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Location of unified power flow controller for congestion management

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Abstract

This paper presents the development of simple and efficient models for suitable location of unified power flow controller (UPFC), with static point of view, for congestion management. Two different objectives have been considered and the results are compared. Installation of UPFC requires a two-step approach. First, the proper location of these devices in the network must be ascertained and then, the settings of its control parameters optimized. The effectiveness of the proposed methods is demonstrated on two test systems. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Unified power flow controller; UPFC location; Sensitivity analysis; Congestion management

1. Introduction

As a consequence of the ongoing power system restructuring, increased wheeling transactions are common which requires an opening of unused potentials of transmission system due to environmental, right-of-way and cost problems that are major hurdles for power transmission network expansion. Patterns of generation that results in heavy flows tend to incur greater losses and to threaten stability and security ultimately make certain generation patterns economically undesirable. Hence, there is an interest in better utilization of available power system capacities by installing new devices such as Flexible AC transmission systems (FACTS). FACTS devices can be an alternative to reduce the flows in heavily loaded lines, resulting in an increased loadability, low system loss, improved stability of the network, reduced cost of production and fulfilled contractual requirement by controlling the power flows in the network. Variable series capacitors, phase shifters and unified power flow controllers (UPFCs) can be utilized to change the power flow in the lines by changing their parameters to achieve various objectives.

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FACTS devices [1,2] provide new control facilities, both in steady state power flow control and dynamic stability control. The possibility of controlling power flow in an electric power system without generation rescheduling or topological changes can improve the performance considerably [4]. The increased interest in FACTS devices are essentially due to two reasons. Firstly, the recent development in high power electronics has made these devices cost effective [5] and secondly, increased loading of power systems, combined with deregulation of power industry, motivates the use of power flow control as a very cost-effective means of dispatching specified power transactions. It is important to ascertain the location for placement of these devices because of their considerable costs.

There are several methods for finding locations of FACTS devices such as thyristor control series compensator (TCSC), thyristor controlled phase angle regulator (TCPAR) and static var compensators (SVC) in both vertically integrated and unbundled power systems [6–14]. However, there is no, to the best of authors knowledge, paper that suggest a simple and reliable method for determining the suitable location of UPFC with static considerations. Using controllable components of UPFC, the line flows can be changed in such a way that thermal limits are not violated, losses mini-

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mized, stability margin increased, contractual requirement fulfilled etc, without violating specified power dispatch. Liu and Song [15] have compared the performance of UPFC with SVC and phase shifter.

Congestion in a transmission system, whether vertically organized or unbundled, cannot be permitted except for very short duration, for fear of cascade outages with uncontrolled loss of load. Some corrective measures such as outage of congested branches (lines or transformers), using FACTS devices, operation of transformer taps, re-dispatch of generation and curtailment of pool loads and/or bilateral contracts can relieve congestion. If there is no congestion, the placement of FACTS devices, from the static point of view, can be decided on the basis of reducing losses but this approach is inadequate when congestion occurs. A method based on the real power flow performance index (PI) has been considered, in this paper, for this purpose due to security and stability reasons. If PI sensitivity of control parameters of UPFC placed in lines is comparable, the loss sensitivity can be considered.

A method to determine the suitable locations of UPFC, with static point of view, has been suggested, in this paper, based on the sensitivity with respect to control parameters for two objectives: the total system real power loss and the real power flow PI. The proposed algorithm has been demonstrated on 5-bus and IEEE 14-bus test systems.

2. Static model of unified power flow controller

2.1. Basic principles of unified power flow controller

The UPFC, which was first proposed by Gyugi in 1991 [3], consists of shunt (exciting) and series (boosting) transformers as shown in Fig. 1. Both transformers are connected by two-gate turn off (GTO) converters and a DC circuit represented by the capacitor. Converter 1 is primarily used to provide the real power demand of converter 2 at the common DC link terminal from the AC power system. Converter 1 can also

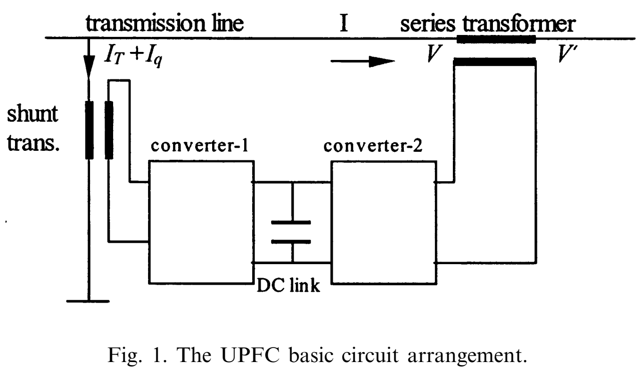

Fig. 1. The UPFC basic circuit arrangement.

