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ANN Controlled VSC STATCOM with Harmonic Reduction for VAR Compensation

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ABSTRACT

Complete close-loop smooth control of reactive power can be achieved using shunt connected FACTS devices. STATCOM is one of the shunt connected FACTS device which can be utilized for the purpose of reactive power compensation. Intelligent FACTS devices make them adaptable and hence it is emerging in the present state of art. This paper presents close loop control techniques based on artificial neural networks (ANNs) to control reactive power generated by long transmission line over wide range so as to maintain constant voltage profile at the receiving end. With ANN technique and H-bridge multilevel VSC topology harmonics are eliminated to accepted level. A 9-Level H-Bridge VSC based STATCOM is used to handle the reactive power of the line .The close loop control is achieved by PI and neural network. . This paper is about real time simulation and implementation of PI controlled VSC STATCOM for 750km lab model of artificial transmission line. PI controller and neural network control schemes implemented and investigated. With Matlab simulation and actual testing proves that these devices when installed, they keep the bus voltage same as reference voltage (sending-end voltage). The results are prominent and give a way for real-time implementation of the proposed control schemes. These control schemes are simulated for the real-time control along with real-time modeling and simulations. Relative Harmonic analysis, for both the schemes are discussed. The results are prominent and give a way for real-time implementation.

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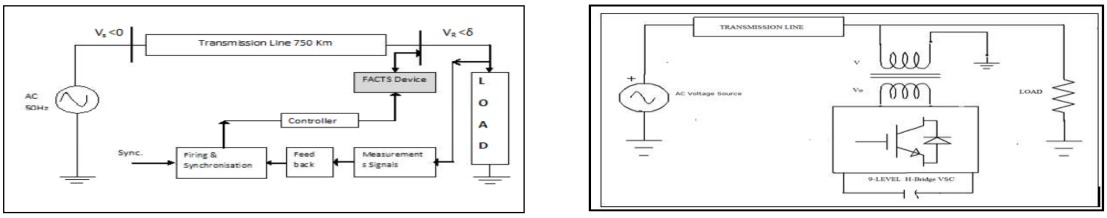
1. INTRODUCTION

The transmission line itself is the source of reactive power. A line that is open on the other end (without load) is like a capacitor and is a source of capacitive (leading) reactive power. The lengthwise inductances without current are not magnetized and do not introduce any reactive components. On the other hand, when a line is conducting high current, the contribution of the lengthwise inductances is prevalent and the line itself becomes a source of inductive (lagging) reactive power. Reactive power has significant effect on the operation of power system. For each line has a characteristic value of power flow Sk. If the transmitted power is above Sk, the line will introduce additionally inductive reactive power, and if it is below Sk, the line will introduce capacitive reactive power. The value of Sk depends on the voltage, for 400 kV line it is about 32% of the nominal transmitted power, for 220 kV line it is about 28% and for 110 kV line is about 22% [2]. The percentage will vary according to the construction parameters. The reactive power introduced by the lines themselves becomes a nuisance for the transmission system operator. When the demand is low it is necessary to connect parallel reactors for consuming the additional capacitive reactive power of the lines. Sometimes it is necessary to switch off a low-loaded line, in peak hours not only the customer loads cause big voltage drops but also the inductive reactive power of the lines adds to the total power flow and causes further voltage drops. In order to maintain the terminal voltage constant, reactive reserves are needed. FACTS devices like SVC and STATCOM can supply or absorb the reactive power in the transmission line, which helps in achieving better economy of power transfer [1], [2],[3]. In deregulated environment reactive power generated by transmission line is one of the important aspects to be considered. Reactive current control through SVC considering load power factor discussed in [5], [6]. SVC control system is implemented in [5] with software and modern industrial controller (using SIMATIC-TDC).

