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PERFORMANCE ANALYSIS OF CASCADE MULTILEVEL INVERTER USING STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

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Abstract *— This Dissertation is dedicated to Performance analysis of cascade multilevel inverter using static synchronous compensator (STATCOM). The main object is maintaining the voltage stability and improves the power quality in the power system. Therefore a new control strategy is proposed in order to reduce the voltage fluctuation and also to minimize current and voltage harmonics in the transmission system. So in flexible AC Transmission systems (FACTS) controller, the STATCOM have shown easiest in terms of cost effectiveness in a wide range of problem solving abilities from transmission to distribution levels. A cascade multilevel inverter is power electronics device which convert DC voltage into desired AC voltage. A standard cascade multilevel inverter requires "n" DC source for 2n+1 level. To operate a high voltage application a large number of DC capacitors are utilized in a cascade multilevel inverter using STATCOM. To achieve a low distortion output voltage or a nearly sinusoidal output waveform, a triggering signal should be generated to control the switching frequency of each power semiconductor switch. The simulation results of MATLAB/SIMULINK model indicate the performance of the proposed control system as well as the precision of the proposed system.*

Key Words*: Cascade Multilevel inverter, STATCOM, SPWM Techniques, THD*

I. INTRODUCTION

Nowadays, Transformation has been introduced into the structure of electrical power utilities to improve efficiency of the power system networks by deregulating the industries and opening it to their competitors. This global trend and similar structural change has occurred elsewhere in other industries. The effect of such adjustments will mean that the generation, transmission and distribution systems must now built the new set of rules by open markets. Particular for this transmission sector of power utilities, this adaption may require the construction or modification of inter-connection between regions and countries. In more adaption the new generation patterns will necessitate changes and will require increased flexibility and availability of the transmission system. For these problems are the growing environmental concern and the constraints upon the rights-of way for new installations and facilities. Yet some more demands are continually being made upon utilities to supply increased loads to improve reliability and deliver energy at the lowest possible cost and with improved power quality. The power industry has responded to these challenges with the power electronics based technology of flexible AC transmission systems (FACTS). This term covers a whole family of power electronics controller, some of which may have achieved maturity within the industry, while some others are in the design stage [18]. Medium voltage motor drives and utility application require medium voltage and megawatt power level. For a medium voltage grid some problems occurred to connect only one power semiconductor switch directly. A result of multilevel power inverter structure has been introduced as an alternative in high power and medium voltage application. Multilevel inverters not only achieve high power ratings but also for the use of renewable energy sources. Renewable energy sources such as photovoltaic, wind and fuel cells can be easily provide to a multilevel converter system for a high power application. The concept of multilevel inverter has been introduced since 1975. The term multilevel begun with the three level inverters [1]. Furthermore several multilevel inverter topologies have been developed. The basic concept of a multilevel inverter to achieve higher power is to use a series of power semiconductor switches with lower voltages dc sources to perform the power conversion by converting a staircase voltage waveform. Capacitors, batteries and renewable energy voltage sources can be used as the multiple dc sources in order to achieve high voltage at the output; however the rated voltage of the power semiconductor switches depends only upon the rating of the dc voltage sources to which they are connected. Inverter convert DC power into AC power through waves called either sine wave or modified sine wave. Sine wave is typically found in power from a power plant. Modified sine waves are made to simulate sine waves. Inverter with modified sine waves works well for backup power in houses and are much less expensive. Although there are several types of inverters, all standard inverter use only one switch, or in other words one power circuit.

A. Multilevel Inverter

The converters have to be designed to obtain a quality output voltage or a current waveform with a minimum amount of ripple content. In high voltage and high power applications the conventional two level inverters have some limitations in operating at high frequency mainly due to switching losses and constraints of the power device ratings. Series and parallel combination of power switches in order to achieve the power handling voltages and currents. The conventional two level inverters produce THD levels around sixty percent even under normal operating conditions which are undesirable and cause more losses and other power quality problems too on the AC drives and utilities. For high voltage applications, two or more power switches can be connected in series in order to provide the desired voltage rating. However, the characteristics of devices of the same type are not identical. For the same OFF state current, their OFF state voltages differ. Even during the turn OFF of the switches the variations in stored charges cause difference in the reverse voltage sharing. The switch with the least recovered charge faces the highest transient voltage. For higher current application, the switches are connected in parallel, however because of uneven switch characteristics the load current is not shared equally. If a power switch carries more current than that of the others, then the power dissipation in it increases, thereby increasing the junction temperature and decreasing the internal resistance. This in turn increases its current sharing and may damage the devices permanently which is undesirable for critical applications. The multilevel inverters perform power conversion in multilevel voltage steps to obtain improved power quality, lower switching losses, better electromagnetic compatibility and higher voltage capability. Considering these advantages, multilevel inverters have been gaining considerable popularity in recent years [14].

B. Cascade Multilevel Inverter

A cascaded multilevel inverter consists of a series of H-bridge (single-phase full-bridge) inverter units. The general function of this multilevel inverter is to synthesize a desired voltage from several separate dc sources (SDCS's), which may be obtained from batteries, fuel cells, or solar cells.

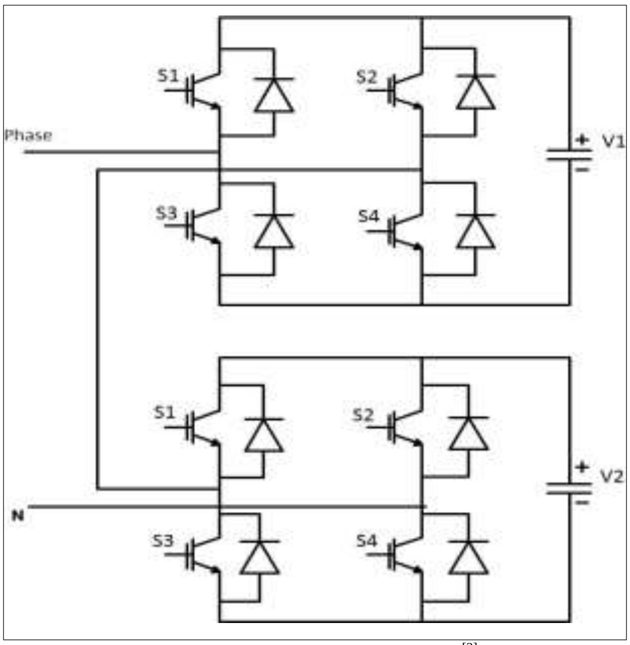


Figure 1.Cascade multilevel inverter [3]

