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Optimal Placement of FACTS Device to Maximize the Loadability of Transmission Lines

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Abstract: This paper deals with the optimal location of Facts device in electrical power systems, using proposed sensitivity performance index using Ant colony based UPFC controlled parameters. The proposed method ACO based optimal power flow control for optimal location. The proposed approach is tested on IEEE-14 bus system. The results obtained are quite promising for the power system operation environment.

Keywords: *FACTS device; Sensitivity factor; Any colony method (ACO); OPF; performance index*

I. INTRODUCTION

Expansion of power transmission network is a major challenge in both Regulated (bundled) and deregulated (unbundled) electricity utility structure due to requirement of large investment, difficulty in getting right-of-way and environmental concerns. In market scenario, some transmissions corridors get frequently overload or critically loaded due to willingness of buyer s to purchase power from the cheap generators. Hence there is an interest in better utilization of available power transmission capacities by installing new devices, such as flexible AC Transmission System (FACTS) facts controller can be effectively enhance the system load ability through power flow control in the lines. However, it is important to ascertain the optimal placement of these controllers, because of their considerable cost.

Several methods [1, 2, 3, 4, 5] have been suggested to find the optimal location of FACTS Controllers, such as Thyristor Controlled Series Compensator (TCSC), Thyristor Controlled Phase Angle Regulator (TCPAR), Static VAR Compensator (SVC) and Unified Power Flow Controller (UPFC). In [3], a loss sensitivity approach has been proposed for placement of series capacitor, phase shifters and SVC s in [2] have used continuation Power Flow (CPF) method for obtaining the size and location of series compensators to increase the load ability limit of the system. With placement of series compensator in each line, the maximum load ability, with loads changed by a uniform loading factor at each bus, has been computed with the help of a CPF method.

In [6] proposed Eigen-vector analysis for optimizing location, size and control modes of SVC and TCSC in order to achieve the maximum load ability. In [7] studied the impact of FACTS controller, Available Transfer Capability (ATC) evaluation. The best location of SVC was obtained to improve voltage profile and Total Transfer Capability (TTC) of the transmission system. In [8] proposed a mixed integer linear programming approach for optimal location of FACTS controller for a load ability enhancement in pool and hybrid electricity markets. The impact of FACTS controllers for load ability enhancement pool and hybrid electricity markets. The impact of FACTS controller on system load ability, in competitive environment, has been evaluated in [9].

Most of the works, reported, have obtained optimal location of the FACTS controller at a given operating point. Howe ever due to its high cost, it is desirable to obtain a location of FACTS controller valid under different loading condition and contingency cases. Amongst various FACTS controller, UPFC possess more versatile characteristics due to its ability to simultaneously control line flows and bus voltages.

This paper has suggested a method to determine the optimal location of UPFC, based on sensitivity of system loading factor with respect to its control parameter. The proposed sensitivity factors have been derived considering the impact of change in system loading on bus voltage and angles. The effectiveness of the sensitivity factors, for placement of the UPFC, has been obtained on IEEE 14-bus and in terms of the enhancement of maximum load ability, utilizing an optimal power flow simulation.

II. PROPOSED METHOD FOR OPTIMAL LOCATION OF FACTS DEVICE

The real power mismatch (P_{is}) and reactive power mismatch (Q_{is}) at a bus-i can be expressed in terms of voltage magnitudes (V), voltage angles (δ), elements of bus admittance matrix (Y) and loading factor (λ), as

$$P_{is} = P_{Gi} + P_{iu} - (1+\lambda)P_{Di} - \mathrm{Re}\left(V_i \sum_{j=1}^{Nb} (V_j V_{ij})^*\right) \quad (1)$$

$$Q_{is} = Q_{Gi} + Q_{iu} - (1+\lambda)Q_{Di} - \mathrm{Im}\left(V_i \sum_{j=1}^{Nb} (V_j V_{ij})^*\right) \quad (2)$$

