DYNAMIC STABILITY IMPROVEMENT BY USING UNIFIED POWER FLOW CONTROLLER

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In this paper, using the Lyapunov energy function, improvement of the dynamic stability of a unified power flow controller (UPFC) by proper control of the coefficients is studied. The proposed method uses the particle swarm optimization (PSO) algorithm to estimate the coefficients in order to improve the stability. The proposed method is robust against changing the parameters of the system and the damping ratio of fluctuations is fast when the topology is changed. Simple implementation of the control function is of the benefits of the proposed method. Simulation results for SMIB with UPFC show the effectiveness of the proposed method.

Keywords dynamic stability, unified power flow controller, transient energy function, algorithm particle swarm optimization

1. Introduction

One of important issues in power system is stability, that can be divided into angular and voltage stabilities. In angular stability, often transient and dynamic stabilities are studied. Small disturbances can have long-term effects on the power system, and are studied in the field of dynamic stability [1].

In improving dynamic stability, usually the power system stabilizers (PSS) are used. PSS gets the feedback of the velocity signal and converts it to the equivalent voltage by a Lead-Lag controller and adds this voltage to the reference voltage [2-4].

Flexible AC transmission systems (FACTS), are alternating current transmission systems which can be used to increase the availability of controlling and the power transfer capacity and act by the combination of power electronics and other static controllers. Using power electronic equipment in the transmission networks is one of the newest developments in the electricity industry. Due to considerations of transient, dynamic and voltage stabilities, it is hardly to utilize electrical lines in their maximum level of heat capacity. Using FACTS elements, with no need to produce additional energy or to change the existing transmission lines, we can utilize the highest transmission capacity. Also, we can control the power distribution in specific and desired lines. FACTS is used, in order to

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maintain stability, regulating voltage and etc. while PSS has limited capabilities and it cannot properly damp inter area swing of multimachine system.

One of the FACTS elements that can help improving the dynamic stability is unified power flow controller (UPFC). UPFC is formed from the connection between the Static Synchronous Compensators (STATCOM) and the Static Synchronous Series Compensators (SSSC). Series and shunt parts in UPFC are fed in common by a DC capacitor. UPFC does series and parallel compensations together and can continuously control the phase angle, the impedance and the amplitude of the voltage. Thus, it can control the active and the reactive power of transmission line independently. Also, series and shunt parts in UPFC operate independently [5]. Therefore, among the elements FACTS, UPFC is more superior towards the other elements. UPFC basic idea is presented in [6, 7].

Various methods have been proposed for the modeling and control of the UPFC. In some of these methods the Proportional and Integral (PI) controller is used to control UPFC [8,9], In this case if system has several modes then the PI controller is less effective in damping oscillations. In addition, if the operating point of the system at which the controller was tuned, is changed, the PI controller shows poor performance. In some other methods, UPFC is modeled as a power injection system [10,11].

Using the feedback linearization control with UPFC [12], the nonlinear dynamical model of the power system becomes linear, and then linear control methods are used. In nonlinear control methods, a Lyapunov function is used [13]. It is not easy to obtain a suitable and comprehensive Lyapunov function. So Lyapunov energy function is suitable for controller design [14,15].

In this paper, first a nonlinear dynamic model is presented and then a nonlinear control method based on energy function is introduced. Using nonlinear control methods for the UPFC, inter-area oscillations are decreased. Hence, the proposed nonlinear control method is affected by changing the operating conditions. This enables the system to operate well even with topology changes.

2. Power System Modeling with UPFC

Fig. 1 shows the diagram of single machine infinite bus power system connected with UPFC. The main components of a UPFC are converters, transformers and a DC link capacitor. The pulse width modulation (PWM) technique is applied to the inverters. Here, the resistances of transformers, transmission lines and other parts are ignored. The line and machine with UPFC characteristics are shown in the Appendix.

