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STATCOM Controller Design Based on MLP for Power Flow Control

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Abstract—The static synchronous compensator (STATCOM) is one of the developed converter-based flexible AC transmission systems (FACTS) controllers, recently. The STATCOM is shunts with power system and can absorb/deliver reactive power from/to power systems. In this paper, to power flow control in power system by STATCOM, a controller based on neural networks (NNs) have been designed; i.e. multilayer perceptron (MLP). The designed controller has been compared with two conventional controllers; i.e. PI and PID controllers. Influence of each controller on injected active power, injected reactive power and injected current by STATCOM have been analyzed. Three control parameters have used as decision criteria; i.e. peak time, fall time, peak value, fall value and site time. Simulations are performed in MATLAB/SIMULINK environment.

***Index Terms*—Power Flow Control, static synchronous compensator (statcom), multilayer Perceptron (MLP).**

I. Introduction

Due to the rapidly increasing progress in the power electronics, many Flexible AC Transmission Systems (FACTS) controllers have been introduced. FACTS devices are used in power systems to improve both the steady state and dynamic performances of the systems [1], [2]. So far several papers have described STATCOM controller design and how this device could be utilized for various aims.

To control reactive component, new variations on fuzzy control scheme has been proposed in [3]. The obtained control signal extracted from a combined generator speed deviation and STATCOM bus voltage deviation lead to the variable structure fuzzy controller. Simulations have been implemented in two cases (i.e. single-machine and multi-machine power systems) and compared with PI controller. Reference [4] presented a multi-control functional model to create power system steady-state in presence STATCOM. In this paper, 16 simulation cases have been performed on 30-bus, 118-bus and 300-bus IEEE systems. Main focus of reference [5] is on design of robust controller for power system damping. For variations of the operating points modeling and selecting a suitable open-loop transfer function have employed the method of multiplicative uncertainty and a loop-shaping technique, respectively. Simulation results of STATCOM controller have been compared with PID controller. In [6], STATCOM damping controller has been designed using the phase compensation technique to eliminate its negative influence to improvement of power system oscillations.

Authors of reference [7] proposed a STATCOM controller with a fixed modulation index during the transient period and presented harmonic analysis of STATCOM based on Bessel functions. The proposed controller by the pole assignment method was used to regulate AC system bus voltage. The step load change was used to illustrate proposed controller. Wang, in [8], has reported negative interactions between STATCOM AC and DC control and then has proposed multiple control functions of the STATCOM. The designed single multivariable PI controller has used as a MIMO control system.

Particle swarm optimization (PSO) algorithm has been used to solve optimal controller parameters, optimal STATCOM placement problem (for transient stability improvement) and coordinated design problem of STATCOM-based controller with multiple power system stabilizers (PSSs) (for system damping improvement). Two test systems were used in this paper; a two-area test system for optimal location and controller parameters and a four-machine two-area system for coordinated design problem. Simulations have been implemented on MATLAB/SIMULINK environment [9].

To have faster dynamic response, higher accuracy of tracking the reference signal, and stronger robustness to parameters variation and external disturbances, controller configuration has been suggested in [10] with two-level control; i.e. internal and external control systems. In internal level, H_{∞} control approach has been applied to simplify control system design. After controller design, improvements and optimizations based on dynamic analysis of STATCOM have developed to achieve better dynamical performance and higher tracking accuracy. Results of proposed controller have been compared with conventional PI controller.

Reference [11] proposed a controller variable structure for damping under damped power oscillations. To reach the controller the combination of continuous and discontinuous actions was utilized which exhibits an especially good performance.

Power system consists of many transmission lines and buses (generation or load). In complicated power networks, power flow conditions are of important problems. Power system designers and operators trying to control this aspect of electric power. FACTS devices are best alternatives among the shunt type of these devices, STATCOM has simple concept and structure. Main target of this study is to control power flow in the presence of STATCOM. To do this, novel

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controller based on NNs has been designed. Proposed MLP controller installed on STATCOM to control three parameters; injected current, active and reactive power. Obtained results of the proposed controller have been compared with PI and PID controllers.

This paper has been organized in seven sections; after literature review in section one, section two presents concept of STATCOM and then power flow control in presence this. In third section, control system of STATCOM has been described. Switching method and respective equations will be discussed in next section. In section five Concepts of NN and MLP and proccess of controller desgin have been presented. Designed controller has been installed on part of power system and ability of this controller has been compared with two conventional controllers in four vectors. Results of design and comparison have been presented in six sections. The work has been concluded in section seven.

