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Design of a Multilevel Inverter System Based STATCOM for Reliable Power System

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Abstract

In an electrical power system, control of voltage is very essential for better and reliable operation of electrical equipments. A constant voltage profile and reactive power management in the transmission lines is very important to avoid any damage for e.g. overheating of motors and generators, to reduce the losses in the transmission lines and to improve the ability of a power system to withstand and prevent power outages. Reactive power compensator devices such as static synchronous compensator in the transmission lines provides the better management of reactive power, which further leads to more reliability and the commercial transactions can be done across the transmission lines. Nowadays, with the advancement of multilevel inverter field, static synchronous compensator devices with conventional inverters are completely obsolete and are replaced with multilevel inverters. This paper presents a novel technique for designing of a multilevel inverter based static synchronous compensator. The designed multilevel inverter based static synchronous compensator provides lower source current distortions and lower switching losses and is suitable for smart grid applications. The proposed model takes care of all the reactive power requirement of the load and therefore results in the reduction of total harmonic distortion and improved power factor.

Keywords— *Cascaded H-Bridge, Flexible Alternating Current Transmission, Harmonics, Multilevel Inverter, Pulse Width Modulation, System Static Synchronous Compensator, Total Harmonic Distortion*

1. Introduction

With the deployment in technology, the power electronics field has become very popular and most widely used in numerous industrial applications. Basically, power inverters have taken very significant place in today’s industrial world. Initially, conventional inverters, which were limited up to two levels, were used [1]. Nowadays, power inverters beyond two levels are widely in use. These power inverters having more than two levels, are known as Multilevel Inverters (MLIs). The concept of MLIs was originated in the late 1970s, when the first MLI system came into picture [2]. A MLI system is capable of generating staircase output waveform in terms of several voltage levels. The generated output waveform by a MLI system is consists of lesser harmonics and lower losses [3-4]. Due to the advantages offered by a MLI system, MLIs are gaining much attention in the field of power, energy distribution and control [5]. MLIs have been designed using numerous topologies and control strategies. Most commonly used topologies of MLIs are Neutral Point Clamped (NPC), Flying Capacitor (FC) and Cascaded H-bridge (CHB) topologies. In recent years, increasing attention has been paid to MLIs that have emerged as the solution for high power applications, as it is difficult to use single power semiconductor switch directly in medium voltage networks. Figure 1 depicts a comparison between the conventional inverters and MLIs. MLIs can be used for high power Flexible Alternating Current Transmission Systems (FACTS) devices such as Static Synchronous Compensator (STATCOM), medium voltage drives and power grids [6-7].

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The main motive is to achieve better output with minimum harmonics and to increase the overall efficiency of the system with the aid of MLIs.

In the past years, power system has been undergoing too many variations. Main essential requirements of the power system are the voltage stability, voltage control, compensation of reactive power and minimization of harmonics. All these factors enhance the power system performance, stability, minimized line losses, maximum energy efficiency, better utilization of power capacity etc. Therefore, in order to maintain the better power system security and stability, all these parameters should be carefully handled. One of the essential requirements in the modern power system is the Power Quality (PQ). PQ refers to the ability of electrical appliances to consume the energy being supplied to them. Numerous PQ issues such as electrical harmonics, low power factor, minimum energy efficiency, voltage instability and bad effects on the electrical equipments are arising nowadays in the power systems because of massive proliferation of power electronics based appliances. These appliances draw reactive current from the source and generate the harmonics. This further leads to voltage and current distortions in the output waveform and reduces the power quality further. Thus, the control of voltage disturbances is must in a power system; otherwise the consumers connected to the grid will be affected. Nowadays, PQ issues are growing rapidly due to following reasons:

a) Variations in the characteristics of electrical loads and the failure of the appliances due to harmonics produced in the output.

b) Deregulation of the market: In the electric power systems, any variations or disturbances can have serious economic impact on the consumers due to process shutdown.