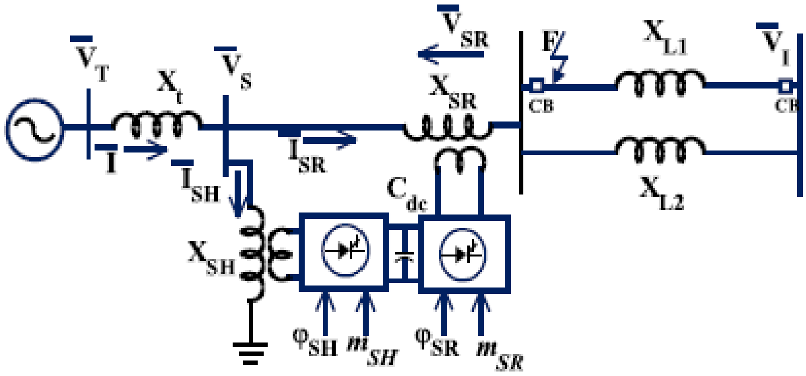

Fig. 1 single machine infinite bus power system with UPFC

In Fig. 1 $\bar{V}_T$ and $\bar{V}_I$ are the voltage of the terminal of the generator and the voltage of the infinite bus respectively. The relevant equations are as follows.

$$P_e = V_{Td} I_d + V_{Tq} I_q \tag{1}$$

where

$$V_{Td} = X_q I_q \ ; \qquad I_d = I_{SHd} + I_{SRd} \ ;$$

$$V_{Tq} = E_q' - X_d' I_d \ ; \quad I_q = I_{SHq} + I_{SRq} \ ; \quad E_q' = E_q - (X_d - X_d') I_d;$$

where I_d and I_q are the d-q components of generator terminal current $\bar{I}$. I_{SHd}, I_{SHq}, I_{SRd} and I_{SRq} are the d-q of shunt and series currents components ($\bar{I}_{SH}$ and $\bar{I}_{SR}$) of UPFC.

V_{SHd}, V_{SHq}, V_{SRd} and V_{SRq} are the d-q components of the voltage injected by shunt and series converters (V_{SH} and $\bar{V}_{SR}$) of UPFC which are as follows [16].

$$\begin{bmatrix} V_{SHd} \\ V_{SHq} \\ V_{SRd} \\ V_{SRq} \end{bmatrix} = \begin{bmatrix} 0 & -X_{SH} & 0 & 0 \\ X_{SH} & 0 & 0 & 0 \\ 0 & 0 & 0 & -X_{SR} \\ 0 & 0 & 0 & X_{SR} \end{bmatrix} \begin{bmatrix} I_{SHd} \\ I_{SHq} \\ I_{SRd} \\ I_{SRq} \end{bmatrix} \begin{bmatrix} m_{SH} V_{dc} \cos(\varphi_{SH}) / 2 \\ m_{SH} V_{dc} \sin(\varphi_{SH}) / 2 \\ m_{SR} V_{dc} \cos(\varphi_{SR}) / 2 \\ m_{SR} V_{dc} \cos(\varphi_{SR}) / 2 \end{bmatrix} \tag{2}$$

where

$$I_{SHd}=\frac{X_{SRL}\,E_q'}{X_{DT}}-\frac{X_{SRLTD}\,m_{SH}\,V_{dc}\sin(\varphi_{SH})}{2X_{DT}}+\frac{X_{TD}\,V_I\cos(\varphi)}{X_{DT}}+\frac{X_{TD}\,m_{SR}\,V_{dc}\sin(\varphi_{SR})}{2\,X_{DT}} \quad (3)$$

$$I_{SHq}=\frac{X_{SRLTQ}\,m_{SH}\,V_{dc}\cos(\varphi_{SH})}{2\,X_{QT}}-\frac{X_{TQ}\,V_I\sin(\delta)}{X_{QT}}-\frac{X_{TQ}\,m_{SR}\,V_{dc}\cos(\varphi_{SR})}{2\,X_{QT}} \quad (4)$$

$$I_{SRd}=\frac{X_{SH}E_q'}{X_{DT}}+\frac{X_{TD}m_{SH}V_{dc}\sin(\varphi_{SH})}{2X_{DT}}-\frac{X_{TSHD}V_I\cos(\delta)}{X_{DT}}-\frac{X_{TSHD}m_{SR}V_{dc}\sin(\varphi_{SR})}{2X_{DT}} \quad (5)$$

$$I_{SRq}=\frac{X_{TSHQ}m_{SR}V_{dc}\cos(\varphi_{SR})}{2X_{QT}}-\frac{X_{TSHQ}V_I\sin(\delta)}{X_{QT}}-\frac{X_{TQ}m_{SH}V_{dc}\cos(\varphi_{SH})}{2X_{QT}} \quad (6)$$

Equations (7) to (9) represent the nonlinear dynamic model of generator [17]. Equation (10) shows the dynamical model of UPFC.

