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A New Jaya Optimization Technique for the Stability Improvement of 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 Jaya 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 Jaya 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, Jaya optimization technique, Multi-machine power systems, small-signal stability, Transient stability

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I. 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 novel tracker 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 of UPFC. 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], Jaya algorithm a newly proposed algorithm which has a strong ability to solve the constrained and unconstrained optimization problems. The algorithm is based on the concept that the solution obtained for a given problem should move towards the best solution and should avoid the worst solution.

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 reactive current, series real and reactive voltage controllers have been chosen as in [12][13]. The coordinate tuning of SMC parameters has been performed using the new Jaya 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 Jaya 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 dynamic models of the UPFC SMCs determine the efficiency of new Jaya optimization in damping low frequency oscillations.

II. CONTROL LAWS 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. The pre-selected parameters of the three controllers are tuned simultaneously through a constrained JAYA optimization approach to obtain coordination among controllers.

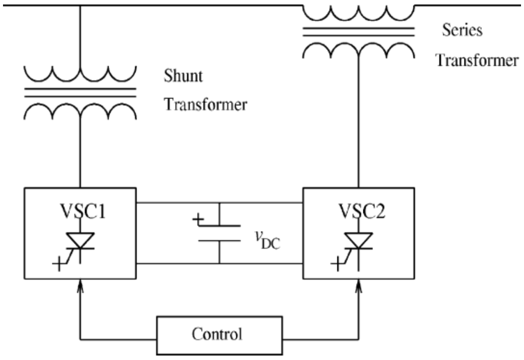

Figure 1: Unified power flow controller.

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

III. TUNING OF UPFC SUPPLEMENTARY MODULATION CONTROLLERS USING JAYA OPTIMIZATION TECHNIQUE

In this section, the tuning of SMCs of UPFC by using JAYA optimization technique has been analyzed. The tuneable UPFC 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 JAYA 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

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

and

$\sigma_i \leq C_2$, i=1,2,…….n

where *m* is the total number modes of interest; *n*, number of eigenvalues; σ_i and ω_i, are the real and imaginary parts of eigenvalues; *D* the damping ratio of eigenvalue; W_j, weight associated with the mode of interest; *k*, vector of control parameters, where each of the elements of the vector is positive, C_1 and C_2 are positive and negative respectively.

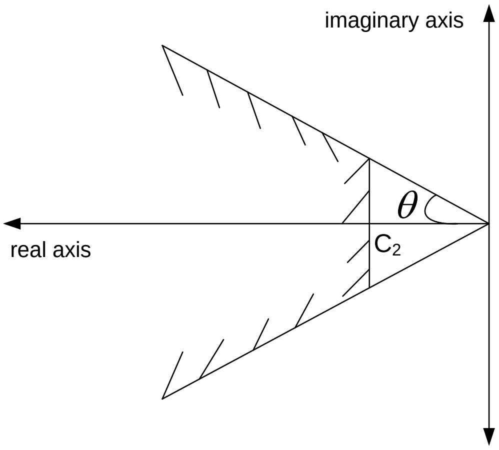

Figure 2: Permissible region for location of closed loop eigenvalues in the left half plane.

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 Jaya optimization technique. The problem formulation given by equations (1) is based on analysis of eigenvalues of the system. For the constrained objective function that has been considered, an initial random candidate solution with the design parameters within boundaries, would be considered. The best and worst solutions would be identified within the candidate solution at a given iteration would be approximated to a better solution based on the Jaya optimization strategical mathematical equation as detailed below in (4). The mathematical formulation helps in improving the better eigen values to become best as well as eliminate the worse eigen values. The modified objective function becomes the input to the next iteration, and the eigenvalues are improved continuously at the end of every iteration and the problem would be successively terminated. The details of the Jaya algorithm and the flow chart have been shown in fig. (3).

