

# Analysis of STATCOM Using Symmetrical Multilevel Inverter

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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 sinusoidal pulse width (SPW) modulation control techniques simulated in MATLAB Simulink. The main objective of this paper is to maintain voltage stability in the power system using Multilevel Inverter based STATCOM. Hence, a new symmetrical modular multilevel STATCOM is employed to reduce voltage fluctuations like sag and swell conditions and also to isolate current and voltage harmonics in the transmission system. The multilevel STATCOM is used at the point of common coupling (PCC). The performances are analysed by applying it to 110 kV transmission line with and without STATCOM. The system without STATCOM technique has faults like Voltage sag and Voltage swell, Harmonics and Voltage fluctuations. Whereas, the system with STATCOM technique the voltage profile is improved which are shown in simulation results. The proposed symmetrical 5 level inverter based STATCOM, whose output levels can be increased by adding the modules is analyzed and found it is able to maintain uniform voltage profile under regular and nonlinear loads.

**KEYWORDS:** Multi-level inverter, Sinusoidal Pulse-width modulation (SPWM), STATCOM, Voltage sag and swell, Harmonics and Fluctuations.

## I. INTRODUCTION

Power Generation and Transmission is a complex process, requiring the working of many components of the power system in tandem to maximize the output. One of the main components to form a major part is the voltage in the system. It is required to maintain the voltage to deliver the active power through the lines. Power electronics technology has advanced a lot over the last two decades and as a result of this the research of power electronics applications has spread to all voltage levels, starting from EHV transmission to low voltage circuits in the end user facilities. The employment of FACTS devices in transmission lines becomes necessary owing to reasons like over loaded transmission lines in special paths, power flow in unwanted paths, and non-optimal operation of line capacity. Flexible AC Transmission Systems (FACTS) were firstly developed in the 1990's [19]. 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. In this project multilevel inverters are chosen as an effective way to improve the performance of the ac system. Multilevel converters are successfully replacing old-fashioned two-level inverters with high power losses and bulky filters [53]. Hence a multilevel STATCOM and a control system should be designed for this purpose. The focus of all the published work on STATCOM has been on using VSC topology are given by [14]–[18]. The designed multilevel STATCOM topology employed sinusoidal pulse width modulation as from [1]–[2] helps in fast Switching and harmonics reduction.

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## II. STATIC SHUNT COMPENSATOR (STATCOM)

One of the many devices under the FACTS family, a STATCOM is a regulating device which can be used to regulate the flow of reactive power in the system independent of other system parameters. STATCOM has no long term energy support on the dc side and it cannot exchange real power with the ac system. In the transmission systems, STATCOMs primarily handle only fundamental reactive power exchange and provide voltage support to buses by modulating bus voltages during dynamic disturbances in order to provide better transient characteristics, improve the transient stability margins and to damp out the system oscillations due to these disturbances.

As it is clear from Fig.1, STATCOM consists of a three phase inverter (generally a PWM inverter) using SCRs, MOSFETs or IGBTs, a dc capacitor which provides the dc voltage for the inverter, a link reactor which links the inverter output to the ac supply side, filter components to filter out the high frequency components due to the PWM inverter. From the dc side capacitor, a three phase voltage is generated by the inverter. This is synchronized with the ac supply. The link inductor links this voltage to the ac supply side. This is the basic principle of operation of STATCOM. For two ac sources which have the same frequency and are connected through a series inductance, the active power flows from the leading source to the lagging source and the reactive power flows from the higher voltage magnitude source to the lower voltage magnitude source. The phase angle difference between the sources determines the active power flow and the voltage magnitude difference between the sources determines the reactive power flow. Thus, a STATCOM can be used to regulate the reactive power flow by changing the magnitude of the VSC voltage with respect to source bus voltage. It has long been recognized that the steady-state transmittable power can be increased and the voltage profile along the line controlled by appropriate reactive shunt compensation.

### A) WORKING PRINCIPLE OF STATCOM

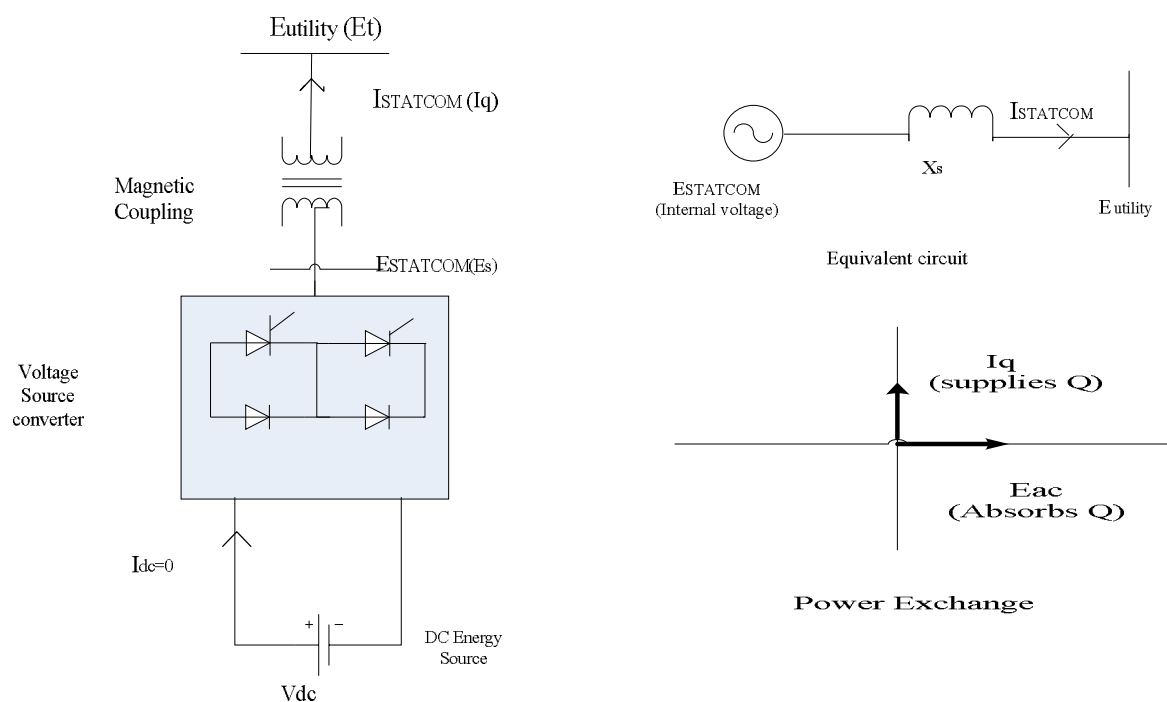


Fig: 1. Schematic Configuration Of STATCOM

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Vol. 6, Issue 9, September 2017

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. From the figure, we can observe that if  $E_s > E_t$  then the reactive current 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  $E_s < E_t$  then current flows from ac system to the converter by absorbing reactive power from the system. Finally, if  $E_s = E_t$  then there is no exchange of reactive power.

Where  $E_s$  is magnitude of STATCOM output voltage

$E_t$  is magnitude of system voltage

$I_q$  is magnitude of reactive current.

$X_s$  is Equivalent impedance between STATCOM and the system.

