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Dynamic Analysis of Power Loss Minimization and Voltage Profile Enhancement Using UPFC Device with Differential Evolution Algorithm

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ABSTRACT

Unified Power Flow Controller (UPFC) is a versatile FACTS device which can provide full dynamic control of a transmission line parameters, bus voltage, line impedance and phase angle for improved system security. However, the extent that performance of UPFC can be brought out, it greatly dependent upon the location and size of this device in the system. This paper present Differential Evolution (DE) Technique for optimal placement of UPFC device under steady state (i.e normal, moderate and critical) conditions and is aimed at real power loss minimization and voltage profile enhancement of an interconnected power system. The proposed method is applied on the IEEE 14 bus power system which is demonstrated through MATPOWER simulation package. The results obtained indicate that DE is robust and can significantly enhance the security of power system by reducing line losses and improved bus voltage profile within the acceptable limit.

Key words: Flexible AC Transmission System (FACTS); Unified Power Flow Controller (UPFC); Differential Evolution (DE)

INTRODUCTION

A power system is a complex network comprising of numerous generators, transmission lines, variety of loads, switches, active or passive compensators and transformers. So in practice, such a network is prone to disturbances. As a consequence of increasing power demand, some transmission lines are more loaded than was planned when they were built. As the volume of power transmitted and distributed increases, so do the requirement for high quality and reliable supply. At the same time, the construction of new generating units and transmission circuits becomes more difficult because of economic (rising cost) and growing environmental concerns. Therefore, power utilities are compelled to maximize the use of their available resources. Moreover, the continued demand in electric power system network has caused the system network to be heavily loaded leading to huge power losses and voltage instability. These and host of other factors make the process of building new power transmission and distribution lines increasingly complicated and time consuming. These situations have therefore called for comprehensive analysis to evaluate the present power system performance and investigate the effectiveness of new devices for improved system security and reliability.

FACTS devices are generally known as such new devices emanating from recent innovative technologies that promise to enhance security, capacity and flexibility of an existing power transmission system while maintaining the operating margins necessary for grid stability [1]. As a result, more power can reach consumers with a minimal impact on the environment and at a lower investment cost when compared to the alternative of building new transmission lines. FACTS are used for dynamic control of voltage, Impedance and phase angle of high voltage transmission lines, [2-3]. Other broader benefit of FACTS devices can be found in [4-5].

However, to achieve such functionality of UPFC, it is highly important to determine the optimal location of this device in the power system. The following are some factors that can be considered in the selection of the optimal location of UPFC: The stability margin improvement, the power transmission capacity increasing, and the power blackout prevention; Therefore, conventional power flow algorithm should consider one, two, or all of the above-mentioned factors [6]. However, in this paper, we only consider power transmission capacity increasing, in other words, enhancing the security of power system under steady state stability condition by improving transmission capacity through installing UPFC in an optimal location.

Steady state stability of a power system refers to the ability of the power system to regain synchronism after small and slow disturbance, such as gradual power changes, [7]. A system enters a state of voltage instability when a disturbance, or increased in load or change in system condition causes progressive and uncontrollable decline in voltage. The main factor causing voltage instability is the inability of the power system to meet the demand for reactive power [8-9]. Insertion of FACTS devices is found to be highly effective in preventing voltage instability and minimize the active power loss on transmission line. [10-11]. UPFC are used to enhance voltage stability margin and reduce the real power loss appreciably. Furthermore, case studies of voltage stability improvement using suitable FACTS devices are compare with standard base system [12-13]. Model representations of UPFC devices are analyzed using base case study to compare and assess voltage stability. The outcome of the studies shows that those methods used have drawback of assessed the normal state of the system only [14-15]. In order to improve the voltage stability, contingencies of the network require to be adopted. One way to place the UPFC device in the system is taking into consideration of the nature of network condition as paramount than the operating state of the system or network; stability indices are exhibit to determine the closeness of the system to voltage stability [3, 16-19]. Another approach uses the significance of contingency in terms of load demand index i.e. increase the real power (increase in power demand) is applied in this work.