Figure 1.Shows a single-phase structure of a cascade inverter with SDCS's. Each SDCS is connected to a single-phase full bridge inverter. Each inverter level can generate three different voltage outputs, +Vdc , 0 and -Vdc, by connecting the dc source to the ac output side by different combinations of the four switches, S1, S2, S3 and S4. To obtain +Vdc, switches S1and S4 are turned on. Turning on switches S2 and S3 yields. By turning on S1 and S2or S3 and S4, the output voltage is 0.The ac outputs of each of the different level full-bridge inverters are connected in series such that the synthesized voltage waveform is the sum of the inverter outputs. The number of output phase voltage levels in a cascade inverter is defined by m=2s+1, where S is the number of dc sources [3].

II. STATCOM

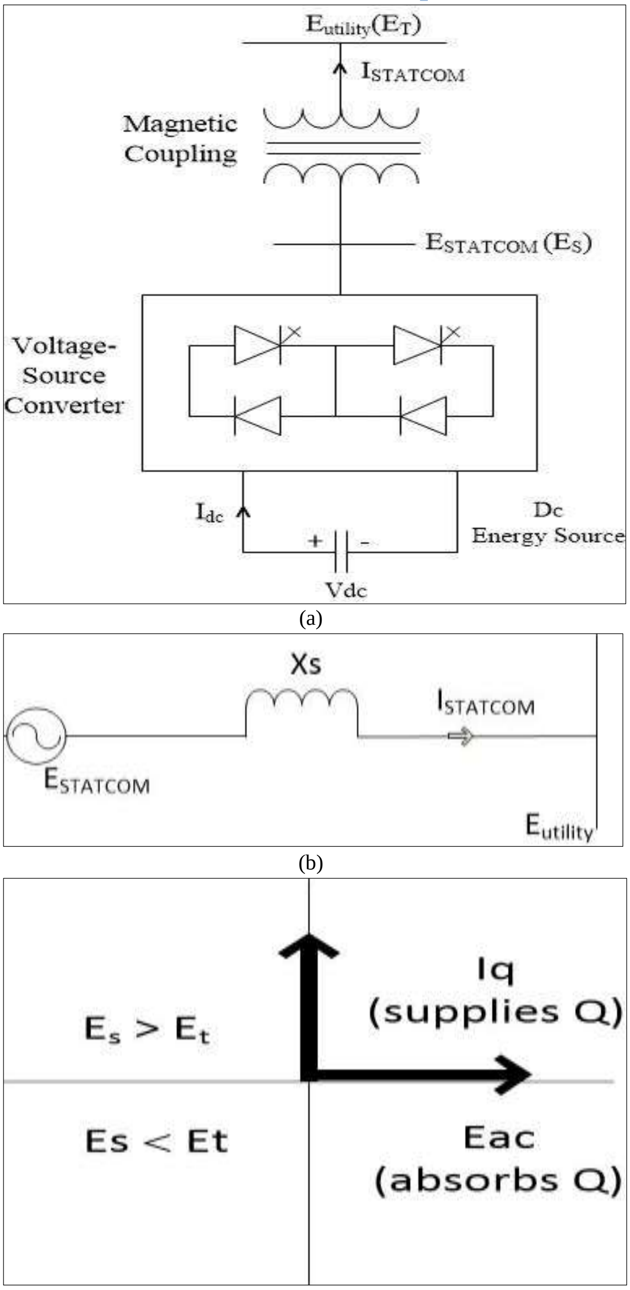
The STATCOM (or SSC) is a shunt-connected reactive-power compensation device that is capable of generating and/or absorbing reactive power and in which the output can be varied to control the specific parameters of an electric power system. It is in general a solid-state switching converter capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an energy source or energy-storage device at its input terminals. Specifically, the STATCOM considered in this chapter is a voltage-source converter that, from a given input of dc voltage, produces a set of 3-phase ac-output voltages, each in phase with and coupled to the corresponding ac system voltage through a relatively small reactance (which is provided by either an interface reactor or the leakage inductance of a coupling transformer). The dc voltage is provided by an energy-storage capacitor. A STATCOM can improve power-system performance in such areas as the following:

- The dynamic voltage control in transmission and distribution systems;
- The power-oscillation damping in power-transmission systems;
- The transient stability;
- The voltage flicker control; and
- The control of not only reactive power but also (if needed) active power in the connected line, requiring a dc energy source.

A STATCOM is analogous to an ideal synchronous machine, which generates a balanced set of three sinusoidal voltages at the fundamental frequency with controllable amplitude and phase angle. This ideal machine has no inertia, is practically instantaneous, does not significantly alter the existing system impedance, and can internally generate reactive (both capacitive and inductive) power [16].

A. CONSTRUCTION AND OPERATION

A STATCOM is a controlled reactive-power source. It provides the desired reactive-power generation and absorption entirely by means of electronic processing of the voltage and current waveforms in a voltage-source converter (VSC). A single-line STATCOM power circuit is shown in (a), where a VSC is connected to a utility bus through magnetic coupling. In Fig.(b), a STATCOM is seen as an adjustable voltage source behind a reactance meaning that capacitor banks and shunt reactors are not needed for reactive-power generation and absorption, thereby giving a STATCOM a compact design, or small footprint, as well as low noise and low magnetic impact[15].



