Simulated Control System Design of a Multilevel STATCOM for Reactive Power Compensation

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Abstract—**This paper deals with the design and implementation of a multilevel voltage source converter based static synchronous compensator (STATCOM) employing an effective modulation control technique simulated in a MATLAB Simulink environment. The main objective of this paper is to maintain the voltage stability by compensating the reactive power in the power system. Hence, a new efficient control strategy is proposed, in order to reduce the voltage fluctuations like sag and swell conditions and also to isolate current and voltage harmonics in the transmission system. The multilevel STATCOM which can be used at the point of common coupling (PCC), for improving power quality is modelled and simulated using proposed control strategy and the performance is compared by applying it to an 110kv line with and without STATCOM. Relative Harmonic analysis is also discussed in this paper based on the total harmonic distortion (THD) calculations.**

Keywords—**Power Quality, Reactive Power Compensation, Voltage Source Converter (VSC), STATCOM, GTO, SHEM, Phase Locked Loop (PLL), Multilevel Inverter, THD.**

I. INTRODUCTION

Most if not all of the world's electric power supply systems are widely interconnected, involving connection utilities inside own territories which extend to inter-utility interconnections and then to interregional and international connections. This is done for economic reasons, to reduce the cost of electricity and to improve reliability of power supply. However, the long switching periods and discrete operation of the devices in the present power grid, cause difficulty in handling the frequently changing loads smoothly and damp out the transient oscillations quickly. Severe black-outs happened recently in power grids worldwide and these have revealed that conventional transmission systems are unable to manage the control requirements of the complicated interconnections and variable power flow. Therefore, improvement is necessary in the security and stability of the power grid, as well as the control schemes of the transmission system. Different approaches such as reactive power compensation and phase shifting have been implemented to meet the requirements. The demands of lower power losses, faster response to system parameter change, and higher stability of system have stimulated the development of the FACTS (flexible AC transmission systems). Based on the success of research in power electronics switching devices and advanced control technology, FACTS has become the technology of choice in voltage control, reactive/active power flow control, transient and steady-state stabilization that improves the operation and functionality of existing power transmission and distribution system. The achievement of these studies enlarge the efficiency of the existing generator units, reduce the overall generation and fuel consumption, and minimize the operation cost. In this paper reactive power compensation is chosen an effective way to improve the performance of the ac system. Hence a multilevel STATCOM and a control system should be designed for this purpose. Ben-Sheng Chen and Yuan-Yih Hsu [1] proposed a controller design of STATCOM and gave an analytical approach for harmonics based on Bessel functions. T. Manokaran, B.Sakthivel, and S. Mohamed Yousuf [2] designed a cascaded two level inverter based STATCOM for harmonic reduction. R.S. Dhekekar and N.V. Srikanth [3] developed a voltage-source inverter for high-voltage and high-power applications and implemented using Fuzzy control schemes. A hybrid fuzzy-PI (proportional integral) control algorithm of a two-level 12-pulse VSC based STATCOM is presented by K. Venkata Srinivas, Bhim Singh, Ambrish Chandra and Kamal-Al-Haddad [4]. Nitus Voraphonpiput, Teratam Bunyagul, and Somchai Chatratana [5] discussed cascaded multilevel converter circuit with chain link topology. Chunyan Zang, Zhenjiang Pei, Junjia He, Guo Ting, Jing Zhu and Wei Sun [6] summarized the common modulation strategies of a cascaded 5-level STATCOM. The operation of a 48 pulse STATCOM in unbalanced systems with negative sequence components have been reported by Carlos A.C. Cavaliere, Edson H. Watanabe, Maurício Aredes [7]. Naveen Goel, R.N. Patel and Saji T. Chacko [8] discussed about genetically tuned STATCOM for Voltage Control and Reactive Power Compensation. Amir H. Norouzi and A. M. Sharaf [9] developed two control schemes to enhance the dynamic performance of the STATCOM and SSSC. Hung-Chi Tsai, Chia-Chi Chu and Sheng-Hui Lee [10] gave passivity-based nonlinear STATCOM controller design for improving transient stability of power systems.

