ANFIS based 48-Pulse STATCOM Controller for Enhancement of Power System Stability

Subir Datta and Anjan Kumar Roy

***Abstract*—The paper presents a new ANFIS-based controller for enhancement of voltage stability of a 500-kV, three-bus power system using a 48-pulse, ±100 Mvar GTO-based STATCOM. To study the effectiveness of the STATCOM in enhancement of voltage stability, the induced voltage of one of the generators is varied during simulation using programmable voltage source and the variations in voltage at the load end before and after the use of STATCOM is observed. The dynamic performance is studied using time-domain digital simulation of the complete system in MATLAB Simulink environment using its Power System Blockset (PSB). Control is carried out on a decoupled strategy using direct and quadrature components of STATCOM current. Operation of the STATCOM is validated in both capacitive and inductive modes. The complete power system, its PSB model and results of the investigations, showing the effectiveness of the proposed ANFIS-controller in voltage stabilization, have been presented with different figures. For the sake of comparison, time-domain simulation of the same system has been carried out with PI-controller and presented side-by-side. Analysis of the results and a conclusion are presented.**

***Index Terms*—48-pulses GTO based STATCOM, Voltage stability, reactive power compensator, ANFIS and PI controller, decoupled control strategy.**

I. INTRODUCTION

Voltage stability is increasingly becoming limiting factor in planning and operation of some power systems, mainly in longitudinal lines. A suitable reactive power control scheme can provide a number of important benefits in the power system operation such as reduction of voltage gradients, efficient utilization of transmission capacities, increase in transient stability margin etc. Different control techniques have so far been applied to avoid voltage collapse and also to maintain the load voltage within certain specified limits.

Commercial availability of Gate Turn Off thyristor (GTO) devices with high power handling capability, and the advancement of other types of power-semiconductor devices such as IGBT′s, have led to the development of controllable reactive power sources utilizing electronic switching converter technology [1]. These technologies additionally offer considerable advantages over the existing ones in terms of space reductions and performance.

The GTO thyristors enabled the design of solid-state shunt reactive compensation equipment based upon switching converter technology. The GTO thyristors enabled the design of solid-state shunt reactive compensation equipment based upon switching converter technology. This concept was used to create flexible shunt reactive compensation device named Static Synchronous Compensator (STATCOM) due to similaririty in operating characteristics with that of a synchronous compensator but without mechanical inertia.

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S. Datta is with the Mizoram University, India (e-mail: subirnerist@gmail.com).

A. K. Roy is with the National Institute of Technology Silchar, India (e-mail: anjan_kumarroy@rediffmail.com).

In this paper, a 48-pulse VSI converter is built by combining four 12-pulses VSI converters and used as STATCOM. For high power applications it is most suitable as harmonics of the order $48r \pm 1$, r=0, 1, 2.. only would be generated; although by using 24-pulse converter with filters, tuned to the 23th - 25th, adequate amount of harmonics could be eliminated. But, the 48-pulse converter scheme can ensure minimum power quality problems and reduced harmonic resonance conditions on the interconnected grid network.

II. STATIC SYNCHRONOUS COMPENSATOR

The Static Synchronous Compensator (STATCOM) is shunt connected reactive compensation equipment which is capable of delivering or absorbing variable reactive power to control the required parameters of the electric power system. The STATCOM provides operating characteristics similar to those of a rotating synchronous compensator. Due to the use of solid state power switching devices it does not suffer from mechanical inertia and hence can provide rapid response.

STATCOM is basically a three phase GTO or IGBT-based voltage source inverter (VSI) with a DC capacitor at one of its ends and a step-up transformer (called coupling transformer having leakage reactance) at the other-end; the secondary of the transformer remains connected in shunt with the line. The basic voltage-source inverter representation of STATCOM for reactive power generation is shown schematically in Fig. 1.