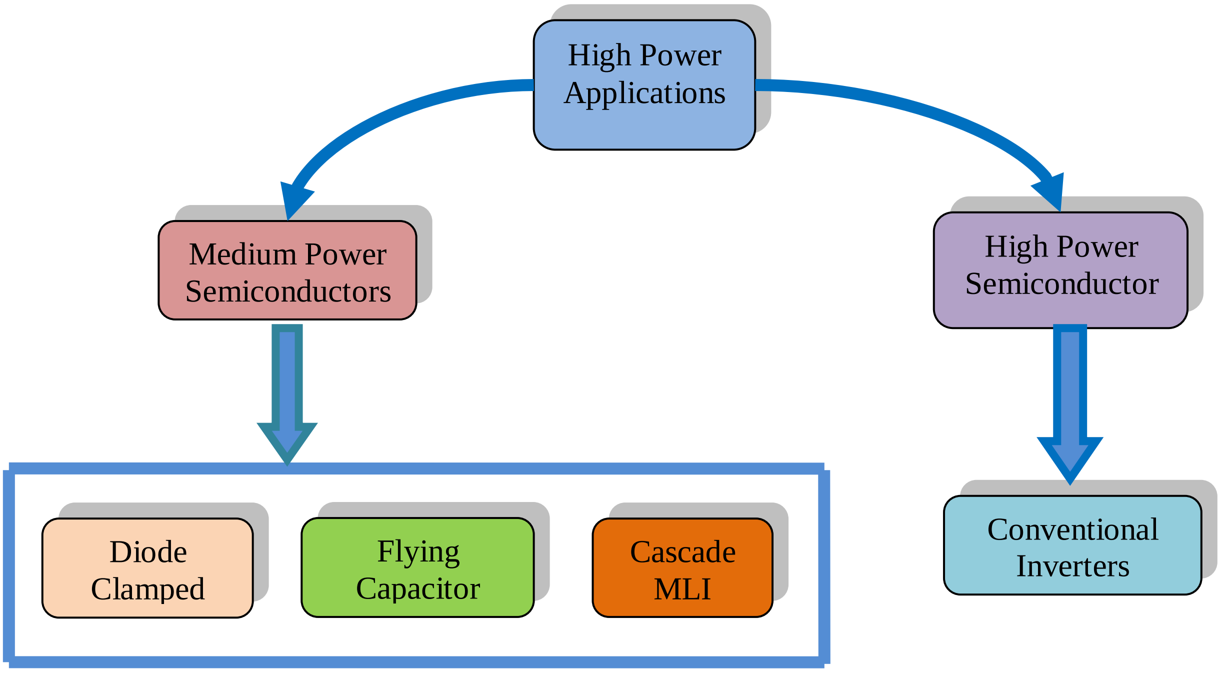

Figure1 Conventional Inverters versus Multilevel Inverters

Power quality improvement is getting more attention at national as well as international level because of the reason that non-linear loads comprise a very large portion of the total connected load. This further leads to implementation of the standards like IEEE-51-1992 “Recommended practices for harmonic control in electric power systems”. Such type of standards imposes certain responsibilities on the consumers and utilities to work for the PQ improvement. MLIs offer the solution to the problem of PQ issues and also deal with the economic impacts associated with the PQ issue. Reactive power compensation devices such as STATCOM along with MLIs results in an improvement in the power quality [8]. Earlier, reactive power compensator devices were made up of conventional inverters such as two level inverters, which work on high switching frequency.

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Due to high switching frequency for enhanced operation, switching losses are high. MLIs operate on fundamental switching frequency, which results in lesser switching losses and lesser EMIs. MLIs produce output voltage with minimum harmonics, which further leads to an improvement in the PQ [9]. Furthermore, any voltage disturbances are also minimized by the MLIs. Nowadays, MLIs have been evolved from a mere theoretical concept to real time applications because of the benefits of MLIs such as better PQ, higher modularity, lesser harmonics and switching losses and their connectivity directly to the medium voltage.

Table 1 Advantages of Multilevel Inverter System over the Conventional Inverters

S. No.	Parameter	Multilevel Inverters	Conventional Inverters
1	Total Harmonic Distortion	Low	High
2	Switching Losses	Low	High
3	Voltage Levels	High voltage levels can be generated	High voltage levels cannot be generated
4	Switching Frequency	Lower switching frequency, reduced switching losses	Higher switching frequency, increased switching losses
5	Applications	Used for high voltage applications	Not used for high voltage applications

Considering the need of MLI based STATCOM system for reliable operation of power system, a seven level CHB inverter based STATCOM is being proposed in this research article. The proposed system results in lesser harmonics as depicted in FFT analysis of simulated results. Also, there is increase in voltage stability as well as power quality of the overall system. This ensures the reliable operation of power system.

