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Enhancement of Voltage And Power System Stability Performance By Optimal Placement of UPFC

[1] Akhilesh Tiwari, [2] A. K Jain , And [3] Bharat Mishra
[1.2] Dept. of Electrical Engg. Rustamji Inst. Of Technology, BSF Academy, Tekanpur Gwalior, India
[3] Dept. of Computer Science MGCGV, Chitrakoot Satna, India
Corresponding Author: Akhilesh Tiwari

Abstract: *Recently Flexible AC Transmission System (FACTS) Controller has created new opportunities for increasing power system stability including voltage stability. Due to excessive cost, these devices must be located optimally. For the last few years, the focus of research in the FACTS area is mainly on Unified Power Flow Controller (UPFC). It is only Facts Controller having the unique ability to simultaneously control all three parameters of power flow i.e. voltage, line impedance and phase angle. This paper presents a method for optimal location of UPFC to enhance the system voltage stability margin of the power system. The suitable location of the UPFC is identified using a sensitivity-based approach. The effectiveness of the proposed method, simulation has been performed on bench mark 5-bus and IEEE-30 bus power system.*

Keywords: *FACTS, Optimal Placement, Sensitivity Based Approach, N-R Method, UPFC, Voltage Stability Margin.*

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I. Introduction

Power systems are being subjected to stress operating conditions due to ever increasing load demand and environmental constraints on expansion of transmission networks [1]. The problem of voltage instability which may sometimes result into voltage collapse in the system, has become a matter of great concern to the utilities in view of its prediction, prevention and necessary correction to ensure a stable operation[2]. Flexible AC Transmission System (FACTS) Controllers can be helpful in utilizing the maximum capacity of the transmission network to their limits without threatening the stability and security of the network [3]. Out of different types of FACTS controller, Unified Power Flow Controller seen to be more effective in voltage stability enhancement due to its ability to control series and shunt variable, simultaneously. However, due to high cost and for maximum enhancement in voltage stability margin, these are to be optimally placed in the system. Using controllable component of the UPFC, the Line flow can be changed. In such a way that more loading on the network can made without violating operating limits of the system.In this paper, sensitivity based approaches has been proposed to optimally locate the UPFC for enhancing the power system voltage stability margin and system security under different operating conditions. The effectiveness of the proposed method has been demonstrated on a bench mark 5-bus and IEEE-30 bus system [4].

II. Modelling of Upfc

The UPFC consists of a shunt (exciting) and a series (boosting) transformers as shown in Fig.1. Converter-I is primarily used to provide the real power demand of converter- 2 at the common DC link terminal from the AC power system and can also generate or absorb reactive power, similar to the Static Compensator (STATCOM), at its AC terminal, which is independent of the active power transfer to (or from) the DC terminal. Converter-2 is used to generate a voltage source at the fundamental frequency with variable amplitude ($0 < V_T < V_T\text{max}$) and phase angle ($0 < \varphi_T < 2\pi$), which is added to the AC transmission line by the series connected boosting transformer. Thus, UPFC can be used for direct bus and line voltage control, series compensation, phase shifter, and their combinations. With these features, UPFC is probably the most powerful and versatile FACTS controller which combines the properties of TCSC, TCPAR and SVC. It is only FACTS controller having the unique ability to simultaneously control all three parameters of power flow i.e. voltage, line impedance and phase angle.

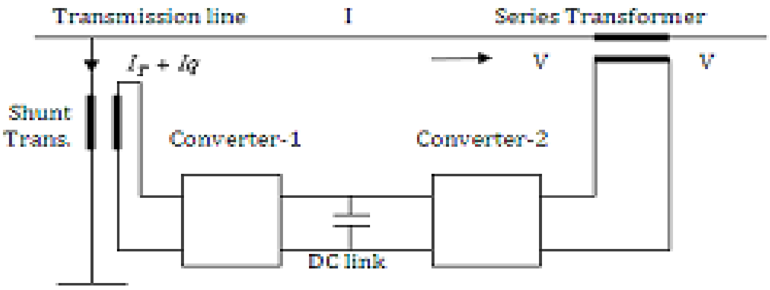

Fig. 1. The UPFC Basis Arrangement

The equivalent circuit of UPFC placed in line-k connected between bus-*i* and bus-*j* is shown in Fig.2.