Where, P_{Gi} , Q_{Gi} are the real and reactive power generations at the bus-*i*, can be respectively. P_{iu} and Q_{iu} are the UPFC's real and reactive power injections at the bus-i, respectively. P_{Di} and Q_{Di} are the base case real and reactive power demands at the bus-*i*, respectively . N_b is the number of buses in the system. The real and reactive power loads at all the buses are assumed to be increased by a factor λ **.**

Equation (1) and (2), in presence of of an UPFC, will be function of bus voltage magnitude (V), voltage angles (λ), injected series voltage magnitude (V_s) and its angle (ϕ_s) and the loading factor (λ).

$$\left.\begin{aligned} P_{is} &= f_{pi}(V, \delta, \phi_s, V_s, \lambda) \\ Q_{is} &= f_{qi}(V, \delta, \phi_s, V_s, \lambda \end{aligned}\right\} \quad (3)$$

From Taylor's series expansion, equation (3) can be written as

$$\begin{bmatrix} \Delta f_p \\ \Delta f_q \end{bmatrix} = -[J] = \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} - [K\phi_s][\Delta\phi_s] - [K_{V_S}][\Delta V_s] - [L][\Delta\lambda] \quad (4)$$

$$[J] = \begin{bmatrix} \frac{\partial f_p}{\partial \delta} & \frac{\partial f_p}{\partial V} \\ \frac{\partial f_q}{\partial \delta} & \frac{\partial f_q}{\partial V} \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix}$$

$$[L] = \begin{bmatrix} \frac{\partial f_p}{\partial \lambda} \\ \frac{\partial f_q}{\partial \lambda} \end{bmatrix} = \begin{bmatrix} P_D \\ Q_D \end{bmatrix}$$

$$[K\phi_s] = \begin{bmatrix} \frac{\partial f_p}{V_s \partial \phi_s} \\ \frac{\partial f_q}{V_s \partial \phi_s} \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{V_s \partial \phi_s} \\ \frac{\partial Q}{V_s \partial \phi_s} \end{bmatrix}$$

$$[K_{V_S}] = \begin{bmatrix} \frac{\partial f_p}{V_s} \\ \frac{\partial f_q}{V_s} \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{V_s} \\ \frac{\partial Q}{V_s} \end{bmatrix}$$

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} \left[\Delta\delta_2\ \Delta\delta_3 .....\Delta\delta_i ...\Delta\delta_{N_b}\right]^T \\ \left[\Delta V_2\ \Delta V_3 .....\Delta V_i ...\Delta V_{N_b}\right]^T \end{bmatrix}$$

$[\Delta V_S] = [\Delta V_{si,j} .....]^T$ and $\forall\ i, j \in N_l$, represents injected voltage magnitude and phase angle vectors, respectively.N_l Is the total number of lines in the system.

The derivatives corresponding to the slack bus are not included in the above Jacobin matrix and shunt current I_q has been taken to be zero. The size of matrices **[*J*], [*K*]** and **[*L*]** are $(2N_b - 2) \times (2N_b - 2)$, $(2N_b - 2) \times (N_i)$ and $(2\mathrm{N_b} - 2) \times l$ respectively**.**

In equation (4), the change in load is assume to be met by the slack bus and can be written as

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = -[N_{\phi_s}][\Delta\phi_s] - [N_{V_s}][\Delta V_s] - [R][\Delta\lambda] \quad (5)$$

(3)

Where,

$$[N_{\phi_s}] = [J]^{-1}[K_{\phi_s}];\ [N_{V_s}] = [J]^{-1}[K_{V_s}]\ and\ [R] = [J]^{-1}[L]$$

The line real and reactive power flows vectors, P_m and Q_m can be represented in terms of voltage magnitudes, voltage angles and line reactance as

$$\left.\begin{aligned} P_m &= f^{\,p}(V, \delta, \varphi, V, \lambda) \\ Q_m &= f^{\,q}(V, \delta, \varphi, V, \lambda) \end{aligned}\right\} \quad (6)$$