## B) CASCADED MULTILEVEL STATCOM CIRCUIT:

The general concept of is to utilize isolated dc sources or a bank of series capacitors to produce ac voltage waveforms with higher amplitude and near sinusoidal waveform. Multi-level inverters have obtained great attention as a single stage inverter due to their advantages such as generating output voltage with extremely low distortion factor, low dv/dt, small output filter size, low electromagnetic interference, and low total harmonic distortion. MLI are classified into two main categories:

1) single dc-source inverter such as, fixed capacitor and neutral point diode clamped inverters;

2) multi-dc source inverters such as cascade H bridge inverter. While, multi-dc source inverter is divided into symmetrical and nonsymmetrical topologies. Principally, nonsymmetrical topologies produce more voltage levels compared to symmetrical topologies. Almost all of these topologies can be extended for more voltage levels by increasing the number of the primary configuration. The main disadvantage of MLI is that are suffering from increased components number per level, and complex control architecture. In order to overcome this problem modular MLI are used.

## III. PROPOSED MODULAR MLI

A new modular three-phase with reduced components count is proposed. The proposed three phase symmetrical inverter is shown in Fig.2. Each arm consists of series connection of basic cells with a series connected switch, for example arm A is consists of one cell connected in series with switch. Adding the common dc voltage (E) source in to each arm forms the pole, creating the pole voltages ( $V_{Ao}$ ,  $V_{Bo}$ ,  $V_{Co}$ ). In order to obtain the zero state pole voltage another switch Q2 is added to the pole, similarly Q4 and Q6 for pole B and C.

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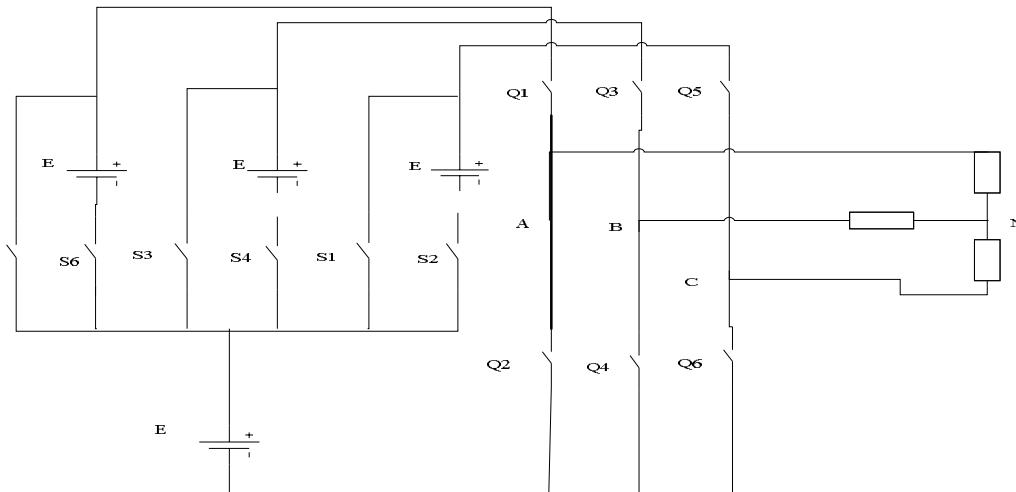


Fig 2: Modular Multi Level Inverter:

The following equations provide the relations of the proposed topology:

$$N_{pole} = N_{cell} + 2$$

$$M_{level} = 2N_{cell} + 3$$

$$N_{sw} = 3(2N_{cell} + 2)$$

$$N_{ps} = 3N_{cell} + 1$$

For example if  $N_{cell} = 1$ ,  $N_{pole} = 3$  which is the pole voltage levels and  $M_{level} = 5$  which is the output line-to-line voltage levels.

VAB	VBC	VCA	S1	S2	Q1	Q2	S3	S4	Q3	Q4	S5	S6	Q5	Q6
E	-2E	E	1	0	1	0	0	0	0	1	0	1	1	0
2E	-2E	0	0	1	1	0	0	0	0	1	0	1	1	0
2E	-E	-E	0	1	1	0	0	0	0	1	1	0	1	0
2E	0	-2E	0	1	1	0	0	0	0	1	0	0	0	1
E	E	-2E	0	1	1	0	1	0	1	0	0	0	0	1
0	2E	-2E	0	1	1	0	0	1	1	0	0	0	0	1
-E	2E	-E	1	0	1	0	0	1	1	0	0	0	0	1
-2E	2E	0	0	0	0	1	0	1	1	0	0	0	0	1
-2E	E	E	0	0	0	1	0	1	1	0	1	0	1	0
-2E	0	2E	0	0	0	1	0	1	1	0	0	1	1	0
-E	-E	2E	0	0	0	1	1	0	1	0	0	1	1	0

Table1: Switching states of proposed topology (Switch ON: 1, Switch OFF: 0)

From the fig 2, when switch S1 and Q1 are ON the voltage across the pole is E volt. When S2 and Q1 are ON the voltage across pole is 2E. When only Q2 is ON the pole voltage is 0. When switch S1 and Q2 are ON the pole voltage

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is  $-2E$ . When switches  $S_2$  and  $Q_2$  are ON the pole voltage is  $-E$ . In this manner, by operating the switches we obtained 5 voltage levels  $-2E, -E, 0, E, 2E$ . From the pole voltages  $V_{AO}, V_{BO}, V_{CO}$  line voltages  $V_{AB}, V_{BC}, V_{CA}$  are determined which are shown in the table 1 below.

## IV. MODULATION TECHNIQUES FOR THE PROPOSED MLI:

The modulation techniques are classified into two main groups according to the switching frequency used to drive inverter switches: 1) low frequency modulation technique, 2) pulse-width modulation techniques that cover conventional techniques, sinusoidal pulse-width modulation, space vector pulse-width modulation, sub-harmonic pulse-width modulation, and switching frequency optimal pulse-width modulation. In this paper, Sinusoidal Pulse Width (SPW) modulation techniques are investigated to achieve sinusoidal output voltages waveforms as described in the following.

### Sinusoidal Pulse-Width Modulation Technique (SPWM):—

The straight way to generate the signals is to compare a sinusoidal waveform signal with a triangular waveform. The comparison operation will produce the Boolean signals that are required to synthesize the switches control pulses. The technique is successfully applied for the proposed topology. Two different approaches have been proposed as follows.

#### 1) Scheme I: SPWM Using Single Carrier Signal:

This scheme uses one carrier signal centered with the sinusoidal modulation signal (sine waveform), and it has an amplitude equal to peak-to-peak value of the modulation signals as shown in Fig. 3. The modulation signal is shifted by dc level equals to  $CR/2$ , where  $CR$  is the carrier signal amplitude. The resulted Boolean output from the comparison between the carrier and the modulating signal produces the main pulse signal  $G_1$ . Also the pulse signal  $G_{p1}$  is generated by comparing the modulating signal with zero value. After logical processing on and, the switching pulses  $S_1, S_2, Q_1$  and  $Q_2$  can be generated as specified below

$$S_1 = (G_1 \times \overline{GP_1}) + (\overline{G_1} \times GP_1)$$

$$S_2 = (G_1 \times GP_1)$$

$$Q_1 = GP_1 + \{(G_1 \times \overline{GP_1}) + (\overline{G_1} \times GP_1)\}$$

$$Q_2 = \{\overline{GP_1} \times \overline{(G_1 \times \overline{GP_1})}\}$$

Where  $x$  stands for logic AND,  $+$  for logic OR,  $\overline{\phantom{x}}$  for invert.  $S_1, S_2, Q_1, Q_2$  are the signals which will be applied to the gates drive belong to switches, respectively. In order to avoid dc-power sources short circuit,  $(S_1, S_2)$  and  $(Q_1$  and  $Q_2)$  operate in a complementary mode with dead time.