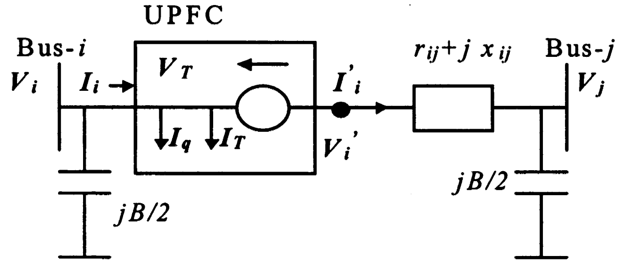

Fig. 2.

generate or absorb reactive power at its AC terminal, which is independent of the active power transfer to (or from) the DC terminal. Therefore with proper control, it can also fulfil the function of an independent advanced static VAR compensator providing reactive power compensation for the transmission line and thus executing indirect voltage regulation at the input terminal of the UPFC.

Converter 2 is used to generate a voltage source at the fundamental frequency with variable amplitude ($0 \leqslant V_T \leqslant V_{T_{\max}}$) and phase angle ($0 \leqslant \phi_T \leqslant 2\pi$), which is added to the AC transmission line by the series connected boosting transformer. The inverter output voltage injected in series with line can be used for direct voltage control, series compensation, phase shifter and their combinations. This voltage source can internally generate or absorb all the reactive power required by the different type of controls applied and transfers active power at its DC terminal.

With these features, UPFC is probably the most powerful and versatile FACTS device which combines the properties of TCSC, TCPAR and SVC. It is only FACTS device having the unique ability to simultaneously control all three parameters of power flow: voltage, line impedance and phase angle. Therefore, when the UPFC concept was developed in 1991, it was recognized as the most suitable and innovative FACTS device.

2.2. Static representation of unified power flow controller

The equivalent circuit of UPFC placed in line-k connected between bus-i and bus-j is shown in Fig. 2 and control vector diagram in Fig. 3. UPFC has three controllable parameters, namely the magnitude and the angle of inserted voltage (V_T, ϕ_T) and the magnitude of the current (I_q).

Based on the principle of UPFC and the vector diagram, the basic mathematical relations can be given as

$$\mathbf{V}'_i = \mathbf{V}_i + \mathbf{V}_T, \quad \mathrm{Arg}(\mathbf{I}_q) = \mathrm{Arg}(\mathbf{V}_i) \pm \pi/2,$$

$$\mathrm{Arg}(\mathbf{I}_T) = \mathrm{Arg}(\mathbf{V}_i), \quad \mathbf{I}_T = \frac{\mathrm{Re}[\mathbf{V}_T \mathbf{I}'_i{}^*]}{\mathbf{V}_i}. \tag{1}$$

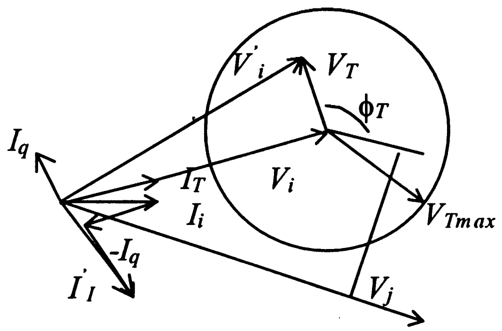

Fig. 3. Vector diagram of UPFC.

The power flow equations from bus-i to bus-j and from bus-j to bus-i can be written as

$$\mathbf{S}_{ij} = P_{ij} + jQ_{ij} = \mathbf{V}_i\mathbf{I}_{ij}^* = \mathbf{V}_i(j\mathbf{V}_iB/2 + \mathbf{I}_T + \mathbf{I}_q + \mathbf{I}_i')^*, \quad (2)$$

$$\mathbf{S}_{ji} = P_{ji} + jQ_{ji} = \mathbf{V}_j\mathbf{I}_{ji}^* = \mathbf{V}_j(j\mathbf{V}_jB/2 - \mathbf{I}_i')^*. \quad (3)$$