In this paper scaled down artificial transmission line of 750Km (λ /8) is simulated and tested. Shunt FACTS devices STATCOM is placed at the receiving end for balanced load condition. The receiving end voltage fluctuations were observed for different loads. The close loop control circuit is designed for STATCOM. The phase angle and modulation index for STATCOM are control for various loading conditions to make the receiving end voltage equal to sending end voltage. In this paper neural network based close loop phase angle and modulation index control scheme implemented for STATCOM to achieve the better control, such that it maintains a sending end-voltage equal to receiving end-voltage with fast response with less harmonics injection. General Control structure of single line shunt connected FACTS device (close loop control) is shown in Fig.1 (a) and (b)



(a) (b)

Fig.1 General Control structure of: (a) single line Shunt device (close loop control)
(b) Single line diagram for VSC

2. H-BRIDGE CASCADE STATCOM VSC CONFIGURATION

For high power transmission system application, the switching frequency of the semiconductor switches is limited to below 500 Hz. Hence multi-step cascade H-Bridge configurations of STATCOM have been chosen for experiment and testing. 1) It is much more suitable to high-voltage, high-power applications than the conventional inverters. 2) It switches each device only once per line cycle and generates a multistep staircase voltage waveform approaching a pure sinusoidal. 3) Since the inverter structure itself consists of a cascade connection of many single-phase, full-bridge inverter (FBI) units and each bridge is fed with a separate dc source, it does not require voltage balance (sharing) circuits or voltage matching of the switching devices. 4) Output switching frequency is n_c times of individual unit, so it can operate at lower carrier frequency, hence less switching losses. As reported high power applications uses 48 module with 150 Hz carrier frequency to synthesis a 50 Hz sinusoid , despite of low pulse number (m_f =3) used ,the first unconcealed carrier appear at 48*150=7200Hz, with minimum THD =5% .5)Packaging/layout is much easier because of the simplicity of structure and lower component count.

2.1 Single-Phase Structure

The single-phase configuration for multilevel with separate dc-source inverter is as shown in fig.2. It consists of (m-1)/2 single-phase FBI units connected in cascade to generate m level output voltage over half fundamental cycle. Each full-bridge inverter has its own dc source and does not require any transformers, clamping diodes, or flying capacitors [4] Each FBI unit can generate three-level output, $+V_{dc}$,0.-V_{dc} .This is made possible by connecting the dc-source sequentially to the ac side via the four switching devices and each device is switched only once per line cycle. For example, a nine-level output phase voltage waveform can be obtained with four-separated dc sources and four H-bridge cells. The phase voltage is the sum of each H-bridge outputs and is given as

$$V_{Can} = V_{Ca1} + V_{Ca2} + V_{Ca3} + V_{Ca4} \quad (1)$$

Because zero voltage is common for all inverter outputs, the total level of output voltage waveform becomes 2*s*+1 According to sinusoidal-liked waveform, each H-bridge output waveform must be quartersymmetric as illustrated by waveform Obviously, even harmonic components are absent in such a waveform. To minimize THD, all switching angles will be numerically calculated.

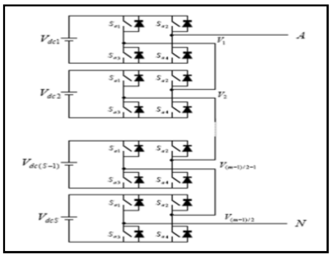


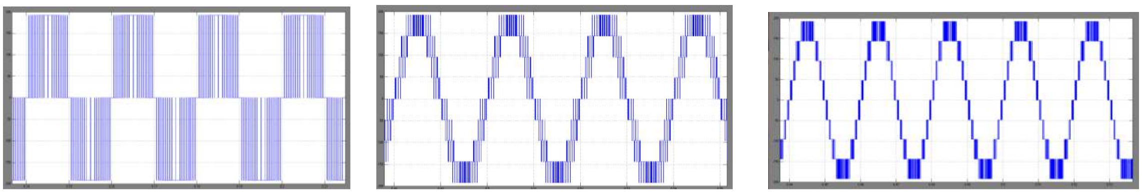
Fig.2.Single-phase 9-level cascaded VSC

2.2 Control Strategy

Carrier Phase Shift PWM (CPSPWM) technique is suitable for cascade multilevel VSC. In this technique a number of carrier wave carriers equal to the number of full bridge inverters employed in the cascaded inverter structure shifted by 1/ (m.fc), where $1/f_C$ is the period of carrier reference and m is no of cell. The ratio of the carrier wave frequency (f_c) and modulating wave frequency (f_R) is termed as frequency modulation index (m_f) is always multiple of three to have a symmetry in the output voltages. Frequency modulation index is defined as:

$$m_f = \frac{f_C}{f_R}, \text{ with } m_f = 3, 6, 9\ldots \quad (2)$$

A number of cascaded cells in one phase with their carriers shifted by an angle θC^0 and using the same control voltage produce a load voltage with the smallest distortion. The effect of this carrier phase-shifting technique can be clearly observed in fig.3 with corresponding THD. This result has been obtained for the multi-cell inverter in a nine-level configuration, which uses four series-connected cells in each phase. The smallest distortion is obtained when the carriers are shifted by an angle $\theta_C = 360/\ 2*4 = 45^0$ on half cycle basis.