In this paper the proposed control is tested on a power system to which a nine level cascaded multilevel converter is connected. The remaining part of the paper is organized as

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follows: Section-II gives the working principle of STATCOM; Section-III gives the cascaded multilevel circuit and its implementation in MATLAB simulink; Section-IV gives the STATCOM controller and its design; Section-V gives the implementation of STATCOM and its controller to a power system, along with test results and comparison of THD calculations; Section-VI gives the conclusion; references related to this topic.

II. WORKING PRINCIPLE OF STATCOM

STATCOM is a primary shunt device of the FACTS family, which uses power electronics to control power flow and improve transient stability on power grids. The STATCOM regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. For purely reactive power flow the three phase voltages of the STATCOM must be maintained in phase with the system voltages. The variation of reactive power is performed by means of a VSC connected through a coupling transformer. The VSC uses forced commutated power electronics devices (GTO's or IGBT's) to synthesize the voltage from a dc voltage source. The operating principle of STATACOM is explained in Fig.4. It can be seen that if $V_2>V_1$ then the reactive current I_q flows from the converter to the ac system through the coupling transformer by injecting reactive power to the ac system. On the other hand, if $V_2< V_1$ then current I_q flows from ac system to the converter by absorbing reactive power from the system. Finally, if $V_2= V_1$ then there is no exchange of reactive power. The amount of reactive power exchange is given by:

$$Q = \frac{V_1(V_1-V_2)}{X_S}$$

(1)

Where,

V_1: Magnitude of system Voltage.
V_2: Magnitude of STATCOM output voltage.
X_S: Equivalent impedance between STATCOM and the system.

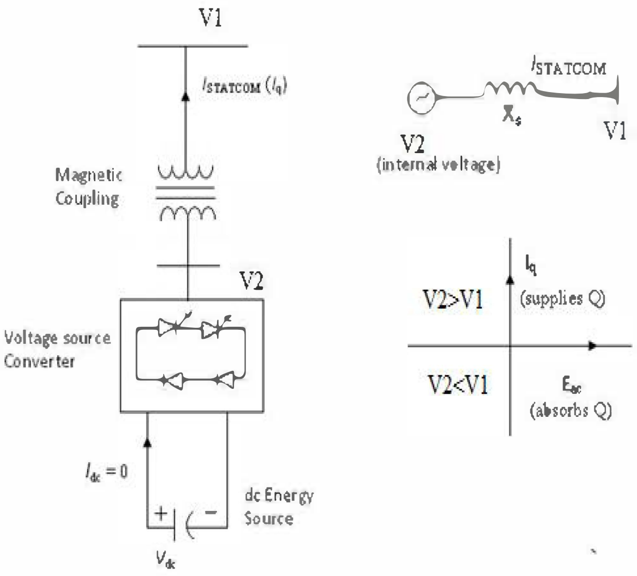


Fig 1: Schematic Configuration of STATCOM

A capacitor connected on the DC side of the VSC acts as a dc voltage source.

III. CASCADED MULTILEVEL CIRCUIT

A cascaded multi-level converter circuit is shown in Fig. 2. It is a three phase VSC which comprises of three single phases and each phase consists of H-bridges connected in series. The three phases in the converter are star connected. Each single phase H-bridge converter has two arms consisting of two pairs of GTO and diode connected in anti-parallel. Each H-bridge has its own capacitor, acting as a voltage source. Individual capacitors of same capacitance are selected to meet the economic and harmonic criteria.

The peak output voltage of STATCOM is *N* times to that of the capacitor voltage, where *N* is the number of H-bridges in each phase. Each H-bridge generates three voltage levels $+V_{dc}$, 0 and $-V_{dc}$ and the total output voltage of each phase is the combination of individual H-bridge voltages. A STATCOM with N converters per phase can synthesize *2N+1* voltage levels.

