International Journal of Natural and Engineering Sciences 7 (3): 01-06, 2013
ISSN: 1307-1149, E-ISSN: 2146-0086, www.nobel.gen.tr

Dynamic Performance Improvement of Power System using UPFC based on ANFIS Controller

Mohammad Hasan ESLAMI[1*] Amir ASHTIANI[2] Hadi ASKARIPOOR[3] Tohid JAFARI[4]
[1] Department of Electrical Engineering, College of Boys Qom branch, Technical and Vocational University, Tehran, Iran
[2] Department of Electrical Engineering, Mashhad branch, Islamic Azad University, Mashhad, Iran.
[3] University of Birjand, Birjand, Iran
[4] Young Researchers and Elite Club, Islamic Azad University, Tabriz, Iran

*Corresponding author
eslami118@yahoo.com

Received: September 12, 2013
Accepted: October 25, 2013

Abstract

In this paper, a novel control system for Unified Power Flow Controller (UPFC) by Adaptive Neuro-Fuzzy Inference System (ANFIS) has been designed to control dynamic performance of power system. Proposed controller has been used to control active power, reactive power and DC-link voltage of power system. UPFC based on designed ANFIS controller has been installed between two buses of power system. Three control parameters have been used as decision criteria; i.e. peak, fall, and settle times. To illustrate priority of proposed controller, results of ANFIS controller has been compared with two conventional controllers; i.e. PI and PID and a neural-based controller. To compare and discuss the capability of four controllers' behavior, two statistical indices are used: Absolute Percentage Error (APE) and Symmetric Mean Absolute Percentage Error (SMAPE). Simulations have been carried out on SIMULINK/MATLAB software.

Keywords: ANFIS, FACTS, Power system control, Statistical analysis, UPFC.

INTRODUCTION

Flexible AC transmission system (FACTS) devices based on VSCs provide a potentially attractive solution to control power flow in the modern electric network [1]. FACTS devices consist of three shunt, series and shunt-series categories. UPFC has been suggested by Gyugyi *et al.* at 1995 and used to loop-flow and power flow controls, damping oscillations, and voltage regulation [2].

Many techniques have been employed to design controller for FACTS devices. In this paper, four famous approaches are reviewed; i.e. fuzzy sets, neural networks, intelligence algorithm and probabilistic method.

Fuzzy sets are in first category which has been used to design controller for FACTS devices in [3-4]. Following fuzzy sets are not suitable and always do not present distinctive answers for specified input and finally other disadvantage of fuzzy sets are difficult programming.

NNs are other techniques employed to design controller for FACTS devices in [5-6]. Main problems of NNs are that NNs need to be trained and difficulty in design and model as well as trapping in local optimal point (respect to intelligence techniques).

Two well-known intelligence algorithms are Evolution Algorithm (EA) and Swarm Intelligence Algorithm (SIA), that among these algorithms, Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) have proved their abilities to solve several power system problems such as designing controller for FACTS devises in [7-8]. Main disadvantage of PSO is high possible to be trapped in local optimum point, particularly, in problems with large scattering. In [9-10], the probabilistic method has been suggested to design controller for FACTS devices.

In this paper, a novel controller based on Adaptive Neuro-Fuzzy Inference System (ANFIS) has been proposed for UPFC to improve dynamic behavior of power systems. This paper has been organized in seven Sections: in second Section, UPFC structure and its equations for power flow control have been presented. In third Section, control strategies of shunt and series will be introduced and in next Sections, structure and training ANFIS is analyzed. The equations of statistical analysis and simulation results have been introduced in Sections 5-6, respectively. The statistical analysis has been performed in Section 7. The work has been concluded in Section 8.

Unified Power Flow Controller (UPFC)

Structure of UPFC

UPFC consists of two inverters based on Voltage Source Converters (VSCs) which are connected to line by two transformers. One of the VSCs is connected in series with the line through a series boosting transformer (ET) and other VSC is shunted with the line through excitation transformer. The two VSCs are connected together by a DC-link. The Shunt inverter injects controlled current with varying amplitude. By this injection, UPFC can compensate reactive power of system. The series converter by adding series voltage with controllable amplitude and phase angle active power is set on interest value.

