LOW FREQUENCY OSCILLATIONS DAMPING OF A TWO-AREA MULTI-MACHINE POWER SYSTEM, INCLUDING UPFC, USING A HYBRID EMOTIONAL INTELLIGENT CONTROLLER

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In this paper, using an Emotional Learning Based Intelligent Controller (BELBIC) the low frequency oscillations damping of a multi-machine power system including UPFC is investigated. The utilization of BELBIC is based on the emotion processing mechanism in the brain .Considering a two-area multi-machine power system including UPFC, assuming a three phase symmetrical fault, occurring in this network, a BELBIC controller is designed in order to generate the magnitude of the UPFC injected series voltage. Moreover using the sixth reduced order model of synchronous machine, some simulation results are presented in order to verify the validity and effectiveness of the proposed control approach.

Keywords: Emotional intelligent controller; Power systems low frequency oscillations; UPFC

1. Introduction

In recent years, the fast progress in the field of power electronics has opened new opportunities for the power industry via utilization of the controllable FACTS devices such as Unified Power Flow Controller (UPFC), Thyristor Controlled Series Capacitor (TCSC) and Static VAR Compensator (SVC) as alternative means to mitigate power system oscillations [1–3]. Because of the extremely fast control action associated with FACTS-device operations, they are promising candidates for mitigation power system oscillation and improving power system steady-state performance [4, 5]. UPFC, regarded as one of the most versatile ones in the FACTS device family [6,7], has the capabilities of controlling power flow in the transmission line, improving the transient stability, mitigating system oscillation and providing voltage support. It performs this through the control of the in-phase voltage, quadrate voltage and shunts compensation due to

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its main control strategy [7, 8].

Several investigations on UPFC main control effects show that UPFC can improve system transient stability and enhance the system transfer limit as well. The application of UPFC to the modern power system can therefore lead to a more flexible, secure and economic operation [9].

FACTS devices and their power system applications are described in [10-12]. From the view point of power system dynamics, the essential problem is how to control specific FACTS devices, and in particular UPFC. For example, one approach is to apply optimal control [13–16]. The problem with standard optimal control is that it tends to use a linearized system model, which is valid only for a given operating point. This raises the question of robustness, as the control based on linearized system model is valid only when the system is in the vicinity of the chosen operating point and one can never be sure whether or not the control will still be satisfactory when the system operating conditions change or when the system model changes due to line or generator outages. Moreover, stressed power systems are known to exhibit nonlinear behavior. Hence the motivation for the work reported so far is to derive a state-variable control using a nonlinear system model in order to take into account the influence of changing operating conditions.

Several attempts have been made to model the emotional behavior of the human brain [17], [18]. Based on the cognitively motivated open-loop model, the brain emotional learning based intelligent controller (BELBIC) was introduced for the first time by Lucas in 2004 [19]. During the past few years, this controller has been used in control systems in several industrial application, and some characteristic of the controller such as; 1- simple structure, 2- model-free, 3- adaptive operating, 4- independent of parameter variations and operating-point conditions, 5- high auto-learning and etc. were shown in [20]-[25]. In [21], a BELBIC was designed and implemented in field-programmable gate arrays (FPGA), and applied for controlling a laboratorial overhead traveling crane in a model-free and embedded manner. In addition, successful implementation of the emotional controller (BELBIC) in some electric drives has been reported in [20], [22]-[26], as speed/torque controller with different control strategies. For the first time, the implementation of the BELBIC method for electrical drive control was presented by Rahman et al. [22]. In [27] two BELBIC controllers are used as two coordinated power system stabilizers (PSSs) for damping the power system oscillations.

The main contribution of this paper is to use an emotional intelligent controller and a conventional PI regulator in order to damp the low frequency oscillations of typical multi-machine power systems including UPFC [28].

The emotional controller is designed in order to generate the magnitude of the UPFC injected series voltage. The magnitude of the UPFC injected shunt current is produced by a conventional PI controller. The phase angles of these signals are online adjusted to be respectively in 90 degrees lagging and leading with respect to UPFC transmission line current and its bus voltage vector.

Considering the six reduced order model of synchronous machine, some simulation results are presented to verify the capability and effectiveness of the proposed control approach. The static forth order Runge-Kutta method is used to solve the system nonlinear differential equations using MATLAB® code with a time step Δt of 10^{-4}s.

