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OPTIMAL LOCATION OF UPFC IN POWER SYSTEM USING SYSTEM LOSS SENSITIVITY INDEX

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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.

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

1. Introduction

As a consequence of the on-going 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. 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. 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 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 [4]. Using controllable components of UPFC, the line flows can be changed in such a way that thermal limits are not violated, losses minimized, stability margin increased, contractual requirement fulfilled etc, without violating specified power dispatch.

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. 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 the objective: the total system real power loss. The proposed algorithm has been demonstrated on 5-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 Gyugyi 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 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 ($0 \leq V_T \leq V_{Tmax}$) and phase angle ($0 \leq \phi_T \leq 2\pi$), which is added to the AC transmission line by the series connected boosting transformer.

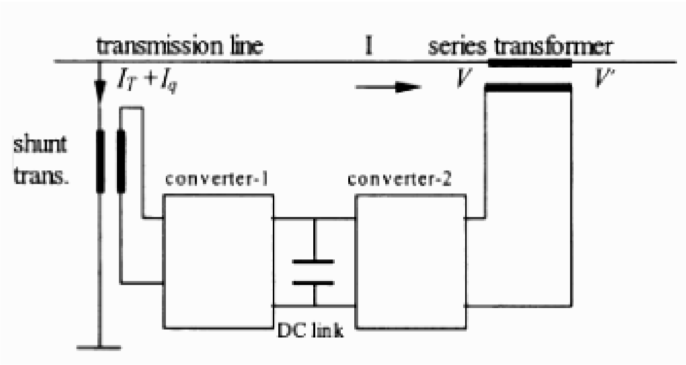

fig.1. The basic circuit arrangement of UPFC

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.

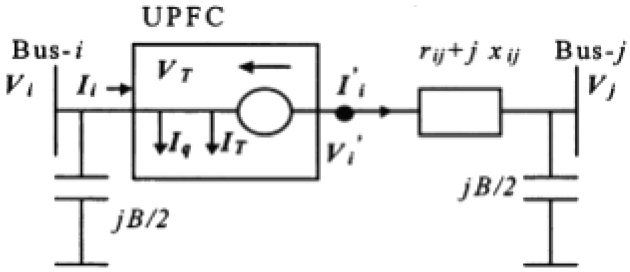

Fig.2

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

$$\mathbf{V}_i' = \mathbf{V}_i + \mathbf{V}_T,$$
$$\mathrm{Arg}(\mathbf{I}_q) = \mathrm{Arg}(\mathbf{V}_i) \pm \pi/2,$$
$$\mathrm{Arg}(\mathbf{I}_T) = \mathrm{Arg}(\mathbf{V}_i),$$
$$I_T = \left[\frac{V_T I_i'^{*}}{V_i}\right] \qquad (1)$$

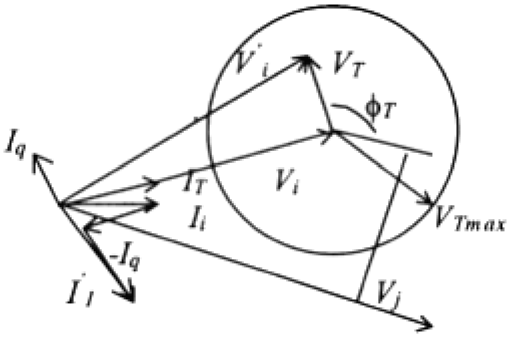

Fig.3. vector diagram of UPFC

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

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

$$\mathbf{S}_{ji} = P_{ji} + jQ_{ji} = \mathbf{V}_j\,\mathbf{I}^{*} = \mathbf{V}_j\,(j\,\mathbf{V}_j\,B/2 - \mathbf{I}_i^{*}) \qquad (3)$$

