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Optimal placement of DPFC based on load curtailment sensitivity factors

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ABSTRACT

This paper presents a new method in terms of sensitivity factors, called as the Load Curtailment Sensitivity Factors (LCSF) for the optimal location of DPFC to minimize the system load curtailment requirement and to maintain the system security. In this work, DPFC has been proposed for the study to minimize the load curtailment as it is most versatile device in FACTS family. The main aim of finding such a sensitivity coefficient is to find out the best possible location for the DPFC in the given system for this purpose. The proposed method has also been compared with some of the existing methods available in the literature.

Keywords-FACTS, DPFC, LCSF

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INTRODUCTION

In today's complex power system, with increasing demand and supply in the power systems every instant, it has become a big challenging task to maintaining the stability, reliability and security of the system. In a deregulated power system, the main hurdle is to provide a distribution network capable of delivering contracted power from suppliers to consumers over large geographic area under market forces-controlled, and continuously varying patterns of demand and supply. Flexible AC Transmission Systems (FACTS) are being popularly used by utilities due to their capability to enhance power system static as well as dynamic performance. The FACTS initiative [1,2,3,4,5,6,7,8,10,11,15] was originally launched in 1980s to solve the emerging problems faced due to restrictions on transmission line construction, and to facilitate growing power export/import and wheeling transactions among utilities.

In case of a contingency or a steep load increment, line overload or low/high bus voltage are likely to occur, some amount of load has to be curtailed in such a situation in order to maintain the system security. In order to shed the least amount of load, re-dispatch of generation using OPF is one solution. However, some lines may reach their capacity limits while there may be others whose capacity is not completely used due to system topology. Directing the power in such a way that the lightly loaded branches are also loaded to reduce the system load curtailment is an option which can be achieved by making use of FACTS devices.

It is common to find optimal location for placement of FACTS controllers for various purposes and there have been suggested several methods in [16,17,18,19,20] optimal location of FACTS controllers for loading capability enhancement has been presented. No significant work has been done on finding the optimal location of FACTS controllers in order tominimize the load curtailment requirement. Load curtailment has been worked upon with respect to other parameters such as voltage stability margin, for example in [21] an evaluation of system load curtailment has been carried out while incorporating voltage stability margin and it has been concluded that the amount of load curtailment evaluated is observed to increase if more voltage stability margin, from a possible collapse is required in a system.

LOAD CURTAILMENT

Load curtailment can be defined as a coordinated set of control strategies that will result in decrease of the electric power load in the system. It is one of the possible corrective actions that aim at forcing the disturbed system to a new stable equilibrium state [22]. Load curtailment is normally carried out in order for the system to stay in its stability limits. Utilities often offer commercial and industrial building owners reduced rates for electricity in exchange for a curtailed energy use at the request of the utility. This reduction in load is purchased as an ancillary service as is suggested [23]. Such requests usually are generated on the occurrence of high loads such as a hot summer afternoon; the consumers can get lower rates by reducing their consumption or switching to alternate sources of energy.

The main reasons for load curtailment are the following

- Due to the occurrence of contingencies or congestions at various points in the system, if at a certain time it is not possible for the system to be kept within the stability limits, curtailing the load in order to avoid a total black out becomes inevitable. In such a situation, the consumers that have a contract to curtail the loads are notified to meet a certain load demand as per the contract, the utility has to pay for any amount of load thus curtailed in this manner.
- Utility rate structures provide all kinds of customers with fixed rates regardless of generation costs. These utilities use most efficient (least costly) of their generation plants in order to supply the bulk of the load, they operate the more expensive plants only when the load increases. Since the energy to the consumer is supplied at a fixed cost it leaves a negative impact on the utility's profit margins to use less efficient plants. The best option at a certain cost level for the utility is; instead of bringing in a costly generator (may be a coal generator with large start-up cost) is to pay the consumer instead to restrict his use of electricity.

Both the utility and customer will incur costs to add controls and equipment in customer's facility, both will also commit resources to track the operation of load curtailment and they also have to give reports. Apart from that, curtailing the load is not a good sign for the system reliability and customers, thus the load curtailment must be minimized. A global Particle Swarm-Based-Simulated Annealing Optimization technique for under-voltage load shedding problem has been used to tackle load curtailment [24]. Some schemes for load curtailment have been developed using dynamic optimal power flow analysis, it is based on issue concerning the selection of optimal interruptible load selection [10].

