy[2,3]

[1] Department of Electrical and Electronics Engineering, Aditya Engineering College (A), Surampalem, India
[2] Jawaharalal Nehru Technological University Kakinada, Kakinada, India
connectvsr@gmail.com
[3] Department of Electrical and Electronics Engineering, Aditya College of Engineering, Surampalem, India
[4] Department of Electrical and Electronics Engineering, University College of Engineering Kakinada, JNTUK, Kakinada, India

Abstract. This research proposes a differential analysis for determining the suitable location for FACTS devices (TCSC) and TCPAR to enhance network security during single-line outages (N-1). To ensure optimal device deployment when dealing with sensitivity variables, the proposed technique is based on performance index (PI) and ranking index (RI). The severity of the line in the network is ranked by the contingency case. The system loading level for a specific outage is computed using RI. Differentiating the proposed performance index (PI) applied to system parameters of TCSC and TCPAR yields sensitivity factors. The sensitivity factors determined by RI are utilized to determine best placement of TCSC and TCPAR devices. The goal of this problem is to reduce line overloads on transmission lines in the event of a network outage. The proposed technique is tested in a MATLAB environment on IEEE 5 bus and 14 bus networks.

Keywords: TCSC · TCPAR · performance index · sensitivity approach · differential analysis

1 Introduction

Power system is large integrated set with several devices and different types of equipment located at various places via transmission lines, such as generators and transformers. Any outage of these cables can affect system reliability, hence security of this equipment is critical. As complexity of operating system grows, devices are necessary to operate systems at close to confined limitations. Without rescheduling generating or making network improvements, Power Flow (PF) regulation in a network can significantly improve system performance. As a result, it is possible to use FACTS in a network to enhance power system's steady-state security [1]. FACTS can change line flows in process to

minimise losses while maintaining stability without breaching specified load flow and economic dispatch limitations. Because FACTS devices are preferably high-cost, their deployment at the optimal site is required to increase power flow performance in an overloaded system while also ensuring system security and dependability. For the best locations and parameter settings of FACTS devices, several approaches are presented. S.N. Singh et al. [2] used sensitivity analysis to establish the optimal deployment of FACTS devices and PF performance. R. Srinivasa Rao et al. [3] proposed sensitivity indices and RPFPI sensitivity indices using a generalised technique to determine the best site for FACTS allocation. FACTS devices have become more expensive as modern power electronics has progressed [4]. In their investigation, they took into account the influence of generational shift as well as the comparison of various strategies. However, they failed to examine the impact of various network circumstances while placing the TCSC, as well as the optimum FACTS device to deal with the problem. H.M. Ravi Kumar et al. [5] used a three-step process to discover the best settings, position, and number of TCSC to reduce transmission line burdens during network failures or contingencies. To discover the optimal TCSC deployment and parameters, H.I. Shaheen et al. [6] employed GA and PSO. For calculating the optimum TCSC deployment and size for a system network, the authors proposed a unique decomposition technique [7]. The authors developed a FACTS device placement technique based on multi-objective optimization [8]. The authors of [9] devised a mixed-ILP based technique for TCSC allocation. The authors proposed a method for boosting security by gradually limiting FACTS device operational points [10]. The Researchers considered line to locate and set up the perfect TCSC. When it comes to modelling meshed networks, however, LFB equations appear to be ineffective. So, the use of LFB calculations in FACTS location problem is restricted. According to TCSC and TCPAR requirements, its use aids in reduction of PFs on densely loaded energy transmission lines. Both active and reactive energy can be controlled by these energy flow controllers. Authors proposed a branch flow model for the analysis and optimization of mesh as well as radial networks [11].

The key contribution in paper is to consider the Real PF Performance Index (RPFI) to place devices optimally under a single line contingency (N1 contingency). Energy management solutions are used as an alternative to rigid planning in contingency based planning, and by partially differentiating RPFI subject to the parameter of the device to be optimised, sensitivity indices are constructed. Under single line contingency, this method is used to locate TCSC and TCPAR on IEEE 5 bus and 14 bus systems.

