

Locating Unified Power Flow Controller for Enhancing Power System Loadability

S. N. Singh, *Senior Member, IEEE*, and I. Erlich, *Member, IEEE*

Abstract: In a power system transmission network, there are some corridors which are lightly loaded whereas some of the corridors are critically loaded and thus power system is operating near to critical state. Flexible AC Transmission Systems (FACTS) plays a vital role in improving the power system performance, both the static and dynamic, and enhanced the system loading capability by rerouting the power flow in the network. Due to excessive cost, these devices must be located optimally. This paper suggests the suitable locations to enhance the system loadability with Unified Power Flow Controller (UPFC), a very versatile and powerful FACTS controller. The effectiveness of the proposed algorithm is tested and illustrated on 5-bus and IEEE 14-bus systems.

Index Terms: FACTS, UPFC, Loadability, Sensitivity approach

I. INTRODUCTION

AN opening of unused potentials of transmission system due to environmental, right-of-way and cost problems is a major concern of power transmission network expansion planners and policy makers. Flexible AC Transmission Systems (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. FACTS controllers [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 [3].

The increased interest in FACTS devices is essentially due to two reasons. Firstly, the recent development in high power electronics has made these devices cost effective [4] and secondly, increased transactions in deregulated power industry motivate the use of power flow control as a very cost-effective means of dispatching specified power transactions. However, it is important to locate these devices optimally in the network 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), Static Var Compensators (SVC) and Unified Power Flow Controller (UPFC) in both vertically integrated and unbundled power systems [5-6] for meeting the different objectives. However, to the best of authors' knowledge, there is no paper, that suggests a simple and reliable method for determining the suitable location of the UPFC for enhancing the loadability of the power system. A unified power flow controller (UPFC) is the most effective and versatile FACTS device capable of controlling instantaneous power flow and provides dynamic control of system parameters (voltage, line impedance, and phase angle) independently or simultaneously in appropriate combinations.

Using controllable components of the UPFC, the line flows can be changed in such a way that more loading on the network can be made without violating operating limits of the system. Since insecure cases often represent the most severe threats to secure system operation, it is important that the FACTS devices should enhance the system security by enhancing the system loadability along with the other control devices.

A parallel Tabu search based optimal location of UPFC and its impact on enhancement of ATC has been proposed in ref. [7]. Lima et al. [8] proposed number, network location, and settings of phase shifters to maximize system loadability in a electricity market using MILP. References [9-12] deal with location of FACTS controllers for different objectives. Harinder et al. [13] presented the application of third generation FACTS controller, the unified power flow controller to improve the transfer capability of the power system. Kazemi et al. [14] proposed eigen vector analysis for optimizing location, sizing and control modes of SVC and TCSC in order to achieve the maximum loadability. The installation and operation of FACTS controllers to enhance steady state security of power system have been reported in [15].

Reference [16] focused on the evaluation of the impact of FACTS controllers on ATC using GA for the best location of SVC improving voltage profile and TTC of the system. Kumar et al. [17] proposed mixed integer linear programming approach for combined optimal location of FACTS controllers for loadability enhancement in pool and hybrid electricity markets. The system loadability in competitive environment has been calculated in [18].

A method to determine the suitable locations of unified power flow controller, with static point of view, has been suggested, in this paper, based on the sensitivity of system loading with respect to control parameters of the UPFC. The

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effectiveness of the proposed algorithm has been demonstrated on 5-bus and IEEE 14-bus test systems.

II. STATIC MODEL OF UPFC

The UPFC consists of a shunt (exciting) and a series (boosting) transformers as shown in Fig 1. 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 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 ($0 \leq V_T \leq V_{Tmax}$) and phase angle ($0 \leq \phi_T \leq 2\pi$), which is added to the AC transmission line by the series connected boosting transformer. 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.