2. Power System Configuration

A simplified UPFC model is shown in Figs. 1(a) and 1(b), where Y_u is the admittance of the transmission line containing UPFC. With reference to Fig. 1(b), the angles of UPFC injected series and shunt space vectors (V_{se}, I_{sh}) are assumed to be respectively in 90 degrees lagging and leading with respect to transmission line current (I_{upfc}) and UPFC bus voltage (V_{upfc}). Such assumption is necessary to make in order to modulate the instantaneous active power that flows in the transmission line including UPFC, with main objective of damping the low frequency oscillations of the power system in the abnormal conditions [28, 29]. Notice that if in Fig. 1(b), the angle of V_{se} is adjusted for a phase angle different from 90 degrees with respect to the phase angle of the I_{upfc}, both the instantaneous active and reactive powers of the UPFC line are modulated [10,49], which is not necessary for the purpose described in this paper.

Referring to Fig. 1(b), when the instantaneous active power of the UPFC transmission line tends to increase, the UPFC series injected voltage (V_{se}) acts as an inductive series reactance. Reversely, when the instantaneous active power of this line tends to decrease the mentioned signal acts as a capacitive shunt reactance. Such behavior of signal (V_{se}) causes to damp the system low frequency oscillations. It is not necessary to say that at each step Δt of time in seconds, the phase angle of I_{upfc} and V_{upfc} space vectors are obtained by simulation and in practice by measurement. Having achieved these angles, the angles of the UPFC injected signals V_{se} and I_{sh} (δ_{se} and δ_{sh}) are obtained as:

$$\delta_{sh} = \angle V_{upfc} - 90^\circ \quad \text{and} \quad \delta_{se} = \angle I_{upfc} + 90^\circ.$$

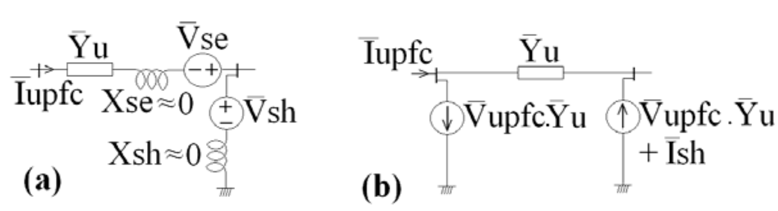

Fig. 1. UPFC Model (a) with voltage sources (b) with current sources

The electrical configuration of a two-area multi-machine power system with one UPFC is shown in Fig. 2 [28]. In this power system the magnitude of the UPFC injected series voltage is produced by BELBIC controller which is described in the subsequent section. The magnitude of the UPFC injected shunt current is produced by a conventional PI controller. The phase angles of these signals are online adjusted to be respectively in 90 degrees lagging and leading with respect to UPFC transmission line current and its bus voltage vector.

