POWER SYSTEM SECURITY ENHANCEMENT BY OPTIMAL PLACEMENT OF UPFC

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ABSTRACT

In this paper, a new approach to enhance power system security has been suggested by optimal placement of UPFC based on sensitivity indices. The sensitivity indices have been obtained, using ac power flow method, in terms of change in line real power flow Performance Index (PI) with respect to the change in the UPFC parameters viz., injected voltage magnitude and phase angle. In order to validate the accuracy of the proposed method, an Optimal Power Flow (OPF) formulation has been used to measure the security in terms of minimum PI values, with placement of UPFC based on the proposed sensitivity factors. The results have also been compared with existing dc power flow based method on IEEE 30-bus and practical NREB 246-bus Indian systems. Test results obtained on the two systems show that the new sensitivity factors could be effectively used for the optimal placement of UPFC in order to enhance the static security of the power system.

KEY WORDS

Unified power flow controller, Optimal placement, OPF, PI sensitivity, System security.

1. Introduction

In emerging electric power systems, increased transactions may often lead to the situations where the systems no longer remain in the secure operating region. The security [18,19] of a power system can be defined as its ability to withstand a set of severe, but credible, contingencies and being in an acceptable new steady state condition. Various factors, such as environmental, right-of-way and high installation cost, limit the expansion of the transmission networks. Utilities try to maximize the utilization of the existing transmission asset that may, sometimes, lead to insecure operation of the system. Increased loading in power systems, combined with deregulation of the power industry, motivates the use of Flexible AC Transmission Systems (FACTS) controllers [1-3], such as Thyristor Controlled Series Compensator (TCSC), Thyristor Controlled Phase Angle Regulator (TCPAR) and Unified Power Flow Controller (UPFC), for power flow control as a cost-effective means of dispatching specified power transactions and maintaining system's security. However, due to the high cost of these controllers, it is necessary to locate them optimally in the network.

The line real power flow Performance Index (PI) is a good measure to the power system security for especially to avoid the equipment outage related contingency. By continuously monitoring the Performance Index (PI), the level and appropriate control actions could be predicted to maintain the system remains operable subjected to post disturbances or outages. There are few work reported in literatures which suggested different methodology for enhancement of power system security by FACTS controllers. However, most of method used many assumptions like dc power flow to find out the location of FACTS controllers and security measures, which are less accurately represented.

Reference [5], deals with the optimal location of TCSC and [7] has presented a method of optimal location of UPFC in view of enhancing the security. These work used dc power flow approximation model and, hence, less accurate and also did not suggest a method to determine the optimal settings of these controllers. Momoh *et al.* [6] suggested the use of phase shifter for security enhancement and obtained its parameters using Optimal Power Flow (OPF) formulation. Yorino *et al.* [9] proposed a new formulation for reactive power planning problem including the allocation of FACTS devices, but the results have been demonstrated on very small system. In [10], two objective functions have been considered, viz. maximization of system security and minimization of investment cost of FACTS devices, for their optimal placement. The effectiveness of the method was tested only on IEEE 14-bus system. Three heuristic methods, viz. Genetic Algorithm, Tabu Search and Simulated Annealing, have been applied in [11] for optimal location of the FACTS devices.

In this paper, indices, based on ac power flow, representing sensitivity of a line real power flow Performance Index (PI) with respect to UPFC series control parameters has been proposed for its optimal location in view of enhancing the system security under different operating conditions. The proposed sensitivity factors have been derived considering the impact of change in the system loading on bus voltages and angles. The effectiveness of the proposed method has been demonstrated on IEEE 30-bus and practical 246-bus Indian system utilizing an optimal power flow model that minimizes the line flow PI value. The results have been compared with an existing approach utilizing dc power flow approximation [15].

2. Static Model of UPFC

The Unified Power Flow Controller (UPFC) [1,2,7,12] can be viewed as a combination of Static Synchronous Compensator (STATCOM) and a Static Synchronous Series Compensator (SSSC). Both the compensators are coupled via a common dc-link, which allows bi-directional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM. The conventional UPFC consisting of two converters is capable of simultaneously controlling three power system quantities, i.e. the bus voltage at substation, real and reactive power flows in a line. UPFC has three controllable parameters, namely the magnitude and the angle of inserted voltage (V_s , ϕ_s) and the magnitude of the shunt current (I_q). The real component (I_T) of the shunt current is in phase and current component (I_q) is in quadrature with the voltage at bus- i . In this work, I_q was taken as zero because having less effect on real power flow control. The equivalent circuit of the UPFC placed in line- k , connected between bus- i and bus- j having series impedance $r_{ij}+jx_{ij}$ ($=1/(g_{ij}+jb_{ij})$), is shown in Fig. 1 and a power injection model of UPFC is shown in Fig. 2.