In the present paper, the STATCOM is used to absorb reactive power from the line or to deliver the same to the line with the aim of regulating the bus voltage, dynamically. The basic principle of STATCOM operation can be illustrated by the phasor diagrams, shown in Fig. 2. By proper switching operation, the magnitude and phase of the STATCOM output (ac) voltage, V_S is controlled with respect to the bus (or line) voltage, V_B. The difference, $\Delta V_L=|V_B|-|V_S|$ between the line voltage and STATCOM voltage appears across the leakage reactance. Let, V_{SD} and V_{SQ} are the in-phase and out of phase components of STATCOM output voltage, V_S with respect to the line voltage, V_B, such that $V_B = |V_B|\angle 0^0$ & $V_S = V_{SD} + jV_{SQ}$. The potential difference between the line voltage and the in-phase component of STATCOM voltage, $\Delta V_{LD} =$

$|V_B|$-$|V_{SD}|$ appears across the leakage inductance between line and STATCOM and causes flow of reactive current, I_Q=-j$\Delta V_{LD}/X_L$ from the line to the STATCOM and hence flow of reactive power, $Q_{BS}=V_BI_Q^*=$ j$V_B(\Delta V_{LD}/X_L)$= j$|V_B|[|V_B|-|V_{SD}|]/X_L$ from the line to the STATCOM.

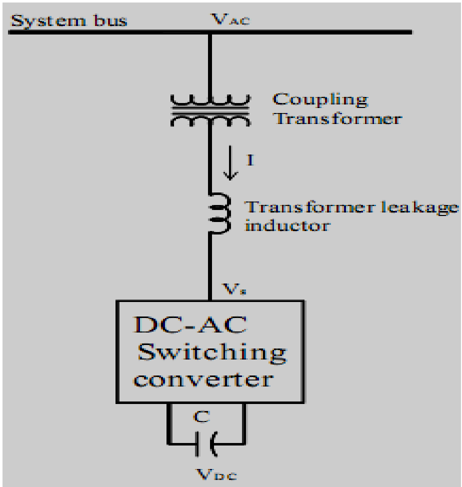
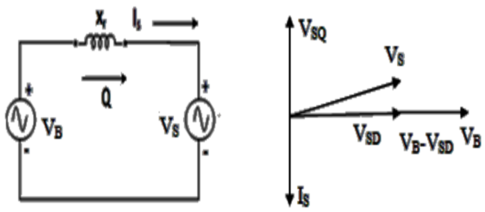
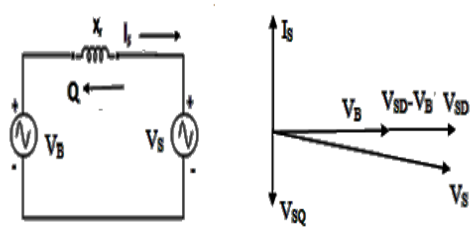


Fig. 1. Schematic diagram of STATCOM



(a)



(b)

Fig. 2. STATCOM Operation (a) Inductive operation (b) Capacitive operation

When $|V_{SD}|<|V_B|$, Q_{BS} is positive and the STATCOM absorbs inductive power, Q_{BS} from the bus and acts like an inductor. On the other hand, when $|V_{SD}|>|V_B|$, Q_{BS} is negative and the STATCOM delivers inductive power, Q_{BS} to the bus and acts like a capacitor. When $|V_{SD}|=|V_B|$ reactive power exchange is zero. Thus, by controlling the magnitude of the in-phase component, V_{SD} of STATCOM with respect to the line voltage, V_B, the STATCOM can be made to absorb reactive power from the line or deliver the same to the line.

The potential difference between line voltage and out of phase component of STATCOM voltage, ΔV_{LQ} = 0-j$|V_{SQ}|$. It appears across the leakage inductance between line and STATCOM and causes flow of active current, I_P =$\Delta V_{LQ}/X_L$=-V_{SQ}/X_L and hence flow of active power, $P_{BS}=V_BI_P^*=-V_BV_{SQ}/X_L$ from the STATCOM to the line. Direction of active power flow can be reversed by reversing the sign of V_{SQ}, i.e., by making it to lag V_B. For delivering real power to the power system, energy storage device should be connected to the DC side of the STATCOM. When a capacitor is connected at the DC-side of STATCOM, under steady state operation V_{SQ} is kept lagging V_B by a very small angle to compensate the small active power losses in the inverter.

III. Harmonic Reduction Schemes

With simple inverter, a STATCOM produces square voltage waveform. To produce a near sinusoidal AC voltage, with minimal harmonic distortion three of the several basic techniques are:

1) Harmonic neutralization using magnetic coupling (multi-pulse converter configuration),
2) Harmonic reduction using multi-level converter configuration and
3) Pulse-Width Modulation (PWM) technique.