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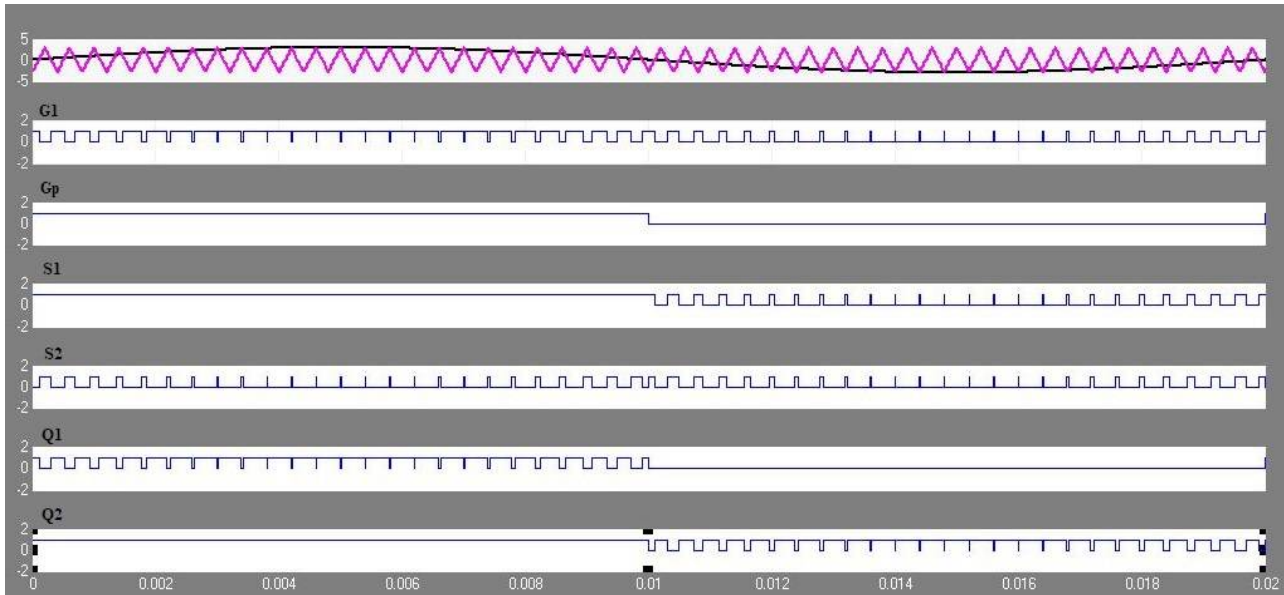


Fig. 3: Switching patterns of the proposed MLI for scheme I:

## 2) Scheme II: SPWM Using Two Carrier Signals:

This scheme compares single modulating signal with two identical and shifted in level carrier signals. Both of them have amplitude equal the modulating signal peak. In addition, the carrier signals are shifted by a dc offset equals to the carrier signal amplitude (CR1) as in the Fig.4. Using the same procedure followed in scheme I, scheme II can be executed. However, due to using two carrier signals, there are two Boolean signals named G1 and G2 resulted from the comparison. By carrying out several logical operations on these two signals (G1,G2), the required control pulses for MLI can be obtained as below

$$S1 = (G1 \times \overline{G2})$$

$$S2 = G2$$

$$Q1 = \overline{G2} \times \overline{(G1 \times G2)}$$

$$Q2 = \overline{G2} \times (G1 \times \overline{G2})$$

Where x stands for logic AND, + for logic OR, \_ for invert.

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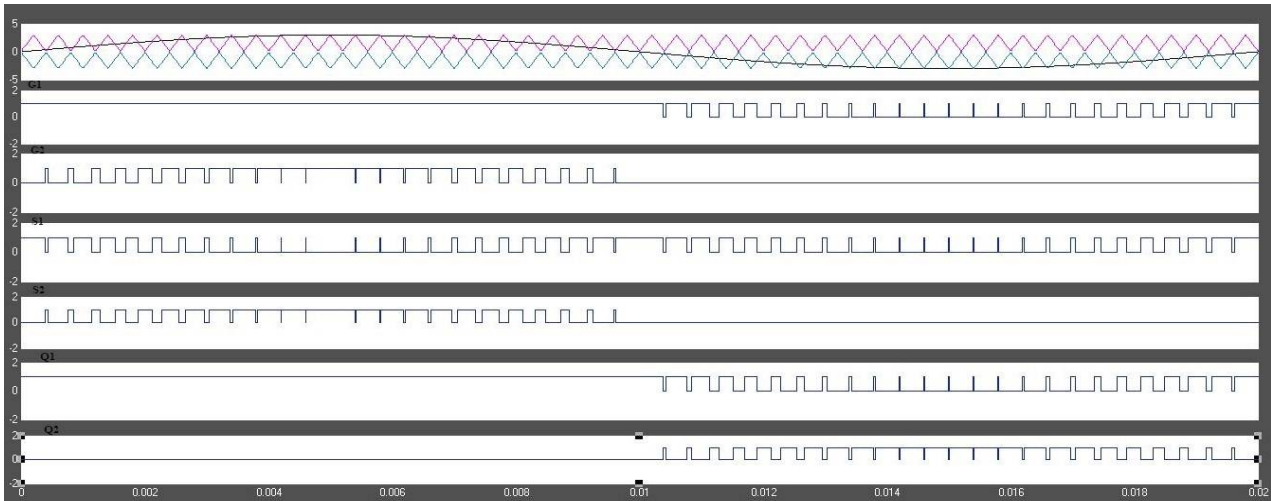


Fig.4: Switching patterns of the proposed MLI for scheme II

## V. SIMULATION AND EXPERIMENTAL RESULTS:

The proposed topology has been simulated using MATLAB software package tools. A single cell has been chosen to produce five levels per line-to-line load voltages according to (3). However, the proposed topology can be extended to n cells. The prototype of the proposed MLI is implemented and setup using the ideal switch as switching devices and symmetrical dc-power supplies.

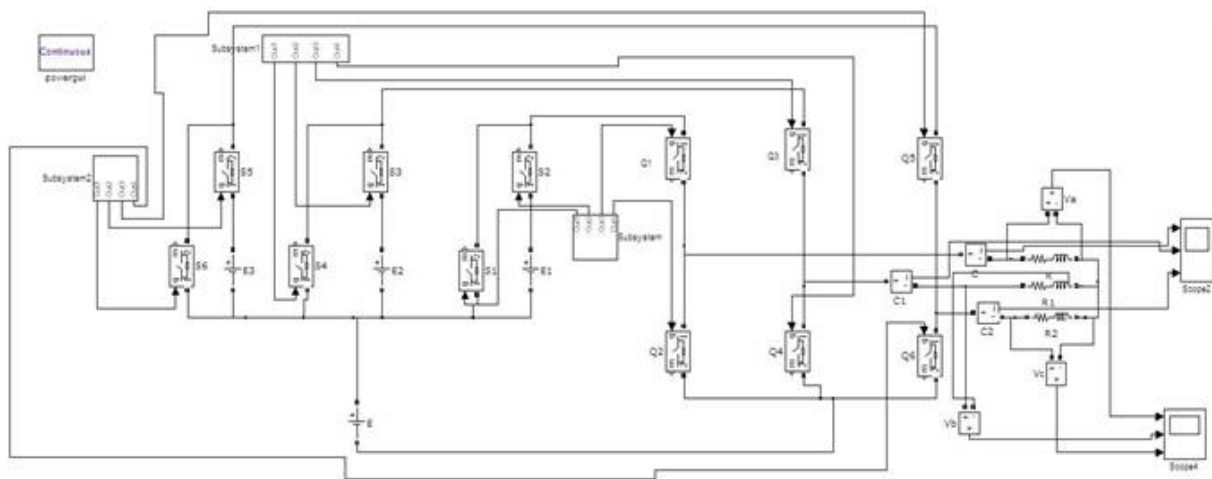


Fig:5 Simulation diagram for proposed MLI with scheme 1 switching signals

Fig:5 shows the prototype setup used for the proposed MLI, which includes four dc-power supplies, switching devices, measurement tools, the controller and three-phase resistive and inductive load ( $R=147\text{ohm}$ ,  $L=73\text{mH}$ ). This section demonstrates the control flexibility of the proposed based on single carrier based sinusoidal pulse width modulation technique. The key element in the generation of the output voltages wave forms is the pole voltages ( $V_{AO}$ ,  $V_{BO}$  and  $V_{CO}$ ). Each one of them is shifted by 120 in order to generate balanced three phase sinusoidal output voltages. The