A) Jaya Algorithm

Step 1: Define the constrained optimization problem according to equations (1), Initialize the 5 design parameters within certain maximum & minimum limits, with a population size 'n' defines the number of candidate solutions and then compute the eigen values.

Step 2: The constraints for the given problem i.e., minimization of the eigen value and maximization of the damping ratio are set.

Step 3: The computation of eigenvalues is performed for each candidate solution and the value of objective function is calculated that corresponds to each solution.

Step 4: Identify the best and worst solutions among the candidate solutions.

Step 5: Based on the best and worst solutions modify all candidate solutions.The proposed modification is expressed as follows:

$$X'_{j,k,i} = X_{j,k,i} + r_{1,j,i}\left(X_{j,best,i} - \left|X_{j,k,i}\right|\right) - r_{2,j,i}\left(X_{j,worst,i} - \left|X_{j,k,i}\right|\right) \quad (4)$$

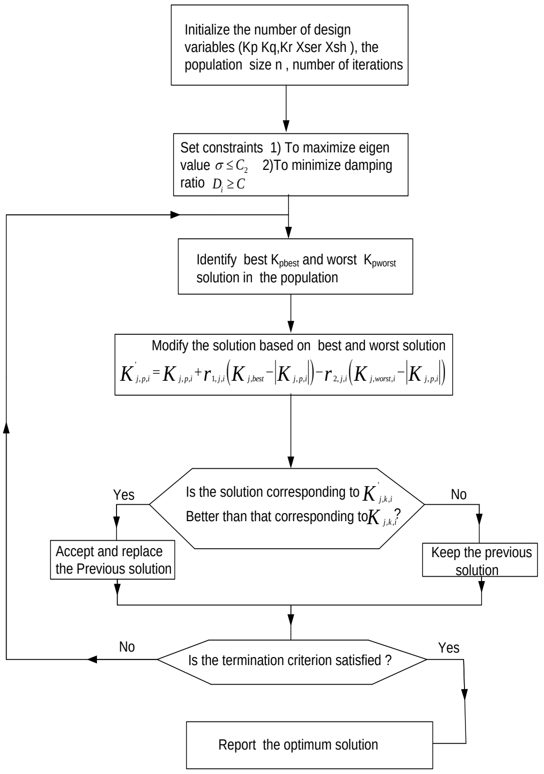

Figure 3: Flow chart for computing optimal values of SMC parameters

IV. DESIGN OF UPFC SUPPLEMENTARY MODULATION CONTROLLERS

The coordinate tuning of UPC control parameters is carried out by using the JAYA 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 control parameters are achieved by subsequent tuning of the JAYA 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.

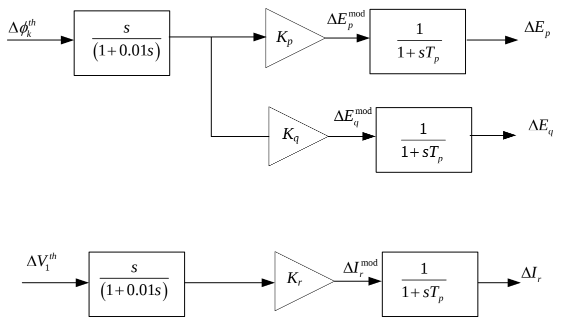

Figure 4: Block diagram of UPFC with supplementary modulation controllers

V. CASE STUDY

Two multimachine study systems that have been considered for the performance of UPFC supplementary modulation controllers by using Jaya 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.

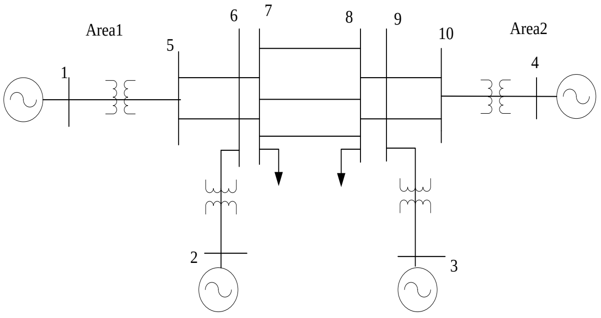

Figure 5: Single line diagram of 4-machine 2-area system.