IV. 48-Pulse Voltage Source GTO Converter

Two 24-pulse GTO converters, phase-shifted by 7.5^o from each other, are used to provide the full 48-pulse converter operation. The 48-pulse converter comprises of four identical 12-pulse GTO converters interlinked by four 12-pulse transformers with phase-shift windings [2, 3]. Fig-3 depicts the schematic diagram of a 48-pulse Voltage Source GTO STATCOM. Transformer connections, phase shifting using zig-zag transformers and firing pulse logics, for generation of STATCOM output voltage are shown in the said Fig. to get the final 48-pulse operation.

The 48-pulse converter can be used in high power applications without the need for any AC filters due to its high performance and very low harmonic content on the AC side. The output voltage have harmonics n = 48r ±1, where, r = 0, 1, 2,...; i.e., 47th, 49th, 95th, 97th, ..., with typical magnitudes of 1/47th, 1/49th, 1/95th, 1/97th,..., respectively, with respect to the fundamental; on the DC side, the lower circulating dc current harmonic content is the 48th. The phase-shift pattern on each 12-pulse converter is referred in [3].

The resultant output voltage generated by 48-pulses GTO STATCOM controller is given below:

The resultant output voltage generated by 1st 12-pulse converter is,

$$v_{ab_{12}}(t)_1=2[v_{ab_1}\sin(\omega t+30^\circ)+v_{ab_{11}}\sin(11\omega t+195^\circ)+v_{ab_{12}}\sin(13\omega t+255^\circ)+v_{ab_{23}}\sin(23\omega t+60^\circ)+...] \quad (1)$$

The resultant output voltage generated by 2nd 12-pulse converter is,

$$v_{ab_{12}}(t)_2=2[v_{ab_1}\sin(\omega t+30^\circ)+v_{ab_{11}}\sin(11\omega t+15^\circ)+v_{ab_{12}}\sin(13\omega t+75^\circ)+v_{ab_{23}}\sin(23\omega t+60^\circ)+...] \quad (2)$$

The resultant output voltage generated by 3rd 12-pulse converter is,

$$v_{ab_{12}}(t)_3=2[v_{ab_1}\sin(\omega t+30^\circ)+v_{ab_{11}}\sin(11\omega t+285^\circ)+v_{ab_{13}}\sin(13\omega t+345^\circ)+v_{ab_{23}}\sin(23\omega t+240^\circ)+\ldots] \quad (3)$$

The resultant output voltage generated by 4th 12-pulse converter is,

$$v_{ab_{12}}(t)_4=2[v_{ab_1}\sin(\omega t+30^\circ)+v_{ab_{11}}\sin(11\omega t+105^\circ)+v_{ab_{13}}\sin(13\omega t+165^\circ)+v_{ab_{23}}\sin(23\omega t+240^\circ)+..] \quad (4)$$

Output AC voltages of these four 12-pulse, given by equations (1-4) appears across secondary windings of the transformers and are added by connecting the windings in series. The expression for the 48-pulse AC output voltage is given by:

$$v_{ab_{48}}(t)=8[v_{ab_1}\sin(\omega t+30^\circ)+v_{ab_{47}}\sin(47\omega t+150^\circ)+v_{ab_{49}}\sin(49\omega t+210^\circ)+v_{ab_{95}}\sin(95\omega t+330^\circ)+..] \quad (5)$$

The 48-pulse VSC generates less harmonic distortion and reduce power quality problems than other converters, such as (6, 12 and 24-pulse. This results in minimum operational overloading and system harmonic instability problems. The simulation model of the 48-pulse STATCOM is prepared.