Active and reactive power flows in the line having UPFC can be written, with above Eqs. (1)–(3), as

$$\begin{aligned} P_{ij} = {} & (V_i^2 + V_T^2)g_{ij} + 2V_iV_Tg_{ij}\cos(\phi_T - \delta_i) \\ & - V_jV_T[g_{ij}\cos(\phi_T - \delta_j) + b_{ij}\sin(\phi_T - \delta_j)] \\ & - V_iV_j(g_{ij}\cos\delta_{ij} + b_{ij}\sin\delta_{ij}), \end{aligned} \quad (4)$$

$$\begin{aligned} P_{ji} = {} & V_j^2g_{ij} - V_jV_T[g_{ij}\cos(\phi_T - \delta_j) - b_{ij}\sin(\phi_T - \delta_j)] \\ & - V_iV_j(g_{ij}\cos\delta_{ij} - b_{ij}\sin\delta_{ij}), \end{aligned} \quad (5)$$

$$\begin{aligned} Q_{ij} = {} & -V_iI_q - V_i^2(b_{ij} + B/2) \\ & - V_iV_T[g_{ij}\sin(\phi_T - \delta_i) + b_{ij}\cos(\phi_T - \delta_i)] \\ & - V_iV_j(g_{ij}\sin\delta_{ij} - b_{ij}\cos\delta_{ij}), \end{aligned} \quad (6)$$

$$\begin{aligned} Q_{ji} = {} & -V_j^2(b_{ij} + B/2) \\ & + V_jV_T(g_{ij}\sin(\phi_T - \delta_j) + b_{ij}\cos(\phi_T - \delta_j)) \\ & + V_iV_j(g_{ij}\sin\delta_{ij} + b_{ij}\cos\delta_{ij}). \end{aligned} \quad (7)$$

From basic circuit theory, the injected equivalent circuit of Fig. 4 can be obtained. The injected active power at bus-i (P_{is}) and bus-j (P_{js}), and reactive powers (Q_{is} and Q_{js}) of a line having a UPFC are

$$\begin{aligned} P_{is} = {} & -V_T^2g_{ij} - 2V_iV_Tg_{ij}\cos(\phi_T - \delta_i) \\ & + V_jV_T[g_{ij}\cos(\phi_T - \delta_j) + b_{ij}\sin(\phi_T - \delta_j)], \end{aligned} \quad (8)$$

$$P_{js} = V_jV_T[g_{ij}\cos(\phi_T - \delta_j) - b_{ij}\sin(\phi_T - \delta_j)], \quad (9)$$

$$Q_{is} = V_iI_q + V_iV_T[g_{ij}\sin(\phi_T - \delta_i) + b_{ij}\cos(\phi_T - \delta_i)], \quad (10)$$

$$Q_{js} = -V_jV_T[g_{ij}\sin(\phi_T - \delta_j) + b_{ij}\cos(\phi_T - \delta_j)]. \quad (11)$$

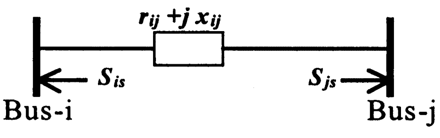

Fig. 4. Injection model of UPFC.

3. Methods for optimal location of unified power flow controller

This paper utilizes two objectives: reduction in the total system real power loss (P_{LT}) and reduction in the real power flow PI. Reduction in the total system active power loss will reduce or eliminate unwanted loop flows but there is no guarantee that lines will not be overloaded though this is unlikely in the absence of congestion.

3.1. Total system loss sensitivity indices (method-1)

The exact loss formula of a system having N buses is, from [16],

$$P'_{LT} = \sum_{j=1}^{N}\sum_{k=1}^{N}[\alpha_{jk}(P_jP_k + Q_jQ_k) + \beta_{jk}(Q_jP_k - P_jQ_k)],$$

where P_j and Q_j, respectively, are the real and reactive power injected at bus-j and α, β are the loss coefficients defined by

$$\alpha_{jk} = \frac{r_{jk}}{V_jV_k}\cos(\delta_j - \delta_k) \text{ and } \beta_{jk} = \frac{r_{jk}}{V_jV_k}\sin(\delta_j - \delta_k),$$

where r_{jk} is the real part of the j–kth element of $[Z_{\text{bus}}]$ matrix. This total real power loss (P_{LT}) if UPFC, placed in line one at a time, is used, can be written as follows (the symbols on the right hand side are defined in Eqs. (8) and (9)

$$P_{LT} = P'_{LT} - (P_{is} + P_{js}). \quad (12)$$

The total system real power loss sensitivity factors with respect to the control parameters of UPFC placed in line-k can be defined as

$$b_1^k = \left.\frac{\partial P_{LT}}{\partial V_T}\right|_{V_T=0}$$

= total loss sensitivity with respect to V_T,

$$b_2^k = \left.\frac{\partial P_{LT}}{V_T\partial\phi_T}\right|_{\phi_T=0}$$

= total loss sensitivity with respect to ϕ_T,

$$b_3^k = \left.\frac{\partial P_{LT}}{\partial I_q}\right|_{I_q=0}$$

= total loss sensitivity with respect to I_q.