(a) (b) (c)

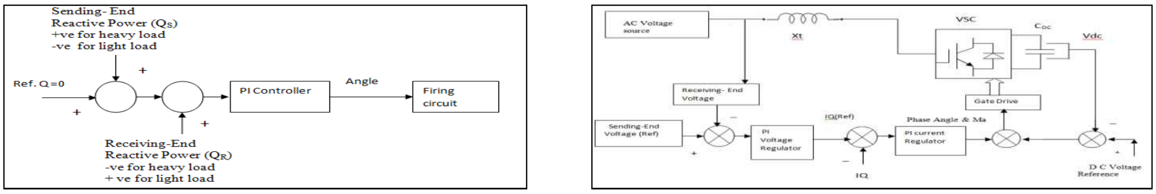
Fig.3 (a) Outpot voltage for carrier phase shift = 0^0 with THD= 59.97% (b) Output voltage for Carrier phase shift =30^0 with THD= 39.03% (c) Output Voltage for carrier phase shift = 45^0 with THD = 16.05%

2.3 VSC close loop Control

The voltage source converter (VSC) is the integral part of SATCOM FACTS device, which supply or absorb the reactive power in the transmission line to control of voltage (primary objective) of bus to which it is connected.VSC inject current into the system at the point where they are connected. They can be used as a good way to control the voltage in and around the point of connection by injecting current into the system. The importance of this device is increasing with time for various power system control applications. The basic principle of VSC STATCOM is well documented in the literature [4-11]. The reactive power exchange between STATCOM and the AC system can be control by varying the magnitude and phase and modulation index of VSC. The successful functioning of VSC depends up on the generation of near sinusoidal voltage at output terminals. However, due to switching of IGBTs/ MOSFETs or GTO'S from converter circuit, harmonics are generated at the output of VSC, thus minimization of these harmonics to the acceptable level is one of the aspect of VSC control.

2.4 PI Control Scheme

There are many control schemes proposed for shunt VAr compensator. Controller can be made by different schemes by using PI controller. These methods of feedback control are useful when minimization of error signal is a primary goal. Fig.4 shows the simulation block diagram of control circuit which is based on reactive power request. Reference reactive power is set as zero , comparing sending-end and receiving end reactive power, the generated error signal is given to PI controller (tuned to Kp = 0.0001 and Ki = 5.7) . This automatically generates STATCOM phase angle for given input conditions; for this modulation index is kept constant. Close loop with PI Controller for both phase angle and modulation index control can be achieve as shown in fig.4(a) and (b).



(a) (b)

Fig.4 Phase angle control with PI keeping modulation index constant (b) Close loop with PI Controller for both phase angle and modulation index control

2.5. DC-bus voltage control

The aim of the DC voltage control unit is to maintain the DC voltage equal to the reference value. Three possible schemes for the setting of the DC voltage are discussed in [6].

Method 1: The DC voltage is kept constant, resulting in a Simplified DC voltage control. However, since the same DC voltage is used for generating both leading and lagging reactive power, the required modulation index *M* is low for lagging VAr compensation. This significantly increases the harmonic distortion of the output voltage and the stress on the switches.

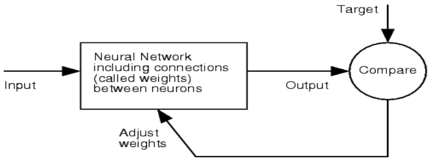
Method 2: The DC voltage varies according to the reactive power demand so that the modulation index can be kept at its maximum value, significantly reducing the output voltage harmonic distortion. However, with each change of VAr demand, the DC voltage is changed from one level to another, which results in slow transient response.