Figure 1. Equivalent circuit of UPFC

The injected active (P_{iu}) and reactive (Q_{iu}) powers, by UPFC only, at bus- i will be given as

$$P_{iu} = -V_s^2 g_{ij} - 2V_s V_i g_{ij} \cos(\phi_s - \delta_i) + V_s V_j [g_{ij} \cos(\phi_s - \delta_j) + b_{ij} \sin(\phi_s - \delta_j)] \quad (1)$$

$$Q_{iu} = V_i I_q + V_i V_s [g_{ij} \sin(\phi_s - \delta_i) + b_{ij} \cos(\phi_s - \delta_i)] \quad (2)$$

Similarly, the real (P_{ju}) and reactive (Q_{ju}) power injections, by UPFC only, at bus- j can be derived as

$$P_{ju} = V_j V_s (g_{ij} \cos(\phi_s - \delta_j) - b_{ij} \sin(\phi_s - \delta_j)) \quad (3)$$

$$Q_{ju} = -V_j V_s (g_{ij} \sin(\phi_s - \delta_j) + b_{ij} \cos(\phi_s - \delta_j)) \quad (4)$$

Figure 2. Power injection model of UPFC

3. Methodology Development for Optimal Placement of UPFC

The relative severity of the system loading under normal and contingency cases, using line real power flow Performance Index (PI) [14], can be written as

$$PI = \sum_{m=1}^{N_l} \frac{w_m}{2a} \left(\frac{P_m}{P_m^{\max}} \right)^{2a} \quad (5)$$

where, P_m is the real power flow and $P_m^{\max}$ is the rated capacity of line- m , a is an exponent and w_m is a real non-negative weighting coefficient, which may be used to reflect the relative importance of the lines. In this work, w_m has been taken as 1.0 for all the lines. N_l is the total line number in power network system.

3.1 PI Sensitivity using dc Power Flow Approximation

The control parameters of the UPFC, considered in this work, are the magnitude and angle of the series injected voltage, V_s and ϕ_s , respectively. The PI sensitivity factors with respect to the control parameters of the UPFC can be defined as

$$C_1^k = \left. \frac{\partial PI}{\partial V_s} \right|_{V_s=0} = \text{PI Sensitivity with respect to } V_s \quad (6)$$

$$C_2^k = \left. \frac{\partial PI}{\partial \phi_s} \right|_{\phi_s=0} = \text{PI Sensitivity with respect to } \phi \quad (7)$$

For deriving the PI sensitivity terms using dc power flow approximation, the value of 'a' in equation (5) has been taken as 2. Using equations (6) and (7), the sensitivity of PI with respect to the UPFC series parameters, in k^{th} line, X_k (V_s and ϕ_s), can be written as

$$\frac{\partial PI}{\partial X_k} = \sum_{m=1}^{N_l} w_m P_m^3 \left(\frac{1}{P_m^{\max}} \right)^4 \frac{\partial P_m}{\partial X_k} \quad (8)$$

The real power flow (P_m), in a line- m , can be represented in terms of bus real power injections using dc power flow equations, as

$$P_m = \begin{cases} \sum_{n=1, n \neq s}^{N_b} S_{mn} P_n & \text{for } m \neq k \\ \sum_{n=1, n \neq s}^{N_b} S_{mn} P_n + P_{ju} & \text{for } m = k \end{cases} \quad (9)$$

where, S_{mn} is the mn^{th} element of sensitivity matrix $[S]$, which relates line flow with power injections at the buses without placement of UPFC [7], N_b is the number of buses in the system and s is the slack bus. Assume that the line- k , between bus- i and bus- j , is the line containing the UPFC. The effect of UPFC can be represented as additional power injections at bus- i and bus- j , as shown in Fig. 2.

Using equations (8) and (9), the following relationship can be derived,

$$\frac{\partial P_m}{\partial X_k} = \begin{cases} \left(S_{mi} \frac{\partial P_{iu}}{\partial X_k} + S_{mj} \frac{\partial P_{ju}}{\partial X_k} \right) & \text{for } m \neq k \\ \left(S_{mi} \frac{\partial P_{iu}}{\partial X_k} + S_{mj} \frac{\partial P_{ju}}{\partial X_k} \right) + \frac{\partial P_{ju}}{\partial X_k} & \text{for } m = k \end{cases} \quad (10)$$

The terms $\left. \frac{\partial P_{iu}}{\partial X_k} \right|_{X_k=0}$ and $\left. \frac{\partial P_{ju}}{\partial X_k} \right|_{X_k=0}$ can be obtained

by partially differentiating the equations (1) and (3), with respect to the UPFC's series parameters.

3.2 Proposed PI Sensitivity Factors using ac Power Flow Approximation

The real power mismatch (P_{is}) and reactive power mismatch (Q_{is}) at any bus- i can be expressed in terms of voltage magnitudes (V), voltage angles (δ) and elements of bus admittance matrix (Y) as

$$P_{is} = P_{Gi} + P_{iu} - P_{Di} - \text{Re} \left(V_i \sum_{j=1}^{N_b} (V_j Y_{i,j})^* \right) \quad (11)$$

$$Q_{is} = Q_{Gi} + Q_{iu} - Q_{Di} - \text{Im} \left(V_i \sum_{j=1}^{N_b} (V_j Y_{i,j})^* \right) \quad (12)$$

where, P_{Gi} , Q_{Gi} are the real and reactive power generations, respectively, at bus- i . P_{iu} and Q_{iu} are the injections, given by equations (1) - (4), at bus- i due to the UPFC. P_{Di} and Q_{Di} are the base case real and reactive power demands, respectively, at the bus- i .