Mathematical Model of UPFC

The UPFC has been connected between bus *i* and *j*. Eqs. (1-4) present exchanged active and reactive power between UPFC and transmission lines [11],

$$P_s^{UPFC} = 0.02V_s^{\,2} B_{SE} r \sin\gamma - 1.02V_s V_e B_{SE} r \sin(\theta_s - \theta_r + \gamma) \quad (1)$$

$$Q_r^{UPFC} = V_s\ V_r B_{SE} r\cos(\theta_s - \theta_r + \gamma) \quad (2)$$

$$Q_s^{UPFC} = -V_s^{\,2} B_{SE} r\cos\gamma \quad (3)$$

$$P_r^{UPFC} = V_s V_r B_{SE} r\sin(\theta_s - \theta_r + \gamma) \quad (4)$$

Control strategy and control systems for UPFC

Series converter control

The series part of the UPFC operates like as Static Synchronous Series Compensator (SSSC) controller, and could control active and reactive powers by injecting series voltage into transmission line. For this purpose, UPFC first sampled from voltage and current of transmission line and then by converting the sampling waveforms to *dq0* parameters by Parks transformation, calculates active and reactive powers in per unit using following equations:

$$P_{mes} = V_d \cdot I_d + V_q \cdot I_q \quad (5)$$

$$Q_{mes} = V_d \cdot I_d - V_q \cdot I_q \quad (6)$$

Eqs. (5) and (6) compares them with reference values according and gives their error signals to the PI controller. By adjusting controlling constants, K_p and K_i, PI control set the error signal to zero and could stable active and reactive powers in distinct reference value.

Shunt converter control

Shunt part of the UPFC operates like a Static Synchronous Compensator (STATCOM) controller, and by injecting current in parallel with transmission line could control bus voltage and active power. For this purpose, the UPFC samples from DC-link capacitor voltage as well as from bus voltage and then by converting these values to dq0 parameters by Parks transformation and calculating voltages in per unit as follows:

$$V_{bus} = \sqrt{V_d^2 + V_q^2} \quad (7)$$

where, V_{bus} is compared by distinct value.

Generated error signals carried to PI controllers and output of PIs converted to *abc* parameters again and passed through the PWM pulse generating unit. By adjusting control parameters of PI and switching, then, error signals set to zero. Accordingly V_{bus} and V_{dc} stabled in their reference values [12].

Adaptive Network Fuzzy Inference System

ANFIS structure

Neuro-Fuzzy models which is developed in 1993, combine fuzzy logic with Artificial Neural Network (ANN). If these solutions are combined together, better results will be obtained. Main reason of this combination is to use training capability of neural network. ANFIS structure, similar to other fuzzy systems, consists of two parts; preliminary and inference which are connected to each other using set of rules. ANFIS structure has five layers which are analyzed as multilayer network.

First layer (input nodes): Each node *i* in this layer is specified as square nodes. Output of each node in this layer is membership degree of input variable in this fuzzy set.

$$O_i^1 = \mu_{A_i}(x) \qquad i = 1,2 \quad (8)$$

$$O_i^1 = \mu_{B_{i-2}}(y) \qquad i = 3,4 \quad (9)$$

where, *x* (or *y*) is input of node *i*. A_i (or B_{i-2}) is fuzzy set related to this node. Each node parameters define fuzzy set membership function form the same node.

Second layer (rule node): Each node *i* in this layer have been illustrated as a circle and called Π. In this layer, input signals are multiplied together and sent to the next layer. For example, for the first node,

$$O_i^2 = \mu_{A_i}(x)\mu_{B_i}(y) \quad (10)$$

where, $\mu_{Ai}(x)$ and $\mu_{Bi}(y)$ are membership degree of *x* and *y* in sets of A_i and B_i, respectively.

Third layer (intermediate nodes): In this layer, each node has been shown similar to second layer and named *N*. Nodes of this layer calculate relative weight, for this; ratio of *i*th rule weight to weight of sum of total rules is normalized.

$$O_i^3 = \overline{W} = w_i \Big/ \sum_{i=1}^{n} w_i \qquad i = 1,2,..,n \quad (11)$$

where, *n* is the number of nodes of each layer and W_i is relative weight of rule *i*th.

Fourth layer (result nodes): This is called rule layer. The rules are obtained from operations on input signals to this layer,

$$O_i^4 = \overline{W}_i f_i = \overline{W}_i (p_i x_i + q_i x_2 + r_i) \quad (12)$$

where, W_i is the third layer of output, and p_i as well as q_i are consequent parameters.