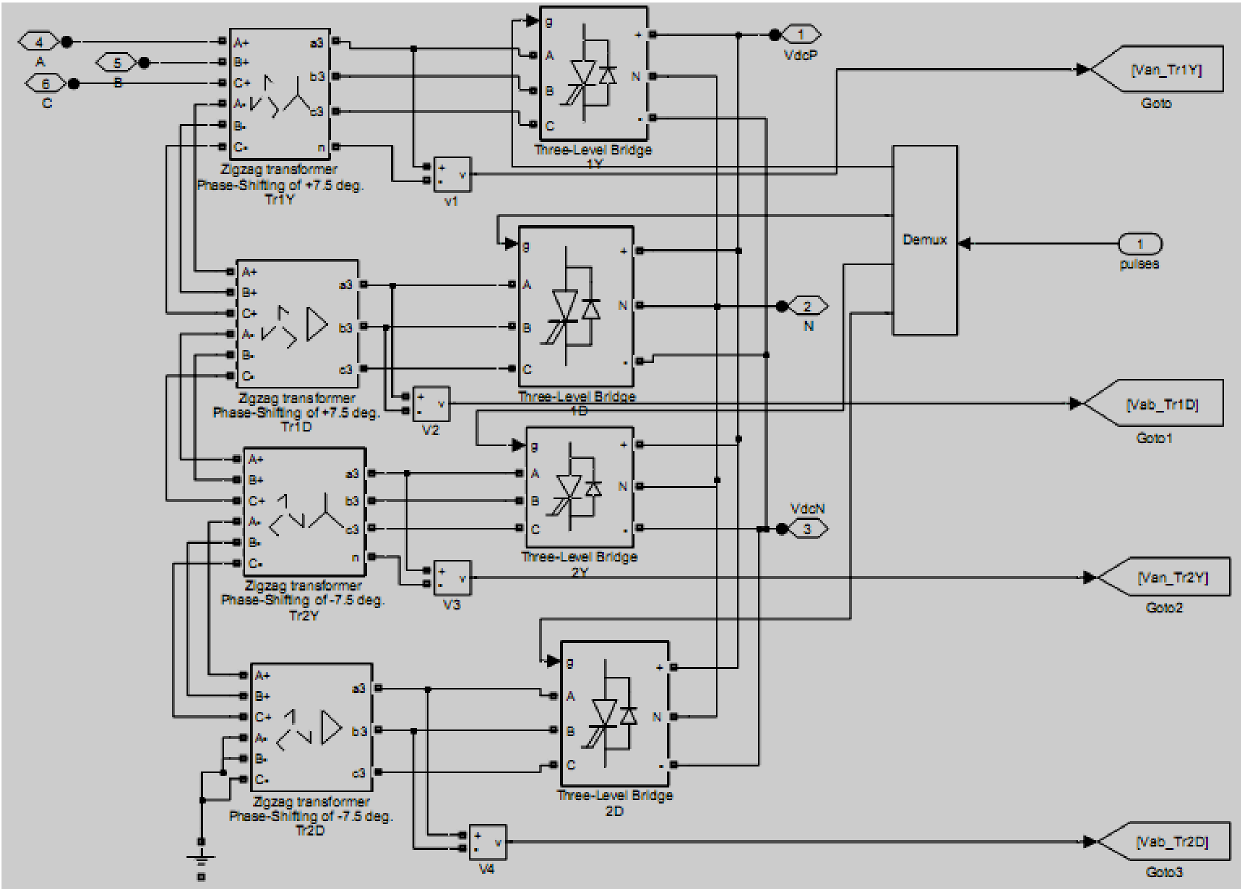


Fig. 3. 48-Pulse GTO-based STATCOM

V. Power System Description

A 3-bus (1, 2, 3 at 500-kV), loop connected power system, with loads at bus-1 & 2, as shown in Fig-4, has been considered. One (bus-1) of the buses is supplied from a programmable voltage source (voltage varying between ±5% with time) whereas the other two are supplied from constant voltage sources. The details of the system parameters are given in Table-1.

The 48-pulse, ±100 Mvar STATCOM has been connected at the mid-point between the bus-1 & bus-2 with the aim of controlling and maintaining the voltages at bus-1 & bus-2 near to 1.00 pu.

VI. Adaptive Neuro-Fuzzy Inference System

The Adaptive Neuro-Fuzzy Inference System (ANFIS), developed in the early 90s by Jang [4], [5], combines the concepts of fuzzy logic and neural networks to form a hybrid intelligent system that enhances the ability to automatically learn and adapt. Here, the membership function parameters are tuned using a combination of least squares estimation and back-propagation algorithm. Their adjustment is facilitated by a gradient vector, which provides a measure of how well the FIS is modeling the input/output data for a given set of parameters. Once the gradient vector is obtained, any of several optimization routines could be applied in order to adjust the parameters so as to reduce error between the actual and desired outputs. This allows the fuzzy system to learn from the data it is modeling. The approach has the advantage over the pure fuzzy paradigm that the need for the human operator to tune the system by adjusting the bounds of the membership functions is removed.