Equations (11) and (12), with UPFC, are function of bus voltage magnitudes (V) and angles (δ), magnitude (V_s) and angle (ϕ_s) of the injected voltage due to UPFC.

$$\left. \begin{aligned} P_{is} &= f_{pi}(V, \delta, \phi_s, V_s) \\ Q_{is} &= f_{qi}(V, \delta, \phi_s, V_s) \end{aligned} \right\} \quad (13)$$

From Taylor's series expansion, equation (13) can be written as,

$$\begin{bmatrix} \Delta f_p \\ \Delta f_q \end{bmatrix} = [J] \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} + [K_\phi] [\Delta \phi_s] + [K_{V_s}] [\Delta V_s] \quad (14)$$

where, variables written in bold face are the vector quantities and

$$[J] = \begin{bmatrix} \frac{\partial f_p}{\partial \delta} & \frac{\partial f_p}{\partial V} \\ \frac{\partial f_q}{\partial \delta} & \frac{\partial f_q}{\partial V} \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix};$$

$$[K_\phi] = \begin{bmatrix} \frac{\partial f_p}{\partial \phi_s} \\ \frac{\partial f_q}{\partial \phi_s} \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \phi_s} \\ \frac{\partial Q}{\partial \phi_s} \end{bmatrix}; \quad [K_{V_s}] = \begin{bmatrix} \frac{\partial f_p}{\partial V_s} \\ \frac{\partial f_q}{\partial V_s} \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial V_s} \\ \frac{\partial Q}{\partial V_s} \end{bmatrix}$$

$$\begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} [\Delta \delta_2 \ \Delta \delta_3 \dots \Delta \delta_i \dots \Delta \delta_{N_b}]^T \\ [\Delta V_2 \ \Delta V_3 \dots \Delta V_i \dots \Delta V_{N_b}]^T \end{bmatrix};$$

$[\Delta V_s] = [\Delta V_{s,ij} \dots \dots \dots]^T$; and $[\Delta \phi_s] = [\Delta \phi_{s,ij} \dots \dots \dots]^T$; $\forall i, j \in N_b$, represent injected voltage magnitude and phase angle vectors, respectively.

The derivatives corresponding to the slack bus is not included in the above derivation and shunt current I_q has been taken as zero. The size of matrices $[J]$ and $[K]$ are $(2N_b-2) \times (2N_b-2)$ and $(2N_b-2) \times (N_i)$, respectively.

In equation (14), the change in loading has been assumed to be met by the slack bus generator, which can be rewritten as,

$$\begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} = -[N_{\phi_s}] [\Delta \phi_s] - [N_{V_s}] [\Delta V_s]$$

where, $[N_{\phi_s}] = [J]^{-1} [K_{\phi_s}]$; $[N_{V_s}] = [J]^{-1} [K_{V_s}]$

The line real power flow (P_m) can be represented in terms of voltage magnitudes, voltage angles and UPFC parameters as,

$$P_m = f(V, \delta, \phi_s, V_s) \quad (16)$$

Using the Taylor's series expansion, equation (16) can be expressed as,

$$[\Delta P_m] = \begin{bmatrix} \frac{\partial P_m}{\partial \delta} & \frac{\partial P_m}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} + \begin{bmatrix} \frac{\partial P_m}{\partial \phi_s} \end{bmatrix} [\Delta \phi_s] + \begin{bmatrix} \frac{\partial P_m}{\partial V_s} \end{bmatrix} [\Delta V_s] \quad (17)$$

From equations (15) and (17), the following relationship can be obtained.

$$[\Delta P_m] = [M] \left[-[N_{\phi_s}] [\Delta \phi_s] - [N_{V_s}] [\Delta V_s] \right] + [T^{\phi_s}] [\Delta \phi_s] + [T^{V_s}] [\Delta V_s] \quad (18)$$

or

$$[\Delta P_m] = [MNT^{\phi_s}] [\Delta \phi_s] + [MNT^{V_s}] [\Delta V_s] \quad (19)$$

where, $[M] = \begin{bmatrix} \frac{\partial P_m}{\partial \delta} & \frac{\partial P_m}{\partial V} \end{bmatrix}$;

$$[T^{\phi_s}] = \begin{bmatrix} \frac{\partial P_m}{\partial \phi_s} \end{bmatrix}; [T^{V_s}] = \begin{bmatrix} \frac{\partial P_m}{\partial V_s} \end{bmatrix};$$

$$[MNT^{\phi_s}] = [[T^{\phi_s}] - [M][N^{\phi_s}]] \text{ and}$$

$$[MNT^{V_s}] = [[T^{V_s}] - [M][N^{V_s}]]$$

From equation (19),

$$\begin{bmatrix} \frac{\Delta P_m^{\phi_s}}{V_s \Delta \phi_s} \end{bmatrix} = [MNT^{\phi_s}] \quad (20)$$

$$\begin{bmatrix} \frac{\Delta P_m^{V_s}}{\Delta V_s} \end{bmatrix} = [MNT^{V_s}] \quad (21)$$