REPRESENTATION OF TRANSMISSION LINES

A simple transmission line, connected between bus-i and bus-j with the line admittance $g_{ij} + jb_{ij} = \frac{1}{r_{ij}+jx_{ij}}$, can be represented by its lumped π equivalent parameters as shown in Figure. 1. Let complex voltages at bus-i and bus-j be $V_i\angle\delta_i$ and $V_j\angle\delta_j$ respectively. The real $\left(P_{ij}\right)$ and reactive $\left(Q_{ij}\right)$ power flows from bus-i to bus-j can be written as,

$$P_{ij} = V_i^2 g_{ij} - V_i V_j\left[g_{ij}\cos\delta_{ij} + b_{ij}\sin\delta_{ij}\right] \qquad (1)$$

$$Q_{ij} = -V_i^2\left[b_{ij} + \frac{B_{sh}}{2}\right] - V_i V_j\left[g_{ij}\sin\delta_{ij} - b_{ij}\cos\delta_{ij}\right] \qquad (2)$$

Where, $\delta_{ij} = \delta_i - \delta_j$

The real power, P_{ji} and reactive power, Q_{ji} flowing from bus j to bus I is given by the expression

$$P_{ji} = V_j^2 g_{ij} - V_i V_j [g_{ij} \cos\delta_{ij} - b_{ij} \sin\delta_{ij}] \qquad (3)$$

$$Q_{ji} = -V_j^2 \left[b_{ij} + \frac{B_{sh}}{2}\right] + V_i V_j [g_{ij} \sin\delta_{ij} + b_{ij} \cos\delta_{ij}] \qquad (4)$$

Where, B_{sh} is the full line charging impedance.

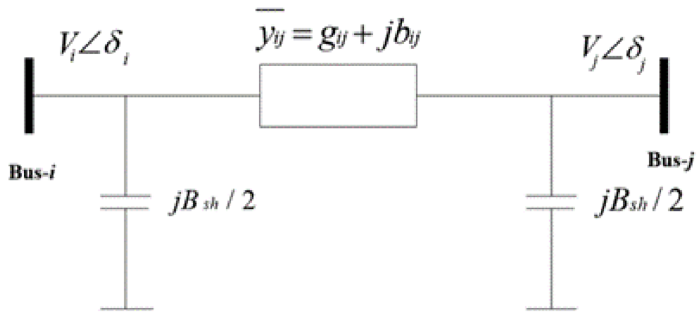

Figure. 1. Representation of Transmission Lines

REPRESENTATION OF DPFC

In this paper, the DPFC model with PEM fuel cell has been used [25]. The model of DPFC with PEM fuel cell and Z Source Inverter (ZSI) gave better performance as compare to normal model of DPFC [25]. The MATLAB model of DPFC is shown in Figure. 2.

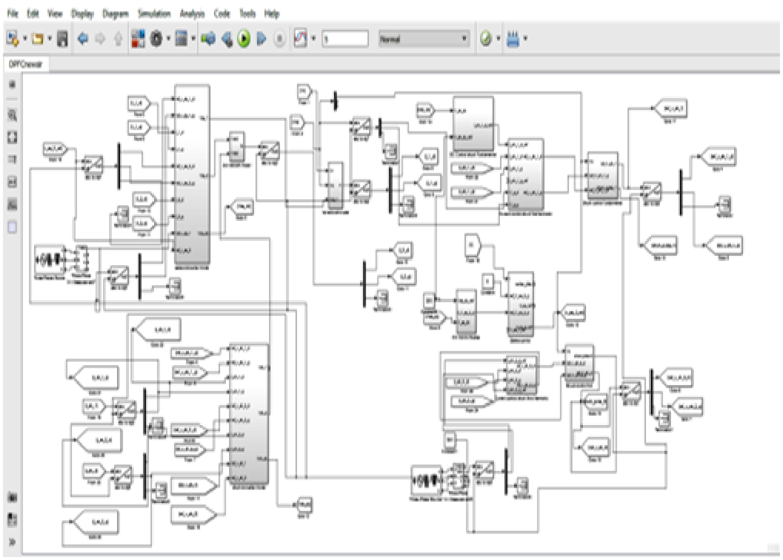

Figure. 2. DPFC with Fuel Cell

PROPOSED METHODOLOGY FOR OPTIMAL LOCATION OF DPFC

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 derive the criteria for the placement of UPFC, the load curtailment in a system is written as

