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Application of UPFC for enhancement of voltage profile and minimization of losses using Fast Voltage Stability Index (FVSI)

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Abstract: Transmission line loss minimization in a power system is an important research issue and it can be achieved by means of reactive power compensation. The unscheduled increment of load in a power system has driven the system to experience stressed conditions. This phenomenon has also led to voltage profile depreciation below the acceptable secure limit. The significance and use of Flexible AC Transmission System (FACTS) devices and capacitor placement is in order to alleviate the voltage profile decay problem. The optimal value of compensating devices requires proper optimization technique, able to search the optimal solution with less computational burden. This paper presents a technique to provide simultaneous or individual controls of basic system parameter like transmission voltage, impedance and phase angle, thereby controlling the transmitted power using Unified Power Flow Controller (UPFC) based on Bacterial Foraging (BF) algorithm. Voltage stability level of the system is defined on the Fast Voltage Stability Index (FVSI) of the lines. The IEEE 14-bus system is used as the test system to demonstrate the applicability and efficiency of the proposed system. The test result showed that the location of UPFC improves the voltage profile and also minimize the real power loss.

Key words: Flexible AC Transmission Systems (FACTS), real and reactive power, Unified Power Flow Controller (UPFC), Bacterial Foraging (BF) algorithm

1. Introduction

Most large power system blackouts, which occurred worldwide over the last twenty years, are caused by heavily stressed system with large amount of real and reactive power demand and low voltage condition. When the voltages at the system buses are low, the losses will also be increased. This study is devoted to develop a technique for improving the voltage and minimizing the loss and hence eliminate voltage instability in a power system [1]. Thyristor-Controlled Series Capacitors (TCSC), Thyristor Controlled Phase Shifting Transformer (TCPST) and Static Var Compensator (SVC) can maintain voltage in the power system and, therefore, can control the active power through a transmission line [2, 16]. On the other hand UPFC has a series voltage source and a shunt voltage source, allowing independent control of the voltage magnitude, and the real and reactive power flows along a given transmission line [3-8, 11, 12]. The UPFC was proposed for real time control and dynamic compensation of AC transmission systems, providing the necessary functional flexibility required to solve many of the problems which are being facet by the industry. Many advantages in power system operation and planning can be immediately realized by achieving the function of globally regulating the power flows and simultaneously supporting the bus voltages. Such advantages include the minimization of system losses, elimination of line over loads and low voltage profiles. Recently, the success achieved by Evolutionary Computation (EC) in the solution of complex problems and the improvement made in computation such as parallel computation like Differential Evolution (DE) [20], Particle Swarm Optimization (PSO) [21], Ant Colony Optimization (ACO), and multi agent PSO are some of the heuristic techniques having great converge characteristics and capability of determining global optima. Nur Dianah Mohd.Radzi et. al [22] proposed a technique to voltage profile improvement based on Artificial Immune System (AIS) using UPFC. Seyed Abbas Taher and Seyed Mohammad Hadi Tabi [23] proposed an application of HPSO to solve the optimal location of UPFC problems in restructured power systems for considering system loadability and the overall cost function.

The voltage stability assessment is analyzed using Fast Voltage Stability Index (FVSI) approach. FVSI gives a scalar number to each line of the system. This index ranges from zero (no load system) to one (voltage collapse). Thus the line with the highest FVSI value will be critical line and the load bus connected in the line will be vulnerable bus in the system [18, 19]. Hence this method helps in identifying the weak load buses in the system which needs critical reactive power support. This paper uses minimization of FVSI of the system as one of the objectives of the optimization problem.

Bacterial Foraging algorithm is proposed in this paper to find the optimal rating, location of UPFC and also to minimize the losses and voltage profile improvement. The Bacterial Foraging algorithm is a computational intelligence based technique that is not largely affected by the size and nonlinearity of the problem and can converge to the optimal solution in many problems where most analytical methods fail to converge. The bacterial foraging based FVSI is calculated in each step after performing Newton-Raphson (N-R) load flow study. The BF based FVSI clearly indicates the location and status of critical line. The proposed algorithm has been tested on IEEE 14-bus reliability test system. A load flow program written in MATLAB using bacterial foraging technique was used to compute power flow. The test results show that the location and sizing of the UPFC identified by the proposed technique improves voltage level of the system and also minimize the losses. For practical and economic considerations, the number of UPFC units is limited to one. Here UPFC is connected in between buses 5 and 6 (line 18) in IEEE 14-bus system.