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nonzero part determines the number of the utilized sources. Conventionally, generating the negative parts in the output voltage needs an H-bridge and as a direct result, the number of the used switches is increased. However, the proposed topology benefits from the zero part in the pole voltages waveform to produce the positive and negative parts in the output voltages waveforms. It achieved by subtracts each pole voltage with the neighboring one to produce the line voltage (as an example:  $V_{AB}=V_{AO}-V_{BO}$ ).

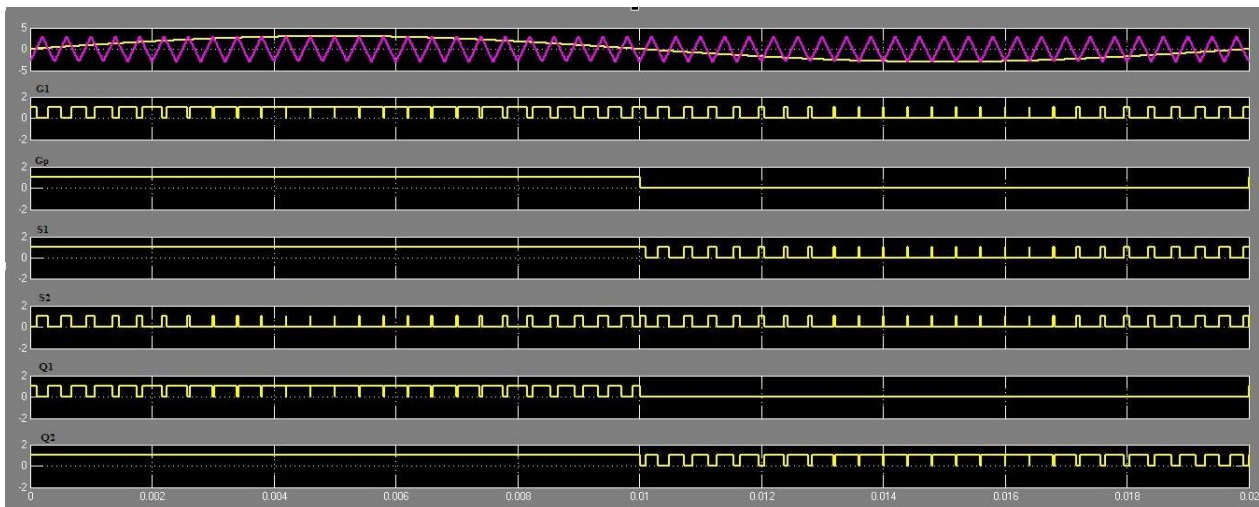


Fig:6 Simulated Switching pattern for scheme 1 modulation technique:

According to switching states provided in Table1 corresponding switching patterns are generated as shown in Fig.6, the suggested MLI produces three phase balancing line voltages, each line voltage has five levels and has a phase shift of 120 between each other. Also, as the pole voltages have three voltage levels (0,E,2E volts), the output line-to-line voltages have five voltages level (2E,E,0,-E,-2E volts). The phase voltages are deduced from the pole voltages: they produce seven levels on the output phase voltages i.e.,  $(E,(4/3)E,(2/3)E,0,-E,-(4/3)E,-(2/3)E$  volts). The simulation and experimental results of the output phase voltage and currents are shown in Fig.7 and Fig.8 respectively. It is notable that switching signals for S1, S2 cannot be operate simultaneously; the same criteria are applied to the switches Q1 and Q2.

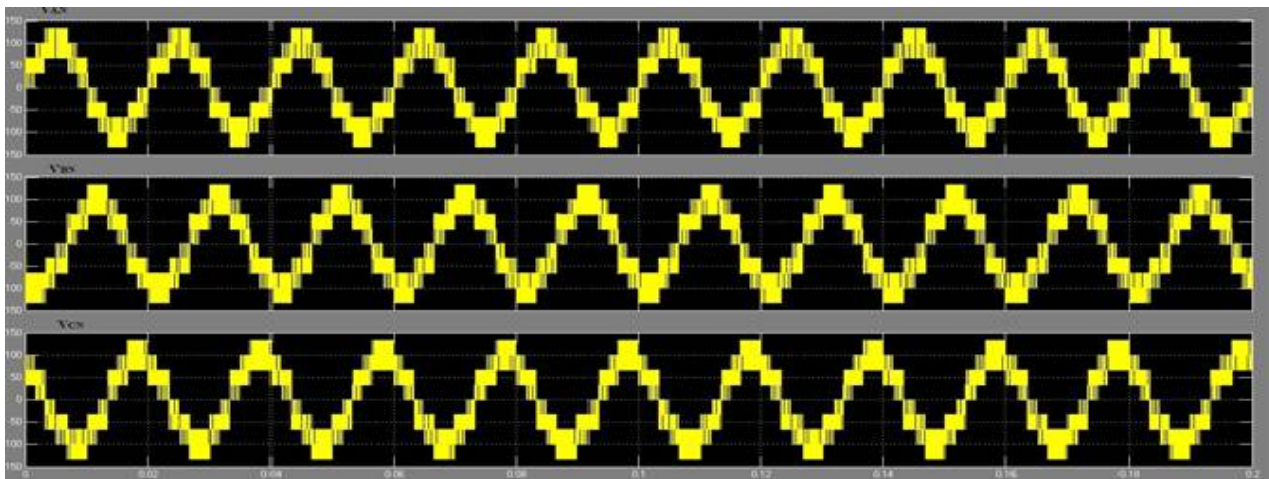


Fig: 7 Output phase voltages ( $V_{AN}, V_{BN}, V_{CN}$ ) of proposed MLI With scheme 1 modulation technique