$$\dot{\delta}=\omega-\omega_0 \quad (7)$$

$$\dot{\omega}=\frac{1}{M}(P_m-P_e-D\frac{(\omega-\omega_0)}{\omega_0} \quad (8)$$

$$\dot{E}_q'=\frac{1}{T_{d0}'}(E_{fd}-(X_d-X_d')I_d-E_q') \quad (9)$$

$$\dot{V}_{dc}=\frac{3m_{SH}}{4C_{dc}}(\cos(\cos\varphi_{SH})I_{SHd}+\sin(\varphi_{SH})I_{SHq})+\frac{3m_{SR}}{4C_{dc}}(\cos(\varphi_{SR})I_{SRd}+\sin(\varphi_{SR})I_{SRq}) \quad (10)$$

where δ, ω, P_m, D, M, and T_{d0}' are rotor angle, angular velocity, input mechanical power, damping coefficient, generator inertia and direct axis open circuit time constant of the generator, respectively.

2.1. New Dynamic model of Power Network

Equations (1) to (6) are algebraic equations, while equations (7) to (10) are the differential equations. Combining these equations together, an approximating model of the power system is formed. However, designing the controller in this environment is difficult. So, it is better to use other proper equations instead of the algebraic equations. For this purpose, using the derivative of the equations of the generator terminal current $I_d=I_{SHd}+I_{SRd}$ and $I_q=I_{SHq}+I_{SRq}$, a dynamical model of power network is achieved [18,19].

$$\frac{\partial I_d}{\partial t}=\frac{\partial I_d}{\partial\delta}\dot{\delta}+\frac{\partial I_d}{\partial E_q'}\dot{E}_q'+\frac{\partial I_d}{\partial V_{dc}}\dot{V}_{dc}+\frac{\partial I_d}{\partial m_{SH}}\dot{m}_{SH}+\frac{\partial I_d}{\partial\varphi_{SH}}\dot{\varphi}_{SH}+\frac{\partial I_d}{\partial m_{SR}}\dot{m}_{SR}+\frac{\partial I_d}{\partial\varphi_{SR}}\dot{\varphi}_{SR} \quad (11)$$

$$\frac{\partial I_q}{\partial t} = \frac{\partial I_q}{\partial \delta}\dot{\delta} + \frac{\partial I_q}{\partial E'_q}\dot{E}'_q + \frac{\partial I_q}{\partial V_{dc}}\dot{V}_{dc} + \frac{\partial I_q}{\partial m_{SH}}\dot{m}_{SH} + \frac{\partial I_q}{\partial \varphi_{SH}}\dot{\varphi}_{SH} + \frac{\partial I_q}{\partial m_{SR}}\dot{m}_{SR} + \frac{\partial I_q}{\partial \varphi_{SR}}\dot{\varphi}_{SR} \tag{12}$$

By solving equations (8) and (9), new dynamical equations are obtained. Parameters $a_{11} \cdots a_{23}$ and $b_{11} \cdots b_{24}$ are mentioned in the Appendix.

$$\begin{bmatrix} \dot{I}_d \\ \dot{I}_q \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{bmatrix} \begin{bmatrix} \dot{\delta} \\ \dot{E}'_q \\ \dot{V}_{dc} \end{bmatrix} + \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} \\ b_{12} & b_{22} & b_{23} & b_{24} \end{bmatrix} \begin{bmatrix} \dot{m}_{SH} \\ \dot{\varphi}_{SH} \\ \dot{m}_{SR} \\ \dot{\varphi}_{SR} \end{bmatrix} \tag{13}$$

The terms $\dot{I}_d$ and $\dot{I}_q$ express a nonlinear dynamic model of single machine power system that its inputs are derivative of the UPFC control parameters, m_{SH} , φ_{SH} , φ_{SH} and m_{SR}. Also UPFC control parameters can be obtained by integrating the control inputs. Substituting $\dot{\delta}$, $\dot{E}'$ and $\dot{V}_{dc}$ from equations (7) to (10) in equation (13), the following equation is achieved

$$\begin{bmatrix} \dot{I}_d \\ \dot{I}_q \end{bmatrix} = \begin{bmatrix} C_1(x) \\ C_2(x) \end{bmatrix} + \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} \\ b_{12} & b_{22} & b_{23} & b_{24} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} \tag{14}$$

According to equation (14), there are four choices for the input control signals. The converter 2 of the main function of the UPFC can be controlled by injecting a voltage V_{SR} (with controllable amplitude and phase angle). Also Control of the injected power from the UPFC is essential for oscillation damping. Therefore the variable V_{SR} with constant phase angle can be used for designing of the controller. With this assumption, rewriting equation (14) gives:

$$\begin{aligned} \dot{I}_d &= C_1(x) + b_{13}u_3 \\ \dot{I}_q &= C_2(x) + b_{23}u_3 \end{aligned} \tag{15}$$