2 Static Modelling of TCSC and TCPAR

2.1 Thyristor Controlled Series Compensator

Figure 1 depicts a network line model with a TCSC connected to bus-i and bus-j.

$$P_{ij}^c = V_i^2 G_{ij}^{'} - V_i V_j \left[G_{ij}^{'} \cos \delta_{ij} + B_{ij}^{'} \sin \delta_{ij} \right] \tag{1}$$

$$Q_{ij}^c = -V_i^2 \left(B_{ij}^{'} + B_{sh} \right) - V_i V_j \left[G_{ij}^{'} \sin \delta_{ij} - B_{ij}^{'} \cos \delta_{ij} \right] \tag{2}$$
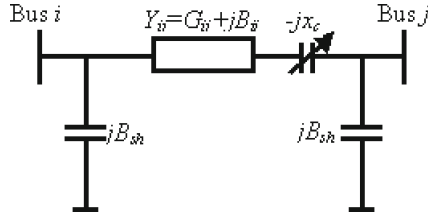
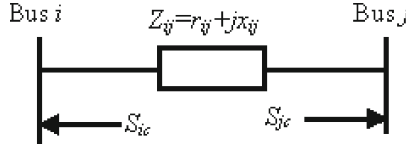**Fig. 1.** Transmission Network with TCSC

Fig. 2. TCSC Injection

$$P_{ji}^c = V_j^2 G_{ij}' - V_j V_i \left[G_{ij}' \cos \delta_{ij} - B_{ij}' \sin \delta_{ij} \right] \tag{3}$$

$$Q_{ji}^c = -V_j^2 \left(B_{ij}' + B_{sh} \right) + V_j V_i \left[G_{ij}' \sin \delta_{ij} + B_{ij}' \cos \delta_{ij} \right] \tag{4}$$

The active power los in line-k, which connects buses i and j, is calculated as follows:

$$P_{Lk}^c = (V_i^2 + V_j^2) G_{ij}' - 2V_i V_j G_{ij}' \cos \delta_{ij} \tag{5}$$

where $G_{ij}' = \frac{r_{ij}}{r_{ij}^2 + (x_{ij} - x_c)^2}$ and $B_{ij}' = \frac{-(x_{ij} - x_c)}{r_{ij}^2 + (x_{ij} - x_c)^2}$.

Equal power injections at the receiving and sending lines demonstrate the effect of series capacitance on PF in Fig. 2. Real power injections on both ends at bus-i and bus-j can be described using basic circuit theory as

$$P_{ic} = V_i^2 \Delta G_{ij} - V_i V_j \left[\Delta G_{ij} \cos \delta_{ij} + \Delta B_{ij} \sin \delta_{ij} \right] \tag{6}$$

$$P_{jc} = V_j^2 \Delta G_{ij} - V_j V_i \left[\Delta G_{ij} \cos \delta_{ij} - \Delta B_{ij} \sin \delta_{ij} \right] \tag{7}$$

Similarly, at *bus-i* (Reactive power Q_{ic}) and *bus-j* (Q_{jc}) are injected and can be displayed as follows;

$$Q_{ic} = -V_i^2 \Delta B_{ij} - V_i V_j \left[\Delta G_{ij} \sin \delta_{ij} - \Delta B_{ij} \cos \delta_{ij} \right] \tag{8}$$

$$Q_{jc} = -V_j^2 \Delta B_{ij} + V_i V_j \left[\Delta G_{ij} \sin \delta_{ij} + \Delta B_{ij} \cos \delta_{ij} \right] \tag{9}$$

$$\Delta G_{ij} = \frac{x_c r_{ij} (x_c - 2x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)} \tag{10a}$$

$$\Delta B_{ij} = \frac{-x_c (r_{ij}^2 - x_{ij}^2 + x_c x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)} \tag{10b}$$

2.2 Thiristor Controlled Phase Angle Regulator (TCPAR)

TCPAR's Static Model [12] and the transmission line between and are shown in Fig. 3. The real and reactive PFs following TCPAR deployment are shown below.

$$P_{ij}^s = V_i^2 T^2 G_{ij} - V_i V_j T \left[G_{ij} \cos(\delta_{ij} + \phi) + B_{ij}\sin(\delta_{ij} + \phi) \right] \tag{11}$$

$$Q_{ij}^s = -V_i^2 T^2 B_{ij} - V_i V_j T \left[G_{ij} \sin(\delta_{ij} + \phi) - B_{ij}\cos(\delta_{ij} + \phi) \right] \tag{12}$$

$$P_{ji}^s = V_j^2 G_{ij} - V_j V_i T \left[G_{ij} \cos(\delta_{ij} + \varphi) - B_{ij} \sin(\delta_{ij} + \varphi) \right] \tag{13}$$

$$Q_{ji}^s = -V_j^2 B_{ij} + V_j V_i T \left[G_{ij} \sin(\delta_{ij} + \varphi) + B_{ij} \cos(\delta_{ij} + \varphi) \right] \tag{14}$$

$$P_{Lk}^s = V_i^2 T^2 G_{ij} + V_j^2 G_{ij} - 2 V_i V_j T G_{ij} \cos(\delta_{ij} + \phi) \tag{15}$$

The injected equivalent circuit (Fig. 4) is created using circuit theory concepts.