(a) (b) (c)

Figure 2.The STATCOM principle diagram: (a) a power circuit; (b) an equivalent circuit; and (c) a power exchange [15]

The exchange of reactive power between the converter and the ac system can be controlled by varying the amplitude of the 3-phase output voltage, Es, of the converter, as illustrated in Figure (c). That is, if the amplitude of the output voltage is increased above that of the utility bus voltage, Et, then a current flow through the reactance from the converter to the ac system and the converter generates capacitive-reactive power for the ac system. If the amplitude of the output voltage is decreased below the utility bus voltage, then the current flows from the ac system to the converter and the converter absorbs inductive-reactive power from the ac system. If the output voltage equals the ac system voltage, the reactive-power exchange becomes zero, in which case the STATCOM is said to be in a floating state. Adjusting the phase shift between the converter output voltage and the ac system voltage can similarly control real power exchange between the converter and the ac system. In other words, the converter can supply real power to the ac system from its dc energy storage if the converter output voltage is made to lead the ac-system voltage. On the other hand, it can absorb real power from the ac system for the dc system if its voltage lags behind the ac- system voltage. A STATCOM provides the desired reactive power by exchanging the instantaneous reactive power among the phases of the ac system. The mechanism by which the converter internally generates and/or absorbs the reactive power can be understood by considering the relationship between the output and input powers of the converter. The converter switches connect the dc-input circuit directly to the ac-output circuit. Thus the net instantaneous power at the ac output terminals must always be equal to the net instantaneous power at the dc input terminals (neglecting losses). Assume that the converter is operated to supply reactive-output power. In this case, the real power provided by the dc source as input to the converter must be zero. Furthermore, because the reactive power at zero frequency (dc) is by definition zero, the dc source supplies no reactive power as input to the converter and thus clearly plays no part in the generation of reactive-output power by the converter. In other words, the converter simply interconnects the three output terminals so that the reactive-output currents can flow freely among them. If the terminals of the ac system are regarded in this context, the converter establishes a circulating reactive-power exchange among the phases. However, the real power that the converter exchanges at its ac terminals with the ac system must, of course, be supplied to or absorbed from its dc terminals by the dc capacitor[15].

III. BLOCK DIAGRAM AND STATCOM CONTROLLER

A Block Diagram of cascade multilevel inverter using STATCOM is shown in the below figure

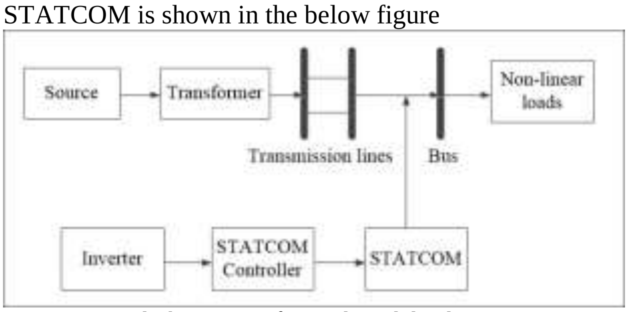


Figure 3.Block Diagram of Cascade Multilevel Inverter using STATCOM [12]

Here the source are connected to the transformer and nonlinear load are connected to the transformer threw the transmission lines. In the diagram STATCOM controller connected with the transmission line in parallel also inverter connected to STATCOM control.

A. STATCOM CONTROLLER

The main objective for control of STATCOM is to improve the power transmission by injective or absorbing reactive power to or from the grid. The basic control method used for the proposed STATCOM controller is direct control. In this method reactive output current can be controlled directly by the internal voltage control device of the converter in which the internal dc voltage is kept constant. The STATCOM is controlled to deliver whichever inductive or capacitive currents to the power system by varying the output voltages V_a, V_b and V_c. in the design of the STATCOM controller, the three phase quantity (voltage and current) are first transfer into direct and quadrature components. Then, a current regulator is employed for the current control and 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 figure 4 shown a transient modulation index controller and a steady state modulation index regulator are proposed to achieve the goal the goals of good transient response and minimal steady state harmonics respectively. Detail for the design of transient modulation index controller, steady state modulation index regulator, phase locked loop(PLL), abc to dq0transformation, AC voltage controller, current regulator, PWM generator are describe below:

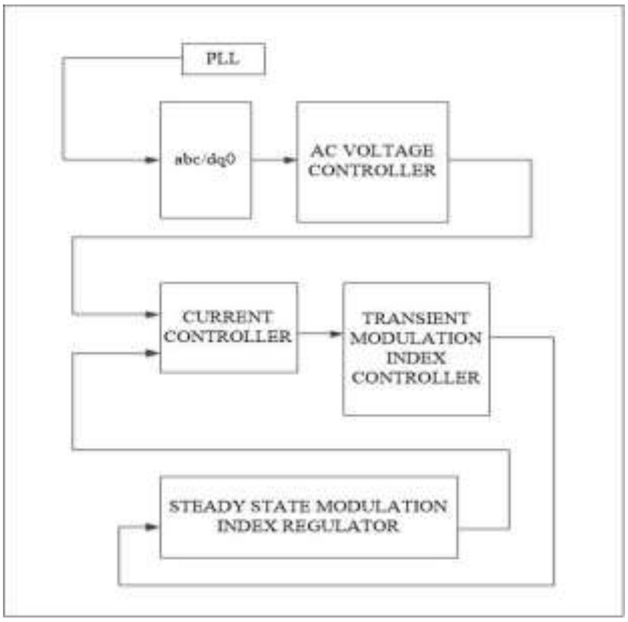


Figure 4.STATCOM Controller

PLL:

The PLL provides the basic coordinating signal which is the phase angle of the bus. In the case of a sudden change in the power system, such has 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 changed. Depending on the amount of phase angle change and whether it is increased or decreased, a controlled 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 instant.

abc to dq0Transformation:

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.