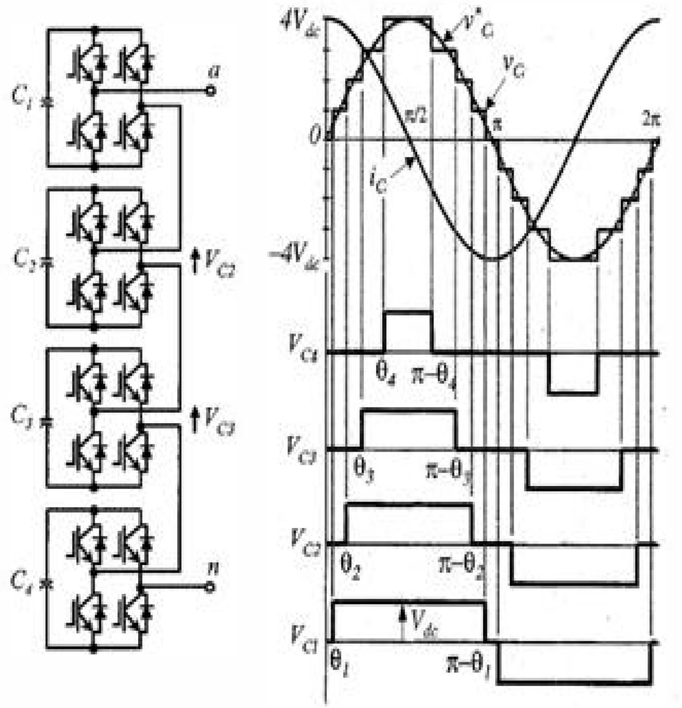


Fig. 2 Single phase 9 level H-bridge inverter and switching strategies

The output voltage waveform of the cascaded *N*-level STATCOM depends on the switching pattern, which is controlled by the switching angles of the converters. These switching angles can be independently selected, but appropriate switching angles are required to achieve good quality of the output voltage waveform. By employing SHEM, lower order harmonics can be eliminated in the output waveform. The amplitude of the odd harmonic order of the output voltage with 2N+l level can be represented using Fourier's series method as,

$$V_n = \frac{4V_{dc}}{n\pi}\sum_{k=1}^{N}\cos(n\theta_k) \qquad (2)$$

Where,

V_n is the amplitude of voltage harmonic of nth order
V_{dc} is the DC voltage across the capacitor
N is the number of the bridges in each phase
n is the odd harmonic order
θ_k is the switching angle of the single phase bridge

In this paper a nine level cascaded multilevel converter is designed and is simulated in MATLAB simulink environment.