This paper is organized as follows: Problem formulation is given in Section 2. Bacterial Foraging algorithm for proposed method is given in Section 3. Results and discussion are given in Section 4 and the conclusion is drawn in Section 5.

2. Problem formulation

The objective function of this paper is to find the optimal rating and design of UPFC which minimizes the real power loss, voltage deviation and FVSI. This is mathematically stated as [10, 11, 14, 18]:

Minimize

$$F = [f_1, f_2, f_3]. \tag{1}$$

The first term f_1 represents real power loss as [10, 14]

$$f_1 = \sum_{k \in Nl} g_k \left(V_i^2 + V_j^2 - 2V_i V_j \cos\theta_{ij} \right) = P_{loss}^l. \tag{2}$$

The second term f_2 represents the total voltage deviation (VD) of all load buses from desired value of 1 p.u.

$$f_2 = VD = \sum_{k=1}^{N_{PQ}} \left(V_k - Vref_k \right)^2. \tag{3}$$

The last term f_3 is the Fast Voltage Stability Index (FVSI) of the line *ij* and is given by [20]

$$f_3 = FVSI_{ij} = \frac{4Z^2 Q_j}{V_i^2 X_{ij}}, \tag{4}$$

where: Z – line impedance, X_{ij} – line reactance, Q_j – reactive power at the receiving end, V_i – sending end voltage.

The minimization problem is subject to the following equality and inequality Constraints:

(i) Power Flow Constraints with UPFC Device:

$$P_i - V_i \sum_{j=1}^{Ng} V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) = 0, \; i = 1, 2, \ldots, N_B - 1. \tag{5}$$

$$Q_i - V_i \sum V_j \left(G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij} \right) = 0, \; i = 1, 2, \ldots, N_{PQ} - 1. \tag{6}$$

$$P_{ij} - V_i^2 \, G_{ij} + V_i \, V_j \, G_{ij} \cos(\delta_i - \delta_j) + V_i \, V_j \, B_{ij} \sin(\delta_i - \delta_j) = 0. \tag{7}$$

$$Q_{iij} + V_i^2 \left(B_{ij} + B_{sh} \right) + V_i \, V_j \, G_{ij} \sin(\delta_i - \delta_j) - V_i \, V_j \, B_{ij} \cos(\delta_i - \delta_j) = 0. \tag{8}$$

(ii) Voltage Constraints:

$$V_i^{\min} \le V_i \le V_i^{\max}; \, i \in N_B. \tag{9}$$

(iii) Reactive Power Generation Limit:

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max}; \quad i \in N_g. \tag{10}$$

(iv) Reactive Power Generation Limit of capacitor banks:

$$Q_{ci}^{\min} \le Q_{ci} \le Q_{ci}^{\max}; \quad i \in N_c. \tag{11}$$

(v) Transformer tap setting limit:

$$t_k^{\min} \le t_k \le t_k^{\max}; \quad k \in N_t. \tag{12}$$

(vi) Transmission line flow limit:

$$S_i \le S_i^{\max}; \; i \in N_l \tag{13}$$

(vii) For series compensation:

$$-0.8 \; \mathrm{X_L} \le \mathrm{X} \le 0.2 \; \mathrm{X_L} \text{ p.u.} \tag{14}$$

(viii) For shunt compensation:

$$-100 \text{ MVAR} \le \mathrm{Q} \le 100 \text{ MVAR} \tag{15}$$

(ix) For both series and shunt compensations (UPFC)

$$\text{Equations (14) and (15) for UPFC,} \tag{16}$$

where: t_k – transformer tap setting, V_i – load bus voltage, B_{sh} – suceptance value of shunt compensation, B_{ij} – susceptance value of the line, Q_{ci} – reactive power generation of capacitor bank, Q_{gi} – reactive power generation, S_i – line flow.