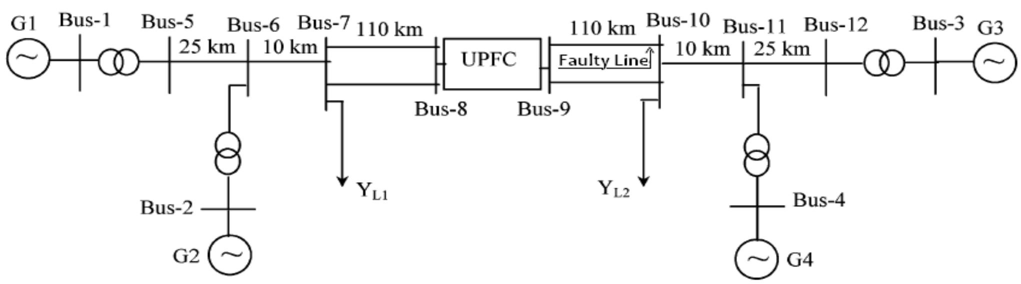

Fig. 2. Configuration of power system

3. Computational Model of BELBIC System

Motivated by the success in the functional modeling of emotions in control engineering applications [25]-[27], and [30]-[39], the main purpose of this paper is to use a structural model based on the limbic system of the mammalian brain and its learning process for the control of series voltage of a UPFC. The network connection structure of the mammalian brain developed by Moren and Balkenius [26], [30] is utilized in this paper as a computational model that mimics the Amygdala, orbitofrontal cortex, thalamus, sensory input cortex, and, generally, those parts of the brain thought to be responsible for processing emotions. Fig. 3 shows the pertinent pictures of the human brain. Fig. 4 shows a graphical depiction of the modified sensory signal and learning network connection model inside the brain. The neurobiological aspects of the Amygdala, orbitofrontal cortex, thalamus, hippocampus, and associated areas are relevant for the functional and computational perspectives of the emotional responses. The small almond-shaped subcortical area of the Amygdala in Fig. 3 is well placed to receive stimuli from all sensory cortices and other sensory areas of the hippocampus in the brain [37]. There are two approaches to intelligent and cognitive control, namely, direct and indirect approaches. In the indirect approach, the intelligent system is utilized for tuning the parameters of the controller.

For the sake of simplicity, the BELBIC is called emotional controller in this paper. The model of the proposed BELBIC input and output structure is shown in Fig. 4. The BELBIC technique is essentially an action-generation mechanism based on sensory inputs and emotional cues. For our purpose, the sensory signals are active power passing through UPFC series branch and its output bus voltage. The emotional learning occurs mainly in the Amygdala. It has been suggested that the relation between a stimulus and its emotional consequences takes place in the Amygdala part of the brain [20]. The Amygdala is a part of the brain that must be responsible for processing emotions and must correspond with the orbitofrontal cortex, thalamus, and sensory input cortex in the network model. The Amygdala and the orbitofrontal cortex have a network like structure, and within the computational model of each of them, there is one connection in lieu of each sensory input. Also, there is another connection for thalamus input within the Amygdala. The value of this input is equal to the maximum value of the sensory inputs.

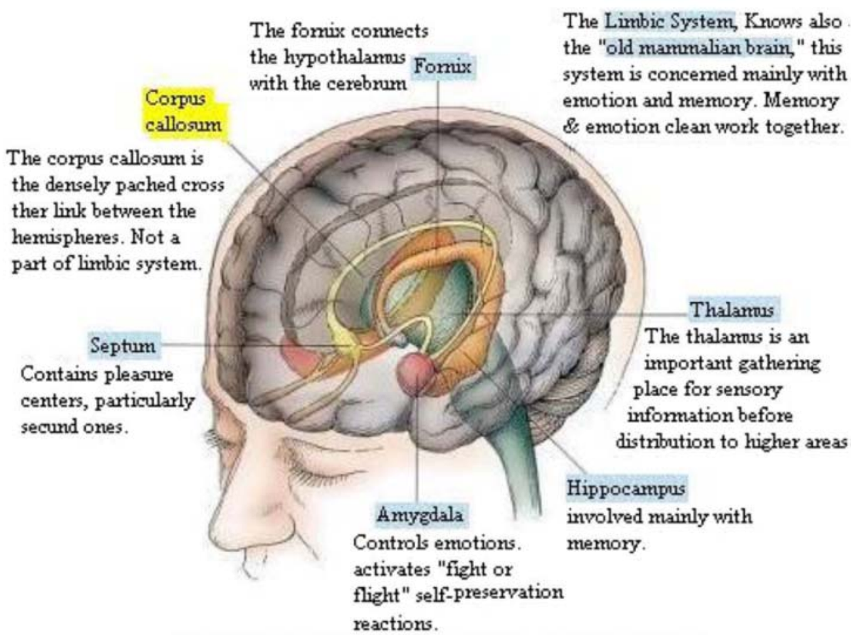

Fig. 3. Sectional view of the human brain for emotion processing

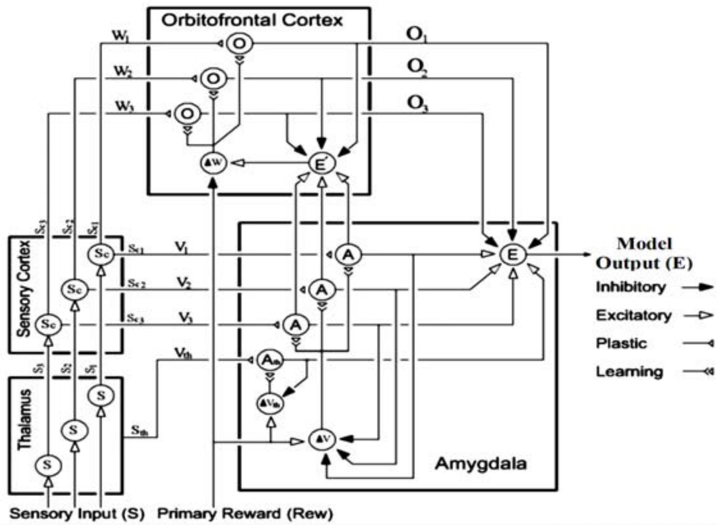

Fig. 4. Graphical depiction of the developed network model of the BEL process (BELBIC).

