STATCOM Dc-bus Voltage Fuzzy-Controller Design using ANFIS

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Abstract: *Static Synchronous Compensator (STATCOM) regulates the voltage and corrects the power factor at the point of common coupling (PCC) by injecting reactive power. Also, this device plays a vital role as a stability aid for small and large transient disturbances in an interconnected power system. This work deals only with power-factor correction which means STATCOM in Var compensation mode. PI controller is very common in the control of various systems including STATCOM. However, one disadvantage of this conventional controller is its inability to still working well under a wider range of operating conditions. So, as a solution fuzzy controller is proposed in literature. But, the main problem with the conventional fuzzy controllers is that the parameters associated with the membership functions and the rules depend broadly on the intuition of the experts. To overcome this problem, this paper investigates the application of Adaptive Neuro-Fuzzy Inference System (ANFIS) approach to design a fuzzy controller for controlling the DC capacitor voltage under steady and transient condition. The simulation results using MATLAB/SIMULINK have proved that the proposed design method gives reliable powerful fuzzy controller with a minimum number of membership functions and has very good characteristics such as: fast dynamic response, high accuracy of tracking the DC-voltage reference, and strong robustness to load parameters variation.*

Keywords: *STATCOM; ANFIS, Sugeno fuzzy controller; Power-Factor Correction; Dc-bus Voltage.*

1. INTRODUCTION

The rapid development of the high-power electronics industry has made Flexible AC Transmission System (FACTS) devices practical and attractive for utility applications. As one kind of the typical FACTS devices, the static synchronous compensator (STATCOM) is playing more and more important roles in reactive power provision, voltage regulation support and even in the improvement of the transient stability of power systems; because of its attractive steady state performance and operating characteristics, which have been well studied in the past years [1,2]. STATCOM is connected in parallel to the power network devices and it is based on the principle that a voltage source inverter generates a controllable AC voltage source behind a transformer-leakage reactance so that the voltage difference across the reactance produces active and reactive power exchange between the STATCOM and the transmission network[3].

Proper control strategies corresponding to the control objectives are necessary in order to achieve efficient utilization of STATCOM. Most of the controllers used for this device are based on the PI controller [4]. Although the PI controller has a simple structure and it can offer relatively a satisfactory performance, its main problem is the correct choice of the PI gains and the fact that by using fixed gains, the controller may not provide the required control performance, when there are variations in the system parameters and operating conditions. Unlike the PI controllers, fuzzy logic controllers (FLCs) are capable of tolerating uncertainty and imprecision to a greater extent. So, they produce good results under changing operating conditions and uncertainties in system parameters [4]. During the past few decades, there are many successful applications with Fuzzy Logic Controllers (FLCs) in industry. It has been reported that they are successfully used in a number of complex and non-linear processes [5]. Moreover, the experience has shown that fuzzy controls are often a favored method of designing controllers for dynamic systems even if traditional methods can be used [6]. But, the main problem with the conventional fuzzy controllers is that the parameters associated with the membership functions and the rules depend broadly on the intuition of the experts. If it is required to change the parameters, it is to be done by trial and error only. There is no scientific optimization methodology inbuilt in the general fuzzy inference system [7]. To overcome this problem, Adaptive Neuro-Fuzzy Inference System (ANFIS) is used. In ANFIS, the parameters associated with a given membership function are chosen so as to tailor the input/output data set.

In this paper, a Sugeno fuzzy logic controller (SFLC) is proposed for controlling the STATCOM DC capacitor voltage under steady and transient conditions. The STATCOM is operating in Var compensation mode. The proposed controller is generated using ANFIS method design. Simulations using MATLAB/SIMULINK are carried out to verify the performance of the proposed controller. The results are illustrated and discussed.