Method 3: Two reference signals for the DC voltage level are used. A high DC voltage reference is used for leading VAr compensation, and for lagging VAr compensation a low DC voltage reference is selected. As a result, the modulation index is relatively high for both leading and lagging VAr compensation. In the case of a changing demand from leading VAr to lagging VAr, the DC voltage is controlled from the high level to the low level, and conversely when the VAr demand changes from lagging to leading. On comparing these three DC voltage methods, it can be seen that method 1 results in fast dynamic response since there is no need for DC voltage changing, which normally involves a slow process of additional active power exchange between the source supply and the DC capacitor. However, the harmonic distortion and the stress on the switching devices are high, especially for generating lagging reactive power. This is due to the operation of the convertor at a relatively low modulation index. Alternatively, method 2 maintains a maximum modulation index for both leading and lagging VAr compensation, by varying the DC voltage accordingly. Therefore, the harmonic distortion is kept at a minimum. However, the dynamic response is poor since every change of VAr demand requires a change of the DC voltage, hence problems of harmonics generation can be optimized by selecting appropriate generation of phase angle and modulation index for STATCOM as well as different VSC topology like H-Bridge VSC topology for effective Var compensation is discussed in this paper, ANN techniques also implemented for achieving fast response as well as minimum harmonics generation.

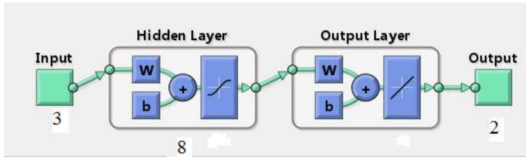
3. ANN CONTROLLER DESIGN

Neural Networks may be trained to mimic the control action of existing VSC controllers, Neuro-controllers are also developed utilizing evolutionary reinforcement learning techniques [16]. Neural networks are beneficial to an adaptive scheme. Neural network are collections of neurons, with each neuron specifying the weights from the input layer (process states) to output layer (control actions). Neuro controller parameters are the neural network weights. Back-propagation is the generalization of the Widrow-Hoff learning rule to multiple-layer networks and nonlinear differentiable transfer functions. Input vectors and the corresponding target vectors are used to train a network until it can approximate a function, associate input vectors with specific output vectors, or classify input vectors in an appropriate way as defined by user as shown Fig.5 (a).

Networks with biases, a sigmoid layer, and a linear output layer are capable of approximating any function with a finite number of discontinuities. Properly trained back-propagation networks tend to give reasonable answers when presented with inputs that they have never seen. Typically, a new input leads to an output similar to the correct output for input vectors used in training that are similar to the new input being presented. This generalization property makes it possible to train a network on a representative set of input/target pairs. In fitting problems, we want a neural network to map between a data set of numeric inputs and a set of numeric targets. The Neural Network Fitting Tool will help to select data, create and train a network, and evaluate its performance using mean square error and regression analysis. A two-layer feed-forward network with sigmoid hidden neurons and linear output neurons, shown in Fig 5(b) can fit multi-dimensional mapping problems arbitrarily well, given consistent data and enough neurons in its hidden layer. The network will be trained with Leven-berg-Marquardt back propagation algorithm (trainlm).



(a)



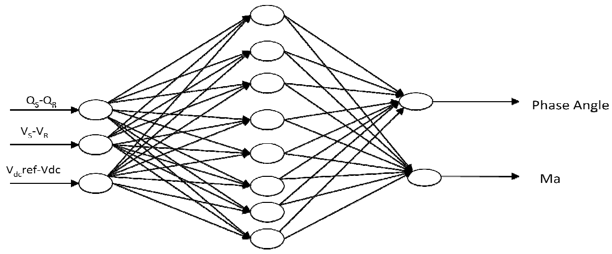
(b)

Fig.5 (a) Network with input and targets and errors. (b) ANN simulation model representation

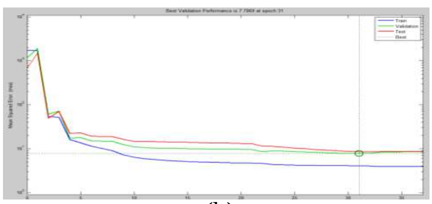
3.1. Validation of ANN

The network is trained and tested with off line open loop data. The switching test circuitry used three inputs and two outputs is shown in Fig.8a. The Mean Squared Error is the average squared difference between outputs and targets. Three inputs to network are

