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A Novel TLBO Optimization Technique for the Stability Improvement of Multimachine Power Systems Using UPFC Controllers

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Abstract

For consistent and stable operation of power systems the damping of small-frequency oscillations is a must. Newer approaches to system stabilization are made possible because of the advancement of FACTS controllers that boosts both steady state and transient operation. This paper presents work to assess the performance of UPFC supplementary modulation controllers (SMCs) by applying the new Teaching Learning Based Optimization (TLBO) optimization algorithm. The approach ensures co-ordination among the three controllers of the SMC of UPFC and hence enhances damping of oscillations by using SMCs. The usefulness of the SMCs for UPFC based on TLBO optimization technique in damping the significant modes is tested on a 4-machine-10-bus system and 10-machine 39-bus, New England system for the first time.

Keywords: Supplementary modulation controllers; Low frequency electromechanical oscillations; TLBO optimization technique.

1. INTRODUCTION

It is intricate to control and investigate the small-frequency oscillations that arise within interconnected synchronous machines. These oscillations show inadequate damping when the transfer of power within the network of transmission lines is higher. Hence, curtailment of these small-frequency oscillations is mandatory for stable and reliable control of power systems. The classification of modes of oscillations has been made into three categories [1] in a large power system network built around the range of frequency and the states of system due to which the modes are influenced. The intra-plant modes,has an oscillation frequency between 1.5–3.0 Hz, and only the alternators in a power plant participate. Local modes, with frequency oscillations from 0.8 to 1.8 Hz and many alternators in an area participate. Inter-area modes include larger groups of machines swinging, with frequency oscillations from 0.2–0.5 Hz. The damping of these different modes of oscillations is a challenging task to maintain a stable power system. Traditional method of damping power swings has been the incorporation of power system stabilizer (PSS) in the generation excitation system. However, the invention of power-electronics based FACTS controllers has offered an economical way to increase the damping of the small frequency oscillations besides voltage control and steady power flow. In the recent years SMC has been applied effectively to some of the FACTS controllers.

This paper [2], analyses transient stability through direct feedback linearization technique to deal with uncertainties caused by parameter variations and inclusion of UPFC controller. In the paper [3], a components-based unified-power-flow-controller (UPFC) that consists of noveltracker of differential (TD) and a nonlinear PID (NLPID) control system for the UPFC. This paper [4] uses a current injection model of UPFC and a newton type iteration formulation applied to generator models, networks and loads to evaluate transient stability. This paper [5] develops a control strategy that maximizes and minimizes flow of line power and obtains the voltage and current injected by the UPFC from the solution of an optimization problem with constrains at each step. This paper [6] analyses how the UPFC parameters should be controlled in order to achieve the maximal desired effect in solving first swing stability problem and a new identification method of reference identification also were analyzed. This paper [7] presents a center node unified power flow controller (CUPFC) transient model that consists of three voltage source inverters (VSI) with common DC link. C-UPFC can independently control the power flow at either end of line, the AC voltage magnitude at mid-point of line, can balance line current also by addition of a supplementary control system to the shunt inverter control system. This paper [8] uses radial basis function neural network (RBFNN) for the control ofUPFC. The method based on a single neuron architecture with input related to the error difference and the parameter updating is performed through a relative error and thereby depicted by genetic algorithm. In this paper [9], the damping capabilities of UPFC and IPFC are evaluated using small-signal stability, with series branches creating a structure to improve the damping without the necessity of feedback controller. In [10], a control scheme that uses the energy function was developed for UPFC. The sensitivities of generator outputs are evaluated based on Thevenin’s theorem and the DC power flow method. This paper [11] develops a damping controller of the UPFC designed by using modal control theory to render adequate damping characteristics. These papers[12][13] have developed control theory for the series voltage and the shunt current controllers based on the electro-mechanical system. This paper [14] performs and evaluates the design of SMCs for UPFC.In this paper [15], TLBO algorithm that does not require any algorithm-specific parameters unlike the evolutionary and swarm intelligence-based algorithms has been developed. The TLBO algorithm requires only common controlling parameters like population size and number of generations for its working.

The main goal of the work presented in this paper is to highlight the simultaneous design and tuning methodology of the UPFC damping controller to mitigate low frequency oscillations. The control laws for the shunt current, series voltage controllers have been chosen as in [12][13]. The coordinate tuning of SMC parameters has been performed using the new TLBO optimization algorithm and the combination of three controllers are investigated to evaluate the superiority of the UPFC damping controller. The performance of the UPFC SMCs has been evaluated using the proposed new TLBO optimization algorithm from case study conducted on a 4-machine 10-area and 10-machine 39-bus new England systems. The results acquired from evaluated small signal stability and transient stability on nonlinear models of the UPFC SMCs determine the efficiency of new TLBO optimization in damping low frequency oscillations.