From the Taylor's series expansion, equation (6) can be expressed as

$$[\Delta P_m] = [S_p]\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} + [T_{\phi_s}][\Delta\phi_s] + [T_{V_S}][\Delta V_s] - [P_m^{dc}][\Delta\lambda] \quad (7)$$

Where,

$$[S_p] = \begin{bmatrix} \frac{\partial P_m}{\partial \delta} & \frac{\partial P_m}{\partial V} \end{bmatrix};\ [[T_{\phi_s}] = \begin{bmatrix} \frac{\partial P_m}{V_s \partial \phi_s} \end{bmatrix};\ [T_{V_S}] = \begin{bmatrix} \frac{\partial P_m}{\partial V_s} \end{bmatrix};$$

$$P_m^{dc} = \frac{\partial P_m}{\partial \lambda} = \frac{\partial}{\partial \lambda}([S](1+\lambda)[P]) = [S][P]$$

The elements of matrix [S] relates line flow (P_m) with the bus power injections $P = P_G - P_D$ without UPFC. Eliminating voltage angle and voltage magnitude vectors in equation (7) by using equation (5), provides

$$[\Delta P_m] = [TW_{\phi_s}][V_s \Delta\phi_s] + [TW_{V_s}][\Delta V_s] - [Y_p][\Delta\lambda] \quad (8)$$

Where,

$$[TW_{\varphi s}] = \{[T_{\varphi s}] - [S_p][N_{\varphi s}]\};$$

$$[TW_{Vs}] = \{[T_{Vs}] - [S_p][N_{Vs}]\};$$

$$[Y_p] = [S_p][R] - [P_m^{dc}]$$

Equation (8) consist of two sensitivity factors , one with respect to the injected voltage magnitude and the second with respect o the injected voltage angle , considering the other terms constant, can be written as

$$\left[\frac{\Delta V_s}{\Delta\lambda}\right] = [TW_{V_s}]^{-1}\left\{\left[\frac{\Delta P_m}{\Delta\lambda}\right] + [Y_p]\right\} \quad (9)$$

$$\left[\frac{V_s \Delta\phi_s}{\Delta\lambda}\right] = [TW_{\phi_s}]^{-1}\left\{\left[\frac{\partial P_m}{\partial\lambda}\right] + [Y_p]\right\} \quad (10)$$

The sensitivity factors are derived as the change inline flow with respect to the system loading. The system loading sensitivity (considering line real power flow) with respect to the change in the injected voltage magnitude is expressed as

$$S_m^{V_s} = \left[\frac{\Delta\lambda}{\Delta V_s}\right] = \frac{1}{\left([TW_{V_s}]^{-1}\left\{\left[\frac{\Delta P_m}{\partial\lambda}\right] + [Y_p]\right\}\right)} \quad \forall m \in N1 \quad (11)$$

Similarly, the sensitivity factors corresponding to the injected voltage angle, at constant (V_s) is defined as

$$S_m^{\phi_s} = \left[\frac{\Delta\lambda}{V_s \Delta\phi_s}\right] = \frac{1}{\left([TW_{\phi_s}]^{-1}\left\{\left[\frac{\Delta P_m}{\partial\lambda}\right] + [Y_p]\right\}\right)} \quad \forall m \in N1 \quad (12)$$

Above sensitivity factors have been computed at different loading conditions with considering the load increment factor $\Delta\lambda$ =0.01 p.u. i.e., $S_k^{V_s}$ and $S_k^{\phi_s}$ are calculated at different loading, corresponding λ_k =[0.1,0.2,0.3,0.4,0.5…….. $\Delta\lambda$ ×*P*].The average value of the sensitivity factors at different loadings is obtained as

$$S^{V_s} = \frac{1}{p}\sum_{k=1}^{p} S_k^{V_s} \quad (13)$$

$$S^{\phi_s} = \frac{1}{p}\sum_{k=1}^{p} S_k^{\phi_s} \quad 14)$$

III. LINE CONTINGENCY RANKING

The relative severity of the system loading under normal and each of the contingency cases can be described by a line real power flow performance Index (PI) [10], as given below.

