A Novel Method of UPFC Location Based on Sensitivity Factors

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Abstract :- This paper presents a novel method of identifying the suitable location for Installation of Unified Power Flow Controller (UPFC), with static point of view, for reducing the severity of a load bus. Bus ranking Index which incorporates the combined effect of line outage contingency and bus load reaching to its voltage stability margin (VSM) is used for deriving the sensitivity factors. These sensitivity factors are developed with an objective of reducing the severity index of the load bus by embedding an UPFC in one of the line. The proposed method is applied for several systems and results of IEEE-30 bus test system are presented.

Key words :- Contingencies, Voltage Stability Margin, Unified Power Flow Controller, Severity Index.

1. Introduction

Recent power systems are undergoing a profound transformation in the form of restructuring. Many private power companies have entered in to the power industry. This has resulted in complicated operation and control of large interconnected grid systems. In this changing scenario, the primary challenge for power engineers is to efficiently control the active and reactive power flows in a specific transmission line or the corridor due to dynamically changing inter grid transactions. Control of power flows should be achieved without generation rescheduling or topological changes in order to enhance the power system performance [1]. Flexible AC Transmission systems (FACTS) controllers are proved to be very useful in achieving the control of power flows without disturbing the generation scheduling or topological changes and in addition these devices will also enhance the secured operation of power systems [2-3].

Among the family of FACTS controllers, the UPFC is emerged as the most comprehensive device as it is capable of providing simultaneous control of active and reactive power flow. For the past one decade the research in FACTS area is primarily focused on UPFC. First phase of research in this area was focused on developing suitable models of UPFC [6-8], proposing control strategy [9-10] and studies related to system stability enhancement [11-12]. It is obvious that the location of UPFC has a major role to play in achieving the desired results. Reference [13] has very vividly demonstrated the changes in the system performance with the change in UPFC locations. Hence the second phase of research has laid more stress on identification of suitable location for UPFC installation.

A parallel taboo search based on the optimal location of UPFC is proposed in [14]. K.S.Verma et al [15] have derived a set of loss sensitivity factors with respect to UPFC control parameters and have used it to identify the suitable location for UPFC installation. K.Vishakha et al [16] have proposed a method to select the best location for UPFC installation based on Voltage stability enhancement criterion.

It is obvious from the literature review that though the primary role of UPFC is to effectively control the active and reactive power flows in a specific line/corridor of the power system, the placement of UPFC is being identified by using the several other system performance criteria. This is mainly because of the dominating effect of UPFC on other system performance. In this paper one such criterion is proposed which will help in reducing the severity of a load bus under line outage contingencies due to installation of UPFC at an appropriate location.

Severity ranking index is used to initially rank the buses for a set of line outage contingencies. Sensitivity of severity ranking index with respect UPFC control parameter are obtained using sensitivity factors and these are used to identify the best line section for UPFC installation. Further the effect of installation of UPFC at the determined location on severity of the selected bus and other buses in the system is monitored. The study is carried out on several standard systems and the results of IEEE 30 bus system are presented.

Section 2 briefly explains the static model of UPFC, the behavior of the severity index with the incorporation of UPFC is presented in section 3. In section 4 the sensitivity factors are derived the case study and results are shown in section 5.

2. UPFC MODEL

The static UPFC model proposed in [6] is incorporated in this paper. This UPFC injection model can easily be incorporated in to the steady state power flow model.

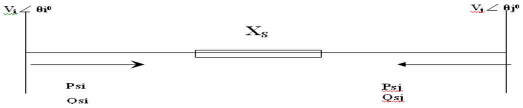

Fig. 1 The UPFC injection model

The active and reactive powers at the connecting buses are:

$Psi = r\,bs\,Vi\,Vj\,\sin(\theta ij + \gamma)$

$Psj = -r\,bs\,Vi\,Vj\,\sin(\theta ji + \gamma)$

$Qsi = r\,bs\,Vi^2 \cos\gamma$

$Qsj = -r\,bs\,Vi\,Vj\,\cos(\theta ij + \gamma)$

The UPFC is located between node **i** and node **j** in a power system. The admittance matrix is modified by adding a reactance equivalent to Xs between node **i** and node **j.** The jacobian matrix is modified by addition of appropriate injection powers. If the linearized load flow model is