There is one *A* node for every stimulus *S*, including one for the thalamic stimulus. There is also one *O* node for each of the stimuli, except for the thalamic node. There is one output node *E* that is common for all the outputs of the model. The *E* node simply sums the outputs from the *A* nodes and then subtracts the inhibitory outputs from the *O* nodes. The result is the output of the closed-loop model. In other words, the output *E* of the emotional controller can be obtained from the following:

$$E = \sum_j Aj + Ath - \sum_j Oj \tag{1}$$

The internal area outputs are computed pursuant to
where A_j and O_j are the values of Amygdala output and the output of the orbitofrontal cortex at each time, ⊗ is convolution operator, V_j is the gain in the Amygdala connection, W_j is the gain in the orbitofrontal connection, S_j and Sc_j are sensory and sensory-cortex outputs, respectively, and j is the j^{th} input. Variations of V_j and W_j can be calculated as:

$$\Delta V_i = \alpha.(\max(0, Sc_i.(R - \sum_i A_i))) \tag{6}$$

$$\Delta V_{th} = \alpha_{th}.(\max(0, S_{th}.(R - A_{th}))) \tag{7}$$

Moreover, likewise, the *E'* node sums the outputs from *A* except A_{th} and then subtracts from inhibitory outputs from the *O* nodes.

$$E' = \sum_j Vj \,.\, \sum_j Oj \tag{8}$$

$$\Delta W_i = \beta.(Sc_i.(E' - R)) \tag{9}$$

Where $(\alpha, \alpha_{\text{th}})$ and β are the learning steps in the Amygdala and orbitofrontal cortex, respectively. *R* is the value of the emotional cue function at each time. The learning rule of the Amygdala is given in (13), which cannot decrease. It means that it does not forget the information in the Amygdala, whereas idiomatically inhibiting (forgetting) is the duty of the orbitofrontal cortex (12). Eventually, the model output is obtained from (7). Fig. 4 shows the BELBIC controller configuration. The used functions in the emotional cue R and sensory input S blocks can be given by the following:

$$R = f(E, e, y, y_d) \tag{10}$$

$$S_j = g_j(e, y, y_d) \tag{11}$$

In this paper, functions f and g_j are given by:

$$f = k_1 S_1 + k_2 S_2^2 + k_3 S_3^2 \tag{12}$$

$$g_1 = P_{upfc} - P_{upfcREF} \tag{13}$$

$$g_2 = V_{upfc} - V_{upfcREF} \tag{14}$$

$$g_3 = Q_{upfc} - Q_{upfcREF} \tag{15}$$

Where P_{upfc} and Q_{upfc} are active and reactive powers passing through UPFC and V_{upfc} is its output bus voltage. $P_{upfcREF}$, $Q_{upfcREF}$, and $V_{upfcREF}$ are steady state values of these signals. Other parameters are given in paper appendix.

4. Simulation Results

Based on power system model described in section 2 and computational model of BELBIC controller described in the previous section, using the reduced sixth order model of synchronous machine given in the paper appendix, a computer program has been developed for simulation of power system shown in Fig. 2. The flowchart of this program is illustrated in Fig. 7.

In this program the system nonlinear differential equations are solved by using the numerical fourth order static Runge-Kutta method using MATLAB® code with a time step Δt of 10^{-4}s.

The UPFC have been arranged to be automatically switched on just after clearing the fault and automatically switched off when a reasonable damp is achieved for the power system. As a result, the subtransient states of the synchronous machines have been neglected in simulations.

Considering power system shown in Fig. 2 in the normal condition, using the output data corresponding to steady state AC load flow analysis of this network as initial values, the PI controller is designed (by trial and error method) to adjust the UPFC transmission line active power equal to P=0.433pu. Then stepping up the PI controller reference value from P=0.433pu to P=0.5pu, assuming an initial error of +20% in the power system resistances as well as an initial error of -20% in the synchronous machines direct axis transient reactance, simulation results obtained for this test are shown in Figs. 6.