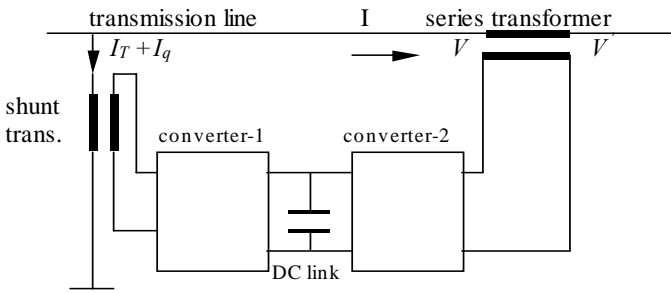


Fig.1. The UPFC basic circuit arrangement

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

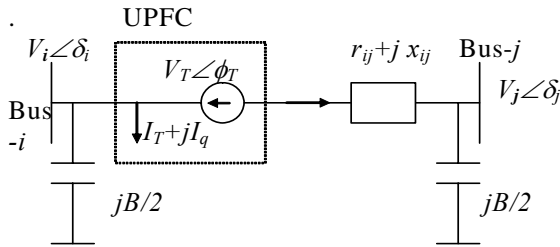


Fig.2. Equivalent circuit of UPFC

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 [6],

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

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

where $g_{ij} + jb_{ij} = 1/(r_{ij} + jx_{ij})$ and I_q is the 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

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

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

III. LOCATION OF UPFC FOR LOADABILITY ENHANCEMENT

The real power and reactive power injections at bus- i with the system loading (λ) can be written as

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

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

where P_{Di}^0 and Q_{Di}^0 are the initial real 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. In equation (5), uniform loading with the same power factor at all the load buses has been considered and the increase in the loading is assumed to be taken care by the slack bus whereas any sharing of generation amongst the generators can be easily incorporated in this model. 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

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

where c_1^k and c_2^k 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 i^{th} bus of line- k where UPFC is placed will be

$$c_1^k = \left(\frac{-2V_i g_{ij} \cos(\delta_i) + V_j (g_{ij} \cos(\delta_j) - b_{ij} \sin(\delta_j))}{P_{Di}^0} \right) \quad (8)$$

$$c_2^k = \left(\frac{-2V_i g_{ij} \sin(\delta_i) + V_j (-g_{ij} \sin \delta_j + b_{ij} \cos \delta_j)}{P_{Di}^0} \right) \quad (9)$$

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

$$c_3^k = (V_i(-g_{ij} \sin(\delta_i) + b_{ij} \cos(\delta_i))) / (Q_{Di}^0) \quad (10)$$

$$c_4^k = (V_i(g_{ij} \cos \delta_i + b_{ij} \sin \delta_i)) / (Q_{Di}^0) \quad (11)$$

where c_3^k and c_4^k 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. MAXIMUM LOADABILITY FORMULATION

To see the effectiveness of proposed approach, the maximum loadability is obtained by solving the following optimal power flow formulation.

$$\text{Max } \lambda \quad (12)$$

Subject to the following constraints:

(a) *Equality constraints*: Power flow equations corresponding to both real and reactive powers as defined in (5) and (6) must satisfy.

(b) *Inequality constraints*: These include the operating limits on the various power system variables and the parameters of UPFC as given below.

$$Q_{gi}^{\min} \leq Q_{gi} \leq Q_{gi}^{\max} \quad i = 1, 2, 3, \dots, N_b \quad (13)$$

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad i = 1, 2, 3, \dots, N_b \quad (14)$$

$$\delta_i^{\min} \leq \delta_i \leq \delta_i^{\max} \quad i = 1, 2, 3, \dots, N_b \quad (15)$$

$$0 \leq V_T \leq V_{T,max}; 0 \leq \phi_T \leq 2\pi; I_q^{\min} \leq I_q \leq I_q^{\max} \quad (16)$$

Equation (13) represents the limits on the reactive power generations. The limits on the bus voltage magnitude and angle are given by (14) and (15), respectively. Equation (16) includes limitation of the UPFC parameters.