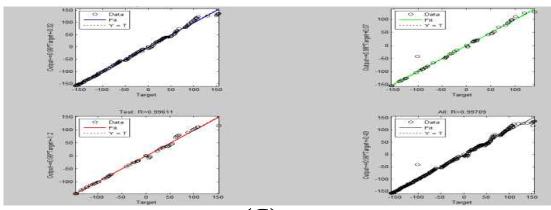
1) Difference of reactive power (Var error)
2) Difference of voltage (Voltage error)
3) Difference of reference dc voltage and capacitor dc voltage (dc Voltage error) and target values taken as open loop phase angle and modulation index for various loading conditions as shown in fig 6(a), Trained network placed in the circuit with online input and outputs. Training and testing data is shown in fig. 6 (b) and (c). Regression R Values measure the correlation between outputs and targets. Analysis is comparative in nature as the PI controller circuit the same except that the phase angle of reference voltage as well as modulation index for the VSC are now generated by the adaptive neuro controller which forms the part of the feedback circuit which has its reference from the conventional VSC circuitry and then the neuro controller generates the phase angle to be required for VSC reference voltage for generating firing PWM pulses for the VSC .The comparison between phase angle issues by PI and ANN controller shown in fig.7.Form this figure it is cleared that ANN controller has fast response i.s. within .01 sec within half cycle of AC voltage.



(a)



(b)



(C)

Fig.6 (a) ANN network (b) ANN testing (c) ANN training results

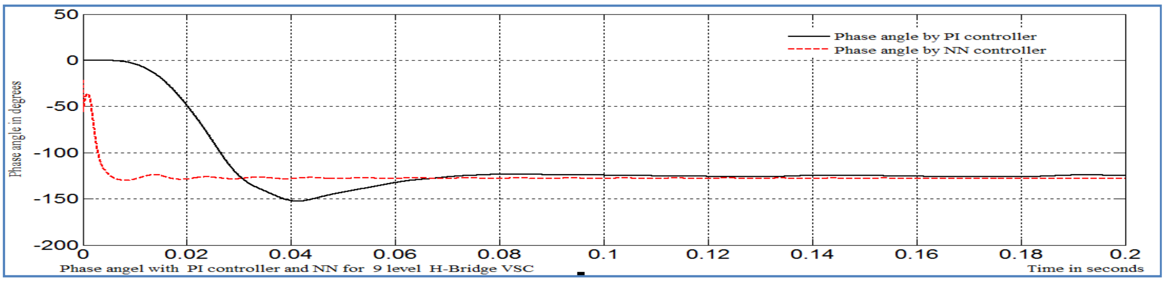


Fig.7. Response of phase angle issued by PI controller and ANN controller for PWM Controller

4. TEST SYSTEM MODEL AND RESULTS

The primary objective is to control the reactive power of line and not the reactive power of load hence only resistive load is considered. A 220Kv 100MVA line scale down to 400V, 1.5KA model with 4 π line segments with 750 km distributed parameters is given in Table 1 and Table 2. With the change of load, the variation in voltages is observed at receiving end without and with STATCOM. In most of the transmission lines Ferranti effect is predominant and receiving end voltage is greater than that of the sending end voltage at light load. Transmission line without any compensation was not satisfying the essential condition of maintaining the voltage within the reasonable limits. The effect of increasing load was to reduce the voltage level at the load end. At light loads, the load voltage is greater than the sending end voltage as the reactive power generated is greater than absorbed. At higher loads the load voltage drops, as the reactive power absorbed is greater than generated as indicate unequal voltage profiles shown in fig.8. The Fig.9 shows compensated RMS and instantaneous voltage by (a) with PI and (b) with ANN controller indicated.
Online ANN compensated sending end and receiving end voltage with nine levels VSC STATCOM. (STATCOM is on at t= 0.1sec and made off at t= 0.25sec.) At the common point of coupling indicated in fig. 10. Fig.11 shows output voltage and current of Nine Level H-bridge VSC STATCOM (STATCOM on at t=0.1 sec and off at t=0.3 sec). Fig.12 Load current harmonics (a) Load current harmonics with PI (without ANN) controller with three level VSC topology (having THD= 0.95%) (b) Load current harmonics with ANN Controller with three level VSC topology (having THD= 0.79%) (c) Load current harmonics with ANN Controller with nine level H-Bridge VSC topology (having THD= 0.38%).

