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Full Length Research Paper

Voltage support and stability improvement using unified power flow controller tuned based on simulated annealing

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In this paper, the authors are willing to study the effects of unified power flow controller (UPFC) on voltage support and also stability enhancement at a multi-machine electric power system. Proportional-Integral (PI) type controllers are considered for UPFC control and the parameters of these PI type controllers are tuned using simulated annealing (SA). In order to show the ability of UPFC in voltage control and also stability enhancement, the results of the system with UPFC are compared with the results without UPFC. Nonlinear time domain simulation results emphases on the ability of UPFC in simultaneous control of voltage and also stability enhancement

Key words: Unified power flow controller, voltage support, dynamic stability enhancement, multi-machine electric power system, simulated annealing.

INTRODUCTION

New types of flexible AC transmission systems (FACTS) devices have been investigated that may be used to increase power system operation flexibility and controllability, to enhance system stability and to achieve better utilization of existing power systems (Hingorani and Gyugyi, 2000). UPFC is one of the most complex FACTS devices in a power system today. It is primarily used for independent control of real and reactive power in transmission lines for flexible, reliable and economic operation and loading of power systems. Until recently, all three parameters that affect real and reactive power flows on the line, that is, line impedance, voltage magnitudes at the terminals of the line, and power angle, were controlled separately using either mechanical or other FACTS devices. But UPFC allows simultaneous or independent control of all these three parameters, with possible switching from one control scheme to another in real time. Also, the UPFC can be used for voltage support and transient stability improvement by damping of low frequency power system oscillations (Eghtedari et al., 2011; Ozturk and Dosoglu, 2010; Hassan et al, 2010; Farahani et al., 2011; Alasooly and Redha, 2010; Mehraeen et al., 2010; Jiang et al., 2010a; Jiang et al., 2010 b; Jiang et al., 2010c; Faried, 2009). Low frequency oscillations (LFO) in electric power system occur frequently due to disturbances such as changes in loading conditions or a loss of a transmission line or a generating unit. These oscillations need to be controlled to maintain system stability. Many in the past have presented lead-Lag type UPFC damping controllers (Zarghami et al., 2010; Guo and Crow, 2009; Tambey and Kothari, 2003; Wang, 1999). They are designed for a specific operating condition using linear models. More advanced control schemes such as particle-swarm method, fuzzy logic and genetic algorithms (Taher and Hematti, 2009; Taher et al., 2008; Al-Awami, 2007; Eldamaty et al., 2005) offer better dynamic performances than fixed parameter controllers.

The objective of this paper is to investigate the ability of UPFC for control voltage and also stability enhancement. UPFC internal controllers (bus-voltage controller and DC

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Abbreviations: FACTS, flexible AC transmission systems; **UPFC,** unified power flow controller; **SA,** simulated annealing; **LFO,** low frequency oscillations;

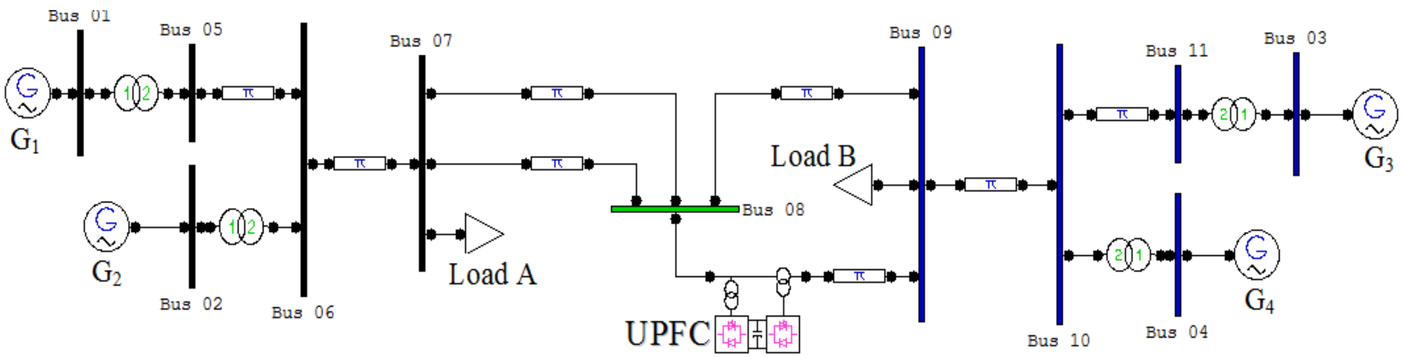

Figure 1. Four-machine eleven-bus power system.