2. SYSTEM CONFIGURATION AND THE BASIC OPERATION

Figure 1 shows the proposed STATCOM system configuration. In its simplest form, The STATCOM consists of a coupling transformer, a voltage-sourced inverter, a control system and a dc capacitor. In this arrangement, the steady-state power exchange between the device and the ac system is mainly reactive [8]. Regulating the amplitude of the STATCOM output voltage controls the reactive power exchange of the STATCOM with the ac system. If the amplitudes of the STATCOM output voltage and the ac system voltage are equal, the reactive current is zero and the STATCOM does not generate or absorb reactive power. If the amplitude of the STATCOM output voltage is increased above the amplitude of the ac system voltage, the current flows through the transformer reactance from the STATCOM to the ac system, and the device generates reactive power (capacitive). lf the amplitude of the STATCOM output voltage is decreased to a level below that of the ac system, then the current flows from the ac system to the STATCOM, resulting in the device absorbing reactive power (inductive). Since the STA'I'COM is generating or absorbing only reactive power, the output voltage and the ac system voltage are in phase, when neglecting circuit losses. The current drawn from the STATCOM is 90°- shifted with respect to the ac system voltage, and it can be leading (generates reactive power) or lagging (absorbs reactive power). A capacitor is used to maintain dc voltage to the inverter.

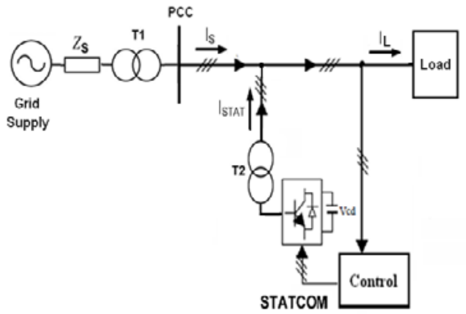

Fig.1. The studied system configuration

The principle of control reactive power via STATCOM is well known that the amount of type (capacitive or inductive) of reactive power exchange between the STATCOM and the system can be adjusted by controlling the magnitude of STATCOM output voltage with respect to that of system voltage. The reactive power supplied by the STATCOM is given by:

$$Q = \frac{V_{stat} - V_s}{x} V_s \quad (1)$$

Where

Q is the reactive power.

V_{stat} is the magnitude of STATCOM output voltage.

V_s is the magnitude of system voltage.

x is the equivalent impedance between STATCOM and the system.

3. SYNCHRONOUS REFERENCE FRAME (SRF) METHOD

Several control methods involved in generating reference signals have been discussed in literature among them being the Synchronous Reference Frame method. This method is based on the transformation of the currents in a-b-c frame to synchronously rotating d-q-0 frame. Fig. 2 explains the basic building blocks and their implementation in MATLAB/SIMULINK. The abc_to_dq0 Transformation block computes the direct axis, quadratic axis, and zero sequence quantities in a two-axis rotating reference frame for a three-phase sinusoidal signal. The following transformation is used:

$$i_d = \frac{2}{3}(i_a \sin(\omega t) + i_b \sin(\omega t - 2\pi/3) + i_c \sin(\omega t + 2\pi/3))$$
$$i_q = \frac{2}{3}(i_a \cos(\omega t) + i_b \cos(\omega t - 2\pi/3) + i_c \cos(\omega t + 2\pi/3))$$
$$i_0 = \frac{1}{3}(i_a + i_b + i_c) \quad (2)$$

Where ω = rotation speed (rad/s) of the rotating frame.

The reference frame is synchronized with the ac currents, and is rotating at the same frequency (ω=2πf). The angle of the transformation is detected by using a phase locked loop (PLL). i_0 is the zero sequence component which is equal to zero in 3-phase 3-wire balanced system. To return back into a-b-c frame, the following transformation is used:

$$i_a = i_d \sin(\omega t) + i_q \cos(\omega t) + i_0$$
$$i_b = i_d \sin(\omega t - 2\pi/3) + i_q \cos(\omega t - 2\pi/3) + i_0$$
$$i_c = i_d \sin(\omega t + 2\pi/3) + i_q \cos(\omega t + 2\pi/3) + i_0 \quad (3)$$

One of the most important characteristics of this method is that the reference currents are obtained directly from the loads currents without considering the source voltages. This is an important advantage since the generation of the reference signals is not affected by voltage distortion, so, increasing the compensation robustness and performance.