The active and reactive powers of a transmission line with a phase shift are expressed as

$$P_{is} = -V_i^2 K^2 G_{ij} - V_i V_j K \left[G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij} \right] \tag{16}$$

$$P_{js} = -V_i V_j K \left[G_{ij} \sin \delta_{ij} + B_{ij} \cos \delta_{ij} \right] \tag{17}$$

$$Q_{is} = V_i^2 K^2 B_{ij} + V_i V_j K \left[G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij} \right] \tag{18}$$

$$Q_{js} = -V_i V_j K \left[G_{ij} \cos \delta_{ij} - B_{ij} \sin \delta_{ij} \right] \tag{19}$$
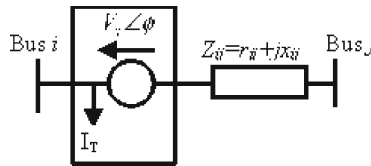
$$K = \tan(\phi)$$

Fig. 3. Transmission Network with TCPAR
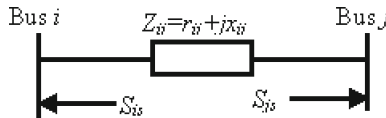

Fig. 4. TCPAR Model

3 Optimal Allocation of TCSC and TCPAR Considering Differential Analysis

3.1 Ranking Index

In order of severity, a contingency ranking is computed [13, 14]. For example, a ranking index (RI) is considered to determine level of system network loading following a certain outage.

$$RI = \frac{1}{b} \sum_{k=1}^{b} \left(\frac{|P_{f_k}|}{P_{f_k}^{max}} \right) \tag{20}$$

where P_{f_k} - branch flow of element k, $P_{f_k}^{max}$ - rated capacity of line-k

The line outage distribution factors are designated $\rho_{k,1}$:

$$\rho_{k,l} = \frac{\Delta P_k}{P_l^0} \tag{21}$$

where $\rho_{k,1}$ - line outage distribution factor when monitoring *line-k* after an outage on *line-l*, ΔP_k - change in PF on *Line-k*, P_l^0 - original PF on *Line-l* before it was outage (opened).

After all probable contingencies have achieved RI, they are assessed in ascending order.

3.2 Sensitivity Indices (PI)

The equation's PI depicts severity of network loads under ordinary and contingency conditions.

$$PI = \sum_{m=1}^{N_l} \frac{W_m}{2n} \left(\frac{P_{lm}}{P_{lm}^{max}} \right)^{2n} \tag{23}$$

where, W_m - real nonnegative weight coefficient, P_{lm} - RPF and P_{lm}^{max} - rated capacity of line-*m*. The exponent *n* reflects significance of lines

PI is a metric for determining the severity of line overloading. The value of the exponent is set to 2.0, while weight coefficient is set to 1.0. Sensitivity factor is written as a differentiation of PI exposed to capacitive reactance, and on a phase controlled basis, as a differentiation of PI subjected to phase angle shift, as shown below.

$$c_k^c = \left.\frac{\partial PI}{\partial x_{ck}}\right|_{x_{ck}=0} = PI\ Sensitivity\ w.r.t\ TCSC\ in\ Line\text{-}k.$$

$$c_k^s = \left.\frac{\partial PI}{\partial \phi_k}\right|_{\phi_k=0} = PI\ Sensitivity\ w.r.t\ TCPAR\ in\ Line\text{-}k.$$

It is possible to calculate PI's sensitivity to device parameters as

$$\frac{\partial PI}{\partial X_k} = \sum_{m=1}^{N_l} W_m\, P_{lm}^3 \left(\frac{1}{P_{lm}^{\max}}\right)^4 \frac{\partial P_{lm}}{\partial X_k} \tag{24}$$

The sum of actual power injections can be represented by the active power flowing via line-m utilizing DC load flow equation [17]. 'S' stands for slack bus

$$P_{lm} = \begin{cases} \displaystyle\sum_{n=1,n\neq s}^{N} S_{mn}P_n & for\ m \neq k \\ \displaystyle\sum_{n=1,n\neq s}^{N} S_{mn}P_n + P_j & for\ m \neq k \end{cases} \tag{25}$$

S_{mn} is the mn^{th} element of the matrix [Sf] that connects line PF to power injections on buses without FACTS [17].

