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Research/Technical Note

Load Curtailment Sensitivity Indices Through Optimal Placement of Unified Power Flow Controller

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Abstract: The optimal power flow (OPF) is one of the key tasks to be performed in the complicated operation and planning of a power system. Directing the power in such a way that the lightly loaded branches are loaded to reduce the system load curtailment is an option which can be achieved by making use of FACTS devices. This paper proposes a set of load curtailment sensitivity indices for optimal placement of Unified Power Flow Controller (UPFC) in power system network. An OPF formulation considering the minimization of load curtailment requirement as an objective has been developed in this paper to study the impact of optimal placement of UPFC. The effectiveness of the proposed method has been tested on IEEE-14 bus test system. The obtained results have been presented in terms of change in system load curtailment with respect to changes in UPFC controller parameters for the best location. The optimal location of UPFC in a line has been decided based on the calculated sensitivity indices. Conclusion is made on different results to see the benefit of UPFC in power system.

Keywords: OPF, Optimal Location, Load Curtailment Requirement, Sensitivity Based Indices, UPFC's Series Controller

1. Introduction

Nowadays, actual power systems are facing new challenges due to deregulation and restricting of the electricity markets. Hence, in order to obtain high operational efficiency and network security, large interconnected systems have been developed. In this context, one possible solution to improve the system operation is the use of FACTS technologies [1]. These technologies improve the performance of power system network with organization of real and reactive power control. FACTS components, particularly responsible for power quality problems such as voltage flicker, power losses and transient stability problems. These problems can be mitigated by sufficient power flow control.

Among a variety of FACTS devices, Unified Power Flow Controller (UPFC) is the most versatile one. Gyugyi L. et al. proposed the concept of UPFC [2]. In principle, a UPFC can perform voltage support, power flow control and dynamic stability improvement [3]. To achieve such functionality, it is equally important to determine the appropriate location for installation of UPFC. The effectiveness of UPFC varies when it is installed in different locations. Placement of UPFC in an optimal location is decided based on the various performance indices.

Due to the high cost of UPFC, it is important to decide their optimal placement to meet the desired objective [4-6]. In the last few years, a number of landmark publications have appeared in the open literature to find suitable location of UPFC devices [6-9]. In these literatures, there are few work reported for the use of UPFC in order to reduce the system load curtailment which can be defined as a coordinated set of control strategies that will result in decrease of the electric power load in the system [10]. In [11], G. M. Huang and Paing Yan proposed and examined the impacts of TCSC and SVC on load curtailment in a power system.

This paper proposes a new approach to find the optimal location of UPFC in a line to minimize the required load curtailment considering sensitivity factors for injected voltage magnitude and voltage phase angle.

The remainder of this paper is organized as follows. Section 2 briefs UPFC load flow model used in this study. The load curtailment formulation and optimal power flow solution are presented in section 3. The effective of proposed method is performed on IEEE-14 bus test system and simulation results are discussed in section 4 and conclusions are drawn on simulated results and limitations of current research are stated in section 5.

2. Modeling of UPFC in Power System for Steady State Operation

2.1. UPFC Steady State Modeling

The UPFC comprises shunt and series control elements and offers a unique combination of fast shunt and series compensations [11, 12]. The UPFC injects a voltage in series with the transmission line through a series transformer. The active power involved in the series injection is taken from the transmission line through a shunt transformer, and the UPFC generates or absorbs the needed reactive power locally by the switching operation of its two converters. In the steady state operation, the main objective of the UPFC is to simultaneously control the active and reactive power flow through the transmission line and bus voltage at which shunt component of the UPFC is connected.

In this study, the basic schematic and power injection model of UPFC are used (shown in Figure 1). Here, the two voltage converters of UPFC are modeled as two ideal voltage sources. Further details about the series and parallel converters can be found in [13].