These factors are computed using Eq. (12) at a base load flow solution. Consider a line-k connected between bus-i and bus-j. The total system loss sensitivity with respect to control parameters of UPFC can be derived as given below:

$$b_1^k = \left.\frac{\partial P_{LT}\partial P_i}{\partial P_i\,\partial V_T}\right|_{V_T=0} + \left.\frac{\partial P_{LT}\partial P_j}{\partial P_j\,\partial V_T}\right|_{V_T=0} + \left.\frac{\partial P_{LT}\partial Q_i}{\partial Q_i\,\partial V_T}\right|_{V_T=0} + \left.\frac{\partial P_{LT}\partial Q_j}{\partial Q_j\,\partial V_T}\right|_{V_T=0} - \left.\left(\frac{\partial P_{is}}{\partial V_T} + \frac{\partial P_{js}}{\partial V_T}\right)\right|_{V_T=0}, \quad (13)$$

$$b_2^k = \left.\frac{\partial P_{LT}}{\partial P_i}\frac{\partial P_i}{V_T\partial\phi_T}\right|_{\phi_T=0} + \left.\frac{\partial P_{LT}}{\partial P_j}\frac{\partial P_j}{V_T\partial\phi_T}\right|_{\phi_T=0} + \left.\frac{\partial P_{LT}}{\partial Q_i}\frac{\partial Q_i}{V_T\partial\phi_T}\right|_{\phi_T=0} + \left.\frac{\partial P_{LT}}{\partial Q_j}\frac{\partial Q_j}{V_T\partial\phi_T}\right|_{\phi_T=0} - \left.\frac{1}{V_T}\left(\frac{\partial P_{is}}{\partial\phi_T}+\frac{\partial P_{js}}{\partial\phi_T}\right)\right|_{\phi_T=0}, \quad (14)$$

$$b_3^k = \left.\frac{\partial P_{LT}\partial P_i}{\partial P_i\,\partial I_q}\right|_{I_q=0} + \left.\frac{\partial P_{LT}\partial P_j}{\partial P_j\,\partial I_q}\right|_{I_q=0} + \left.\frac{\partial P_{LT}\partial Q_i}{\partial Q_i\,\partial I_q}\right|_{I_q=0} + \left.\frac{\partial P_{LT}\partial Q_j}{\partial Q_j\,\partial I_q}\right|_{I_q=0} - \left.\left(\frac{\partial P_{is}}{\partial I_q}+\frac{\partial P_{js}}{\partial I_q}\right)\right|_{I_q=0}, \quad (15)$$

where

$$\frac{\partial P_{LT}}{\partial P_i} = 2\sum_{m=1}^{N}(\alpha_{im}P_m - \beta_{im}Q_m),$$

$$\frac{\partial P_{LT}}{\partial Q_i} = 2\sum_{m=1}^{N}(\alpha_{im}Q_m + \beta_{im}P_m).$$

The derivatives of real and reactive powers with respect to control parameters of UPFC are given in Appendix A. The sensitivity factors b_1^k, b_2^k and b_3^k can now be found out by substituting Eqs. (A.1), (A.2), (A.3), (A.4), (A.5), (A.6), (A.7), (A.8), (A.9), (A.10), (A.11) and (A.12) in Eqs. (13)–(15), respectively.

3.2. Real power flow performance index sensitivity indices (method-2)

The severity of the system loading under normal and contingency cases can be described by a real power line flow PI [17], as given below.

$$\mathrm{PI} = \sum_{m=1}^{N_l}\frac{w_m}{2n}\left(\frac{P_{lm}}{P_{lm}^{\max}}\right)^{2n}, \quad (16)$$

where P_{lm} is the real power flow and $P_{lm}^{\max}$is the rated capacity of line-m, n is the exponent and w_m a real non-negative weighting coefficient which may be used to reflect the importance of the lines. N_l is the total number of lines in the network.