Fifth layer (output signal): Signal node calculates all outputs as the sum of all input signals. This layer has been shown as *Σ*,

$$O_i^5 = \sum_{i=1}^{n} \overline{w}_i f_i \quad (13)$$

ANFIS learning

Hybrid learning technique has been used to learn ANFIS in this context. Learning process in ANFIS consists of two steps. In other word, each learning epoch in hybrid learning algorithm includes a forward pass and a backward pass.

First step: In forward pass of hybrid learning algorithm, input signal goes forward up to output layer and parameters of consequent part is calculated by least squares error method, while premise part parameters are kept constant.

Second step: In backward pass, after error calculation, parameters of rules premise part membership functions change using error descent gradient method. In other word, consequent section parameters are updated by error descent gradient method.

The consequent part parameters which have been determined so far only if parameters of premise part are fixed, are under optimal condition. Then, this learning algorithm will be converged much faster. For more simplifying, it is assumed that the output of studied system is based on Eq.(14),

$$output = f(\vec{I}, S) \quad (14)$$

where, I and S are sets of input variables and parameters, respectively. By hybrid learning approach the speeds of learning process is increased respect to the alone gradient method, which exhibits the tendency to become trapped in local minima.

The proposed controller

In this work, direct inverse control used to design ANFIS controller; this technique has obtained from neural networks counterpart's methodologies. The ideal input of this system is *r(t)*, and the output of the controlled object is *y(t)*. Neural network models NN1 and NN2 are two inverse models of the controlled object which are just the same and can be got from the inverse identification of the controlled object. If the error between *r(t)* and *y(t)* is small enough, the calculated error e will be also very small.

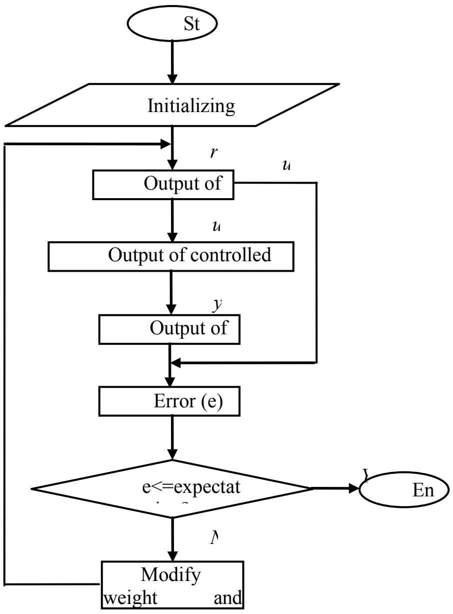

Fig.1. Flowchart of proposed technique to design controller

According to the given expected error, the weights and thresholds of both NN1 and NN2 will be modified through online learning in order to decrease the error e to achieve the expected range. As a result, y(t) is a infinite approximation of r(t), and the control objective is achieved. In this paper, the inverse models NN1 and NN2 adopt the three-layer neural network models showed as the Fig. 1. Because there is no theory of setting the number of the hidden nodes, according to the experiences and some calculation, a structure of 2-12-1 is chosen. The input layer has 2 nods, hidden layer 12 and output layer 1 [13].

Statistical Analysis

Main contribution of this study is to design controller system based on ANFIS for UPFC to improve dynamic performance of power systems. We have considered how to control the active power, reactive power and DC-link voltage as comparison criteria. In this section, two statistical indices, i.e. APE and SMAPE, are used to analyze and discuss obtained results by four controllers.

APE is the first index used as comparison criterion; this index is defined as,

$$APE = \left| \frac{f_{SS} - f_{other}}{f_{SS}} \right| \times 100 \quad (20)$$

where, f is the value of three analyzed parameters (DC-link voltage and active power as well as reactive power). SS and other Indices are values corresponding to the steady state and controllers, respectively.

SMAPE is an index to show magnitude difference. In this index, difference of two parameters is divided by sum of the parameters. In fact, the SMAPE normalizes absolute percentage error (Eq.(21)).The SMAPE values of four controllers have been presented in Table 5.

$$SMAPE = \frac{|f_{SS} - f_{other}|}{|f_{SS} + f_{other}|} \times 100 \quad (21)$$

Case Study

Test system is executed in MATLAB/SIMULINK environment. In the system, a UPFC has been used to control the dynamic performances over 230 *KV* transmission line. This system is constructed in meshed form consisting of two buses (bus-1 and bus-2) connected to each other through a 500 km transmission line named L1. In the mode without UPFC, active and reactive powers given to the system by the infinite buses; these two buses give identical powers to the system equal to (1.642-j0.4089) in per unit. UPFC is located in the left side of the line L and utilized to control active and reactive powers of bus-2 as we; as UPFC voltage. UPFC is composed of two voltage sourced converters based on IGBT, one in series and other in shunt connection [14].