Table 1. System loading conditions.

Load	Nominal		Heavy	
	P	Q	P	Q
A	18.5535	-2.625	20.4089	-2.630
B	10.1535	-1.050	11.1689	-1.055

link voltage regulator) are considered as PI type controllers. Simulated annealing (SA) optimization method is considered for tuning the parameters of these PI type controllers. Different load conditions are considered to show ability of UPFC under different loading conditions. Simulation results show the effectiveness of UPFC in power system stability and control.

SYSTEM TESTING

Figure 1 show a multi machine power system installed with UPFC. The static excitation system, model type IEEE – ST1A, has been considered. The UPFC is assumed to be based on pulse width modulation (PWM) converters. Detail of the system data are given in (Kundur, 1993). To assess the effectiveness and robustness of the proposed method over a wide range of loading conditions, two different cases as nominal and heavy loading are considered and listed in Table 1.

Dynamic model of the system with UPFC

The nonlinear dynamic model of the system installed with UPFC is given as (1). The dynamic model of the system is completely presented in (Kundur, 1993) and also dynamic model of the system installed with UPFC is presented in (Nabavi-Niaki and Iravani, 1996; Wang, 2000).

$$\begin{cases} \dot{\omega}_i = \dfrac{(P_m - P_e - D\omega)}{M} \\ \dot{\delta}_i = \omega_0(\omega - 1) \\ \dot{E}'_{qi} = \dfrac{(-E_q + E_{fd})}{T'_{do}} \\ \dot{E}_{fdi} = \dfrac{-E_{fd} + K_a(V_{ref} - V_t)}{T_a} \\ \dot{V}_{dc} = \dfrac{3m_E}{4C_{dc}}\left(\sin(\delta_E)I_{Ed} + \cos(\delta_E)I_{Eq}\right) + \dfrac{3m_B}{4C_{dc}}\left(\sin(\delta_B)I_{Bd} + \cos(\delta_B)I_{Bq}\right) \end{cases} \quad (1)$$

where, i = 1, 2, 3, 4 (the generators 1 to 4); m_B, pulse width modulation of series inverter. By controlling m_B, the magnitude of series- injected voltage can be controlled; δ_B, phase angle of series injected voltage; m_E, pulse width modulation of shunt inverter. By controlling m_E, the output voltage of the shunt converter is controlled; δ_E: phase angle of the shunt inverter voltage; The series and shunt converters are controlled in a coordinated manner to ensure that the real power output of the shunt converter is equal to the power input to the series converter. The fact that the DC-voltage remains constant ensures that this equality is maintained.

UPFC controllers

In this paperm two control strategies are considered for

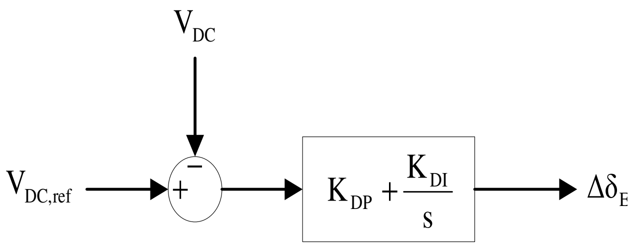

Figure 2. DC-voltage regulator.

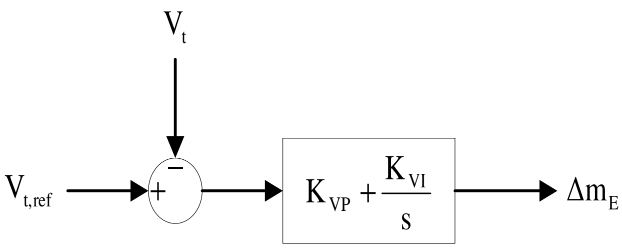

Figure 3. Bus voltage controller.