The above optimal power flow problem involves a nonlinear objective function and a set of nonlinear equality and inequality constraints. This problem can be solved successfully by any nonlinear optimization procedure such as Newton methods, (successive) quadratic programming, gradient methods etc. Newton based methods have gained wide spread importance due to their quadratic convergence properties. The main difficulties in all the Newton based methods are the indirect incorporation of inequality constraints such as by penalty terms; interior or unlimited point methods. In this work a sequential quadratic programming (SQP) has been used to obtain the OPF solution. NAG FORTRAN library subroutine E04UCF has been used for solving the above problem.

V. SIMULATION RESULTS

To establish the effectiveness of the proposed method, simulations have been performed on a 5-bus system and IEEE 14-bus system [19]. Five-bus system consists of three

generator buses and two load buses as shown in Fig. 3. The two lines 1-2 and 3-5 are of impedance $0.0258 + j0.0966$ pu each while other four lines have an impedance of $0.0129 + j0.0483$ pu each, all to a 100 MVA base. Bus-1 has been taken as the reference bus. The initial loading at buses 4 and 5 are 80 and 200 MW, respectively. The outputs of generator-2 and generator-3 are set to 100 and 150 MW, respectively.

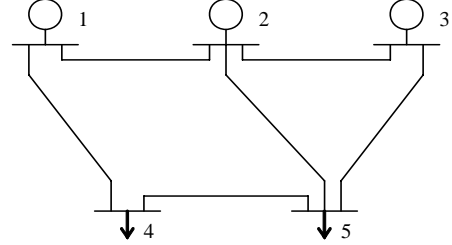


Fig. 3: 5-Bus system

Sensitivity factors 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 I. Only load buses are considered, in this work, for UPFC location. Thus sensitivities corresponding to the lines 1-2 and 2-3 are 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 I. Sensitivity factor corresponding to third control parameter of UPFC ie I_q is not considered as it will have less impact on the power flow control but it will improved the voltage profile of the network.

TABLE I
SENSITIVITY FACTORS OF 5-BUS SYSTEM

Line- k (i to j)	c_1^k	c_2^k	c_3^k	c_4^k
5-2	-6.724	-25.320	-101.762	21.277
5-4	-7.732	-23.894	-98.298	25.756
5-3	-2.348	-12.906	-49.149	12.878
4-1	-2.521	-9.629	-95.301	29.986

The magnitude of sensitivity factors c_1^k for line 5-4 is more negative 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 (c_2^k) of UPFC placed in line 5-2 (shunt converter is at bus-5) is the highest followed by line 5-4. This indicates that placement of UPFC in line 5-2 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 I (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. The absolute value of sensitivity c_3^k is the highest for the line 5-2 with UPFC placement. This indicates that this line is a potential candidate for UPFC placement. In loadability enhancement reactive power support obtained by the shunt converter is very important.

To show the effectiveness of the proposed approach an optimal power flow as formulated in section IV has been used to maximize system loadability subjected to the power balance equations, system operating and UPFC parameter constraints. The loadability of the system is obtained and presented in Fig. 4, with the lower and upper voltage limits of 0.90 and 1.10 pu, respectively. The shunt converter is assumed to be connected at the sending end of the line. The maximum loadability is achieved to 2.785 pu when UPFC is placed in the line 5-2 having the shunt converter at bus 5. It can also be seen from the Fig. 3 that bus 5 has maximum load of 2.0 pu where as load at bus-4 is only 0.8 pu.