Assuming a three phase symmetrical fault occurring at t=0.1s exactly at the middle of the transmission line which connects buses 98 and 10, clearing at t=0.2s accomplish with line interruption and line reclosing at t=1.2s, the PI and BELBIC controllers are designed to damp the low frequency oscillations of the power systems under consideration. These controllers are arranged to be automatically switched on just after clearing the fault and automatically switched off when a reasonable damping is achieved for the power system. Simulation results obtained for this test are shown in Figs. 7 to 12.

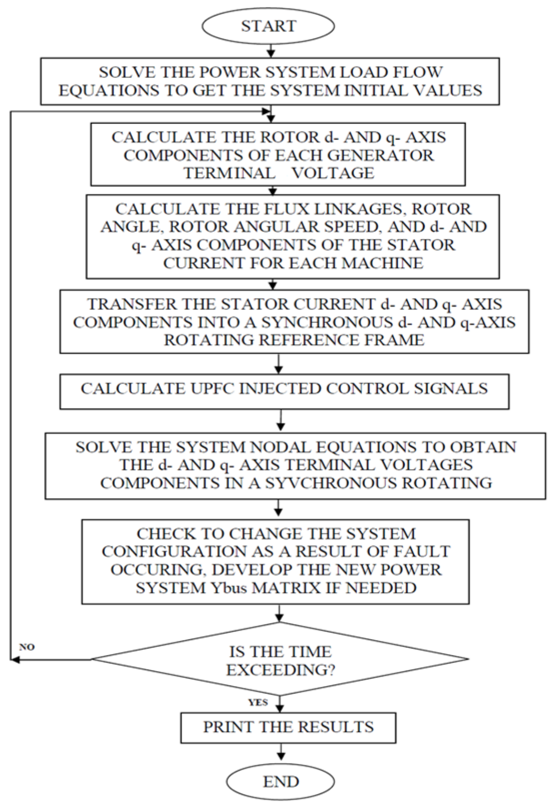

Fig. 5. Flowchart of the simulation

One may notice that by using the mentioned controllers is not expected to enhance the transient stability of the power system during the fault. It is not necessary to say that the transient stability of the system is guaranteed by a high performance protection system using high speed circuit breakers. That can be obtained by selecting a proper system fault clearing time. One more point is that UPFCs used in the modern power systems should have high capacity PWM inverters with low frequency power switches. As a result, these types of FACTS devices practically are not able to have any contribution for improving the system transient stability in the first few cycles after the fault occurring. Considering these points there is no need to switch on controllers during the power system fault. From simulation results shown in Figs. 7 to 12, one can see that the proposed controllers in this paper are capable of damping the low frequency oscillations of the power system effectively.

5. Conclusion

This paper has presented a real-time implementation of an alternate but improved emotional controller for damping the inter-area low frequency oscillations of a typical multi-machine power system including UPFC. The implementation of the emotional controller shows good control performance in terms of robustness and adaptability. A simple structure of BELBIC with its fast auto learning and model-free features maybe used instead of conventional parameter-dependent methods.

The BELBIC controller generates the magnitude of UPFCs injected series voltage vector and a PI controller generates the magnitude of the UPFC injected shunt current vector. At each step Δt of time in seconds, the phase angles of these vectors are obtained to be respectively in 90 degrees lagging and leading with respect to UPFC transmission line current and its bus voltage. The BELBIC and PI controllers' coefficients, have been obtained by trial and error method.

The proposed emotional intelligent technique can be easily adopted for multi-machine multi-FACTS devices power systems.