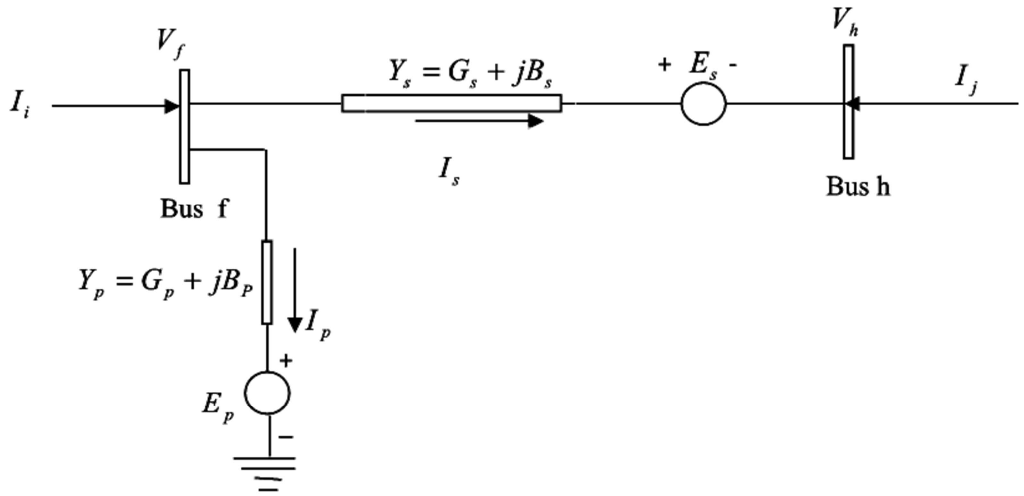

Figure 1. *Schematic representation of UPFC model.*

2.2. UPFC Power Flow Equations

Using the power injection model of UPFC, the following formulation can be extracted:

$$P_j = P_{jh} + \sum_{j=1}^{N} |V_f||V_j||Y_{jj}|\cos\left(\delta_f - \delta_j - \theta_{fj}\right) \quad (1)$$

$$Q_f = Q_{fh} + \sum_{j=1}^{N} |V_f||V_j||Y_{fj}|\sin\left(\delta_f - \delta_j - \theta_{fj}\right) \quad (2)$$

$$P_h = P_{hf} + \sum_{j=1}^{N} |V_h||V_j||Y_{hj}|\cos\left(\delta_h - \delta_j - \theta_{hj}\right) \quad (3)$$

$$Q_h = Q_{hf} + \sum_{j=1}^{N} |V_h||V_j||Y_{hj}|\sin\left(\delta_h - \delta_j - \theta_{hj}\right) \quad (4)$$

The active and the reactive power flow through the transmission line connected between the f[th] and the h[th] bus having UPFC can be derived as follows[14].

$$\begin{aligned} P_{fh} &= |V_f|^2 (G_p + G_s) - |V_f||E_p||Y_p| \\ &\cos(\theta_p - \delta_f + \delta_p) - |V_f||V_h||Y_s|\cos(\theta_s - \delta_f + \delta_h) \\ &+ |V_f||E_s||Y_s|\cos(\theta_s - \delta_f + \delta_s) \end{aligned} \quad (5)$$

$$\begin{aligned} Q_{fh} &= -|V_f|^2 (B_p + B_s) - |V_f||E_p||Y_p| \\ &\sin(\theta_p - \delta_f + \delta_p) + |V_f||V_h||Y_s|\sin(\theta_s - \delta_f + \delta_h) \\ &- |V_f||E_s||Y_s|\sin(\theta_s - \delta_f + \delta_s) \end{aligned} \quad (6)$$

$$\begin{aligned} P_{hf} &= |V_h|^2 G_s - |V_h||E_s||Y_s|\cos(\theta_s - \delta_h + \delta_s) \\ &- |V_h||V_f||Y_s|\cos(\theta_s - \delta_h + \delta_f) \end{aligned} \quad (7)$$

$$\begin{aligned} Q_{hf} &= -|V_h|^2 B_s - |V_h||E_s||Y_s|\sin(\theta_s - \delta_h + \delta_s) \\ &+ |V_h||V_f||Y_s|\cos(\theta_s - \delta_h + \delta_f) \end{aligned} \quad (8)$$

where, V_f and V_h are the voltage magnitudes at the f[th] and the h[th] bus, respectively; Y_p is the admittance of the parallel component; G_p and B_p are the conductance and susceptance, respectively, of the parallel components; Y_s is the summation of the admittance of the transmission line connected between the f[th] bus and the admittance of the series component of UPFC; G_s and B_s are the conductance and susceptance, respectively, of the series components of UPFC; θ_s is the admittance angle of the admittance that includes the admittance of the link k-m and the admittance of the series component of UPFC; δ_p and δ_s are the voltage source angle of the parallel and series components of UPFC; E_p and E_s are the voltage sources of the parallel and series converters, respectively, of the UPFC devices.