$$PI = \sum_{m=1}^{N_l} \frac{w_m}{2a}\left(\frac{P_m}{P_m^{\max}}\right)^{2a} \quad (15)$$

Where, P_m is the real power flow and $P_m^{\max}$ is rated capacity of line-*m*, *a* is an exponent and w_m is a real non negative weighting coefficient, which may be used to reflect the relative importance of the lines. The lack of discrimination, in which the performance index for a case with many small violations may be comparable in value to the index for a case with a few large violation, is known as *Masking effect*. By most of the operational standards, the system with few large violation is much more severe than that with many small violations, Masking effect, to some extent, can be avoided by using higher order performance indices (i.e. a>1). In this study, the value of exponent '*a*' has been taken as 2 and weighting coefficient ' w_m ' for all the lines as 1.0.

IV. OPTIMAL POWER FLOW WITH FACTS DEVICES

The effectiveness of the proposed sensitivity factor based approach for optimal placement of UPFC has been verified in terms of its impact on enhancing the maximum system loadability . While increasing the system loading, power factor at all load buses is assumed to remain constant. The problem to determine the system maximum loadability has been formulated as an OPF problem, as described below.

Maximize = $\sum \lambda$

Subject to the following constraints:

Equality constraints: Power balance equation corresponding to both the real and the reactive power s as defined in equation (1) and (2), must be satisfied.

Inequality constraints: These include the operating limits on various power system variables and the parameter of the UPFC as given below.

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\min} \quad (16)$$

$$V_i^{\min} \le V_i \le V_{gi}^{\max} \quad (17)$$

$$\delta_i^{\min} \le \delta_i \le \delta_i^{\max} \quad (18)$$

$$0 \le V_s \le V_s^{\max}; -\pi \le \phi_s \le \pi \quad (19)$$

Equation (16) represents the limits on the reactive power generations. The limit on the bus voltage magnitude and angle are given by equations (17) and (18), respectively. Equation (19) represents the limits on the UPFC (V_s, ϕ_s) parameters. The shunt current 'I_q' has taken zero in this work, as it has no significance impact on real power control because it is quadrature of sending end voltage.

The above OPF problem involves a nonlinear function and a set of nonlinear equality and inequality constraints. Many researchers used mixed integer nonlinear methods and sequential quadratic programming for OPF .We proposed Ant Colony Optimization nonlinear optimization technique for solving the OPF problem. In this work, ACO algorithm been used for solving the above OPF problem. ACO has been designed in separately in object oriented programming, Advanced java programming and XML parser for data wrapping for storage of persistence for designing graphical format.

A. Optimal Power Flow Using Ant Colony Optimization

In the ant colony optimization (ACO), a colony of artificial ants cooperates in finding good solutions to difficult optimization problems. Cooperation is a key design component of ACO algorithms. The choice is to allocate the computational resources to a set of relatively simple agents (artificial ants) that communicate indirectly by stigmergy. In [11-13] Good solutions are an emergent property of the agent's cooperative interaction. Artificial ants have a double nature. On the one hand, they are an abstraction of those behavioral traits of real ants which seemed to be at the heart of the shortest path finding behavior observed in real ant colonies. On the other hand, they have been enriched with some capabilities which do not find a natural counterpart. In fact, we want ant colony optimization to be an engineering approach to the design and implementation of software Systems for the solution of difficult optimization problems. It is therefore reasonable to give artificial ants some capabilities that, although not corresponding to any capacity of their real ant's counterparts, make them more effective and efficient

RSA is a contribution method to ACO algorithm, to insure that ACO program will converge to optimal solution at very short time. Without RSA, ACO may require more than 30 seconds computation time to find the optimal solution. This method is performed by running load flow program consisting of UPFC repeatedly, i.e. the UPFC voltage constant and angle are selected step by step within the range. And send to power system model.

The general algorithm ACO operators for the implementation of OPF. The process involves initialization, state transition rule, local updating rule, fitness evaluation and global updating rule.

Step 1: Initialization; during the initialization process *n*, *m*, t_{max}, d_{max}, β, ρ, α and *q0* are specified.