For deriving the PI sensitivity terms using ac power flow approximation, the value of 'a' and 'w_m' in equation (5) have been taken as unity. Substituting equations (20) and (21) in equation (8), a new set of PI sensitivity factors are obtained and can be written as

$$F_1^k = \frac{\partial PI}{\partial V_s} = \sum_{m=1}^{N_l} P_m \left(\frac{1}{P_m^{\max}} \right)^2 [MNT_m^{V_s}] \quad (22)$$

$$F_2^k = \frac{\partial PI}{V_s \partial \phi_s} = \sum_{m=1}^{N_l} P_m \left(\frac{1}{P_m^{\max}} \right)^2 [MNT_m^{\phi_s}] \quad (23)$$

The sensitivities of real power flow Performance Index (PI) with respect to UPFC's series parameters (voltage

magnitude and phase injection) have been calculated by both dc and ac power flow approximation. The following criteria have been used for optimal placement of an UPFC, in the system.

- The branches having transformers are not considered for the UPFC placement.
- The line having highest absolute PI angle sensitivities (C_2^k & F_2^k) with respect to the change in injected voltage phase angle (ϕ_s) is considered as the best location for the UPFC placement followed by other lines having next highest sensitivities.
- When the values of absolute PI angle sensitivities (C_2^k & F_2^k) are very close to each other, the line having the highest absolute value of the PI voltage sensitivities (C_1^k & F_1^k) with respect to the change in injected voltage magnitude V_s is considered as the best location for the UPFC.

4. Methodology to Assess the Impact of Optimal UPFC Placement

The effectiveness of the proposed PI sensitivity factor based approach for UPFC placement has been verified in terms of reduction in the line flow Performance Index (PI) values. For this purpose, an Optimal Power Flow (OPF) formulation with line real flow (P_m) as control variable, as described below, has been used.

$$\text{Minimize } PI = \sum_{m=1}^{N_l} \frac{1}{2a} \left(\frac{P_m}{P_m^{\max}} \right)^{2a} \quad (24)$$

subject to the following constraints:

(a) *Equality constraints*: Power balance equations corresponding to both real and reactive powers at each bus must be satisfied. This can be expressed, in general form, as

$$G(V, \delta, Y, V_s, \phi_s) = 0; \quad (25)$$

where, G is the vector of the real and the reactive power flow equations at all the buses.

(b) *Inequality constraints*: These include the operating limits on the various power system variables and the parameters of the UPFC, as given below.

$$Q_G^{\min} \leq Q_G \leq Q_G^{\max} \quad (26)$$

$$V^{\min} \leq V \leq V^{\max} \quad (27)$$

$$\delta^{\min} \leq \delta \leq \delta^{\max} \quad (28)$$

$$\left. \begin{aligned} 0 \leq V_s \leq V_s^{\max}, \\ -\pi \leq \phi_s \leq \pi \end{aligned} \right\} \quad (29)$$

Equation (26) represents the limits on the reactive power generations. The limits on the bus voltage magnitude and angle are given by equations (27) and (28), respectively. Equation (29) represents the limits on the UPFC parameters (V_s , ϕ_s). The values of exponent ' a ' and w_m have been taken as 2 and 1, respectively.

The above OPF problem involves a nonlinear objective function and a set of nonlinear equality and inequality

constraints. This problem can be solved by any nonlinear optimization procedure. In this work, optimization software called Generalized Algebraic Modeling of System (GAMS) [17] has been used to obtain the optimal solution.

5. System Studies

The proposed line flow PI sensitivity method, derived based on dc power flow as well as ac power flow approximations, for optimal location of UPFC has been tested on IEEE 30-bus [13] and NREB 246-bus Indian [16] systems. Fig. 3 shows 400 kV and higher voltage network and the geographical locations of the NREB system covering nine states of India. The results of the system studies are given in following subsections.

Figure 3. NREB 246-bus Indian system [16] (connections shown are 400 kV and above only)

5.1 Line outage Contingency Ranking

To obtain the critical contingencies (line outages) in the IEEE 30-bus system and 246-bus NREB system, the PI values, as defined in equation (5), are computed for each of the single-line outage (N-1 contingency) cases. For both the systems, five most critical lines are listed in Table 1. Contingencies, for which feasible ac load flow solutions have not been obtained, are not included in this list. For the base case, the PI value obtained from the ac power flow solution for the IEEE 30-bus and NREB 246-bus systems are found to be 0.4142 and 5.4391, respectively.

Table 1
Line outage contingency ranking based on PI values in 30-bus and 246-bus systems

Rank order	IEEE 30-bus system			NREB 246-bus system		
	Line outage	End buses $i-j$	PI	Line outage	End buses $i-j$	PI
	Intact case	-	0.4142	Intact case	-	5.4391
1	12	1- 27	1.9030	223	154 - 240	6.8691
2	33	27 - 11	1.8160	355	223 - 39	6.5420
3	5	2 - 5	0.6475	206	137 - 141	6.5326
4	7	11 - 13	0.6168	197	18 - 134	6.4473
5	9	13 - 12	0.5889	359	233 - 235	6.2829

5.2 Optimal Placement of UPFC in IEEE 30-bus System and its Impact on System Security

PI sensitivity factors C_1^k & C_2^k , based on dc power flow method and F_1^k & F_2^k , based on ac power flow approximation, with respect to the UPFC parameters, are obtained and shown in Table 2. First column shows the priority number, columns 2 and 3 show the PI sensitivities with respect to the UPFC parameters based upon dc and ac power flow approximations, respectively.