3. Controller design

The problem of improving the dynamic stability of UPFC is designed with the purpose of controlling of the two quantities of the generator, i.e. load angle δ and the angular velocity ω relative to their values before the fault δ_0 and ω_0. First, the new state variables are defined as follows:

$$\begin{aligned} x_1 &= \delta - \delta_0 \\ x_2 &= \omega - \omega_0 \\ x_3 &= \frac{1}{M}(\mathrm{P}_m - P_e) \end{aligned} \tag{16}$$

Considering that $P_e = E'_q I_q$, the new system equations become

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= x_3 - \frac{D}{M\omega_0} x_2 \\ \dot{x}_3 &= f_T + g_T u_3 \end{aligned} \tag{17}$$

where

$$f_T = \frac{1}{M}\left[\frac{I_q E_{fd}}{T'_{d0}} - \frac{I_q E'_q}{T'_{d0}} - E'_q C_2(x)\right] + \frac{I_d I_q}{M T'_{d0}}(X_d - X'_d)$$

$$g_T = -\frac{E'_q b_{2i}}{M}$$

In study of the dynamic stability, the worst state is that the value of the generator damping coefficient D is zero. In other words, if system becomes stable with this value of D, then it will remained stable in other conditions. Hence in equation (17) value of this coefficient is considered zero, so we have:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= x_3 \\ x'_3 &= f_T + g_T u_3 \end{aligned} \tag{18}$$

The power system with UPFC is a nonlinear system. Therefore, to achieve better and effective control, the control law for modulation index m_{SR} is designed by a nonlinear control method.

3.1. Energy Function

One of the evaluating tools for the system stability and controller design is the Lyapunov function. According to Lyapunov theorem if such a scalar function $V(x)$ exists that in all regions, the value function $V(x)$ is semi definite positive and $\dot{V}(x)$ is semi definite negative, then system is asymptotically stable around the balance point.

In power systems, the Lyapunov function is the sum of the kinetic and potential energies of the system. The energy function is [20]:

$$V(\delta,\omega) = \frac{1}{2} M(\omega - \omega_0)^2 + [-P_m(\delta - \delta_0) - P_{\max}(\cos\delta - \cos\delta_0)] \tag{19}$$

where the first term represents the kinetic energy and the second term represents potential energy of system relative to the balance point δ_0. According to equation (19) the value of the Lyapunov energy function at the balance point δ_0 is zero. The energy function of system starts to increase after fault occurring. To improve the stability of the system, the energy function must rapidly move to zero. Since zero value for Lyapunov energy function represents that the system reaches the stable condition.

Inserting the variables of (13) in the derivative of (16), we have:

$$\dot{V}(x) = Mx_3x_2 - P_m x_2 + P_{\max}\sin(x_1 + \delta_0)x_2 \tag{20}$$

As it is mentioned, the system is asymptotically stable around the balance point, when $\dot{V}(x)$ is semi definite negative. This will be achieved by the following assumption

$$x_3 = \frac{1}{M}[-K_d x_2 + P_m - P_{\max}\sin(x_1 + \delta_0)] \tag{21}$$

The design constant K_d is selected in a way that the Eigen-values of the linear system have negative real parts. The control input u_3 is obtained by inserting the derivative of equation (21) in equation (18) as follows.

$$u_3 = \frac{1}{g_T}[\frac{1}{M}(-K_d x_3 - P_{\max}x_2\cos(x_1 + \delta_0)) - f_T] \tag{22}$$

For optimizing the design parameters of the controller, the Velocity Update Relaxation Particle Swarm Optimization (VURPSO) algorithm is used.

3.2. Velocity Update Relaxation Particle Swarm Optimization

The VURPSO algorithm completes the PSO algorithm. The PSO algorithm is originated from social behavior of fishes, bees and birds. In the PSO algorithm, a group of particles (as the variables of the optimization problem) are distributed in the search region. Based on the inrush behavior of particles**,** other particles try to reach the position of the top particles**.** However, the position of the top particles is changing. In PSO algorithm, validity of the position of the particles is checked and then measuring the position of each region must be done in every iteration of the algorithm. In VURPSO algorithm without checking the validity of positions, the validity of the speed of the particles in each region is investigated in every iteration, Also in the PSO algorithm, the velocity of the particles is updated in every iteration while in the VURPSO algorithm, if the fitness function of each particle in the current iteration is better than that of the preceding one, then the velocity of that particle is kept unchanged, otherwise the velocity is updated.