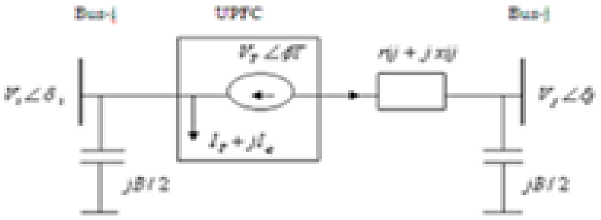

Fig. 2. Equivalent Circuit of UPFC

Based on the basic principle of UPFC and network theory, the active and reactive power flows in the line, from bus-i to bus-j, having UPFC can be written as [5],

$$P_{ij} = (V_i^2 + V_T^2)g_{ij} + 2V_iV_TG_{ij}\cos(\phi_T - \delta_i) - V_jV_T[g_{ij}\cos(\phi_T - \delta_j) + b_{ij}\sin(\phi_T - \delta_j)] - V_iV_j(g_{ij}\cos\delta_{ij} + b_{ij}\sin\delta_{ij}) \quad (1)$$

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

Where $g_{ij} + jb_{ij} = 1/(r_{ij} + jx_{ij})$ and *Iq* reactive current flowing in the shunt transformer to improve the voltage of the shunt connected bus of UPFC. Similarly, the active and reactive power flows in the line, from bus-*j* to bus-*i*, having UPFC can be written as

$$P_{ji} = (V_j^2 g_{ij} - V_jV_T[g_{ij}\cos(\phi_T - \delta_j) - b_{ij}\sin(\phi_T - \delta_j)] - V_iV_j(g_{ij}\cos\delta_{ij} - b_{ij}\sin\delta_{ij}) \quad (3)$$

$$Q_{ij} = -V_j^2(b_{ij} + B/2) - V_jV_T[g_{ij}\sin(\phi_T - \delta_j) - b_{ij}\cos(\phi_T - \delta_j)] + V_iV_j(g_{ij}\sin\delta_{ij} + b_{ij}\cos\delta_{ij}) \quad (4)$$

III. Optimal Location of Upfc For Vsm Enhancement

The active and reactive power injection at bus I is given as:

$$P_i = P_{Gi} - P_{Di}^0(1+\lambda) = \sum_{j\in N_b} P_{ij} \quad (5)$$

$$Q_i = Q_{Gi} - Q_{Di}{}^0(1+\lambda) = \sum_{j\in Nb} Q_{ij} \quad (6)$$

Where P_{Di}^0 and Q_{Di}^0 are the initial active and reactive power demands. P_{Gi} and Q_{Gi} are the real and reactive power generations at bus-i respectively. N_g and N_b are the numbers of generator and system buses, respectively. The sensitivity of system loading factor (λ), corresponding to the real power balance equation, with respect to the control parameters of UPFC is defined as

$$c_1 = \left.\frac{\partial\lambda}{\partial V_T}\right|_{vT=0} \quad \text{and} \quad c_2 = \left.\frac{\partial\lambda}{V_T\partial\phi_T}\right|_{\phi T=0} \quad (7)$$

Where C1 and C2 are the system real power loading sensitivity with respect to the series injected voltage magnitude (V_T) and the series injected phase angle (φ_T) of the UPFC, placed in line-k, respectively. Using equation (5), the sensitivity factor calculated at ith bus of line-k where UPFC is placed will be

$$C1 = (-2V_ig_{ij}\cos(\delta_i) + V_j(g_{ij}\cos(\delta_j) - b_{ij}\sin(\delta_j))\}/(P_{Di}^0) \quad (8)$$

$$C2 = (-2V_ig_{ij}\sin(\delta_i) + V_j(-g_{ij}\sin(\delta_j) + b_{ij}\cos(\delta_j))\}/(P_{Di}^0) \quad (9)$$