2. Multilevel Inverter Based STATCOM

A MLI based STATCOM consists of a coupling transformer, an energy source, controller and a MLI. Figure 2 demonstrates the general block diagram of a MLI based STATCOM. Generally, a STATCOM is a regulating device, which is connected in shunt with the power system networks and is capable of generating or absorbing the reactive power to the power system networks and therefore, helps to improve the power factor and provides the voltage stability. A STATCOM with MLI rather than STATCOM with conventional inverter is more beneficial due to numerous benefits of MLI [10-11]. MLI based STATCOM provides better voltage stability and is more useful for smart grid applications [12]. In this modern era, main objective is to provide better power quality in the transmission grid with minimum losses and harmonics. STATCOM either by absorbing or by injecting the power from and to the transmission networks, controls the power flow of the power system and thus maintains the improved power factor and leads to better power quality in the transmission grids. Thus the MLI based STATCOM provides a platform for the researchers working towards the better voltage stability and power quality in the transmission grids.

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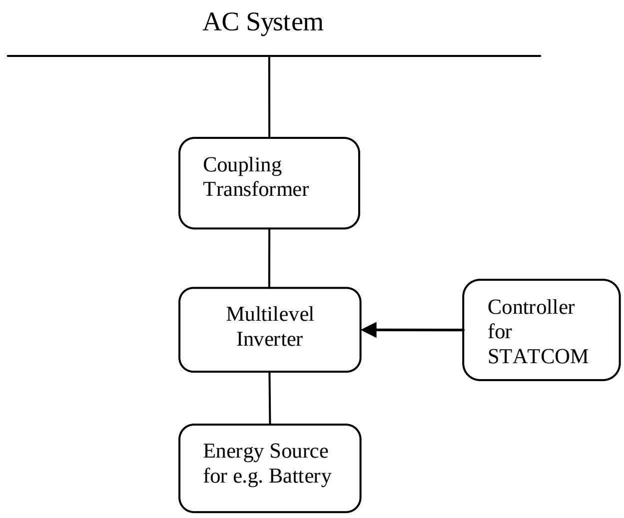

Figure 2 Multilevel Inverter Based STATCOM

Efficient operation of any power system network depends upon the reactive power compensation mechanism. In this context, STATCOM proves to be a boon for the transmission networks. STATCOM is connected in shunt with the transmission lines and maintain the active and reactive power in the lines.

3. Proposed Multilevel Inverter Based STATCOM

A seven level CHB topology based MLI is being designed and then it is embedded in the STATCOM. This section is divided into three parts: Sub section 1 elaborates the designing of the proposed seven level CHB inverter. Particle Swarm Optimization (PSO) algorithm is being used for calculating the three firing angles of seven level inverter. At the optimized firing angles, switching devices of the MLI are fired, which results in minimized Total Harmonic Distortion (THD). In sub section 2, proposed seven level CHB based STATCOM is demonstrated. Mathematical model and design of controller are mentioned. Finally, implementation of the MLI based STATCOM system is depicted in section 4.

3.1 Designed Seven Level CHB Inverter

The main concern of system designers and application engineers has been the task of appropriate designing of multilevel converters which produce desired staircase wave with fewer harmonics. This has been mainly due to the reason that on increasing the number of levels, more harmonics are introduced in the output of the inverters. The multilevel inverter having harmonics free output attracted importance in all industrial, commercial, domestic and defense applications [13]. Hence, there has arisen the need for suitable optimization techniques to achieve harmonics free output in multilevel inverters [14-15].