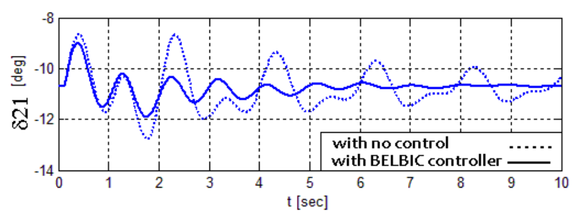

Fig. 8. Rotor angles difference between machines 3 and 1

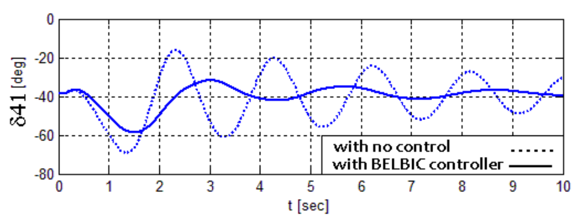

Fig. 9. Rotor angles difference between machines 4 and 1

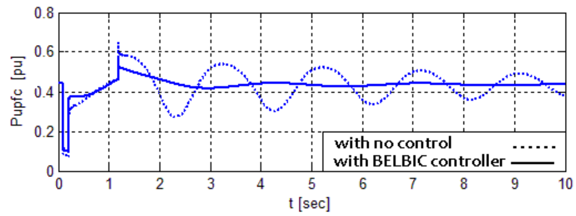

Fig. 10. Active power of UPFC during the transient state

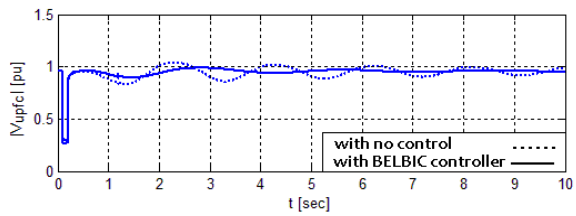

Fig. 11. UPFC bus voltage during the transient state

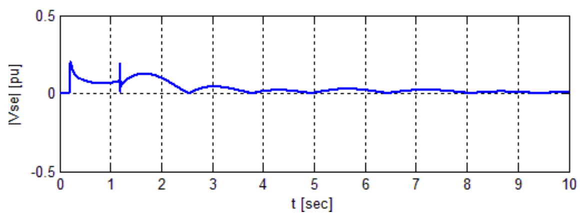

Fig. 12. UPFC injected series voltage magnitude

6. Appendix

A. Synchronous machines of the power system are presented by reduced sixth order model [40]:

$$\frac{d\psi'^{r}_{kq1}}{dt} = \omega_b \cdot \left[v'^{r}_{kq1} + \frac{r'_{kq1}}{X'_{lkq1}} \left(\psi^{r}_{mq} - \psi'^{r}_{kq1} \right) \right]$$

$$\frac{d\psi'^{r}_{kq2}}{dt} = \omega_b \cdot \left[v'^{r}_{kq2} + \frac{r'_{kq2}}{X'_{lkq2}} \left(\psi^{r}_{mq} - \psi'^{r}_{kq2} \right) \right]$$

$$\frac{d\psi'^{r}_{fd}}{dt} = \omega_b \cdot \left[\frac{r'_{fd}}{X'_{lfd}} E_{fd} + \frac{r'_{fd}}{X'_{lfd}} \left(\psi^{r}_{md} - \psi'^{r}_{fd} \right) \right]$$

$$\frac{d\psi'^{r}_{kd}}{dt} = \omega_b \cdot \left[v'^{r}_{kd} + \frac{r'_{kd}}{X'_{lkd}} \left(\psi^{r}_{md} - \psi'^{r}_{kd} \right) \right]$$

$$\frac{d\delta}{dt} = \omega_b .(\omega_r - 1)$$

$$\frac{d\omega_r}{dt} = \frac{1}{2H} .(P_m - P_e)$$

Where subscripts *ds* and *qs* show d- and q-axis of the rotor, kq1 and kq2 show the dampers of the q-axis, *kd* shows the damper of the d-axis, and *fd* shows filed winding. ψ illustrates the flux in volt-second, P_m and P_e are turbine mechanical power and generator active power respectively, ω_b is the base angular speed, ω_r is the angular speed, δ is the rotor angle, and *H* denotes constant inertia.

A. BELBIC parameters:

$$\alpha = 0.004 \ , \ \beta = 0.01 \ , \ \alpha_{th} = 0.01 \ , \ k_1 = 8 \ , \ k_2 = 0.5 \ , \ k_3 = 2.5$$

B. PI controller of UPFC shunt current source (see Fig. 1): Gain=40 Time constant=0.2

REFERENCES

[1]. *Tambey, M. Kothari, B. P.* "UPFC based damping controllers for damping LFO in a power system," 2003, Available: http://www.ieindia.org/publish/el/0603.