In this paper, latest version of EAs method (DE) was use to indicate the optimal location of UPFC device thereby improving the system security while strengthening of the transmission line power control capability combine with bus voltage profile. Depending on the UPFC device modeling and simulation, a steady state analysis within specify operating network limit is selected to implement DE using tailored MATPOWER software, in MATLAB system. The success of the unique algorithm of the propose system has been confirmed by the test performed on the standard IEEE 14-Bus system with outcome of the result positive.

METHODOLOGY

A. Modeling of UPFC and System Losses

To examine the effect of DE on the optimal positioning of UPFC device on power system, it is significant to model the UPFC device correctly. Figure 1 presents the equivalent circuit model of UPFC device of power flow.

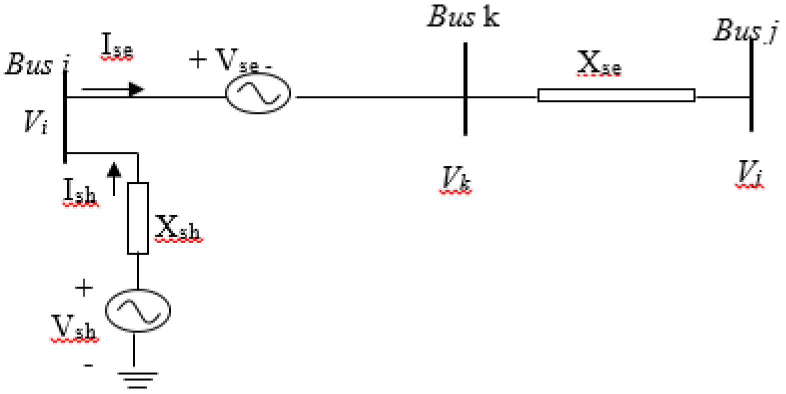

Fig. 1 UPFC Equivalent Circuit Representation

In the circuit, two interconnected synchronous voltage source expound the UPFC steady-state analysis. Representing a mathematical model of ac output terminal with standard voltage source V_s and V_{sh}, these are in series with their respective reactance X_{sc} and X_{sh} which represent leakage reactance of the coupling transformer. Following the approach of [20]:

In the figure 1 above, the imaginary voltage in series with reactance X_{se} are designate with V_k. i.e.

$$V_k = V_{se} + V_i \tag{1}$$

An ideal series voltage, $\overline{V}_{se}$ represent model series connected voltage source that can be controlled by each of the magnitude and phase. It can be seen that

$$V_{se} = rV_i \ell^{j\gamma} \tag{2}$$

Such that, $0 \le r \le r_{\max}$ and $-\pi \le \gamma \le \pi$

The parameters r and γ represent injected voltage magnitude in p.u and voltage angle of the UPFC, this are expounding in [20] modeling.

The power flow P_{ij} equation, the voltage magnitude V_i, V_j and phase angle for both sending and receiving end voltage δ_i,δ_j are given by

$$P_{ij} = \frac{V_i V_j}{X_{ij}}.\sin(\delta_i - \delta_j) \quad (3)$$

The control of power flows can be achieve using FACTS devices and by adjusting variables V_i,V_j and δ_i,δ_j the system losses controlled to a minimum value possible. As FACTS devices are very fast and efficient in control of above variable, they are appropriate for dynamic control of power system.

Objective Function

The main objective of this work is to determine the optimal location of UPFC in the network based on DE technique for improving system security. Therefore, this improvement can be achieved through minimizing the real power losses and bus voltage limit violations. The objective function for the optimal location of UPFC device considering the above criteria can be expressed as:

Minimize the objective function

$$F_{obj}\ (V, P)$$

$$F_{Obj} = w_v \sum_{i=1}^{nb} \left(V_i - V_i^{lim}\right)^2 + w_l \sum_{j=1}^{nl} P_{Loss_{ij}} \quad (4)$$

Where

w_v and w_l: are appropriately selected weighting factors for voltage and power losses,
nb: Number of buses in the system,
nl: Number of lines in the system,
V_i: Bus voltage at bus i,
V_i^{lim}: Specified bus voltage limits at bus i,
$P_{Loss_{ij}}$: Real power loss on line i-j,

The minimization of the objective function is subject to the constraints.