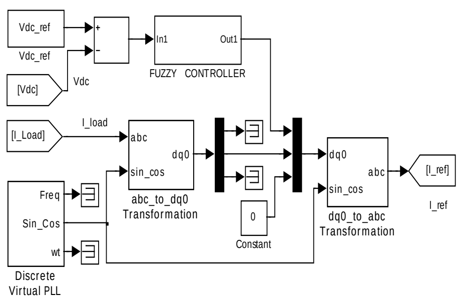

Fig.2. Block diagram of the reference current extraction and Dc-bus voltage regulation through SRF method.

4. SUGENO FUZZY LOGIC CONTROLLER (SFLC) DESIGN BASED ON ANFIS

This section introduces the basics of ANFIS network architecture and its hybrid learning rule. Inspired by the idea of basing the fuzzy logic inference procedure on a feed forward network structure, Jang [9] proposed an Adaptive Network-based Fuzzy Inference System (ANFIS) or semantically equivalently, the Adaptive Neural Fuzzy Inference System, whose architecture is shown in Figure 3. He reported that the ANFIS architecture can be employed to model nonlinear functions, identify nonlinear components on-line in a control system, and predict a chaotic time series.

It is a hybrid neuro-fuzzy technique that brings learning capabilities of neural networks to fuzzy inference systems. The learning algorithm tunes the membership functions of a Sugeno-type Fuzzy Inference System using the training input-output data. The ANFIS is, from the topology point of view, an implementation of a representative fuzzy inference system using a back propagation (BP) neural network-like structure. It consists of five layers. The role of each layer is briefly presented as follows: let O_i^l denote the output of node *i* in layer *l*, and x_i is the i_{th} input of the ANFIS, $i = 1, 2,...,p$. In layer 1, there is a node function *M* associated with every node:

$$O_i^1 = M_i(x_i) \tag{4}$$

The role of the node functions M_1, M_2 ...Mq here is equal to that of the membership functions $\mu(x)$ used in the regular fuzzy systems, and *q* is the number of nodes for each input. Gaussian shape functions are the typical choices. The adjustable parameters that determine the positions and shapes of these node functions are referred to as the premise parameters. The output of every node in layer 2 is the product of all the incoming signals:

$$O_i^2 = M_i(x_i) \; AND \; M_j(x_j) \tag{5}$$

Each node output represents the firing strength of the reasoning rule. In layer 3, each of these firing strengths of the rules is compared with the sum of all the firing strengths. Therefore, the normalized firing strengths are computed in this layer as:

$$O_i^3 = \frac{O_i^2}{\sum_i O_i^2} \tag{6}$$

Layer 4 implements the Sugeno-type inference system, i.e., a linear combination of the input variables of ANFIS, x_1, x_2, ...x_p plus a constant term, c_1, c_2, ...,c_p, form the output of each IF −THEN rule. The output of the node is a weighted sum of these intermediate outputs:

$$O_i^4 = O_i^3 \sum_{j=1}^{p} P_j x_j + c_j \tag{7}$$

Where parameters P_1, P_2, ...,P_p and c_1,c_2, ...,c_p, in this layer are referred to as the consequent parameters. The node in layer 5 produces the sum of its inputs, i.e., defuzzification process of fuzzy system (using weighted average method) is obtained:

$$O_i^5 = \sum_i O_i^4 \tag{8}$$

The flowchart of ANFIS procedure is shown in Figure 4. ANFIS distinguishes itself from normal fuzzy logic systems by the adaptive parameters, i.e., both the premise and consequent parameters are adjustable. The most remarkable feature of the ANFIS is its hybrid learning algorithm. The adaptation process of the parameters of the ANFIS is divided into two steps. For the first step of the consequent parameters training, the Least Squares method (LS) is used, because the output of the ANFIS is a linear combination of the consequent parameters. The premise parameters are fixed at this step. After the consequent parameters have been adjusted, the approximation error is back-propagated through every layer to update the premise parameters as the second step. This part of the adaptation procedure is based on the gradient descent principle, which is the same as in the training of the BP neural network. The consequence parameters identified by the LS method are optimal in the sense of least squares under the condition that the premise parameters are fixed [10].