Where

n : no. of nodes

m : no. of ants

t_{max} : maximum iteration

d_{ma} : maximum distance for every ants tour

β : parameter, which determines the relative importance of pheromone versus instance ($\beta > 0$)

ρ : heuristically defined coefficient ($0 < \rho < 1$)

α : pheromone decay parameter ($0 < \alpha < 1$)

q_0 : parameter of the algorithm ($0 < q0 < 1$)

τ_0 : initial pheromone level

Every parameter requires to be set for limiting the search range in order to avoid large computation time.

d max can be calculated using the following formula:

$$d_{max} = \max\left[\sum_{i=1}^{n-1} d_i\right] \tag{20}$$

Where:

r : current node

u : unvisited node

d : distance between two nodes

Step 2**:** Generate first node randomly; the first node will be selected by generating a random number according to a uniform distribution, ranging from 1 to *n*.

Step 3**:** Apply state transition rule; in this step the ant located at node *r* (current node) will choose the nodes *s* (next node) based on the following rule.

$$s = \begin{cases} \arg\max_{u\in}\left\{[\tau(r,u).[\eta(r,u)^{\beta}]\right\}, \; if\ q \le q_0\ (\exp loration) \\ s,\ \ otherwise\,(biased\ \exp loration) \end{cases} \tag{21}$$

Where:

q : random number uniformly distributed in [0…1]

S : random variable selected according to the probability distribution given in equation (21)

The probability for an ant *k* at node *r* to choose the next node *s*, is calculated using the following equation

$$P_k(r,s) = \begin{cases} \dfrac{[\tau(r,s)].[\eta(r,s)^{\beta}]}{\sum_{u\varepsilon J_{k(r)}}[\tau(r,u)].[\eta(r,u)^{\beta}]}, \; if\ s\,\varepsilon\, J_{k(r)} \\ 0,\ \ otherwise \end{cases} \tag{22}$$

where

τ : Pheromone

$J_{k(r)}$: set of nodes that remain to be visited by ant *k* positioned on node (to make the solution feasible)

η 1/δ, is the inverse of the distance $\tau(r,s)$

Ants that have the highest fitness are chosen as "selected ants" (*m nodes)* and path visited by them are chosen for neighborhood search.

***Step 4*:** Apply local updating rule; while constructing a solution of UPFC optimization, ants visit edges and change their pheromone level by applying the local updating rule of equation (23)

$$\tau(r,s) \leftarrow (1-\rho)\,\tau(r,s) + \rho.\Delta\tau(r,s) \tag{23}$$

ρ : Heuristically defined coefficient ($0 < \rho < 1$)

$$\Delta\tau(r,s) = \tau_0$$

***Step 5*:** Determine tuned parameters; two variables (x1, x2) required to represent the UPFC parameters (i.e. UPFC voltage constant, Vs and angle, ϕ_s) and are selected within the specified ranges from RSA method.

***Step 6*:** Fitness evaluation; it is performed after all ants have completed their tours. In this step, the control variable is computed using the following equation

$$x = \frac{d}{d_{\max}} \times x_{\max} \tag{24}$$

Where:

d : Distance for every ants tour

$x_{\max}$: Maximum x

The values of *x* will be assigned for UPFC parameters. The fitness is computed by performing ac load flow program. This program is called repeatedly into the ACO main program for the whole process.

***Step 7*:** Apply global updating rule; to simplify the problem, this step is applied to edges belonging to the best ant tour which give the best fitness among all ants. The pheromone level is updated by applying the global updating rule in equation (25)

$$\tau(r,s) \leftarrow (1-\alpha)\,\tau(r,s) + \alpha.\Delta\tau(r,s)$$

Where,

$$\Delta(r,s) = \begin{cases} (L_{gb})^{-1},\ if\ (r,s)\ \varepsilon\ global - best\ tour \\ 0,\ otherwise \end{cases} \tag{25}$$