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix} H & N\\ J & L\end{bmatrix} \begin{bmatrix}\Delta\Theta\\ \Delta V\!/\!V\end{bmatrix}$$

considered as below:

The Jacobian matrix is modified as given below.(where the superscript 'o' denotes the Jacobian elements without UPFC)

$H(i,i) = \overset{o}{H}(i,i) - Qsj$ $H(i,j) = \overset{o}{H}(i,j) + Qsj$ $H(j,i) = \overset{o}{H}(j,i) + Qsj$ $H(j,j) = \overset{o}{H}(j,j) - Qsj$	$N(i,i) = \overset{o}{N}(i,i) - Psj$ $N(i,j) = \overset{o}{N}(i,j) - Psj$ $N(j,i) = \overset{o}{N}(j,i) + Psj$ $N(j,j) = \overset{o}{N}(j,j) + Psj$
$J(i,i) = \overset{o}{J}(i,i)$ $J(i,j) = \overset{o}{J}(i,j)$ $J(j,i) = \overset{o}{J}(j,i) - Psj$ $J(j,j) = \overset{o}{J}(j,j) + Psj$	$L(i,i) = \overset{o}{L}(i,i) + 2Qsi$ $L(i,j) = \overset{o}{L}(i,j)$ $L(j,i) = \overset{o}{L}(j,i) + Qsj$ $L(j,j) = \overset{o}{L}(j,j) + Qsj$

Modified Jacobian Matrix This modified Jacobian matrix is incorporated in to the Newton Ramphson load flow algorithm to implement the proposed criterion

3. Severe Bus Ranking Method

There are few methods proposed in the past for ranking/ identification of severe/weak buses incorporating the voltage collapse phenomenon [20-25]. A careful study of these papers reveal that the combined effect of line outage contingency and the bus load reaching to its voltage stability margin (VSM) has not accounted for in any of the methods proposed in the literature. However in a large power system, it is quite common that both line outage contingency and bus load reaching to its VSM occur simultaneously, Manish jain,et.al [17] have proposed a method which accounts for the both and a new severity index (ΔSI) is developed using load curtailment approach.

The basic concept of this method is to assign a suitable severity to each of the load bus in a system based on the indicator which accounts for the combined effect of occurrence of a specific line outage contingency and the systems proximity to voltage collapse due to bus load increase in the post contingency condition. This severity is quantified with an accurate severity index (ΔSI).

3.1 Behavior of the Severity Index.

In order to assess the sensitivity of the severity index for the changes in the control parameters of the UPFC, following simulations are carried out.

(a) Effect of UPFC: As explained in section 2, incorporation of UPFC in the line section causes the bus power to change and hence the load flow Jacobian also modifies. This necessitates modification in the variables considered for $SI_{vc\,(ij)}$ computation as shown below:

$$SI_{VC}' \sum_{\substack{k=1\\k\neq i\\k\neq j}}^{k=n} [(\Delta V_k^{\,2} - 2V_k^{\,0}\Delta V_k)(P_k^{\,2} + Q_k^{\,2})^{1/2} / [(V_k^{\,0})^2]] +$$

$$[(\Delta V_i^{\,2} - 2\Delta V_i V_i^{\,0})((P_i - P_{si})^2 + (Q_i - Q_{si})^2)^{1/2} / [(V_i^{\,0})^2]] +$$

$$[(\Delta V_j^{\,2} - 2\Delta V_j V_j^{\,0})((P_j - P_{sj})^2 + (Q_j - Q_{sj})^2)^{1/2} / [(V_j^{\,0})^2]] \ldots\ldots(1)$$

Considering UPFC location between bus i and j, additional terms Psi, Qsi, Psj and Qsj appears in the above equation which are corresponding to the injected powers of UPFC at bus i and j. These terms will have UPFC parameter r and γ. The simulations are carried out for different values of r and γ, maintaining one as a constant and the other as a variable. The results are shown in figures 2 and 3.