3. Location of UPFC for Load Curtailment Sensitivity Analysis

3.1. Methodology for Optimal Location of UPFC

Load curtailment is normally carried out in order for the system to stay in its stability limits. Load curtailment may be required even when some lines reach their capacity limits but others still have not utilized their capacity completely, such a scenario can occur due to system topology [11].

Total load curtailment requirement in a system and the active and reactive power balance on every node are the basic equations which are used to drive the criteria for the placement of UPFC, the load curtailment in a system is written as

$$LC = \sum_{i=1}^{n}\left(S_{ireq} - S_{iavl}\right) \quad (9)$$

where, S_{ireq} is the total apparent power demand on a particular bus whereas S_{iavl} is the complex power available on that particular bus. The apparent power can be given as

$$S_{iavl} = \sqrt{P_{iavl}^2 + Q_{iavl}^2} \quad (10)$$

$$P_{iavl} = P_{Gi} - \left(V_i \sum_{j=1}^{n} V_j \begin{pmatrix} G_{ij}\cos(\delta_i - \delta_j) \\ +B_{ij}\sin(\delta_i - \delta_j) \end{pmatrix}\right) + P_{iu} \quad (11)$$

$$Q_{iavl} = Q_{Gi} - \left(V_i \sum_{j=1}^{n} V_j \begin{pmatrix} G_{ij}\sin(\delta_i - \delta_j) \\ -B_{ij}\cos(\delta_i - \delta_j) \end{pmatrix}\right) + Q_{iu} \quad (12)$$

where, G_{ij} and B_{ij} are the real and imaginary elements of Y-bus matrix while P_{iu} or P_{fh} and Q_{iu} or Q_{fh} are the active and reactive powers injected from the UPFC into the bus-i; it can be seen from (5) and (6).

In the presence of UPFC, (9) can be a function of bus voltage magnitude (V), voltage angle (δ) and injected UPFC parameters (X) and given as

$$LC = f_{LC}(V, \delta, X) \quad (13)$$

From Taylor's expansion, equation (13) becomes

$$\begin{aligned} \Delta LC &= \left[\frac{\partial LC}{\partial \delta}\frac{\partial LC}{\partial V}\right]\begin{bmatrix}[\partial\delta_2 \ldots \partial\delta_i \ldots \partial\delta_{Nb}] \\ [\partial V_2 \ldots \partial V_i \ldots \partial V_{Nb}]\end{bmatrix} + \left[\frac{\partial LC}{\partial X}\right][\Delta X] \\ &= [H]\begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix} + [W][\Delta X] \end{aligned} \quad (14)$$

The UPFC parameters representing X: $[\Delta V_s] = [\Delta V_{si,j} \ldots]^T$ and $[\Delta \varphi_s] = [\Delta \varphi_{si,j} \ldots]^T$ are the end buses of line 'l'.

The dimension of matrix [H] is $1 \times (2N_b - 1)$ as the derivatives corresponding to slack bus not included in the above matrices.

Using these parameters, (14) becomes

$$\Delta LC = [H]\begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix} + [W_{Vs}][\Delta V_s] \; \Delta LC = [H]\begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix} + [W_{\varphi s}][\Delta\varphi_s] \quad (15)$$

where, $[W_{Vs}] = \left[\frac{\partial LC}{\partial V_s}\right]$ and $[W_{\varphi s}] = \left[\frac{\partial LC}{\partial \varphi_s}\right]$ their dimensions are $1 \times N_l$. The power balance equation at each node can be written as

$$P_{Gi} = P_{Di} + \left(V_i \sum_{j=1}^{n} V_j \begin{pmatrix} G_{ij}\cos(\delta_i - \delta_j) \\ +B_{ij}\sin(\delta_i - \delta_j) \end{pmatrix}\right) - P_{iu} \quad (16)$$

$$Q_{Gi} = Q_{Di} + \left(V_i \sum_{j=1}^{n} V_j \begin{pmatrix} G_{ij}\sin(\delta_i - \delta_j) \\ -B_{ij}\cos(\delta_i - \delta_j) \end{pmatrix}\right) - Q_{iu} \quad (17)$$

At steady state, the power balanced equations can be expressed as a function of bus voltage (V), bus angle (δ) and UPFC's parameters (X) and are written for each node as

$$\begin{aligned} 0 &= f_{PB}(V, \delta, X), \text{and} \\ 0 &= f_{QB}(V, \delta, X) \end{aligned} \quad (18)$$