Table 2
PI sensitivity factors (30-bus system)

Rank order	dc power flow approximation [7]				ac power flow approximation			
	Line no.	C_1^k	Line no.	C_2^k	Line no.	F_1^k	Line no.	F_2^k
1	33	-0.3134	12	-2.0657	12	-1.0626	12	-2.0385
2	12	-0.2639	33	-2.0295	33	-0.7441	33	-2.0279
3	7	-0.1722	11	1.7068	11	0.6687	11	2.0185
4	11	0.1501	7	-0.9631	14	0.3785	14	1.1567
5	14	0.1372	14	0.8885	7	-0.2380	7	-0.6874
6	6	0.0897	6	0.5018	9	-0.1606	6	0.5659
7	5	0.0743	9	-0.3463	8	0.1208	9	-0.3112
8	9	-0.0740	8	0.3325	6	0.1060	5	0.3061
9	8	0.0711	5	0.3087	5	0.0941	8	0.3029
10	3	-0.0648	3	-0.2420	38	0.0598	13	0.2087

Table 3
Impact of UPFC placement based on C_1^k (30-bus system)

Rank order	Line no.	C_1^k	Considering variation of V_s (pu) only		Considering variation of V_s (pu) and ϕ_s (rad)		
			Optimal PI	V_s	Optimal PI	V_s	ϕ_s
1	33	-0.3134	0.3178	0.1873	0.2862	0.1079	1.1663
2	12	-0.2639	0.2949	0.2000	0.2858	0.1028	1.0293
3	7	-0.1722	0.3754	0.0682	0.3574	0.0708	1.7240
4	11	0.1501	0.3304	0.1539	0.2869	0.1179	1.5967
5	14	0.1372	0.3726	0.1219	0.3237	0.1531	1.6194
6	6	0.0897	0.3820	0.0642	0.3581	0.1043	1.7329

Table 3 shows the optimal PI values obtained after optimal placement of the UPFC in few lines having high value of the PI sensitivity factors (C_1^k). Optimal values of the PIs, given in the 4th column, are when only series injected voltage magnitude of the UPFC is varied and those given in the 5th column are when both the magnitude and phase angle of the injected voltage by UPFC are varied in the corresponding lines. From Table 3, it can be seen that the line-12 is the best location for optimal placement of UPFC in the 30-bus system.

Table 4 shows the optimal PI values after placing the UPFC in the respective lines, one at a time, selected based on the PI sensitivity factors C_2^k . The PI values given in the column 4 are obtained with the fixed values of series injected voltage magnitude (considered as 0.01pu) and varying the phase angle injection by the UPFC. The optimal values of the series injected voltage angle are shown in the 4th column. The effect of variation of both the series voltage magnitude and phase angle injection by the UPFC on optimal PI values is shown in the 5th column. From Tables 2, 3 and 4, the best location for the UPFC placement, in the

IEEE 30-bus system, is found to be line-12, as the optimal PI value is minimum in most of the cases with the UPFC placement in this line.

Table 4
Impact of UPFC placement based on C_2^k (30-bus system)

Rank order	Line no.	C_2^k	Considering variation of ϕ_s (rad) only		Considering variation of V_s (pu) and ϕ_s (rad)		
			optimal PI	ϕ_s	optimal PI	V_s	ϕ_s
1	12	-2.0657	0.3668	1.1114	0.2858	0.1028	1.0293
2	33	-2.0295	0.3676	1.2382	0.2862	0.1079	1.1663
3	11	1.7068	0.3686	1.2638	0.2869	0.1179	1.5967
4	7	-0.9631	0.3775	1.2407	0.3574	0.0708	1.7240
5	14	0.8885	0.3775	1.3234	0.3237	0.1531	1.6194
6	6	0.5018	0.3805	1.3654	0.3581	0.1043	1.7329

It can be seen that the best locations for the UPFC placement based on the optimal PI values (Table 4, column 5) are lines-12, 33, 11, 14, 7 and 6 in the rank order. However, the ranking order obtained from the sensitivity factors (C_2^k) are lines-12, 33, 11, 7, 14, and 6, which are almost similar, but not the same.

The rank order of line provided by the PI sensitivity factors (F_1^k , F_2^k) obtained using ac power flow approximation, as shown in Table 2, for the optimal locations of UPFC are the lines-12, 33, 11, 14, 7, and 6, respectively. This order is exactly same as verified through the optimal value of the PI obtained after placement of the UPFC in these lines. This confirms the validity of the proposed PI sensitivity factors, based on ac power flow approximation, for the UPFC placement (Table 4). It can also be seen from Table 2 that the PI sensitivity factors with respect to the injected voltage phase angle provide more accurate result for optimal UPFC location in order to improve system security, as reflected by the optimal PI values.