NOMENCLATURE

V_{bus}	Bus voltage
V_d	Voltage of d vector
V_q	Voltage of q vector
m_a	Amplitude modulation index
$V_{m,sine}$	Magnitude of reference signal
$V_{n,tri}$	Magnitude of wave
m_f	Triangular carrier wave frequency
f_{sine}	Reference sinusoidal wave frequency
f_{tri}	Triangular carrier wave frequency
t	Target output
o	Output generated by the perceptron
η	Constant called the learning rate (e.g., 0.1).

II. POWER FLOW CONTROL BY STATCOM

A. Principle of STATCOM

The STATCOM is made up of a shunt transformer, a voltage source converter (VSC), a DC capacitor, a magnetic circuit, and a controller. If there is no energy storage device coupled to the DC link and the losses are neglected, neither shunt converter is capable of absorbing or generating real power so that only operating in the reactive domain is possible. The reactive power exchange of STATCOM with the AC system is controlled by regulating the output voltage amplitude of VSC. If the amplitude is increased above that of the AC system, the current flows through the shunt transformer from the STATCOM to the AC system, and the device generates reactive power (capacitive). If the amplitude is decreased to a level below that of the ac system, then the current flows from the AC system to STATCOM.

The capacitor is used to maintain DC voltage to the VSC, which itself keeps the capacitor charged to the required levels. Thus, by controlling the VSC output voltage lead or lag with respect to the AC system voltage, the capacitor DC voltage can be decreased or increased, respectively, to control the reactive power output of the device. When the VSC voltage leads the bus voltage, the capacitor supplies active power to the system, reducing its voltage; on the other hand, when the VSC voltage lags the bus voltage, the capacitor is charged by consuming active power from the system. The structure of a STATCOM with phase and PWM based voltage controls are depicted in Fig. 1 [12], [13].

B. Power Flow Constrains of the STATCOM

Based on the operating principle shown in Fig. 1, the equivalent circuit of the STATCOM can be derived, which is given in Fig. 2. In the derivation, it is assumed that (a) harmonics generated by the STATCOM are neglected; (b) the system as well as the STATCOM are three phase balanced. Then the STATCOM can be equivalently represented by a controllable fundamental frequency positive sequence voltage source. In principle, the STATCOM output voltage can be regulated such that the reactive power of the STATCOM can be changed.

According to the equivalent circuit of the STATCOM shown in Fig. 2, suppose $V_{sh}= V_{sh} \angle\theta_{sh}$, $V_i= V_i \angle\theta_i$ then the power flow constraints of the STATCOM are[14]:

$$P_{sh} = V_i^2 g_{sh} - V_i V_{sh}(g_{sh}\cos(\theta_i - \theta_{sh}) + b_{sh}\sin(\theta_i - \theta_{sh})) \quad (1)$$

$$Q_{sh} = -V_i^2 b_{sh} - V_i V_{sh}(g_{sh}\sin(\theta_i - \theta_{sh}) - b_{sh}\cos(\theta_i - \theta_{sh})) \quad (2)$$

Where,

$g_{sh}+jb_{sh}=1/Z_{sh}$

Operating constraint of the STATCOM – the active power exchange via the DC link is zero, which is described by

$$PE = \mathrm{Re}(V_{sh} V_{sh}^*) = 0 \quad (3)$$

Where,

$$\mathrm{Re}(V_{sh}V_{sh}^*) = V_{sh}^2 g_{sh} - V_i V_{sh}(g_{sh}\cos(\theta_i - \theta_{sh}) + b_{sh}\sin(\theta_i - \theta_{sh})$$

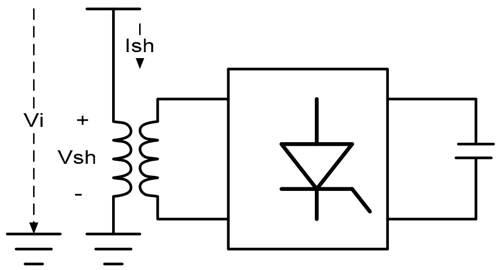


Fig. 1. STATCOM.