The equality constraints given by Equations (7) and (8) are satisfied by running the Newton Raphson Power flow algorithm based on the bacterial foraging optimization technique. Transformer tap settings (t_k) and the reactive power generation of capacitor bank (Q_{ci}) are the optimization variables and self restricted between the minimum and maximum by the bacterial foraging optimization algorithm. The limit on reactive power generation (Q_{gi}), Load bus voltage(v_i) and line flow (S_i) are state variables which is used to minimize the real power loss, voltage deviation and FVSI.

3. Bacterial foraging algorithm for the proposed method

Foraging theory is based on the assumption that animals search for nutrients which maximizes their energy intake (E) per unit time (T) spent for foraging [9]. The E.coli bacterium is probably the best understood micro organism. Mutation in E.coli occurs at a rate of about 10^{-7} per gene, per generation and can affect its physiological aspects. The E.coli bacterium has a control system that enables it to search for food and avoid noxious substance. To find the minimum of $J(\theta)$, $\theta \in R^p$ where there is no measurements or analytical description of the gradient $\nabla J(\theta)$. θ is the position of a bacterium and $J(\theta)$. represents the combined effects of attractants and repellents from the environment, for example $J(\theta) < 0$, $J(\theta) = 0$ and $J(\theta) > 0$ representing that the bacterium at location θ is nutrient-rich, neutral and noxious environments respectively.

Basically chemotaxis is a foraging behavior that implements a type of optimization where bacteria try to climb up to the nutrient concentration, avoid noxious substance and search for ways out of neutral media. It implements a type of biased random walk, which defines a chemotactic step, be a tumble followed by another tumble or by a run.

Let j be the index for the chemotactic step, k be the index for the reproduction step and l be the index of the elimination-dispersal event.

Let

$$P(j, k, l) = \left\{\theta^i(j, k, l) i = 1, 2, \ldots, S\right\}. \tag{16}$$

The Equation (16) represents the position of each member in the population of the S bacteria, at the j^{th} chemotactic step, k^{th} reproduction step and l^{th} elimination dispersal event.

Let N_c be the length of the life time of the bacteria as measured by the number of chemotactic steps taken during their life. Let $C(i) > 0$, $i = 1, 2, \ldots.$ S denotes a basic chemotactic step size, that is used to define the lengths of steps during runs. To represent a tumble, the unit length random direction say $\phi(j)$ is generated. This will be used to define the direction of movement after a tumble. This swim is continued as long as it continues to reduce the loss, but only up to a maximum number of steps, Ns. This represents that the cell will tend to keep moving if it is headed in the direction of increasingly favourable environments. After N_c chemotactic steps, a reproduction step is taken.

Let N_{re} be the number of reproduction steps to be taken. For reproduction the population is sorted in order that the least healthy bacteria die and the healthiest bacteria each split into two bacteria which are placed at the same location. This method rewards bacteria that have encountered a lot of nutrients and this allows it to keep a constant population size which is convenient in coding the algorithm.

Let N_{ed} be the number of elimination-dispersal events and for each elimination-dispersal event each bacterium in the population is subject to elimination-dispersal with probability P_{ed}. Assume that the frequency of chemotactic steps is greater than the frequency of reproduction steps, which is in turn greater in frequency than elimination-dispersal events.

3.1. Algorithm

Step 1. Initialize the parameters p, S, N_c, N_s, N_{re}, N_{ed}, P_{ed} and the $C(i)$, (i = 1, 2, ..., S). Choose the initial value for the θ^i, $i = 1, 2, \ldots, S$. These must be done in areas where an optimum value is likely to exist. Here θ is the control variable and is randomly distributed across the domain of the optimization space. After computation of θ is completed, the value of P is updated automatically and termination test is done for maximum number of specified iterations.

Step 2. Elimination-Dispersal loop: $l = l + 1$.

Step 3. Reproduction loop: $k = k + 1$.