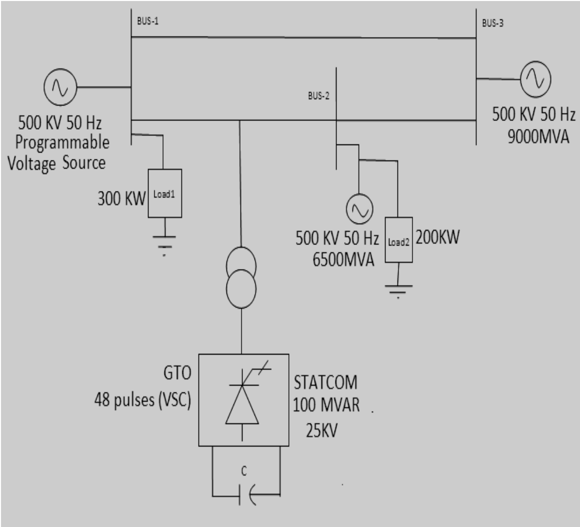


Fig. 4. Single line diagram of the 3-bus power system

To maintain good dynamic response at various operating conditions of STATCOM control signal, the controller gains need to be adapted based on system conditions. An adaptive neuro-fuzzy inference system has been used to adapt the controller gains of STATCOM controller.

Training data and target data, required to design such types of ANFIS controller, are generated from the conventional (PI) controller. The adaptive network is trained using the training data generated and the hybrid learning algorithm.

VII. Decoupled Current Control

The dc link voltage of the STATCOM is provided by the capacitor, C which is charged from the AC line. The decoupled control is used to ensure the dynamic regulation of the bus voltages and the dc link voltage V_C.

The STATCOM current is divided into two components (direct axis component, I_d and & quadrature axis component, I_q) with reference to the line voltage, measured using PLL. I_q is compared with the reference current (I_{qref}) obtained from the outer regulation loop for ac-voltage regulation, used to control the reactive power.

The scheme for implementing the decoupled control loop is shown in Fig-5. The voltage regulator is a PI controller with K_p=12 and K_i=3000. The current regulator is also PI controller with K_p=5 and K_i=40. The Phase-Locked Loop (PLL) system generates the basic synchronizing-signal which is the phase angle, θ of the transmission system voltage, V_B and the selected regulation-slope; k determines the compensation behavior of the STATCOM device.

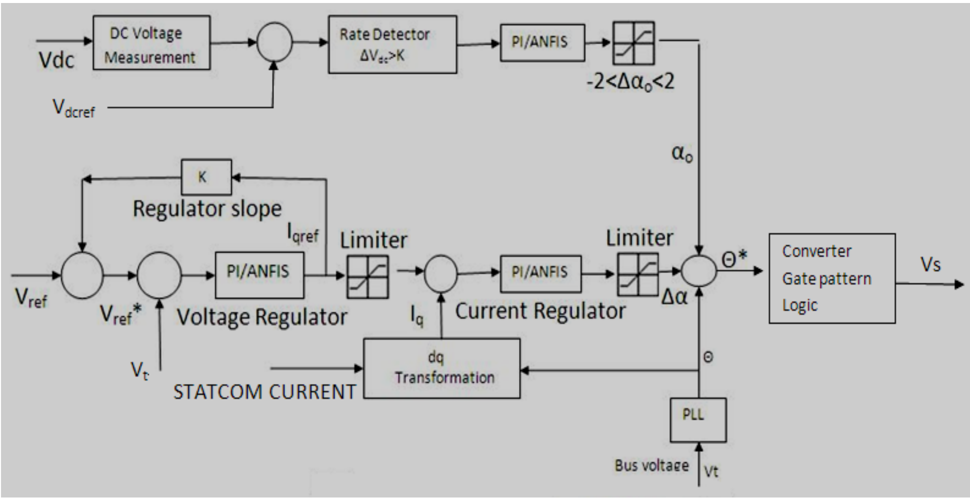


Fig. 5. Controller for STATCOM’s d-q decoupled current control system

VIII. Supplementary Regulator Loop

To enhance the dynamic performance of the full 48-pulse STATCOM a supplementary regulator loop is added using the dc capacitor voltage. The charging of dc capacitor is chosen based on the rate of the variation of the dc voltage.

Within specified short interval of time, Δt the variations in the magnitude of V_{dc} is measured along with the rate of charging the capacitor. If $|\Delta V_{dc}|$ is found greater than a specified threshold, k, the supplementary loop is activated.

