Optimal Allocation of UPFC and IPFC in Network Considering Sensitivity of Line Flows under Single Line Contingency

V. Srinivasa Rao, R. Srinivasa Rao, M. Ravindra

Abstract ***: This paper presents, optimal location for deployment of Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC) in network considering sensitivity of line flows under single contingency. A sensitive approach is proposed which is considered based on Ranking Index (RI) and Performance Index (PI). A unitary change of power flow (PF) in each transmission line after outage of a branch element can be obtained from proposed index. The proposed Index is used to quantify loading level of network after a given outage. Contingencies are structured in descending order depending on value of proposed Index. Sensitivity factors are obtained by differentiating PF indices subject to parameters of UPFC and IPFC devices. Optimal deployment of UPFC and IPFC device is considered by the value of sensitivity factors attained by considering line outages in order of their severities which is given by proposed Index. The efficacy of proposed approach is computed and programmed on 5bus and IEEE 14bus networks under MATLAB environment.***

Keywords **:** ***UPFC and IPFC, contingency analysis, sensitivity approach, ranking index, optimal placement.***

I. INTRODUCTION

Due to severe contingencies or due to heavy loads, it will direct to a condition where the network is no longer present in secured operating region. Under these constraints, by applying controlling actions it is main objective of operator to bring back to normal secure state. The system leads in to unstable region due to delay of information or due to lack applicable control actions. In reality, contingencies such as line -outages lead to voltage constraint violations and results in to excess loading of the lines. The system can be recovered from this excess loading condition by reconfiguration of power system network and by controlling line parameters. However, the present transmission line infrastructure is not upgraded to the required level and hence it can lead to unstable condition. Because of meshed topology of electrical network and large quantity of equipment, the planning and operation of power system became very complex and research have been carried out on standard and abnormal conditions. One such abnormal conditions of power transmission network is the occurrence of contingencies. The contingency analysis is significant when future circumstances are uncertain. Thus, Contingency based forecast can give efficient energy management practices and helps to make more resilient power system. Also, it tends to minimize cost, improve energy efficacy, and develop the array of possible solutions compared with more firm planning. The sufficient generation has been running to meet up the load and that required transmission has been put up to transmit power to load. The equipment installed in network can fail, due to internal or external faults, such as transmission towers fall off, setting relay errors or lightning strikes. It is too expensive, to reconfigure a network design with adequate redundancy (i.e., reserve generation, additional transmission lines, etc.) so that load cannot be dropped due to internal or external faults rather, networks are reconfigured in such a way that dropping of load is adequately small. Thus, electrical networks are reconfigured to have adequate measurements and devices to endure all failure measures, but this cannot assure that the network can be 100% reliable. rectification is not possible.

In [1], the author presented Nonlinear program (NLP) and computed considering General Algebraic Modeling System(GAMS) and MATLAB parameters. It is known that FACTS devices are right solutions to enhance the stability of network and to minimize the congestion problems in overloaded lines and control voltages by governing their limits considering series and shunt impedance, voltage, current and phase angle [2]. The operation method of FACTS devices is suggested to improve steady-state security taking into consideration of line contingency problem [2]. Power systems are commonly designed and controlled based on N-1 constraint in security, which implies that system should remain secure under all first contingencies. It is suggested that, appropriate position and sizing of FACTS Controllers has enhanced system performance enormously [3]-[7]. PF in network is directed by allocating the FACTS devices in suitable lines in network without altering generation program and structure of system. There is much better significance of FACTS devices due to improvement in modernization of power electronics. The UPFC is the efficient FACTs device, PF controller as it can direct active and reactive PF in parallel or independently throughout lines and buses [8]-[12].

In [13], the author proposed two algorithms for optimal deployment of UPFC and wind farm in network to mitigate power congestion problem. UPFC can be utilized for bus and line voltage control through phase shifting, series compensation. UPFC integrates the properties of shunt and series controllers. IPFC device

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is combination of two or more series FACTS controllers. The advantage of IPFC over UPFC, static synchronous series compensator (SSSC)[14], synchronous (shunt) compensator (STATCOM) is that, IPFC can control PF through the set of lines or multi- lines and sub networks, whereas UPFC can control PF of only one transmission line[15]. Many studies have been considered for realizing how to enhance system security under contingencies. In [16], the author proposed evolutionary algorithms for optimal deployments and constraint settings of TCSC. In [17]-[20], optimal placement techniques are discussed for deployment of devices.

Therefore, the objective of this work is to optimally allocate UPFC and IPFC by means of proposed PI in case of single line contingency (N−1 contingency).Sensitivity indices are obtained by partially differentiating proposed PI subject to parameter of UPFC and IPFC devices to be optimized. This technique is tested on 5 bus and IEEE14 bus networks for deployment of UPFC and IPFC devices under single line contingency.