The reactive power loading sensitivity can play an important role in enhancing the system loadability and placing UPFC for this, the sensitivity factors are calculated taking equation (6) along with UPFC placed in different lines as

$$C3 = (V_i(-g_{ij}\sin(\delta_i) + b_{ij}\cos(\delta_i)))/(Q_{Di}^0) \qquad (10)$$

$$C4 = (V_i(g_{ij}\cos(\delta_i) + b_{ij}\sin(\delta_i)))/(Q_{Di}^0) \quad (11)$$

Where C3 and C4 are the system loading sensitivities corresponding to the reactive power with respect to the series injected voltage magnitude (V_T) and the series injected phase angle (φ_T) of the UPFC, placed in line-k, respectively. It should be noted that the sensitivities corresponding to the sending end and receiving end of the lines are different.

IV. Sample System Studies on Sensitivity Based Approach

To demonstrate the impact of UPFC, 5-bus [6] and IEEE 30-bus systems [7] have been considered. In this network, it is desirable to keep the voltage deviations between ±10 percent to avoid voltage collapses during faulty condition. In general, if the load requirement increases, the voltage at the corresponding buses may drop below 0.90 pu. and consequently an additional voltage support will be provided by UPFC, and its optimal location will be determined by using Newton-Raphson load flow method. For this purpose, Sensitivity factor were calculated for the two control parameters (injected series voltage magnitude and phase angle) of UPFC placed in every line, one at a time, for the same operating conditions and are presented in Table A. Only load buses are considered, in this work, for UPFC location. Thus sensitivities corresponding to the lines 1-2 is not calculated as these are the lines between generating stations. The shunt converter is connected at the starting bus (i) of line as shown in Table A. Sensitivity factor corresponding to third control parameter of UPFC i.e. Iq is not considered as it will have less impact on the power flow control but it will improved the voltage profile of the network.The magnitude of sensitivity factors C1 for line 3-4 is more positive than other lines whereas the magnitude of sensitivity factor of total system loading (corresponding to the real power balance equation) with respect to phase angle C2 of UPFC placed in line 3-4 (shunt converter is at bus 3) is the highest. This indicates that placement of UPFC in line 3-4 will enhance the real power loadability more compared to the other lines. For controlling the power in a line, phase angle control is more effective than the series injected voltage magnitude. The reactive power loading sensitivities are also shown in Table A (column 4 and 5 with respect to the injected series voltage magnitude and series phase angle of UPFC respectively). These sensitivities are useful when the sensitivities with respect to real power loadability are very close to each other.

TABLE –A

NRLF Program for UPFC Sensitivity Calculation, C1, C2, C3 & C4 5-Bus system, load flow results with UPFC

Line(i-j)	C1	C2	C3	C4
1-2	-	-	-	-
3-1	0.0252	0.084	0.239	-0.102
3-2	0.0399	0.104	0.319	-0.136
3-4	**0.2762**	**0.599**	**1.915**	**-0.816**
4-2	0.0446	0.116	0.952	-0.412
4-5	0.0402	0.082	0.714	-0.309
5-2	0.0434	0.115	0.701	-0.315

The absolute value of sensitivity C3 is the highest for the line 3-4 with UPFC placement. This indicates that this line is a potential candidate for UPFC placement. In voltage stability margin enhancement reactive power support obtained by the shunt converter is very important. The shunt converter is assumed to be connected at the sending end of the line. The maximum voltage stability margin enhancement achieved when sensitivity factor λ of line 3-4 is 2.95 pu, when UPFC is placed in the line 3-4 having the shunt converter at bus 3. This is a vital observation, which highlights the importance of identifying an appropriate location for UPFC instillation. Some of the important observations about the VSM enhancement due to installation of a UPFC between bus no. 3 and bus no.4.