UPFC. These controllers are Bus voltage controller and DC voltage regulator. The real power output of the shunt converter must be equal to the real power input of the series converter or vice versa. In order to maintain the power balance between the two converters, a DC-voltage regulator is incorporated. DC-voltage is regulated by modulating the phase angle of the shunt converter voltage. Figure 2 shows the structure of the DC-voltage regulator. Also Figure 3 shows the structure of the bus voltage controller. The bus voltage controller regulates the voltage of bus during post fault in system.

The most important subject is to tuning the UPFC controller parameters K_{DP}, K_{DI}, K_{VP} and K_{DI}. The system stability and suitable performance is guaranteed by appropriate adjustment of these parameters. Many different methods have been reported for tuning UPFC parameters so far. In this paper, an optimization method named SA is considered for tuning UPFC parameters. In the next section, an introduction about SA is presented.

SIMULATED ANNEALING

In the early 1980s, the method of simulated annealing (SA) was introduced. This method simulates the annealing process in which a substance is heated above its melting temperature and then gradually cooled to produce the crystalline lattice, which minimizes its energy probability distribution. This crystalline lattice, composed of millions of atoms perfectly aligned, is a beautiful example of nature finding an optimal structure. However, quickly cooling or quenching the liquid retards the crystal formation, and the substance becomes an amorphous mass with a higher than optimum energy state. The key to crystal formation is carefully controlling the rate of change of temperature.

The algorithmic analog to this process begins with a random guess of the cost function variable values. Heating means randomly modifying the variable values. Higher heat implies greater random fluctuations. The cost function returns the output, *f*, associated with a set of variables. If the output decreases, then the new variable set replaces the old variable set. If the output increases, then the output is accepted provided that:

$$r \leq e^{[f(P_{old}) - f(P_{new})]/T} \tag{2}$$

where, *r* is a uniform random number and *T* is a variable analogous to temperature. Otherwise, the new variable set is rejected. Thus, even if a variable set leads to a worse cost, it can be accepted with a certain probability. The new variable set is found by taking a random step from the old variable set as (3).

$$P^{new} = dP^{old} \tag{3}$$

The variable *d* is either uniformly or normally distributed about p^{old}. This control variable sets the step size so that, at the beginning of the process, the algorithm is forced to make large changes in variable values. At times the changes move the algorithm away from the optimum, which forces the algorithm to explore new regions of variable space. After a certain number of iterations, the new variable sets no longer lead to lower costs. At this point, the value of T and d decrease by a certain percent and the algorithm repeats. The algorithm stops when $T \rightarrow 0$. The decrease in *T* is known as the cooling schedule. Many different cooling schedules are possible. If the initial temperature is T_0 and the ending temperature is T_N, then the temperature at step *n* is given by (4).

$$T_n = f(T_0, T_N, N, n) \tag{4}$$

where, *f* decreases with time. Some potential cooling schedules are as follows:

a. Linearly decreasing: $T_n = T_0 - n(T_0 - T_n)/N$
b. Geometrically decreasing: $T_n = 0.99\, T_{n-1}$
c. Hayjek optimal: $T_n = c/\log(1+n)$, where *c* is the smallest variation required to get out of any local minimum.

Many other variations are possible. The temperature is usually lowered slowly so that the algorithm has a chance to find the correct valley before trying to get to the lowest point in the valley. This algorithm has been applied successfully to a wide variety of problems (Randy and Sue, 2004).

Table 2. Optimal parameters of UPFC using SA.