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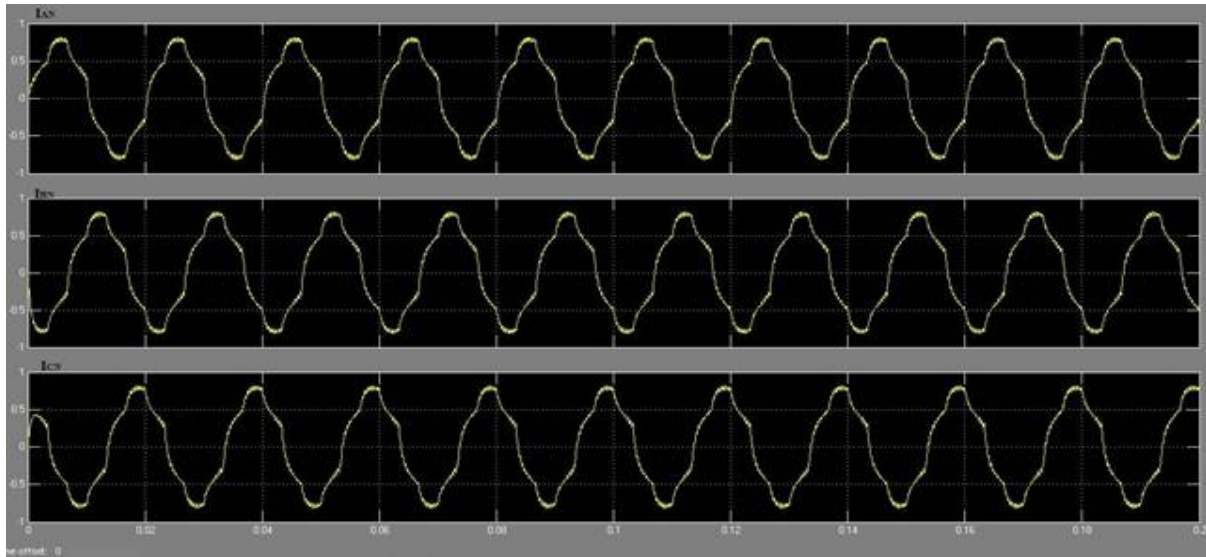


Fig:8 Output Phase Currents (IAN,IBN,ICN ) of proposed MLI With scheme 1 modulation technique.

Similarly, Fig. 9 shows the prototype setup used for the proposed MLI, which includes four dc-power supplies, switching devices, measurement tools, the controller and three-phase resistive and inductive load ( $R=147\text{ohm}$ ,  $L=73\text{mH}$ ). This section demonstrates the control flexibility of the proposed based on double carrier based sinusoidal pulse width modulation technique (i.e., for scheme 2). The simulation and experimental results of the output phase voltage and currents are shown in Fig.11 and Fig.12 respectively .It is notable that switching signals for S1, S2 cannot operate simultaneously; the same criteria are applied to the switches Q1 and Q2.

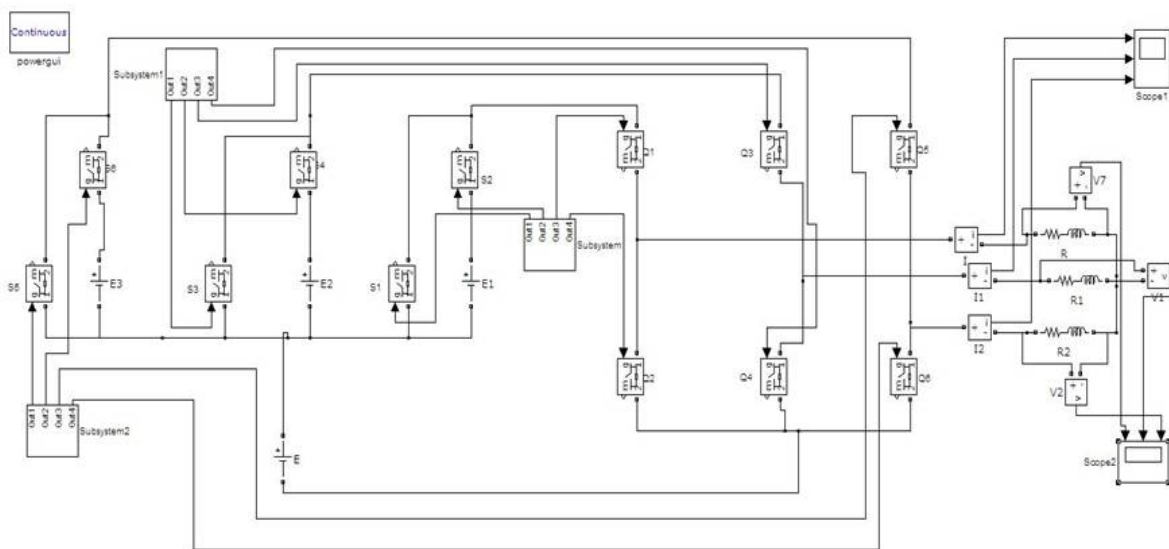


Fig:9 simulated Switching pattern for scheme 2 modulation technique:

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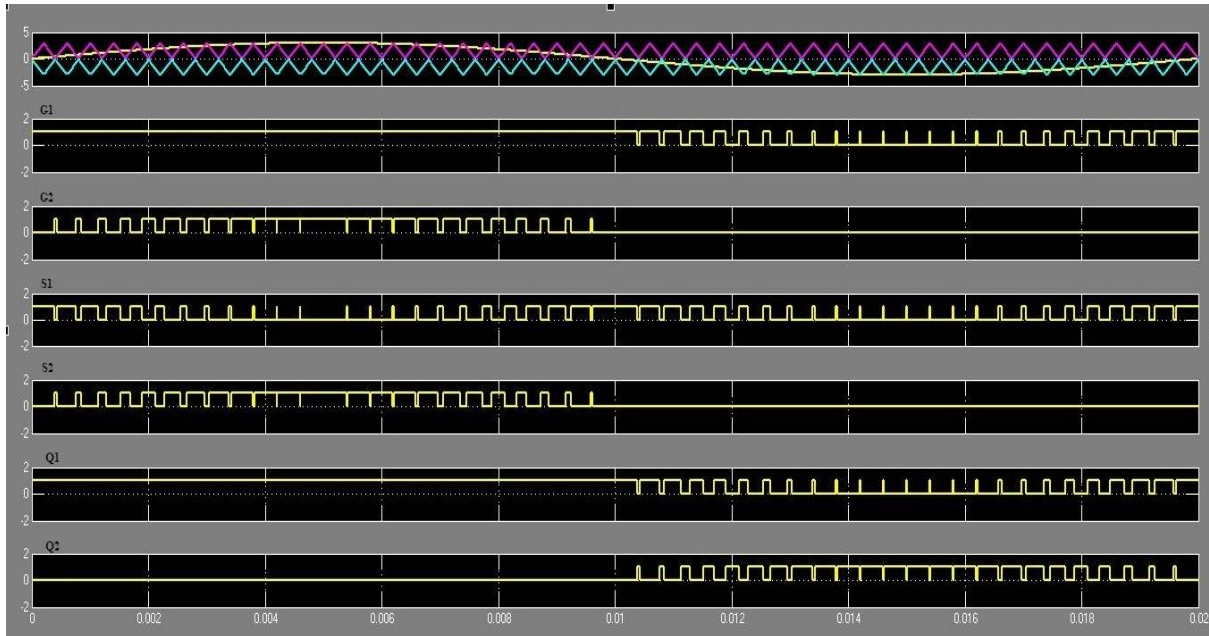


Fig:10 simulated Switching pattern for scheme 2 modulation technique.

According to switching states provided in Table1 corresponding signals are generated as shown in Fig.10, the suggested MLI produces three phase balancing line voltages, each line voltage has five levels and has a phase shift of 120 between each other. Also, as the pole voltages have three voltage levels (0,E,2E volts), the output line-to-line voltages have five voltages level (2E,E,0,-E,-2E volts). The phase voltages are deduced from the pole voltages: they produce seven levels on the output phase voltages i.e., (E,(4/3)E,(2/3)E,0,-E,-(4/3)E,-(2/3)E volts). The simulation and experimental results of the output phase voltage and currents are shown in Fig.11 and Fig.12. It is notable that switching signals for S1, S2 cannot operate simultaneously; the same criteria are applied to the switches Q1 and Q2.