Bus voltage constraints;

$$\left|V_i^{\min}\right| \le \left|V_i\right| \le \left|V_i^{\max}\right| \quad i = 1, \ldots\ldots\ldots\ldots\ldots.\ Nb \quad (5)$$

Real Power generation constraints

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{Max} \quad i = 1, \ldots\ldots\ldots\ldots\ldots.\ Ng \quad (6)$$

Reactive Power Generation Constraint

$$\square_{Gi}^{min} \le \square_{Gi} \le \square_{Gi}^{Max} \quad i = 1, \ldots\ldots\ldots\ldots\ldots.\ Ng \quad (7)$$

Where N_b and N_g are the sets of buses and generation buses indices respectively

REALIZATION OF DE BASED TOOL

Overview of DE

DE is a parallel direct search method proposed by Storn and Price (1995). Similar to other EAs techniques, DE is a heuristic, population-based optimization method that uses a population of points to search for a global minimum of a function over continuous search space. Basically, DE generates new vectors of parameter by adding the weighted difference between two population vectors to a third one. If the resulting individual provides a smaller objective function value than a predetermined population individual, in the next generation the new individual replaces the one with which it is compared; otherwise, the old individual is retained. There are several variants of DE [21,22].

The general notation of DE variants can be expressed as follows:

$$DE/x/y/z \quad (8)$$

Where x denotes the mutated vector, y is the number of difference vectors and z is the crossover scheme. The advantages of DE are summarized in [23]:

DE Based Optimal Location and Sizing of UPFC

In this paper, the following variables are considered as the optimization variables:

(i) The location of UPFC in the network is considered as the first variable to be optimized, and the location candidates for this variable can be any line in the network, except the lines where the transformers are existed.

(ii) The series voltage source magnitude (V_{se}) of the UPFC is considered as the second variable to be optimized, and the working range for this variable is [0.001 0.2].

(iii) The shunt voltage source (V_{sh}) of UPFC is considered as the third variable to be optimized, and the working range for this variable is [0.9, 1.1].

Because of higher cost of UPFC device, the installation is not recommended to all possible line outage. Hence the aforementioned line contingency screening is carried out by DE algorithm to identify the most critical line during whose UPFC can be positioned and system can be operated under stable condition. However, the computational steps of DE based tools evolved are summarized below.

Step I: Initialize power flow data, and DE-related parameter such as the size of population (NP), the maximum number of iteration or generation (G_{max}), the number of variables to be optimized (D), CR, and F.

Step II: Randomly generate the initial population of NP individuals in the feasible space by:

$$X_{i,k}^{G} = X_{k\,min} + rand\,[0,1] * (X_{kmax} - X_{kmin}) \qquad (9)$$

Step III: Evaluate the fitness for each individual in the population according to the objective function in (4).

Step IV: Create a new population by:

Mutation operation

Several population members are involved in creating a member of the subsequent population. Randomly choose three different vectors from the current population and generate a trial vector.

Crossover operation

The crossover function is very important in any evolutionary algorithm. It should also be noted that there are evolutionary algorithms that use mutation as their primary search tool as opposed to crossover operators. In DE, three parents are selected for crossover and the child is a perturbation of one of them whereas in GA, two parents are selected for crossover and the child is a recombination of the parents. Where, CR is the cross over rate of DE.

Selection operation

In DE algorithm, the target vector $X_{i,G}$ is compared with the trial vector $V_{i,(G+1)}$ and the one with the better fitness value is admitted to the next generation.