TABLE-B

NRLF Program for UPFC Sensitivity Calculation, C1, C2, C3 & C4 IEEE 30-BUS SYSTEM

Line (i-j)	C1	C2	C3	C4	Line (i-j)	C1	C2	C3	C4
1	0.2447	0.7162	1.238	-0.550	21	0.9078	0.7893	2.1536	-1.7486
2	0.4991	2.1033	4.1483	-1.652	22	0.357	0.2479	1.2586	-1.1506
3	0.2835	0.6113	3.0623	-1.616	23	1.533	1.042	5.7764	-5.4244
4	**5.1654**	**8.2378**	**18.864**	**-9.698**	24	0.9734	0.6628	2.8715	-2.736
5	0.1127	0.1916	0.3812	-0.1304	25	0.5197	0.4076	1.7429	-1.4703
6	-	-	-	-	26	1.204	1.1843	4.608	-3.4727
7	1.4351	2.4568	13.242	-6.3725	27	1.4492	1.1093	4.7757	-4.1434
8	0.2084	0.228	0.6059	-0.4208	28	0.7317	0.5297	2.333	-2.093

9	-	-	-	-	29	1.5186	1.0901	2.5777	-2.3739
10	-	-	-	-	30	0.3848	0.2668	1.3553	-1.247
11	-	-	-	-	31	-	-	-	-
12	-	-	-	-	32	0.7286	0.5093	1.5695	-1.4491
13	-	-	-	-	33	0.223	0.1245	0.276	-0.2922
14	-	-	-	-	34	-	-	-	-
15	0.1539	0.5624	2.6156	-0.4453	35	-	-	-	-
16	0.1803	0.6588	0.9713	-0.2658	36	-	-	-	-
17	0.2239	0.168	0.3747	-0.3257	37	-	-	-	-
18	0.4468	0.3077	0.714	-0.6478	38	-	-	-	-
19	0.2851	0.2211	0.4855	-0.4182	39	0.5921	0.337	1.5404	-1.5417
20	0.5098	0.0112	0.9558	-1.9675	40	-	-	-	-
21	0.9078	0.7893	2.1536	-1.7486	41	-	-	-	-

The sensitivities of IEEE 30-bus system were also calculated using equation (8)-(11). As this system has 41 lines, only the lines having maximum sensitivities are presented in the Table B. The first bus of the line is chosen for the shunt converter of UPFC. The sensitivities are also presented in the Table B. From Table B, it can be seen that real power loading sensitivity with respect to the series injected phase angle (C2) is 8.2378. Thus the voltage stability margin enhancement will be the maximum with the UPFC placement in the line connected between bus 3 and bus 4. To control the power, series injected phase angle is more effective than the series injected voltage magnitude because the increase in the line voltage is limited due to line design. The reactive power loadability is also the maximum for the line 4 with UPFC placement. The sensitivity factors corresponding to the reactive power loading is more compared to the real power loading sensitivities. This shows that UPFC is also useful in reactive power control. The line between generator buses and transformer branches are not considered for the UPFC location and the sensitivity factors corresponding to these lines are not shown in the Table – B.

V. Conclusion

The unified power flow controller has a unique capability of changing real and reactive power flows in a given line section. This capability can be explored for enhancing the system security levels during network contingencies. As the cost of installation of a UPFC in the system is very high, the location for placement of UPFC controller is to be identified by sensitivity based criteria. In this paper the enhancement of voltage stability margin of the system is achieved through placement of a UPFC in a particular line section. The results indicate that the proposed technique has a great potential in identifying a suitable location for UPFC installation.

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[8]. Akhilesh Tiwari received received B.E. and M. Tech. degrees in electrical engineering from Madhav Institute of Science and Technology Gwalior, India. He is currently working with the Electrical Engineering Department at RJIT, Gwalior, India. His current research interests include FACTs applications, and AI applications to power systems.

[9]. Arvind Kumar Jain (SMIEEE) received M. Tech. and Ph.D. degrees in Electrical Engineering from Indian Institute of Technology Kanpur, India in 2007 and 2013, respectively. He is currently an Associate Professor with the Electrical Engineering Department at RJIT, BSF, Gwalior, India. His current research interests include power systems restructuring, power system economics and optimization, demand response, smart grid and FACTs applications.

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