Table 1. 220Kv, 100MVA Line Parameters

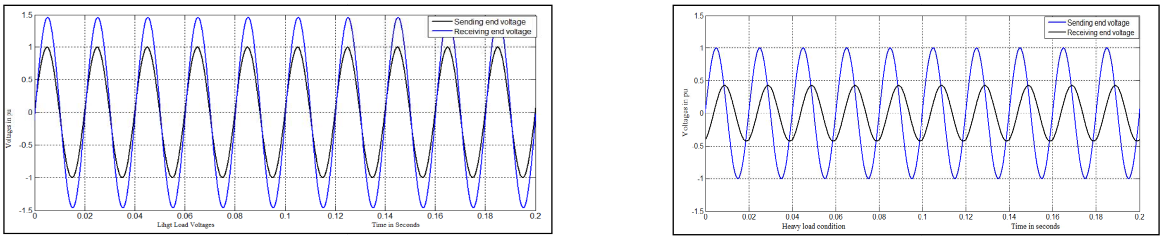
Parameter	Value
Power Rating of the Line	100 MVA
Voltage Rating of the Line	220 kV.
Resistance	0.073 Ω per km.
Inductive Reactance	0.4794 Ω per km.
Shunt Admittance	3.35 μ mho per km.
Series Inductance L	1.525 x 10-5 H per km.
Shunt Capacitance C	11.3 nF per km
Base Impedance of 220kv Line	484Ω
SIL	100MW
Propagation Constant γ	4.15 x 10-6.

Table 2. Scale down Artificial Transmission Line

Scale down single phase 750km line Parameters.	
The line Inductance	0.1 mH/Km
Line Resistance	0.001Ω /km
Line Capacitance	0.10 μF/km
Surge Impedance	31.6 Ω
Supply Voltage (Single Phase)	230V(p-p)
The line Inductance (L)	0.1 mH/Km

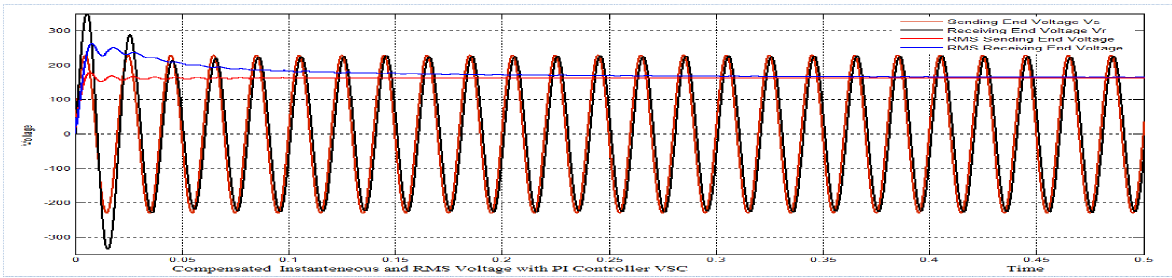
Table 3. Open- loop reading of scale down 750 Km Artificial Transmission Line.

Change in load in Ω	Reactive Power Var by (S.d.)Line	Sending- End Voltage (S.d.) line in Volts .	Variations Of Receiving-End Voltage in Volts	For compensation of reactive power	
				Required Phase Angle in degree For VSC	Required modulation Index of VSC
500	-800	162.6	220.9	-135	0.2
200	-763	162.6	220.4	-133	0.2
100	-731	162.6	271.7	-132	0.2
50	-633	162.6	210.02	-130	0.3
40	-344	162.6	187.9	-110	0.4
31.5(SIL)	-193	162.6	175.4	-95	0.5
25	-8	162.6	158	-44	0.5
20	176	162.6	141.2	-35	0.6
10	345	162.6	122.8	30	0.7
5	704	162.6	70.86	35	0.8
2	842	162.6	37.5	60	0.9