5.3 Optimal Placement of UPFC in NREB 246-bus System and study its Impact on System Security

The PI sensitivities, based on the dc & ac power flow method, have also been computed for the 246-bus system, as defined in equations (6)-(7) and (22)-(23), which are listed in Table 5.

Table 5
PI sensitivity factors (246-bus system)

Rank order	dc power flow approximation [7]				ac power flow approximation			
	Line no.	C_1^k	Line no.	C_2^k	Line no.	F_1^k	Line no.	F_2^k
1	213	2.7445	198	-19.2473	198	22.3704	213	-65.6967
2	218	-2.5946	218	-19.1484	218	21.8200	218	65.4654
3	198	-2.4618	213	19.0337	213	-21.1940	198	65.2810
4	193	-2.1875	197	-17.0890	197	14.5429	206	-50.0659
5	197	-2.1563	193	-16.9992	193	14.0577	205	49.8826
6	205	-1.9746	205	-12.5719	206	-13.9627	197	44.9844
7	206	1.9741	206	12.5691	205	13.8662	193	44.7622
8	196	1.9498	196	12.1520	174	10.9895	196	-44.0145
9	349	-1.1543	191	6.4431	196	-10.7936	191	-35.6772
10	191	1.0888	276	-5.8666	191	-10.3694	173	-34.2384

Table 6 shows the optimal PI values, obtained after optimal placement of the UPFC in few lines, having high value of the PI sensitivity factors (C_1^k). Optimal values of the PIs, given in the 4th column, are when only series injected voltage of UPFC is varied and those given in the 5th column are when both the magnitude and the phase angle of the injected voltage by the UPFC are varied in the corresponding lines. From Table 6, it can be seen that the line-213 is the best location for the optimal placement of the UPFC in the 246-bus system.

Table 6

Impact of UPFC placement based on C_1^k (246-bus system)

Priority no.	Line no.	C_1^k	Considering variation of V_s (pu) only		Considering variation of V_s (pu) and ϕ_s (rad)		
			Optimal PI	V_s	Optimal PI	V_s	ϕ_s
1	213	2.7445	4.9446	0.0543	4.9445	0.0492	-3.1093
2	218	-2.5946	4.9446	0.0541	4.9446	0.0489	-3.1121
3	198	-2.4618	4.9447	0.0532	4.9447	0.0487	0.0306
4	193	-2.1875	4.9804	0.0361	4.9760	0.0827	2.9697
5	197	-2.1563	4.9811	0.0360	4.9812	0.0358	-3.1416

Table 7 shows the optimal PI values after placing the UPFC in the respective lines, one at a time selected based on the PI sensitivity factors C_2^k . The PI values, given in the column 4, are obtained with the fixed values of the series injected voltage magnitude (considered as 0.01pu) and varying the voltage phase angle injection by the UPFC. The optimal values of the series injected angle are shown in the 4th column. The effect of both the series voltage magnitude and phase angle variation by the UPFC, on the optimal PI values, is shown in the 5th column. From Tables 5, 6 and 7, the best location for the UPFC placement, in the 246-bus system, is found to be line-213, as the optimal PI value is minimum in most of the cases with the UPFC placement in this line.

Table 7

Impact of UPFC placement based on C_2^k (246-bus system)

Priority no.	Line no.	C_2^k	Considering variation of ϕ_s (rad) only		Considering variation of V_s (pu) and ϕ_s (rad)		
			Optimal PI	ϕ_s	Optimal PI	V_s	ϕ_s
1	198	-19.2473	4.9605	1.2307	4.9447	0.0487	0.0306
2	218	-19.1484	4.9604	1.2370	4.9446	0.0489	-3.1121
3	213	19.0337	4.9604	1.2391	4.9445	0.0492	-3.1093
4	197	-17.0890	4.9882	0.9491	4.9812	0.0358	-3.1416
5	193	-16.9992	4.9879	0.9506	4.9860	0.0827	2.9697
6	205	-12.5719	4.9808	1.3104	4.9493	0.1024	3.1416
7	206	12.5691	4.9852	3.1416	4.9482	0.1246	2.5092

The PI sensitivity factors, obtained using ac power flow approximation, are also shown in Table 5, gives the rank order for the optimal locations of UPFC as lines- 213, 218, 198, 206, 205, 197, and 193. This order is exactly same as verified through the optimal value of the PI, obtained after placement of UPFC in these lines. This confirms the validity of the proposed PI sensitivity based factors for the UPFC placement (Table 5). It can also be seen, from Table 5, that

the PI sensitivity factors with respect to the injected voltage phase angle provides more accurate results for optimal location of the UPFC in order to improve system security, as reflected by the optimal PI values.

5.4 UPFC Placement based on PI Sensitivity Factors at increased Loading Condition

This case was simulated by increasing the loads at all the buses by 5% from their base case values in the 30-bus system. Table 8 shows the optimal location of UPFC based on the PI sensitivity factors obtained from dc & ac power flow approximations.