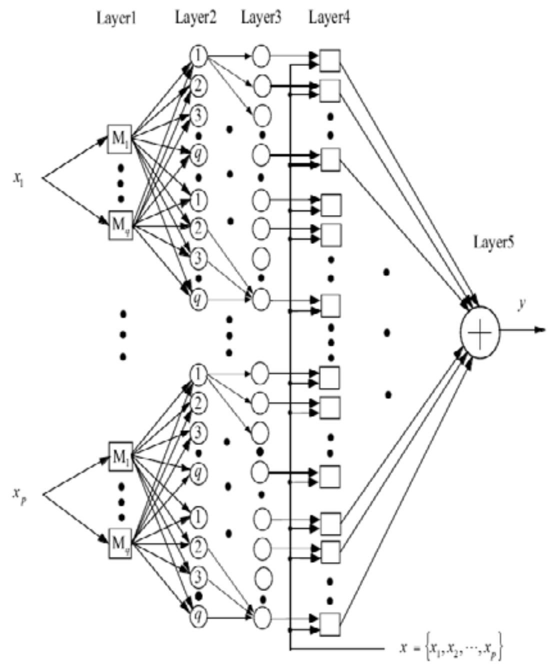

Fig.3. Structure of ANFIS.

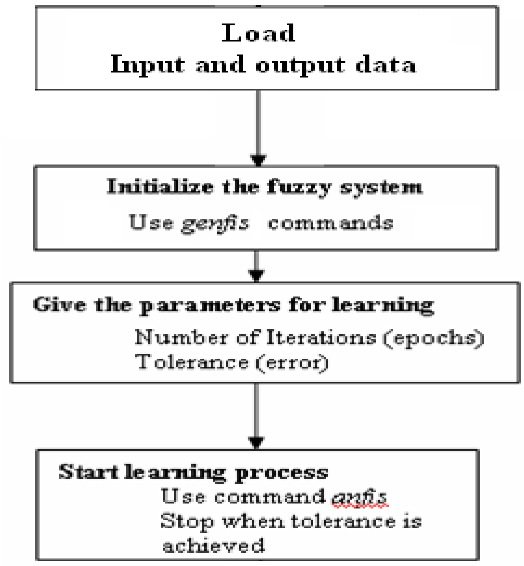

Fig.4. ANFIS procedure

The MATLAB/SIMULINK implementation of the Sugeno fuzzy controller is shown in figure 5.

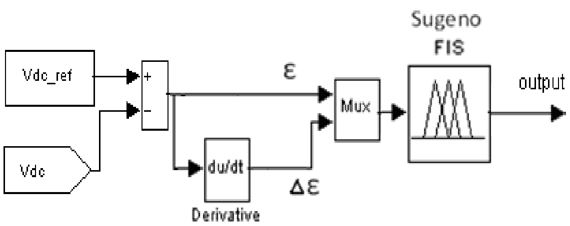

Fig.5. SIMULINK model of the proposed controller

5. SIMULATION RESULTS AND DISCUSSION

The proposed system configuration of Figure 1 has been simulated by Simulink of Matlab as it is shown in Figure 6.

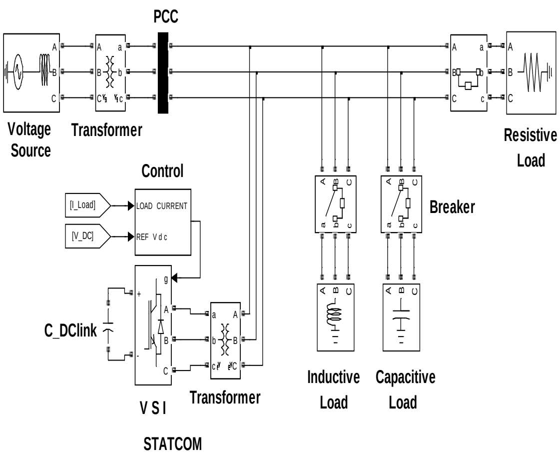

Fig.6. MATLAB/SIMULINK model for the studied system configuration

The input–output data pairs for training the ANFIS were generated using the conventional PI controller. ANFIS structure with Sugeno model containing 9 rules (Tables I) have been considered. Hybrid learning algorithm method was used to adjust the parameter of membership function. All the variables' fuzzy subsets for the inputs ε and Δε are defined as (M1, M2, M3) with triangular membership function. The membership functions and initial universes of the inputs generated by ANFIS training are illustrated in Figure 7 and 8. The output variable Y given by ANFIS training is a vector of constants. Y= [y_1, y_2, y_3, y_4, y_5, y_6, y_7, y_8, y_9] where, y_1=-1449, y_2=3.42 10^5, y_3=0, y_4=5341, y_5=8.624 10^7, y_6=2.173, y_7=2833, y_8=3.796 10^6, y_9=10^4. The control rules are illustrated in Tables I.

