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DESIGN OF STATIC SYNCHRONOUS COMPENSATOR STATCOM BASED ON NEURO-FUZZY LOGIC CONTROL

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Abstract: One of major issues involved in power transmission are enhancing the capability of transfer the active power through the existing transmission system and flexible control of power flow through these transmission lines. To achieve these goals the use of solid-state devices for reliable operation and faster control. The power electronics devices are utilized to control the flow of power these are classified under the flexible ac transmission systems (FACTS). Static synchronous compensator (STATCOM)is a FACTS device, STATCOM is designed by solid state device based on voltage source inverter(VSI), provide a controllable compensating voltage over the identical range of inductive and capacitive independent of the line current. In this study, a design scheme of STATCOM by utilize Neuro-Fuzzy logic controller is proposed, Sugeno type fuzzy logic, by using off-line rules are trained, also, d-q theory was used to calculate the parameters of power system due to its less computation and high accuracy. The simulation results show the proposed controller is reliable and robust compared to the conventional controllers where it needs less than cycle to reach the steady state and also less oscillation.

Keywords: *FACTS; STATCOM; VSI; d-q theory; park transformation; FLC; Pulse Width Modulation PWM.*

تصميم المعوض المتزامن الساكن بأستخدام المتحكم المنطقي المضبب الهجين

الخلاصة: يعد تعزيز قابلية خط نقل القدرة المستعمل وكذلك التحكم المرن بسريان القدرة الفاعلة واحدة من أهم القضايا الرئيسية في نقل القدرة الكهربائية. لتحقيق هذه الأهداف استعملت نبائط الحالة الصلبة لوثوقية الأداء وسرعة التحكم. ان نبائط الكترونيات القدرة المستخدمة للتحكم بسريان القدرة تصنف تحت اسم النظام المتناوب المرن (FACTS). أحد أجهزة النظام المتناوب المرن الحديثة يسمى المعوض المتزامن الساكن (STATCOM)، يعتمد عمل المعوض المتزامن الساكن على مغير مصدر الفولتية، يستطيع المعوض المتزامن الساكن ان يزود فولتية تعويض قابلة للتحكم على مدى التعويض الحثي والتعويض السعوي بدون الاعتماد على تيار الخط. تم في هذا البحث تصميم جديد للمعوض المتزامن الساكن باعتماد المتحكم المنطقي المضبب الهجين، استعمل المنطق المضبب نوع سوجينو كما تم تدريب شبكة العصبية في حالة ال off-line. كذلك تم استعمال نظرية ال d-q لحساب عناصر انظمة القدرة حيث تمتاز بعمليات حسابية اقل وكذلك دقة عالية. أظهرت نتائج المحاكاة أن المتحكم المقترح ذو وثوقية و ثبات مقارنة بالمتحكمات التقليدية التي بحثت في السابق.

1.Introduction

Parallel capacitive is widely utilize for compensation in the power transmission lines to maintain the total line impedance. The compensation using parallel capacitance increases the capacity of power transfers and enhance the stability as well. Parallel compensation using capacitors are installed in all power networks in the world as effective and economic way for provide the compensation. New technologies like flexible AC transmission system (FACTS) controllers, have made it's possible the electric utilities deal with mentioned issues[1]. In addition of allowing a better utilization of the power systems capacity, FACTS controllers can control the parameters of the network, such as line impedance, terminal voltage, and load angle, to improve both dynamic and the steady state performance of the power system [2].

Subsequently, FACTS devices were demonstrated that different types of parallel compensation is very efficient in both power flow through the lines and controlling in enhancing stability. The parallel compensator based on voltage sourced converter, called static synchronous compensator (STATCOM). STATCOM can provide the virtual compensation to the transmission line impedance this done by injecting the controllable voltage (magnitude and phase angle) in parallel with the transmission system [3]. Artificial intelligence has been proposed to design a controller of FACTS devices in recent year. These new approaches involve particle swarm optimization(PSO) [4], genetic algorithm(GA) [5], differential evolution (DE) [6], and multiobjective evolutionary algorithm [7].