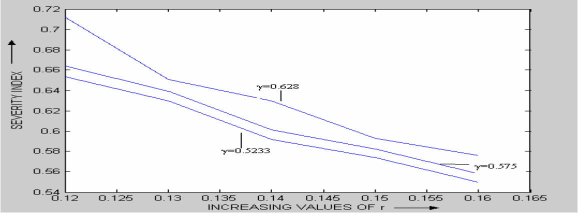

Fig.2. Behavior of the severity index w.r.t UPFC parameter (r) (cont. 10-21)

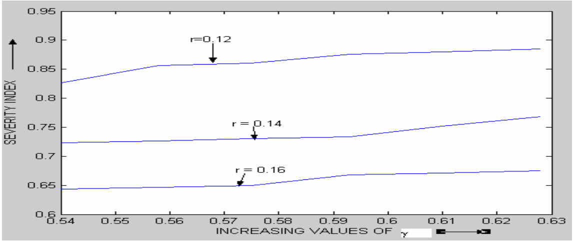

Fig.3. Behavior of the severity index w.r.t. UPFC parameter (γ) (cont.4-6)

From the figures, it is obvious that $SI_{vc\,(ij)}$ values are changing considerably with the changes in the UPFC parameters and hence the sensitivity factors can be derived with respect to these control parameters to know the changes in the severity of a bus. Further, it is also evident from the figures that the index is more sensitive for a change in r than γ. This is arbitrated to the fact that severity index used is based on the reactive power load curtailment and the role of r in the UPFC is to change the magnitude of bus voltage.

4. Criterion for Optimal location of UPFC

In this section, the criterion developed for identification of optimal location of UPFC placement is described. The basic objective of this criterion is to identify such location which minimizes the severity of a selected bus as indicated by the reduction in the value of the severity index for several contingencies.

4.1 Sensitivity Factors: The severity index sensitivity factors with respect to control parameters of UPFC are given below

$S^1_k = \partial SI_{VC}' / \partial r \;|_{r=0}$

= Sensitivity Factor with respect to r

$S^2_k = \partial SI_{VC}' / \partial \gamma \;|_{\gamma=0}$

= Sensitivity Factor with respect to γ

These factors are computed using Eq. (1). Consider a line-k connected between bus-i and bus-j. The sensitivity of the Severity Index (SI_{vc}') with respect to control parameters of UPFC is shown below.

$$
\begin{aligned}
S^1_k = \; & \partial SI_{VC}' / \partial P_i \partial P_i / \partial r \,|_{r=0} + \partial SI_{VC}' / \partial P_j \partial P_j / \partial r \,|_{r=0} \\
& + \partial SI_{VC}' / \partial Q_i \partial Q_i / \partial r \,|_{r=0} + \partial SI_{VC}' / \partial Q_j \partial Q_j / \partial r \,|_{r=0} \\
& - (\partial SI_{VC}' / \partial P_{si} \partial P_{si} / \partial r \,|_{r=0} + \partial SI_{VC}' / \partial P_{sj} \partial P_{sj} / \partial r \,|_{r=0} \\
& + \partial SI_{VC}' / \partial Q_{si} \partial Q_{si} / \partial r \,|_{r=0} + \partial SI_{VC}' / \partial Q_{sj} \partial Q_{sj} / \partial r \,|_{r=0})
\end{aligned}
$$

$$
\begin{aligned}
S^2_k = \; & \partial SI_{VC}' / \partial P_i \partial P_i / \partial \gamma \,|_{\gamma=0} + \partial SI_{VC}' / \partial P_j \partial P_j / \partial \gamma \,|_{\gamma=0} \\
& + \partial SI_{VC}' / \partial Q_i \partial Q_i / \partial \gamma \,|_{\gamma=0} + \partial SI_{VC}' / \partial Q_j \partial Q_j / \partial \gamma \,|_{\gamma=0} \\
& - (\partial SI_{VC}' / \partial P_{si} \partial P_{si} / \partial \gamma \,|_{\gamma=0} + \partial SI_{VC}' / \partial P_{sj} \partial P_{sj} / \partial \gamma \,|_{\gamma=0} \\
& + \partial SI_{VC}' / \partial Q_{si} \partial Q_{si} / \partial \gamma \,|_{r=0} + \partial SI_{VC}' / \partial Q_{sj} \partial Q_{sj} / \partial \gamma \,|_{\gamma=0})
\end{aligned}
$$