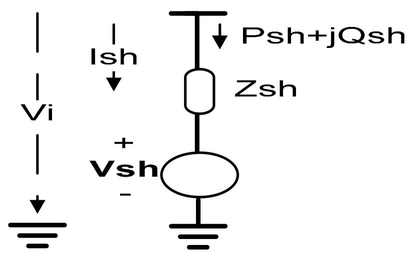


Fig. 2. STATCOM equivalent circuit.

III. CONTROL STRATEGY AND CONTROL SYSTEMS FOR STATCOM

STATCOM by injecting current in parallel with transmission line could control bus voltage and active power. For this purpose, the STSTCOM sampling from DC-link capacitor voltage as well as the UPFC connected bus voltage and then by converting these values to dq0 parameters by Parks transformation and calculating voltages in per unit as follows:

$$V_{bus} = \sqrt{V_d^2 + V_q^2} \quad (4)$$

V_{bus} and V_{dc} are compared by distinct values according to the block diagram depicted in Fig. 1, and generates error signals as follows:

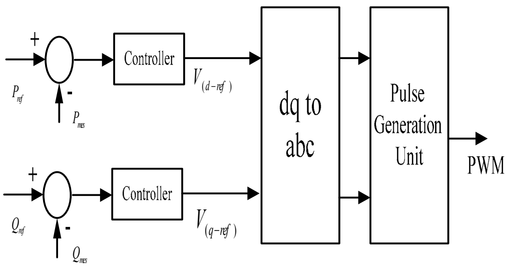


Fig. 3. Shunt converter control system

Generated error signals carried to controllers and output of controllers converted to *abc* parameters again and enter to the PWM pulse generating unit. By adjusting control parameters of controllers and switching, finally error signals carried to zero. And accordingly V_{bus} and V_{dc} stabled in their reference values [15].

IV. Switching Method

Switching technique is shown in figure 4. According to this figure, SPWM compares reference signal and carrier signal which is a triangular signal to generate switching pulses. In this technique, if the reference signal is more than carrier one then switch will be on, else off.

Pulse widths could be changed to control the output voltage. Although pulse widths could be different to each other, we can select the pulse width in such way that desired harmonics come out and the most common technique is sinusoidal pulse width modulation (SPWM). As the reference signal in this way is a sinusoidal form, this PWM technique is called SPWM. In SPWM, DF is unity and power factor will be corrected.

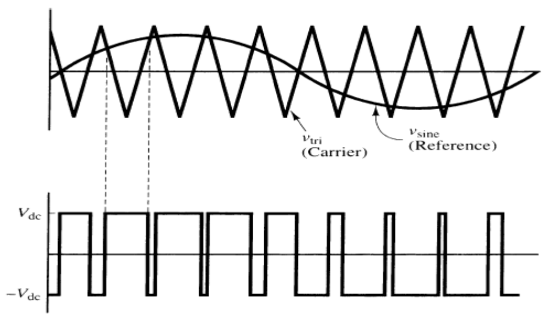


Fig. 4. SPWM technique for switching

Modulation amplitude index, m_a and Modulation frequency modulation, m_f are expressed using following equations [16]:

$$m_a = \frac{V_{m,\sin e}}{V_{n,tri}} = V_{m,\sin e} \quad (5)$$

$$m_f = \frac{f_{\sin e}}{f_{tri}} \quad (6)$$

$$V_{out} = m_a V_{DC} \sin(2\pi f_{\sin e} t - \theta) \quad (7)$$

Thus, output voltage of inverter can be controlled by and θ.

V. Multilayer Perception (MLP)

Neural Networks (NNs) have succeeded to solve several power system problems, such as: planning; control; analysis; protection; design; load forecasting; and fault diagnosis. The last three ones are the most popular [17]. The simple neuron model is made from studies of the human brain neurons. A neuron in the brain receives its chemical input from other neurons through its dendrites. If the input exceeds a certain threshold, the neuron fires its own impulse on to the neurons it is connected to by its axon [18].

A. Concept of perceptron

Type of NN has been created based on computations unit, that is named perceptron. A perceptron receives vector of inputs with real values and calculates liner composition of these inputs. If result is more than threshold value, perceptron output is 1 and otherwise is -1. This concept has been shown in Fig.5.