Since 1988, the methodology of Artificial Neural Networks (ANN) has taken the significant in many applications in power engineering. These applications are include power system stabilizers (PSS), economical load dispatching, etc. The results of these applications have shown that ANN controllers have great potential in enhancing power system off-line and online applications [8]. The artificial neural network controller based on fuzzy control, i.e., (Neuro-Fuzzy controller) is applied for parallel FACTS device, i.e., static synchronous compensator (STATCOM). The aim of this study is to design STATCOM based on Adaptive Neuro Fuzzy controller to regulate the flow of active power and voltage regulation in transmission system. The proposed controller performances are optimized by using Neuro Fuzzy logic. The rules of fuzzy logic are trained by using of least squares estimate and gradient descent to tune the rule. The designed controller has small time of computation compared to mamdani type the classical fuzzy controller. The selected system consists of single machine infinite busbar. For controller design, power system model in MATLAB-Simulink with STATCOM controller has been developed.

2. Statcom Modeling And Control

Static Synchronous Compensator (STATCOM) injects voltage with variable phase angle and variable amplitude the output almost sinusoidal. The main part of STATCOM is a Voltage Source Inverter (VSI) the input is supplied by a DC source. The fundamental configureuration of STATCOM shown in Figure 1. Without of external DC source, the injected controlled voltage has two components: the main component is in quadrature with respect to the line current and emulate as a capacitive or inductive reactance compensation that in parallel with the transmission line, the second component is of the injected controlled voltage is in phase with line current and emulate as a power that cover the losses of inverter.

Depending on the line current, when the injected controlled voltage is lagging the line current, STATCOM will emulate as an inductance in parallel with the transmission line, causing the line current also active power flow to decrease [9]. When the injected controlled voltage is leading line current, STATCOM will emulate an capacitance in parallel with transmission line, leads to increase the line current as well as power flow through the line to decrease. A *V* versus *I* characteristic of STATCOM is shown in Figure 2. The benefits of using STATCOM are [10]:

1. The voltage regulation in distribution and transmission lines;
2. The damping the oscillation in power transmission lines;
3. The dynamic stability;
4. Control the flicker of voltage;
5. The control of power flow and also reactive power in the transmission lines, and this requiring dc energy source.
6. Ability to compensate in capacitive mode and inductive mode.
7. Exchange real power with the AC network when supply energy from DC side.

A coupling transformer is used to connect STATCOM to the transmission system. Through the transformer STATCOM inject controlled voltage to the transmission line. This voltage can be controlled on its magnitude and phase. The transmitted powers P and Q, become a parametric function of the injected voltage. By reversing the compensated voltage 180° phase angle, the reactive voltage drop of the line increase causing the reactive impedance of the line to increase and the power flow decrease. When the compensated voltage is larger than the total voltage through the uncompensated line by difference between sending and receiving voltage $|V_{comp}| > |Vs - Vr|$, this will reverse the power flow. STATCOM fast response time with less than one cycle. A typical power flow control using STATCOM is shown in Figure 3.