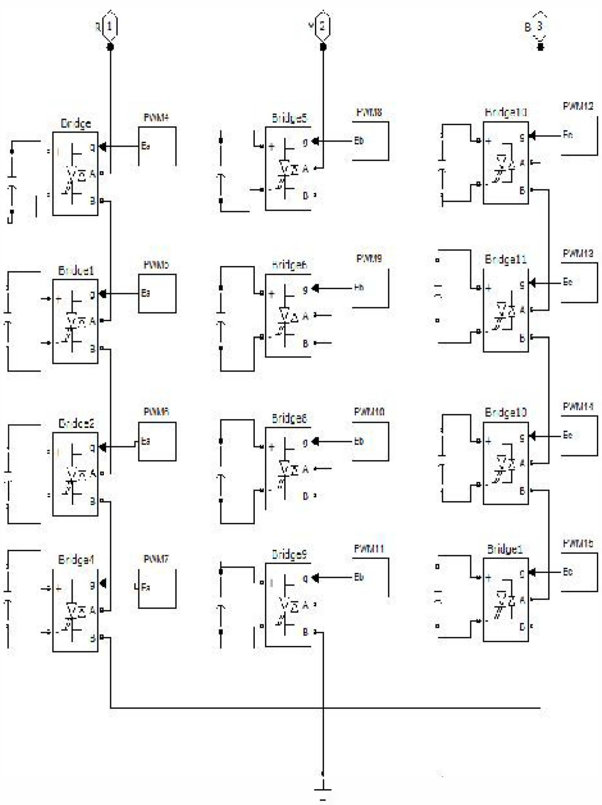


Fig. 3 MATLAB implementation of 9 level

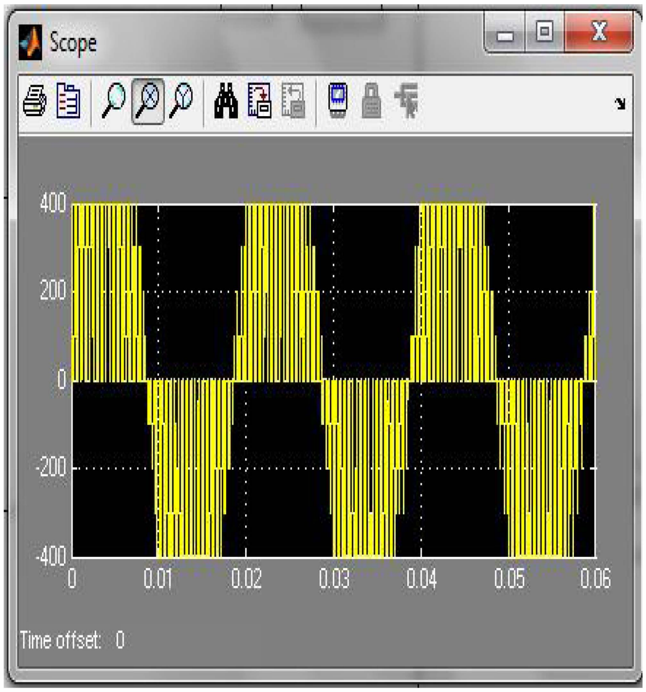


Fig.4 Output voltage of 9 level VSC

The firing angles of the bridges in the converter are so chosen such that 5th, 7th, 11th and13th harmonics are eliminated and the THD of phase voltage is minimized. For the optimal values of firing angles the following equations must be solved (considering the modulation index M = 1).

$$\cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3) + \cos(5\theta_4) = 0$$
$$\cos(7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3) + \cos(7\theta_4) = 0$$

$$\cos(11\theta_1) + \cos(11\theta_2) + \cos(11\theta_3) + \cos(11\theta_4) = 0$$
$$\cos(13\theta_1) + \cos(13\theta_2) + \cos(13\theta_3) + \cos(13\theta_4) = 0$$
$$\cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) + \cos(\theta_4) = (m-1)M \tag{3}$$

This set of nonlinear transcendental equations can be solved by iterative methods such as the Newton-Raphson method. We get,

$$\theta_1 = 6.57°, \theta_2 = 18.94°, \theta_3 = 27.18°, \theta_4 = 45.15°$$

Thus, if the H-bridges are symmetrically switched during the positive half-cycle of the fundamental voltage to $+V_{dc}$ at 6.57°, $+2V_{dc}$ at 18.94°, $+3V_{dc}$ at 27.18° and $+4V_{dc}$ at 45.15° and similarly in the negative half-cycle to $-V_{dc}$ at 186.57°, $-2V_{dc}$ at 198.94°, $-3V_{dc}$ at 207.18° and $-4V_{dc}$ at 255.15° to eliminate 5th, 7th, 11th and 13th harmonics. The 9 level PWM (pulse width modulation) converter is implemented in MATLAB simulink and respective output voltage waveform is shown in Fig 4.

IV. STATCOM CONTROLLER

The main objective for control of STATCOM is to enhance the power transmission by injecting or absorbing reactive power to or from the grid. The basic control strategy used for the proposed STATCOM controller is direct control. In this approach reactive output current can be controlled directly by the internal voltage control mechanism of the converter (e.g.: PWM) in which the internal dc voltage is kept constant. The STATCOM is controlled to deliver either inductive or capacitive currents to the power system by varying its output voltages V_{2a}, V_{2b} and V_{2c}. In the design of the STATCOM controller, the three-phase quantities (voltage and current) are first transformed into direct and quadrature components in a synchronously rotating reference frame. Then, a current regulator is employed for the current control.