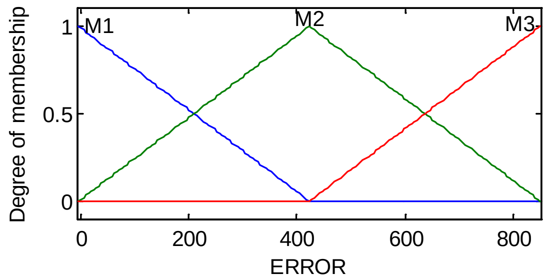

Fig.7. Membership function curves of the input ε

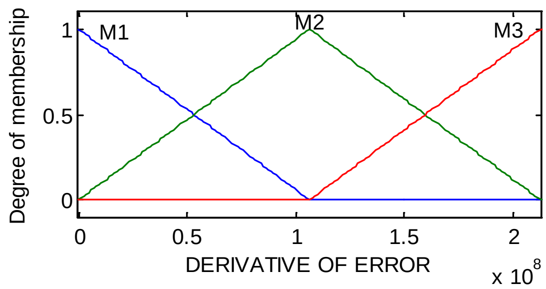

Fig.8. Membership function curves of the input Δε

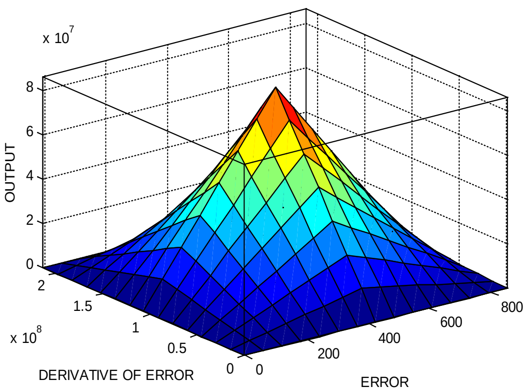

Fig.9. Surface plot of the Sugeno fuzzy controller

Table I: Fuzzy control rules

ε / Δε	M1	M2	M3
M1	y_1	y_2	y_3
M2	y_4	y_5	y_6
M3	y_7	y_8	y_9

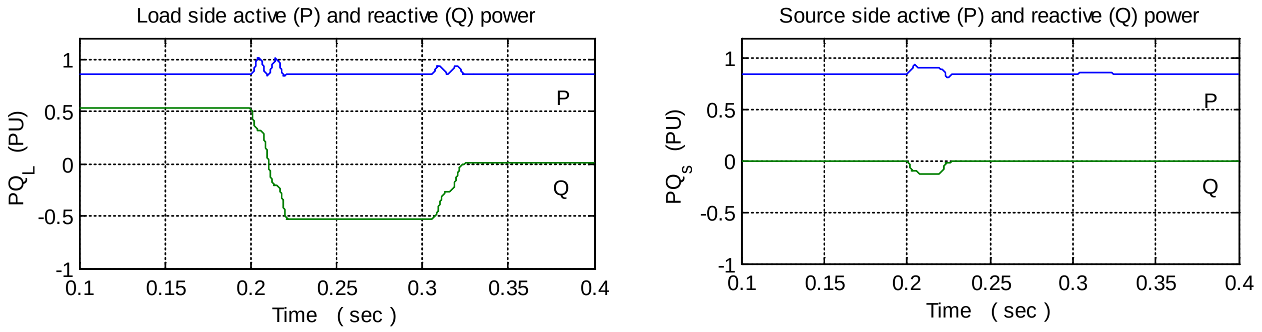

Fig.10. Active and reactive power in source and load sides for inductive, capacitive and resistive load in steady and transient state condition.