II. MODELING OF UPFC AND IPFC

A. UPFC

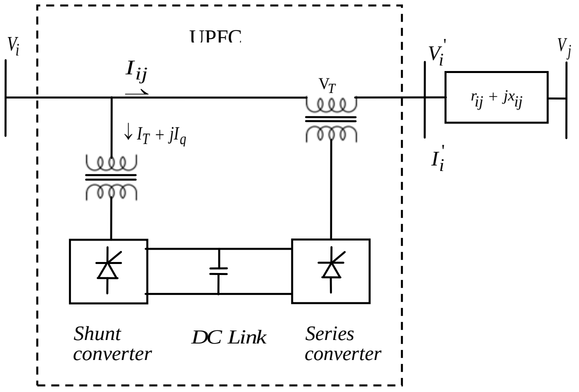

Fig. 1. **Single line diagram of UPFC.**

Fig. 1.shows a transmission line model with UPFC connected between bus-i and j. Converter-1 transmits real power required by converter-2 at DC link terminal connected from AC terminal.

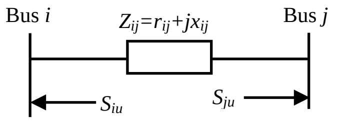

Fig. 2. **Injection Model of UPFC.**

Hence it can perform the utility of a self-regulating static VAR by furnishing reactive power compensation and consequently performing voltage regulation at input terminals of UPFC. The output voltage of inverter is induced in series such that it is utilized for control of voltage and series compensation. Injection Model of UPFC is shown in Fig.2. This injected voltage can produce or absorb reactive power by dissimilar types of control actions applied and transmit active power to its DC terminal. The control parameters of UPFC namely magnitude voltage, and angle (V_T, δ_T) and magnitude of current (I_q). Active and reactive power (P_{iu}, P_{ju}) and(Q_{iu}, Q_{ju}) injected at bus-i and bus-j of line connecting UPFC can be written as

$$P_{iu} = -V_T^2 G_{ij} - 2V_i V_T G_{ij} \cos\delta_{Ti} + V_j V_T \left[G_{ij} \cos\delta_{Tj} + B_{ij} \sin\delta_{Tj} \right] \quad (1)$$

$$P_{ju} = V_j V_T \left[G_{ij} \cos\delta_{Tj} - B_{ij} \sin\delta_{Tj} \right] \quad (2)$$

$$Q_{iu} = V_i I_q + V_i V_T \left[G_{ij} \sin\delta_{Ti} + B_{ij} \cos\delta_{Ti} \right] \quad (3)$$

$$Q_{ju} = -V_j V_T \left[G_{ij} \sin\delta_{Tj} + B_{ij} \cos\delta_{Tj} \right] \quad (4)$$

Where $\delta_{Ti}= \delta_T- \delta_i$ and $\delta_{Tj}= \delta_T- \delta_j$

B. IPFC

With application of series reactive compensation, any converter can be directed to provide real power to DC link from transmission line. The schematic model of IPFC has 2-DC-to-AC converters, connected back to back via transformers in series to transmission lines. IPFC is connected between lines as shown in fig.3 and network bus voltages are defined as $V_i\angle\delta_i$, $V_j\angle\delta_j$ and $V_k\angle\delta_k$ respectively.

V_{sein} is series induced voltage source, defined as

$$V_{se_{in}} = V_{se_{in}} \angle \delta_{se_{in}}$$

Z_{in} is transmission line impedance where n = j, k. The Fig.3 shows single line diagram of IPFC.

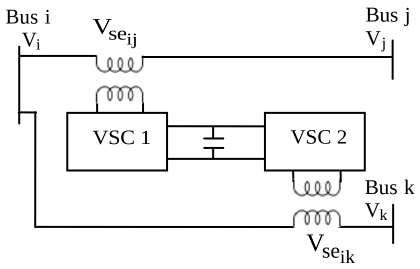

Fig. 3. **Schematic diagram of two converter IPFC.**

Schematic diagram is presented in Fig.3 and Injection model is presented in Fig 4. Mathematical modeling of IPFC is derived as follows. The injections of active and reactive power at bus -i, j and k of lines-l and m having IPFC can be defined as:

$$P_{iI} = -V_i V_{se_{in}} \left[G_{in} \cos\delta_{\mathrm{ise}_{in}} + B_{in} \sin\delta_{\mathrm{ise}_{in}} \right] \quad (5)$$

$$P_{nI} = V_n V_{se_{in}} \left[G_{in} \cos\delta_{\mathrm{nse}_{in}} + B_{in} \sin\delta_{\mathrm{nse}_{in}} \right] \quad (6)$$

$$Q_{iI} = -V_i V_{se_{in}} \left[G_{in} \sin\delta_{\mathrm{ise}_{in}} - B_{in} \cos\delta_{\mathrm{ise}_{in}} \right] \quad (7)$$

$$Q_{nI} = V_n V_{se_{in}} \left[G_{in} \sin\delta_{\mathrm{nse}_{in}} - B_{in} \cos\delta_{\mathrm{nse}_{in}} \right] \quad (8)$$