Parameter	Optimal value
K_{DP}	22.331
K_{DI}	1.067
K_{VP}	77.209
K_{VI}	0.0561

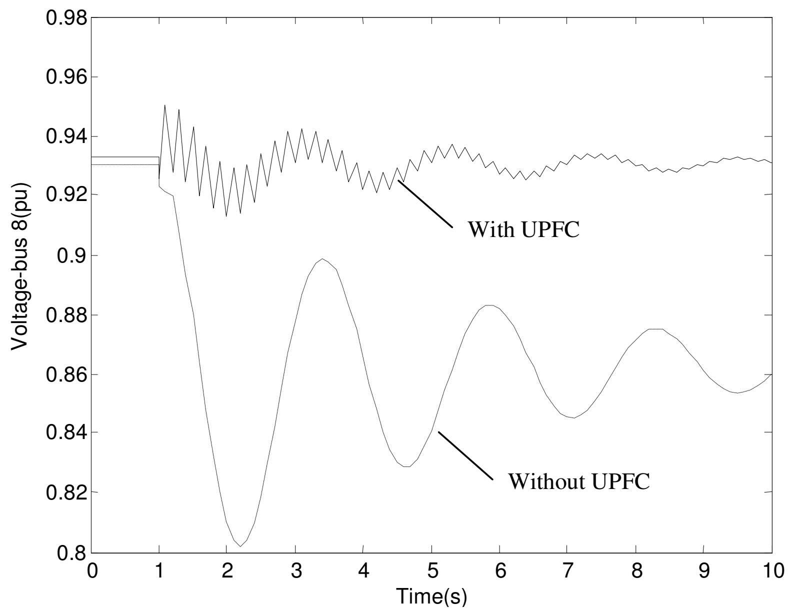

Figure 4. Voltage of bus number 8 under scenario 1 in nominal load condition; solid, with UPFC; dashed, without UPFC.

UPFCTUNING BASED ON SA

Here, the parameters of the UPFC controllers are tuned using SA. The optimum values of KDP, KDI, KVP and KDIwhich minimize different performance indices are accurately computed using SA. In optimization methods, the first step is to define a performance index for optimal search. In this study the performance index is considered as (5). In fact, the performance index is the integral of the time multiplied absolute value of the error (ITAE).

$$ITAE{=}ITAE{=}0tt\Delta\omega 1dt{+}0tt\Delta\omega 2dt{+}0tt\Delta\omega 3dt{+}0tt\Delta\omega 4dt(5)$$

where, $\Delta\omega$ shows the frequency deviations. It is clear to understand that the controller with lower ITAE is better than the other controllers. To compute the optimum parameter values, a 10 cycle three phase fault is assumed in bus 3 and the performance index is minimized using SA. The optimum values of parameters, resulting from minimizing the performance index is presented in Table 2.

SIMULATION RESULTS

Here, the SA-based UPFC is exerted to voltage support in the under study system. In order to study and analysis system performance under different scenarios, two scenarios are considered as follows:

Scenario 1: Disconnection of the line between bus 8 and bus 9 by breaker
Scenario 2: 10 cycle three phase short circuit in bus 1.

It should be noted that this tuning have been done for the nominal operating condition. The simulation results are presented in Figures 4 to 11.

Each figure contains two plots; solid line which indicates the system installed with UPFC and dashed line for system without UPFC. The UPFC is placed at bus 8, as seen in Figure 1. As it is clear from the figures, in case with UPFC, the voltage of bus 8 which installed with UPFC is controlled very well. Where, the bus voltage is

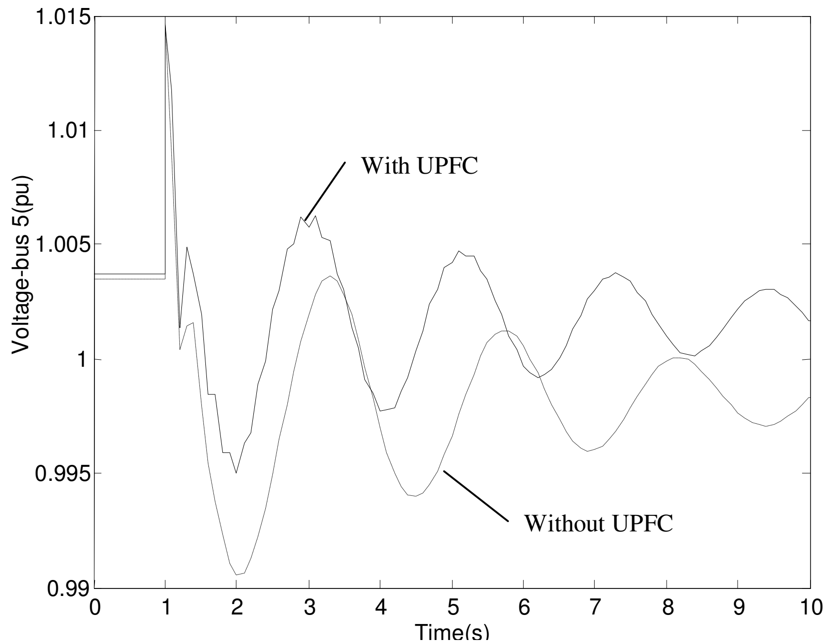

Figure 5. Voltage of bus number 5 under scenario 1 in nominal load condition; solid, with UPFC; dashed, without UPFC.