Figure 1 shows an excess flow of Pj at bus-j in Line-k (between buses i and j) when the FACTS device is installed. The equation can be constructed using (24) and (25)

$$\frac{\partial P_{lm}}{\partial X_k} = \begin{cases} \left(S_{mi}\frac{\partial P_i}{\partial X_k} + S_{mj}\frac{\partial P_j}{\partial X_k}\right) & for\ m \neq k \\ \left(S_{mi}\frac{\partial P_i}{\partial X_k} + S_{mj}\frac{\partial P_j}{\partial X_k}\right) + \frac{\partial P_j}{\partial X_k} & for\ m = k \end{cases} \tag{26}$$

3.3 Optimal Allocation of TCPAR and TCSC Based on RI and PI

Criteria
On the most sensitive line, the TCSC and TCPAR have to be placed. The following are the main criteria used to determine the best location for a device:

i)   TCSC is sited in line with lowest sensitivity index.
ii) The TCPAR is sited in line with highest absolute sensitivity factor.
iii) Even if the sensitivity is highest, the TCSC and TCPAR have not be positioned in a generation bus line.
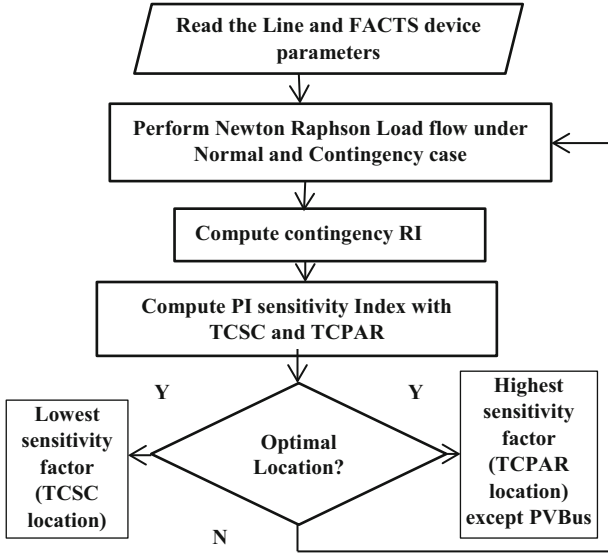
Algorithm (Fig. 5)

Fig. 5. TCPAR and TCSC location based on RI and PI.

4   Results and Analysis

The proposed technique is put to the test on two different test cases with five and fourteen buses, respectively, and line outages. The simulations are run in MATLAB environment, with results displayed.

4.1   5-Bus System

The 5-bus network is made up of three generators, two load buses, and six transmission lines [14]. The lines 1-2 and 1-4 each have (0.002 + j0.01) p.u and 0.002 p.u shunt susceptance, while the other four lines have a p.u and 0.004 p.u shunt susceptance. 100 MVA is used as the starting point. The line flow limit is set at 800 MW, with bus-5 serving as the reference bus. Table 1 shows the electricity flows without the FACTS device with contingency. According to Table's base load flow solutions using the N-R technique, active PFs in the base case were 8.97 p.u, which is greater than the line loading limit, and in the event of a line outage, it is demonstrated that it is overloaded in vast majority of situations, excluding outage scenarios. In the event that the line is overloaded. The overloaded lines are bolded in the last row. The TCSC and TCPAR FACTS are used in this study Under similar operating conditions, sensitivity values are generated one by one for each control parameter of the FACTS device attached to each line.

Table 1. Line flow (in p.u) under normal condition for 5 bus system

Line-k		Power flows (in p.u)						
		No outage	Line outages					
No	i-j	Base case	1-2	1-3	1-4	2-5	3-4	4-5
L1	1-2	0.96	–	−0.53	−3.52	5.08	1.38	−1.2
L2	1-3	−6.99	−6.80	–	**−11.5**	−7.82	**−9.61**	7.43
L3	1-4	**−8.97**	**−8.20**	−14.5	–	**−12.3**	−6.77	**10.0**
L4	2-5	−4.04	−5.00	−5.53	**−8.59**	–	−3.62	3.10
L5	3-4	2.79	3.00	**10.0**	2.40	1.81	–	−2.5
L6	4-5	1.06	2.05	2.07	5.07	−3.41	0.55	–
Over loads		L3	L3	L3 & L5	L2 & L4	L3	L2	L3