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

No UPFC	With UPFC	Modes
-0.7645 ± 7.2942 i	-1.0358 ± 7.3567 i	SM 1
-0.7409 ± 6.6902 i	-0.8745 ± 6.7476 i	SM 2
-0.0088 ±.4.4445 i	-0.8445 ± 5.6187 i	IAM

Table II
Optimized values of SMC parameters from JAYA optimization algorithm

Modulated 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

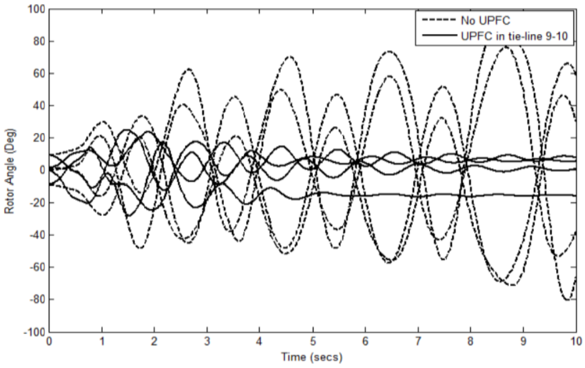

Figure 6: Plot of rotor angles of generators 1-4 for a 3-phase fault at bus no. 7.

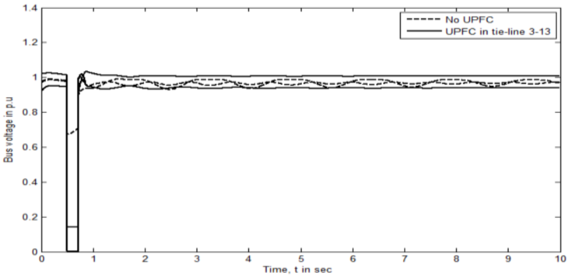

Figure 7: Plot of terminal voltages of generators 1-4 for a 3-phase fault at bus no. 7.

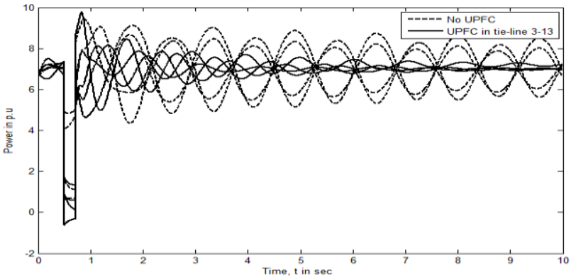

Figure 8: Plot of real power of generators 1-4 for a 3-phase fault at bus no. 7.

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 JAYA 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.

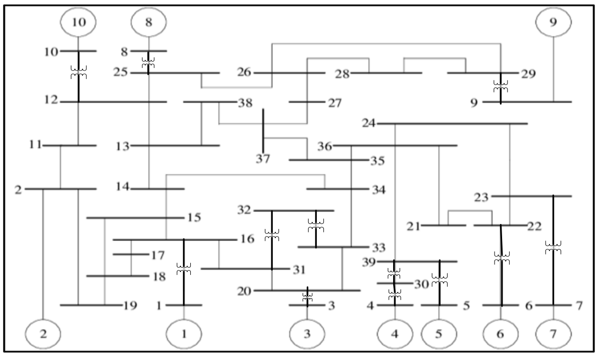

Figure 9: Single line diagram of 10-machine 39-bus New England system.