In the VURPSO algorithm, two variables V and X is defined as the position and velocity of the particle respectively. The modified equations for velocity and position of a particle are as follows [21].

$$V_{i,j}^{(K+1)} = V_{i,j} + c_1 * Rand1 * (p\_best_{i,j} - X_{i,j}^{(K)}) + c_2 * Rand2 * (g\_best_{i,j} - X_{i,j}^{(K)}) \quad (23)$$

$$X_{i,j}^{(K+1)} = (1 - mf) * X_{i,j}^{(K)} + mf * V_{i,j}^{(K+1)} \quad (24)$$

where $i = 1,2 \ldots \mathrm{n}$ and $j = 1,2 \ldots \mathrm{m}$ that n is the number of particles of the group and m the number of members forming the particles. p_best is the best position of each particle and g_best is the best position of all particles during the running of the algorithm. $Rand1$ and $Rand2$ are random numbers in range (0, 1). c_1 and c_2 are called acceleration factors and are positive numbers. mf is the momentum factor and its value is between zero and one.

4. Simulation results

In this section, using MATLAB programming, the performance of controller in damping the oscillation of the rotor angle of the power system in a single machine system has been studied. The simulation results of the energy function controllers are compared with those of the Lyapunov controller [19]. The system is simulated without any fault for 0.2 sec. Then, a three-phase fault for 4 cycles (66 ms) in one of the transmission lines marked with F is happened as in Fig. 1. It can be inferred from the Fig. that after the fault occurs, the fluctuations are high and the system becomes unstable. But using the proposed controller, damping is reduced very much. In Figs. 2 to 5 the ability of the proposed controller in improving the damping of the system is shown which is damped in less than 1.2 second. Fig. 6 shows the input signal of the controller which is in is the admissible range.