3.1.1 The Fourier Series

Joseph Fourier was the first to introduce the mathematical tool named Fourier Series. Joseph sir applied the tool for the solution of a heat equation in a metal plate. Fourier series decomposes any periodic function into the sum of sine and cosine terms. Any periodic function $f(t)$ in the time period $(0,2\pi)$ can be represented in terms of sine and cosine form as depicted in equation (1), where the number of coefficients N tends to infinity:

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$$f(t)=\frac{a_0}{2}+\sum_{n=1}^{N}[\mathrm{a}_n\cos(nwt)+b_n\sin(nwt)]$$

(1)

Where, a_n and b_n are the Fourier coefficients and defined as follows:

$$a_n=\frac{1}{\pi}\int_0^{2\pi}f(t)\cos(\mathrm{n}\,\omega\,\mathrm{t})\,\mathrm{dt}$$

(2)

$$b_n=\frac{1}{\pi}\int_0^{2\pi}f(t)\sin(\mathrm{n}\,\omega\,\mathrm{t})\,\mathrm{dt}$$

(3)

Fourier series equation (1) represents that a periodic function can be decomposed into an infinite number of trigonometric terms at different frequencies. In fact, the defined function $f(t)$ is composed of a fundamental frequency component when n =1, a DC component (a_0) and various harmonic components when n = 2, 3, 4, 5,…..and so on. The output voltage of a MLI can be represented using the Fourier series as depicted in equation (4).

$$V_{an}(wt)=\sum_{m=1,3,5,....}^{\infty}\frac{4V_{dc}}{m\Pi}(\cos(\mathrm{m}\,\alpha_1)+\cos(\mathrm{m}\,\alpha_2)+..............+\cos(\mathrm{m}\,\alpha_n))\sin(\mathrm{m}\,wt)$$

(4)

where,

Vdc : DC voltage
m : Harmonic component
αi : i^{th} switching angle

The harmonic factor (percentage) of the nth harmonic is calculated as:

$$HF_n=\frac{V_n}{V_1}\mathrm{X}100;n>1$$

(5)

Here V_n represents the n^{th} harmonic voltage and V_1 is fundamental output voltage. Equation (4) can be divided into three parts as:

$$V_{an}(wt)=V_{l1}(\mathrm{t})+V_{l2}(\mathrm{t})+V_{l3}(\mathrm{t})$$

(6)

Where $V_{l1}(t)$ is the fundamental frequency voltage, represented as:

$$V_{l1}(t)=\frac{4V_{dc}}{\Pi}(\cos\alpha_1+\cos\alpha_2+\cos\alpha_3)\sin wt$$

(7)

Equation (7) represents the output voltage for seven level CHB inverter. $V_{l2}(t)$ is the triplen harmonic voltages as:

$$V_{l2}(t)=\sum_{m=3,9,15,.....}\frac{4V_{dc}}{m\Pi}(\cos(m\alpha_1)+\cos(m\alpha_2)+\cos(m\alpha_3))\sin(mwt)$$

(8)

$V_{l3}(t)$ is the odd harmonic (except triplen) voltages as:

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$$V_{l3}(t) = \sum_{m=5,7,11,.......} \frac{4V_{dc}}{m\Pi}(\cos(m\alpha_1) + \cos(m\alpha_2) + \cos(m\alpha_3))\sin(m\,\mathrm{wt})$$

(9)

In three phase applications, triplen harmonic voltages in each phase cancel out automatically, hence no need to cancel these voltages. Another important parameter is modulation index (m_I), which represents the relationship between the fundamental voltage (V_1) and the maximum obtainable voltage (V_{1max}). It is defined as the ratio of the fundamental output voltage to the maximum obtainable fundamental voltage. Switching angles α_1, α_2 and α_3 (in case of 7 level cascaded MLI) can be found using optimization techniques. Equation (4) is known as non linear transcendental equations. For solving these transcendental equations, PSO based approach is used by the investigators. The harmonic contents depend upon the switching angles of a MLI. For seven level CHB inverter, there exists three switching angles corresponding to three H-bridges. In this research work, SHE technique has been applied and using PSO three switching angles have been calculated. SHE works on fundamental switching frequency, which further results in minimum losses. Equation (7) can be converted into SHE equations as:

$$\begin{aligned}
&\cos\alpha_1 + \cos\alpha_2 + \cos\alpha_3 = 3M \\
&\cos 5\alpha_1 + \cos 5\alpha_2 + \cos 5\alpha_3 = 0 \\
&\cos 7\alpha_1 + \cos 7\alpha_2 + \cos 7\alpha_3 = 0
\end{aligned}$$

(10)

In equation (10), M represents the modulation index and is defined as the ratio of fundamental output voltage to the maximum obtained fundamental voltage. Three switching angles must satisfy the constraint:

$$0 < \alpha_1 < \alpha_2 < \alpha_3 < \frac{\Pi}{2}$$

(11)

Figure 3 represents the designed seven level CHB inverter and its corresponding output waveform.