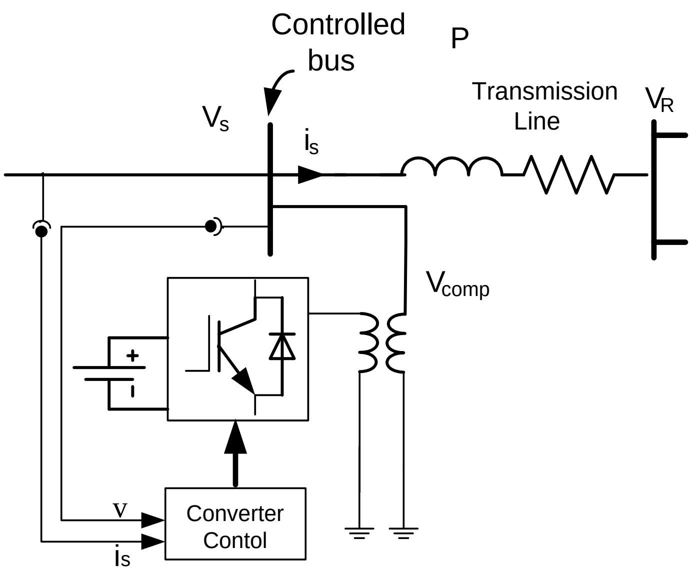


Figure 1 Fundamental configuration of STATCOM

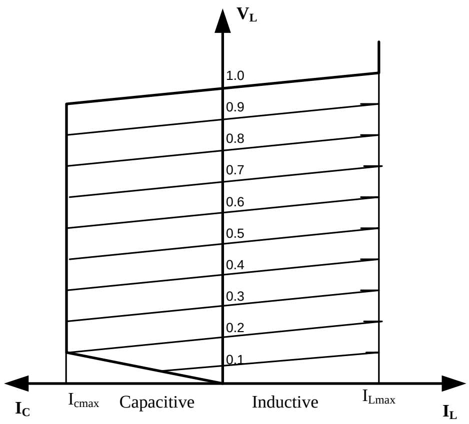


Figure 2 V-I characteristics of the STATCOM [9]

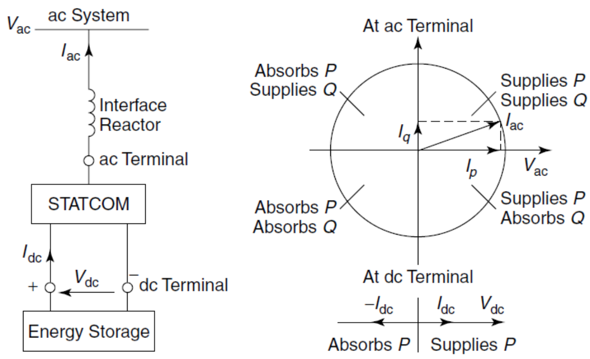


Figure 3. The power exchange between STATCOM and the ac system [9]

3. Measuring Active and Reactive Power

D-q theory was used for calculating active power flow and reactive power. Time domain based theory, and can apply for transient state or steady-state , also can apply for generic waveforms of current and voltage. Another advantage is simple of the transformation, which includes simple calculation. D-q theory implement Park transformation of a stationary coordination a-b-c to d-q rotating coordinates [11]. The transform applied to time-domain voltages in the natural frame (i.e. v_a, v_b and v_c) is as follows:

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\emptyset) & \cos(\emptyset - \frac{2\pi}{3}) & \cos(\emptyset + \frac{2\pi}{3}) \\ -\sin(\emptyset) & -\sin(\emptyset - \frac{2\pi}{3}) & -sin(\emptyset + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\emptyset) & \cos(\emptyset - \frac{2\pi}{3}) & \cos(\emptyset + \frac{2\pi}{3}) \\ -\sin(\emptyset) & -\sin(\emptyset - \frac{2\pi}{3}) & -sin(\emptyset + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2)$$

Where v_d, v_q, i_d, and i_q are the quadrature

$$\emptyset = (\omega t + \theta) \quad (3)$$

Where $\emptyset$ is the angle between the rotating and fixed coordinate system and θ is the phase shift between phase voltage and the line current. From (1) and (2), the active and reactive power compensated calculated by:

$$p = V_d I_d + V_q I_q \quad (4)$$

$$q = V_d I_q - V_q I_d \quad (5)$$

4. Statcom Controlling Scheme

Block diagram of STATCOM control system is shown in Figure 4. Three phase line voltages and three phase currents are sensed and P and Q, active and reactive power flow are calculated by park transformations. The signals of P & Q are the feedback of closed loop control. The references values of active and reactive power p_{ref} and q_{ref} (the desired values) are compared with the P and q this will produce the error signals $Erorr_p$ & $Erorr_q$ [11]. These signals (error signals) are used in the controller where:

$$Erorr_p = P_{ref} - P \quad (6)$$

$$Erorr_q = q_{ref} - q \quad (7)$$

The phase angle of the injected voltage can be adjusted to make the compensation either in capacitive mode or inductive mode by change the sign of the signal:

$$\delta = \emptyset \pm \gamma \quad (8)$$

Where γ can be adjusted in capacitive/inductive mode operations depending on the sign of the $Error_q$ in (7).

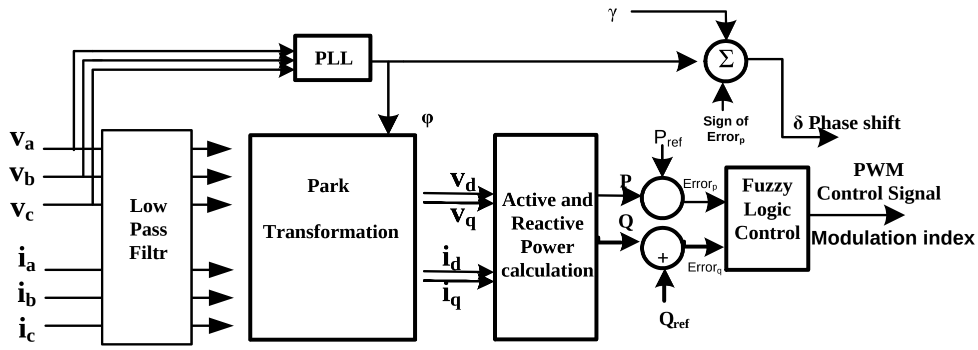


Figure 4 Block diagram for STATCOM control system

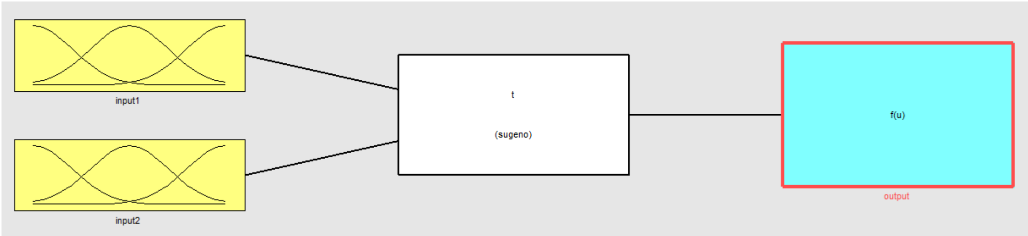
5. Fuzzy Logic Controller

Fuzzy logic is adequate for approximate reason, essential to the system have mathematical model that is not easy to derive. Fuzzy logic controllers use in many applications. There are many inference mechanisms in fuzzy control system, in this paper Takagi-Sugeno (TS) is selected. For tunning the membership functions of the TS fuzzy like-PI controller Artificial Neural Network (ANN) is used in this paper. The TS fuzzy controller has a highly non-linear variable gain controller. [12]. For modified the response Neuro-Fuzzy is used to adjust the fuzzy parameters and ANN algorithm utilize the rules. Since it combines the adaptive learning algorithms abilities of the ANN and fuzzy qualitative approach, this system can easily trained [13].