***Step 8*:** End condition; the algorithms stop the iteration when a maximum number of iterations have been performed otherwise, repeat step 3. Every tour that was visited by ants should be evaluated. If a better path is discovered in the process, it will be kept for next reference. The best path selected between all iterations engages the optimal scheduling solution to UPFC optimal parameters problem. The overall steps of the ACO algorithm can be represented in the flow chart of Figure 1

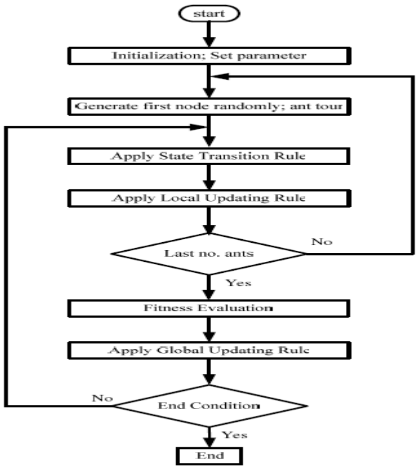

Figure1: Ant Colony Flow Chart

TABLE 1: LINE OUTAGE CONTINGENCY RANKING BASED ON PI VALUES IN14-BUS SYSTEMS

Rank order	**14-bus system**		
	Line outage	***End buses***	***PI value***
-	Base case	-	0.2678
1	8	1-2	1.6967
2	4	1-8	1.6271
3	7	9-8	0.4311
4	9	2-4	0.3317
5	6	4-9	0.3077
6	1	8-3	0.2901
7	16	3-13	0.2555
8	14	3-11	0.2601
9	18	10-11	0.2512
10	20	13-14	0.2516

V. SIMULATION RESULTS AND DISCUSSIONS

The proposed sensitivity approach for optimal placement of UPFC has been tested on IEEE14-bus system.

A. Line Outage Contingency Ranking

To obtain the critical contingency (line outage) ranking in the 14-bus system, the PI values, as defined in equations (5), are computed for each single line outage case and for different loading conditions, which are listed in Table1. For the 14-bus, ten most critical lines in order of relative sensitivity

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(descending order of the PI values) are given in Table1. It can be seen from Table.1 that the outage of line-8 in the 14 bus system is a most critical contingencies.

B. UPFC placement in IEEE 14-bus system

The sensitivity factors, as derived in equations (13) and (14), are calculated for all the lines and shown in Table 2. Although, the increase in system loading is assumed to be made by the slack bus generator, the formulation in general and sharing of the loads by other generators can be easily incorporated in the mismatch vector elements. The sensitivity factors are calculated at different loading conditions and the final sensitivities are shown as average of the sensitivity factors calculated at different loading values. The maximum loading factor as shown in Table.2 are obtained through OPF solutions by placing UPFC in each line, taken one at time.

TABLE 2: SENSITIVITY FACTORS (S^{V_s}) AND LOADABILITY MARGIN IN 14-BUS SYSTEM

Rank order	Line no.	Buses i-j	Sensitivity factors (S^{V_s})	OPF result s by varying V_s (pu) only		OPF result by varying both V_s (pu) and ϕ_s (rad)		
				λ	V_s	λ	V_s	ϕ_s
1	4	1-8	0.8071	0.8119	0.4437	0.9280	0.5000	0.5312
2	9	2-4	0.4890	0.7112	0.3545	0.7774	0.5000	0.7091
3	11	2-9	0.2519	0.7141	0.4137	0.7546	0.5000	0.5650
4	5	8-2	0.1911	0.6903	0.5000	0.7021	0.5000	0.4605
5	12	7-6	0.1712	0.6246	0.1282	0.6767	0.5000	0.9483

The maximum loading factor as defined in equations (16) is found to be 0.5312without UPFC at the base case loading. The maximum and minimum voltage limits at all the buses, with fixed value of slack bus voltage, are taken as 1.1 pu and 0.9pu, respectively. Table.2 also shows that the value of the sensitivity factor S^{V_s} is the highest for line-4 followed by line-9,11and 12, respectively. The corresponding system loading factor λ after placement of an UPFC in these lines, is given in the 5th column of the table with the limit on the series injected voltage of the UPFC magnitude set at $V_s^{\max}$ =0.50pu