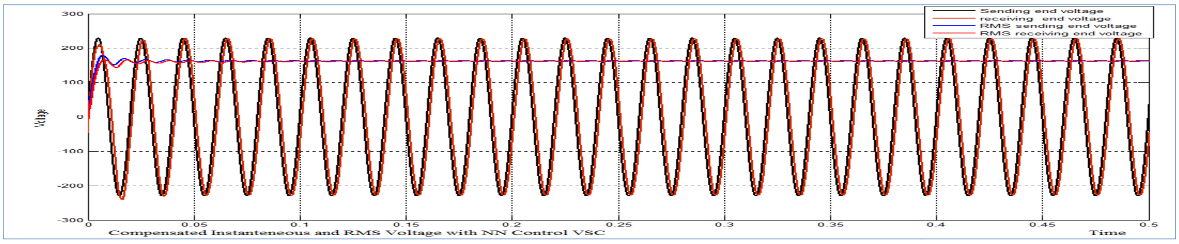


(a) (b)

Fig.8. Unequal sending end and receiving end voltages (a) For light load V_R is greater than V_S (b) For heavy load V_R less than V_S.



(a)



(b)

Fig.9. Compensated Instantaneous and RMS Voltages (a) With PI Controller (taking 0.4 seconds to make sending end and receiving end voltage equal) (b) With ANN Controller (taking 0.01 seconds to make sending end and receiving end voltage equal) with faster response

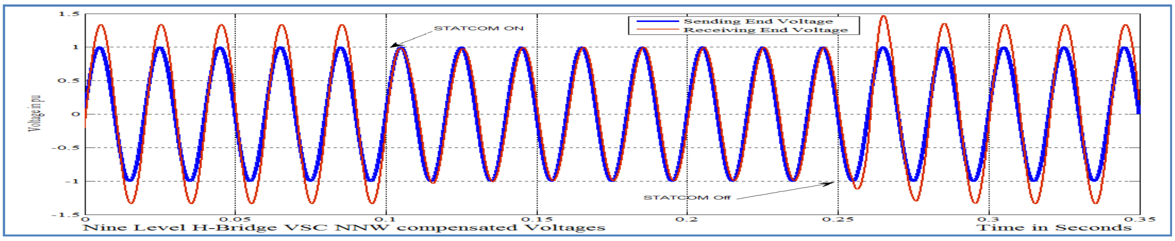


Fig.10. Online ANN compensated sending end and receiving end voltage with nine levels VSC STATCOM. (STATCOM is on at t= 0.1sec and made off at t= 0.25sec.). At the common point of coupling.

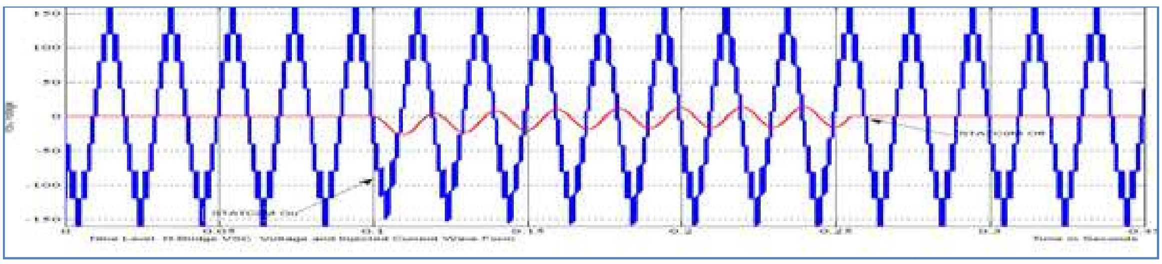
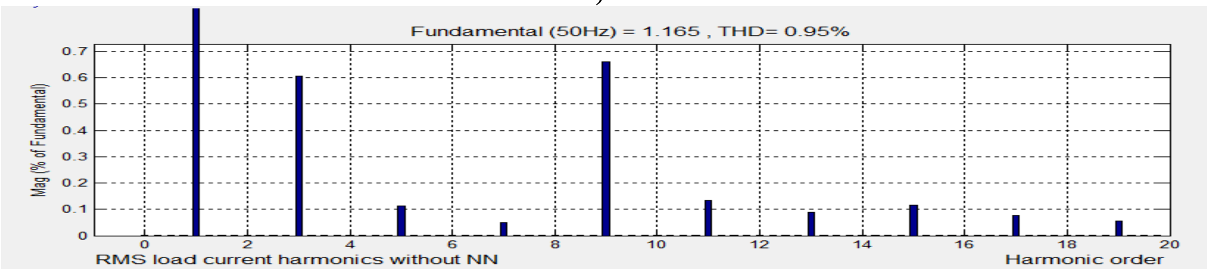