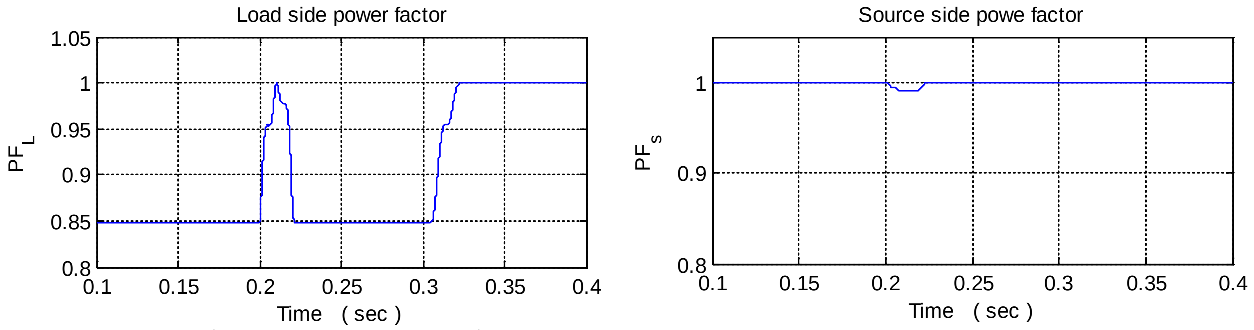

Fig.11. Power factor in source and load sides for inductive, capacitive and resistive load in steady and transient state condition.

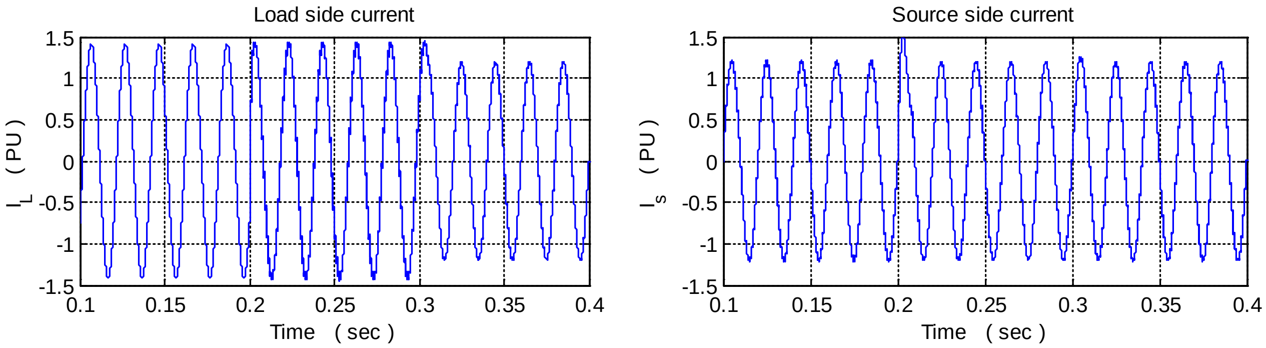

Fig.12. Current in source and load sides for inductive, capacitive and resistive load in steady and transient state condition.

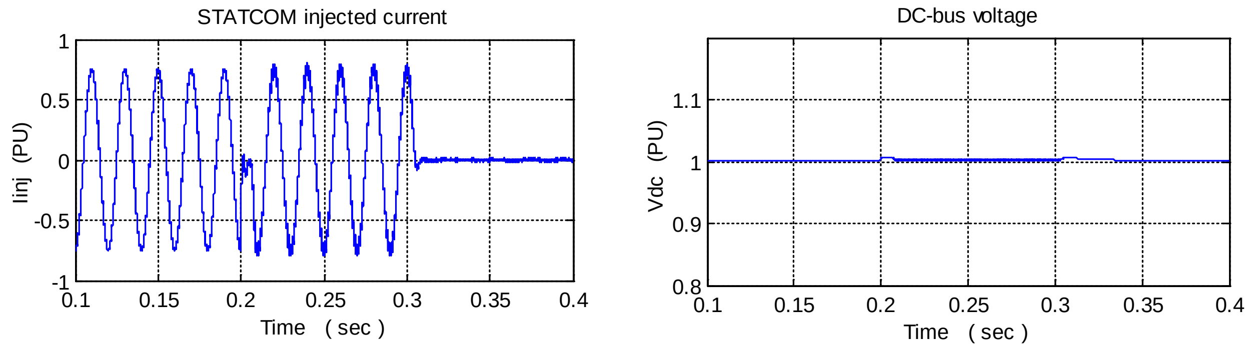

Fig.13. STATCOM injected current and DC-bus voltage regulation for inductive, capacitive and resistive load in steady and transient state condition.

