

Optimal Location of FACTS Device on Enhancing System Security

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ABSTRACT

In this paper, a Unified Power Flow Controller (UPFC) is a FACTS device that can be control the power flow in transmission line by injecting active and reactive in voltage components in series with the lines. The proposed methodologies are based on the use of line loading security Performance Index (sensitivity factors have been suggested in this paper for optimal placement of UPFC. This methods are computationally efficient 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. The proposed methodologies are tested validated for locating UPFC in IEEE 30-bus system. ACO based Optimal Power Flow (OPF) formulation has been suggested to determine the optimal PI values, after placement of UPFC based on the proposed sensitivity factors. 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 system

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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 [1, 2] of a power system can be defined as its ability to withstand a set of severe, but credible contingencies and remain 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 network. 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, motivate the use of Flexible AC Transmission Systems (FACTS) controllers [3-13] 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 transaction and maintain systems security.

However, due to the high cost of these controllers, it is necessary to locate them optimally in the network. Several papers, reported in the literature, deal with the optimal placement of FACTS controllers. However very few [5, 6] have discussed the method of their optimal location in view of enhancing the system security. In [6] deals with optimal location of TCSC and [7] have presented a method of optimal al location of UPFC in view of enhancing the security. These works used DC power flow approximation model and did not suggest a method to determine optimal settings of controllers. In [5] suggested the use of phase shifter for security enhancement and obtained its parameter using Optimal Power Flow (OPF) formulation. In [8] have proposed a new formation for reactive power planning problem including the allocation of FACTS device, but the result have been demonstrated on a very a 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 IEEE14-bus system. Three heuristic methods, viz. Genetic Algorithm, Tabu-Search and Simulated Annealing, have been applied in [9] for optimal location of the facts devices.

In this paper, a new index representing sensitivity of line real power flow Performance Index (PI) with respect to UPFC parameters have been suggested for its optimal location in view of enhancing the system security under different operating conditions. The sensitivity of real power with respect to optimum tuning control parameters of the UPFC has been obtained utilizing AC power flow approximation. The effectiveness of the proposed method has demonstrated on IEEE 30-bus system, utilizing an Object Oriented Programming of Ant Colony Based model that minimizes the line flow PI values. The results have been compared with an existing real power flow performance index (PI) sensitivity approach utilizing DC power flow approximation [4].

2. MATHEMATICAL FORMULATION

2.1. Optimal Location of FACTS device Using Improved Performance Index

The relative severity of the system loading under normal and each of the contingency cases can be described by a line real power flow performance Index (PI) [4], as given below.

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

where P_m is the real power flow and P_m^{\max} is 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. The lack of discrimination, in which the performance index for a case with many small violations may be comparable in value to the index for a case with a few large violations, is known as *masking effect*. By most of the operational standards, the system with few large violation is much more severe than that with many small violations, Masking effect, to some extent, can be avoided by using higher order performance indices (i.e. $a > 1$). In this study, the value of exponent ' a ' has been taken as 2 and weighting coefficient ' w_m ' for all the lines as 1.0.

2.2. PI sensitivity using DC power flow approximation

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

$$C_1^K = \left. \frac{\partial PI}{\partial V_s} \right|_{V_s=0} = \text{PI Sensitivity with respect to } V_s \quad (2)$$

$$C_2^K = \left. \frac{\partial PI}{\partial V_s \partial \phi_s} \right|_{\partial \phi_s=0} = \text{PI Sensitivity with respect to } \phi_s \quad (3)$$

For deriving the PI sensitivity terms using DC power flow approximation, the value of ' a ' in equation (1) has been taken as 2. Using equations (2) and (3), 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

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

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 [4, 6] as

$$P_m = \begin{cases} \sum_{\substack{n=1 \\ n \neq s}}^{N_b} S_{mn} P_n & \text{for } m \neq k \\ \sum_{\substack{n=1 \\ n \neq s}}^{N_b} S_{mn} P_n + P_{ju} & \text{for } m = k \end{cases} \quad (5)$$

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, 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. Using equations (4) and (5), the following relationship can be derived,

$$\frac{\partial P_m}{\partial X_k} = \begin{cases} (S_{mi} \frac{\partial P_{iu}}{\partial X_k} + S_{mj} \frac{\partial P_{ju}}{\partial X_k}) & \text{form} \neq k \\ (S_{mi} \frac{\partial P_{iu}}{\partial X_k} + S_{mj} \frac{\partial P_{ju}}{\partial X_k}) + \frac{\partial P_{ju}}{\partial X_k} & \text{form} = k \end{cases} \quad (6)$$

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, with respect to the UPFCs series parameters.