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

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

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

Table IV
Optimized values of SMC parameters from JAYA optimization algorithm

Modulated UPFC	K_r	K_p	K_q	X_{sh}^{th}	X_{ser}^{th}
$E_p+E_q+I_r$	27.4	1.33	0.17	0.004447	0.031

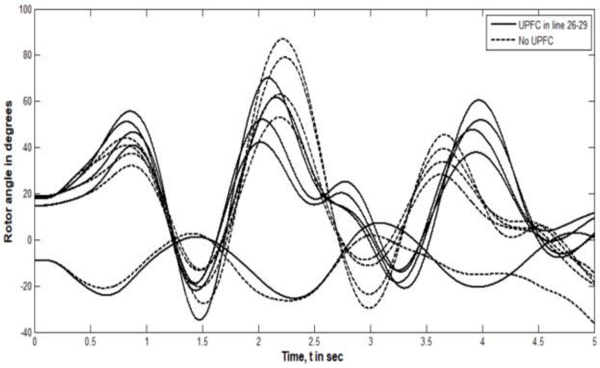

Figure 10: Plot of rotor angle of generators 1-5 for a 3-phase fault at bus no. 26.

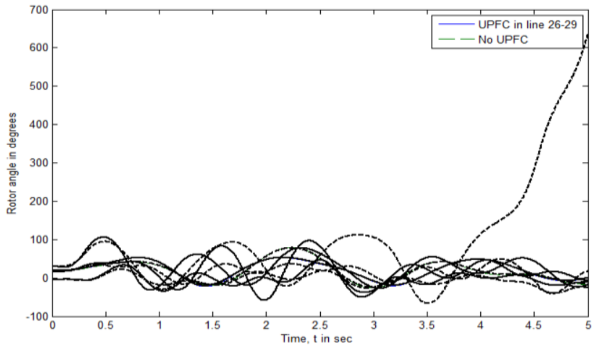

Figure 11: Plot of rotor angle of generators 6-10 for a 3-phase fault at bus no. 26.

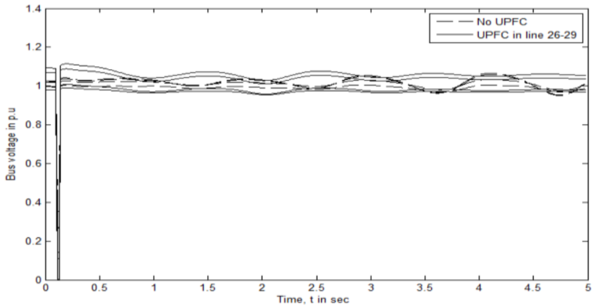

Figure 12: Plot of terminal voltages at buses 26, 27, 28, 29 for a 3-phase fault at bus no. 26

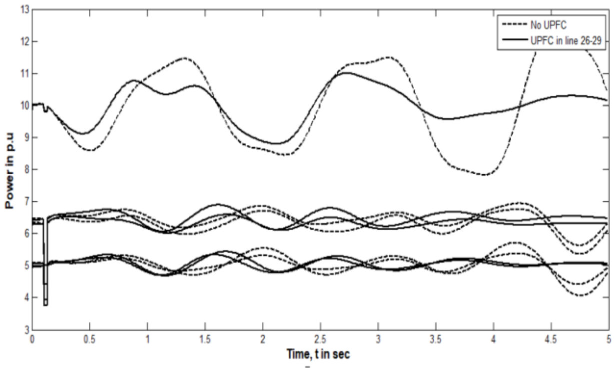

Figure 13: Plot of real power of generators 1-5 for a 3-phase fault at bus no. 26.

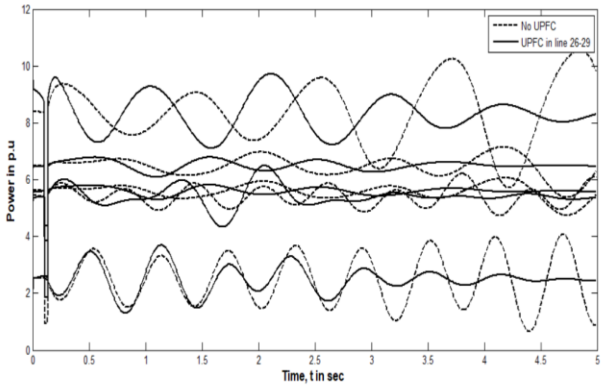

Figure 14: Plot of real power of generators 6-10 for a 3-phase fault at bus no. 26.