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

$$P_{ij} = (V_i^2 + V_T^2)\,g_{ij} + 2V_i V_T g_{ij} \cos(\phi_T - \delta_i) - V_j V_T\,[g_{ij}\cos(\phi_T - \delta_j) + b_{ij}\sin(\phi_T - \delta_j)] - V_i V_j\,(g_{ij}\cos\delta_{ij} + b_{ij}\sin\delta_{ij}), \qquad (4)$$

$$P_{ji} = V_j^2 gij - V_j V_T\,[g_{ij}\cos(\phi_T - \delta_j) - b_{ij}\sin(\phi_T - \delta_j)] - V_i V_j\,(g_{ij}\cos\delta_{ij} - b_{ij}\sin\delta_{ij}) \qquad (5)$$

$$Q_{ij} = -V_i I_q - V_i^2(b_{ij} + B/2) - V_i V_T[g_{ij}\sin(\phi_T - \delta_i) + b_{ij}\cos(\phi_T - \delta_i)] - V_i V_j\,(g_{ij}\sin\delta_{ij} - b_{ij}\cos\delta_{ij}) \qquad (6)$$

$$Q_{ji} = -V_j^2\,(b_{ij} + B/2) + V_j V_T(g_{ij}\sin(\phi_T - \delta_i) + b_{ij}\cos(\phi_T - \delta_i)) + V_i V_j\,(g_{ij}\sin\delta_{ij} + b_{ij}\cos\delta_{ij}) \qquad (7)$$

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

$$P_{is} = -V_T^2\,g_{ij} - 2V_i V_T\,g_{ij}\cos((\phi_T - \delta_i) + V_j V_T\,[g_{ij}\cos(\phi_T - \delta_j) + b_{ij}\sin(\phi_T - \delta_j)] \qquad (8)$$

$$P_{js} = V_j V_T[g_{ij}\cos(\phi_T - \delta_j) - b_{ij}\sin(\phi_T - \delta_j)] \qquad (9)$$

$$Q_{is} = V_i\,I_q + V_i V_T[gij\,\sin(\phi_T - \delta_i) + bij\,\cos(\phi_T - \delta_i)] \qquad (10)$$

$$Q_{js} = -V_j V_T[g_{ij}\sin(\phi_T - \delta_j) + b_{ij}\cos(\phi_T - \delta_j)] \qquad (11)$$

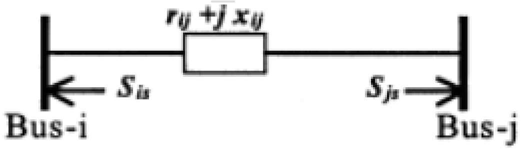

Fig.4. Injection model of UPFC

3. Methods for optimal location of unified power flow controller

This paper utilizes the objective: reduction in the total system real power loss (P_{LT}). 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*

The exact loss formula of a system having *N* buses is, from [8],

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

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

$$\alpha jk = \left[\frac{r_{jk}}{V_jV_k}\right]\cos(\delta_j - \delta_k)$$

and,

$$\beta_{jk} = \left[\frac{r_{jk}}{V_jV_k}\right]\sin(\delta_j - \delta_k)$$

where r_{jk} is the real part of the *j*–*k*th element of $[Z_{bus}]$ 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)

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

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

$$b_1^k = \frac{\delta P_{LT}}{\delta V_T} \text{ at } V_T = 0$$

= total loss sensitivity with respect to V_T,

$$b_2^k = \frac{\delta P_{LT}}{V_T\delta\phi_T} \text{ at } \phi_T = 0$$

= total loss sensitivity with respect to ϕ_T,

$$b_3^k = \frac{\delta P_{LT}}{\delta I_q} \text{ at } I_q = 0$$

=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:

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

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

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

where

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

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

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) to (15), respectively.

4. Simulation results

To establish the effectiveness of the proposed method, it has been tested on a 5-bus system.

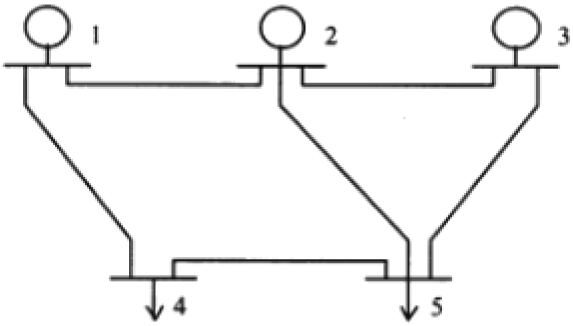

Fig.5. five bus system

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 with respect to UPFC control parameters is presented in Table 1. The highest negative sensitivities b_1^k, b_2^k and the highest absolute value of sensitivity b_3^k are presented. 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. 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.