Table 2. Sensitivities ($a_k{}^c$) with TCSC (in p.u) of 5 bus network

Line-k		Base Case	Outage of lines					
No	i-j		1-2	1-3	1-4	2-5	3-4	4-5
L1	1-2	2.2141	–	−4.3548	−4.3157	2.3260	0.5585	0.0008
L2	1-3	−7.6532	**−1.9413**	–	26.070	**−16.746**	0.6270	**−9.1701**
L3	1-4	41.8957	5.4876	106.73	**–**	47.173	4.0738	12.945
L4	2-5	**−10.8975**	0.1563	**−32.848**	**−9.818**	–	**−1.7441**	0.0101
L5	3-4	3.1272	1.0761	−7.3273	3.3354	4.7151	–	2.6179
L6	4-5	−2.4405	−0.0030	−8.4846	−6.4161	0.0095	−0.2231	–
Factors		L4	L2	L4	L4	L2	L4	L2

4.1.1 TCSC Placement

To place TCSC, the sensitivity factor with the lowest value is employed. The sensitivity factor is determined by subtracting the RPFPI index from the FACTS device's control parameter. The TCSC is the device under examination, and the reactance of the TCSC is the control parameter. Table 2 shows the sensitivity values of a line for TCSC deployment in the absence and presence of line outages. Table 2's column 3 shows sensitivity values without any line outages. With line outages L1 to L6, the values of sensitivity are presented in columns 4–9. Table 2 shows that line-4 has the least value of base case compared to the other lines. As a result, line-4 is appropriate for putting TCSC in the basic case. In the event of a line outage, is appropriate in three instances, followed by, which is appropriate in three cases. As it is comparable to base case, is the primary priority for effective placement of TCSC. In the last row, along with the base scenario, are the least sensitivity parameters for a line outage.

4.1.2   TCPAR Placement

The RPFPI of TCPAR is differentiated with respect to TCPAR phase angle. The line with highest absolute value of sensitivity factor is thought to be best position. From Column 3 of Table 3, it is observed that L3 has largest absolute for base case. Hence, L3 is suitable for placement of TCPAR under base case. The sensitivity is positive, indicating that TCPAR's phase angle shift have to be negative. L3 is suited for four cases in line outages, followed by L2 and L6, which are each acceptable for one case. L6 is connected between two generators, making it unsuitable for TCPAR installation. As a result, L3 is acceptable for TCPAR allocation with negative phase shift since factors are positive values, as in the base situation. The second option is to put TCPAR in L2, which is only applicable in one case: when L6 is down. The line with highest absolute sensitivity factor in both base case and for specific outage is shown in the table's last row.

4.1.3   Optimal Allocation of FACTS Devices Considering Single Line Contingency

Column 1 in Table 4 shows line outages that have been considered. Column 2 lists connected line's transmitting and receiving end buses. Under line outage, Columns 3–7 show ideal distribution of TCSC and TCPAR devices, one in each column. The active PF in lines can be successfully controlled by controlling phase angle of series injected voltage.

The ideal arrangement of TCSC and TCPAR devices with no line outage is shown in last row of the Table. The severity of fault is indicated b RI. As a result, column 9 signifies order in which line outages occurred in ascending order. The line order is determined by RI. Table 1 shows lines that are being overloaded due to a line outage. Sensitivity factors are used to determine the appropriate place for regulating PFs in overloaded lines. Table 4 demonstrates that the optimal location for the most severe fault matches the no-contingency situation. The location of the FACTS gadget is highlighted in bold.

Table 3. Sensitivities ($a_k{}^s$) with TCPAR (in p.u) of 5 bus network

Line-k		Base Case	Outage of lines					
No	i-j		1-2	1-3	1-4	2-5	3-4	4-5
L1	1-2	−2.3058	–	−4.3633	−0.7960	−0.2595	−0.4071	−0.0000
L2	1-3	−1.0444	−0.2794	–	1.4285	−1.9124	0.0593	**−1.1873**
L3	1-4	**4.0133**	**0.5146**	**5.7550**	–	**2.8923**	**0.4697**	1.0823
L4	2-5	−2.3999	0.0216	−4.9126	−0.9647	–	−0.4210	0.0014
L5	3-4	−1.2953	−0.4145	0.7923	1.3126	−2.5501	–	−1.1778
L6	4-5	2.6582	0.0013	5.5660	**1.4608**	0.0020	0.4662	–
Factors		L3	L3	L3	L6	L3	L3	L2