2. CONTROL ANALYSIS FOR UPFC SUPPLEMENTARYMODULATION CONTROLLERS

The UPFC is the most adaptable FACTS controller that is versatile and can improve stability of multimachine power systems. Its characteristic feature to control the power flow in the transmission line by simultaneous or selective control of some or all parameters is contemporary [12]. In this paper, the details of control configuration of UPFC considered from [12,13] can control three parameters, viz. the shunt reactive current I_r, the real voltage E_p, and the reactive voltage E_q. The function of UPFC shown in Fig. 1 is not only to control the power flow and voltage but also damp the low-frequency oscillations provided the reference signals of UPFC are regulated by suitably fed local control signals. Thepre-selectedparametersofthethree controllers are tuned simultaneously through a constrained TLBO optimization approach to obtain coordination among controllers.

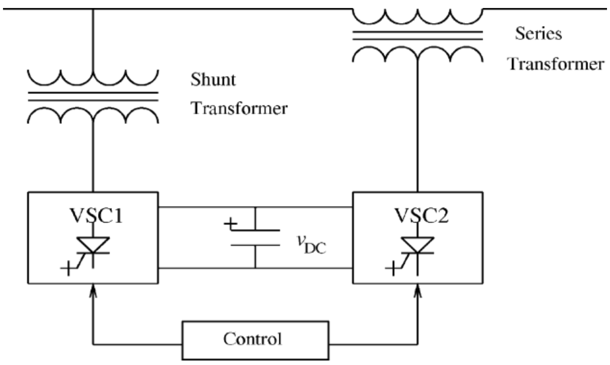

Fig. 1. Unified power flow controller.

The series voltage and shunt current modeling of UPFC has been considered from [12,13].

3. TUNING OF UPFC SMCs USING TLBO OPTIMIZATION TECHNIQUE

In this section, the tuning of SMCs of UPFC by using TLBO optimization technique has been analyzed. The tuneableUPFC parameters [12,13] are the controllable gain parameters K_p, K_q, K_r and the reactances, X_{ser}^{th} and X_{sh}^{th}. The solution to a constrained TLBO optimization problem is obtained by the coordinate tuning of the UPFC parameters as defined below:

The objective function $f(x)$ is formulated as:

$$\underset{k}{Min} \sum_{j=1}^{m} W_j \sigma_j \tag{1}$$

such that

$$D_i = \frac{-\sigma_i}{\sqrt{\sigma_i^2 + w_i^2}} \geq C_1, \tag{2}$$

and

$$\sigma_i \leq C_2, \text{ i=1,2,.......n} \tag{3}$$

where m is the total number modes of interest; n, number of eigenvalues; $\sigma_i$and ω_i, are the real and imaginary parts of eigenvalues; D the damping ratio of eigenvalue; W_j, weight associated with themode of interest; k, vector of control parameters, where each of the elements of the vector is positive, C_1andC_2 are positive and negative respectively.

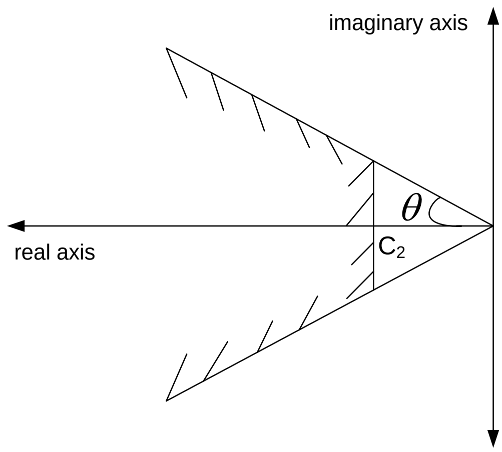

Fig 2 Permissible region for location of closed loop eigenvalues in the left half plane.

If the constraints on damping ratio and the real part of the eigenvalues defined by Eqs. (2) and (3), respectively, are satisfied ($\theta = cos^{-1}(C_1)$ in Fig. 2), then of all the closed loop poles of the system would lie on the boundary or within the sector shown in Fig. 2. In the work that has been presented in the paper, the tuning of coordinate controllers is obtained by the application of TLBO optimization technique. The problem formulation and the constrained objective function given by equations (9) is based on analysis of eigenvalues of the system. The TLBO works in two phases, 'Teacher phase' and 'Learner phase' that is explained below:

1. Teacher phase: In this phase, the learners learn through the

teacher and he can enhance the mean result of the class in the subject taught by him depending on his capability. The best learner can be considered as one who achieves the best overall result from all the subjects in the entire population of learners. However, the best learner identified by the algorithm is the teacher as he is usually considered as a highly learned person. Then, the difference between existing mean result of each subject and the corresponding result of teacher for each subject is obtained mathematically. The updated function value at the end of teacher phase becomes the input to the learner phase.The detailed mathematical formulation of TLBO during the teacher phase is as follows:

At any iteration i, assume that there are 'm' number of subjects (i.e. design variables), 'n' number of learners (i.e. population size, k=1,2,…,n) and $M_{j,i}$ be the mean result of the learners in a particular subject 'j' (j=1,2,…,m). The best overall result $X_{total\text{-}kbest,i}$ considering all the subjects together obtained in the entire population of learners can be considered as the result of best learner *kbest*.

$$Difference\_Mean_{j,k,i} = r_i \, (X_{j,kbest,i} - T_F M_{j,i}) \qquad (4)$$

where,

r_i is the random number in the range [0, 1]

$X_{j,kbest,i}$ is the result of the best learner in subject j.