$$LC = \sum_{i-1}^{n} S_{ireq} - S_{iavl} \quad (5)$$

where ,S_{ireq} denotes 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

$$S_{iavl} = \sqrt{P_{iavl}^2 + Q_{iavl}^2} \quad (6)$$

$$P_{iavl} = P_{Gi} - \left(V_i \sum_{j=1}^{n} V_j \left(G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j) \right) \right) + P_{iu} \quad (7)$$

$$Q_{iavl} = Q_{Gi} - \left(V_i \sum_{j=1}^{n} V_j \left(G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j) \right) \right) + Q_{iu} \quad (8)$$

Where, G_{ij} and B_{ij} are the real and imaginary elements of Y-bus matrix. $P_{iu}$and$Q_{iu}$are the active and reactive powers injected from the FACTS device into the bus-*i*, which can be represented by the equation

$$P_{iu} = -V_s^2 g_{ij} - 2V_s V_i g_{ij} \cos(\varphi_s - \delta_i) + V_s V_j \left[g_{ij} \cos(\varphi_s - \delta_i) + b_{ij} \sin(\varphi_s - \delta_i) \right] \quad (9)$$

$$Q_{iu} = V_i I_q + V_i V_s \left[g_{ij} \sin(\varphi_s - \delta_i) + b_{ij} \cos(\varphi_s - \delta_i) \right] \quad (10)$$

Equation (5), in the presence of a FATCS device, can be a function of bus voltage magnitude (*V*) voltage angle (δ) and injected FACTS parameter (*X*) and given as,

$$LC = f_{LC}(V, \delta, X) \quad (11)$$

From Taylors expansion, equation (11) can be writtenas

$$\Delta LC = [H] \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} + [W][\Delta X] \quad (12)$$

Where, matrices *H* and *W* have the following values.

$$[H] = \begin{bmatrix} \frac{\partial LC}{\partial \delta} & \frac{\partial LC}{\partial V} \end{bmatrix} \quad (13)$$

$$[W] = \begin{bmatrix} \frac{\partial LC}{\partial X} \end{bmatrix} \quad (14)$$

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} [\Delta\delta_2 \, \Delta\delta_3 \cdots \, \Delta\delta_i \ldots \Delta\delta_{Nb}]^T \\ [\Delta V_2 \, \Delta V_3 \cdots \, \Delta V_i \ldots \Delta V_{Nb}]^T \end{bmatrix} \quad (15)$$

$[\nabla X] = [\Delta X_{ij} \ldots]^T; \forall\, i, j \in N_l$, represents injected FACTS parameter, $N_l$is the total of lines in thesystem.

When using DPFC as the FACTS device

$[\Delta V_s] = [\Delta V_{si,j}]^T$ *and* $[\Delta\varphi_s] = [\Delta\varphi_{si,j}]^T; \forall\, i, j \in N_l, i, j$ are the end buses of line l.

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

While using DPFC, equation (12) becomes

$$\Delta LC = [H]\begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix} + [W_{V_s}][\Delta V_s] \qquad (16)$$

Where

$$[W_{V_s}] = \left[\frac{\partial LC}{\partial V_s}\right] (17)$$

Similarly for DPFC angle

$$\Delta LC = [H]\begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix} + [W_{\varphi_s}][\Delta\varphi_s] \qquad (18)$$

Where,

$$[W_{\varphi_s}] = \left[\frac{\partial LC}{\partial \varphi_s}\right] \qquad (19)$$

The dimensions for $[W_{V_s}]$ and $[W_{\varphi_s}]$ are $1 \times N_l$

The power balance equation at each node can be written as

$$P_{Gi} = P_{Di} + \left(V_i \sum_{j=1}^{n} V_j\left(G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)\right)\right) - P_{iu} \qquad (20)$$

$$Q_{Gi} = Q_{Di} + \left(V_i \sum_{j=1}^{n} V_j\left(G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j)\right)\right) - Q_{iu} \qquad (21)$$