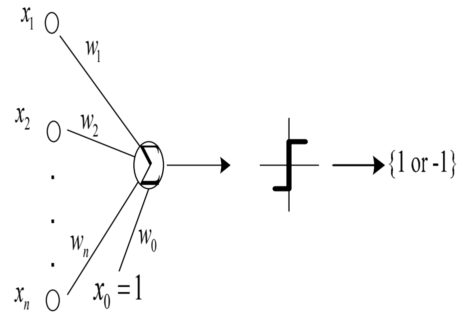


Fig. 5. Perceptron operator

The perceptron can be trained by adjusting the weights of the inputs with Supervised Learning. In this learning technique, the patterns to be recognized are known in advance, and a training set of input values are already classified with the desired output. Before commencing, the weights are initialized with random values. Each training set is then presented for the perceptron in turn. For every input set the output from the perceptron is compared to the desired output. If the output is correct, no weights are altered. However, if the output is wrong, we have to distinguish which of the patterns we would like the result to be, and adjust the weights on the currently active inputs towards the desired result [18].

For training of a perceptron used relationship (8):

$$(8) \quad O(x_1, x_2, \ldots, x_n) = \begin{cases} 1 & \text{if } w_0 + w_1x_1 + w_2x_2 + \ldots + w_nx_n > 0 \\ -1 & otherwise \end{cases}$$

B. Structure of MLP

Building on the algorithm of the simple Perceptron, the MLP model not only gives a perceptron structure for representing more than two classes, it also defines a learning rule for this kind of network.

The MLP is divided into three layers: the input layer, the hidden layer and the output layer, where each layer in this order gives the input to the next. The extra layers gives the structure needed to recognise non-linearly separable classes [18]. The stucture has been illustared in Fig.6.

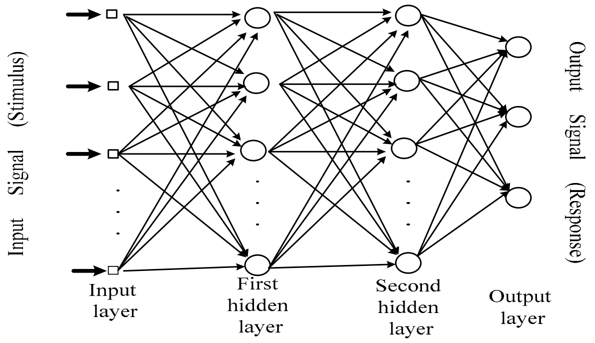


Fig. 6 shows structure of MLP.

Output of first layer is input vector of second layer, and also second layer output creates third layer inputs and third layer outputs are real response of network. The number of first and third layer neurons are equal to the number of system inputs and outputs, respectively. The number of middle layer is determined based on bourdensome of problem.

The threshold function of the units is modified to be a function that is continuous derivative, the sigmoid function. The use of the sigmoid function gives the extra information necessary for the network to implement the back-propagation training algorithm. Back-propagation works by finding the squared error (the Error function) of the entire network, and then calculating the error term for each of the output and hidden units by using the output from the previous neuron layer. The weights of the entire network are then adjusted with dependence on the error term and the given learning rate.

C. Adjustment of MLP

In this paper, this system has two inputs (dq0 parameters) and three outputs (active and reactive power as well as current) thus first layer and third layer of MLP has two neurons and three neurons, respectively. The number of middle layer neurons are three neurons determined by trail and error. Sigmoid function used for middle layer and output layer. The function has been explained in Appendix A. Weights between layers has been extracted by training network. The neural network has been simulated using Neural Networks Toolbox in MATLAB software. The proccess of MLP controller desgin follows:

1) Derivation of data by PI controller
2) Neural network training and selection of the number of middle layer and its neurons
3) Derivation of weights between layers
4) System implementation.

In this paper, perceptron rule was used for perceptron training. In training, for $X=(x_1, x_2, \ldots, x_n)$ in each step, weights are changing based on perceptron rule:

$$w_i = w_i + \Delta w_i \tag{9}$$

where,

$$\Delta wi = \eta\,(t-o)\,xi$$

VI. Simulation

In this section to illustrate effectiveness as well as reliability of the proposed controller, work of designed MLP controller has been conventional PI and PID controller. PI controller is the PID controller lacking the D branch. PI controller is a kind of feedback control, and has a fast response time due to the integrated proportional action. PI controller prevents the system from the oscillations. Also, could return the system to the desired state. Although, the PI response time is less than I controller, but could work up to 50% of the P controller, therefore this controller is combined with P controller to reduce the response time.