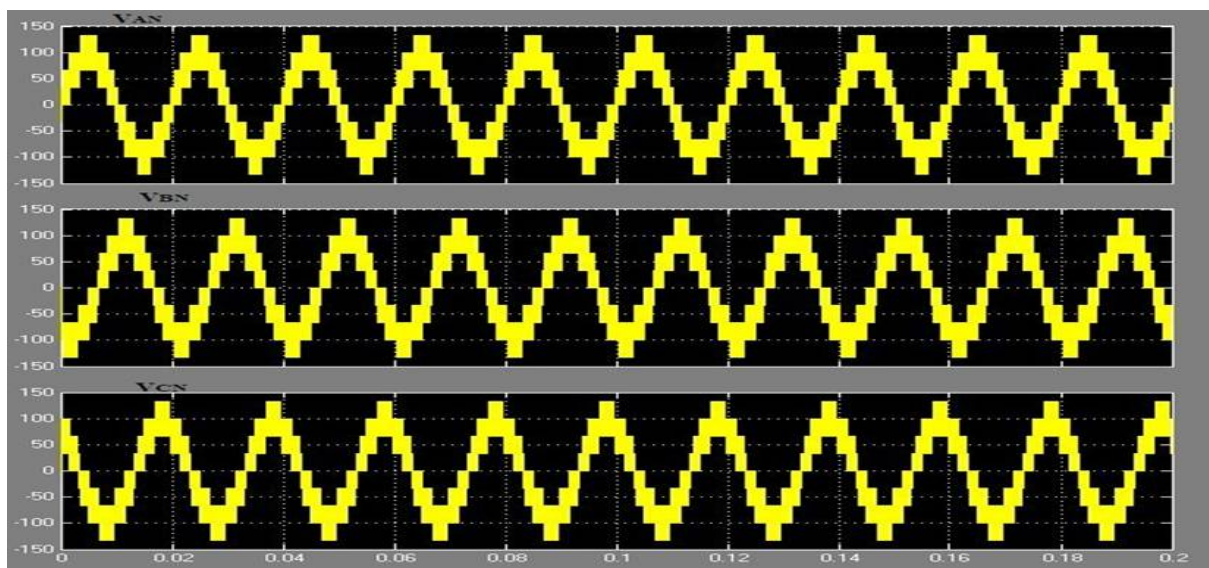


Fig:11 Output phase voltages (VAN,VBN,VCN) of proposed MLI With scheme 2 modulation technique

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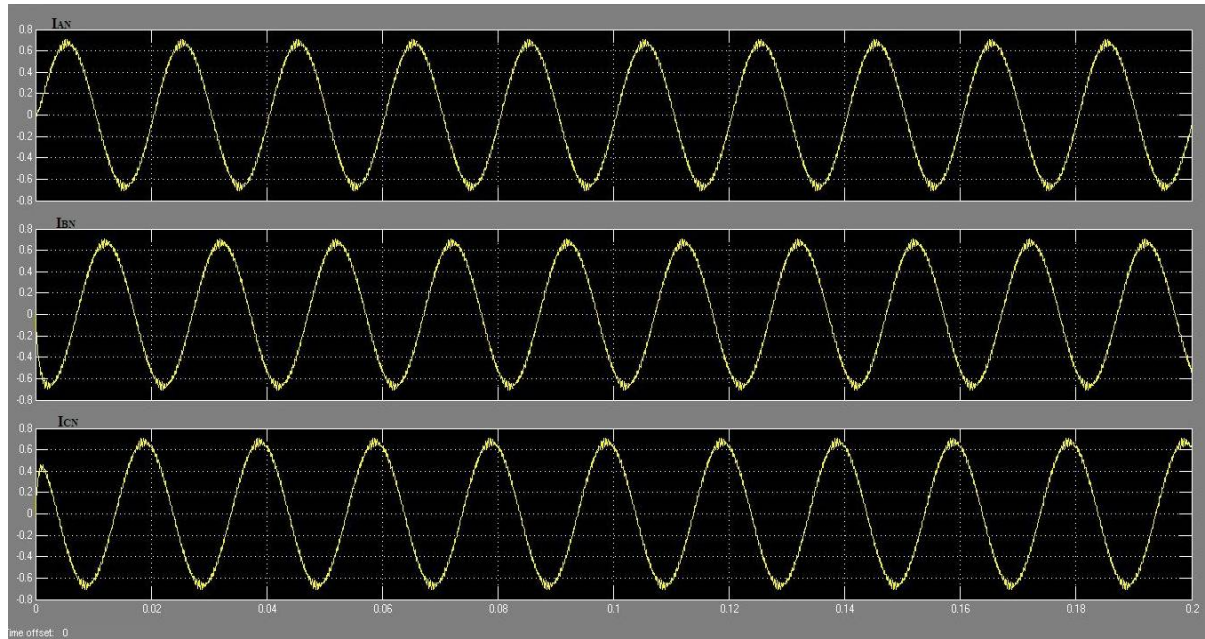


Fig:12 Output Phase Currents ( $I_{AN}, I_{BN}, I_{CN}$ ) of proposed MLI With scheme 2 modulation technique:

MLI has many advantages such as low distortion factor low  $dv/dt$  small output filter size, low electromagnetic interface and low total harmonic distortion. A Multilevel inverter utilize isolated dc source or a bank of series capacitors to produce ac voltage waveforms. The proposed topology compared to the present topologies provides a good solution from both system topology and control algorithm point of view. The problematic issues related to electrolytes capacitors and their voltages balancing have been eliminated. In addition, the path of load current has been shorted to pass through minimum power switches during zero voltage across the inverter pole. Therefore, the proposed inverter has better efficiency. Due to the modularity of the presented topology, it can be extended to higher stages number leads to a good performance and two SPW schemes are successfully applied to control the suggested MLI.

### □ Application- Simulation design of Multilevel STATCOM for Voltage Stability:

This paper deals with the design and implementation of a 5 level voltage source converter based static synchronous compensator (STATCOM), employing an effective modulation control technique (sinusoidal pulse width modulation) (SPWM) simulated in a MATLAB Simulink environment. The main objective of this project is to maintain the voltage stability in the power system. Hence, a new efficient 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 modeled and simulated using proposed control strategy and the performance is compared by applying it to a 110Kv line with and without STATCOM. The VSC uses forced commutated power electronics devices (GTO's or IGBT's) to synthesize the voltage from a dc voltage source.

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## A) Load Without STATCOM

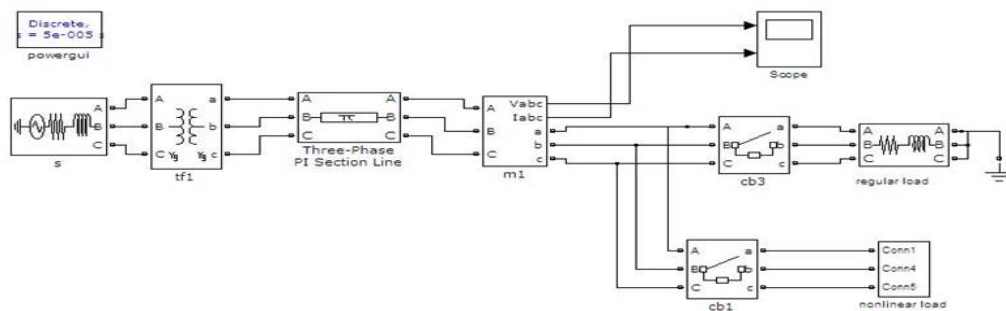


Fig:13 Simulation Diagram of load without STATCOM:

The simulation diagram for this model is shown in Fig. 13, consists of a three phase source (110Kv and 50 Hz). The transmission line is expanded for (100 Km) to reach the destination area. Source is connected to load/destination area through a step-down transformer of 110kv/415 rating. There are two different load connected to the transmission lines are regular inductive load ( $R= 300$  ohm and  $L= 1.537 \times 10^{-3}H$ ) and nonlinear load.