[2]. *So, P. L. Yu, T.* "Coordination of TCSC and SVC for inter-area stability enhancement," Power System Technology, 2000. Proceedings. PowerCon 2000. International Conference on , vol.1, pp.553-558, 2000.

[3]. *Swift, F. J. Wang, H. F. Li, M.* "Analysis of controllable series compensator to suppress power system oscillations," Inter. Conf. on AC and DC power transmission, 1996.

[4]. *Al-Awami, Abido, M. A. and Abdel-Magid, Y. L.* "A PSO-based approach of power system stability enhancement with UPFC," Electric Power Energy System, vol. 29(3),pp251–9, 2007.

[5]. *Padiyar, K.R. Saikumar, H.V.* "Coordinated design and performance evaluation of UPFC supplementary modulation controllers," Electric Power Energy System vol. 27(2), pp101–111, 2005.

[6]. *Gyugyi, L.* "UPFC concept for FACTS," IEE Proc vol. 139(4), pp 323–31, 1992.

[7]. *IEEE Power Eng Soc CIGRE,* "FACTS overview," IEEE publ. no. 95, TP 108; 1995.

[8]. *Song, Y. H. Johns, A.T.* "Flexible AC transmission systems", UK : IEE Press, 1999.

[9]. *Huang Z. et al.* , "Application of UPFC in interconnected power systems- Modeling, interface, control strategy, and case study," IEEE Trans. Power System, vol. 15, No. 2, pp. 817-824, May 2000.

[10]. *N. G. Hingorani, L. Gyugyi,* "Understanding FACTS", IEEE Press, 2000

[11]. "Modeling of power electronics equipment (FACTS) in load flow and stability programs", T-F 38.01.08, Cigre1999

[12]. *K.S. Smith, L. Ran, and J. Penman,* "Dynamic modeling of a unified flow controller", IEE Proc. Gener. Transm. Distrib., 1997, 144 (1), pp. 7–12

[13]. *K.R. Padiyar, and K. Uma Rao,* "Modeling and control of unified power flow controller for transient stability", Electric Power Energy Syst., 1999, 21, pp. 1–11

[14]. *C. T. Chang, and Y. Y. Hsu,* "Design of UPFC controllers and supplementary damping controller for power transmission control and stability enhancement of a longitudinal power system", IEE Proc. Gener. Transm. Distrib., 2002, 149, (4), pp. 463–471

[15]. *L.Y. Dong, L. Zhang, and M. L. Crow,* "A new control strategy for the unified power flow controller", Proc. IEE Power Eng. Soc. Winter Meeting, 2002, 1, pp. 562–566

[16]. *Yoke Lin Tan and Youyi Wang,* "Design of Series and Shunt FACTS Controller Using Adaptive Nonlinear Coordinated Design Techniques," IEEE Transactions on Power Systems, Vol. 12, No. 3, pp. 1374 - 1379, 1997.

[17]. *Orlowska-Kowalska T. and Szabat, K.* "Control of the drive system with stiff and elastic couplings using adaptive neuro-fuzzy approach," IEEE Trans. Ind. Electron., vol. 54, no. 1, pp. 228–240, February 2007.

[18]. *Lin, F. J. Fung, R. F. and Wai, R. J.* "Comparison of sliding-mode and fuzzy neural network control for motor-toggle servomechanism," IEEE/ASME Trans. Mechatronics, vol. 3, no. 4, pp. 302–318, December 1998.

[19]. *Al-Olimat, S. Ghandakly, A. A. and Kamalasadan, S. K.* "Induction motor speed control via fuzzy logic modification of reference model," in Proc. IEEE PES, pp. 1–7, 2007.

[20]. *Chen T. C. and Sheu, T. T.* "Model referencing neural network controller for induction motor

speed control," IEEE Trans. Energy Convers., vol. 17, no. 2, pp. 157–163, Junuary 2002.

[21]. *Wlas, M. Krzeminski, Z. Guzinski, J. Abu-Rub, H. and Toliyat, H. A.* "Artificial-neural-network-based sensorless nonlinear control of induction motors," IEEE Trans. Energy Convers., vol. 20, no. 3, pp. 520–528, September 2005.

[22]. *Löpez, J. C. Romeral, L. Arias, A. and Aldabas, E.* "Novel fuzzy adaptive sensorless induction motor drive," IEEE Trans. Ind. Electron., vol. 53, no. 4, pp. 1170–1178, Junuary 2006.