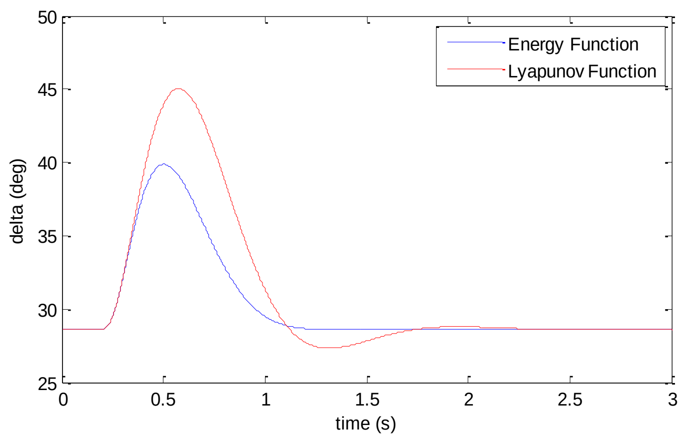

Fig. 2:The rotor angle δ

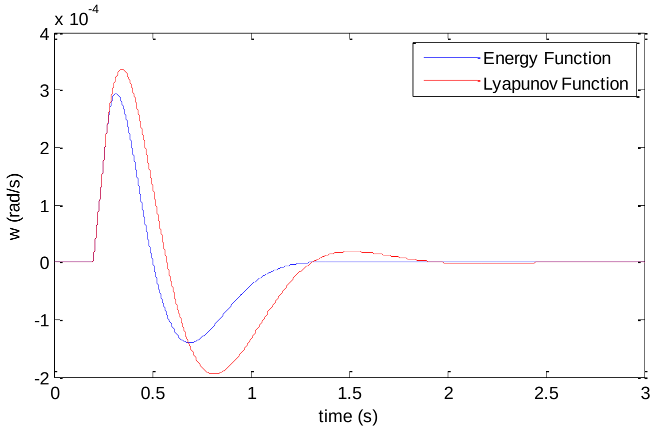

Fig. 3 :The angular velocity ω

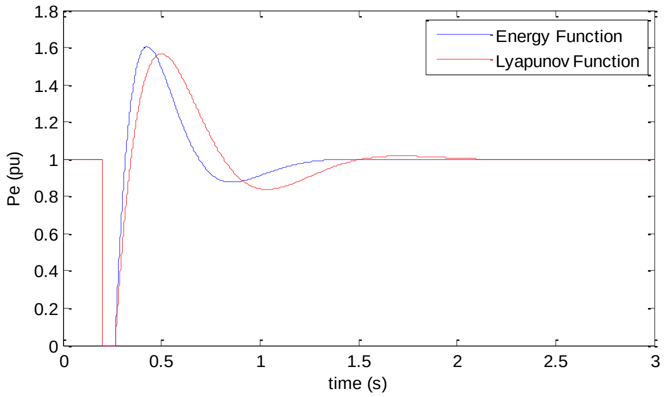

Fig. 4 :The active power transfer from the generator P_e

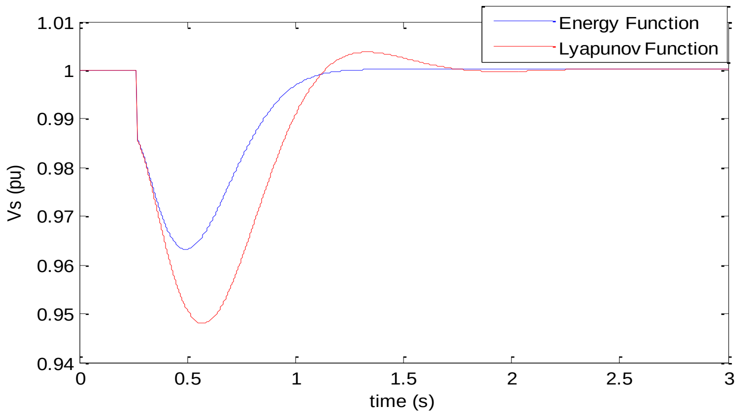

Fig.5: Voltage V_s

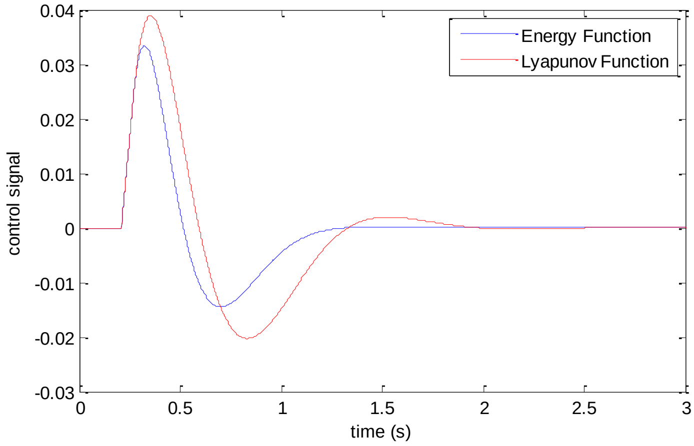

Fig. 6:control input u_3

Using the proposed nonlinear controller, inter-area oscillations are decreased. Hence, the proposed nonlinear controller is affected by changing the operating conditions. This makes the system be able to operate well even with topology changing and show proper behavior in damping power system fluctuations. Figs. 7 and 8 show the topology changing with disconnecting line L2 after fat removal. As it is expected, the proposed energy function controller shows good performance.