The results of proposed ANFIS controller have been compared with PID and PI as well as MLP controllers. The results of PI and PID controllers on this test system and structure of MPL controller to control dynamic behaviors have been published in [14-15], respectively.

DC-link voltage

When the UPFC is entered to the system by a circuit breaker, active and reactive powers as well as amplitude of the bus voltages changed. In the system, it is assumed that the voltage magnitude of bus-1 is fixed in 1 per unit, also active and reactive powers of bus-2 in 1.5 per unit and -0.3 per unit, respectively. To achieve these objective values, DC-link capacitor voltage between two converters of UPFC should be maintained constant. To do this, operating point has to be determined using controllers and by changing parameters desired values could be exactly reached. Fig. 2 shows comparison of controller effect on DC-link voltage.

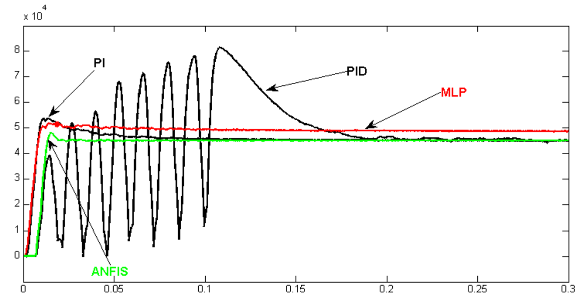

Fig. 2. DC-link voltage of UPFC

According to the Fig. 2, PID and ANFIS present the worst and best results, respectively. Over shoot of MLP controller is more than PI controller and the MLP controller never arrives to reference value, while PI is damped after ANFIS controller with acceptable delay and over shoot of MLP controller is between PI and ANFIS controllers. Table 1 shows values of three control parameters.

Active Power

Fig. 3 shows active power of bus-2 in the presence of UPFC based on convetional and proposed controllers. In this case, ANFIS acts with the lowest distortion and over shoot between these controllers. The PI controller has resulted toward to MLP controller. Unlike Fig. 1 that distortion of MLP and PI controllers not were sizeable. The worst outcome obtains from PID controller. Values of control parameters have been listed in Table 2.

According to the results of Table 2, presented peak value by ANFIS controller are 0.049 and 0.055 as well as 0.052 *pu* less than PID, PI and MLP controllers, repectively. Fall value of PI controller is 0.038 *pu* which is more than related parameter of ANFIS controller and this parameter of PID and MLP controllers are 0.292 and 0.056 *pu* which are more than related parameter of proposed ANFIS controller. Settle time of ANFIS controller is 0.0644, 0.009 and 0.0022 *sec* less than PID and PI as well as MLP controllers, repectively.

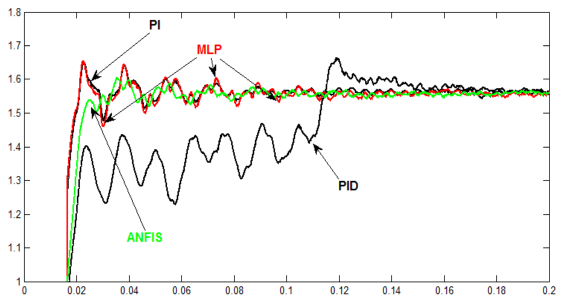

Fig. 3. Bus-2 active power comparison

By attending results of Table 1, peak value of proposed ANFIS controller is 33.48, 5.58 and 3.68 *kV* less than PID, PI and MLP controllers, repectivelly. Fall value of PID controller is 0.723 *kV* while other controllers are free of fall value. Desgined ANFIS controller reachs to stady state after 0.0032 and 0.0551 as well as 0.0012 *sec* earlier than PID, PI and MLP controllers, respectively.

Reactive Power

Finally, results of simulation for reactive power have been illustrated in Fig.4.