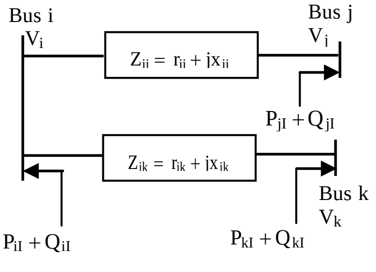

Fig. 4. **Injection Model of UPFC.**

III. STRATEGY FOR DEPLOYMENT OF UPFC AND IPFC

A. Ranking Index

A commonly used method to detect critical contingencies is based on determining a contingency ranking in descendent order of severity [18][19]. RI is used to quantify the loading level of the system after a given outage.

$$\mathrm{RI}=\frac{1}{b}\sum_{k=1}^{b}\left(\frac{\left|\mathrm{P}_{\mathrm{f}_k}\right|}{\mathrm{P}_{\mathrm{f}_k}^{\max}}\right) \tag{9}$$

Where $\mathrm{P}_{\mathrm{f}_k}$ is the branch flow of element k, and $\mathrm{P}_{\mathrm{fk}}^{\max}$ is the rated capacity of line-k, from a total of b lines, obtained approximately using distribution factors, that is, linear factors that represent the unitary change of PF in each transmission line after outage of a branch element. To calculate in an approximate way the active PF of each branch after a given contingency, it is sufficient to multiply the corresponding distribution factor by the PF of the lost branch before contingency. Distribution factors for line outages are designated $\rho_{k,l}$ and have following definition:

$$\rho_{k,l}=\frac{\Delta P_k}{P_l^0} \tag{10}$$

Where $\rho_{k,l}$ is distribution factor of line outage, when monitoring line-k after outage on line-*l*, ΔP_k is PF change on line-k and P_l^0 is original PF on line-*l* before outage (opened).

If power on line-k and line-*l* is known, the PF on line-k with line-*l* out can be computed using "ρ" factors.

$$\hat{P}_k=P_k^0+\rho_{k,l}\,P_l^0 \tag{11}$$

Where P_k^0, P_l^0 are pre-outage flows on lines-k and *l*, respectively and $\hat{P}_k$ is the PF on line-k with line-*l* out.

This procedure can be repeated for outage of each line in turn. The RI indicates, average rate of flow of power in lines. Once RI have been obtained for all possible contingencies, they are classified in descendent order. In this way the analysis begins with the a priori most critical contingency, going down in the list until a non-problematic contingency is analyzed.

B. Performance Index (PI)

The PI [40] is determined by following equation which indicates inflexibility of system loading under contingency and normal conditions.

$$PI=\sum_{m=1}^{N_l}\frac{W_m}{2n}\left(\frac{P_{lm}}{P_{lm}^{\max}}\right)^{2n} \tag{12}$$

Where, W_m is real weight coefficient, P_{lm} is real PF and $P_{lm}^{\max}$ is rated capacity of line-*m*. The exponent *n* shows the importance of lines and N_l is total number of lines in network. PI acts as measure of severe overloading of lines in given power system. In this work, the value of exponent has been taken as 2.0 and weight coefficient is taken as 1.0.

The sensitivity factors c_1^u , c_2^u and c_3^u can be defined as partial derivative of PI subject to magnitude of induced voltage (V_T), angle of induced voltage (δ_T) and magnitude of current (I_q) on line-k respectively.

$$c_1^u=\left.\frac{\partial PI}{\partial V_T}\right|_{V_T=0} = \text{PI Sensitivity subject to } V_{T,}$$

$$c_2^u=\left.\frac{\partial PI}{V_T\,\partial\delta_T}\right|_{\delta_T=0} = \text{PI Sensitivity subject to } \delta_{T},$$

$$c_3^u=\left.\frac{\partial PI}{\partial I_q}\right|_{I_q=0} = \text{PI Sensitivity subject to } I_{q,}$$

From equation (12), sensitivity of PI subject to UPFC parameter X_k ($V_{T,}$ δ_T and I_q), linked between bus *i* and *j* can be formulated as:

$$\frac{\partial PI}{\partial X_k}=\sum_{m=1}^{N_l}W_m\,P_{lm}^3\left(\frac{1}{P_{lm}^{\max}}\right)^4\frac{\partial P_{lm}}{\partial X_k} \tag{13}$$

Considering the DC load flow equation, real PF through line-*m* (P_{lm}) can be represented as sum of real power injections. Assume *s* be the slack bus.

$$P_{lm}=\begin{cases}\displaystyle\sum_{n=1,n\neq s}^{N}S_{mn}P_n & \text{for } m\neq k\\ \displaystyle\sum_{n=1,n\neq s}^{N}S_{mn}P_n+P_j & \text{for } m=k\end{cases} \tag{14}$$