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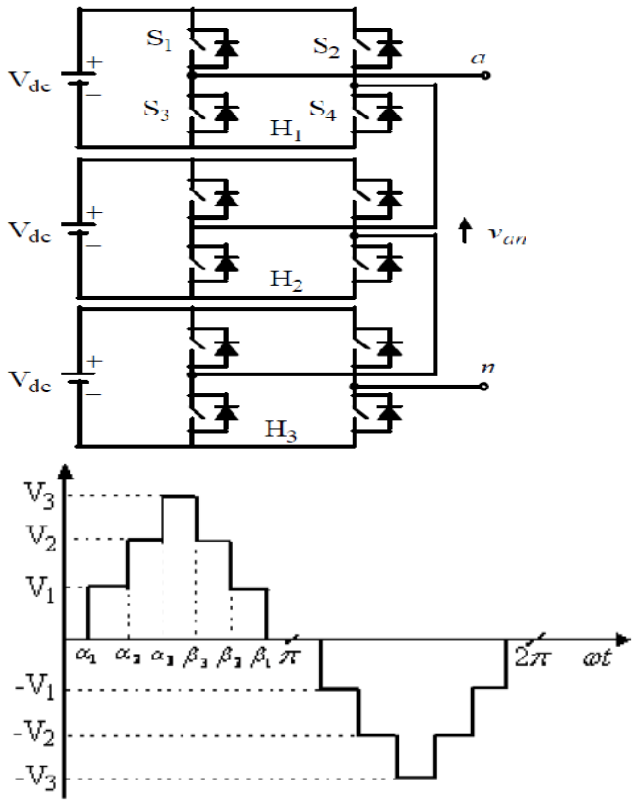

Figure 3 Seven Level CHB Inverter per phase and corresponding output waveform

3.2 Seven Level CHB based STATCOM

Nowadays, STATCOM has taken very significant role in the reactive power compensation applications due to its dynamic performance. Due to benefits offered by STATCOM such as fast response reactive power control and minimized interference with the power system, STATCOM has become most effective devices in FACTS family. Figure 4 represents a STATCOM configuration. STATCOM control is designed using Park transformation. The phase voltages and currents are converted into orthogonal components in a synchronous rotating frame using Park transformation.

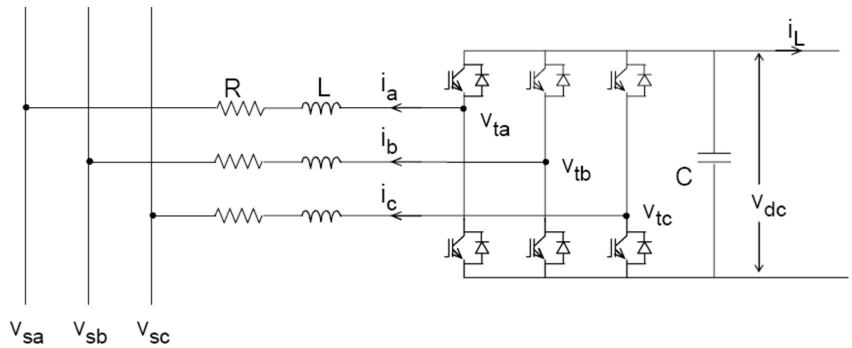

Figure 4 A Typical STATCOM Configuration

The STATCOM can be mathematically represented using the below equations:

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$$\frac{di_{da}}{dt} = -\frac{R}{L} i_{da} + \rho i_{qa} + \frac{1}{L}(V_{tda} - V_{sda})$$
$$\frac{di_{qa}}{dt} = -\rho i_{da} - \frac{R}{L} i_{qa} + \frac{1}{L}(V_{tqa} - V_{sqa})$$
$$\frac{dV_{DC}}{dt} = -\frac{3(V_{tda} i_{da} + V_{tqa} i_{qa})}{2V_{DC} C} - \frac{i_L}{C} \quad (12)$$