From Taylor's expansion of (18),

$$\begin{bmatrix}\Delta P_G \\ \Delta Q_G\end{bmatrix} = \begin{bmatrix}\frac{\partial f_{PB}}{\partial \delta} & \frac{\partial f_{PB}}{\partial V} \\ \frac{\partial f_{QB}}{\partial \delta} & \frac{\partial f_{QB}}{\partial V}\end{bmatrix}\begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix} + \begin{bmatrix}\frac{\partial f_{PB}}{\partial X} \\ \frac{\partial f_{QB}}{\partial X}\end{bmatrix}[\Delta X] \quad (19)$$

By representing first coefficient matrix of (19) as [J] and the second one as [L], and the change in loads is assumed to be met by the slack bus generator and can be written as

$$\begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix} = [J]^{-1}(-[L][\Delta X]) \quad (20)$$

The dimension of matrix [J] is $(2N_b - 1)\times(2N_b - 1)$ and for matrix [L], dimension is $(2N_b - 1)\times l$. For UPFC's parameters: V_s and ϕ_s, (20) becomes

$$\begin{aligned} \begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix} &= [J]^{-1}(-[L_{Vs}][\Delta V_s]), \text{where } [L_{Vs}] = \begin{bmatrix}\frac{\partial f_{PB}}{\partial V_s} \\ \frac{\partial f_{QB}}{\partial V_s}\end{bmatrix} \\ \begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix} &= [J]^{-1}(-[L_{\varphi s}][\Delta\varphi_s]) \text{where } [L_{\varphi_s}] = \begin{bmatrix}\frac{\partial f_{PB}}{\partial \varphi_s} \\ \frac{\partial f_{QB}}{\partial \varphi_s}\end{bmatrix} \end{aligned} \quad (21)$$

Substituting (21) into (15) and driving it gives

$$\left[\frac{\Delta LC}{\Delta V_s}\right] = [H]([J]^{-1}(-[L_{Vs}]) + [W_{Vs}] \quad (22)$$

$$\left[\frac{\Delta LC}{\Delta \varphi_s}\right] = [H]([J]^{-1}(-[L_{\varphi s}]) + [W_{\varphi s}] \quad (23)$$

The sensitivity factors are derived as change in load curtailment with respect to changes in UPFC parameters. Equation (22) describes the sensitivity factor corresponding to injected voltage magnitude having angle of injection as zero, while (23) gives the sensitivity factor corresponding to the voltage angle injection while keeping the injected voltage as constant.

The index calculated from (22) is the Load Curtailment Sensitivity Factor, ($LCSF^{Vs}$) and the index calculated from (23) is the Load Curtailment Sensitivity Factor ($LSCF^{\phi s}$).

3.2. Criterion for Optimal Placement of UPFC

The UPFC can be theoretically located anywhere along a transmission line. However, in this paper, the following criteria have been applied to consider the UPFC allocation on power system transmission lines.

(1) The branches having transformers have not been considered for the UPFC placement.
(2) The branches having generators at both the end buses have not been considered for the UPFC placement.
(3) The line having the highest absolute load curtailment factor with respect to UPFC angle is considered the best location for UPFC.
(4) When two or more lines are having similar sensitivity factors with respect to UPFC angle, with negative sign, of that with respect to UPFC voltage is considered as the best location for UPFC allocation.

3.3. Problem Formulation to Minimize the Load Curtailment Requirement

To see the effectiveness of the proposed approach, for optimal location of UPFC, the minimum required system load curtailment is obtained by solving the following optimal power flow (OPF) problem.

$$Minimize \quad LC = \sum_{i=1}^{N_b} P_{lireq} - P_{li} \quad (24)$$

Subject to the following constraints:

1) *Equality Constraints*: Power balanced equations corresponding to both the real and the reactive powers must be satisfied.

$$\frac{P_{li}}{P_{lireq}} = \frac{Q_{li}}{Q_{lireq}} \quad (25)$$

where, P_{lireq} and Q_{lireq} are the real and reactive power demands at bus-i while P_{li} and Q_{li} are the real and reactive power supplies at bus-j.

2) *Inequality Constraints*: These include the operating limits on various power system variables as well as the parameters of UPFC. They are given below.