Fig.11. Output voltage and current of Nine Level H-bridge VSC STATCOM (STATCOM is on at t= 0.1sec and made off at t= 0.25sec.). At the common point of coupling.(STATCOM on at t=0.1 sec and off at t=0.3

sec)



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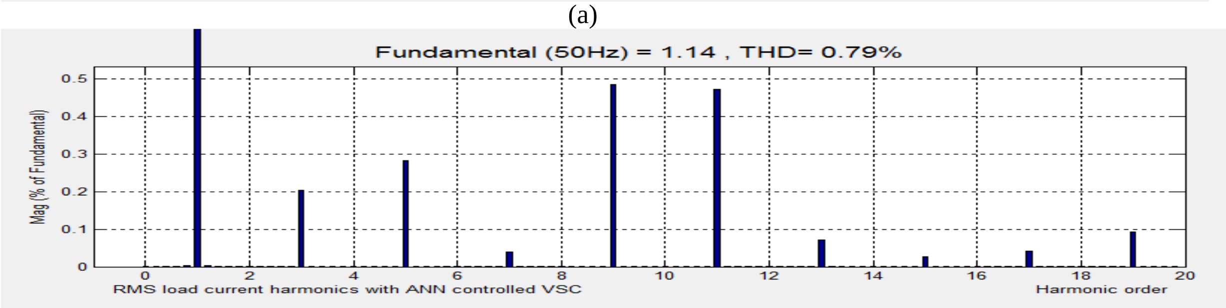

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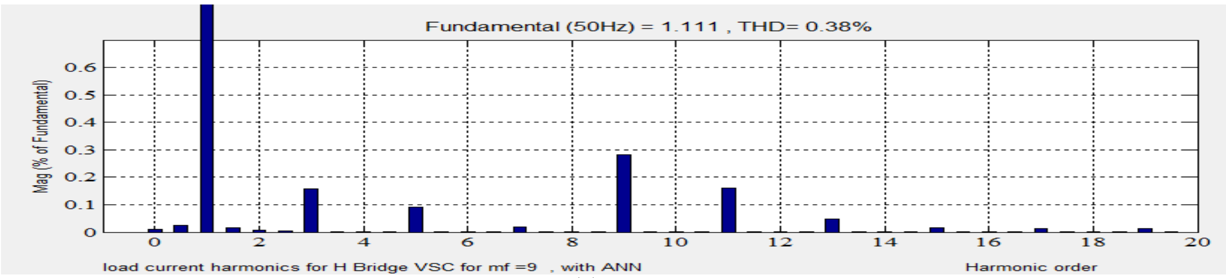

(c)

Fig.12 Load current harmonics (a) Load current harmonics with PI (without ANN) controller with three level VSC topology (having THD= 0.95%) (b) Load current harmonics with ANN Controller with three level VSC topology (having THD= 0.79%) (c) Load current harmonics with ANN Controller with nine level H-Bridge VSC topology (having THD= 0.38%)

5. CONCLUSION

This paper presents simulation of reactive power compensation for 750 km transmission line with STACOM. It is a simplest way of controlling the reactive power of transmission line. It is observed that STATCOM is able to compensate both over and under voltages. The results are prominent and give a way for real-time implementation of the proposed control schemes. With MATLAB simulations and actual testing it is observed that STATCOM provide an effective reactive power control irrespective of load variations. This work describe the ANN based design, simulation and performance of artificial neural network controller of VSC STATCOM. Voltage regulation well as Var compensation and reduction of generated harmonics achieved by optimizing the modulation index and phase angle along with ANN technique and harmonics are eliminated by using cascade H-bridge VSC topology also have a fast response than PI controller and fuzzy controller . With H-Bridge and carrier phase shift harmonics are eliminated to minimum extent, also leads to reduction in switching frequency. The results have shown that the proposed technique developed in this work overcome the problem occurring in conventional PI compensators.

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