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

The real power flow PI sensitivity factors with respect to the control parameters of UPFC can be defined as

$$c_1^k = \left.\frac{\partial \mathrm{PI}}{\partial V_T}\right|_{V_T=0} = \text{PI sensitivity with respect to } V_T,$$

$$c_2^k = \left.\frac{\partial \mathrm{PI}}{V_T\partial \phi_T}\right|_{\phi_T=0} = \text{PI sensitivity with respect to } \phi_T,$$

$$c_3^k = \left.\frac{\partial \mathrm{PI}}{\partial I_q}\right|_{I_q=0} = \text{PI sensitivity with respect to } I_q.$$

Using Eq. (16), the sensitivity of PI with respect to UPFC parameter X_k (V_T, ϕ_T and I_q) connected between bus-i and bus-j, can be written as

$$\frac{\partial \mathrm{PI}}{\partial X_k} = \sum_{m=1}^{N_l} w_m P_{lm}^3\left(\frac{1}{P_{lm}^{\max}}\right)^4\frac{\partial P_{lm}}{\partial X_k}. \quad (17)$$

The real power flow in a line-m (P_{lm}) can be represented in terms of real power injections using DC power flow equations [19] where s is slack bus, as

$$P_{lm} = \begin{cases} \sum\limits_{\substack{n=1\\ n\neq s}}^{N} S_{mn}P_n & \text{for } m\neq k,\\ \sum\limits_{\substack{n=1\\ n\neq s}}^{N} S_{mn}P_n + P_{js} & \text{for } m=k, \end{cases} \quad (18)$$

where S_{mn} is the mnth element of matrix [S] which relates line flow with power injections at the buses without UPFC and N is the number of buses in the system. Observe that line-k, from bus-i to bus-j, is the line containing the UPFC, as illustrated in Fig. 4. P_{js}, therefore, is the addition flow, at bus-j, in the line containing the UPFC, due to the presence of the device.

Using Eqs. (17) and (18), the following relationship can be derived,

$$\frac{\partial P_{lm}}{\partial X_k} = \begin{cases} \left(S_{mi}\dfrac{\partial P_{is}}{\partial X_k} + S_{mj}\dfrac{\partial P_{js}}{\partial X_k}\right) \text{for } m\neq k,\\ \left(S_{mi}\dfrac{\partial P_{is}}{\partial X_k} + S_{mj}\dfrac{\partial P_{js}}{\partial X_k}\right) + \dfrac{\partial P_{js}}{\partial X_k} \text{for } m=k. \end{cases} \quad (19)$$

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

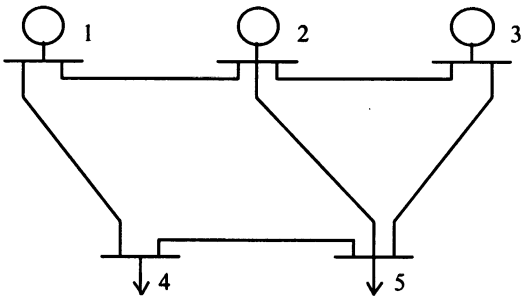

Fig. 5. Five-bus system.

4. Simulation results

To establish the effectiveness of the proposed methods, it has been tested on a 5-bus system [18], IEEE 14-bus system [20] and 75-bus Indian system [21]. Five-bus system consists of three generator buses and two load buses shown in Fig. 5. The two lines 1–2 and 3–5 are of impedance $0.0258 + j0.866$ pu each while other four lines have an impedance of $0.0129 + j0.0483$ pu each, all to a 100 MVA base. The line flow limit is set to 100 MW. Bus-1 has been taken as the reference bus.

Sensitivities were calculated for each control parameters of UPFC placed in every line one at a time for the same operating conditions. The sensitivities of total system real power loss (method-1) and real power flow PI (method-2) with respect to UPFC control parameters are presented in Table 1. The highest negative sensitivities b_1^k and b_2^k, and the highest absolute value of sensitivity b_3^k are presented in bold type.

The magnitudes of sensitivity factors b_1^k are small, that is, reduction in total system loss will be less which can be seen from Table 1 (method-1). For voltage magnitude control, line-4 is suitable as its sensitivity is more negative than other lines. The magnitude of sensitivity of total system real power loss with respect to phase angle (b_2^k) of UPFC placed in line-2 is the highest followed by line-4. This indicates that placement of UPFC in line-2 will reduce the total system real power loss more than the placement in other lines which is a positive value. This indicates that placement of UPFC in line-2 with negative phase shift will reduce the total system real power loss. The sensitivity factor b_3^k is almost same for each line, which is due to uniform voltage profile of the system. The sensitivity for lines 3 and 4 are the highest negative. As method-1 does not consider the loading of the lines it is not suitable for congestion management. In the event of congestion, it is more important, for secure operation of the system, to alleviate the overloads instead of reducing the losses in the system. This shows that method-1 is only appropriate for the placement of this device when there is no congestion.