The task of this simulation is to evaluate the performance of the proposed Sugeno fuzzy controller generated using ANFIS approach in steady and transient state conditions. For the sake of simplicity and clarity, only one phase is shown. The simulation results are shown in Figures 10, 11, 12 and 13, and from these figures we can observe:

1- In steady state condition, it is clear that the performance of STATCOM in the compensation of reactive power is very satisfactory. For inductive load (0.100 s – 0.200 s), a current of amplitude 0.750 pu and phase of -90.10° (Fig. 13) has been injected to compensate a reactive power of 0.529 pu (Fig. 10) which makes the source current passes from 1.413 pu and -32.05° to 1.206 pu and -0.05° (Fig. 12) and the power factor from 0.848 to 1(Fig. 11). For capacitive load (0.221 s – 0.300 s), a current of amplitude 0.750 pu and phase of 90.08° (Fig. 13) has been injected to compensate a reactive power of -0.529 pu (Fig. 10) which makes the source current passes from 1.414 pu and 32.08° to 1.208 pu and 0.03° (Fig. 12) and the power factor from 0.848 to 1 (Fig. 11). For the resistive load (0.324 s – 0.400 s), the STATCOM do nothing because in this case it is in standby mode. In these three cases, the regulation of the DC-bus voltage has remained unchanged and stable (Fig. 13).

2- In transient state condition. The STATCOM is compensating the reactive power under sudden load changing condition. Figures (10, 11, 12 and13) show the dynamic response of the STATCOM when the load changes suddenly from inductive to capacitive then to resistive. The inductive load is switched to capacitive load at t =0.2 sec then this last is removed at t= 0.3sec to remain only a resistive load. It is clear from these figures that the STATCOM succeeded in compensating the reactive power of the load with fast dynamics and with minimum overshoot. The change of inductive load to capacitive load passes through a transition period (0.200 s – 0.221 s) in which the source active power oscillates between 0.935 and 0.814 pu (0.848 pu at steady state) and the source reactive power decreases to -0.121 pu also source current increases to 1.510 pu. the change of capacitive load to resistive load passes through a transition period (0.300 s – 0.324 s) in which the source active power jumps to 0.865 pu and the source reactive power remains near zero, also the source current increases to 1.25 pu. So, we can say that the changes of source active power, reactive power and current are almost negligible compared to the steady state values. For the DC-bus voltage regulation, we can observe an increase in the voltage by 0.5% for the first transition and increase by 0.4% for the second transition. So, the DC-bus voltage change during transition periods is negligible. From the above simulations, it is clear and obvious that the proposed Sugeno fuzzy controller is able to control the DC-bus voltage efficiently in steady or transient state and the performance of STATCOM using this controller in reactive power compensation is very satisfactory.

6. CONCLUSION

In this paper a reliable controller with high performance for DC-bus voltage regulation of a STATCOM in Var compensation mode is presented. The proposed Sugeno fuzzy controller was generated by ANFIS training according to a given input output data. Compared to the traditional fuzzy controller, the proposed one can be considered to be the simplest; it has 3 membership functions for the inputs and 9 rules only which make its implementation practically very easy with a minimum cost. In addition this controller has no gains to adjust and solve the problem of traditional fuzzy controller gains tuning. The proposed scheme combined the SRF identification method and SFLC. One of the major advantages of this scheme is being less sensitive to the system parameters variation; in addition, it is characterized by a negligible response time. Simulation results analysis has shown that the proposed controller has fast dynamic response, high accuracy of tracking the DC-voltage reference, and strong robustness to load sudden variations.

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