Where da = variables for the components in rotating coordinate in direct axis
qa = variables for the components in rotating coordinate in quadrature axis
ρ = angular power frequency

PID controller is being used for the designing of STATCOM controller. The design of controller depends upon the determination of the coefficients values. Table 2 represents the PID controller coefficients. Furthermore, Park transformation is used for controller design. In fact, Park transformation is a very strong tool in the analysis of power system. It converts the phase voltages and currents into orthogonal components which are in a synchronous rotating frame. These orthogonal components are fixed to the rotor and are related with active and reactive power. Using this process, problem of designing of controller is greatly simplified.

TABLE 2 PID Controller Coefficients

Coefficients	PID 1	PID 2	PID 3	PID 4
K_p	488.157	488.157	488.157	257.134
K_i	147.43	33.467	30.676	82.789
K_d	104.716	62.879	42.477	108.757

4. Simulations and Results

A MLI based STATCOM makes the whole power system more reliable in terms of better voltage stability, good power quality and minimized harmonics and losses. Figure 5represents a MLI based STATCOM power system. Here, designed seven level CHB inverter is being used in the STATCOM.

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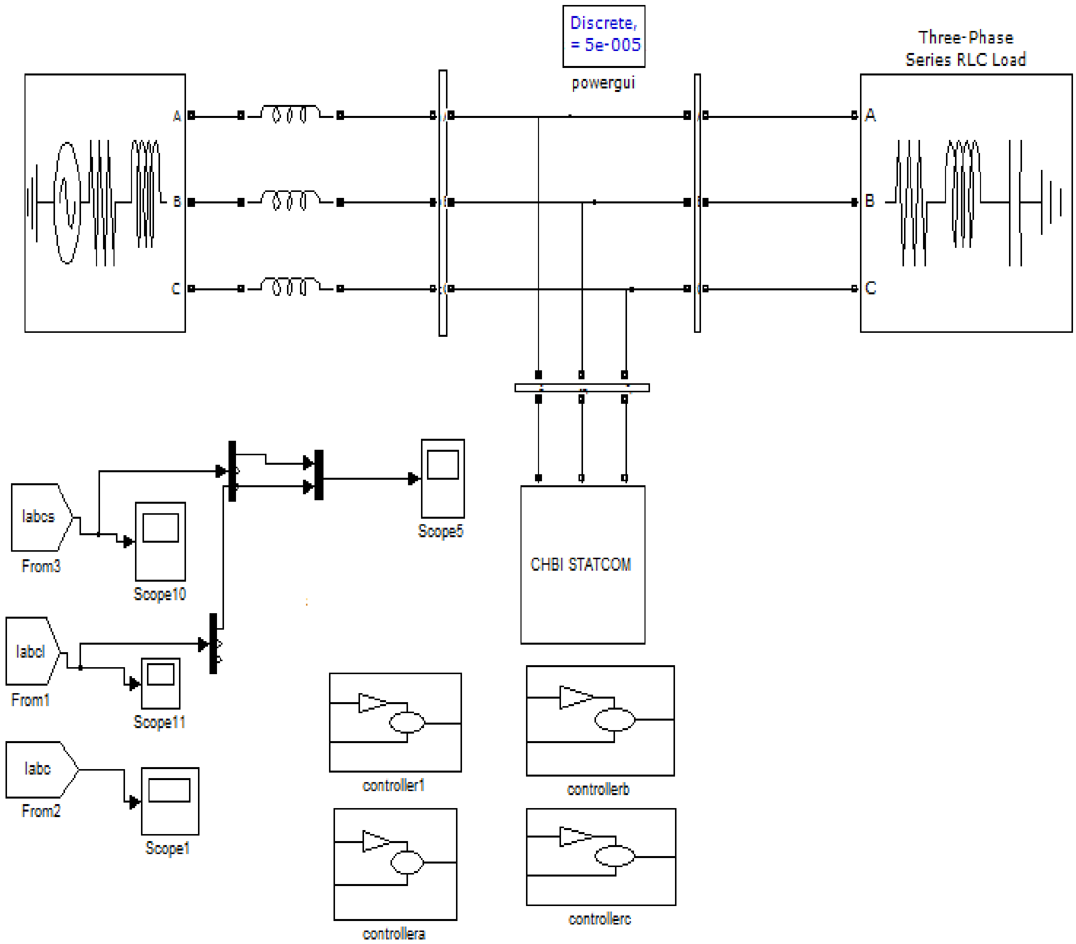
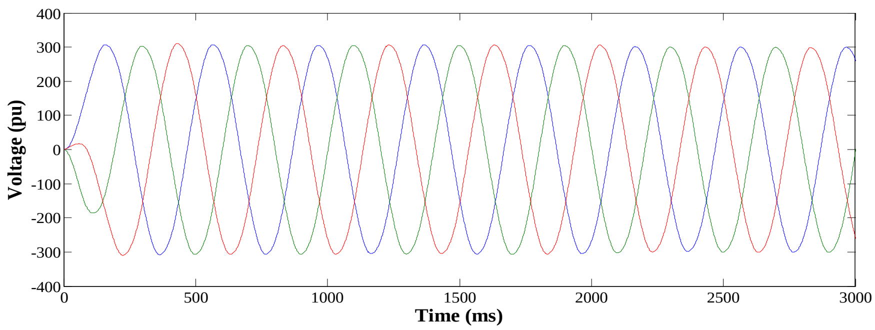