The sensitivities of the real power flow PI with respect to UPFC control parameters has been computed and are shown in Table 1 (method-2). From the load flow, it was found that real power flows in lines 2 and 4 were 1.15 and 1.04 pu, respectively, which are more than their line loading limits. It can be observed from Table 1 that the sensitivity of PI with respect to V_T for line-2 is the highest but it is positive which indicates that increase in V_T will increase the PI thus congestion of the system. Since the value of V_T cannot be negative it is not suitable for PI reduction. However, c_1^k for line-5 is the most negative and thus suitable for PI reduction with control of V_T.

Table 1 (column 7, c_2^k) shows that placement of UPFC in line-2 is more sensitive than the placement in other lines. This sensitivity is positive which indicates that phase angle shift of the UPFC should be negative. Placing of UPFC in line-2 will reduce the loading of lines 2 and 4 (heavily loaded lines) but it will increase the loading of lines 1 and 3 that are under-loaded. Table 1 also shows that the placement of UPFC in line-1 with phase angle control is the next choice as the magnitude of sensitivity factors is the second highest. The sensitivity factor c_3^k is always zero because it cannot control the real power flow of the line as it is in 90° phase with input voltage. Placement of UPFC in lines 2–5 will also reduce the total system real power loss.

To check the effectiveness of the proposed method-2, the line-loading limit of line-4 has been increased to 1.50 pu and the sensitivity factors calculated for UPFC control parameters are given in Table 2. The magnitude of sensitivity of PI with respect to phase angle of UPFC

Table 1
Sensitivities of 5-bus system

Line-*k*		Method-1			Method-2	
No.	*i*–*j*	b_1^k	b_2^k	b_3^k	c_1^k	c_2^k
1	2–1	0.0016	0.2947	−0.6824	−1.409	−5.229
2	2–5	0.0498	**0.5114**	−0.6824	2.186	**9.108**
3	3–5	0.1073	0.3183	**−0.6890**	−1.317	−4.684
4	5–4	**−0.1526**	0.4987	−0.6670	1.087	4.993
5	1–4	−0.1220	0.4223	−0.6693	**−1.525**	−4.847
6	3–2	−0.1100	−0.0167	**−0.6890**	−0.252	4.603

Table 2
PI sensitivities of 5-bus system for different loading limits

Factors	Lines					
	2–1	2–5	3–5	5–4	1–4	3–2
c_1^k	0.268	1.604	2.083	−0.854	0.114	**−2.049**
c_2^k	−1.281	**6.493**	−5.438	1.609	0.798	5.664

for line-2 is still higher than others lines but the value is less than that obtained for uniform line loading of 1.0 pu. The absolute value of sensitivity c_2^k corresponding to line-6 is the second highest which is slightly higher, in magnitude, than line-3. The placement of UPFC in line-6 will be the next choice but also with negative phase shift. The placement of UPFC in line-1 that was the second choice for the lines loading limit of 1.0 pu, is now fifth choice. For voltage control V_T, the placement of UPFC in line-3 gives positive sensitivity, that is, the PI value will increase with increase of voltage V_T. Line-6 is suitable for this whereas line-5 was the choice for the case when the line loadings of all the lines were the same (Table 1).

The proposed approach was also tested on IEEE 14-bus system. The sensitivities were calculated for each control parameters of UPFC placed in every line one at a time and are shown in Table 3. The sensitivity with respect to V_T is relatively higher that the b_2^k that is sensitivity with respect to phase angle control. From Table 3, it is observed that for reduction of total real power loss, voltage control of UPFC in line 9–8 is suitable. The location of UPFC is also line 9–8 for phase angle control of UPFC for same objective. The sensitivity corresponding to I_q is very small as voltage magnitude of each bus is nearly same.

With the given rating of the line, it was found that lines 1–2 and 2–9 get overloaded. It can be seen from Table 3 that for the congestion management, the UPFC will be suitable either in line 7–10 if we consider controlling the inserted voltage magnitude of UPFC or line 1–8 for control of phase angle. The congestion control with V_T will not be so effective as the range of control is limited. The phase angle control of UPFC can be utilized for congestion management. Line 1–2 will be the next choice after line 1–8 but the phase angle will be negative as the flow of power in this line should be reduced which can be also seen that sensitivity is positive.

This paper suggests the only suitable locations of UPFC. In congested system, the suitable locations of UPFC can be effectively decided based on the sensitivity factors c_1^k and c_2^k. If these sensitivities for two lines are comparable, the placement of a UPFC can be decided based on the total real power loss sensitivity factors which indicates the reduction of the total system real power loss and will also improve the system voltage profile. If there is no congestion, the location of UPFC should be decided not only on the loss minimization but also the cost of UPFC that depends on its control parameters. Therefore a comprehensive economic objective must be considered.