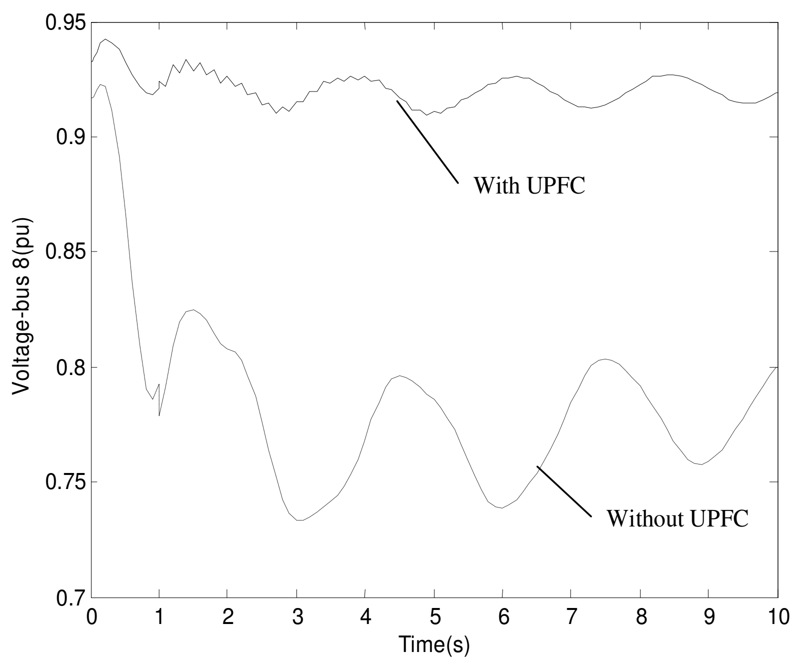

Figure 6. Voltage of bus number 8 under scenario 1 in heavy load condition; Solid, with UPFC; dashed, without UPFC.

driven back to the nominal value during post-fault. However, bus voltage without UPFC is not driven back to nominal value and contains a steady state error. It should be noted that although UPFC has been used for the purpose of controlling the voltage of bus number 8, it has also a good effect on the voltage of other buses. For example, the voltage of bus 5 in the case of having UPFC has less error comparing with the case of lack of UPFC.