Step 4. Chemotaxis loop: $j = j + 1$

(i) for $i = 1, 2, \ldots, S$ take a chemotactic step for bacterium 'i' as follows:

(ii) compute $J(i, j, k, l)$,

(iii) let $J(i, j, k, l) = J(i, j, k, l) + J_{cc}(\theta^i\ (j, k, l), P(j, k, l)$,

(iv) let $J_{last} = J(i, j, k, l)$ to save this value since find better solution via a run

(v) tumble: generate a random vector $\Delta(i) \in R^p$ with each element $\Delta_m(i)$, $m = 1, 2, \ldots, p$ a random number

(vi) Move let $\theta^i(j + 1, k, l) = \theta^i\ (j, k, l) + C(i)$, this results in a step of size $C(i)$ in a direction of the tumble for bacterium i

(vii) Compute $J(i, j + 1, k, l)$; the load flow analysis using N-R method is carried out; the values of FVSI index and real power loss are calculated; if the loss is minimum, then next step can be carried out else go to step (iii)

(viii) Swim.

(a) Let $m = 0$ (counter for swim length).

(b) While $m < N_s$, let $m = m + 1$.

If $J(i, j, k, l) < J_{\text{last}}$ (if there is improvement), let $J_{\text{last}} = J(i, j, k, l)$ and let $\theta^i(j + 1, k, l) = \theta^i(j + 1, k, l) + C(i)$ and use this $\theta^i\ (j + 1, k, l)$ to compute the new $J(j + 1, k, l)$. Else, let $m = N_s$. End of while statement

(ix) Go to next bacterium (i+1) if $i \neq S$

Step 5. If $j < N_c$ go to step 3. In this case, continue chemotaxis, since the life of the bacteria is not over.

Step 6. Reproduction

(a) for the given k and l, and for each $i = 1, 2, \ldots, S$, let

$$J^i_{\text{health}} = \sum_{j=1}^{Nc+1} J(i, j, k, l)$$

be the health of bacterium i. Sort bacteria and chemotactic parameter $C(i)$ in order of ascending value of J_{health}

(b)The S_r bacterium with the highest Jhealth values die and the other S_r bacteria with the best values split.

Step 7. If $k < N_{re}$, go to step 2. In this case we have not reached the number of specified reproduction steps.

Step 8. Elimination-Dispersal. For $i = 1, 2, \ldots, S$ with probability P_{ed}, eliminate and disperse each bacterium. Eliminate a bacterium and disperse one to a random location on the optimization domain. If $l < N_{ed}$, then go to step 1, otherwise end.

The FVSI, real power loss and bus voltages are also obtained separately. The flowchart for the proposed algorithm is shown in Fig. 1. The control parameters of the bacterial foraging algorithm are given in Table 1.