T_F is the teaching factor which decides the value of mean to be changed and it can be either 1 or 2

$$X'_{j,k,i} = X_{j,k,i} + Difference\_Mean_{j,k,i} \qquad (5)$$

where, $X'_{j,k,i}$ is the updated value of $X_{j,k,i}$. $X'_{j,k,i}$ is accepted if it gives a better solution for eigenvalues.

2. Learner phase: During the second phase, learners enhance their knowledge by interaction among themselves. A learner interacts randomly with other learners for enhancing his knowledge. Between two randomly selected learners, one of them who is the best would be selected. The detailed mathematical formulation of TLBO during the learner phase is as follows:

Randomly select two learners P and Q such That $X'_{total\text{-}P,i} \neq X'_{total\text{-}Q,i}$ (where, $X'_{total\text{-}P,i}$ and $X'_{total\text{-}Q,i}$ are the updated function values of $X_{total\text{-}P,i}$ and $X_{total\text{-}Q,i}$ of P and Q respectively at the end of teacher phase)

$$X''_{j,P,i} = X'_{j,P,i} + r_i \, (X'_{j,P,i} - X'_{j,Q,i}), \text{ If } X'_{total\text{-}P,i} < X'_{total\text{-}Q,i} \qquad (6)$$

$$X''_{j,P,i} = X'_{j,P,i} + r_i \, (X'_{j,Q,i} - X'_{j,P,i}), \text{ If } X'_{total\text{-}Q,I} < X'_{total\text{-}P,i} \qquad (7)$$

$X''_{j,P,I}$ is accepted if it gives a better solution for eigenvalues.

The modified TLBO flow chart has been shown in fig. (3).

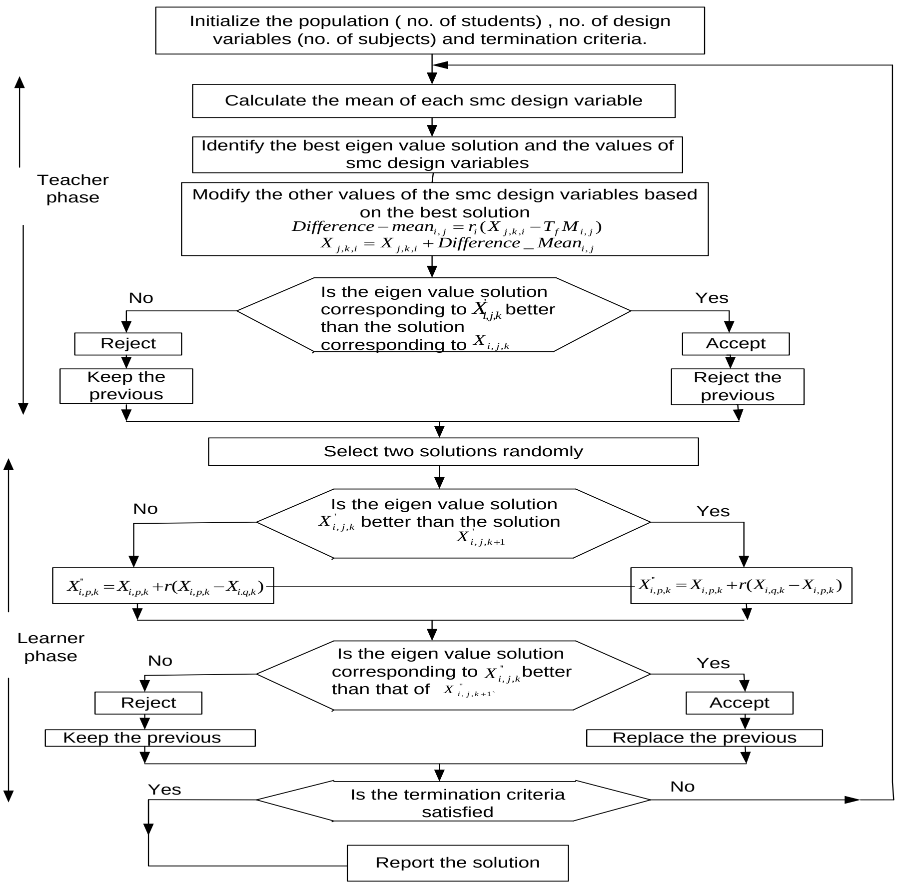

Fig 3: Flow chart for computing optimal values of SMC parameters

4. DESIGN STRATEGY OF UPFC CONTROLLERS

The coordinate tuning of UPC control parameters is carried out by using the TLBO optimization technique to realize the anticipated damping. The steps involved to design the SMCs for UPFC can be reviewed below:

(a) The lightly damped swing modes of interest, that have to be shifted towards left, are to be carefully chosen.