The sensitivity approach has also been tested on a practical Indian power system [18,21] consists of 75 buses and 114 lines. Due to limited space sensitivities are not presented here. It was observed that suitable location of UPFC for reduction of total system transmission loss is line 31–32 followed by line 23–74 with respect to V_T control. However for angle control it is line 23–74 followed by line 31–32. For reduction of total power flow index with respect to V_T line 31–32 is the most suitable followed by line 23–74. For angle control it is line 17–23 followed by line 19–26.

The proposed method does not suggest the interaction of several UPFC devices placed in the system as it requires an optimization tool for getting optimal control parameters of the device. However this method is suitable for suggesting the candidate lines for UPFCs. Based on sensitivities their placement can be ascertained in few areas. To see the interaction of different UPFC, an iterative procedure can be adopted. In this approach, first one UPFC should be placed according to the sensitivity and thereafter sensitivity should be calculated and next UPFC should be placed. But the control parameter of UPFC should be determined using an optimization technique for required objective before calculating the sensitivity for next UPFC placement.

5. Conclusions

In this paper, a sensitivity-based approach has been developed for finding suitable placement of these devices. Test results obtained on test systems show that new sensitivity factors could be effectively used for UPFC placement in response to required objectives. If there is no congestion, the location of UPFC can be decided on the loss minimization. After selecting the suitable locations a comprehensive economic objective must be considered taking the cost of UPFC which depends on its control parameters and the loss factor.

In a congested system, the suitable locations of UPFC can be effectively decided based on the sensitivity factors c_1^k and c_2^k. If these sensitivities for two lines are comparable, the placement of a UPFC can be decided based on the total real power loss sensitivity factors which indicates the reduction of the total system real power loss and will also improve the system voltage profile.

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Appendix A

The terms

$$\left.\frac{\partial P_i}{\partial V_T}\right|_{V_T=0},\quad \left.\frac{\partial P_j}{\partial V_T}\right|_{V_T=0},\quad \left.\frac{\partial P_i}{V_T\partial \phi_T}\right|_{\phi_T=0},\quad \left.\frac{\partial P_j}{V_T\partial \phi_T}\right|_{\phi_T=0},\quad \left.\frac{\partial P_i}{\partial I_q}\right|_{I_q=0},\quad \left.\frac{\partial P_j}{\partial I_q}\right|_{I_q=0}$$

can be obtained using Eqs. (8) and (9), respectively and are given below.

$$\left.\frac{\partial P_i}{\partial V_T}\right|_{V_T=0} = \left.\frac{\partial P_{is}}{\partial V_T}\right|_{V_T=0} = -2V_i g_{ij}\cos(\phi_T-\delta_i) + V_j(g_{ij}\cos(\phi_T-\delta_j) + b_{ij}\sin(\phi_T-\delta_j)), \quad (A.1)$$

$$\left.\frac{\partial P_i}{V_T\partial \phi_T}\right|_{\phi_T=0} = \left.\frac{\partial P_{is}}{V_T\partial \phi_T}\right|_{\phi_T=0} = -2V_i g_{ij}\sin(\delta_i) + V_j(g_{ij}\sin\delta_j + b_{ij}\cos\delta_j), \quad (A.2)$$

$$\left.\frac{\partial P_i}{\partial I_q}\right|_{I_q=0} = \left.\frac{\partial P_{is}}{\partial I_q}\right|_{I_q=0} = 0, \quad (A.3)$$

$$\left.\frac{\partial P_j}{\partial V_T}\right|_{V_T=0} = \left.\frac{\partial P_{js}}{\partial V_T}\right|_{V_T=0} = V_j(g_{ij}\cos\delta_j + b_{ij}\sin\delta_j), \quad (A.4)$$

$$\left.\frac{\partial P_j}{V_T\partial \phi_T}\right|_{\phi_T=0} = \left.\frac{\partial P_{js}}{V_T\partial \phi_T}\right|_{\phi_T=0} = V_j(g_{ij}\sin\delta_j - b_{ij}\cos\delta_j), \quad (A.5)$$

$$\left.\frac{\partial P_j}{\partial I_q}\right|_{I_q=0} = \left.\frac{\partial P_{js}}{\partial I_q}\right|_{I_q=0} = 0. \quad (A.6)$$