Figure 5 Proposed Model of Multilevel Inverter Based STATCOM

A MLI results in better staircase output voltage waveform and minimum THD. Another significant step is the switching of the semiconductor devices of H-bridges of MLI. A Pulse Width Modulation (PWM) strategy is used for the switching purposes. A MLI based STATCOM interfaced with the power system regulates the capacitor voltage of STATCOM, maintain the rated supply voltage for any load variation and also is capable to reduce the THD of the obtained output voltage and current effectively. The proposed system also ensures the reactive power compensation and reduces the harmonics in the output voltage and current waveforms as shown in Figure 6. Finally, the proposed MLI based STATCOM system results in better voltage stability, lesser harmonics and good power quality.



(a) Obtained Voltage in 7 Level CHB STATCOM System

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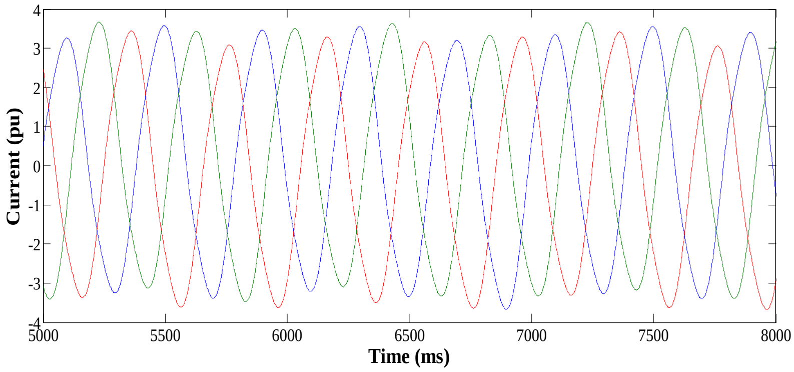

(b) Obtained Current in 7 Level CHB STATCOM System

Figure 6 Voltage and Current Waveforms of a MLI based STATCOM System

5 Conclusion

For reactive power compensation in the transmission networks, a MLI based STATCOM has become very significant and most widely used devices nowadays. With the aid of these STATCOM devices, power system stability and reliability can be increased and also the possibilities of blackout decreases. Because of numerous advantageous of MLIs, applications of MLI based systems are increasing day by day. In this research work, a MLI based STATCOM system is being proposed. The proposed model is implemented and designed in MATLAB and Xilinx software. The designed system results in better output voltage waveform by reducing the harmonics and overall THD. Also, better voltage stability is achieved with the proposed model. The model takes care of the power quality of the system. Furthermore, an improvement in power factor is gained using the implemented MLI based STATCOM system. The system works satisfactorily in terms of harmonics and distortion. Hence, it can be concluded that the a MLI based STATCOM system makes the power system more reliable in terms of better power quality, more voltage stability, an enhanced power factor and lesser harmonics. As a future scope, STATCOM system based on MLIs of higher levels can also be implemented to improve the system efficiency and performance.

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