(b) The optimal controlparametes are achieved by subsequent tuning of the TLBO optimization procedure discussed in [15] Section III.

Fig. 4, depicts the block diagram of the SMCs for UPFC, the dynamics of which are illustrated by a first-order plant transfer function $1/(1+sT_p)$ where T_p is denoted by a single time constant for low-frequency small signal studies.

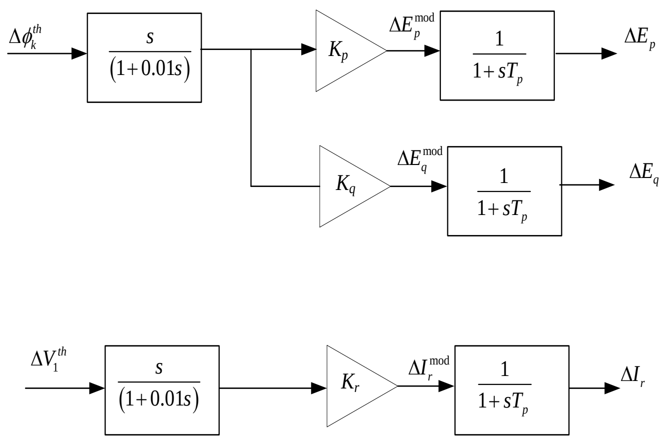

Fig. 4: Block diagram of UPFC with supplementary modulation controllers

5. CASE STUDY

Two multimachine study systems that have been considered for the performance of UPFC supplementary modulation controllers by using TLBO optimization technique are the 4-machine 2-area and 10-machine 39-bus systems [1]. It is motivating to explore the effect of the system damping and hence assess the working of these damping controllers about their potential in damping small frequency oscillations.

a) 4-machine 2-area system: The single line diagram of the system under consideration is shown below in Fig.5. For the system considered [1] the armature resistance is neglected and the damping of all the generators is uniformly taken as 1.0 pu (instead of zero). The UPFC with the supplementary controllers is connected in one of the three AC tie lines between buses 7 and 8, with the shunt branch connected at bus 7. The operating values of E_p, E_q and I_r are assumed to be zero. The performance of UPFC with SMCs is assessed by evaluation of small signal and transient analysis. From small-signal stability, it has been noticed there are three swing modes, out of which there are two local modes and an inter-area mode. The eigenvalues equivalent to the two local modes (swing 1 and swing 2) and the inter-area mode (IAM) at the operating point with and without SMC are given in Table I. The modulation of different control variables that generate the optimized values of the design parameters as given in Table II. Figs. (6)-(8) show the simulation results variation of rotor angles, terminal voltage and power with respect to time for a severe disturbance in the form of a 3-phase fault at 0.1 s at bus no.7 followed by clearing at the end of 5 cycles without any line outage.

The constraints that are selected for the optimization problem of SMCs are as follows:

(i) All the eigenvalues should have a damping ratio which is greater than or equal to 0.10.

(ii) The eigenvalues should have a real part which is less than or equal to -0.8.

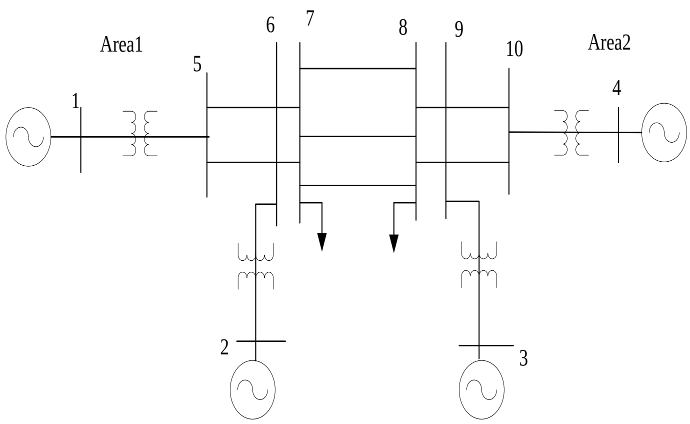

Fig. 5: Single line diagram of 4-machine 2-area system.

The optimized values of the design parameters when the different control variables are modulated are given in Table II.