Table 8

PI sensitivity factors with 5% load increase (30-bus system)

Rank order	dc power flow approximation [7]				ac power flow approximation			
	Line no.	C_1^k	Line no.	C_1^k	Line no.	F_1^k	Line no.	F_2^k
1	33	-0.4031	12	-2.4924	12	-2.2990	12	-4.5272
2	12	-0.3394	33	-2.4469	11	1.7007	33	-4.4940
3	7	-0.2214	11	2.0637	33	-1.5853	11	4.4272
4	11	0.1938	7	-1.1592	14	0.7925	14	2.1625
5	14	0.1770	14	1.0743	7	-0.6667	7	-2.1222
6	6	0.1161	6	0.6082	6	0.4693	6	1.5512
7	5	0.0945	9	-0.4131	9	-0.3381	9	-0.7416
8	9	-0.0942	8	0.3965	5	0.2875	5	0.7268
9	8	0.0904	5	0.3681	8	0.2624	8	0.7263
10	3	-0.0827	3	-0.2895	3	-0.1063	3	-0.1832

The impact of the optimal placement of UPFC on PI value is given in Table 9, with the 5% increase in loading. The PI value was found to be 0.5012, when there was no UPFC in the system. From Table 8, it is found that the line-12 is the most sensitive line for the placement of UPFC in the case of the increased loading case as well. The PI value improves from 0.5012, without UPFC, to 0.3669, with UPFC placed in line-12.

Table 10 shows the sensitivity factors with increased loading in the 246-bus system using dc power flow approximation. It is found that the rank order of lines for optimal location of UPFC is the same as obtained through optimal PI values after placement of UPFC in these lines as shown in Table 9 for both series voltage and phase angle variations.

Table 9

PI sensitivity factors (C_1^k & C_2^k) and optimal PI values after UPFC placement in 30-bus system with 5% load increase

Rank order	PI sensitivities				Optimal PI values and UPFC settings			
	Line	C_1^k	Line	C_2^k	Line	PI	V_s (pu)	ϕ_s (rad)
1	33	-0.4031	12	-2.4924	12	0.3669	0.1117	0.9532
2	12	-0.3394	33	-2.4469	33	0.3676	0.1177	1.1004
3	7	-0.2214	11	2.0637	11	0.3686	0.1301	1.6385
4	11	0.1938	7	-1.1592	7	0.4633	0.0758	1.6804
5	14	0.1770	14	1.0743	14	0.4187	0.1654	1.6153

Similarly, Tables 10 and 11 show the optimal location of UPFC, based on dc and ac power flow approximations, respectively, and its impact after placing them in

corresponding lines, one at a time, for 0.5% load increase condition in 246-bus system. The base case condition of this system is already simulated at a peak load condition. Hence, only 0.5% load increase has been considered. The optimal PI value was obtained as 5.2181, when there was no UPFC in the system. From Table 10 & 11, it is found that the line-213 is the most sensitive for the optimal placement of UPFC in the increased loading case as well. The PI value has improved from 5.2181, without UPFC, to 5.0961, with UPFC placed in line-213.

Table 10

PI sensitivity factors (C_1^k & C_2^k) and optimal PI values after UPFC placement in 246-bus system with 0.5% load increase (dc power flow approximation)

Pr. no.	PI sensitivities C_1^k & C_2^k				PI values and optimal UPFC settings			
	Line	C_1^k	Line	C_2^k	Line	PI	V_s (pu)	ϕ_s (rad)
1	213	-2.3692	213	-14.2958	213	5.0961	0.0359	0.1945
2	218	2.3691	218	14.2951	218	5.0962	0.0355	-2.9486
3	198	2.2820	198	14.3606	198	5.0964	0.0351	-2.9485
4	205	2.0284	193	11.3489	197	5.1111	0.0353	-3.1416
5	206	-1.8659	197	11.3341	193	5.1188	0.0397	-3.1416
6	197	1.7112	206	-11.0970	205	5.0968	0.1115	2.4432
7	193	1.6929	205	11.0456	206	5.0966	0.1120	2.4419

Table 11

PI sensitivity factors (F_1^k & F_2^k) in 246-bus system with 0.5% load increase (ac power flow approximation)

Rank order	Line no.	Buses ($i-j$)	F_1^k	Line no.	Buses ($i-j$)	F_2^k
1	198	134-146	26.4559	213	141-148	-72.8023
2	218	146-148	25.8230	218	146-148	72.5350
3	213	141-148	-25.0930	198	134-146	72.3215
4	197	18-134	18.7002	197	18-134	54.2561
5	193	133-18	18.1167	193	133-18	53.9974
6	206	137-141	-16.0120	206	137-141	-51.9355
7	205	137-140	15.8854	205	137-140	51.7082
8	196	133-183	-15.0548	196	133-183	-50.7227
9	280	183-34	-12.1881	191	132-140	-36.7600
10	174	17-34	12.0331	173	17-229	-34.4049

5.5 Impact of Contingencies on Optimal UPFC Location and System Security

To show the effectiveness of the proposed method under contingencies, the sensitivity factors and optimal PI values were also computed for different line outage cases (Table 1), which are shown in Tables 12 and 13 for the 30-bus and 246-bus systems, respectively. First column shows the line considered for outage and the second column shows the PI values at outage of the corresponding lines without placement of UPFC. In Tables 12 and 13, the column three presents the sensitivity factors (C_2^k & F_2^k) along with corresponding optimal PI values for the few lines in priority order after outage of critical lines, as listed in the first column. Only the sensitivity factors C_2^k and F_2^k with respect to the change in series injected voltage phase angle by the UPFC have been considered, as it provided better results in the base case. Due to the outage of lines, the most optimal locations of the UPFC changed.