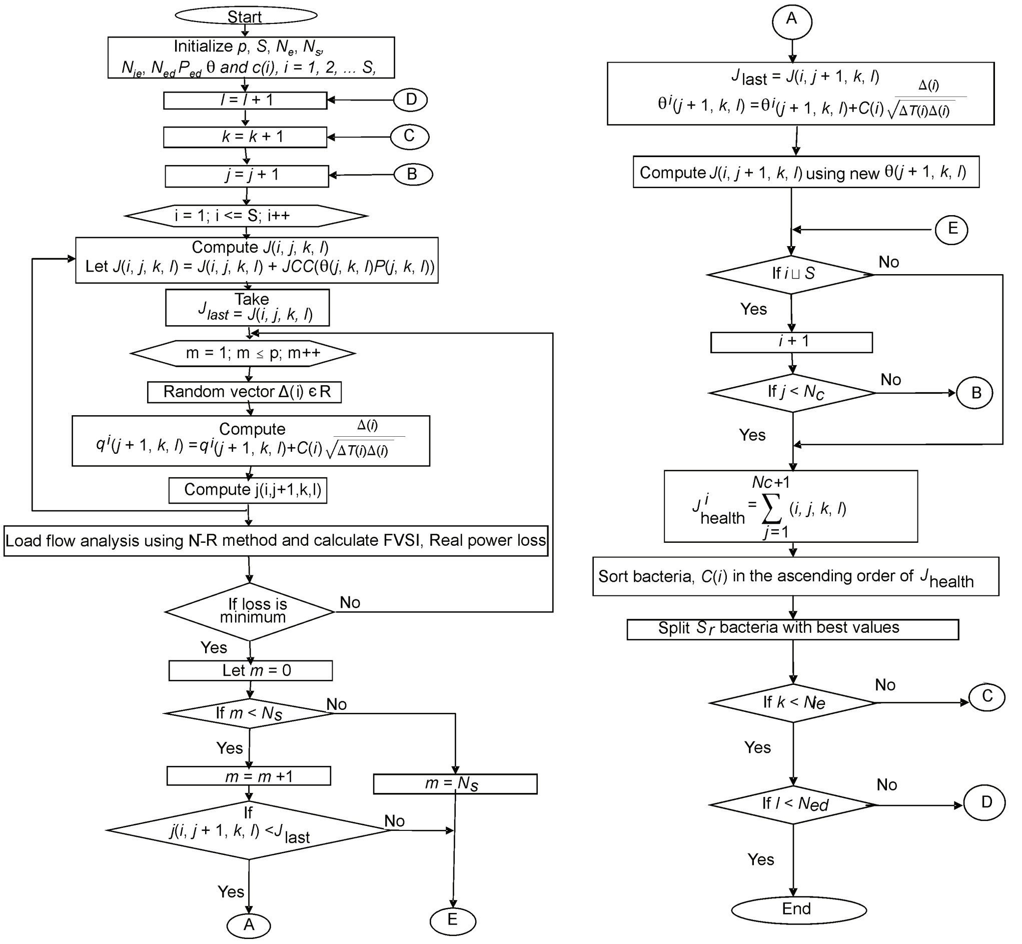

Fig. 1. Flowchart for the proposed algorithm

Table1. Control parameters of the bacterial foraging algorithm [9]

Sl. No	Parameters	Values
1	Number of bacteria, S	50
2	Maximum number of steps, N_s	4
3	Number of chemotactic steps, N_c	100
4	Number of reproduction steps, N_{re}	4
5	Number of elimination-disperse steps, N_{ed}	2
6	Probability, P_{ed}	0.25
7	Size of the step, $C(i)$	0.1

4. Results and discussion

The program for the Bacterial foraging algorithm used in this study were written in Matlab 7.0 on Pentium IV, 3 GHz, 512 MB RAM processor and used to perform the optimization routines with IEEE 14-bus system. System data and results are based on 100 MVA and bus 1 is the reference bus. In order to verify the presented models and illustrate the impacts of UPFC study, two cases for test systems are considered.

Case 1: results of optimal power flow without UPFC and with one UPFC for the base case (i.e. light load).

Case 2: results of optimal power flow without UPFC and with one UPFC for the critical case (i.e. heavy load-whose loads and initial power generations are twice as those of case 1).

The aim of case 2 is to minimize the real power loss with optimal placement of UPFC in weakest line. For practical and economic considerations, the number of UPFC units is limited to one [17]. The impedance of line with UPFC (0.2440 p.u) is connected between buses 5 and 6 (in IEEE 14-bus system) to perform the test for the normal and critical cases. The IEEE 14-bus system which consists of five generator buses (bus 1 is slack bus 2, 3, 6 and 8 are PV buses), 9 load buses and 20 lines (4-7, 4-9 and 5-6) in which three lines are with the tap changing transformers. The line parameters and loads are taken from [21]. Table 2 gives the control variables for the test system. The initial transmission line loss is 13.46 MW for the base case (i.e light load). For critical case, the initial transmission loss is 60.21 MW (Table 4).