Where, *N* is buses count of network and S_{mn} is *mn*th component of matrix [S_f] which includes line PF with power injections [19] at buses without UPFC or IPFC devices. It can be observed that in line-k (between bus i and j) there is an additional flow of P_j at bus *j* when a FACTS device is connected, as shown in Fig. 1. Using (13) and (14) its can be derived that,

$$\frac{\partial P_{lm}}{\partial X_k}=\begin{cases}\left(S_{mi}\dfrac{\partial P_i}{\partial X_k}+S_{mj}\dfrac{\partial P_j}{\partial X_k}\right) & \text{for m} \neq \text{k}\\[2ex] \left(S_{mi}\dfrac{\partial P_i}{\partial X_k}+S_{mj}\dfrac{\partial P_j}{\partial X_k}\right)+\dfrac{\partial P_j}{\partial X_k} & \text{for m} = \text{k}\end{cases} \tag{15}$$

The sensitivity factors c_1^u , c_2^u and c_3^u can be obtained by using equations (A.1), (A.2), (A.3), (A.4), (A.5) and (A.6).

A similar approach has been made for a device IPFC. In this case sensitivity factors 'c_1^I and c_2^I which are formulated by partially differentiating PI subject to induced voltage V_{se} and phase angle ϕ_{se} in line-*l*.

From equation (12), Sensitivity of PI subject to IPFC parameter X_l (V_{se} and δ_{se}) can be formulated as:

$$c_1^I=\left.\frac{\partial PI}{\partial V_{se}}\right|_{V_{se}=0} = \text{PI Sensitivity subject to } V_{se}$$

$$c_2^I=\left.\frac{\partial PI}{V_{se}\,\partial\delta_{se}}\right|_{\delta_{se}=0} = \text{PI Sensitivity subject to } \delta_{se}$$

The sensitivity factors c_1^I and c_2^I are computed by using equations (A.7), (A.8), (A.9) and (A.10).

C. Optimal Deployment Criteria

The conditions followed for purpose of optimal deployment of UPFC and IPFC are same as in [40] which are outlined as

i) The UPFC or IPFC are allocated in line-*k* which has minimum sensitivity subject to static magnitude reactance, induced voltage and current.

ii) The UPFC or IPFC is allocated in line-*k* that has highest value of sensitivity subject to phase angle.

iii) The UPFC or IPFC should not be allocated in line enclosing generation buses, even if sensitivity is high.

IV. SIMULATION RESULTS

The proposed strategy is tested on two different having 5 and 14 buses with five FACTS device with line outages. The simulations are carried out in MATLAB environment and results are presented.

A. 5 bus Network

Table- I: Parameters of IEEE 5-nus

Generators	3 buses
Load buses	2 buses
Transmission lines	6 buses
Line flow limit	800 MW
Reference bus	Bus-5
Base MVA	100MVA

Table- II : Line flows without any FACTS device (in p.u) of 5-bus system

Line-k		**PFs (in p.u)**						
		No outage	***Line outages***					
No	***i-j***	***Base case Case***	***1-2***	***1-3***	***1-4***	***2-5***	***3-4***	***4-5***
1	1-2	0.96	--	-0.53	-3.52	5.08	1.38	-1.2
ℓ_2	1-3	-6.99	-6.80	--	**-11.5**	-7.82	**-9.61**	7.43
ℓ_3	1-4	**-8.97**	**-8.20**	**-14.5**	--	**-12.3**	-6.77	**10.0**
ℓ_4	2-5	-4.04	-5.00	-5.53	**-8.59**	--	-3.62	3.10
ℓ_5	3-4	2.79	3.00	**10.0**	2.40	1.81	--	-2.5
ℓ_6	4-5	1.06	2.05	2.07	5.07	-3.41	0.55	--
Over loads		ℓ_3	ℓ_3	ℓ_3& ℓ_5	ℓ_2& ℓ_4	ℓ_3	ℓ_2	ℓ_3

Table I shows the parameters of the 5 bus network. and Fig.4 shows the single line diagram of 5-bus network. lines 1-2 and 1-4 have shunt susceptance of 0.002 p.u and other four lines have shunt susceptance 0.004 p.u each. The PFs without FACTS device with contingency is presented in Table II. Table II presents sending end PFs for base case and for all line outages. Line flows for every outage are presented in Table I. From Table (sub column 3, base case) the load flow results by NR method indicate that real PFs in line-3 for base case was 8.97 p.u, which is more than its line loading limit and in case of line outage, it can be observed that line-3 is getting overloaded in most of cases except lines-3 and 5 outage case. In case line-3 outage lines-2 and 4 get overloaded and in line-5 outage line-2 get overloaded. The lines which are overloaded are presented in bold. Last row of the table clearly indicates the over loaded line/lines for a given outage. FACTS devices considered in this work are UPFC and IPFC