The power balance equations, at steady state, can be expressed as a function of bus voltage (V), bus angle (δ) and FACTS parameter (X) and are written for each node as,

$$0 = f_{PB}(V, \delta, X) \qquad (22)$$

$$0 = f_{QB}(V, \delta, X) (23)$$

From Taylor`s expansion of equations (22) and (23)

$$\begin{bmatrix}\Delta P_B \\ \Delta Q_B\end{bmatrix} = [J]\begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix} + [L][\Delta X] (24)$$

In equation (24), the change in loads is assumed to be met by the slack bus generator and can be written as

$$\begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix} = [J]^{-1}(-[L][\Delta X]) \qquad (25)$$

$$[J] = \begin{bmatrix}\frac{\partial f_{PB}}{\partial \delta} & \frac{\partial f_{PB}}{\partial V} \\ \frac{\partial f_{QB}}{\partial \delta} & \frac{\partial F_{QB}}{\partial V}\end{bmatrix} \qquad (26)$$

$$[L] = \begin{bmatrix} \frac{\partial f_{PB}}{\partial X} \\ \frac{\partial f_{QB}}{\partial X} \end{bmatrix} \quad (27)$$

The dimension of matrix [J] is $2(N_b - 1) \times 2(N_b - 1)$ and for matrix [L], dimension is $2(N_b - 1) \times N_l$

The DPFC equation (25) can be written as,

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = [J]^{-1}(-[L_{V_s}][\Delta V_s])$$

$$Where, \quad \left[L_{V_s} = \begin{bmatrix} \frac{\partial f_{PB}}{\partial V_s} \\ \frac{\partial f_{QB}}{\partial V_s} \end{bmatrix} \right] \quad (28)$$

and

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = [J]^{-1}(-[L_{\varphi_s}][\Delta\varphi_s])$$

$$Where, \quad \left[L_{\varphi_s} = \begin{bmatrix} \frac{\partial f_{PB}}{V_s \partial \varphi_s} \\ \frac{\partial f_{QB}}{V_s \partial \varphi_s} \end{bmatrix} \right] \quad (29)$$

Substituting equation (28) in equation (16) and equation (29) in equation (18)

$$\Delta LC = [H]\left([J]^{-1}(-[L_{V_S}][\Delta V_s])\right) + [W_{V_S}][\Delta V_s] \quad (30)$$

$$\Delta LC = [H]\left([J]^{-1}(-[L_{\varphi_S}][\Delta\varphi_s])\right) + [W_{\varphi_S}][\Delta\varphi_s] \quad (31)$$

Therefore,

$$\left[\frac{\Delta LC}{\Delta V_s}\right] = [H]\left([J]^{-1}(-[L_{V_S}])\right) + [W_{V_S}] \quad (32)$$

$$\left[\frac{\Delta LC}{V_s \Delta\varphi_s}\right] = [H]\left([J]^{-1}(-[L_{\varphi_S}])\right) + [W_{\varphi_S}] \quad (33)$$

The sensitivity factors are derived as change in load curtailment with respect to change in FACTS parameters.

Equation (32) describes the sensitivity factor corresponding to injected voltage magnitude having angle of injection as zero, while equation (33) gives the sensitivity factor corresponding to the voltage angle injection while keeping the injected voltage as constant. The index calculated from equation (32) is the Load Curtailment Sensitivity Factor ($LCSF^{Vs}$), and the index calculated from equation (33) is the Load Curtailment Sensitivity Factor ($LCSF^{\phi s}$).

CRITERION FOR OPTIMAL LOCATION OF DPFC

The following criteria have been used for optimal placement of DPFC.

- The branches having transformers have not been considered for the DPFC placement.
- The branches having generators at both the end buses have not been considered for the DPFC placement, in this work.
- The line having the highest absolute load curtailment sensitivity factor with respect to DPFC angle is considered the best location for DPFC, followed by other lines having less values of ($LCSF^{\phi s}$).

When two or more lines are having similar sensitivity factors, then the line having the highest magnitude, with negative sign, of load curtailment sensitivity factor withrespect to DPFC voltage is considered as the best location for DPFC placement.