TABLE 3: SENSITIVITY FACTORS (S^{ϕ_s}) AND LOADABILITY MARGIN IN 14- BUS SYSTEM

Rank order	Line no.	Buses i-j	Sensitivit y factors S^{ϕ_s}	OPF results by varying ϕ_s (rad) only		OPF results by varying both V_s (pu) and ϕ_s (rad)		
				λ	ϕ_s	λ	V_s	ϕ_s
1	4	1-8	0.1923	0.5423	0.1160	0.9280	0.5000	0.5190
2	9	2-4	0.1420	0.5354	0.2320	0.7774	0.5000	0.7101
3	11	2-9	0.1056	0.5386	-.0710	0.7546	0.5000	0.5671
4	5	8-2	0.0700	0.5371	-.1100	0.7021	0.5000	0.4503
5	6	9-4	0.0578	0.5329	-.4275	0.5688	0.5000	-1.7136

The value of the sensitivity factors S^{ϕ_s} corresponding to the change in loading factor with respect to the change in series phase angle of the UPFC as shown in Table.3, has the highest absolute value for line-4 followed by lines-9,11,5and 6 ,respectively .The corresponding system loading factor (λ), after placement of an UPFC in these lines, is shown in column 7 assuming constant voltage magnitude injection by UPFC (V_s =0.01pu) and variables angle injection with limiting value of $\pm\pi$ radian

From Table 3, it can be seen that the enhancement in the load ability factor s higher with the UPFC placed in line-4, as compared to the placement in line-9. However, the difference in the loading factor is very small. A final placement 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 in this work . The voltage profile of the system at maximum loading point is shown in Figure 1. The voltage profile of the system is better, when the UPFC PLACED in line-4, as compared to its placement in other lines. Thus, from the Tables 2, 3 and Figure 2, the best location for the placement of the UPFC is in line-4 in the 14-bus system.

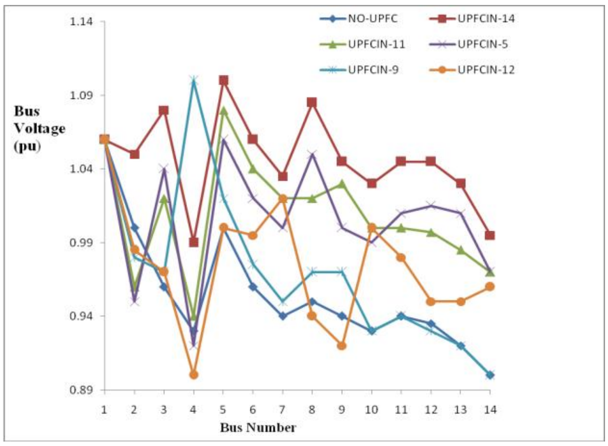

Figure 2: Bus voltage profile with placement of UPFC on IEEE-14 bus

The impact of critical line outage (line-4) on optimal UPFC location is shown in Table 3and 4 for the 14-bus system. Since system configuration is changed due to line outage, the rank order for placement of UPFC also has changed. The optimal location for given case only, however the system load ability for outage of lines-4 and 7 are respectively, without UPFC. In view of the maximum load ability enhancement.

TABLE 4: SENSITIVITY FACTORS (S^{V_s}) AND LOADABILITY MARGIN IN 14-BUS WITHOUTAGE OF LINE-4

Rank order	Line no.	Buses i-j	Sensitivity Factor (S^{V_s})	OPF results by varying V_s (pu) only		OPF results by varying both V_s and ϕ_s (rad)		
				λ	V_s	λ	V_s	ϕ_s
1	4	1-8	0.8769	-	-	-	-	-
2	9	2-4	0.5767	0.2963	0.1149	0.3211	0.5000	-1.5678
3	11	2-9	0.2601	0.3448	0.1075	0.3999	0.5000	0.6783
4	5	8-2	0.1811	0.3036	0.0481	0.3046	0.5070	-1.0211
5	12	7-6	0.1511	-	-	0.2993	0.5000	-1.9601