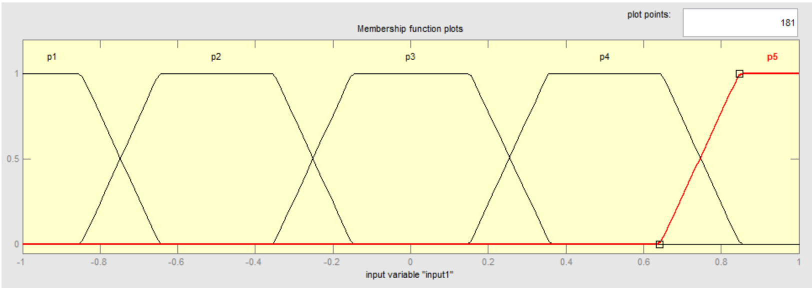
By ANN algorithm, the rule-of fuzzy can be reduced. The input parameters and membership output functions are determined through the training stage. The designed Fuzzy logic control system consists of five layers. The output of the layers emulate the fuzzy logic design proceedings is given in reference [14] for details. The important of the learning algorithm is to set the input parameters and output membership functions using Neuro Fuzzy so the output match the training data. Hybrid learning strategies such as Gradient Descent (GD) and Least Squares Estimate (LSE) is used to identify the parameters of the network.

In this work the input universe of discourse is split into 5 membership functions type of trapezoidal with overlapping of 50%, for two inputs, 25- control rules as shown in table 1 , the consequent linear functions need to be determined as shown in Figure5 a and b. For tuning the rules of TS by using Neuro-Fuzzy, two groups of data are generated. Error$_p$, and Error$_q$ are the vector input data and the output m the modulation index. Figure6 shows the validation test of Fuzzy logic system.

The output surface of STATCOM-control designed is shown in Figure7. This procedure is performed using the GUI of Neuro-Fuzzy file included in the MATLAB/FUZZY Logic Toolbox.



(a) FIS properties



(b) Membership plot

Figure 5 Fuzzy control scheme (a) FIS properties (b) membership plot

Table 1 Fuzzy control Rules

Δe\e	NB	NS	Z	PS	PB
NB	NB	NB	NS	NS	Z
NS	NB	NS	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PS	PB
PB	Z	PS	PS	PB	PB

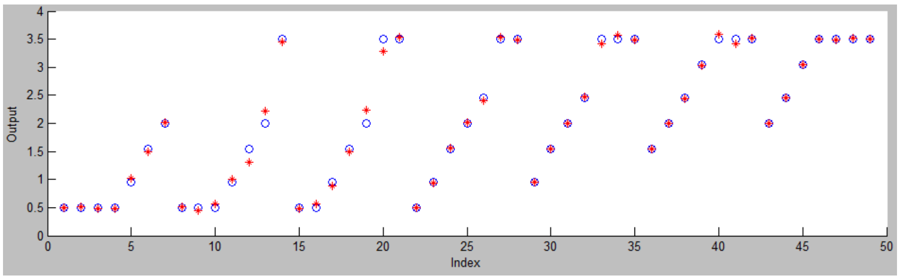


Figure 6. Fuzzy logic validation tests

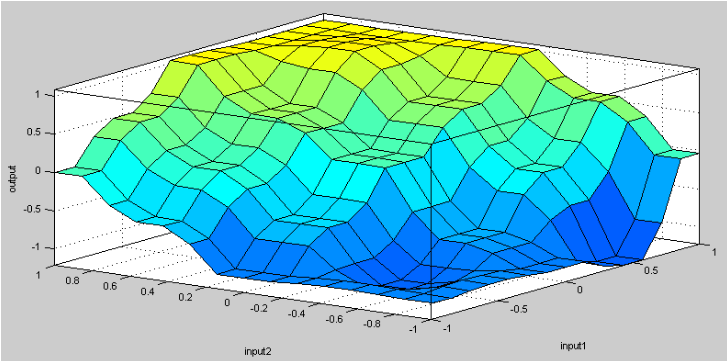


Figure 7. Control surface of STATCOM-based Neuro-fuzzy controller

6. Simulation Study

The system shown in Figure 8 consists of single machine infinite busbar system with trans mission base voltage of 13.8KV and base transmitted power of 5250MW and 2500MVAR for per unit simulation. To investigate the intelligent controller performance, the power model using MATLAB, is simulated by step change of the load. The model consists of two generators linked with transmission line with four busbars where STATCOM connected at BB1 to control the power flow from BB1 to BB2. The STATCOM is supplied with a DC source, this source can absorb or feed the powers (active and reactive) from or to the system. Characteristic of the storage battery model shown in figure 9.