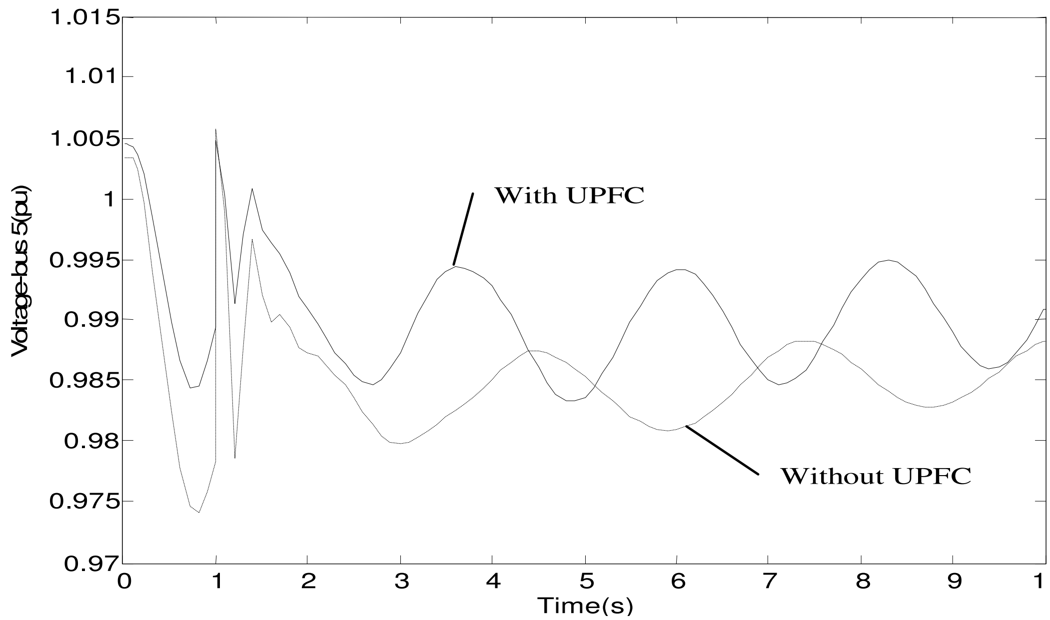

Figure 7. Voltage of bus number 5 under scenario 1 in heavy load condition; solid, with UPFC; dashed, without UPFC.

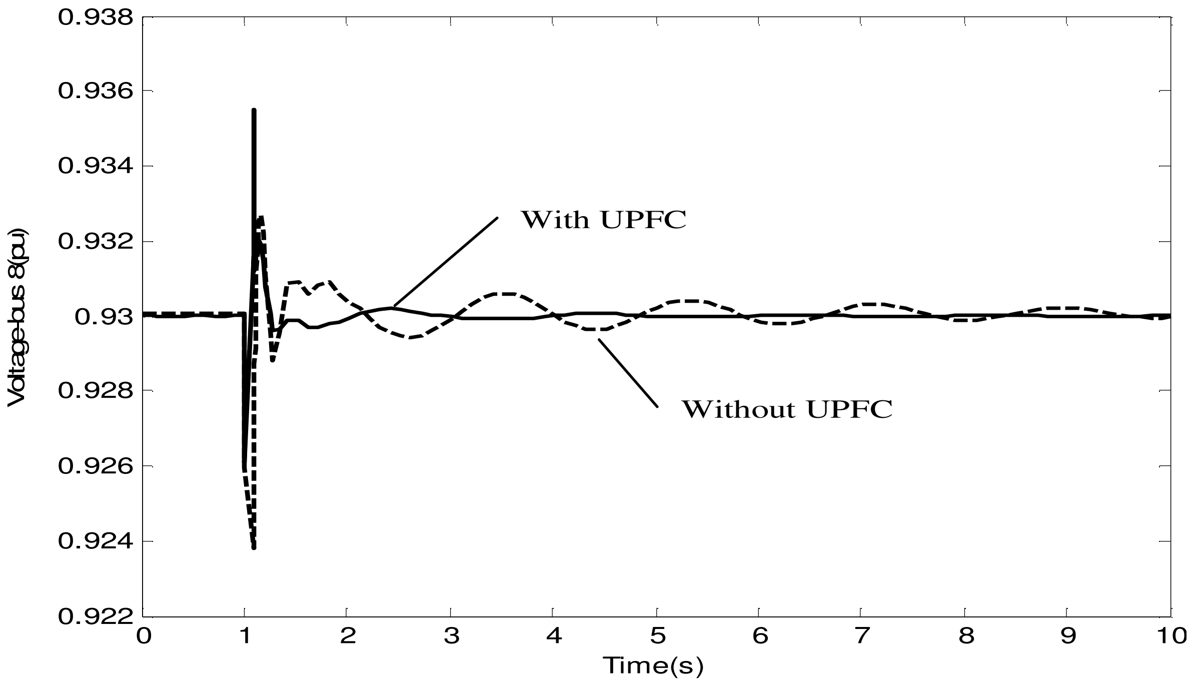

Figure 8. Voltage of bus number 8 under scenario 2 in nominal load condition; solid, with UPFC; dashed, without UPFC.

System responses in heavy load condition have been demonstrated. As is clear these figures, by increasing system load and resultant heavier operation condition, UPFC has good performance in voltage control and cause the voltage to return to its nominal value. The voltages of bus number 5 and 8 under second scenario have been shown in Figures 8 to 11. In this scenario, a three phase short circuit fault occurs and then it is removed. So the system operation point does not change and voltages return to nominal value with and without