Table I. Eigen values of 4-machine 2-area system

Without UPFC	With UPFC	Comments
-0.7645 ± 7.2942 i	-1.0358 ± 7.3567 i	Swing mode 1
-0.7409 ± 6.6902 i	-0.8745 ± 6.7476 i	Swing mode 2
-0.0088 ±.4.4445 i	-0.8445 ± 5.6187 i	Inter area mode

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Table II. Optimized values of SMC parameters from TLBO optimization algorithm

Modulated control variables of UPFC	K_r	K_p	K_q	X_{sh}^{th}	X_{ser}^{th}
$E_p+E_q+I_r$	1.7	0.1	0.9	0.001	0.01

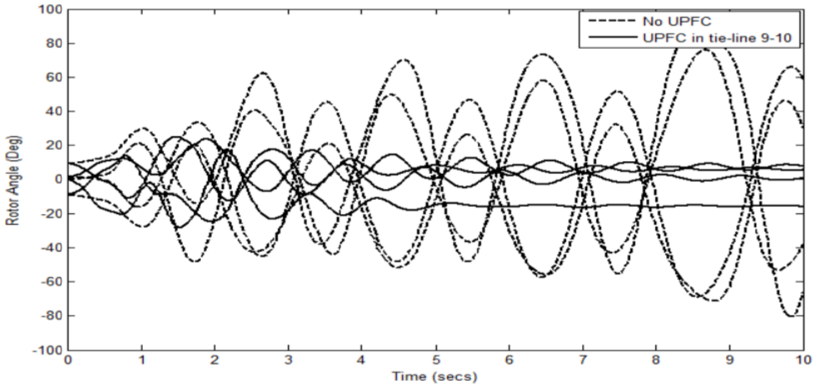

Fig. 6: Plot of rotor angles of generators 1-4 for a 3-phase fault at bus no. 7.

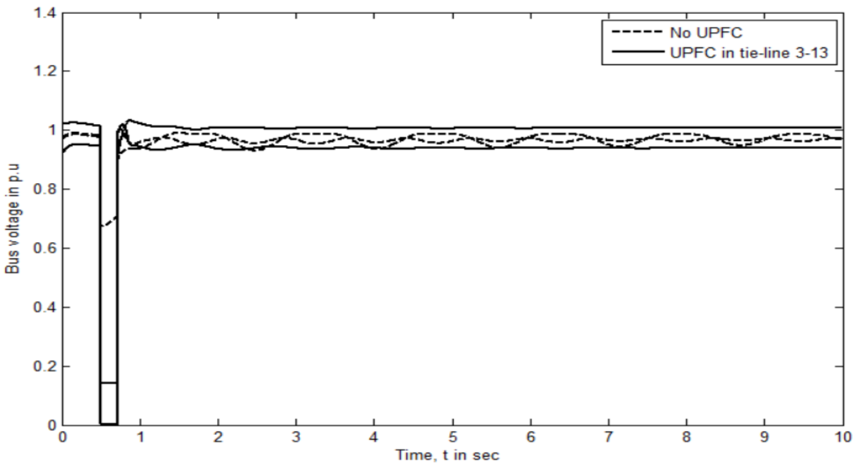

Fig 7: Plot of terminal voltages of generators 1-4 for a 3-phase fault at bus no. 7.

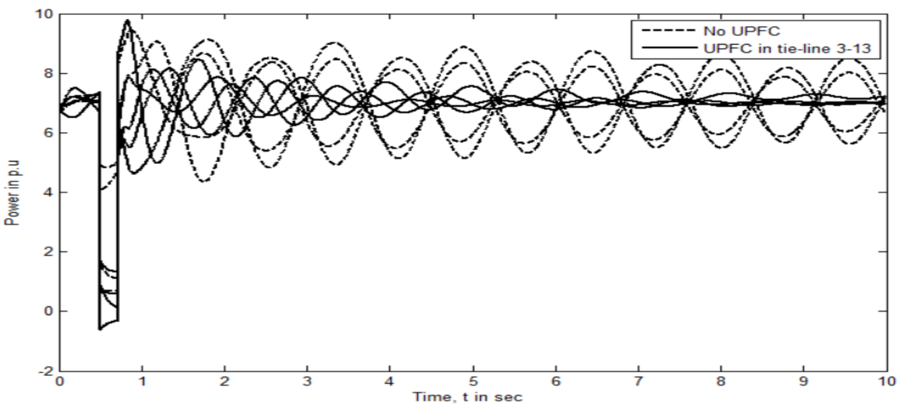

Fig 8: Plot of real power of generators 1-4 for a 3-phase fault at bus no. 7.

b) 10 machine 39 bus system: The single line diagram of the system is shown in Fig.9. The study system is considered as in [1] with generators are represented (1.0) model and the armature resistance is neglected. From the computation of location factors for the detailed model as in [12,13], it is obvious that the line 26-29 is suitable for the damping of swing modes. Hence, the UPFC controller is placed in that line to damp the critical modes. The performance of UPFC with SMCs is assessed by evaluation of small signal and transient analysis. Using small-signal stability analysis, the controller parameters are tuned using TLBO algorithm to obtain optimum values. The closed loop eigen values thus obtained indicate that the improvement was achieved in the damping of the critical modes with just a single controller in line 26-29. The operating values of E_p, E_q and I_r are assumed to be zero. There are 9 swing modes and the eigenvalues corresponding to these modes at the operating point with and without SMC are given in Table III. The modulation of different control variables that generate the optimized values of the design parameters as given in Table IV. Figs.(10)-(14) show the simulation results of variation of rotor angles, terminal voltage and power with respect to time for a severe 3-phase fault disturbance at 0.1 s at bus no. 26 followed by clearing at the end of 0.138 s without any line outage. The eigen value analysis that is performed without and with UPFC SMC controller represent the swing modes.