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} \qquad i = 1, 2, 3, ..., N_b \quad (26)$$

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad i = 1, 2, 3, ..., N_b \quad (27)$$

$$\delta_i^{\min} \le \delta_i \le \delta_i^{\max} \qquad i = 1, 2, 3, ..., N_b \quad (28)$$

$$0 \le V_s \le V_i^{\max} \qquad i = 1, 2, 3, ..., N_b \quad (29)$$

Equation (26) represents the limits on the reactive power generations while (29) represents the limits on UPFC parameter. The limits on the bus voltage magnitude and angle are given by (27) and (28). The shunt current "I_q" has been taken zero in this work since it has no significant impact on real power control.

The above OPF problem involves a nonlinear objective function and a set of nonlinear equality and inequality constraints. This problem can be solved by any nonlinear optimization technique such as Newton methods, successive quadratic programming, gradient methods, etc. In this work, an educational free and open source power system analysis toolbox, PSAT [15, 16] has been used to obtain the OPF solution for solving above problem.

4. Simulation Results and Discussion

4.1. IEEE-14 Bus Test System

The proposed sensitivity approach for optimal placement of UPFC has been modeled and tested on IEEE-14 bus test system (shown in Figure 2) and the network and load data for the test system are taken from [17].

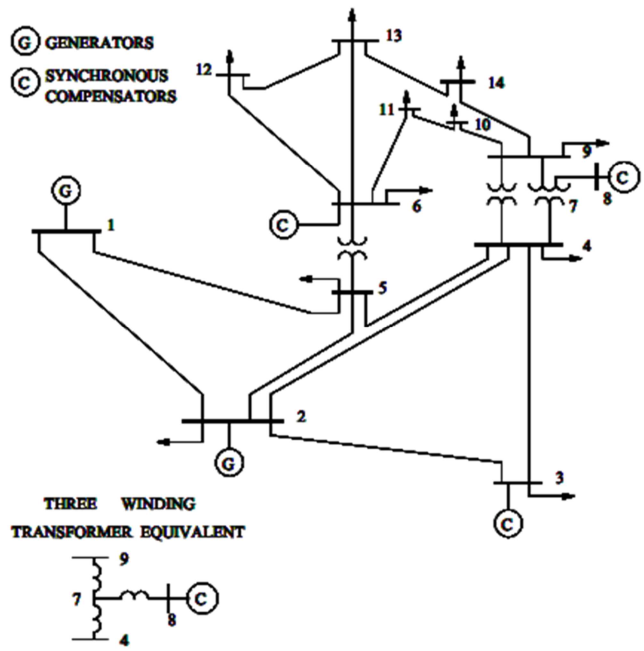

Figure 2. *Single line diagram of IEEE 14 bus test system.*

Figure 2 depicts the IEEE 14-bus benchmark system [17] that consists of two generators, three synchronous compensators, two two-winding and one three-winding transformers, fifteen transmission lines, eleven loads and one shunt capacitor. Bus 1 is used as the slack bus and the power system models are modelled using the dynamic models in PSAT [16].

4.2. Results for UPFC Placement in Test System

In this study, the limiting tap setting values for tap changers are between 0.9 and 1.1 p.u, the allowed voltage changes are between 0.95 and 1.1. The voltage limits of the series sources of the UPFC are taken as 0–0.2 p.u. and the lower and upper limits of the shunt voltage sources of the UPFC are 0 p.u and 1.1 p.u, respectively. The phase angles of both series and shunt sources are within the range of - π to π. The shunt and series impedances of installed UPFC are taken as (0.01 + j0.1) p.u and (0.001 + j0.2) p.u, respectively.

In this paper, UPFC series' controller, two sensitivity factors have been defined: one with respect to series injected voltage magnitude and the second one with respect to injected voltage phase angle. Flat voltage start and a tolerance of accuracy class less than 10^{-5} (p.u) of the maximum absolute mismatch of nodal power injection are used in all analyses. First of all and without any UPFC connection, the system under study is simulated in order to determine the power flow in each of the transmission line.

The sensitivity factors, derived in (22) and (23), have been calculated for IEEE-14 bus system. The best location has been assigned priority (rank) order 1 and so on. Table 1-4 present the results for IEEE 14 bus test system. In Table 1, the result of OPF when UPFC is placed on each line one at a time is shown. The priority list considering sensitivity factor with respect to UPFC voltage have been obtained based on (22) and only top 10 orders have been listed in Table 1. The top 10 locations, in their order, have been given in column 2 based on sensitivity factors which are given in column 4.