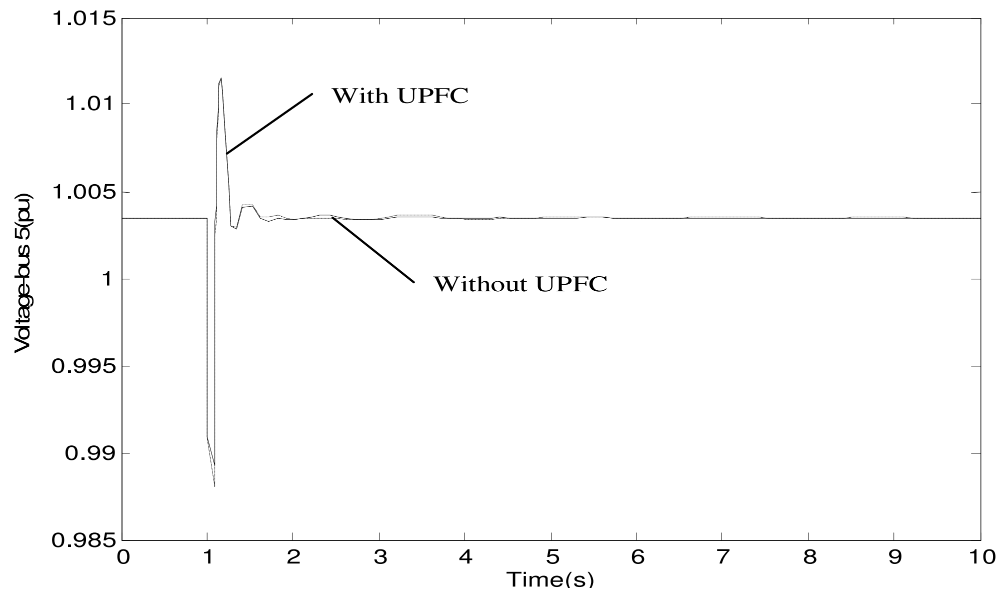

Figure 9. Voltage of bus number 5 under scenario 2 in nominal load condition; solid, with UPFC; dashed, without UPFC.

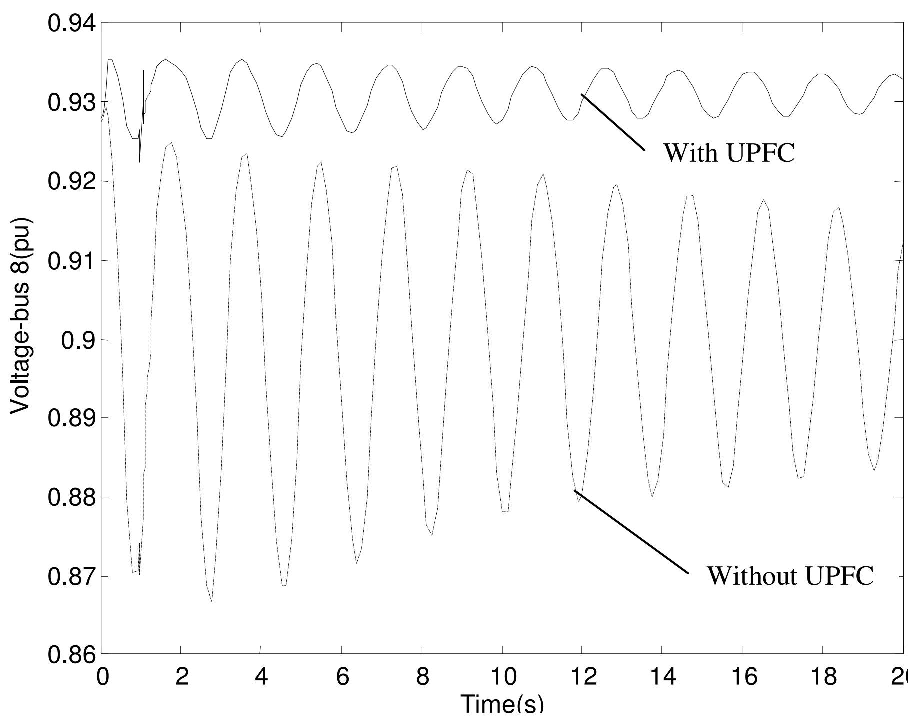

Figure 10. Voltage of bus number 8 under scenario 2 in heavy load condition; solid, with UPFC; dashed, without UPFC.