The supplementary damping regulator corrects the phase angle, Θ* of the STATCOM ac voltage, in respect to the positive and negative sign of variations. When $\Delta V_{dc}>0$, t he dc capacitor charges and increases the capacitor voltage, thereby controls the amplitude of the converter output voltage and thereby controls the var generation. The supplementary loop reduces ripple content in charging or discharging the capacitor and improved controllability of the STATCOM.

IX. Digital Simulation Model and Simulation Results

The model of the complete system has been prepared using

MATLAB Simulink Power System Blocksets (PSB) by combining the respective blocks for each of the individual components systems and simulations has been carried out for the said model. All relevant parameters are given in the Table I.

TABLE I: SELECTED POWER SYSTEM PARAMETERS

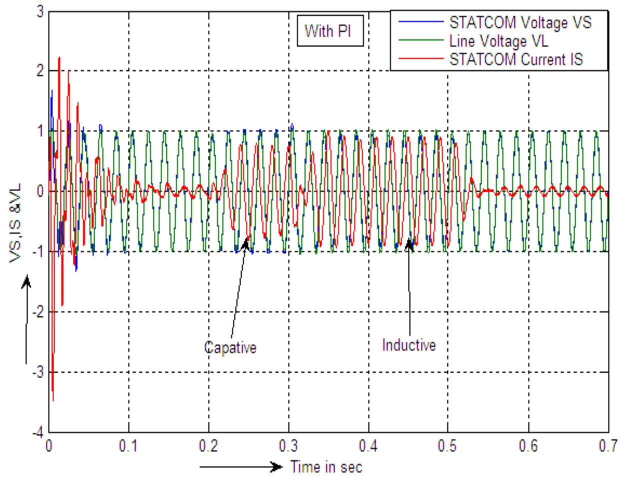
Three Phase AC Voltage Source	
(i) Programmable Three Phase Voltage Source	
Rated Voltage	500*1.049 (KV)
Frequency	50Hz
(ii) Three Phase Constant Voltage Source 1	
Rated Voltage	500 (KV)
Frequency	50 (HZ)
S.C. Level	6500 (MVA)
Base Voltage	500 (KV)
X/R	8
(iii) Three Phase Constant Voltage Source 2	
Rated Voltage	500 (KV)
S.C. Level	9000 (MVA)
X/R	10
Transmission line	
Bus-1to Bus-2	150 (Km)
Bus-1to Bus-3	220 (Km)
Bus-2 to Bus-3	180 (Km)
Three Phase Load	
Load-1	300 (KW)
Load-2	200 (KW)
STATCOM	
Primary Voltage	500 (KV)
Secondary Voltage	15 (KV)
Nominal Power	100 (MVAR)
Frequency	50Hz
Capacitance	3000μF
GTO Switches	
Snubber Resistance	1e-5 (ohm)
Snubber Capacitance	inf
Internal Resistance	1e-4 (ohm)
No. of Bridge arm	3

The induced voltage of the programmable source, connected at bus-1, is varied with respect to time as shown in Table II:

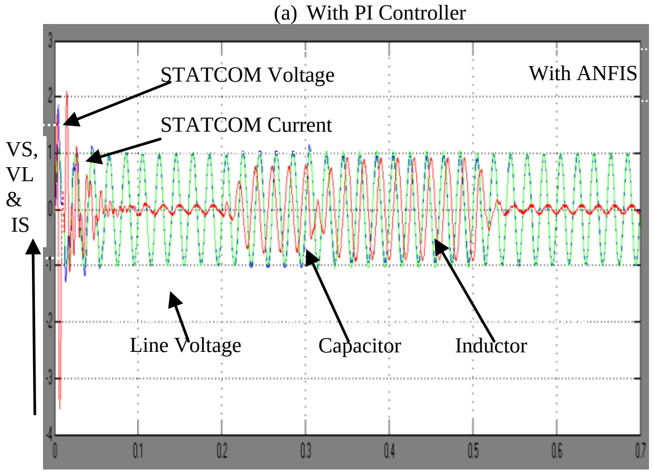
TABLE II: INDUCED VOLTAGE OF THE PROGRAMMABLE SOURCE

Interval	1st	2nd	3rd	4th
Time in sec	0 to 0.2	0.2 to 0.3	0.3 to 0.5	0.5 to 0.7
pu emf	1.0	0.95	1.05	1.0

The time responses of: (i) Load & Source voltages, (ii) Angle (alpha) between V_B & V_S, (iii) Voltage across capacitor, (iv) Reactive current drawn by STATCOM, (v) Active and Reactive powers drawn/delivered by STATCOM, for both the PI and ANFIS based-controllers, in response to the changes in the source voltage, are shown respectively in Figs 5(a,b), 6(a,b), 7(a,b), 8(a,b) and 9(a,b).