Table 2. Control variables for IEEE 14-bus system

Test case	Variables	Minimum (p.u)	Maximum (p.u)
14 bus system	Voltage	0.95	1.10
	X	−0.8 Xline	0.2 Xline
	Q	−1.0	1.0

Table 3 shows the Fast voltage stability Index (FVSI) values of each line of IEEE 14-bus system. Table 4 shows the line losses of IEEE 14 bus system before and after placing UPFC for the two cases (normal load and critical load). Figure 2 shows the Fast Voltage stability Index (FVSI) value variations of IEEE 14-bus system for normal case. Figure 3 shows the Fast Voltage stability Index (FVSI) value variations of IEEE 14-bus system for critical case. From the test results, it is clearly shown that the system voltage magnitudes have been improved; losses and Fast Voltage Stability Index (FVSI) values are reduced with inclusion of UPFC in weakest line. Table 5 shows the voltage improvement of load buses.

Using Newton Raphson Method, the highest value of FVSI is obtained for line 18 of IEEE 14-bus system. Hence line 18 is considered as critical line. In this work, UPFC is placed in between buses 5 and 6 which is connected in the weakest line (line 18) to perform the test for the base and critical cases. On placing line UPFC in line 18 (between buses 5 and 6) FVSI value is decreased from 0.4377 to 0.4251 (for normal case) and it is decreased from 1.0241 to 0.4962 (for critical case) (refer Table 3).

Table 3. FVSI values of each line of IEEE 14-bus system

Line No	FVSI values			
	normal case		critical case	
	before placing UPFC	after placing UPFC	before placing UPFC	after placing UPFC
1	0.0475	0.0475	0.3096	0.3096
2	0.0143	0.0143	0.0285	0.0285
3	0.0060	0.0060	0.5604	0.5604
4	0.0292	0.0292	0.0584	0.0584
5	0.0118	0.0118	0.0236	0.0236
6	0.0305	0.0305	0.0609	0.0609
7	0.0029	0.0029	0.0060	0.0060
8	0.0164	0.0164	0.0329	0.0329
9	0.0188	0.0188	0.0377	0.0377
10	0.0355	0.0355	0.0711	0.0711
11	0.0149	0.0149	0.0312	0.0312
12	0.0314	0.0314	0.0659	0.0659
13	0.0159	0.0159	0.0333	0.0333
14	0.0980	0.0980	0.2000	0.2000
15	0.0290	0.0290	0.0598	0.0598
16	0.0000	0.0000	0.0000	0.0000
17	0.3605	0.3605	0.7502	0.7502
18	0.4377	0.4251	1.0241	0.4962
19	0.1829	0.1829	0.3348	0.3348
20	0.0698	0.0698	0.1443	0.1443

Table 4. Real power loss for normal and critical cases

Real power loss			
normal case		critical case	
before placing UPFC	after placing UPFC	before placing UPFC	after placing UPFC
13.46 MW	13.20 MW	60.21 MW	58.02 MW

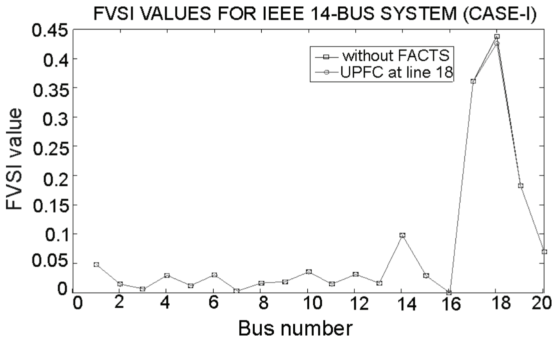

Fig. 2. Line number Vs FVSI values of IEEE 14-bus system (Case-I)

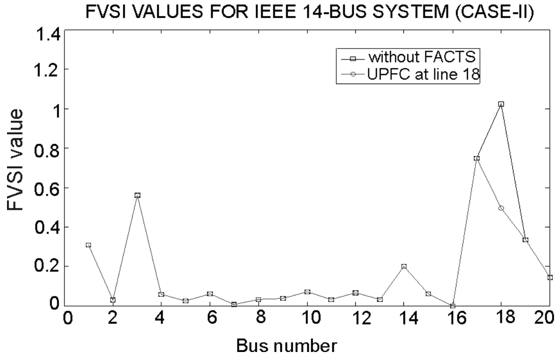

Fig. 3. Line number Vs FVSI values of IEEE 14-bus system (Case-II)