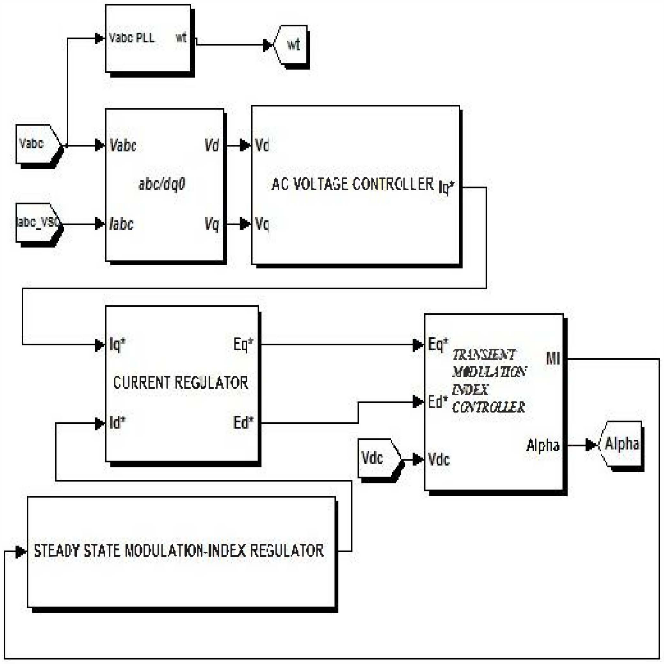


Fig.5 STATCOM controller

In addition, an ac voltage controller is designed to regulate the PCC bus voltage through a PI controller. The ac voltage controller generates the desired reactive current reference for the current regulator.

In the design of the STATCOM controller, it is essential to have good dynamic response in the transient period and to ensure minimal harmonics at steady state. As shown in Fig. 5, a transient modulation-index controller and a steady-state modulation-index regulator are proposed to achieve the goals of good transient response and minimal steady-state harmonics respectively. Details for the design of transient modulation-index controller, steady-state modulation-index regulator, phase locked loop (PLL), abc to dq0 transformation, AC voltage controller, Current regulator, PWM generator are described below:

A. PLL:

The PLL provides the basic synchronizing signal which is the Phase angle of the bus. In the case of a sudden change in the power system, such as load rejection, it takes about half a cycle of voltage (10 ms for 50 Hz) for the PLL to be synchronized with the new voltage phase angle, plus the signal processing delay. During this time the STATCOM operates at the previous phase angle, while the bus voltage phase has changed. Depending on the amount of phase angle change and whether it is increased or decreased, an uncontrolled real power, and reactive power exchange would occur between the STATCOM and the transmission line during this inherent PLL delay. Therefore depending on the amount of the phase angle change and whether it is increased or decreased, the dc capacitor would be charged or discharged at load switching instants.

B. abc to dq0 Transformation :

This block performs the abc to dq0 transformation on a set of three phase signals. It computes the direct axis V_d, quadrature axis V_q, and zero sequence V_0 quantities in a two axis rotating reference frame according to the Park's Transformation shown below.

$$V_d = \frac{2}{3}\left[V_a \sin(\omega t) + V_b \sin(\omega t - \tfrac{2\pi}{3}) + V_c \sin(\omega t + \tfrac{2\pi}{3})\right]$$

$$V_q = \frac{2}{3}\left[V_a \cos(\omega t) + V_b \cos(\omega t - \tfrac{2\pi}{3}) + V_c \cos(\omega t + \tfrac{2\pi}{3})\right]$$

$$V_o = \frac{1}{3}\left[V_a + V_b + V_c\right] \tag{4}$$

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

C. AC Voltage Controller and Current Regulator:

The AC Voltage controller converts V_d , V_q into reference reactive current I_q^* using appropriate PI Controllers as shown in Fig.5.