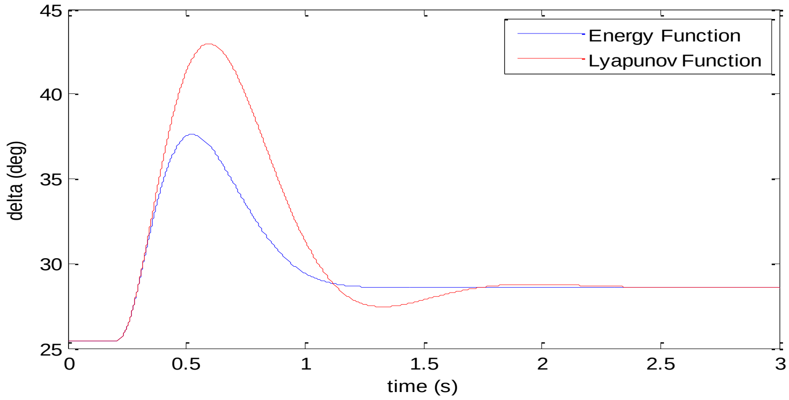

Fig. 7: The rotor angle δ with topology changing

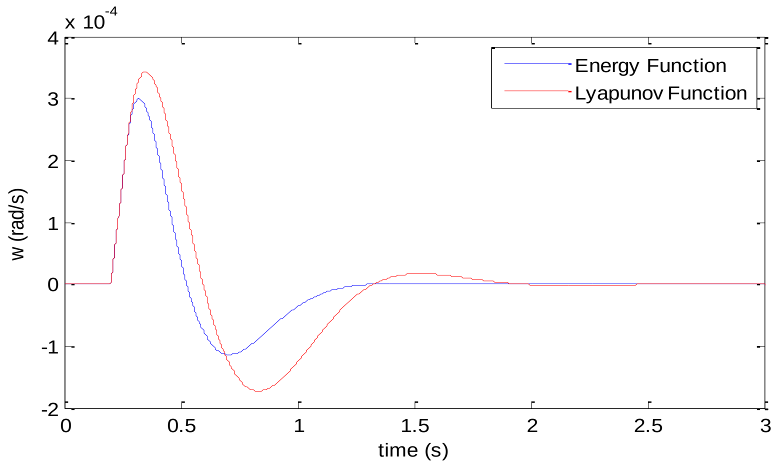

Fig. 8: The angular velocity ω with topology changing

5. Conclusion

In this paper, a dynamic model of power network with a third order generator model and the UPFC stabilizer is presented. Determining the standard form, a nonlinear energy function controller is designed for reducing the fluctuations of the generator. Using this energy function and applying the PSO algorithm to the network with UPFC, the coefficient of the controller were determined in a manner that the robustness of the network against topology changes and faster damping of fluctuations were guaranteed. Considering the simulation results, in comparison to the Lyapunov function controller, the proposed controller has significant effect on reducing the oscillations of the power system, and is robust to the topology changing.

Appendix

Parameters of the power system:

Generator M = 8 MJ/MVA; T'_{do} = 5.044 sec; X_d = 1 pu; X_q = 0.6 pu; X'_d = 0.3 pu

Transformers $X_T = X_{SH} = X_{SR}$ = 0.1 pu.

Transmission lines $X_{L1} = X_{L2}$ = 0.3 pu.

Operating condition P_e = 1.2 pu; V_T = 1 pu; V_l = 1 pu; f = 60 Hz;

DC-link parameters V_{dc} = 1 pu; C_{dc} = 2 pu;

UPFC parameters m_{SH} = 0.1935; φ_{SH} = 52.76°; m_{SR} = 0; φ_{SR} = 131.5° ;

$$X_{SRL} = X_{SR} + X_L; \quad X_{DT} = X_{TSHd}X_{SRL} + X_{SH}X_{Td}; \quad X_{QT} = X_{TSHq}X_{SRL} + X_{SH}X_{Tq};$$

$$X_{SRLTd} = X_{SR} + X_L + X_t + X_d'; \quad X_{TSHd} = X_t + X_{SH} + X_d'; \quad X_{Td} = X_t + X_d';$$

$$X_{SRLTq} = X_{SR} + X_L + X_t + X_q; \quad X_{TSHq} = X_t + X_{SH} + X_q; \quad X_{Tq} = X_t + X_q;$$

$$a_{11} = \frac{X_{SH}V_I \sin(\delta)}{X_{DT}}; \qquad a_{12} = \frac{X_{SRL} + X_{SH}}{X_{DT}};$$

$$a_{13} = -\frac{X_{SRL}m_{SH}\sin(\varphi_{SH}) + X_{SH}m_{SR}\sin(\varphi_{SR})}{2X_{DT}};$$

$$a_{21} = \frac{X_{SH}V_I \cos(\delta)}{X_{QT}}; \quad a_{22} = 0; \quad a_{23} = \frac{X_{SRL}m_{SH}\cos(\varphi_{SH}) + X_{SH}m_{SR}\cos(\varphi_{SR})}{2X_{QT}};$$

$$b_{11} = -\frac{X_{SRL}V_{dc}\sin(\varphi_{SH})}{2X_{DT}}; \qquad b_{12} = -\frac{X_{SRL}m_{SH}V_{dc}\cos(\varphi_{SH})}{2X_{DT}};$$

$$b_{13} = -\frac{X_{SH}V_{dc}\sin(\varphi_{SR})}{2X_{DT}}; \qquad b_{14} = -\frac{X_{SH}m_{SR}V_{dc}\cos(\varphi_{SR})}{2X_{DT}};$$

$$b_{21} = -\frac{X_{SRL}V_{dc}\cos(\varphi_{SH})}{2X_{QT}}; \qquad b_{22} = -\frac{X_{SRL}m_{SH}V_{dc}\sin(\varphi_{SH})}{2X_{QT}};$$

$$b_{23} = -\frac{X_{SH}V_{dc}\cos(\varphi_{SR})}{2X_{QT}}; \qquad b_{24} = -\frac{X_{SH}m_{SR}V_{dc}\sin(\varphi_{SR})}{2X_{QT}};$$

REFERENCES

[1] *Kundur P.*, Power System Stability and Control. 2nd ed.New York,USA: McGraw-Hill, 1994.