Step V: Stop the process and print the best individual (Optimal location and Sizing of UPFC) if the stopping criterion is satisfied, else go back to Step IV.

Table -1 Parameter Initialization of the Implemented DE based UPFC parameters setting adopted to the values reported in the open literature [24-25]

Parameters	Settings
Number of population (NP)	30
Maximum Number generation, G_{max}	100
No. of variables to be optimized (NV)	3
Length of individual (LI)	3
DE Step-size (F)	0.5
Cross over probability constant CR	0.5
DE Strategy	DE/rand/1/bin
Termination Criteria	$1.e^{-6}$ or G_{max}

SIMULATION RESULTS AND DISCUSSION

Modified IEEE 14-Bus system whose data can be obtained from [26] was used to verified the efficiency of the propose technique. The system operates under three different conditions:

Case 1: Using Newton Raphson (NR) load flow analysis, system with 100% loading across all load buses is assume normal loading condition. The loading factor is equal to (1.0).

Case 2: When the system loading increases by 25% in all the load buses, it is considering as moderate condition of loading. However, NR load flow analysis conducted in this condition results in poor voltage profile, there is considerable loss of real power.

Case 3: Critical loading condition refers to when the system loading increases by 50% of the normal loading condition. In such a case, the voltage profile is at its worst condition with unacceptable real power loss.

The simulation results before and after UPFC device optimally located on the test system under different percentage loading of normal, moderate and critical conditions was demonstrated. Under the above loading conditions, Newton Raphson load flow was used to obtain the initial real power loss in MW and bus voltage profile (without UPFC). Then, DE technique is applied to produce the optimal location and sizing of UPFC device as well as the final power loss values in MW and bus voltage profile (With UPFC) for the system under same loadings conditions. Lastly, formulation for the percentage real power loss reduction was also set out. The summary of the results is presented in Table 2.

As observed from the above table, it was realized that under normal and critical loading condition, DE optimally placed UPFC device on line 20 each with value of 119.4MVAr and 185.4MVAr respectively. Whereas line 9 was the optimal location of UPFC under moderate loading condition with rated value 108.3MVAr. The percentage loss reduction of 61.062%, 52.520% and 48.217% was also established for normal, moderate and critical loadings scenarios respectively. Also from the above table, it was deduced that the overall network losses with UPFC installed marginally increases as the system load increases steadily from 100% to 150% loading. Therefore, the efficacy of the UPFC device decreases as the system loading marginally increases. The real power loss (in p.u) convergence characteristics with UPFC against the number of generation on the test system under normal, moderate and critical loading conditions is shown in figure 2, 3 and 4 respectively.

Table - 2 Power Flow Results with and without UPFC Located in IEEE 14-Bus Test System Optimal Location, Sizing and Network Losses

(%) Loading	Losses Without UPFC (MW)	Rating (MVar)	Losses With UPFC (MW)	Line Location	% Power Loss Reduction
Normal (100% loading)	34.232	119.4	13.329	20	61.062
Moderate (125% loading)	47.019	108.3	22.325	9	52.520
Critical (150% loading)	63.822	185.4	34.049	20	48.217