Dynamic performance of STATCOM has been depicted using time domain voltage and current waveforms. Test system has been obtained on MATLAB/SIMULINK environment, i.e. Fig. 7. In the system, a STATCOM has been used to control the power flow over 230 KV transmission line. This system is constructed in meshed form which consisting two buses (bus-1 and bus-2) connected to each other through a 500 km transmission line named "L1". The system supplied by two infinite buses having phase to phase voltage equal to 230kV.

It should be noted that the output real and reactive power of infinite buses are same and equal to (1.642-j0.4089) in per unit.

According to the Fig.7, STATCOM has located between B1 and B2, and was used to control active and reactive power and injected current of bus-B1 [19]. Fig.8 shows voltage, current, active and reactive powers of bus 1.

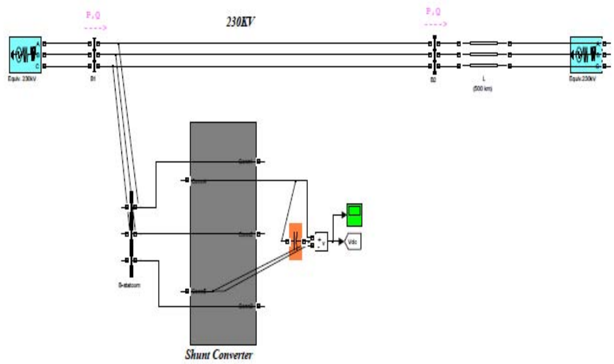
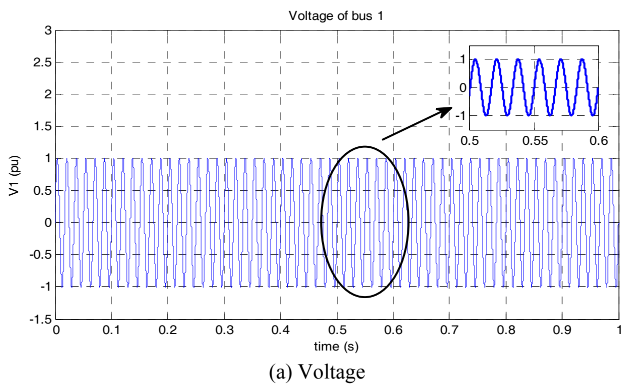
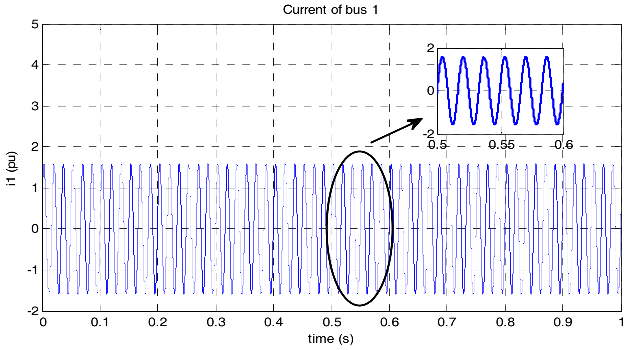


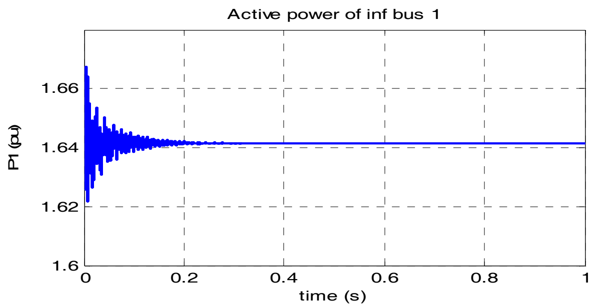
Fig. 7. Power system diagram used in STATCOM simulation References



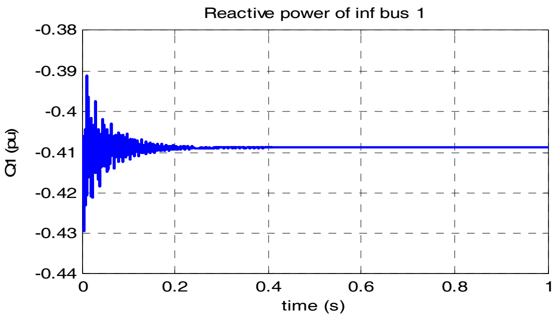
(a) Voltage



(b) Current



(c) Active power



(d) Reactive power

Fig. 8. parameters of bus 1 Fig.9 shows voltage of DC link of STATCOM that has been presented by PI, PID and MLP controller. In the system, it is assumed that the DC-link capacitor voltage is 45kV.