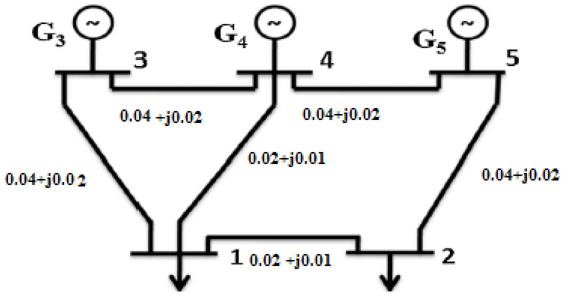

Fig. 5.Single line diagram of 5-bus network[19]

Sensitivities are computed for each control parameters of FACTS device associated with every line one at a time for same operating conditions. The sensitivities of PI subject to FACTS device for base case and different line outages are presented in Tables II, III, IV and VI. The highest negative or most absolute sensitivities are presented in bold type depending on device nature. single line diagram of 5-bus network is shown in Fig.4.

UPFC Deployment: In case of UPFC, PI is differentiated subject to magnitude of induced voltage, phase angle of induced voltage and magnitude of shunt current. UPFC is placed in line with least value of sensitivity factor. Table III presents sensitivity factors subject to V_T. From Table III, it can be seen that sensitivity factor in line-1 is most negative (c_1^u) for base case. So line-1 is applicable for placement of UPFC subject to magnitude of induced voltage (V_T) under base case. In line outages, line-1 is applicable for four cases followed by line-5 in two cases. But line-5 is connected between two generators. So, line-1 is only applicable for placement of UPFC. Last row of the table indicates line with least sensitivity factor for base case and for a given outage.

Table- III : Sensitivities (c_1^u) of UPFC w. r. t V_T (in p.u) of 5 bus system

Line-k		**Base Case**	**Outage of lines**					
No	***i-j***		***1-2***	***1-3***	***1-4***	***2-5***	***3-4***	***4-5***
ℓ_1	1-2	**-0.6257**	--	**-3.1296**	**-0.5237**	**-0.7102**	**-0.2589**	-0.0000
ℓ_2	1-3	-0.0357	0.0536	--	1.3584	-0.3911	0.0529	-0.2644
ℓ_3	1-4	0.9474	0.4820	3.7404	--	3.1883	0.3269	0.4075
ℓ_4	2-5	-0.4095	0.0467	-1.9490	0.0499	--	-0.1704	0.0056
ℓ_5	3-4	-0.2321	**-0.1552**	0.0860	0.2266	-1.5997	--	**-0.4208**
ℓ_6	4-5	0.5042	-0.0001	2.668	0.6469	0.0019	0.2163	--
Factors		ℓ_1	ℓ_5	ℓ_1	ℓ_1	ℓ_1	ℓ_1	ℓ_5

Table IV presents sensitivity factors subject to phase angle of induced voltage (δ_T). UPFC is placed based on a line with the largest absolute value of sensitivity factor (c_2^u). From Table IV, it can be seen that for base case the largest absolute sensitive factor (c_2^u) belongs to line-3. So line-3 is applicable for the placement of UPFC subject to phase angle of induced voltage (δ_T) under base case. positive sensitivity indicates that phase angle of UPFC is negative. The sensitivity for line-4 and-6 is approximately same, as the lines are in series for control of phase angle. In case of line outages, line-3 is applicable for five cases followed by line-2 which is applicable in one case (i.e., line-3 outage). So, line-3 is only applicable for deployment of

UPFC with negative phase shift because factors are positive values as it is similar to base case. Last row of table indicates line with most absolute sensitivity factor for all cases.

Table- IV: Sensitivities (c_2^u) of UPFC w. r. t δ_T (in p.u) of 5 bus system

Line-k		**Base Case**	**Outage of lines**					
No	***i-j***		***1-2***	***1-3***	***1-4***	***2-5***	***3-4***	***4-5***
ℓ 1	1-2	-2.3363	--	-11.477	-2.3418	-0.5710	-1.0122	-0.0000
ℓ 2	1-3	-1.0725	-0.7024	--	**4.1147**	-5.0786	0.1469	**-2.9733**
ℓ 3	1-4	**4.0746**	**1.2759**	**15.1750**	--	**7.2144**	**1.1667**	**2.9571**
ℓ 4	2-5	-2.4411	0.0503	-12.784	-2.7928	--	-1.0478	0.0034
ℓ 5	3-4	-1.2537	-0.9828	1.9137	3.1907	-5.8821	--	-2.8008
ℓ 6	4-5	2.5421	0.0030	13.5326	3.4734	0.0047	1.0862	--
Factors		ℓ 3	ℓ 3	ℓ 3	ℓ 2	ℓ 3	ℓ 3	ℓ 2,

The sensitivity factor (c_3^u) corresponding to magnitude of shunt current (I_q), which is third parameter of UPFC is always zero because it cannot control the real PF of line as it is in 90^0 phase displacement with input voltage.