$$i_q^* = G_1(s)[V_{rms} - V_{rms}^*] \tag{5}$$

$$G_1(s) = k_1 + \frac{k_2}{s} \tag{6}$$

Similarly Current regulator uses reference reactive current I_q^* and reference direct current I_d^* along with PI Controllers to generate reference direct and quadrature voltages E_d^*, E_q^* respectively.

$$E_d^* = -\omega L_f i_q + V_{dc} - x_1 \tag{7}$$

Where

$$x_1 = G_2(s)[i_d^* - i_d] \tag{8}$$

$$G_2(s) = k_3 + \frac{K_4}{s} \tag{9}$$

Where,

L_f is leakage inductance

V_{dc} is capacitor voltage.

D. Transient Modulation-Index Controller

The efficient way to modulate the reactive power output Q of the STATCOM and to regulate the PCC bus voltage is to control the output voltage of the STATCOM in the transient period. STATCOM output voltage is proportional to the product of modulation-index (MI) and V_{dc}. Since it is impossible to change V_{dc} instantaneously, it is desirable to adjust the MI in the transient period such that the PCC bus voltage can be regulated efficiently. Thus, a transient modulation-index controller is proposed to adjust the MI rapidly in the transient period.

$$MI = \frac{\sqrt{E_d^* + E_q^*}}{KV_{dc}} \tag{10}$$

$$\alpha = \tan^{-1}\left(\frac{E_q^*}{E_d^*}\right) \tag{11}$$

E. Steady-State Modulation-Index Regulator:

It has also been observed that a lower modulation index would give more harmonic contents at steady state. Thus, it is desirable to have the MI fixed at unity in order to ensure minimal harmonics at steady state. To achieve this goal, a steady-state modulation-index regulator is proposed to drive the modulation index to the pre-set value (MI*=1 in this work) at steady state through the action of a PI controller. As shown in Fig.5, the real current reference i_d^* is generated by the proposed steady-state modulation-index regulator as given in equations (12) and (13).

$$i_d^* = G_3(s)[MI^* - MI] \tag{12}$$

$$G_3(s) = k_5 + \frac{K_6}{s} \tag{13}$$

Using the proposed steady-state modulation-index regulator and transient modulation-index controller, the advantage of minimal harmonics can be retained under steady-state situations. When there is a need to adjust the reactive power output during the transient period, the actual MI is no longer equal to the steady-state reference MI^* which is equal to the pre-set value. As a result, the MI deviates from the steady-state value MI^*. However, this deviation of the modulation index has little effect on steady-state harmonic contents since the transient lasts for only a very short period. With the adjustment of the modulation index by the proposed STATCOM controller during the transient period, the STATCOM output voltage $|V_2|$ and reactive power Q can be modulated in a very rapid manner.

F. PI Controller:

PI controller generates a gated command to operate the converters and to compensate the error, which has been calculated by comparing defined values against measured values for both reactive and real powers. This is an integral part of the converters which generates a gated command to operate the converters in order to produce the fundamental voltage waveform which compensates the voltage magnitude by synchronizing with the AC system. The internal control also takes preventive measures to limit the maximum voltage and current from the individual power converter to maintain safe operations under any system contingency.

V. IMPLEMENTATION AND RESULTS

A basic power system model is designed consisting of 3-phase source of 100MVA and a line voltage of 11kV.This power is transmitted through a transmission line of length 350km to load centre. At the load centre various loads are considered and are connected to system at different instants of time as shown in the Table 1.