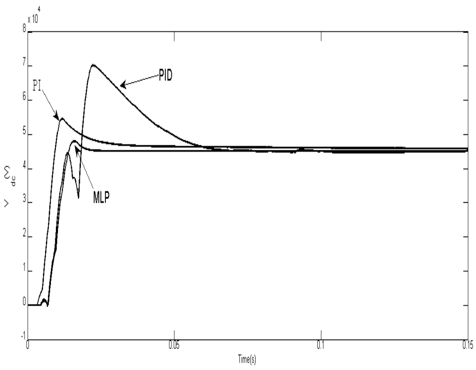


Fig. 9. Voltage of DC-link capacitor of STATCOM

PID and MLP controllers have delay time;i.e. PI controller starts earleir to rise at t=0.00262 sec. At the moment 0.00673 sec., PID and MLP controllers have similer behavior. In Table 1, three control parameters have been listed for each controller.

TABLE 1. COMPARISON OF CONTROL PARAMETERS ON DC-LINK VOLTAGE

Parameter	PID	PI	MLP
Peak Value(kV)	6.88	5.45	4.51
Fall Value(kV)	3.18	None	None
Settle time(s)	0.634	0.0360	0.0199

According to the results of Table 1, peak value of MLP controller is 2.73 and 0.94 kV less than peak value of PID and PI controllers, respectively. Peak time of these controllers is 0.0215, 0.0113 and 0.0153 sec. for PID, PI and MLP controller, respectively. PI and MLP controllers are free fall value but fall value of PID controller is 3.18 kV. MLP controller reaches to steady state prior than that of PID and PI controllers approximately 0.6141 and 0.0161 sec., respectively.

A. Injected Current

Fig. 9 shows behavior of controllers when current injection and Table 2 has presented peak value, fall value and settle time of Fig.10.

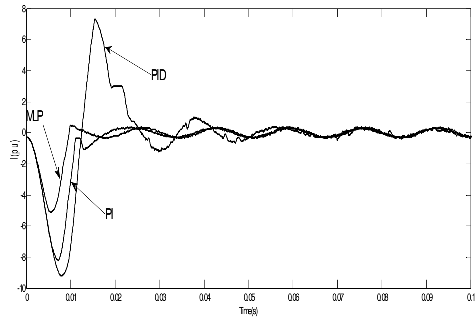


Fig. 10. Injected current by STATCOM

TABLE 2. COMPARISON OF CONTROL PARAMETERS ON INJECTED CURRENT

Parameter	PID	PI	MLP
Peak Value(pu)	7.21	0.445	0.411
Fall Value(pu)	-9.15	-8.08	-5.09
Settle time(s)	0.0248	0.0143	0.0112

In this case, peak and fall values have been considered maximum and minimum swing before arrive to steady state. Considering results of Table 2, MLP controller has least peak and fall values. Peak value of MLP controller is less than PID and PI controllers about 6.799 and 0.034 pu for peak value, respectively. Peak value occurs at moment 7.21, 0.445 and 0.411 sec. for PID, PI and MLP controllers, respectively. Fall value of PID and PI controller is 4.06 and 2.99 pu more than fall value of MLP controller, respectively. Settle time of MLP controller is 0.0136 and 0.0031 sec. less than settle time of PID and PI controllers, respectively. Occurrence instant of fall value is 0.00758, 0.701 and 0.555 sec. for PID, PI and MLP controllers, respectively.

B. Active power

Fig. 11 illustrates injected reactive power by STATCOM controller.

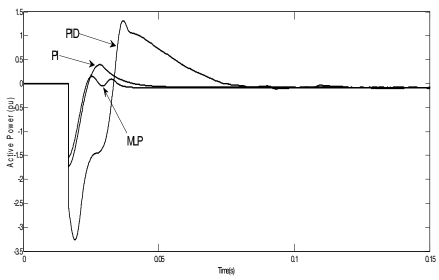


Fig. 11. Active power of bus-2 by STATCOM

Delay Time of three controllers is 0.0163 sec. Values of peak and fall and settle time of Fig.10 have been presented in Table 3.