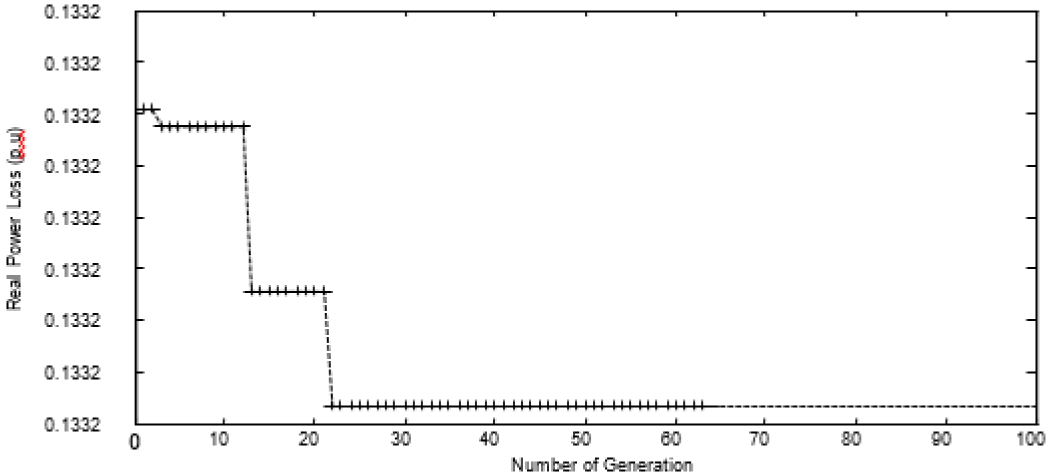

Fig. 2 Convergence Characteristics with UPFC under normal loading condition

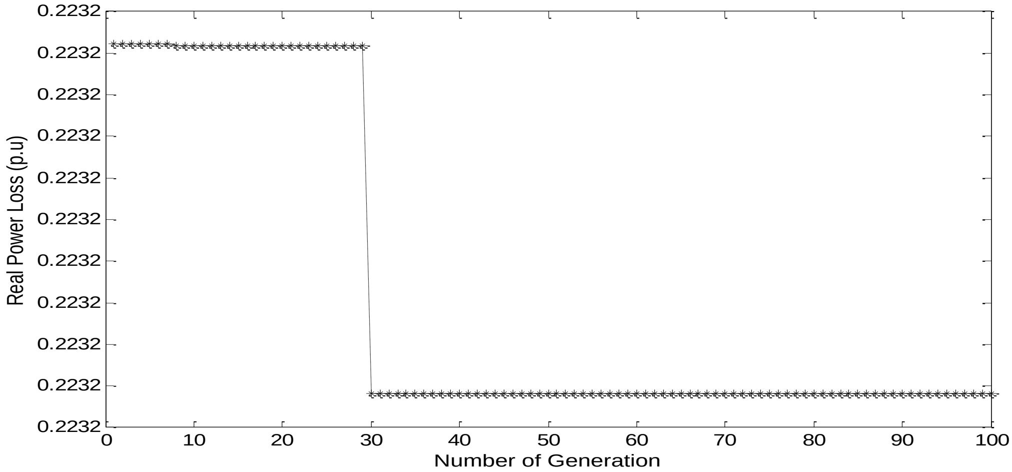

Fig. 3 Convergence Characteristics with UPFC under moderate loading condition

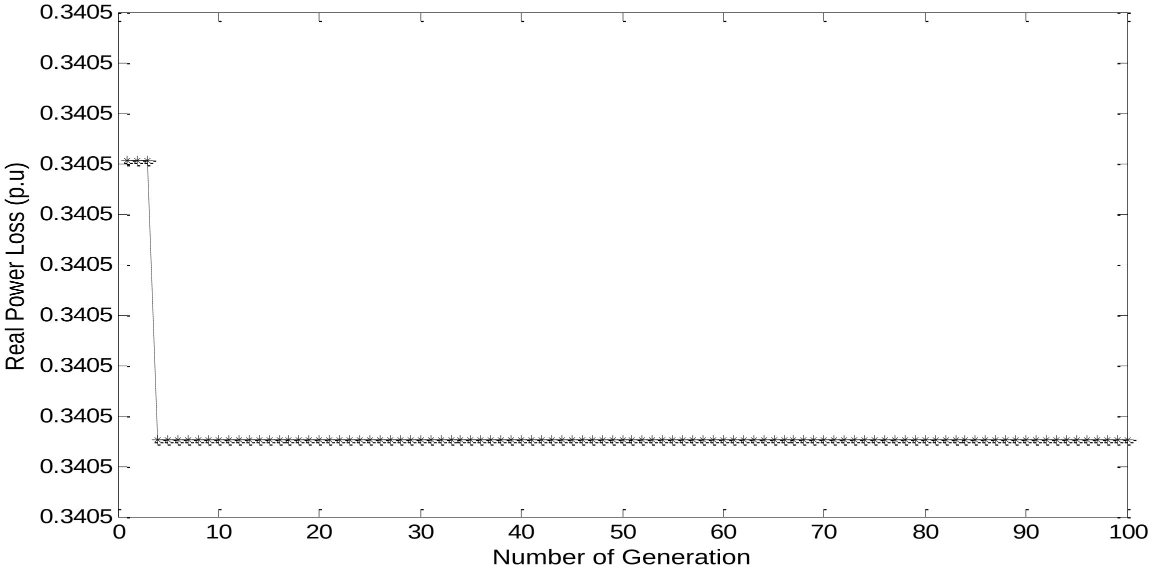

Fig 4: Convergence Characteristics with UPFC under critical loading condition

Power Flow Improvement

Fig. 2 below shows the real power loss convergence characteristics for the optimal location of UPFC by DE technique (DE is made to run for 100 iteration). The convergence of power loss was exhibited for normal loading at 23th generations to a value of 0.1332(p.u). The result shows the value of power loss (real power loss) has gradually converge to an optimum value of 13.324MW (0. 1332p.u) from an initial value of 34.232MW.

Fig.3 below also shows the convergence characteristics of UPFC optimal placement by DE technique of real power loss against the number of generation on the test system under moderate condition. The convergence reaches a final value of loss reduction at 30th generation to a value of 0. 2232p.u (22.325MW). The result reveals the value of P_{loss} converge to a value of 22.325MW from an initial value of 47.019MW. As for the 150% loadings, i.e critical loading condition, the convergence characteristics for the optimal location of UPFC by DE technique is shown in fig. 4 below. However, fast convergence was exhibited within a few numbers of generations (in less than 5th generation) to reach an optimum value of 0.3405 (34.049MW). The result reveals the value of Ploss converge to a value of 34.049MW from an initial value of 63.822MW.

The results as captured in table 2, indicates that the value of loss P_{loss}, which form part of the objective function gradually converges to optimal value of 13.329MW (0. 1332p.u) 22.325MW (0. 2232p.u) and 33.049MW (0. 3405p.u) for normal, moderate and critical loading scenarios respectively. It can be observed that the simulation results convergence before the 30th number of generation for all the loading conditions. The effectiveness of this search was seriously influenced by a choice of control parameter values of DE algorithm captured in table 1.