PROBLEM FORMULATION

The effectiveness of the proposed approach, for optimal placement of UPFC, has been verified in terms of its impact on reducing total required load curtailment in the system. It has been assumed that power factors at all load buses are remains constant while minimizing the system load curtailment. The problem to determine the minimum required system load curtailment has been formulated as an OPF problem which is given below.

$$Min\ LC = \sum_{i=0}^{N_b} P_{lireq} - P_{il} \qquad (34)$$

Subject to the following constraints:

i)

$$\frac{P_{li}}{P_{lireq}} = \frac{Q_{li}}{Q_{lireq}} \qquad (35)$$

Where,

P_{lireq} *is the real power demand at bus i*

P_{li} *is the actual power supply at bus i*

Q_{lireq} *is the reactive power demand at bus i*

Q_{li} *is the reactive power supply at bus i*

ii) The operating limits on various power system variables and the parameters of DPFC are

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \qquad i = 1,2,3, \ldots \ldots \ldots \ldots N_b \qquad (36)$$

$V_i^{min} \leq V_i \leq V_i^{max} \qquad i = 1,2,3, \dots \dots \dots \dots N_b$ (37)

$\delta_i^{min} \leq \delta_i \leq \delta_i^{max} \qquad i = 1,2,3, \dots \dots$ (38)

$0 \leq V_s \leq V_s^{max} \qquad \leq \varphi_s \leq \pi$ (39)

Equation (36) represents the limits on reactive power generations. The limits on the bus voltage magnitude and angle are given by equations (37) and (38) respectively. Equation (39) represents the limits on DPFC (V_s, ϕ_s) parameters. The shunt current, I_q has been taken zero in this work, as it has no significant impact on real power control because it is in quadrature of sending end bus voltage.

The above OPF problem involves a non linear objective function and a set of nonlinear equality and inequality constraints. This problem can be solved by any nonlinear optimization technique. In this work, GAMS/SNOPT solver library[3,4] has been used for solving the OPF problem.

SIMULATED RESULTS FOR IEEE-14 BUS SYSTEM

The proposed sensitivity approach for optimal placement of DPFC has been tested on IEEE 14-bus system. The details of these systems are given in appendix-A and B, respectively. The sensitivity factors ($LCSF^{Vs}$) as derived in equations (32), have been obtained and given in Table.1. The optimal locations based on sensitivity factor with respect to DPFC angle ($LCFS^{\phi s}$) is shown in Table.2. The values of minimum load curtailment obtained through OPF solution by placing DPFC in each line, taken one at a time are given in Table 3.

For an IEEE 14-bus system, using DPFC voltage based sensitivity factor (LCSFVs), the best location for the placement of DPFC is found as line-04, followed by branches 11,12,5 and 16. Load curtailment (LC) value in the absence of a DPFC is 0.643281 pu. The maximum voltage injected by DPFC is set as 0.100 pu. The maximum and minimum limits of bus voltage magnitude are 1.04 and 0.96 pu, respectively. The minimum value of load curtailment as obtained by placing DPFC in line-4 is 0.51348 pu. The results, given in Table 3, have been also shown through bar chart in Figure 3.

Table 1. The sensitivity factor ($LCSF^{Vs}$)

Rank order	Line no.	Buses *i-j*	Proposed sensitivity factor ($LCFS^{Vs}$)
1	08	01-02	-0.9601
2	04	01-08	-0.4509
3	01	08-03	-0.3458
4	11	02-09	-0.3230
5	02	09-06	-0.3172
6	12	06-07	-0.3165
7	09	02-04	-0.3096
8	05	02-08	-0.2485
9	03	09-07	-0.1887
10	16	03-13	-0.1271

Table 2. Optimal location based on sensitivity factor with respect to DPFC angle

Rank order	Line no.	Buses *i-j*	Proposed sensitivity factor ($LCFS^{\varphi s}$)
1	08	01-02	1.1340
2	09	02-04	0.5564
3	07	09-08	0.5384
4	04	01-08	0.5187
5	11	02-09	0.4155
6	05	02-08	0.2913
7	06	09-04	0.2327
8	01	08-03	0.2008
9	02	09-06	0.1833
10	12	06-07	0.1568

Table 3. Minimum load curtailment obtained through OPF solution placing DPFC in each line

				OPF results (Varying Vs)	
Rank order	Line No.	Buses i-j	Sensitivity Factors (LCSFVs)	LC (pu)	Vs(pu)
1	04	01-08	-0.4509	0.51348	0.100
2	11	02-09	-0.3230	0.61533	0.100
3	12	06-07	-0.3165	0.64265	0.041
4	05	02-08	-0.2485	0.60572	0.100
5	16	03-13	-0.1271	0.64307	0.015