IPFC Deployment: In the case of IPFC, the PI is differentiated subject to magnitude of series induced voltage (V_s) and phase angle of series induced voltage (δ_s). IPFC comprises of two series converters; 1) master converter and 2) slave converter. The master line of IPFC is placed in a line which has got least value for sensitivity factor. From Table V, it can be seen that sensitivity factor (c_1^I) for line-4 and line-2 is almost same and least for base case. In line outages, line-2 is applicable for three cases followed by line-4 in one case and line-5 in two cases, but line-5 is connected between two generators. So line-2 is chosen as master line and nearby line-4 is chosen as slave line for deployment of IPFC subject to magnitude of series induced voltage (V_s). Last row of table indicates line with least sensitivity factor for base case and for a given outage.

Table- V: Sensitivities (c_1^I) of IPFC w. r. t V_s (p.u) of 5 bus system

Line-k		**Base Case**	**Outage of lines**					
No	***i-j***		***1-2***	***1-3***	***1-4***	***2-5***	***3-4***	***4-5***
ℓ 1	1-2	-0.5376	--	-3.2938	-1.2785	1.0725	-0.2013	-0.0000
ℓ 2	1-3	**-0.6555**	**-0.7181**	--	-1.4166	**-3.1798**	**-0.3408**	-0.2644
ℓ 3	1-4	0.1670	-0.4383	-2.7420	--	-1.1434	0.0590	0.4075
ℓ 4	2-5	**-0.6590**	-0.1024	-3.5606	**-1.5223**	--	-0.2782	-0.0056
ℓ 5	3-4	-0.3112	-0.1309	**-4.7414**	0.6275	-1.3931	--	**-0.8049**
ℓ 6	4-5	0.4536	-0.0074	1.9486	0.1693	-0.0106	0.2050	--
Factors		ℓ 4, ℓ 2	ℓ 2	ℓ 5	ℓ 4	ℓ 2	ℓ 2	ℓ 5

Table VI, presents sensitivity factors subject to phase angle of induced voltage (δ_T), and IPFC is placed based on a line with largest value of sensitivity factor (c_2^I). It can be seen that line-3 in Table VI is largest absolute sensitive factor (c_2^I) for base case. In case of line outages, line-3 is applicable for five cases followed by line-2 which is applicable for one case (i.e., line-3 outage). So, line-3 is chosen as master line and line-2 which is adjacent to it is chosen as slave line, for deployment of IPFC with a control parameter of phase angle of induced voltage (δ_T) with negative phase shift because factors are positive values as it is similar to base case. Last row of table indicates line with largest absolute sensitivity factor for base case and for a given outage.

Table- VI: Sensitivities of IPFC w. r. t δ_s (in p.u) of 5 bus system

Line-k		Base Case	Outage of lines					
No	i-j		1-2	1-3	1-4	2-5	3-4	4-5
ℓ	1-2	-2.3181	--	-10.633	-1.3347	-2.0609	-0.9981	-0.0000
ℓ	1-3	-0.8657	-0.4547	--	**5.9060**	-3.0254	0.2056	**-2.9733**
ℓ	1-4	**4.6022**	**1.9398**	**18.5108**	--	**10.6336**	**1.4297**	**2.9571**
ℓ	2-5	-2.2442	0.1419	-11.265	-1.2716	--	-0.9498	0.0158
ℓ	3-4	-1.2733	-0.9763	1.1718	2.9695	-5.9961	--	-2.9120
ℓ	4-5	2.5315	0.0013	12.9333	3.3540	0.0071	1.0839	--
Factors		ℓ 3	ℓ 3	ℓ 3	ℓ 2	ℓ 3	ℓ 3	ℓ 2,

Effect of single line contingency on optimal deployment of FACTS devices: Table VII summarizes the above analysis. Line outages considered are present in Column 1. Column 2 shows sending and receiving end buses of the corresponding line. Column 3-7 presents the optimal deployment of FACTS devices one in each column under line outage. Phase angle control of series injected voltage can effectively control real PF in lines. Hence, optimal deployment in case of UPFC and IPFC is decided based on sensitivity factor obtained by differentiating real PF PI subject to phase angle. Last row of table presents optimal deployment of FACTS device without any line outage. RI which represents unitary change of PF in every transmission line subsequent to outage of branch element given in column 1 is given in Column 8. RI indicates the severity of the fault. So, column 9 denotes the rank of line outages in descending order. The order of line outages considered throughout this research work is determined based on RI. Lines getting overloaded because of line outage are presented in Table II. To limit the PFs in overloaded lines, optimal location is determined based on sensitivity factors.

One interesting observation from Table VII is, optimal deployment for most severe fault coincides with case of no-contingency. Decision for deployment of FACTS device is given in bold.

Table- VII: Results of each line outage with FACTS devices in 5 bus test system.