Table 1: Load data of power system

No.	Time range (s)	Type of load	Load
1.	0.1 to 0.2	Nonlinear	R=1800Ω, L=1mH
2.	0.3 to 0.4	Inductive	R=0.242Ω, L=1.537mH
3.	0.5 to 0.6	Capacitive	R=400Ω, C=50μF
4.	0.0 to 0.5 and 0.6 to 0.7	Normal load	R=300 Ω, L= 50mH

Fig. 6 depicts the load voltage and current waveforms of the power system without STATCOM. In the interval 0.3s to 0.4s there is a dip in the voltage level due to inductive load and from 0.5s to 0.6s there is a rise in the voltage level due to capacitive loaded conditions, but such voltage fluctuations are not desirable for a power system.

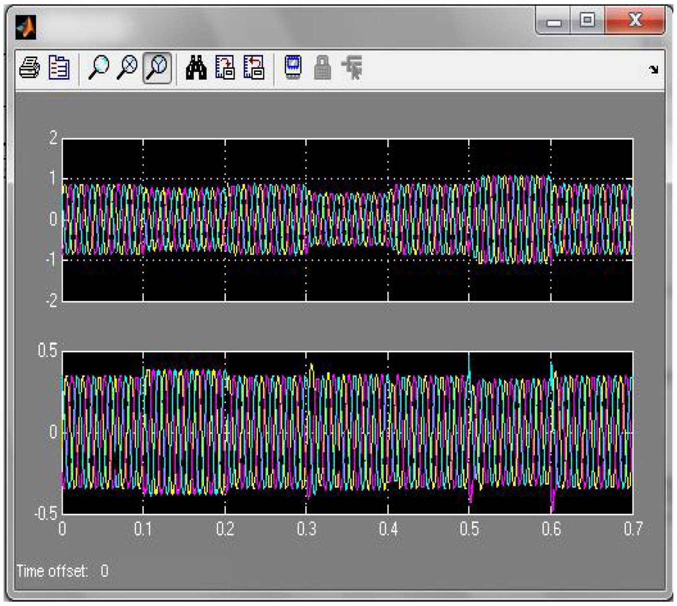


Fig.6 Output Voltage and current of the Power system without STATCOM

Hence the 9 level STATCOM and its controller is connected to the power system as shown in Fig.7 and the corresponding load voltage and current waveforms are shown in Fig. 8. The voltage waveform in the Fig.8 is maintained constant throughout indicating constant load voltage irrespective of the load connected and thereby improving voltage profile of the system.