Table 1. *Optimal location based on sensitivity factor voltage angle ($LCFS^{\Phi s}$).*

Priotiry No.	Priority Location		Proposed SensitivityFactors
	Line No.	Buses (i-j)	
1	01	01-02	-0.9601
2	02	01-05	-0.4509
3	10	05-06	-0.3458
4	04	02-04	-0.3230
5	08	04-07	-0.3172
6	15	07-08	-0.3165
7	03	02-03	-0.3096
8	05	02-05	-0.2485
9	09	04-09	-0.1887
10	13	06-13	-0.1271

Table 2 shows the priority location for the placement of UPFC based on sensitivity factor with respect to UPFC phase angle. The best top 10 locations are depicted in Table 2 where as first column represents rank order and proposed sensitivity factors are expressed in 4th column. Table 1 and Table 2 are constructed for verification purpose using the proposed OPF problem to find the respective sensitivity factors. The priority list formed from proposed methods must capture these best locations. In these candidate locations, the branches with transformers are considered to compare with other transmission lines.

Table 2. *Optimal location based on sensitivity factor voltage magnitude ($LCFS^{Vs}$).*

Priotiry No.	Priority Location		Proposed SensitivityFactors
	Line No.	Buses (i-j)	
1	01	01-02	1.1340
2	03	02-03	0.5564
3	07	04-05	0.5384
4	02	01-05	0.5187
5	04	02-04	0.4155
6	05	02-05	0.2913
7	06	03-04	0.2327
8	10	05-06	0.2008
9	08	04-07	0.1833
10	15	07-09	0.1568

The values of minimum load curtailment obtained through OPF solution with UPFC in each line (taken one at a time) are given in Table 3. Only top 5 candidate locations have been shown in this table. The lines having transformers or having generators at both their end buses have been neglected, in accordance with the criteria, for the placement of UPFC described in section 3.

For the test system, using UPFC voltage based sensitivity factor, the best candidate for the placement of UPFC is found as line 02, followed by branches 04, 15, 05 and 13. Load curtailment value in the absence of UPFC is 0.64328 p.u. The maximum voltage injected by UPFC is set as 0.100 p.u. during OPF operation. The maximum and minimum limits of bus voltages are 1.04 and 0.96 p.u respectively. The minimum value of load curtailment as obtained by placing UPFC in line 02 is 0.51348 p.u. The results, given in Table 3, have been also illustrated through bar chart in Figure 3.

Table 3. *Sensitivity factor(voltage magnitude)and load curtailment.*

Priority No.	Priority Location		Proposed Sensitivity Factors	OPF Results by Varying Vs only	
	Line No.	Buses (i-j)		LC (p.u.)	Vs (p.u.)
1	02	01-05	-0.4509	0.51348	0.100
2	04	02-04	-0.3230	0.61533	0.100
3	15	07-09	-0.3165	0.64265	0.041
4	05	02-05	-0.2485	0.60572	0.100
5	13	06-13	-0.1271	0.64307	0.015

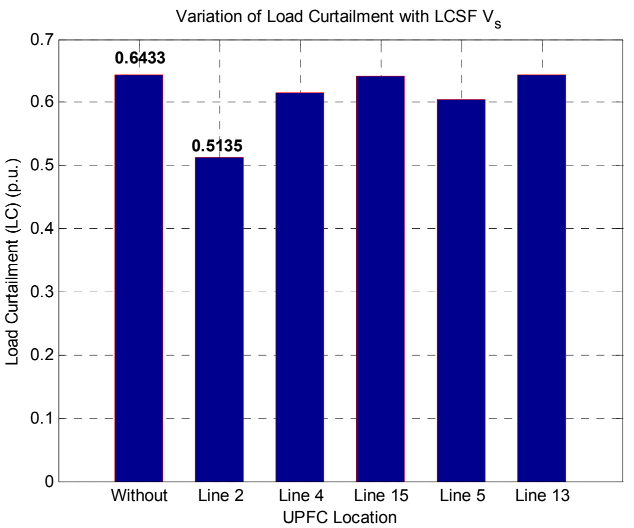

Figure 3. *Variation of load curtailment with rank order of voltage based sensitivity factor.*

The value of load curtailment based on phase angle sensitivity factor have been obtained and given in Table 4 for the case when varying both the injected voltage magnitude from 0 to 0.1 p.u. and phase angle from -π and π. The best location as calculated from the sensitivity factor is line 07 and required load curtailment is found to be 0.50203 p.u. The second best location, based on sensitivity factor, is line 02 and the value of required load curtailment is 0.29462 p.u. This is because of the non-linearity of the system. The branches not fulfilling the criteria, stated in Section 3, have been excluded. The results, given in Table 3, have been also illustrated through bar chart in Figure 4.