Table 4. Optimal locations based on ranking index of 5 bus system

L.O-*l*		Optimal location under line outages		RI	Rank
L.NO	i-j	TCSC ($a_k{}^c$)	TCPAR ($a_k{}^s$)		
L2	1-3	L4	L3	0.671	1
L3	1-4	L4	L3	0.631	2
L4	2-5	L2	L6	0.624	3
L1	1-2	L2	L3	0.521	4
L6	4-5	L2	L2	0.512	5
L5	3-4	L4	L3	0.459	6
OLUN		**L4**	**L3**		

L.O-*l* is line outage in line-*l*, L.NO is line number, OLUN is optimal location under no outage and RI is Ranking Index

4.2 IEEE 14-BusNetwork

Five generator buses, eleven load buses, and twenty transmission lines make up the IEEE 14 bus test network [12, 15, 16, 18]. The maximum line flow is 120 MW. The reference bus has been identified as Bus 1. 100 MVA is considered the system's base MVA. To demonstrate the efficiency of the strategy presented from Tables 1, 2, 3 and 4, a detailed presentation is made for a five-bus system. Every outage causes lines to get overrun on the 14 bus system.

FACTS, like in 5 bus system, are positioned to control PF in overloaded lines by using sensitivity factors. Table 5 shows a summary of findings. Table 5 is organised in same way as Table 4. Column 1 shows line outages in descendent order of RI shown in Column 8. Column 9 displays actual ranking. Present the ideal position of the device determined by differentiation of Active PF PI with regard to device characteristics in Column 3–7. In the instance of TCSC, the device parameter is the device's static reactance. In the case of TCPAR, phase angle is taken into account when calculating the sensitivity factor. It is phase angle of series injected voltage for remaining devices. Table 5 indicates that, despite being connected between two generators, best location for most severe fault does not coincide with no contingency or numerous contingencies and is acceptable for optimal position. The FACTS gadget's location is presented in bold.

Table 5. Optimal locations based on ranking index for 14 bus system

L.O-*l*		Optimal location under line outages		RI	Rank
L.NO	i-j	TCSC ($a_k{}^c$)	TCPAR ($a_k{}^s$)		
L10	5-6	L3	L7, L5	0.3370	1
L3	2-3	L2	L2, L1	0.3186	2
L2	1-5	L9	L4	0.2885	3
L1	1-2	L7	L7	0.2851	4
L13	6-13	L2	L2, L1	0.2844	5
L9	4-9	L2	L2, L1	0.2834	6
L11	6-11	L2	L2, L1	0.2823	7
L4	2-4	L3	L7	0.2815	8
L12	6-12	L2	L2, L1	0.2803	9
L17	9-14	L2	L2, L1	0.2800	10
L18	10-11	L2	L2, L1	0.2787	11
L14	7-8	L2	L2, L1	0.2783	12
L20	13-14	L2	L2, L1	0.2783	13
L19	12-13	L2	L2, L1	0.2777	14
L16	9-10	L2	L2, L1	0.2773	15
L8	4-7	L2	L2, L1	0.2701	16
L15	7-9	L2	L2, L1	0.2696	17
L6	3-4	L2	L2, L1	0.2655	18
L7	4-5	L2	L2, L1	0.2584	19
L5	2-5	L3	L4	0.2578	20
OLUN		**L2**	**L2**		

5   Conclusion

Under single line contingency, a new method for determining the best location for TCSC and TCPAR devices has been developed. The technique is based on two indexes: ranking and performance. For a given outage, the Ranking Index (RI) is utilized to determine the average load level across all network lines. In each situation, the detected lines being overloaded are counted in descending order based on the RI value. TCSC and TCPAR are put in appropriate positions to control power flow in those overloaded cables. Sensitivity analysis is employed to position TCSC and TCPAR devices. Differentiating RPFPI subject to system parameters of FACTS under normal and contingency circumstances yields sensitivity factors. The proposed approach is tested on IEEE 14 bus and 5 bus systems. In the 5 bus system, the optimal site computed for the most severe fault matches the optimal site predicted for the base case, however this is not the case in the 14 bus system. However, in the base scenario, the ideal location of the FACTS device matches

the best location in the event of many contingencies. The five bus systems are likewise observed in the same way.

Authors' Contributions. V. Srinivas Rao: Conceptualization, Methodology, Software. **M. Ravindra:** Visualization, Writing, **A.S. Veerendra:** Review and editing, **A. Ramesh:** Data curation. **R. Srinivasa rao:** Supervision, Software. **K.M.K. Reddy:** Validation.

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