The constraints that are selected for the optimization problem of SMCs are as follows:

(i) All the eigenvalues should have a damping ratio which is greater than or equal to 0.10.

(ii) The eigenvalues should have a real part which is less than or equal to -0.09.

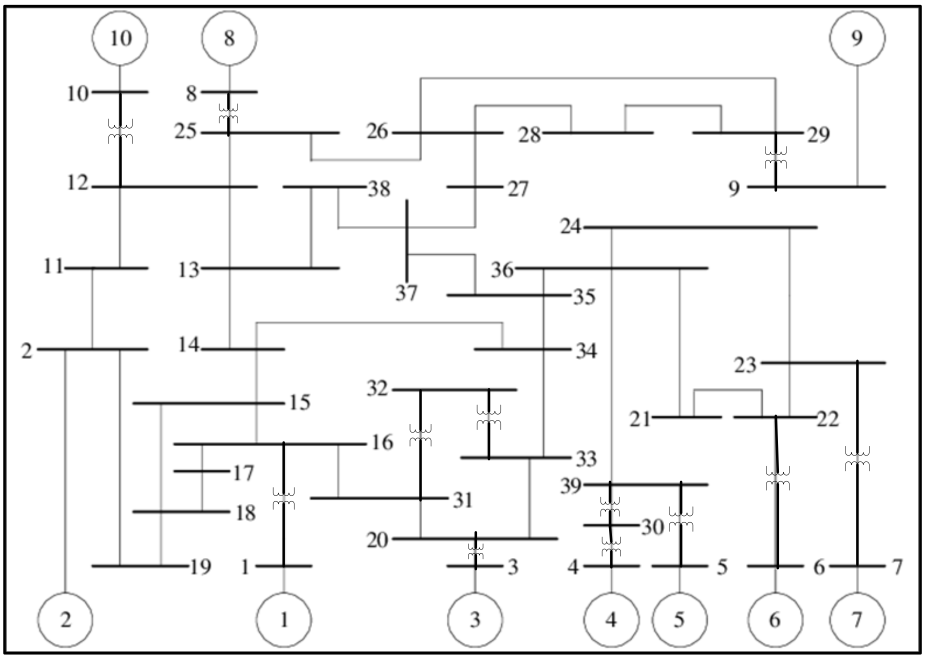

Fig. 9: Single line diagram of 10-machine 39-bus New England system.

Table III. Eigen values of 10-machine 39-bus system

Without UPFC	With UPFC	Comments
-0.2740 ± 8.6877 i	-0.3587 ± 8.6416i	Swing mode 1
-0.2056 ± 8.3452 i	-0.2945 ± 8.3045i	Swing mode 2
-0.2045 ± 8.2615 i	-0.3029 ± 8.1905i	Swing mode 3
-0.1580 ± 7.1570 i	-0.1959 ± 7.1115i	Swing mode 4
-0.1627 ± 6.9796 i	-0.1826 ± 6.9671i	Swing mode 5
-0.1953 ± 6.1813 i	-0.5180 ± 6.1811i	Swing mode 6
-0.0852 ± 6.2701 i	-0.0936 ± 6.4118i	Swing mode 7
0.2071 ± 5.8810 i	-0.1305 ± 6.2969i	Swing mode 8
0.0609 ± 3.9172 i	-0.0469 ± 3.8992i	Swing mode 9

Table IV. Optimized values of SMC parameters from TLBO optimization algorithm

Modulated control variables of UPFC	K_r	K_p	K_q	X_{sh}^{th}	X_{ser}^{th}
E_p+E_q+I_r	27.3946	1.3267	0.1769	0.004447	0.0307534

The optimized values of the design parameters when the different control variables are modulated are given in Table IV.