$V_d =$

$$\frac{2}{3}[Va\sin(wt) + Vb\sin\left(wt - \frac{2\pi}{3}\right) + Vc\sin(wt + \frac{2\pi}{3})]$$

(1)

$V_q=$

$$\frac{2}{3}[Va\cos(wt) + Vb\cos\left(wt - \frac{2\pi}{3}\right) + Vc\cos\left(wt + \frac{2\pi}{3}\right)]$$

(2)

$$V_0=\frac{1}{3}[Va + Vb + Vc \qquad (3)$$

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

AC Voltage Controller and Current Regulator:

The AC Voltage controller converters V_d, V_q into reference reactive current I_q^* using appropriate PI using appropriate PI controller as shown in figure 5.2.

$$I_q^* = G_1(s)\,[V_{rms} - V_{rms}^*] \qquad (4)$$

$$G_1(s) = k1 + \frac{k2}{s} \qquad (5)$$

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.

$$E_d^* = -wL_fI_q + V_{dc} - X_1 \qquad (6)$$

Where

$$X_1 = G_2(s)[I_d^* - I_d] \qquad (7)$$

$$G_2(s) = k3 + \frac{k4}{s} \qquad (8)$$

Where

L_f is leakage inductance

V_{dc} is capacitor voltage

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.

Steady-state Modulation-Index Regulator:

It has also been observed that a lower modulation index would give more harmonics 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 to the pre-set value at steady state through the action of a PI controller. As shown in figure 5.2, the real current reference I_d^* is generated by the proposed steady-state modulation-index regulator as given in below equation

$$I_d^* = G_3(S)\,[MI^* - MI] \qquad (9)$$

$$G_3 = K5 + \frac{K6}{s} \qquad (10)$$

Using the proposed steady-state modulation-index regulator and transient modulation index controller, the advantage of minimal harmonics can be retained under steady state situation. 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 effects on steady-state harmonics 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 periods, the STATCOM output voltage $|V_2|$ and reactive power Q can be modulated in a very quick manner.

PI Controller:

PI controller generates a gated command to operate the converters and to compensate the error, which has been calculated by compering defined values against measured values for both reactive and real power. 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 operation under any system contingency [8].

IV. SIMULATION WORK

Simulink model, results and FFT analysis of two-level inverter using ideal switch with PWM:

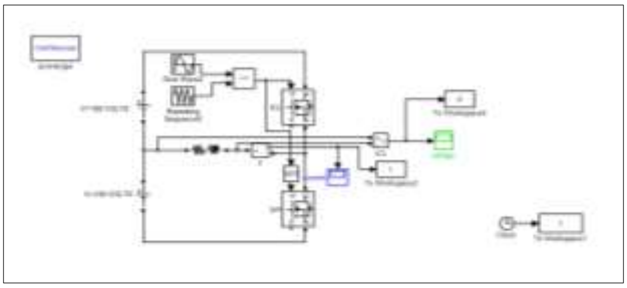


Figure 5.Simulink model of two level inverter using IGBT

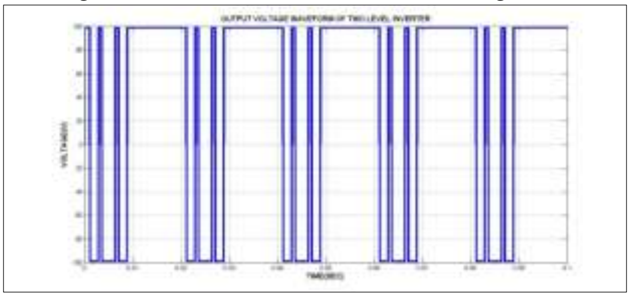


Figure 6.Output of two level inverter using IGBT

Simulink model, results and FFT analysis of third level inverter using IGBT with PWM:

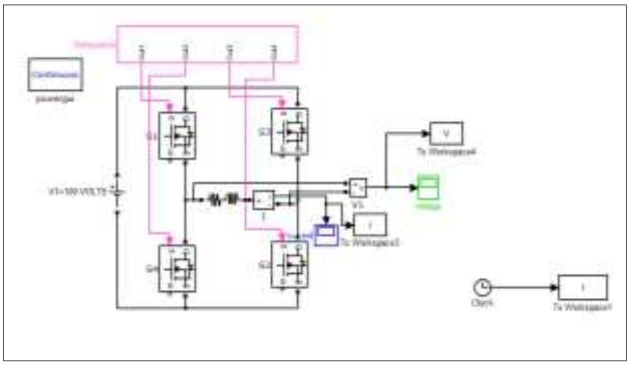


Figure7.Simulink model of three level inverter using IGBT

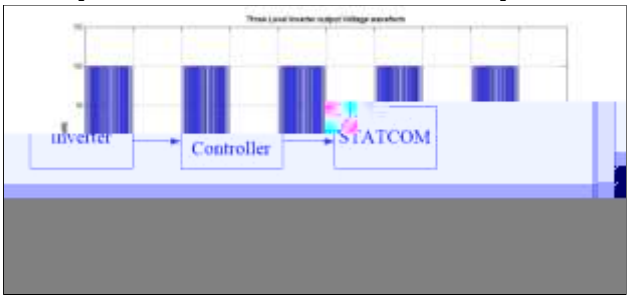


Figure 8.Output voltage waveform of third level inverter using PWM for IGBT

Figure 9.Output current waveform of single phase three level inverter

Figure 10 FFT Analysis for output voltage of three level inverter

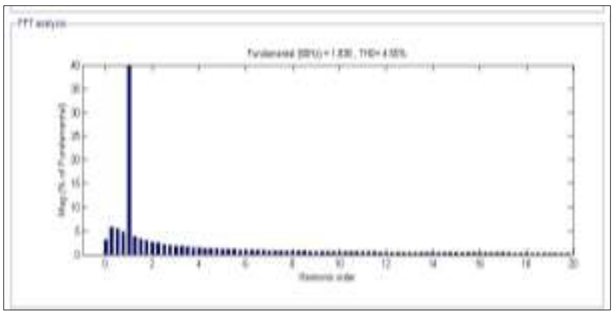


Figure 11 FFT Analysis for output current of three level inverter

Simulink model, results and FFT analysis of three phase five level inverter using IGBT with PWM:

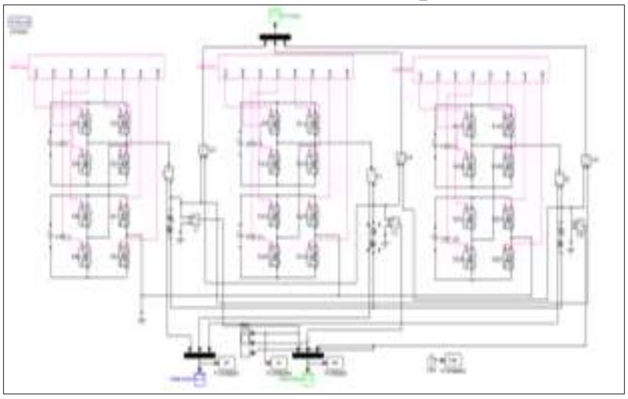


Figure 12.Simulink model of five level inverter using PWM for IGBT

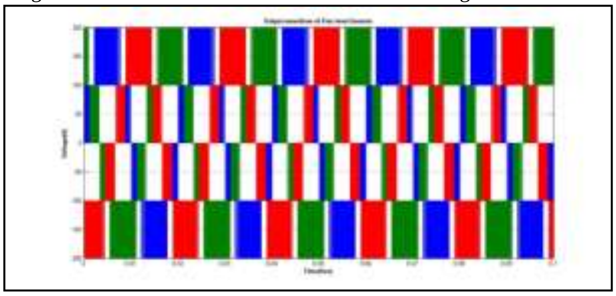


Figure 13.Output of five level inverter using PWM for IGBT

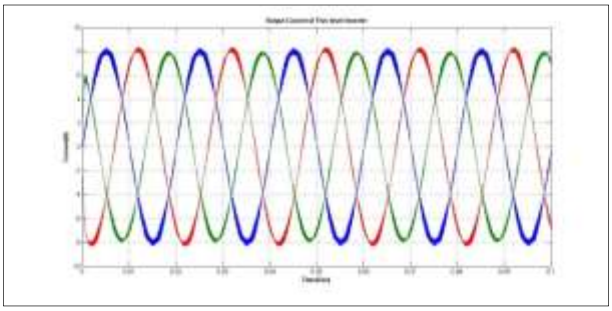


Figure 14 Output current waveform of five level cascade inverter using IGBT

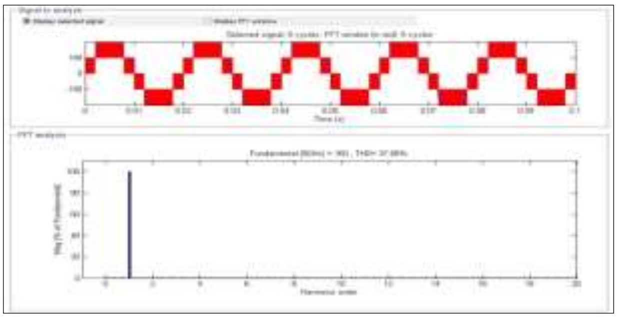


Figure 15 FFT Analysis for output voltage of five level cascade inverter using IGBT for phase- A

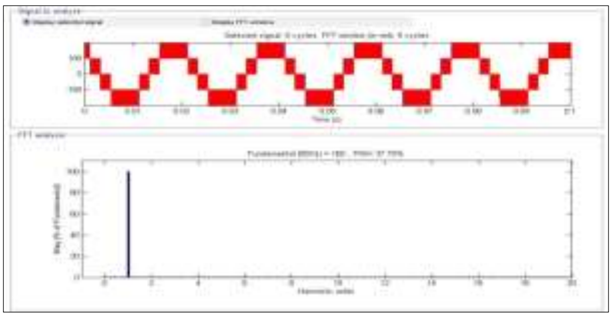


Figure 16 FFI Analysis for output voltage of five level cascade inverter using IGBT for Phase- B

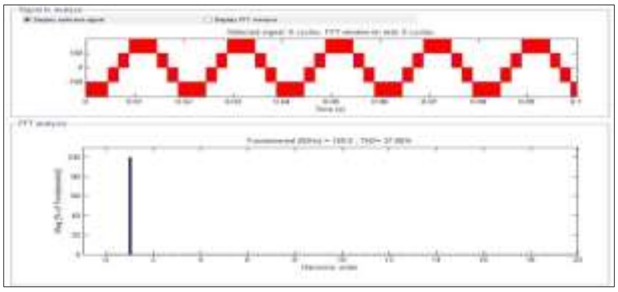


Figure 17 FFT Analysis for output voltage of five level cascade inverter using IGBT for Phase- C

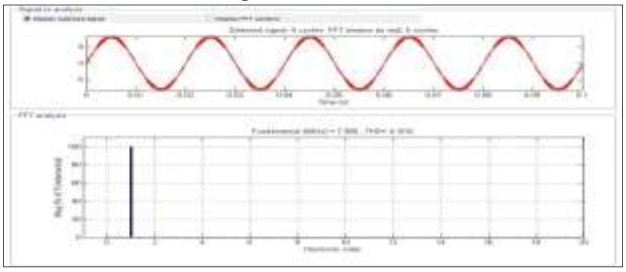


Figure 18 FFT Analysis for output current of five level cascade inverter using IGBT for phase- A

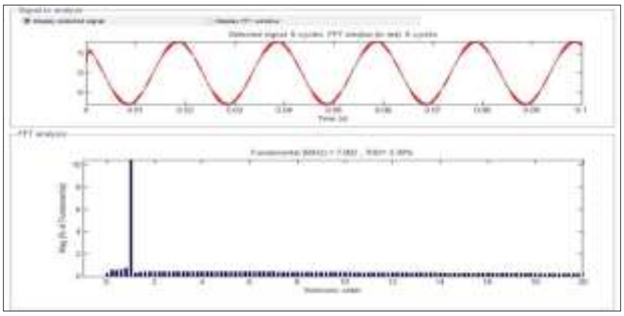


Figure 19 FFT Analysis for output current of five level cascade inverter using IGBT for phase- B