Voltage Profile Enhancement

A signal pattern of voltage profile enhancement before and after UPFC device are placed optimally using DE techniques are shown in figure 5, 6 and 7. These are optically located under different operating condition of normal, moderate and critical loading state respectively. With operating range of (0.9-1.1 p.u), it can be seen from figure 5 that there are violations of operating limit when operate without UPFC device at bus 9, 10 and bus 11 under normal loading conditions. These violations of operating limits of voltage at the bus voltage are cancel or annul after DE method augment the position of UPFC on the system. Likewise, in figure 6 below, the buses 9, 10 and bus 11 operate under moderate loading and are influence by the loading system that results in violating the tolerance limit. Optimizing UPFC location using DE technique eliminates the disturbance-loading situation.

A critical condition as in figure 7, violation permissible operating limit at bus 9, 10, 11, and bus 14 is more noticeable. Application of optimizing technique of DE in optimal location of UPFC eliminates these limit violations. It is observed from figure 5, 6, and 7, bus voltage limits violations increase from 2 buses to 4 buses as system loading increases. (i.e normal, Moderate and critical loading cases). Also the loading scenario steadily increased, bus voltage limits violations also increases, likewise buses violations become more pronounce with increase in loading. However, with optimal placement of UPFC in all loading conditions, bus voltage profile was maintained within the tolerable limits of (0.9 - 1.1p. u). However, it was found that the impact of UPFC on the system voltage and real power flow on the optimized location by the applied DE technique has resulted in eliminating bus voltage limit violations and improved power flow on the test system.