Table 5. Voltage magnitudes of the proposed system

Bus No.	Voltage			
	Case 1(base load)		Case 2 (critical load)	
	before placing UPFC	after placing UPFC	before placing UPFC	after placing UPFC
1	1.0600	1.0600	1.0600	1.0600
2	1.0450	1.0450	1.0450	1.0450
3	1.0100	1.0100	1.0100	1.0100
4	1.0190	1.0246	0.9846	0.9968
5	1.0190	1.0321	0.9035	0.9971
6	1.0200	1.0200	1.0200	1.0200
7	1.0438	1.0461	1.0113	1.0123
8	1.0400	1.0400	1.0400	1.0400
9	1.0313	1.0313	0.9801	0.9836
10	1.0268	1.0301	0.9778	0.9818
11	1.0463	1.0509	1.0178	1.0181
12	1.0512	1.0512	1.0302	1.0302
13	1.0429	1.0429	1.0177	1.0117
14	1.0169	1.0288	0.9522	0.9802

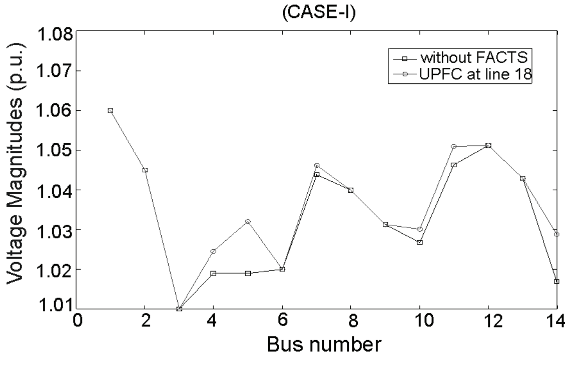

Fig. 4. Bus number Vs voltage values of IEEE 14-bus system (Case-I)

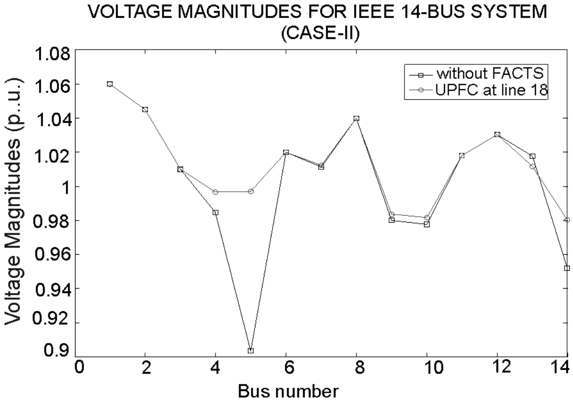

Fig. 5. Bus number Vs voltage values of IEEE 14-bus system (Case-II)

For critical case, the system voltages get reduced below the minimum limit. The voltage of the load bus (bus 5) connected in line 18 during critical load is 0.9035 (below the critical value of 0.9500) (see Fig. 4). When the UPFC is placed in line 18, the voltage gets improved to 0.9971 (see Fig. 5). Also, on placing of UPFC between buses 5 and 6, the line losses get decreased from 60.21 MW to 58.02 MW for the critical case. With regard to IEEE 14 bus system, BF obtains 2.33 % loss reduction compared to the value reported in [23] for the same test system. This shows the effectiveness of the proposed approach in minimizing the transmission line losses and voltage profile improvement simultaneously.

5. Conclusion

This paper made an attempt to find the optimal location of UPFC device for minimizing the losses and voltage profile improvement which are taken as objective functions using Bacterial Foraging algorithm. Results are presented for IEEE 14-bus system. The proposed algorithm used in this study is written in MATLAB software. The test results show that the particle swarm optimization technique is able to improve voltage profile along with minimization of losses in the system. The power loss occurring in the various branches and voltage magnitudes of IEEE 14-bus system are evaluated using Bacterial Foraging based power flow analysis. From the results it is concluded that the system performs better when the UPFC is connected. The voltage magnitudes are improved and the transmission line losses are minimized than the results reported in the literature.

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