The results illustrate the capability of the STATCOM to compensate the reactive power flow and then controlled the line current. PI controller is used for the sake of comparison (the tuned parameters of PI controller evaluated using tune parameters box in Simulink). STATCOM in this study is simulated as a voltage source inverter with controlled output. The step changes response of the system is used to test the performance of the controller. Figure10 shows that the compensated voltage to two steps values of injected voltage in capacitive reactance mode where the injected control voltage lags the current on transmission line, this will change in the line current above the reference values and also the active power.

Figure11shows the response of system to a line current step change, in capacitive mode (forward mode). The reverse direction was done by injection voltage as inductive reactance mode where the injected control voltage leads the line current. Figure 12 shows the step change in the current in inductive mode. It is clear from the simulation results that the Fuzzy logic controller designed has fast response (toke less than 20msec to reach final value) and less oscillation than the conventional PI controller (smoother response).

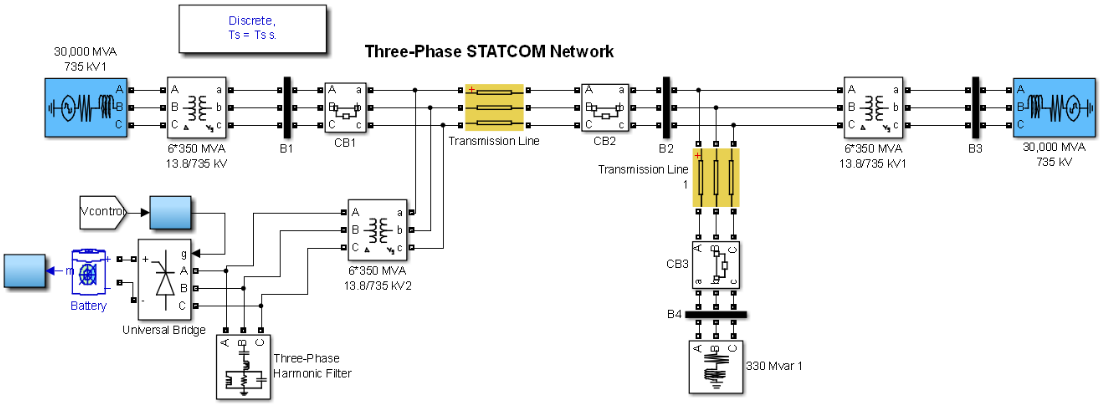


Figure 8. System model for simulation

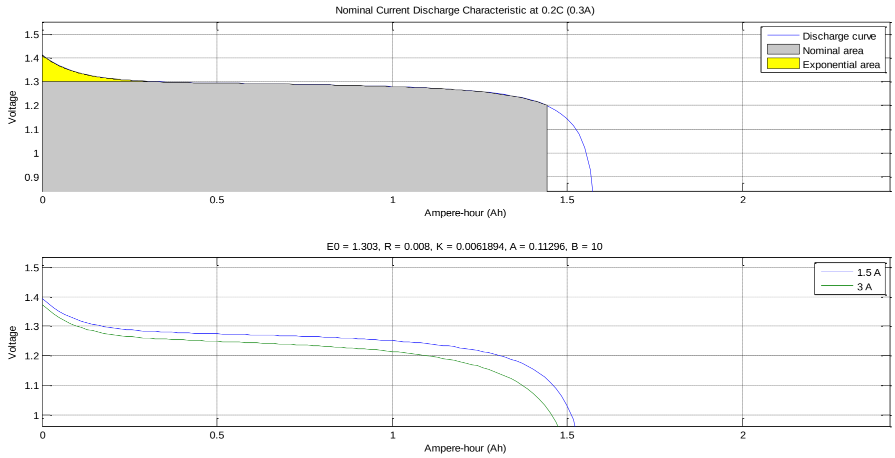


Figure 9. the characteristic of the storage battery model

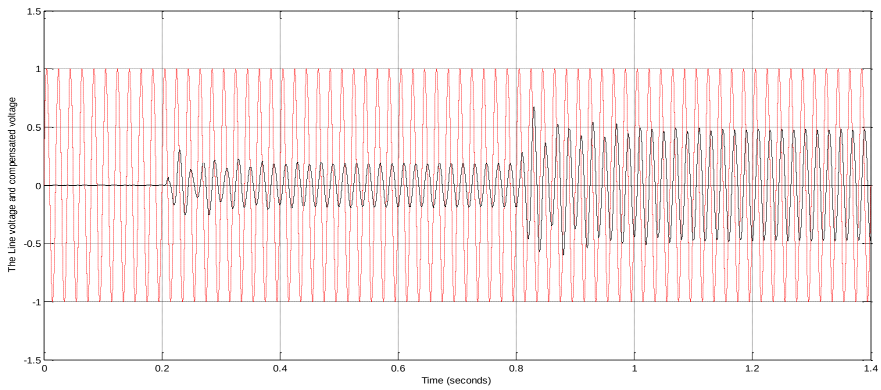


Figure 10. the line voltage versus injected compensated voltage

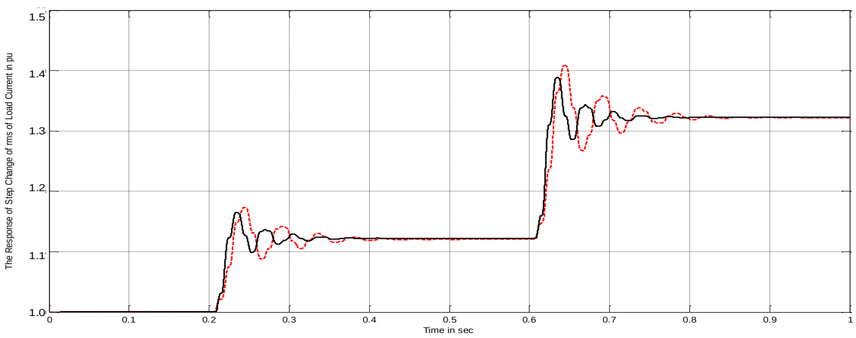


Figure 11.the step change response for two types of controller

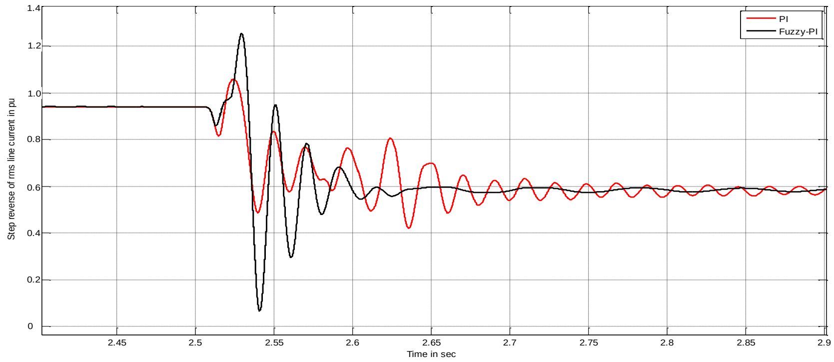


Figure 12.the step change in the current in inductive mode

7. Conclusion

In this paper, Neuro-Fuzzy controller with is used to control STATCOM. Tuning control algorithm is performed using off-line employed the aid of Neuro-Fuzzy System. The output rules defined by training the change of error for real and reactive power to set the tuning process. The small time of computation for measuring the power using d-q theory compared with abc theory that takes more than 20 msec also the controller faster than PI which takes less than one cycle to reach final value.

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