The derivatives of real and reactive powers with respect to control parameters of UPFC are given in appendix II. The sensitivity factors S^1_k and S^2_k are computed using equations (3), (4), (5), (6), (7), (8) (9) and (10).

5. Simulation Results

To demonstrate the effectiveness of the proposed criterion, it has been tested on a IEEE-30 bus test system [18]. This system has 6 generator buses and 23 load buses and 41 transmission lines.

Bus ranking results of severity index (ΔSI) is obtained from [17]. From [17], it is evident that the severity index (ΔSI) of bus 7 is maximum compare to severity indices (ΔSI s) of all other buses and hence reduction in severity index of bus 7 is to be considered as criterion for identification of UPFC location. There are 41 transmission lines sections in the system. Now the task is to identify the appropriate location for UPFC placement where the severity index (ΔSI) value of 7th bus reduces considerably. Sensitivity factors where calculated for both control parameters of UPFC placed in every location one at a time for each of the contingency. Simulation results revealed that only for four line section (14-15,23-24, 16-17 and 4-12) the sensitivity factors are either close to zero or negative and hence only those results are shown in table I. From this table it is observed that at location 14-15 for all the contingencies sensitivity factors (S^k_1, S^k_2) are negative and percentage decrease in severity index (ΔSI) is also more as compare to other locations. Further for location 16-17 sensitivity factors (S^k_1, S^k_2) are negative only for few contingencies. This implies that if the UPFC is installed at line section 14-15, maximum reduction in the severity index is obtained for most of the selected contingencies and hence severity of the bus 7 is reduced considerably as seen in table II. Hence this line section is selected as the most optimal location for placement of UPFC.

Further to observe the effect of locating UPFC at the identified location 14-15, on reduction of severity of other load buses, simulations were carried out and results are illustrated in table II. From this table it is very clear that for most of the contingencies the percentage reduction in the severity index (ΔSI) is as high as 25 to30 % which is a considerable improvement in the security level of the system.

The effect of the installation of UPFC at 14-15 on the voltage profile of the system was monitored and it was found that generally it has improved system wide. Due to the space constraint improvement in the voltage profile of bus 7 is shown in fig. 4

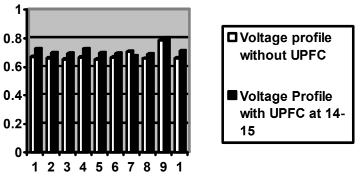

Fig. 4: Voltage profile of Bus 7 for different line outage contingencies

6. Conclusion

In this paper a sensitivity- based approach has been proposed for identifying the most suitable location for UPFC placement based on the reduction in the severity of a load bus under line outage contingencies. The proposed approach uses the UPFC steady state injection model .The candidate buses for identifying the sever bus is found by monitoring the slope of the curve between MSV and the bus power increase. Test results obtained on test systems show that new sensitivity factors have great potential for identification of UPFC location in a real power system where reduction of severity of any bus is a vital requirement

Table I Sensitivity factors at different UPFC location

Contingency	UPFC at 14-15			UPFC at 23-24			UPFC at 16-17			UPFC at 4-12		
	S_k^1	S_k^2	% Reduction in ΔSI	S_k^1	S_k^2	% Reduction in ΔSI	S_k^1	S_k^2	% Reduction in ΔSI	S_k^1	S_k^2	% Reduction in ΔSI
2-6	**-0.206**	0.032	**10.09**	0.109	0.01	5.23	-0.155	-0.02	8.91	0.497	0.034	2.10
6-14	**-0.206**	-0.032	**13.60**	0.068	0.01	6.12	0.107	0.02	9.76	0.466	0.077	2.21
10-21	**-0.218**	-0.033	**8.53**	0.113	0.01	5.32	-0.207	-0.03	7.78	0.381	0.061	2.44
1-3	**-0.208**	-0.029	**8.29**	0.124	0.01	4.42	-0.129	-0.01	8.12	0.424	0.072	1.49
3-4	**-0.290**	-0.140	**8.56**	0.124	0.01	4.75	-0.134	0.01	8.41	0.411	0.070	1.82