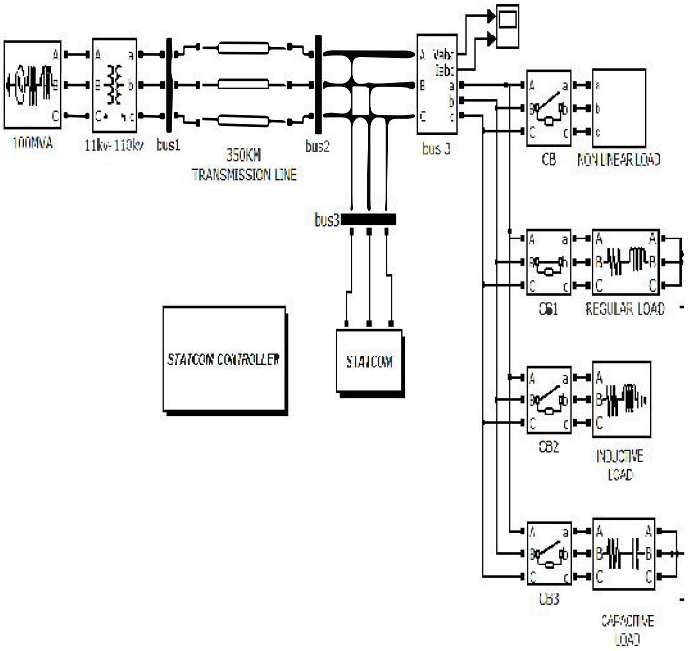


Fig.7 Matlab implementation of power system with STATCOM

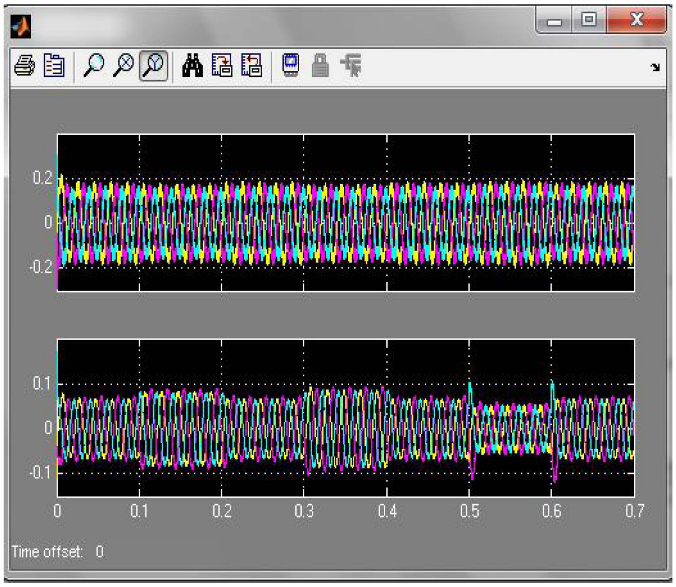
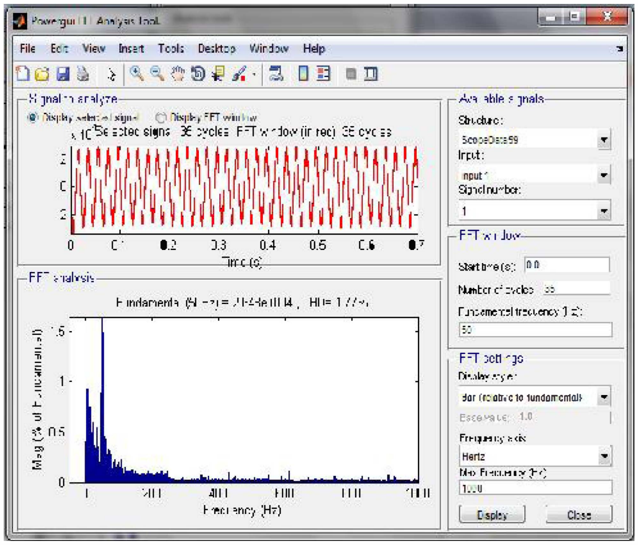


Fig.8 Output Voltage and current of the Power system with STATCOM

For analyzing the quality of the voltage waveform total harmonic distortion calculations are performed using equation (14).

$$THD = \frac{\sqrt{\sum_{K=2}^{\infty} |V_k|}}{|V_1|} \tag{14}$$

The THD of output voltage is calculated and is found to be 1.77% as shown in the Fig. 9 and the same is compared with the THD of various papers as shown in Table.2 and is found to be minimum.



Structure: ScopeData59
Input: input 1
Signal number: 1
Start time (s): 0.0
Number of cycles: 35
Fundamental frequency (Hz): 50
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz
Max Frequency (Hz): 1000

Fig.9 THD analysis of output voltage waveform

Table 2: Results comparison

S.No	Designs	THD
1.	Proposed control	1.77%
2.	Paper [2]	4.24%
3.	Paper [3]	59.9%
4.	Paper [4]	4.84%

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5.	Paper [5]	6.5%
6.	Paper [6] (5-level)	24.92%
7.	Paper [6] (7-level)	15.89%

VI. CONCLUSION

The paper presents a STATCOM model, developed with the necessary components and controllers in order to demonstrate its effectiveness in maintaining simple and fast voltage regulation at any point in the transmission line. On the other hand, the harmonics generated by the STATCOM is kept minimal with the implementation of SHEM. The effectiveness of the proposed control strategy is demonstrated with the help of THD calculations and is found to be minimum when compared with various designs. Hence the proposed STATCOM with it controller employing the direct control strategy is able to maintain the voltage balance under various load conditions.

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