Table 12

Optimal PI values under critical line outages in 30-bus system (dc & ac power flow approximations)

Line outage	PI value after line outage	Sensitivities C_2^k & F_2^k and optimal PI values with UPFC settings					
		Line no.	C_2^k	F_2^k	Optimal PI	V_s (pu)	ϕ_s (rad)
12 (1-17)	1.7530	12	-	-	-	-	-
		33	0.013	0.043	1.7523	0.0040	0.0000
		11	-1.714	0.469	1.7020	0.0908	0.2554
		14	-0.560	0.170	1.7445	0.0479	-0.3551
		7	-0.364	0.061	1.7517	0.0130	-0.1290
33 (27-11)	1.6741	12	-0.000	0.036	1.6741	0.0002	1.5140
		33	-	-	-	-	-
		11	-1.631	0.510	1.6281	0.0885	0.2334
		14	-0.535	0.157	1.6671	0.0421	-0.3499
		7	-0.369	0.053	1.6734	0.0131	-0.1061
5 (2-5)	0.6183	12	-1.039	-2.153	0.5680	0.1073	0.0703
		33	-1.011	-2.232	0.6182	0.0092	0.4499
		11	0.703	2.153	0.5686	0.1121	2.1766
		14	0.677	1.357	0.5839	0.1330	2.2459
		7	0.011	-0.500	0.6122	0.0702	-0.3877

From Table 12, the line-11 is found to be the most suitable location for the optimal placement of the UPFC in view of security enhancement during outage of the lines-12, 33 and 5 in the IEEE 30-bus system. From Table 13, the line-213 is found to be the most suitable location for the optimal placement of the UPFC in view of security enhancement during outage of the lines-223, 355 and 206 in the 246-bus system.

Table 13

Optimal PI values under critical line outage cases in 246-bus system (dc and ac power flow approximations)

Line outage	PI value after line outage	Sensitivities C_2^k & F_2^k and optimal PI values with UPFC settings					
		Line no.	C_2^k	F_2^k	Optimal PI	V_s (pu)	ϕ_s (rad)
223 (154-240)	6.4608	213	-19.711	-73.556	6.3427	0.0525	-3.1416
		218	19.7129	73.297	6.3433	0.0515	-3.1416
		198	19.8103	73.0938	6.3441	0.0503	-3.1416
		197	16.2741	50.6191	6.3770	0.0361	-3.1416
		193	-16.212	50.2972	6.3535	0.0504	-0.4330
		206	-11.935	-48.997	6.2743	0.0387	0.7937
		205	11.8712	48.6857	6.2898	0.1001	3.1416
355 (223-39)	5.9063	213	-19.059	-65.655	5.7958	0.0485	-3.1258
		218	19.0601	65.4231	5.7978	0.0205	-2.6180
		198	19.1457	65.2377	5.7972	0.0153	-2.0944
		197	17.1118	44.9845	5.8437	0.0096	-2.0944
		193	17.1335	44.7686	5.8337	0.0745	2.9715
		206	-12.640	-50.022	5.6871	0.1239	2.5093
		205	12.5806	49.8449	5.7535	0.1020	3.1416
206 (137-141)	5.9772	213	-38.083	-68.580	5.5089	0.1145	-3.1416
		218	38.0905	68.3635	5.5096	0.1137	-3.1416
		198	38.2587	68.1860	5.4566	0.1900	2.9826
		197	39.2914	48.5513	5.6390	0.0743	-3.1416
		193	39.3395	48.2905	5.6365	0.0757	-3.1416
		206	-	-	-	-	-
		205	76.7267	88.1096	4.9868	0.1596	3.1416

From all obtained results, it has been observed that the proposed PI sensitivity factors based approach that utilized

ac power flow, provided more accurate location of the UPFC as compared to that obtained from the dc power flow based PI sensitivity factors method. The placement of the UPFC in a line, obtained from the proposed factors, has resulted in maximum reduction in the line real power flow performance index (PI) values. The optimal placements do not change for increase in system loading. However, the locations differ under critical contingency conditions. Moreover, sensitivities calculated using dc power flow method provides relatively less accurate location of the UPFC in the NREB 246-bus system.

6. Conclusions

Line loading security Performance Index (PI) sensitivity factors have been suggested in this work for optimal placement of UPFC for enhancing the security of the power system. The PI sensitivity factors have been obtained with respect to change in two of the UPFC parameters viz., magnitude and phase angle of the injected voltage in the lines. An Optimal Power Flow (OPF) formulation has been suggested to determine the optimal PI values, another way called as security measure, after placement of UPFC based on the proposed sensitivity factors, in order to validate accuracy of the method. Both ac and dc power flow approximations have been used to define the sensitivity factors and their results have been compared on IEEE 30-bus and NREB 246-bus systems. The impact of the UPFC placement on the security enhancement of the power system has been established, in terms of optimal PI values along with the optimal control settings of the UPFC, for system intact and few critical contingency cases.

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