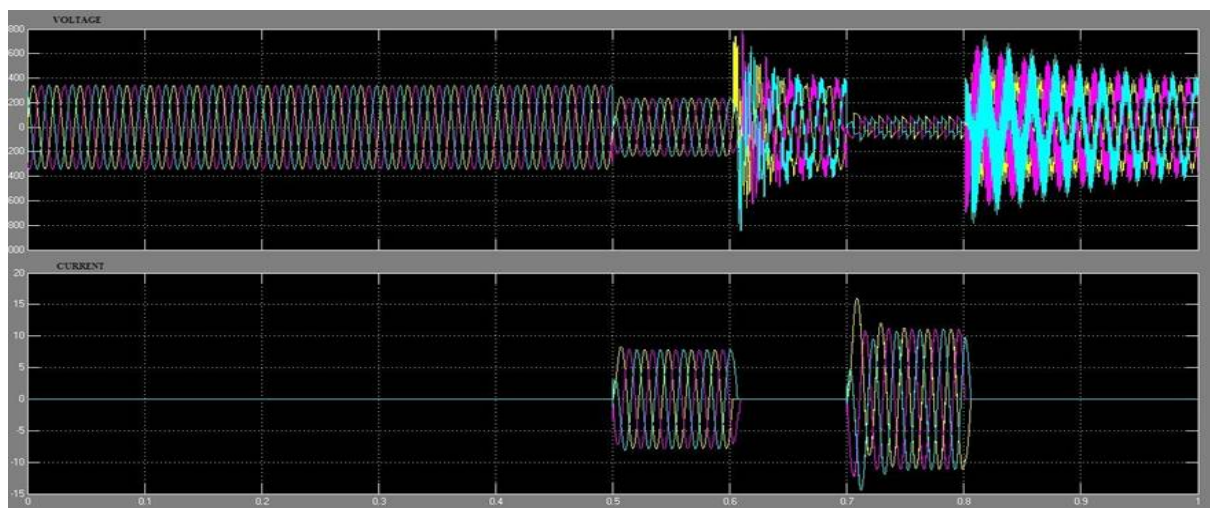


Fig:14 Voltage and Current waveforms at the load without STATCOM

Here we observe that the power transferred from generation unit through the transmission line and reach finally to the load are suffering from many disturbances leading to the sag and swell in the voltage in the transmission line. From the Fig. 14, it is observed that there exists voltage sag in the period of 0.5- 0.6. There is drop in magnitude of voltage in this region, whereas current in this period is increased depending on the regular RL load connected across it. During the

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period 0.6-0.7, fluctuations are observed due to sudden removal of regular inductive loads and current is zero as no load is applied in this period. In the period 0.7 -0.8, it is clearly seen that there is too sag condition in the voltage which occurred due to nonlinear load, whereas the current is increased in this region. In the period after 0.8 we observe huge fluctuations in voltage waveform due to sudden removal of nonlinear load.

## A) Load with STATCOM (Scheme 1)

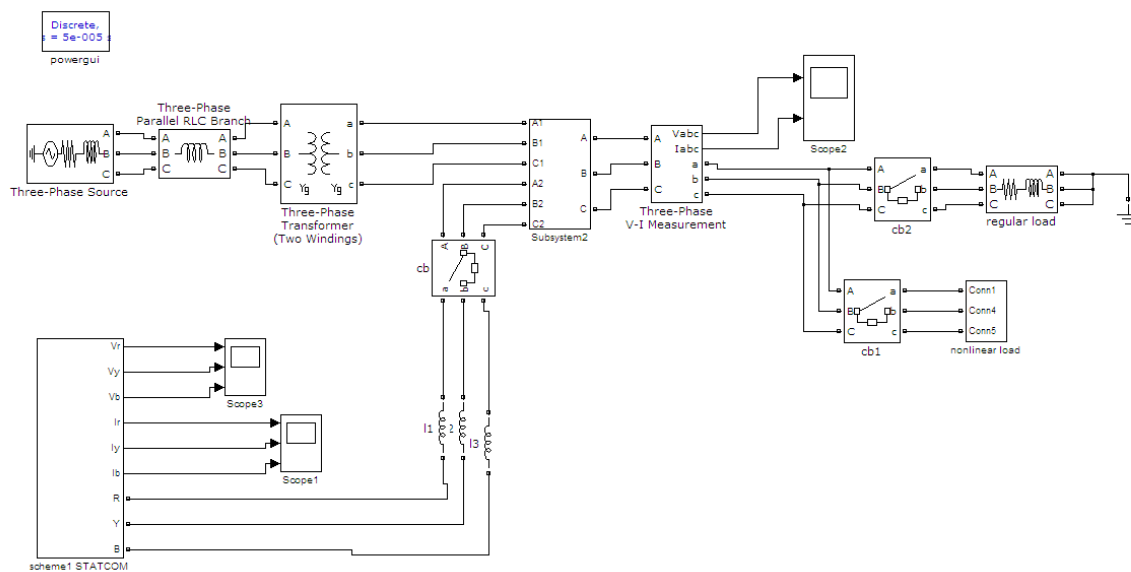


Fig:15 Simulation diagram of load with STATCOM for scheme 1

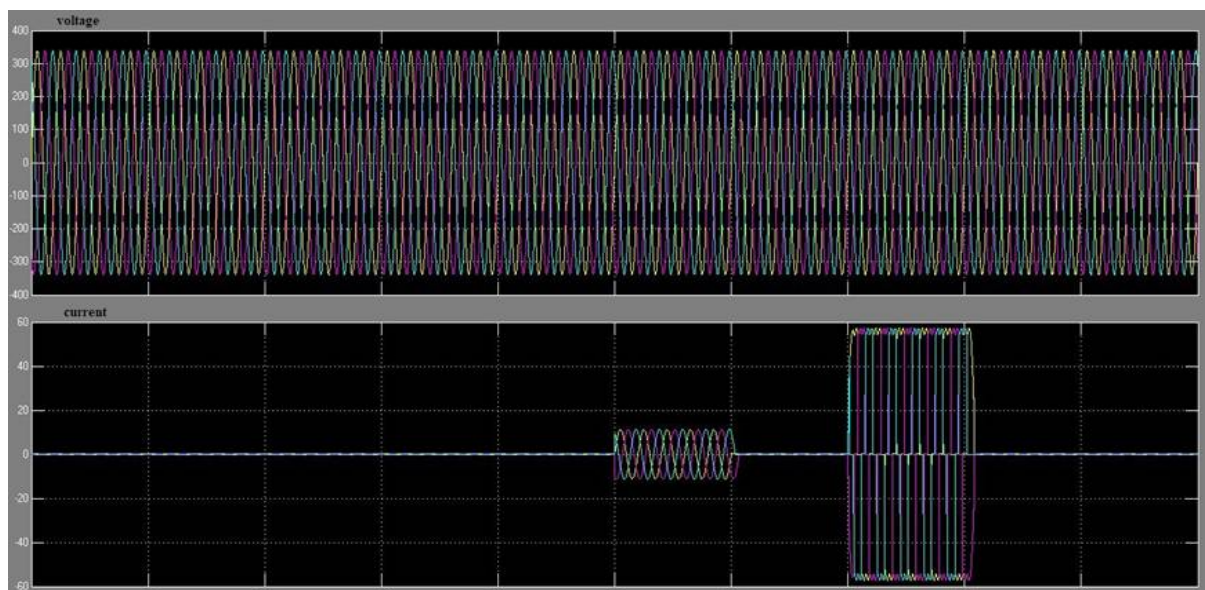


Fig: 16 Voltage and Current Waveforms at the load with STATCOM (scheme 1)

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The simulation diagram for this model is shown in Fig. 15, consists of a three phase source (110Kv and 50 Hz). The transmission line is expanded for (100 Km) to reach the destination area. Source is connected to load/destination area through a step-down transformer of 110kv/415 rating. There are two different loads connected to the transmission lines are regular inductive load ( $R= 300$  ohm and  $L= 1.537 \cdot 10^{-3}H$ ) and nonlinear load. The MLI based STATCOM (scheme 1) is connected across the system through transformer.