ℓ .O -*l*		Optimal deployment under line outages		RI	Rank
L.NO	i-j	UPFC (c_2^u)	IPFC (c_2^I)		
ℓ 2	1-3	ℓ 3	ℓ 3	0.671	1
ℓ 3	1-4	ℓ 2	ℓ 2	0.631	2
ℓ 4	2-5	ℓ 3	ℓ 3	0.624	3
ℓ 1	1-2	ℓ 3	ℓ 3	0.521	4
ℓ 6	4-5	ℓ 3	ℓ 3	0.512	5
ℓ 5	3-4	ℓ 3	ℓ 3	0.459	6
OLUN		**ℓ 3**	**ℓ 3**		

* ℓ .O- *l* is line outage in line-*l*, ℓ .NO is line number, OLUN is optimal deployment under no outage.

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B. IEEE 14 bus network

Table- VIII: Parameters of IEEE 14-bus

Generators	5 buses
Load buses	11 buses
Transmission lines	20 lines
Line flow limit	120 MW
Reference bus	Bus-1
Base MVA	100MVA

Table VIII shows the parameters of IEEE 14-bus network. Detailed presentation is done for 5-bus network to validate the effectiveness of technique proposed from Table I to Table VIII. Lines getting overloaded for every outage are observed on 14 bus system also. To limit PF in overloaded lines, FACTS devices are placed using sensitivity factors in the same way as it is done for the 5 bus system. Table IX presents the results summary. Line outages in column 1 are considered in descending order of RI presented in Column 8. Column -9 shows the actual rank. In the Column 3-7, present the optimal deployment of FACTS device obtained by differentiation of real PFPI subject to device parameters. Device parameter in case of TCSC is static reactance of the device. In the case of TCPAR, phase angle is considered for obtaining sensitivity factor. For remaining devices, it is the phase angle of series injected voltage. Observations from Table IX are optimal placement for most severe fault not-coincides with the case of without contingency and in several contingencies line-2 and-1 are right for optimal deployment, but line-1 is connected between two generators. Decision for deployment of FACTS device is shown in bold.

Table- IX: Results of each line outage with FACTS devices in IEEE14 bus test system.

L.O -*l*		**Optimal deployment under line**		**RI**	**Rank**
L.NO	***i-j***	***UPFC* (*c_2^u*)**	***IPFC* (*c_2^I*)**		
ℓ_{10}	5-6	ℓ_7	ℓ_3, ℓ_5	0.3370	1
ℓ_3	2-3	ℓ_1	ℓ_7	0.3186	2
ℓ_2	1-5	ℓ_4	ℓ_3	0.2885	3
ℓ_1	1-2	ℓ_7	ℓ_7	0.2851	4
ℓ_{13}	6-13	ℓ_2, ℓ_1	ℓ_2, ℓ_1	0.2844	5
ℓ_9	4-9	ℓ_1	ℓ_2, ℓ_1	0.2834	6
ℓ_{11}	6-11	ℓ_2, ℓ_1	ℓ_2, ℓ_1	0.2823	7
ℓ_4	2-4	ℓ_7	ℓ_3	0.2815	8
ℓ_{12}	6-12	ℓ_2, ℓ_1	ℓ_2, ℓ_1	0.2803	9
ℓ_{17}	9-14	ℓ_2, ℓ_1	ℓ_7	0.2800	10
ℓ_{18}	10-11	ℓ_2, ℓ_1	ℓ_2, ℓ_1	0.2787	11
ℓ_{14}	7-8	ℓ_2, ℓ_1	ℓ_2, ℓ_1	0.2783	12
ℓ_{20}	13-14	ℓ_2, ℓ_1	ℓ_2, ℓ_1	0.2783	13
ℓ_{19}	12-13	ℓ_2, ℓ_1	ℓ_2, ℓ_1	0.2777	14
ℓ_{16}	9-10	ℓ_2, ℓ_1	ℓ_2, ℓ_1	0.2773	15
ℓ_8	4-7	ℓ_1	ℓ_7	0.2701	16
ℓ_{15}	7-9	ℓ_2, ℓ_1	ℓ_7	0.2696	17
ℓ_6	3-4	ℓ_2, ℓ_1	ℓ_2, ℓ_1	0.2655	18
ℓ_7	4-5	ℓ_2	ℓ_1, ℓ_3	0.2584	19
ℓ_5	2-5	ℓ_4	ℓ_3	0.2578	20
OLUN		**ℓ_2**	**ℓ_2**		

V. CONCLUSION

A new technique has been suggested to find optimal deployment of UPFC and IPFC (FACTS) devices under single line contingency. The proposed strategy considers Ranking Index and Performance Index. RI is used to quantify average loading level of all lines of the system after a given outage. Contingencies are arranged in descending order depending on value of RI, identified lines getting overloaded in each contingency. For limiting power flow in those over loaded lines, UPFC and IPFC devices are allocated in optimal locations. UPFC and IPFC devices are deployed using sensitivity analysis. Sensitivity factors are attained by differentiating PI subject to system parameters of UPFC and IPFC devices under standard as well as contingency cases. The proposed technique is examined on 5-bus and IEEE 14 bus networks. Six contingencies are considered in 5-bus network and 20 contingencies are considered in 14-bus system. It is observed in 5-bus network that optimal deployment determined for most severe fault coincides with optimal deployment obtained for base case which is not same in case of 14-bus network. But, optimal deployment of UPFC and IPFC devices attained for base case coincides with optimal deployment attained in case of several contingencies. Comparable observation is prepared with the 5- bus systems also.