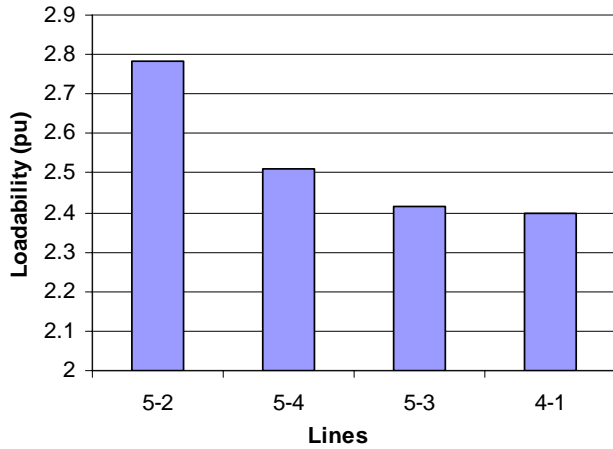


Fig. 4: Loadability of 5-bus system

The sensitivities of IEEE 14-bus system were also calculated using equation (8)-(11). As this system has 20 lines, only the lines having maximum sensitivities are presented in the Table II. The first bus of the line is chosen for the shunt converter of UPFC. The sensitivities are presented in the Table II.

TABLE II
SENSITIVITY FACTORS OF 14-BUS SYSTEM

Line- k (i to j)	c_1^k	c_2^k	c_3^k	c_4^k
8-2	-33.436	-62.762	-327.387	136.603
8-9	-19.974	-246.167	-1306.67	622.965
10-7	-72.758	-85.884	-166.919	112.778
11-3	-86.337	-83.262	-213.658	162.122
11-10	83.444	90.822	-223.50	165.538
8-1	-22.707	-54.844	-278.825	67.544

From Table II, it can be seen that real power loading sensitivity with respect to the series injected phase angle (c_2^k) is -246.167. Thus the loadability will be the maximum with the UPFC placement in the line connected between bus 8 and bus 9. 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 8-9 with UPFC placement. The next line which has highest absolute value of sensitivity c_2^k is line 10-7. 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 II.

To show the effectiveness of the proposed approach, an optimal power flow, as formulated in section IV, has been solved to maximize system loadability subjected to the power balance equations, system operating and UPFC parameter constraints. The loadability of the system is obtained and presented in Fig. 5 for few candidate lines. The lower and upper voltage limits are set to 0.90 and 1.10 pu, respectively. The shunt converter is assumed to be connected at the sending end of the line. In this case, we assume that reactive power support is zero.

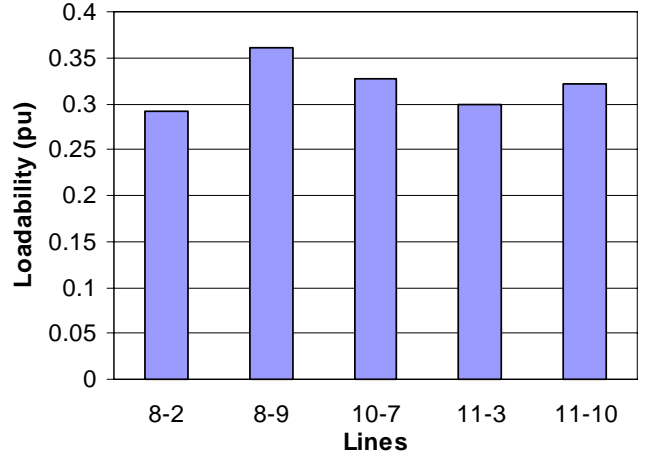


Fig. 5: Loadability of IEEE 14-bus system

To obtain the maximum loadability for the UPFC placement, one at a time, in the lines, the series voltage magnitude is set to 0.05 pu and series injected phase angle is kept at ± 0.022 rad. The shunt reactive power compensation current is fixed to zero. The maximum loadability is obtained to 0.360 pu when UPFC is placed in the line 8-9 having the shunt converter at bus 8.

VI. CONCLUSION

In this paper, a sensitivity-based approach has been developed for finding suitable placement of UPFC. Test results obtained on test systems show that new sensitivity factors could be effectively used for increasing the loadability of the system with UPFC. After selecting the suitable locations a comprehensive economic objective must be considered taking the cost of UPFC which depends on its control parameters. If these sensitivities for two lines are comparable, the placement of a UPFC can be decided based on the other criterion such as line congestion, loss minimization etc.

VII. ACKNOWLEDGEMENTS

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IX. BIOGRAPHIES

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