TABLE 5: SENSITIVITY FACTORS (S^{φ_s})AND LOADABILITY MARGIN IN 14-BUS SYSTEM WITH OUTAGE OFLINE-4

Rank order	Line no.	Buses i-j	Sensitivity factors (S^{ϕ_s})	OPF results by varying ϕ_s (rad) only		OPF results by varying both V_s (pu) and ϕ_s (rad)		
				λ	ϕ_s	λ	V_s	ϕ_s
1	4	1-8	0.1872	-	-	-	-	-
2	9	2-4	0.1529	0.2864	-0.5019	0.3169	0.5000	-1.5578
3	11	2-9	0.1042	0.2961	-0.1825	0.3984	0.5000	0.6683
4	5	8-2	0.0729	0.2921	-0.3401	0.3039	0.0570	-1.0199
5	6	9-4	0.0474	0.2867	1.1682	0.3017	0.2332	1.4675

TABLE 6: SENSITIVITY FACTORS (S^{V_s}) AND LOADABILITY MARGIN IN 14-BUS SYSTEM WITH OUTAGE OF LINE -7

Rank order	Line no.	Buses i-j	Sensitivity factors (S^{V_s})	OPF results by varying V_s (pu) only		OPF results by varying both V_s (pu) and ϕ_s (rad)		
				λ	V_s	λ	V_s	ϕ_s
1	4	1-8	0.7669	0.5957	0.2940	0.5615	.3054	3.1416
2	9	2-4	0.4767	0.6248	0.3398	0.7279	0.5000	0.6849
3	11	2-9	0.2419	0.4509	0.3098	0.7512	0.5000	0.6553
4	5	8-2	0.1711	0.4444	0.0926	0.4464	0.1821	-1.3884
5	12	7-6	0.1401	0.4509	0.0460	0.4766	0.5000	1.2513

TABLE 7: SENSITIVITY FACTORS (S^{φ_s}) AND LOADABILTY MARGIN IN 14 BUS SYSTEM WITH OUTAGE OF LINE -7

Rank order	Line no.	Buses i-j	Sensitivity factors (S^{ϕ_s})	OPF result by varying ϕ_s (rad) only		OPF results by varying both V_s (pu) and ϕ_s (rad)		
				λ	ϕ_s	λ	V_s	ϕ_s
1	4	1-8	0.1872	0.4229	-0.0251	0.5615	0.3054	3.1416
2	9	2-4	0.1529	0.4209	0.2241	0.7279	0.5000	.6849
3	11	2-9	0.1042	0.4251	0.0156	0.7512	0.5000	0.6553
4	5	8-2	0.0729	0.4172	-0.3417	0.4464	0.1821	-1.3884
5	6	9-4	0.0474	0.4176	-0.2459	0.4210	0.0377	3.1416

VI. CONCLUSIONS

A new set of AC power flow based sensitivity indices has been developed , in terms of change in the system load ability with respect to change in UPFC series optimal control parameters, for the optimal placement of UPFC by using ACO approaches . Two set of sensitivity factors have been defined with respect to the series injected voltage magnitude and phase angle parameters of the UPFC the optimal location of UPFC has been decided considering different loading conditions as well. An OPF formulation has been developed; with maximization of the system load ability as an objective on the IEEE 14-bus are the following.

- With the optimal placement of UPFC in a line, based on the proposed system loading sensitivity factors, the system loading margin increases considerably in both the test Systems. It also improves s the system voltage profile.
- The rank order of the lines, Obtained for the optimal placement of the UPFC, is validated through OPF results in terms of relative load ability margin enhancement with the placement of the UPFC. The high ranked lines for the UPFC placement have resulted in greater enhancement of the system loading margin in both the system.
- The optimal placement of the UPFC, based on the proposed sensitivity factors, is also valid under contingency condition s in both IEEE 14- bus systems.

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