VI. DISCUSSION

a) 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.

b) 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.

VII. CONCLUSIONS

This paper emphasizes the design and tuning of SMC for UPFC based on a new JAYA 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 JAYA optimization technique for the first time. This method of tuning the control parameters using JAYA 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.

REFERENCES

[1]. Padiyar KR. *Power system dynamics—stability and control* (New York: Wiley; 1996).

[2]. Huayuan Chen, Youyi Wang, Rujing Zhou, Transient stability enhancement via coordinated excitation and UPFC control, *Electrical Power and Energy Systems*, *24(1),* 2002, 19-29.

[3]. Y.L.Kang, G.B.Shrestha and T.T.Lie, Application of an NLPID controller on a UPFC to improve transient stability of a power system, *IEE Proceedings, Generation, Transmission. Distribution*, *148(6),* 2001, 523-529.

[4]. Chonhoe Kim, Jungsoo Park, Gilsoo Jang, Kwang M. Son, and Tae- Kyun Kim, Modeling of Unified Power Flow Controllers Using a Current Injection Method for Transient Stability Analysis, *IEEE/PES Transmission and Distribution Conference & Exhibition,* Asia and Pacific Dalian, China, 2005.

[5]. S. Krishna, K.R. Padiyar, Discrete control of unified power flow controller for stability improvement, *Electric Power Systems Research, 75 (2-3),* 178–189.

[6]. Eskandar Gholipour and Shahrokh Saadate, Improving of Transient Stability of Power Systems Using UPFC, *IEEE Transactions on Power Delivery*, 20(2), 2005, 1677-1682.

[7]. Ajami, S.H. Hosseini, S. Khanmohammadi, G.B. Gharehpetian, Modeling and control of C-UPFC for power system transient studies, *Simulation Modelling Practice and Theory, 14,* 2006, 564–576.

[8]. Sukumar Mishra, Neural-Network-Based Adaptive UPFC for Improving Transient Stability Performance of Power System, *IEEE Transactions on Neural Networks*, *17(2),* 2006, 461-470.

[9]. Ani M. Gole, Udaya D. Annakkage, and D. A. Jacobson, Damping Performance Analysis of IPFC and UPFC Controllers Using Validated Small-Signal Models Shan Jiang, *IEEE Transactions on Power Delivery, 26(1),* 2011, 446-454.

[10]. Kenichi Kawabe, Akihiko Yokoyama, Transient Stability Improvement by UPFC Using Estimated Sensitivities Based on Thevenin's Theorem and DC Power Flow Method, *Journal of International Council on Electrical Engineering, 2(3),* 2012, 257-263.

[11]. Li Wang, Hao-Wen Li, and Cheng-Tai Wu, Stability Analysis of an Integrated Offshore Wind and Seashore Wave Farm Fed to a Power Grid Using a Unified Power Flow

Controller, *IEEE Transactions on Power Systems, 28(3)*, 2013, 2211-2221.

[12]. Kulkarni AM, Padiyar KR, Damping of power swings using series FACTS controllers, *Electric Power and Energy Systems, 21(4), 1999,* 75–95.

[13]. Kulkarni AM, Padiyar KR. Damping of power swings using shunt FACTS controllers, *Fourth workshop on EHV Technology,* Bangalore, July 1998.

[14]. K.R. Padiyar, H.V. Saikumar Coordinated design and performance evaluation of UPFC supplementary modulation controllers, *Electrical Power and Energy Systems, 27(2),* 2005, 101–111.

[15]. R. Venkata Rao, JAYA: A simple and new optimization algorithm for solving constrained and unconstrained optimization problems, *International Journal of Industrial Engineering Computations, homepage: www.GrowingScience.com/ijiec*.

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