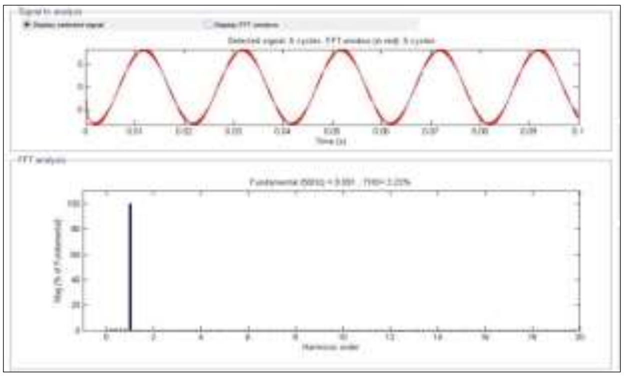


Figure 20 FFT Analysis for output current of five level cascade inverter using IGBT for phase- C

Simulink model, results and FFT analysis of three phase seven level inverter using IGBT with PWM:

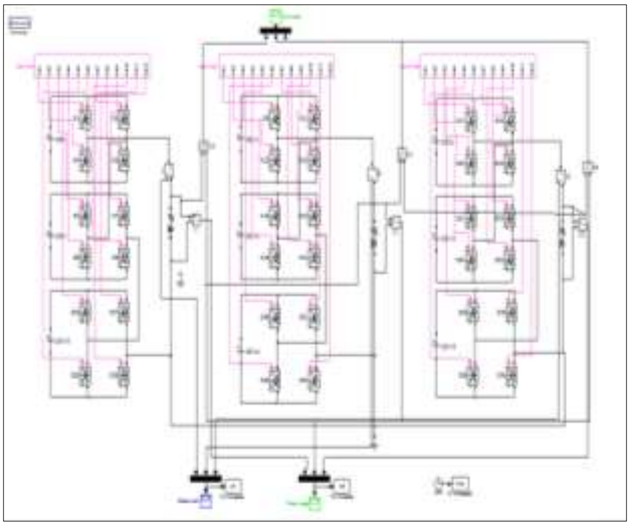


Figure 21 Simulink model of seven level inverter using PWM for IGBT

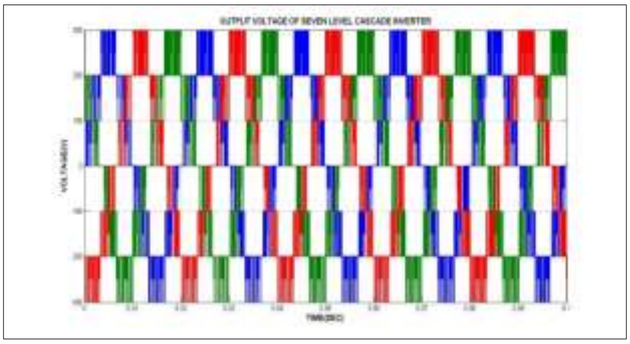


Figure 22 Output of Seven level inverter using PWM for IGBT

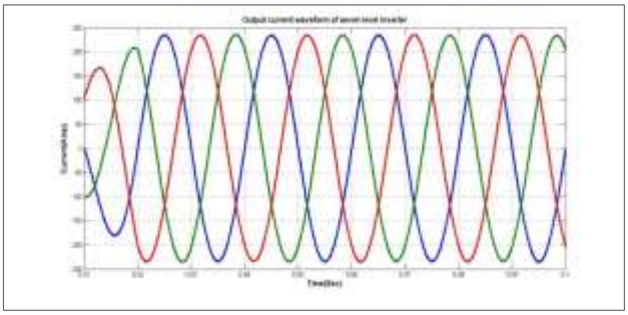


Figure 23 Output current waveform of three phase seven level cascade inverter using IGBT

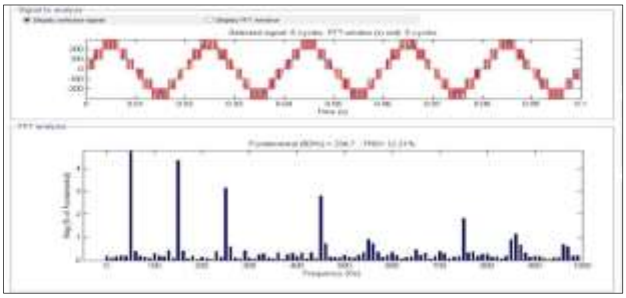


Figure 24 FFT Analysis for output voltage of seven level cascade inverter using IGBT for phase- A

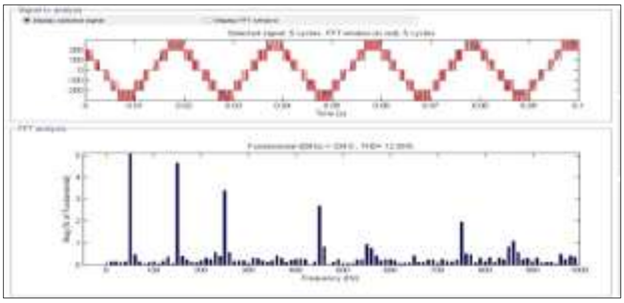


Figure 25 FFT Analysis for output voltage of seven level cascade inverter using IGBT phase- B

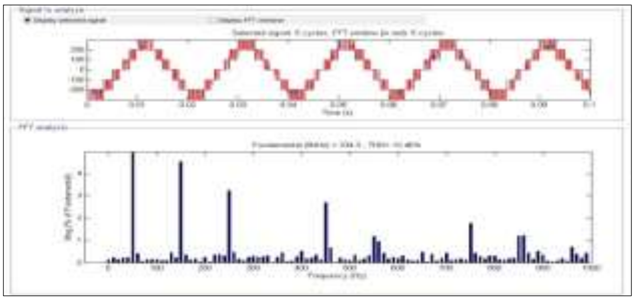


Figure 26 FFT Analysis for output voltage of seven level cascade inverter using IGBT for phase- C