(a) With PI Controller



(b) With ANFIS Controller

Fig. 5(a) & 5(b) V_S, V_B & Is of STATCOM

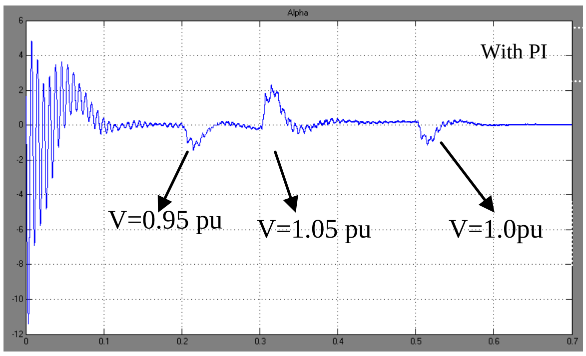


Fig. 6(a). Alpha of STATCOM with PI

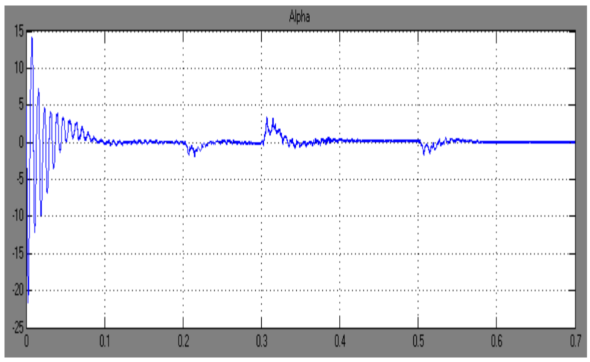
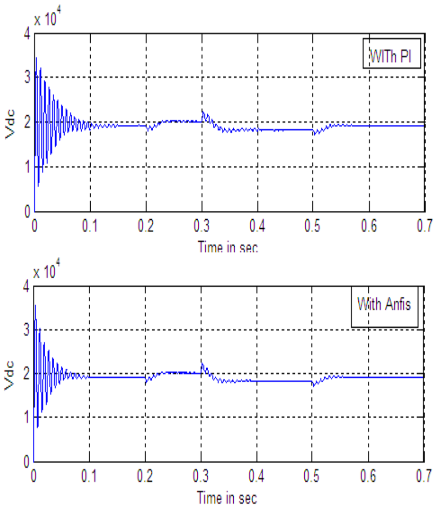


Fig. 6(b). Alpha of STATCOM with ANFIS



A. *First Interval (0 to 0.2 sec)*

Capacitor charges and V_{dc} reaches to nearly 19 KV with oscillations for around 0.1 sec. STATCOM draws lagging current and inductive VAR from the line. Voltage across load is maintained to around 1.0 pu.

B. *Second interval (0.2 to 0.3 sec)*

Capacitor Charges further and Vdc reaches to 20 KV. STATCOM draws leading current and capacitive VAR from the line. Voltage across load is maintained to around 1.0 pu. VS lags VB by a small angle (Δα=-1.2o) as shown in Fig-6(a, b).