2.3. Proposed PI sensitivity 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 element of bus admittance matrix (Y) as

$$P_{is} = P_{Gi} + P_{iu} - P_{Di} - \text{Re} \left(V_i \sum_{j=1}^{N_b} (V_j Y_{i,j})^* \right) \quad (7)$$

$$Q_{is} = Q_{Gi} + Q_{iu} - Q_{Di} - \text{Im} \left(V_i \sum_{j=1}^{N_b} (V_j Y_{i,j})^* \right) \quad (8)$$

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 at bus- i due to UPFC. P_{Di} and Q_{Di} are the base case real and reactive power demands, respectively, at the bus- i . Equation (7) and (8), with UPFC, are function of bus voltage magnitudes (V), and angles (δ), magnitude (V_s) and angles (ϕ_s) of the injected voltage due to UPFC.

$$\left. \begin{aligned} P_{is} &= f_{pi}(V, \delta, \phi_s, V_s) \\ Q_{is} &= f_{qi}(V, \delta, \phi_s, V_s) \end{aligned} \right\} \quad (9)$$

(V_s) is considered as the best location for the UPFC.

The sensitivities of real power flow Performance Index (PI) with respect to UPFCs series parameter s (voltage magnitude and phase injection) have been calculated by both AC and DC power flow approximation. The following criteria have been used for optimal placement of an UPFC in the system.

- [i] The branches having transformer are not considered for the UPFC placement.
- [ii] The line having highest absolute PI sensitivity (C_2^k and 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.
- [iii] When the values of absolute PI sensitivities (C_2^k and F_2^k) with respect to change in injected voltage phase angle (ϕ_s) for line more than one are very close to each other, the line having highest absolute value of the PI sensitivities (C_1^k, F_1^k) with respect to the change in injected voltage magnitude.

3. OPF FORMULATION

The effectiveness of proposed PI sensitivity factors based approach for UPFC placement has been arrived in terms of its impact on the reduction I line flow performance Index (PI) values. For this purpose, an Optimal Power Flow (OPF) formulation is described below has been used.

$$\text{Minimize} = \sum PI \quad (10)$$

Subject to the following constraints:

a. Equality constraints: Power balance equations corresponding to both real and reactive power at each bus must be satisfied. This can be expressed, in general forms as

$$G(V, \delta, Y, V_s, \phi_s) = 0 \quad (11)$$

where G is the vector of 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.

$$Q_G^{\min} \leq Q_G \leq Q_G^{\max} \quad (12)$$

$$\left. \begin{aligned} V_i^{\min} &\leq V_i \leq V_{gi}^{\max} \\ \delta_i^{\min} &\leq \delta_i \leq \delta_i^{\max} \\ 0 &\leq V_s \leq V_s^{\max} \\ -\pi &\leq \phi_s \leq \pi \end{aligned} \right\} \quad (13)$$

Equation (12) represents the limits on the reactive power generations. The limits on the bus voltage magnitude and angle. Equation (13) represents the limits on the UPFC parameters (V_s, ϕ_s) . The above OPF problem involves a nonlinear objective function and a set of non linear equality and inequality constraints. This problem is solved by Ant Colony Optimization procedure. In this work, ACA optimization programming is developed in objected oriented in java programming and UML software is used for design of object oriented class diagram and ACA coding as a sub package and separately run to obtain the optimal solution

4. 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 system.

4.1. Line Outage Contingency Ranking

To obtain the critical contingencies (line outages) in the IEEE 30-bus system, the PI values as defined in equations (3.35) in previous chapter, are computed for each of the single line outage (N-1 contingency) cases. Five most critical lines are listed in Table1. Contingencies, for which feasible Ac load flow solution have not been obtained, are not considered in this list. For the base case, the PI values obtained from AC power flow solution for the IEEE 30-bus system are found to be 0.4250.

Table 1. Line outage contingency ranking based on PI values in 30-bus system

Rank order	IEEE30-bus system		
	Line outage	End buses $i-j$	PI
	Intact case	-	0.4250
1	12	1-27	1.9130
2	33	27-11	1.8110
3	5	2-5	0.6372
4	7	11-13	0.6001
5	9	13-12	0.4889

Table 2. Impact of UPFC placement based on (C_1^k) (30-bus system)

Rank order	Line no.	C_1^k	Considering variation of V_s		Considering variation of V_s (pu) and ϕ_s (rad)		
			(pu) only		Optimal PI	V_s	ϕ_s
			Optimal PI	V_s			
1	33	-0.3130	0.3078	0.1873	0.2662	0.1079	1.1663
2	12	-0.2629	0.2849	0.2000	0.2558	0.1028	1.0293
3	7	-0.1642	0.3554	0.0682	0.3174	0.0708	1.7240
4	11	0.1401	0.3204	0.1539	0.2469	0.1179	1.5967
5	14	0.1272	0.3226	0.1219	0.3037	0.1531	1.6194
6	6	0.0797	0.3520	0.0642	0.3181	0.1043	1.7329

Table 3. Impact of UPFC placement based on C_2^k (30-bus system)

Rank order	Line no.	C_2^k	Considering variation of ϕ_s		Considering variation of V_s (pu) and ϕ_s (rad)		
			(rad) only		Optimal PI	V_s	ϕ_s
			Optimal PI	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

Table 2 shows the optimal PI value 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 3rd 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 2, it can be seen that the line-12 is the best location for optimal placement of UPFC in the 30-bus system.