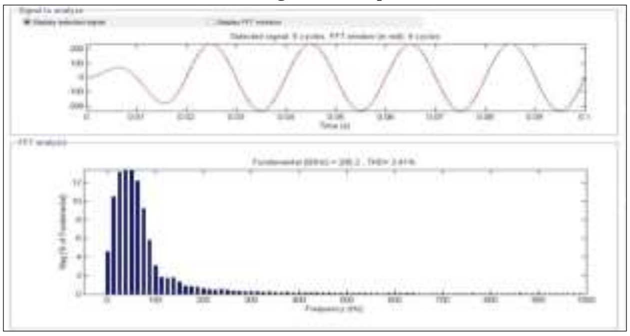


Figure 27 FFT Analysis for output current of seven level cascade inverter using IGBT for phase- A

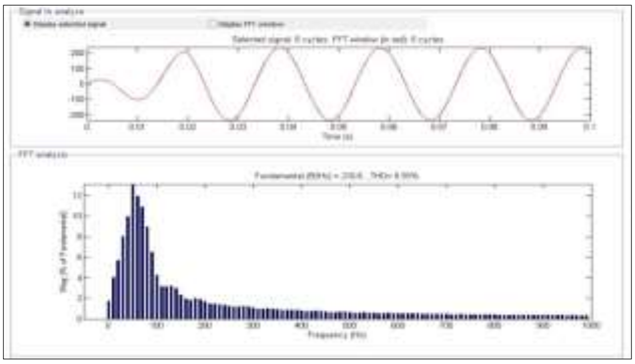


Figure 28 FFT Analysis for output current of seven level cascade inverter using IGBT for phase- B

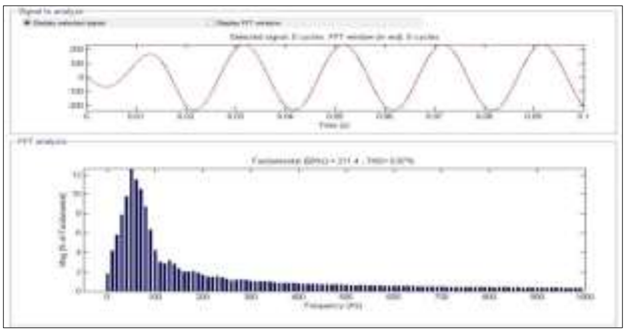


Figure 29 FFT Analysis for output current of seven level cascade inverter using IGBT for phase-C

Simulink model of power system without STATCOM

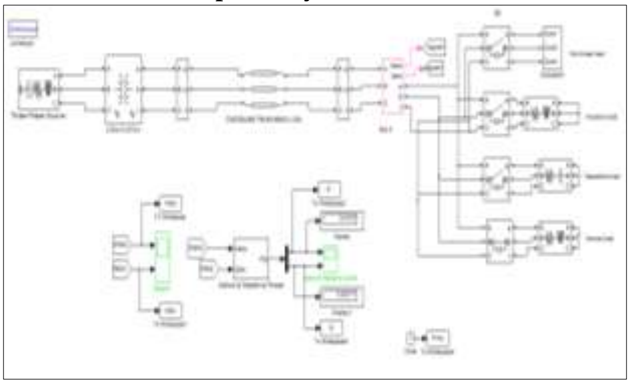


Figure 30 Simulink model of power system without STATCOM

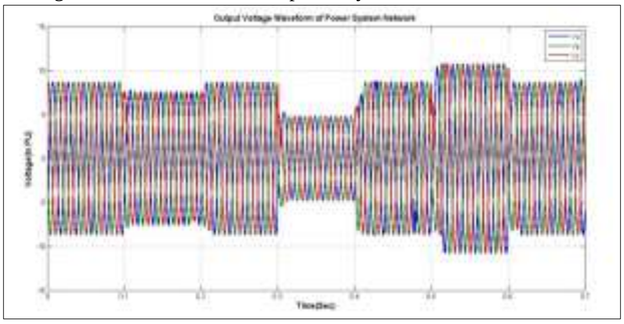


Figure 31 Output voltage and current of power system without STATCOM

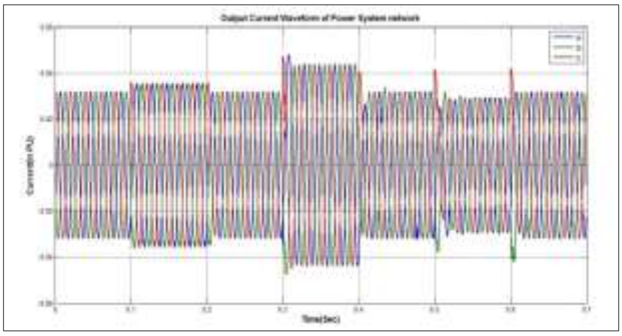


Figure 32 Simulation result of output current for power system network without STATCOM

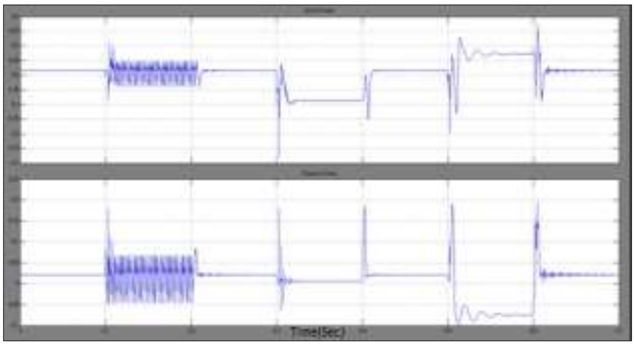


Figure 33 Simulation result of Active and Reactive power for power system network without STATCOM

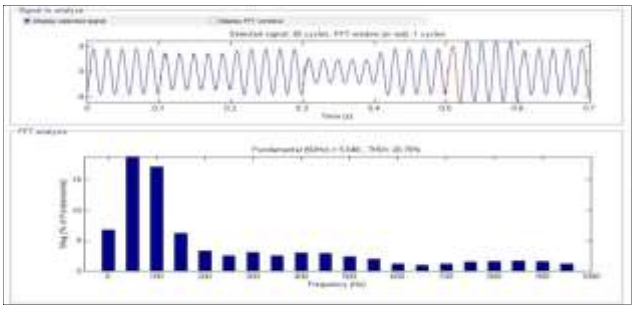


Figure 34 FFT Analysis for output voltage waveform of power system network without STATCOM for phase-A