7 (a) & 7(b) Vdc of STATCOM with PI &ANFIS

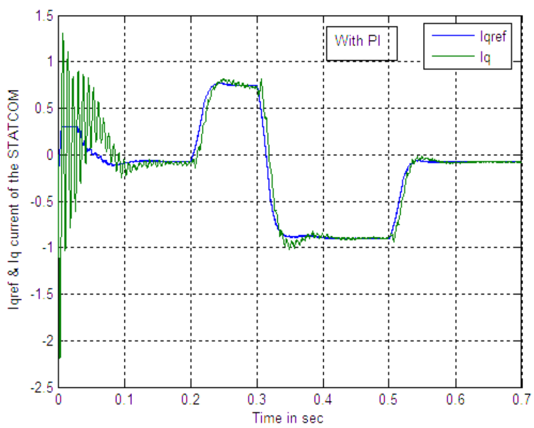


Fig. 8(a). Iq & iqref for PI

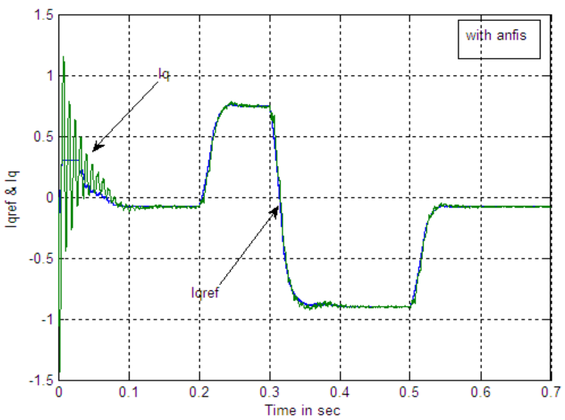


Fig. 8(b). Iq & I_{qref} for ANFIS

C. *Third interval (0.3 to 0.5 sec)*

Capacitor discharges slightly and Vdc falls to nearly 18 KV. STATCOM draws lagging current and inductive VAR from the line. Voltage across load is maintained close to 1.0 pu.

D. *Fourth interval (0.5 to 1.0 sec)*

Capacitor charges and Vdc increases to nearly 19 KV again. STATCOM draws lagging current and inductive VAR from the line. Voltage across load is maintained to around 1.0 pu.

When compared with the responses from Figs-5 to 9, it is observed that ANFIS based decoupled d-q controller has an excellent capability to provides better and smooth transition with respect to that offered by PI Controller.

Figs-5(a) & 5(b) show the voltage and current response of the 48 pulse converter. They further show their instantaneous transition from inductive mode to capacitive mode, then to inductive mode and transition occur with almost no transient overvoltage. This smooth transition is due to the novel controller, which is based on the PI and ANFIS decoupled control strategy and variation of the capacitor voltage.

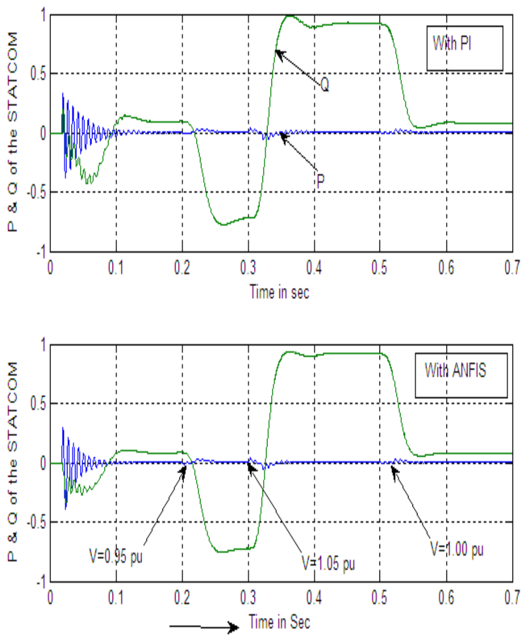


Fig. 9(a) & 9(b) Active and Reactive Power drawn by STATCOM

X. Conclusion

This paper presents the effectiveness of a novel 48-pulse STATCOM for reactive power compensation and voltage regulation of the transmission line. A detailed model of the ±100 MVAR STATCOM, connected to 500 kV AC grid to provide the required reactive compensation, has been developed. The STATCOM is controlled by a novel PI as well as ANFIS-based controller. The control process has been developed based on a decoupled current strategy using direct and quadrature current of the STATCOM. The operation of the STATCOM is validated in both capacitive and inductive modes for a simple power system. The simulation results, obtained in time-domain, demonstrate high quality performance of the 48-pulse STATCOM for voltage regulation while subjected to variations in line voltage. In the present case, simulation has been carried out considering changes in the source voltage. It has been observed that ANFIS based decoupled d-q controller has an excellent capability in providing voltage support with almost no transient over-voltages. Further, it has been noted that the performances of ANFIS-based controller, in some cases, are superior to those offered by PI Controller.

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S. Datta received the B.Tech. and M.Tech. degrees from the North Eastern Regional Institute of science & Technology, India in 2008 and National Institute of Technology Silchar, india in 2010 respectively. He is currently an Assistant Professor of Electrical Engineering Department at Mizoram University, India. His research interests include Power and Energy system and Power Electronics.

Dr. A. Kr. Roy received the Ph.D. degree from the Indian Institute of Technology Kharagpur, India in 1991. He is currently a Professor of Electrical Engineering Department at National Institute of Technology Silchar, India. His research interests include Power and Energy system, FACTS and Power Electronics.