Using Eqs. (10) and (11), the derivative of the reactive power injections with respect to UPFC control parameters can be derived as

$$\left.\frac{\partial Q_i}{\partial V_T}\right|_{V_T=0} = \left.\frac{\partial Q_{is}}{\partial V_T}\right|_{V_T=0} = V_i[-g_{ij}\sin\delta_i + b_{ij}\cos\delta_i], \quad (A.7)$$

$$\left.\frac{\partial Q_i}{V_T\partial \phi_T}\right|_{\phi_T=0} = \left.\frac{\partial Q_{is}}{V_T\partial \phi_T}\right|_{\phi_T=0} = V_i[g_{ij}\cos\delta_i + b_{ij}\sin\delta_i], \quad (A.8)$$

$$\left.\frac{\partial Q_i}{\partial I_q}\right|_{I_q=0} = \left.\frac{\partial Q_{is}}{\partial I_q}\right|_{I_q=0} = V_i, \quad (A.9)$$

Table 3
Sensitivities of IEEE 14-bus system

Line-*k*				Method-1			Method-2	
No.	*i*–*j*	Line loading	Line rating	b_1^k	b_2^k	b_3^k	c_1^k	c_2^k
1	8–3	0.298	0.500	−1.776	−0.0866	−0.00520	−4.442	−1.0020
2	9–6	0.245	0.500	−2.195	−0.1041	−0.00517	−6.304	0.0902
3	9–7	0.140	0.500	−0.911	−0.0384	−0.00517	−2.786	−0.6701
4	1–8	0.668	1.000	−1.178	0.2116	−0.00535	−3.568	**−9.0510**
5	2–8	0.357	0.500	−1.482	0.1020	−0.00527	−1.834	3.2310
6	4–9	0.262	0.500	−1.894	−0.2672	−0.00510	−6.165	−1.9370
7	9–8	0.634	1.000	**−6.599**	**−0.8026**	−0.00517	−15.960	4.3600
8	1–2	**1.409**	1.000	−2.534	0.5209	−0.00535	3.330	7.9820
9	2–4	0.693	1.000	−1.964	0.2028	−0.00527	−5.020	−0.8907
10	6–5	0.000	0.500	−2.670	−0.1280	−0.00537	−8.251	0.0957
11	2–9	**0.503**	0.500	−1.703	0.1940	−0.00527	−0.244	7.2140
12	6–7	0.245	0.500	−4.606	−0.1965	−0.00537	−14.140	0.4185
13	7–10	0.018	0.500	−5.262	−0.2104	−0.00533	**−16.710**	0.3285
14	3–11	0.108	0.500	−1.937	−0.0146	**−0.00540**	−6.029	−0.1777
15	3–12	0.082	0.500	−1.488	−0.0164	**−0.00540**	−4.5140	−0.0048
16	3–13	0.194	0.500	−2.841	−0.0144	**−0.00540**	−8.422	0.2779
17	7–14	0.072	0.500	−1.544	−0.0321	−0.00533	−4.836	0.2250
18	10–11	0.073	0.500	−2.183	−0.1289	−0.00531	−6.669	0.2235
19	12–13	0.020	0.500	−1.104	−0.0238	−0.00533	−3.440	−0.0870
20	13–14	0.078	0.500	−1.187	0.0079	−0.00530	−3.789	0.0054

$$\left.\frac{\partial Q_j}{\partial V_T}\right|_{V_T=0} = \left.\frac{\partial Q_{js}}{\partial V_T}\right|_{V_T=0} = -V_j(-g_{ij}\sin\delta_j + b_{ij}\cos\delta_j), \tag{A.10}$$

$$\left.\frac{\partial Q_j}{V_T\partial\phi_T}\right|_{\phi_T=0} = \left.\frac{\partial Q_{js}}{V_T\partial\phi_T}\right|_{\phi_T=0} = -V_j(g_{ij}\cos\delta_j + b_{ij}\sin\delta_j), \tag{A.11}$$

$$\left.\frac{\partial Q_j}{\partial I_q}\right|_{I_q=0} = \left.\frac{\partial Q_{js}}{\partial I_q}\right|_{I_q=0} = 0. \tag{A.12}$$

The derivatives of real and reactive power with respect to phase angle of UPFC are considered around zero although the phase angle in UPFC can be control from 0° to 360°. The angle difference for both ends of line are generally very small and it is limited to 30° due to stability reasons. In a practical power system control of angle of TCPAR or UPFC are generally limited to ± 15°. Therefore, the derivatives with respect to phase angle around zero is correct. However, it can be calculated around any angle, as derivation is very simple.

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