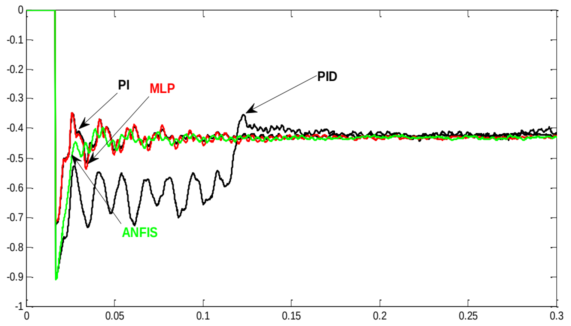

Fig. 4. Bus-2 reactive power comparison

From Fig. 4, behavior of all controllers with higher distortion is compared with active power. The proper action of ANFIS controller is evident; the controller has lower over shoot, and lower distortion. Values of three control parameters have been presented in Table 3.

By considering results given in Table 3, peak value of designed ANFIS controller is 0.0438, 0.05 and 0.502 *pu* less than related parameters of PID, PI and MLP controllers, respectively. Fall value of ANFIS controller is 0.239, 0.0201 and 0.0463 *pu* less than PID, PI and MLP controllers, respectively. The UPFC based on ANFIS controller reaches steady state in 0.00348, 0.1095 and 0.00222 *sec* less than PI and PID as well as MLP controllers, respectively.

Table 1. Comparison of control parameters on DC-link voltage

Parameter	**PID**	**PI**	**MLP**	**ANFIS**
Peak Value(kV)	81.61	53.71	51.81	48.13
Fall Value(kV)	0.723	-	-	-
Settle Time(sec)	0.2062	0.1543	0.1523	0.1511

Table 2. Comparison of control parameters on Active power

Parameter	**PID**	**PI**	**MLP**	**ANFIS**
Peak Value(pu)	1.657	1.651	1.654	1.602
Fall Value(pu)	1.236	1.49	1.472	1.528
Settle Time(sec)	0.1823	0.1201	0.1188	0.1179

Table 3. Comparison of control parameters on Active power

Parameter	**PID**	**PI**	**MLP**	**ANFIS**
Peak Value(pu)	-0.355	-0.3488	-0.3486	-0.3988
Fall Value(pu)	-0.7268	-0.5079	-0.5341	-0.4878
Settle Time(sec)	0.1884	0.08238	0.08112	0.0789

Statistical Analysis

These indices are studied based on steady state values. The steady state values of DC-link voltage and active power as well as reactive power are 45.12 kV, 1.559 pu and -0.428 pu, respectively.

Absolute Percentage Error (APE)

Obtain results from APE values are presented in Table 4.

Considering the values of Table 4, for DC-link voltage, PID controller has the worst solution to improve dynamic performance. While APE of ANFIS is the best case among four controllers and its peak value is 74.202, 12.367 and 8.156 less than related values of PID, PI and MLP controllers, respectively. For peak and least values of active power, the results of ANFIS controller are the best solution. Peak's APE value of ANFIS controller is 3.5279, 3.1430 and 3.3354 less than corresponding parameter of PID and PI as well as MLP controllers, respectively. For least value, this reduction is 18.7299, 2.4374 and 3.5920, respectively. The peak's APE value of ANFIS controller for reactive power is 10.2337, 11.6823 and 11.7290 less than related value of PID, PI and MLP controllers, respectively. This reduction for least value is 55.8411 and 4.6962 as well as 10.8177, respectively.

Symmetric Mean Absolute Percentage Error (SMAPE)

The SMAPE values of four controllers have been presented in Table 5.

By attention to the results of Table 5, peak's SMAPE value of ANFIS controller of DC-link voltage is 25.5656, 5.4638 and 3.6740 less than related parameter of PID, PI and MLP controllers, respectively. PID controller presents least SMAPE value equal to 96.8458. For active power, peak's SMAPE value of PID, PI and MLP controllers is 1.6870, 1.5057 and 1.5964 more than peak's SMAPE value of ANFIS controller, respectively. This increment for least SMAPE value is 10.5522 and 1.2588 as well as 1.8661, respectively. For reactive power, peak's SMAPE value of PID, PI and MLP controllers are 5.7914, 6.664 and 6.6924 more than peak's SMAPE of ANFIS controller, respectively. For fall value, these increments are 19.182 and 1.8448 as well as 4.3356, respectively. Fig.13 shows SMAPE values.