According to the result based on both voltage based sensitivity factor and phase angle based sensitivity factor, the UPFC should be installed on line 02 which connecting bus 01 and bus 05. This line is the main transmission line transmitting power from main generating unit to network. Therefore, installing UPFC on this line will reduce the congestion of line flow and it can be improved the voltage profile of each bus of system.

Table 4. *Sensitivity factor (voltage magnitude) and load curtailment.*

Priority No.	Priority Location		Proposed Sensitivity	OPF Results by Varying Vs only		
	Line No.	Buses (i-j)	Factors	LC (p.u.)	Vs (p.u.)	Φs (p.u.)
1	07	04-05	0.5384	0.50203	0.100	1.570
2	02	01-05	0.5187	0.29462	0.100	1.197
3	04	02-04	0.4155	0.48350	0.100	1.291
4	05	02-05	0.2913	0.52682	0.100	1.267
5	06	03-04	0.2327	0.59214	0.095	1.212

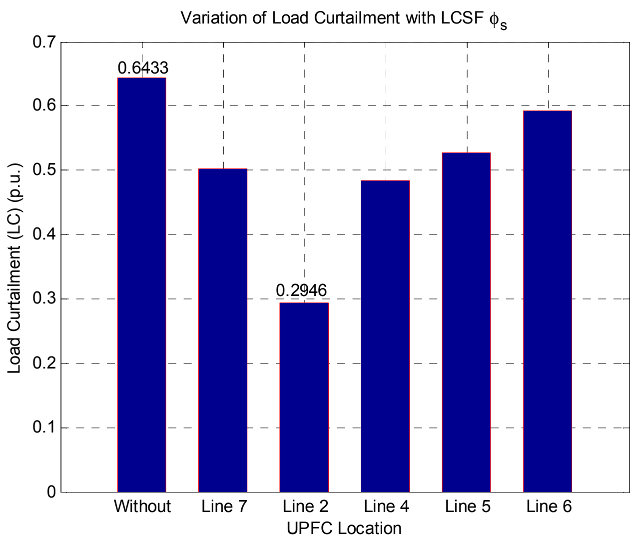

Figure 4. *Variation of load curtailment with rank order of phase angle based sensitivity factor.*

4.3. Summary and Future Research Potential

Based on the results obtained, it can be stated that the required system load curtailment decreases in the test system with optimal placement of UPFC at the optimal location obtained. Moreover, the priority (rank) order of the locations for the optimal placement of the UPFC are validated through OPF results in terms of the decrement in required system load curtailment with the placement of UPFC. The high ranked line for the UPFC placement has resulted in a greater reduction in total system load curtailment in the system.

In this work, there will be some limitations. A final placement may be decided on may be decided based on meeting other objectives such as power flow control, dynamic stability improvements, cost, availability of site, etc, which have not been considered.

However, only static model of UPFC's series controller has been considered in current work, there will be a new approach of hybrid indices for optimal placement using both static and dynamic criteria. Besides static analysis, dynamic performances still need to be considered. And also, for solution of OPF, some of the evolutionary methods such as Particle Swarm Optimization (PSO), Bacteria Foraging Optimization (BFO) and the other Artificial Intelligence based methods can be tried out to get more reliable solutions.

5. Conclusion

In this paper, an approach of optimal power flow based sensitivity indices, in terms of change in system load curtailment with respective to changes in UPFC controller parameters, for optimum location of UPFC has been presented. The optimal placement of UPFC has been decided based on the load curtailment sensitivity factors. Optimal locations for UPFC placement in a line has been considered for the minimization of system load curtailment requirements. With the optimal placement of UPFC at the location obtained based on the sensitivity factors, the required system load curtailment decreases in the test system. For the optimal locations, the rank orders are validated through OPF results in terms of the decrement in required system load curtailment with the placement of UPFC.

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