APPENDIX

Appendix A

The terms, $\left.\frac{\partial P_i}{\partial V_T}\right|_{V_T=0}$, $\left.\frac{\partial P_j}{\partial V_T}\right|_{V_T=0}$, $\left.\frac{\partial P_i}{V_T\partial\delta_T}\right|_{\delta_T=0}$, $\left.\frac{\partial P_j}{V_T\partial\delta_T}\right|_{\delta_T=0}$, $\left.\frac{\partial P_i}{\partial I_q}\right|_{I_q=0}$ and $\left.\frac{\partial P_j}{\partial I_q}\right|_{I_q=0}$ can be obtained using equations (1) and (2) respectively for UPFC and are given below.

$$\left.\frac{\partial P_i}{\partial V_T}\right|_{V_T=0}=\left.\frac{\partial P_{iu}}{\partial V_T}\right|_{V_T=0}=-2V_iG_{ij}\ \cos\delta_{\mathrm{i}}+V_j\left[G_{ij}\ \cos\delta_j-B_{ij}\sin\delta_j\right] \tag{A.1}$$

$$\left.\frac{\partial P_j}{\partial V_T}\right|_{V_T=0}=\left.\frac{\partial P_{ju}}{\partial V_T}\right|_{V_T=0}=V_j\left[G_{ij}\ \cos\delta_j+B_{ij}\sin\delta_j\right] \tag{A.2}$$

$$\left.\frac{\partial P_i}{V_T\partial\delta_T}\right|_{\delta_T=0}=\left.\frac{\partial P_{iu}}{V_T\partial\delta_T}\right|_{\delta_T=0}=-2V_iG_{ij}\ \sin\delta_{\mathrm{i}}+V_j\left[G_{ij}\ \sin\delta_j+B_{ij}\cos\delta_j\right] \tag{A.3}$$

$$\left.\frac{\partial P_j}{V_T\partial\delta_T}\right|_{\delta_T=0}=\left.\frac{\partial P_{ju}}{V_T\partial\delta_T}\right|_{\delta_T=0}=V_j\left[G_{ij}\ \sin\delta_j-B_{ij}\cos\delta_j\right] \tag{A.4}$$

$$\left.\frac{\partial P_i}{\partial I_q}\right|_{I_q=0}=\left.\frac{\partial P_{iu}}{\partial I_q}\right|_{I_q=0}=0 \tag{A.5}$$

$$\left.\frac{\partial P_j}{\partial I_q}\right|_{I_q=0}=\left.\frac{\partial P_{ju}}{\partial I_q}\right|_{I_q=0}=0 \tag{A.6}$$

The terms, $\left.\frac{\partial P_i}{\partial V_{se}}\right|_{V_{se}=0}$, $\left.\frac{\partial P_j}{\partial V_{se}}\right|_{V_{se}=0}$, $\left.\frac{\partial P_i}{V_{se}\partial\delta_{se}}\right|_{\delta_{se}=0}$,and $\left.\frac{\partial P_j}{V_{se}\partial\delta_{se}}\right|_{\delta_{se}=0}$, can be obtained using to equations (5) and (6) respectively for IPFC and are given below.

$$\left.\frac{\partial P_i}{\partial V_{se}}\right|_{V_{se}=0} = \left.\frac{\partial P_{iI}}{\partial V_{se}}\right|_{V_{se}=0} = -V_i\left[G_{ij}\ \cos\delta_i + B_{ij}\sin\delta_i\right] \tag{A.7}$$

$$\left.\frac{\partial P_j}{\partial V_{se}}\right|_{V_{se}=0} = \left.\frac{\partial P_{jI}}{\partial V_{se}}\right|_{Vse=0} = V_j\left[G_{ij}\ \cos\delta_j + B_{ij}\sin\delta_j\right] \tag{A.8}$$

$$\left.\frac{\partial P_i}{V_{se}\partial\delta_{se}}\right|_{\delta_{se}=0} = \left.\frac{\partial P_{iI}}{V_{se}\partial\delta_{se}}\right|_{\delta_{se}=0} = -V_i\left[G_{ij}\ \sin\delta_i - B_{ij}\cos\delta_i\right] \tag{A.9}$$

$$\left.\frac{\partial P_j}{V_{se}\partial\delta_{se}}\right|_{\delta_{se}=0} = \left.\frac{\partial P_{jI}}{V_{se}\partial\delta_{se}}\right|_{\delta_{se}=0} = V_j\left[G_{ij}\ \sin\delta_j - B_{ij}\cos\delta_j\right] \tag{A.10}$$

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