UPFC. But it should be noted that UPFC has tremendous effect on damping of oscillations and make the system response faster.

Conclusions

In this paper, simulated annealing (SA) method has been

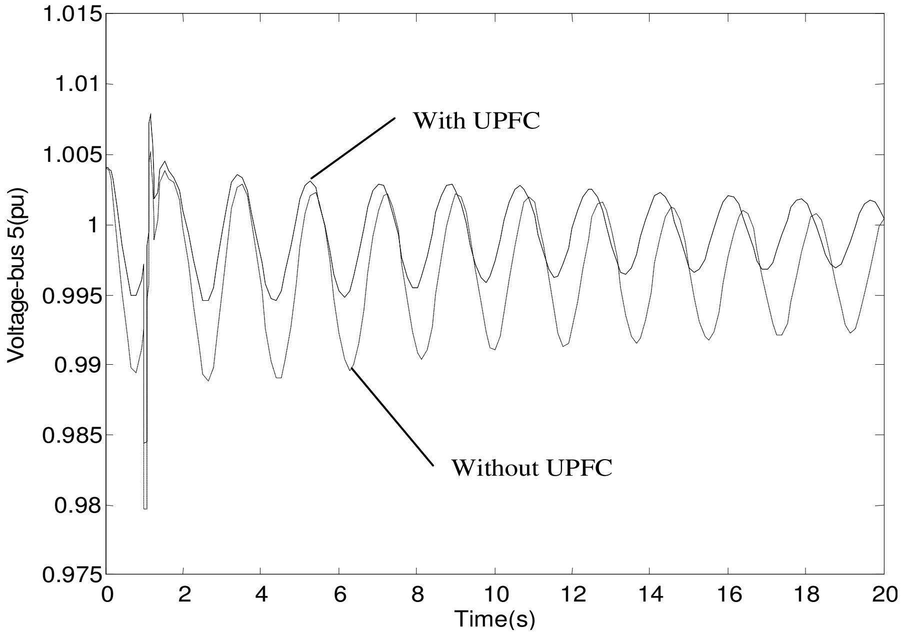

Figure 11. Voltage of bus number 5 under scenario 2 in heavy load condition; solid, with UPFC; dashed, without UPFC.

successfully exerted to adjust UPFC parameters. A multi-machine electric power system installed with a UPFC with various load conditions and disturbances has been assumed to demonstrate the ability of UPFC in voltage support and stability enhancement. Considering real world type disturbances such as three phase short circuit and line disconnection guarantee the results in order to implementation of controller in industry. Simulation results demonstrated that the designed UPFC capable to guarantee the robust stability and robust performance under a different load conditions and disturbances. Also, simulation results show that the SA technique has an excellent capability in UPFC parameters tuning. Application to a multi-machine electric power system which is near to practical systems can increase admission of the technique for real world applications. In regard to this paper, the following researches can be considered as future works: Tuning the parameters of the UPFC using the other optimization methods; using the UPFC for power flow control; using the UPFC for stability improvement; designing the UPFC controllers using other control methods such as adaptive control, robust control and non-linear control.

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Nomenclature

Symbols: **δ,** Rotor angle; **ω,** Rotor speed (pu); **$\Delta\omega$,** the frequency deviation; **P_m,** mechanical input power; **T_m,** mechanical torque (pu); **P_e,** electrical output power (pu); **Te,** electric torque (pu); M, system inertia (Mj/MVA); **E'_q,** internal voltage behind x'_d (pu); **E_{fd},** equivalent excitation voltage (pu); **X'_d,** transient reactance of d axis (pu); **X_q,** steady state reactance of q axis (pu); **X_d,** steady state reactance of d axis (pu); **T'_{do},** time constant of excitation circuit (s); **K_a,** regulator gain; **T_a,** regulator time constant (s); **V_t,** terminal voltage (pu); **t,** simulation time (s); **X_T,** reactance of transmission line (pu); **P,** active power of load (pu); **Q,** reactive power of load (pu); **V_{ref},** reference voltage of excitation system; **m_B,** pulse width modulation of series inverter; **δ_B,** phase angle of series injected voltage; **m_E,** pulse width modulation of shunt inverter; **δ_E,** phase angle of the shunt inverter voltage;

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