Table 3 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 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 values is shown in the 5th column. From Table 1, 2 and 3, the best location for the UPFC placement, in the IEEE30-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.

It can be seen that the best locations for the UPFC placement based on the optimal PI values (Table 3, column 6) 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 exactly the same. This order is exactly same as verified through the optimal value of PI obtained after placement of the UPFC in these lines. This confirms the validity of the proposed PI sensitivity factor for the UPFC placement (Table 3).

Table 4. PI sensitivity factors (C_1^k & C_2^k)

Rank order	PI sensitivity			
	C_1^k		C_2^k	
	Line	C_1^k	Line	C_2^k
1	33	-0.4031	12	-2.4924
2	12	-0.3394	33	-2.4469
3	7	-0.2214	11	2.0637
4	11	0.1938	7	-1.1592
5	14	0.1770	14	1.0743

Table 5. Optimal PI values after UPFC Placement in 30-bus system with 5% load increase
Optimal PI values and UPFC settings

Line	PI	V_s (pu)	ϕ_s (rad)
12	0.3569	0.1117	0.9532
33	0.3576	0.1177	1.1004
11	0.3580	0.1301	1.6385
7	0.4630	0.0758	1.6804
14	0.4181	0.1654	1.6153

The impact of the optimal placement of UPFC on PI value is given in Table 4, with the 5% increase in loading. The PI value was found to be 0.5012, when there was no UPFC in the system. 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 5 for both series voltage and phase angle variations.

To show the effectiveness of the proposed method under contingencies, the sensitivity factors and optimal PI values were also computed for r different line outage cases, which are shown in Table 6 for the 30-bus system. First column show the line considered for outage and the second column show the PI value at outage of the corresponding line without placement of UPFC. In the column three present the sensitivity factors (C_2^k & F_2^k) along with corresponding optimal pi value for the few lines in priority order after outage of critical lines, as listed in the first column. Only the sensitivity factor (C_2^k & F_2^k) with respect to the change in series injected voltage phase angle by UPFC have been considered, as it provided better results in base case. Due to the outage of lines, the most optimal location of the UPFC changed. From, the lines-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 IEEE 30-bus systems.

Table 6. Optimal PI values under critical line outage in 30-bus system (DC & AC power flow approximations)

Line outage	PI value after line outage	Sensitivity (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	0.0129	0.0426	1.7523	0.0040	0.0000
		11	-1.7138	0.4682	1.7020	0.0908	0.2554
		14	-0.5598	0.1695	1.7445	0.0479	-0.3551
		7	-0.3637	0.0614	1.7517	0.0130	-0.1290
33 (27-11)	1.6741	12	-0.0000	0.0356	1.6741	0.0002	1.5140
		33	-	-	-	-	-
		11	-1.6306	0.5100	1.6281	0.0885	0.2334
		14	-0.5353	0.1567	1.6671	0.0421	-0.3499
5 (2-5)	0.6183	7	-0.3685	0.0530	1.6734	0.0131	-0.1061
		12	-1.0391	-2.1527	0.5680	0.1073	0.0703
		33	-1.0113	-2.2315	0.6182	0.0092	0.4499
		11	0.7026	2.1527	0.5686	0.1121	2.1766
		14	0.6770	1.3566	0.5839	0.1330	2.2459
		7	0.0113	-0.5004	0.6122	0.0702	-0.3877

5. CONCLUSIONS

Line loading security Performance Index (sensitivity factors have been suggested in this work for optimal placement of UPFC. 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, 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 system. Test results obtained on the system show that the new sensitivity factors could be effectively used for optimal placement of UPFC in order to enhance the static security of the power system. The following criteria can be effectively used for deciding the optimal locations of the UPFC.

- [i] The UPFC can be placed in a line- k having largest absolute value of the sensitivity factors (C_2^k or F_2^k) with respect to change in ϕ_s .

- [ii] If two lines can be having similar values of (C_2^k or F_2^k), the UPFC should be placed in a line- k having most absolute value sensitivity index (C_1^k or F_1^k) with respect to change in V_s .

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. It is found that the proposed PI sensitivity factors based approach utilizing AC power flow approximation, gives more optimal 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. The optimal placement does not change for increase in system loading. However, the locations differ under critical contingency conditions.

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