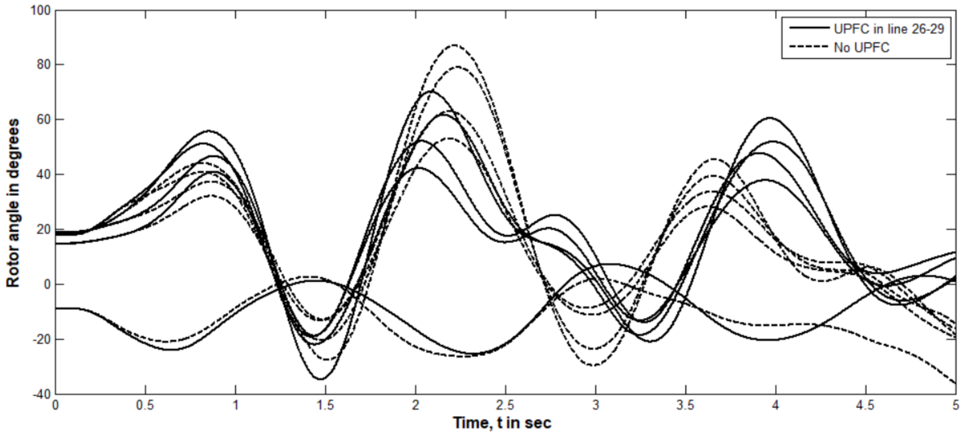

Fig. 10: Plot of rotor angle of generators 1-5 for a 3-phase fault at bus no. 26.

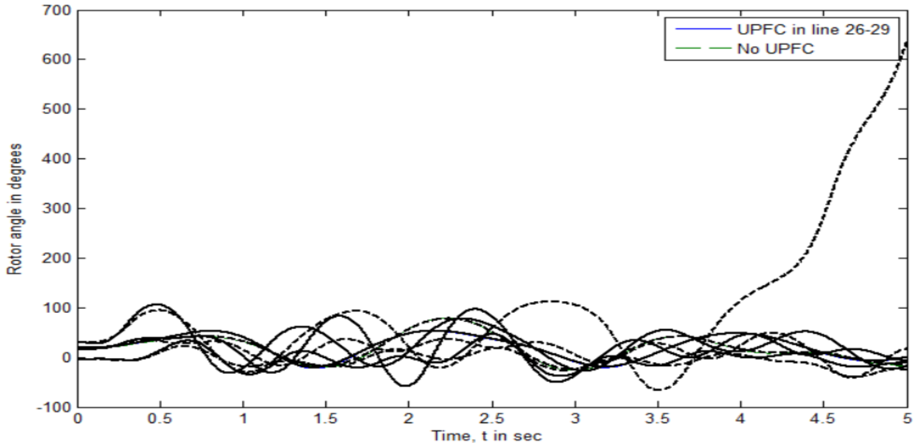

Fig. 11: Plot of rotor angle of generators 6-10 for a 3-phase fault at bus no. 26.

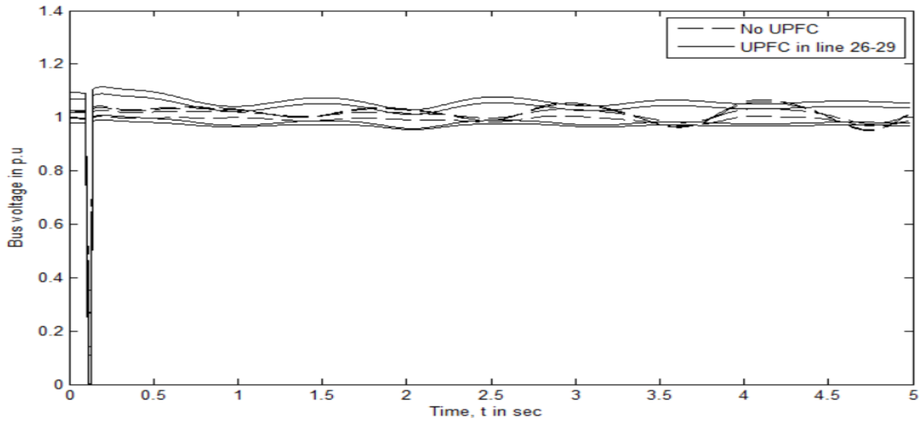

Fig. 12: Plot of terminal voltages at buses 26, 27, 28, 29 for a 3-phase fault at bus no. 26

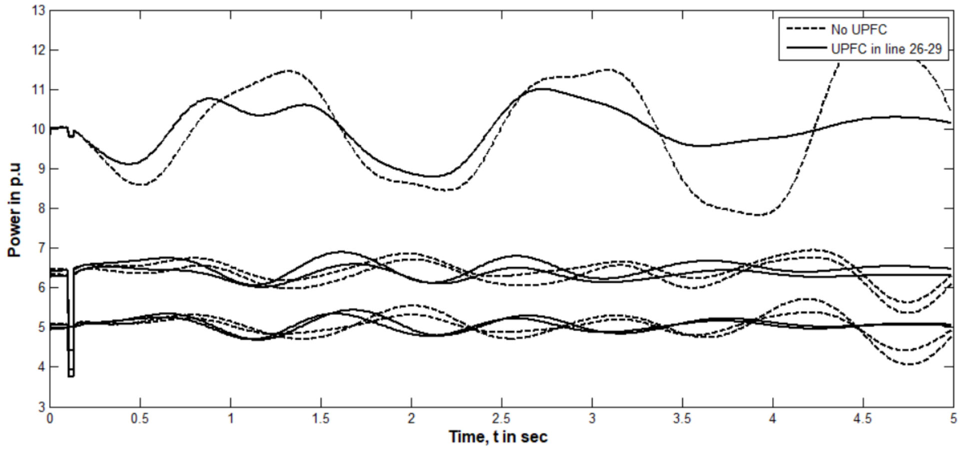

Fig. 13: Plot of real power of generators 1-5 for a 3-phase fault at bus no. 26.