TABLE 3. COMPARISON OF CONTROL PARAMETERS ON ACTIVE POWER

Parameter	PID	PI	MLP
Peak Value(pu)	1.31	0.385	0.155
Fall Value(pu)	-3.21	-1.72	-1.55
Settle time(s)	0.0835	0.0475	0.0403

Peak value of MLP controller is 1.155 and 0.23 pu less than peak value of PID and PI controllers, respectively. The peak value occurs at 0.0365, 0.0297 and 0.0247 sec. for PID, PI and MLP controllers, respectively. Fall value of MLP is 1.66 and 0.17 pu less than settle time of PID and PI controller, respectively. Fall time is 0.0190, 0.0172 and 0.0167 sec. for PID, PI and MLP controllers, respectively. Settle time of MLP controller is 0.0432 and 0.0072 sec., less than PID and PI controllers, respectively.

C. *Reactive power*

Extracted resctive power by STATCOM has been shown in Fig. 12. Table 3 presented three main control parameters of PID, PI and MLP controllers.

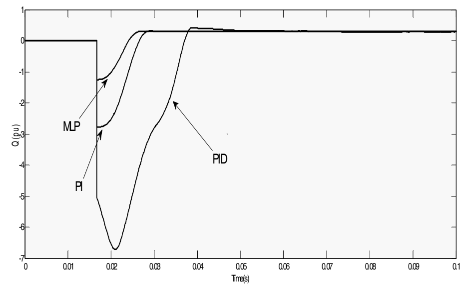


Fig. 12. Reactive power of bus-2 with STATCOM

TABLE 4. COMPARISON OF CONTROL PARAMETERS ON REACTIVE POWER

Parameter	PID	PI	MLP
Peak Value(pu)	0.432	0.256	0.252
Fall Value(pu)	-6.71	-2.77	-1.26
Settle time(s)	0.0485	0.0286	0.0271

Peak value of MLP controller is 0.18 and 0.004 pu less than peak value of PID and PI controllers, respectively. Peak time PID, PI and MLP controllers are 0.0388, 0.0283 and 0.0264 sec., respectively. Fall value of MLP controller is 5.45 pu less than fall value of PID controller and 1.51 pu less than fall value of PI controller. Fall occurs at moment 0.0209, 0.0167 and 0.0164 sec. for PID, PI and MLP controllers, respectively. Settle time of MLP is 0.0214 and 0.0015 sec. less than settle time of PID and PI controllers, respectively.

D. *Comparison*

Table 5 shows improvement percentage of peak value, fall value and settle time in the presence of MLP controller respect to corresponding parameters in comparison to PID and PI controllers.

The results of Table 5 show how peak and fall values as well as settle time reduction of MLP controller respect to corresponding parameter of PID and PI controllers.

TABLE 5. COMPARISON OF IMPROVEMENT PERCENT OF MLP CONTROLLER TO PID AND PI CONTROLLERS

		Peak Value	Fall Value	Settle time
PID controller	Current Injected	1654	79.76	121.43
	Active power	745	107.1	107.2
	Reactive power	71.43	432.54	78.97
PI controller	Current Injected	8.27	58.74	27.68
	Active Power	148.4	10.97	17.87
	Reactive Power	1.59	119.84	5.53

VII. CONCLUSION

In this paper, we proposed new controller based on nueral networks for power flow control in the precence of STATCOM. STATCOM has been installed between two buses and degined MLP controller has used to control injected current, active and reactive power. Our proposed controller has been compared with PI and PID controllers. Peak value, fall value and settle time were decision criteria for selecetion best controller. Results of simulation have been presented as schematic and tabular. From Table 5, in all case we can claim our proposed controller has minimum peak value, minimum fall value, minimum settle time. The results substantiate that MLP controller has ability for power control using STATCOM better than PI and PID controllers.

APPENDIX A

Sigmoid function

The output of this unit cell can be express as following form:

$$o(x_1, x_2, x_3, ..., x_n) = \sigma(WX) \quad (10)$$

where

$$\sigma(WX) = \frac{1}{1 + e^{-WX}}$$

The σ is named Segmond function. The function has following property:

$$d\sigma(y)/dy = \sigma(y)(1 - \sigma(y)) \quad (11)$$

Unlike perceptrons, multilayer networks can used for training nonlinear problems and also problems with multifarious decisions [20].

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