From the Fig. 16, it is observed that the voltage is uniform at all periods, whereas the current is varying based on the loads connected across it. Hence with the implementation of MLI based STATCOM for scheme 1, the cost of the system is reduced and the modulation techniques helps in achieving voltage stability by reducing harmonics.

## B) Load With STATCOM (Scheme 2)

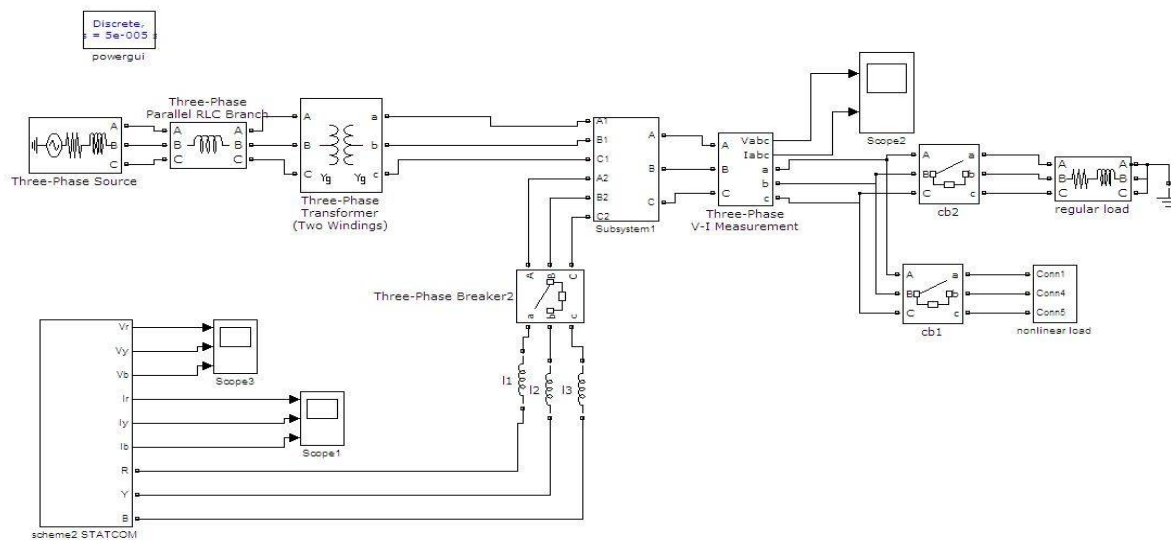


Fig:17 Simulation diagram of load with STATCOM for scheme 2

The simulation diagram for this model is shown in Fig. 17, consists of a three phase source (110Kv and 50 Hz). The transmission line is expanded for (100 Km) to reach the destination area. Source is connected to load/destination area through a step-down transformer of 110kv/415 rating. There are two different loads connected to the transmission lines are regular inductive load ( $R= 300$  ohm and  $L= 1.537 \cdot 10^{-3}H$ ) and nonlinear load. The MLI based STATCOM (scheme 2) is connected across the system through transformer.

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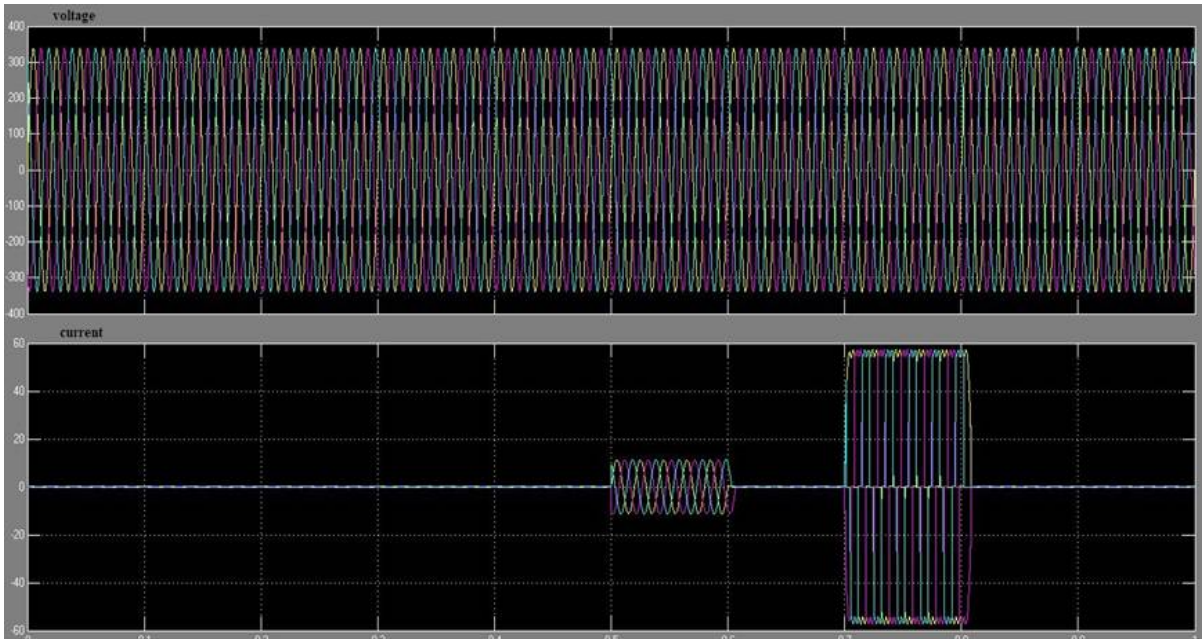


Fig:18 Voltage and Current Waveforms at the load with STATCOM (scheme 2)

From the Fig. 18, it is observed that the voltage is uniform at all periods, whereas the current is varying based on the loads connected across it similar to that of scheme 1. Hence with the implementation of MLI based STATCOM for scheme 2 the modulation techniques help in achieving voltage stability by reducing harmonics.

### V. CONCLUSION

A new modular multilevel inverter topology using two modulation control techniques is presented. The proposed MLI has several advantages compared with existing MLIs topologies. A lower number of components count such as isolated dc power supplies, switching devices, capacitor, power diodes are required. So it exhibits the merits of high efficiency, lower cost, simplified controlled algorithm, increased overall system reliability. Due to modularity of the presented topology, it can be extended to higher stages which leads to a good performance. In this paper, we successfully applied two SPW schemes to control the suggested MLI. This project presents the analysis of system performance with and without connecting STATCOM. The performance of system without system has voltage sag and swell, voltage harmonics at the load side whereas by connecting STATCOM, the voltage profile is maintained uniform. Hence the proposed symmetrical MLI based STATCOM is able to maintain uniform voltage profile under regular and nonlinear loads.

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