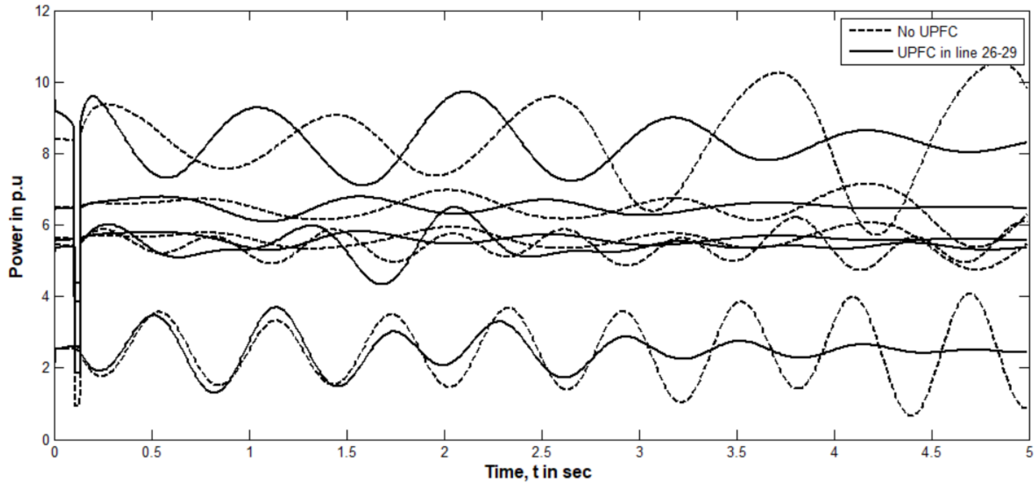

Fig. 14: Plot of real power of generators 6-10 for a 3-phase fault at bus no. 26.

6. DISCUSSION

4-machine 2-area system: From the results it can be observed that there is a considerable enhancement in the damping of local modes and inter-area modes, as evident from the small signal stability. Also, it is clear from the results of transient stability that the small frequency oscillations are damped out faster with UPFC supplementary modulation controllers. It can be examined that the performance of damping controllers is better about initial overshoot and settling time apart from increase in damping of the significant modes. It is noticed from the results obtained with the UPFC supplementary modulation controllers that there is a large enhancement in the damping of the two local modes as well as the inter-area mode. The system response to minor and major disturbances evaluated by carrying out time domain simulation of the nonlinear power system model demonstrates that the small frequency oscillations due to the inter-area mode can be damped out faster with the UPFC supplementary modulation controllers. From the comparison of results obtained from without and with SMCs, it can be noticed that the damping controllers perform better about the settling time and initial overshoot besides increase in damping of the significant modes.

10-machine 39-bus system: From the comparison of the results of small signal stability with and without SMC there is a tremendous enhancement in the damping of swing mode 6 and the remaining modes. Also, the transient stability results show a significant improvement in the damping of rotor angle of machine 9 which is unstable in the absence of UPFC. Rotor angle oscillations of remaining machines are damped with UPFC SMC. Oscillations have also been reduced as observed in the results of terminal voltage and power. The rotor angle of machine 9 is unstable after 3 seconds without UPFC whereas with UPFC the machine 9 is stable.

The equivalent circuit of the electromechanical system present robust control laws for the shunt and series reactive controllers [12,13] that can ensure better damping. However, what is intriguing is the conflict that arises between shunt and series modulation controllers when applied concurrently. The suitable coordination requires agreement while choosing the gains of controllers. An essential feature of the control strategy of UPFC modulation controllers is that they are decoupled, robust and the control signals are produced from local measurements. From theoretical analysis, the control laws are straightforward that are based on simplified models. However, the usefulness of the modulation controllers is examined on multi-machine power systems determined by detailed generator models.

7. CONCLUSIONS

This paper emphasizes the design and tuning of SMC for UPFC based on a new TLBO optimization technique for the first time. The control strategy for the real voltage controller based on energy function, the control laws for shunt reactive current controller and the series reactive voltage controller are adopted. The control laws that are developed independently, are simultaneously applied to the supplementary modulation controllers of UPFC. The coordinate tuning of the controllers of the UPFC supplementary modulation controllers is performed using TLBO optimization technique for the first time. This method of tuning the control parameters using TLBO algorithm maintains a good co-ordination among all the controllers of the supplementary modulation controllers of UPFC and hence guarantees efficient damping of small frequency oscillations. This is clear from the small signal and transient stability results obtained from 10-machine 39-bus and 4-machine 2-area benchmark systems.

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