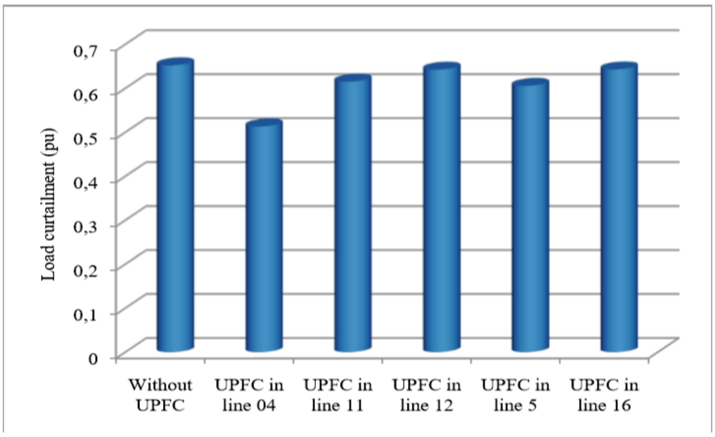

Figure. 3. Variation of load curtailment with rank order for (LCSFVs)

The value of load curtailment have been obtained and given in Table 4 for the case when varying both the injected voltage magnitude (Vs) from 0 to 0.1 pu and phase angle (ϕs) from –π to π. The best location as calculated from the sensitivity factor is line-07 and required load curtailment is found to be 0.50203 pu. The second best location, based on sensitivity factor, is line-04 and the value of required load curtailment is 0.29462 pu. This is due to the non linearity of the system. The branches not fulfilling the criteria, laid out in section VI, have been excluded. The results, given in Table 4, have been also shown through bar chart in Figure 4.

Table 4. Load curtailment value

				OPF results by varying V_s and ϕ_s		
Rank order	Line No.	Buses i-j	Sensitivity Factor ($LCSF^{\phi s}$)	LC (pu)	V_s(pu)	Φ_s (rad)
1	07	09-08	0.5384	0.50203	0.1	1.570
2	04	01-08	0.5187	0.29462	0.1	1.197
3	11	02-09	0.4155	0.48350	0.1	1.291
4	05	02-08	0.2913	0.52682	0.1	1.267
5	06	09-04	0.2327	0.59214	0.1	1.212

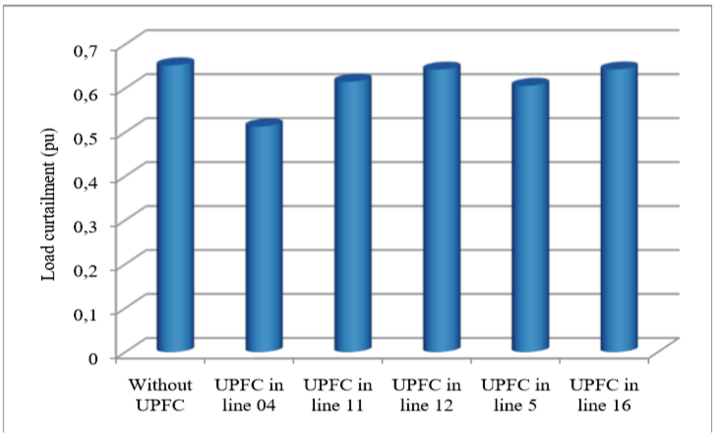

Figure. 4. Variation of load curtailment with rank order for ($LCSF^{\phi s}$)

CONCLUSION

A new set of AC power flow based indices has been developed, in terms of change in system load curtailment with respect to change in DPFC series controller parameters, for the optimal placement of DPFC. Two kinds of sensitivity factors have been defined with respect to the series injected voltage magnitude and phase angle parameters of DPFC. The optimal location of DPFC has been decided based on the calculated indices. A steady state power injection model of DPFC has been utilized in this work. An OPF formulation has been developed, with minimization of required system load curtailment as an objective, to study the impact of the optimal DPFC placement. Results obtained, on IEEE 14-bus and IEEE 30-bus systems, reveal the following.

1. With the optimal placement of DPFC at the location obtained based on the proposed sensitivity factors, the required system load curtailment decreases in both the test systems.
2. The rank order of the locations, obtained for the optimal placement of the DPFC, are validated through OPF results in terms of the decrement in required system load curtailment with the placement of DPFC. The high ranked lines for the DPFC placement have resulted in a larger reduction in total system load curtailment in both the systems.

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