[2] *Boules H.*, *Peres S.*, Analysis and design of a robust coordinated AVR/PSS.IEEE Transactions on Power Systems, May 1998;13:568-575.

[3] *Chung C.Y.*, *Wang K.W.*, *Tse C.T.*, *Niu R.*, Power system stabilizer (PSS) design by probabilistic sensitivity indexes (PSIs). IEEE Transactions Power System, Aug. 2002;17:688-693.

[4] *He P., Wei Y.B., Yang C.X., Wang K.W.*, Adaptive power system stabilizer design for multi-machine power systems. In:IET Conference 2009,8-11 November 2009 ,Hong KONG:IET.pp. 1-6.

[5] *Hingorani N.G. and Gyugyi L.*, Understanding FACTS. Concepts and Technology of Flexible AC Transmission Systems. 2ed.NewYork: Institute of Electrical and Electronics Engineers, 1999.

[6] *Gyugyi L.*, Unified power-flow control concept for flexible AC transmission systems. IEE Proc. GenerationTransmission Distribution,July 1992;139: 323–331.

[7] *Gyugyi L.*, Schauder CD, Williams SL, RietmanTR.The unified power flow controller: a new approach to power transmission control. IEEE Transactions Power Delivery, April 1995;10: 1085–1097.

[8] *Tambey N., and Kothari M.L.*, Damping of power system oscillations with unified power flow controller (UPFC). IEE Proc. Generation Transmission Distribution, March 2003 ;150: 129–140.

[9] *Wang H.F.*, A unified model for the analysis of FACTS devices in damping power system oscillations. III. Unified power flow controller. IEEE Transactions Power Delivery, July 2000;15: 978–983.

[10] *Farsangi M.M., Song Y.H., Lee K.Y.*, Choice of FACTS device control inputs for damping inter area oscillations. IEEE Transactions Power System, May 2004 ;19: 1135–1143.

[11] *Haque M.H.*, Evaluation of first swing stability of a large power system with various FACTS devices. IEEE Transactions Power System, August 2008 ,23: 1144–1151.

[12] *Wang K., Yan B., Crow M.L., Gan D.*, A feedback linearization based unified power flow controller internal controller for power flow control.Electirical Power Componets System, 2012;40: 628–647.

[13] *Therattil J., Panda P.*, Modeling and control of a multi-machine power system with FACTS controller.In IEEE2011International Conference on Power and Energy Systems (ICPS);22-24 December 2011;Chennai India:IEEE.pp. 1–6.

[14] *Azbe V., Gabrijel U., Povh D., Mihalic R.*, The energy function of a general multi machine system with a unified power flow controller. IEEE Transactions Power Systemt, August 2005 ;20: 1478–1485.

[15] *Noroozian M., Ghandhari M., Andersson G., Gronquist J., Hiskens I.*, A robust control strategy for shunt and series reactive compensators to damp electromechanical oscillations.IEEE Trans. Power Delivery, October 2001;16: 812–817.

[16] *Wang H.F.*, Damping function of unified power flow controller.IEE Proceedings on Generation, Transmission and Distribution, 1999;146:81-87.

[17] *Wang K., Xin H., Gan D., Ni Y.*, Non-linear robust adaptive excitation controller design in power systems based on a new back-stepping method.IET Control Theory Appl, December 2010 ;4: 2947–2957.

[18] *Mehraeen S., Jagannathan S., Crow M.L.*, Noval dynamic representation and control of power systems with FACTS devices. IEEE Transactions on Power Systems, 2010; 25:1542-1554.

[19] *Jose P., Therattil P.C.*, Non-linear Dynamic Modeling and Adaptive Control of a Power System with Unified Power Flow Controller.Electric Power Components and Systems, 2012;40:1544–1561.

[20] *Pai M.A.*, Energy Function Analysis for Power System Stability. 2nd ed.Boston: Kluwer Academic Publishers, 1989.

[21] *Mukherjee V.*, *Ghoshal S.*, Craziness based and velocity relaxed swarm optimized intelligent PID controlled AVR system. In: IEEE2008 power system Technology, 12-15 October 2008; New Dehli :IEEE .pp.1-8.