[23]. *Siva Reddy, Y. V. Kumar, M. V. Reddy, T. B. and Amarnath, J.* "Direct torque control of induction motor based on state feedback and variable structure fuzzy controllers," in Proc. IEEE Power India Conf., New Delhi, India, 2006.

[24]. *Jamaly, M. R. Armani, A. Dehyadegari, M. Lucas, C. and Navabi, Z.* "Emotion on FPGA: Model driven approach," Expert Syst. Appl., vol. 36, no. 4, pp. 7369–7378, May 2009.

[25]. *Moren, J.* "Emotion and learning: A computational model of the Amygdala," Ph.D. dissertation, Lund Univ., Lund, Sweden, 2002.

[26]. Bijami*, E. Jadidoleslam, M. Ebrahimi, A. Farsangi, M. M. Lee, K. Y.* "Power System Stabilization Using Brain Emotional Learning Based Intelligent Controller," Power and Energy Society General Meeting, IEEE 2011, pp. 1 - 7 24-29, July 2011

[27]. *Kundur, P.* "Power System Stability and Control", Mc-Graw Hill, 1994

[28]. *Padiyar, K.R.* "FACTS Controller in Power Transmission and Distribution," New Age International Publishers, 2007

[29]. J*. Moren and C. Balkenius,* "A computational model of emotional learning in the amygdala," in Proc. 6th Int. Conf. Simul. Adapt. Behav., Cambridge, MA, 2000.

[30]. *Lucas, C. Shahmirzadi, D. and Sheikholeslami, N.* "Introducing BELBIC: Brain emotional learning based intelligent control," Int. J. Intell. Automat. Soft Comput., vol. 10, no. 1, pp. 11–22, 2004.

[31]. *Sheikholeslami, N. Shahmirzadi, D. Semsar, E. Lucas, C. and Yazdanpanah, M. J.* "Applying brain emotional learning algorithm for multivariable control of HVAC systems," J. Inter. Fuzzy Syst., vol. 17, no. 1, pp. 35–46, 2006.

[32]. *Rouhani, H. Jalili, M. Arabi, B. Eppler, W. and Lucas, C.* "Brain emotional learning based intelligent controller applied to neuro-fuzzy model of micro-heat exchanger," Expert Syst. Appl., vol. 32, no. 3, pp. 911–918, 2007.

[33]. *Milasi, R. M. Lucas, C. and Araabi, B. N.* "Intelligent modeling and control of washing machine using locally linear neuro-fuzzy (LLNF) modeling and modified brain emotional learning based intelligent controller (BELBIC)," Asian J. Control, vol. 8, no. 4, pp. 393–400, December 2006.

[34]. *Milasi, R. M. Jamali, M. R. and Lucas, C.* "Intelligent washing machine: A bio-inspired and multi-objective approach," Int. J. Control Automat. Syst., vol. 5, no. 4, pp. 436–443, August 2007.

[35]. *Jamali, M. R. Valadbeigi, M. Dehyadegari, M. Navabi, Z. and Lucas, C.* "Toward embedded emotionally intelligent system," in Proc. IEEE EWDTS, pp. 51–56, September 2007.

[36]. *Jamali, M. R. Arami, A. Hosseini, B. Moshiri, B. and Lucas, C.* "Real time emotional control for anti-swing and positioning control of SIMO overhead traveling crane," Int. J. Innovative Comput. Inf. Control, vol. 4, no. 9, pp. 2333–2344, September 2008.

[37]. *Jamali, M. R. Dehyadegari, M. Arami, A. Lucas, C. and Navabi, Z.* "Real- time embedded emotional controller," J. Neural Comput. Appl., vol. 19, no. 1, pp. 13–19, 2010.

[38]. *Rahman, M. A. Milasi, R. M. Lucas, C. Arrabi, B. N. and Radwan, T. S.* "Implementation of

emotional controller for interior permanent magnet synchronous motor drive," IEEE Trans. Ind. Appl., vol. 44, no. 5, pp. 1466–1476, September/October 2008.

[39]. *Rolls, E. T.* "The Brain and Emotion", London: Oxford Univ. Press, 1999.

[40]. *Krause, P. C.* "Analysis of Electric Machinery", New York: McGraw-Hill, 1997.