Table 1
Sensitivities of 5-bus system

Line no.	**Line i-j**	$\mathbf{b_1^k}$	$\mathbf{b_2^k}$	$\mathbf{b_3^k}$
1	2-1	0.0016	0.2947	-0.6824
2	2-5	0.0498	**0.5114**	-0.6824
3	3-5	0.1073	0.3183	**-0.6890**
4	5-4	**-0.1526**	0.4987	-0.6670
5	1-4	-0.1220	0.4223	-0.6693
6	3-2	-0.1100	-0.0167	**-0.6890**

.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.

As this method 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 this method is only appropriate for the placement of the UPFC when there is no congestion.

Appendix A

The terms

$$\frac{\delta P_i}{\delta V_T}\Big|V_T{=}0,\quad \frac{\delta P_j}{\delta V_T}\Big|V_T{=}0,\quad \frac{\delta P_i}{V_T\delta\phi_T}\Big|\phi_T{=}0,\quad \frac{\delta P_j}{V_T\delta\phi_T}\Big|\phi_T{=}0,\ \frac{\delta P_i}{\delta I_q}\Big|I_q{=}0,\ \frac{\delta P_j}{\delta I_q}\Big|I_q{=}0$$

can be obtained using eqns.(8) and (9), respectively and are given as follows:

$$\frac{\delta P_i}{\delta V_T}\Big|V_T{=}0 = \frac{\delta P_{is}}{\delta V_T}\Big|V_T{=}0 = -\ 2V_i\, g_{ij} \cos(\phi_T - \delta_i) + V_j(g_{ij} \cos(\phi_T - \delta_j) + b_{ij} \sin(\phi_T - \delta_j)), \qquad (A.1)$$

$$\frac{\delta P_i}{V_T\delta\phi_T}\Big|\phi_T{=}0 = \frac{\delta P_{is}}{V_T\delta\phi_T}\Big|\phi_T{=}0 = -\ 2V_i\, g_{ij} \sin(\delta_i) + V_j(g_{ij} \sin \delta_j + b_{ij} \cos \delta_j), \qquad (A.2)$$

$$\frac{\delta P_i}{\delta I_q}\Big|I_q{=}0 = \frac{\delta P_{is}}{\delta I_q}\Big|I_q{=}0 = 0, \qquad (A.3)$$

$$\frac{\delta P_j}{\delta V_T}\Big|V_T{=}0 = \frac{\delta P_{js}}{\delta V_T}\Big|V_T{=}0 = V_j\,(g_{ij} \cos \delta_j + b_{ij} \sin \delta_j), \qquad (A.4)$$

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

$$\frac{\delta P_j}{\delta I_q}\Big|_{I_q=0} = \frac{\delta P_{js}}{\delta I_q}\Big|_{I_q=0} = 0. \qquad (A.6)$$

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

$$\frac{\delta Q_i}{\delta V_T}\Big|_{V_T=0} = \frac{\delta Q_{is}}{\delta V_T}\Big|_{V_T=0} = V_i[-g_{ij} \sin \delta_i + b_{ij} \cos \delta_i] \qquad (A.7)$$

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

$$\frac{\delta Q_i}{\delta I_q}\Big|_{I_q=0} = \frac{\delta Q_{is}}{\delta I_q}\Big|_{I_q=0} = V_i, \qquad (A.9)$$

$$\frac{\delta Q_j}{\delta V_T}\Big|_{V_T=0} = \frac{\delta Q_{js}}{\delta V_T}\Big|_{V_T=0} = -V_j\,[-g_{ij} \sin \delta_j + b_{ij} \cos \delta_j] \qquad (A.10)$$

$$\frac{\delta Q_j}{V_T \delta \phi_T}\Big|_{\phi_T=0} = \frac{\delta Q_{js}}{V_T \delta \phi_T}\Big|_{\phi_T=0} = -\,V_j\,[-g_{ij} \cos \delta_j + b_{ij} \sin \delta_j], \qquad (A.11)$$

$$\frac{\delta Q_j}{\delta I_q}\Big|_{Iq=0} = \frac{\delta Q_{js}}{\delta I_q}\Big|_{Iq=0} = 0. \qquad (A.12)$$

In a practical power system control of angle of TCPAR or UPFC are generally limited to ±15°.

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