Table II Percentage reduction in severity of other critical buses with an installation of UPFC at 14-15 (best location to reduce the severity of most critical bus 7)

SI. NO.	Contingency		% Decrease in SI for bus 21	% Decrease in SI for bus 24	% Decrease in SI for bus 26	% Decrease in SI for bus 29	% Decrease in SI for bus 30
	From bus	To bus					
1	2	5	0.05	6.31	7.92	5.80	8.06
2	2	6	3.96	19.66	34.78	32.14	33.78
3	4	6	3.76	15.87	31.78	30.89	22.86
4	6	8	11.33	29.05	33.86	30.12	30.35
5	12	14	11.99	29.33	30.64	32.17	27.31

Appendix II

$$\mathbf{A}= (\Delta V_i^{\,2} - 2\Delta V_i V_i^{\,0}) /[(V_i^{\,0})^2]$$

$$\mathbf{B}= (\Delta V_j^{\,2} - 2\Delta V_j V_j^{\,0}) /[(V_j^{\,0})^2]$$

$$\mathbf{S^k{}_1}=$$

$$- A[P_i b_s V_i V_j \sin(\theta_{ij} + \gamma) + Q_i b_s V_i^{\,2} \cos\gamma]/(P_i^{\,2} + Q_i^{\,2})^{1/2}$$

$$+ B[P_j V_i V_j b_s \sin(\theta_{ji} + \gamma) + b_s Q_j V_i V_j \cos(\theta_{ij} + \gamma)]/(P_j^{\,2} + Q_j^{\,2})^{1/2} \quad \ldots (2)$$

$$\mathbf{S^k{}_2}= - A[(P_i - r\, bs\, Vi\, Vj \sin(\theta ij))\, r\, bs\, Vi\, Vj \cos(\theta ij)]/[(P_i - r\, bs\, Vi\, Vj \sin(\theta ij))^2 + (Q_i - r\, bs\, (Vi)^2)^2]^{1/2}$$
$$+B[(P_j + r\, bs\, Vi\, Vj \sin(\theta ji))\, r\, bs\, Vi\, Vj \cos(\theta ji) + (Q_j - (- r\, bs\, Vi\, Vj \cos(\theta ij))(- r\, bs\, Vi\, Vj \sin(\theta ij))]/$$
$$[(P_j + r\, bs\, Vi\, Vj \sin(\theta ji))^2 + (Q_{j-}(- r\, bs\, Vi\, Vj \cos(\theta ij)))^2]^{1/2} \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$(\partial P_{si} / \partial r)_{r=0} = b_s V_i V_j \sin(\theta_{ij} + \gamma) \ldots\ldots (4)$$

$$(\partial Q_{si} / \partial r)_{r=0} = b_s V_i.^2 \cos\gamma \ldots\ldots (5)$$

$$(\partial P_{sj} / \partial r)_{r=0} = -b_s V_i V_j \sin(\theta_{ji} + \gamma) \ldots\ldots (6)$$

$$(\partial Q_{sj} / \partial r)_{r=0} = -b_s V_i V_j \cos(\theta_{ij} + \gamma) \ldots\ldots (7)$$

$$(\partial P_{si} / \partial \gamma)_{\gamma=0} = r b_s V_i V_j \cos(\theta_{ij}) \ldots\ldots (8)$$

$$(\partial Q_{si} / \partial \gamma)_{\gamma=0} = 0 \ldots\ldots (9)$$

$$(\partial P_{sj} / \partial \gamma)_{\gamma=0} = -b_s V_i V_j \cos(\theta_{ji}) \ldots\ldots (10)$$

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