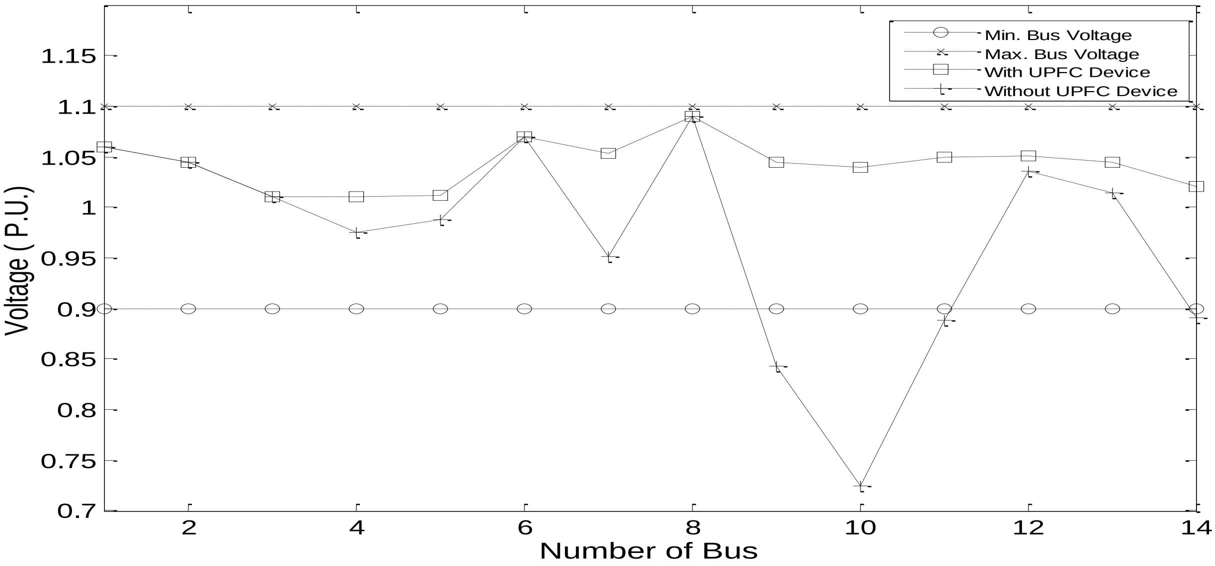

Fig. 5 Voltage Profile with UPFC under normal loading condition

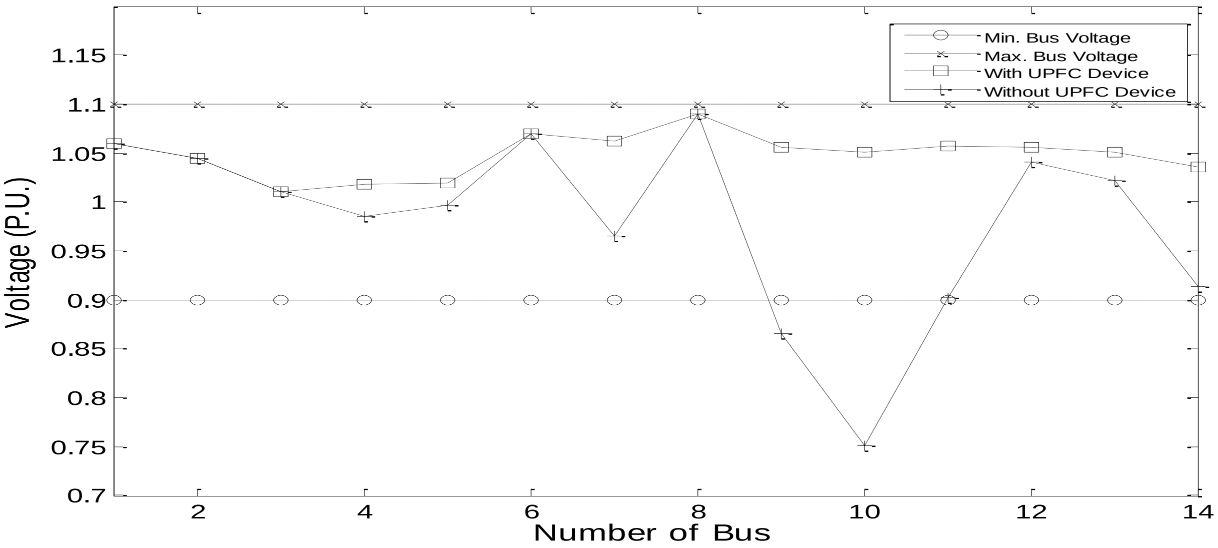

Fig. 6 Voltage Profile with UPFC under moderate loading condition

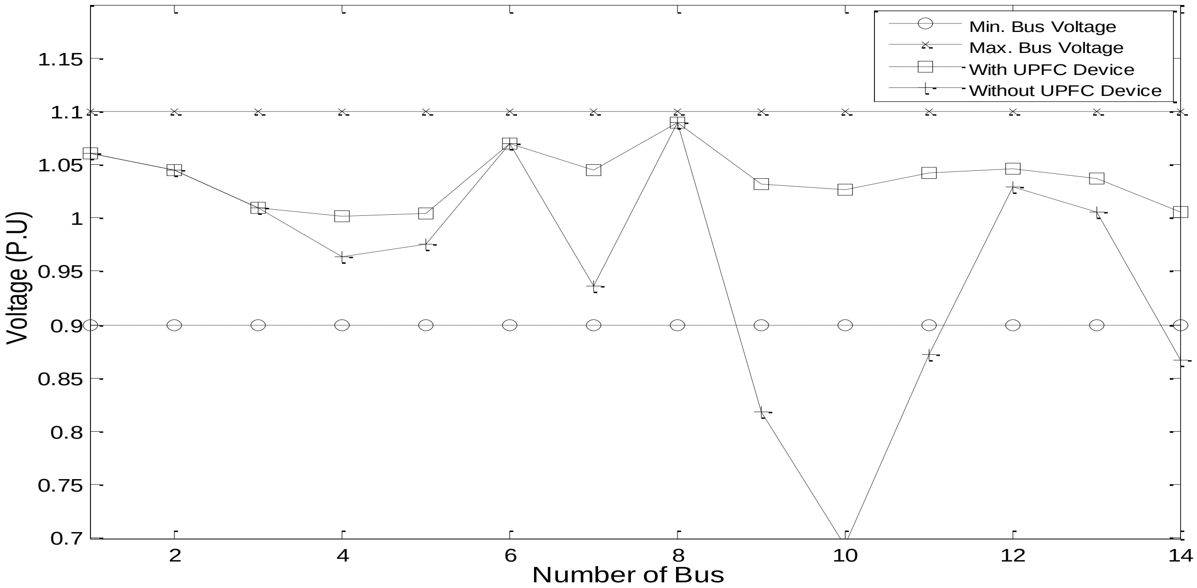

Fig. 7 Voltage Profile with UPFC under critical loading condition

CONCLUSION

In conclusion, different system loading scenarios was studied using IEEE 14 bus test system; DE was applied to produce optimal location and sizing of the UPFC on the test system. Determinations of the severest loading contingency scenarios were performed based on 3 different cases of normal, moderate and critical loading conditions. The proposed DE technique has been successfully applied to the problem under consideration. It was found that the impact of UPFC on the system voltage and real power flow on the location optimized by the applied DE technique has resulted in eliminating bus voltage limit violations and improved power flow on the system. The proposed DE algorithm is proved to be effective and practical approach for the optimal location and sizing of UPFC on the power system.

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