CONCLUSION

In this paper, ANFIS technique has been suggested to design novel controller for improving dynamic performance of power systems in the presence of UPFC. Main goal was to study the active and reactive powers and DC-link voltage. For this, three control parameters are used as comparison criteria; these parameters are peak and fall values as well as settle time. In all cases, ANFIS controller presents better solution respect to other controllers. From the viewpoint of lower overshoot and fast damping, the controllers are classified as follows ANFIS, MLP, PI and PID, respectively. Variation range of reactive power is smaller than active power. For DC-link voltage, ANFIS has the best response but MLP never arrive to reference value. Active power acts such that has the lower distortion compared to the reactive power.

Table 4. APE values of three parameters of four controllers

	PID	PI	MLP	ANFIS
Peak-Voltage	80.8732	19.0381	14.8271	6.6711
Fall-Voltage	98.3976	0	0	0
Peak-Active	6.2861	5.9012	6.0936	2.7582
Fall-Active	20.7184	4.4259	5.5805	1.9885
Peak-Reactive	17.0561	18.5047	18.5514	6.8224
Fall-Reactive	69.8131	18.6682	24.7897	13.972

Table 5. SMAPE values of three parameters of four controllers

	PID	PI	MLP	ANFIS
Peak-Voltage	28.7935	8.6917	6.9019	3.2279
Fall-Voltage	96.8458	-	-	-
Peak-Active	3.0473	2.866	2.9567	1.3603
Fall-Active	11.5564	2.263	2.8703	1.0042
Peak-Reactive	9.3231	10.1957	10.2241	3.5317
Fall-Reactive	25.8746	8.5372	11.028	6.5298

REFERENCES

[1] Song Y.H., and Allan T. J. 1999. Flexible AC transmission systems (FACTS). London, U.K., ,Inst. Elect. Eng. Press.

[2] Gyugyi L., Schauder C.D., Williams S.L., Rietman T.R., Torgerson, Edris D.R. A. 1995. The unified power flow controller: a new approach to power transmission control, IEEE Transactions on Power Delivery, 10(2):1085-1097.

[3] Mak L.O., Ni Y.X., Shen C.M. 2009. STATCOM with fuzzy controllers for interconnected power Systems, Electric Power Systems Research, 55:87-95,

[4] Morris S., Dash P.K., Basu K.P. 2003. A fuzzy variable structure controller for STATCOM, Electric Power Systems Research, 65:23-34.

[5] Changaroon B., Srivastava S.C., Thukaram D., Chirarattananon S. 1999. Neural network based power system damping controller for SVC, IEE Proc. Gener. Transm. Distrib., 146(4):370-736.

[6] Venayagamoorthy G. K., Rani Jetti S. 2008. Dual-function neuron-based external controller for a static VAR compensator, IEEE Transactions on Power Delivery, 23(2):997-1006.

[7] Panda S., Prasad Padhy N. 2008. Optimal location and controller design of STATCOM for power system stability improvement using PSO, Journal of the Franklin Institute, 345:166-181.

[8] Panda S., Padhy N. 2008. Comparison of particle swarm optimization and genetic algorithm for FACTS-based controller design, Applied Soft Computing, 8:1418-1427.

[9] Bian X.Y., Chung C.Y., Wang K.W., Tse C.T. 2004. Choice of SVC location/signal and its controller design by probabilistic method, Electric Power Systems Research, 71:35-40.

[10] Bian X.Y., Tse C.T., Zhang J.F., Wang K.W. 2011.Coordinated design of probabilistic PSS and SVC damping controllers, Electrical Power & Energy Systems, 33:445-452.

[11] Mete Vural A., Tu¨may M. 2007. Mathematical modeling and analysis of a unified power flow controller: a comparison of two approaches in power flow studies and effects of UPFC location, Electrical Power and Energy Systems, 29:617-629.

[12] Liu L., Zhu P., Kang Y., Chen J. 2007. Power-flow control performance analysis of a unified power-flow controller in a novel control scheme, IEEE Transaction on Power Delivery, 22(3):1613-1619.

[13] Al-Jarrah O.M., Al-Rousan M. 2001. Fault detection and accommodation in dynamic systems using adaptive neuro-fuzzy systems, IEE Proc.-Control Theory Appl., 148(4):283- 290.

[14] Nasir Aghdam H., Kaheh M., Najafi B., Farhadi P., Karimi M. 2011. Comparison between PI and PID controllers used in UPFC control for power flow, The 6th International Green Energy Conference (IGEC-VI) Eskişehir/Turkey.

[15] Kazemi Abharian E., Karimi M., P. Farhadi. 2011. STATCOM controller design based on MLP for power flow control, International Journal of Modeling and Optimization, 1(4):328-324.