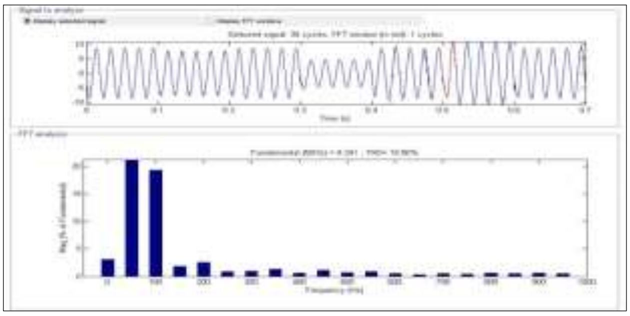


Figure 35 FFT Analysis for output voltage waveform of power system network without STATCOM for phase- B

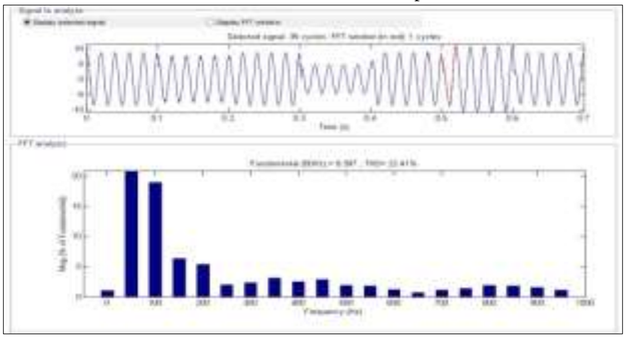


Figure 36 FFT Analysis for output voltage waveform of power system network without STATCOM for phase- C

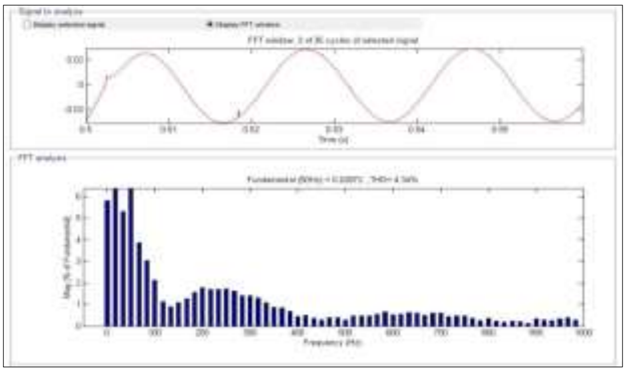


Figure 37 FFT Analysis for output current waveform of power system network without STATCOM for phase- A

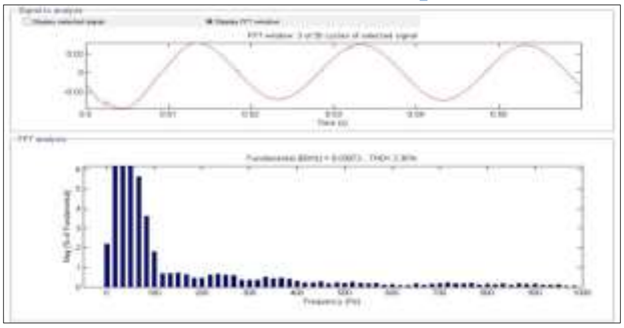


Figure 38 FFT Analysis for output current waveform of power system network without STATCOM for phase- B

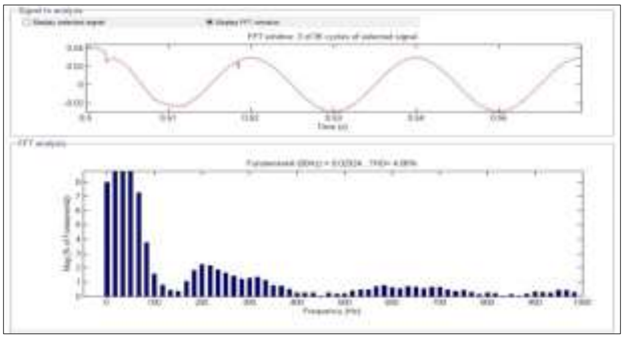


Figure 39 FFT Analysis for output current waveform of power system network without STATCOM for phase- C

Simulink model, results and FFT analysis of three phase five level inverter using STATCOM:

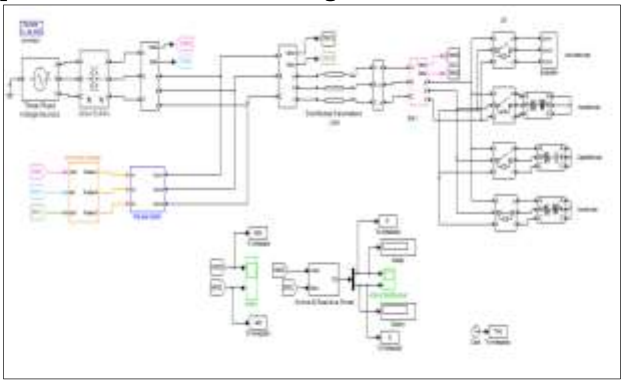


Figure 40 Simulink model of five level inverter using STATCOM

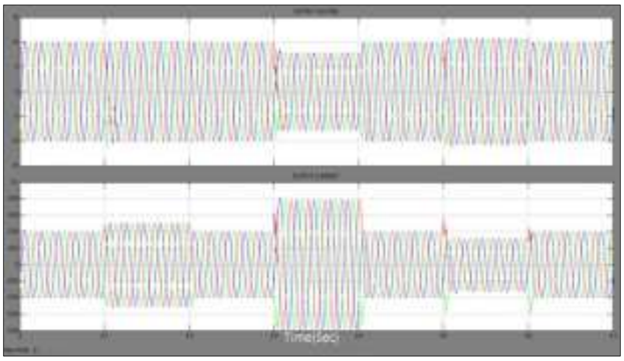


Figure 41 Output voltage and output current waveform of five level cascade inverter using STATCOM

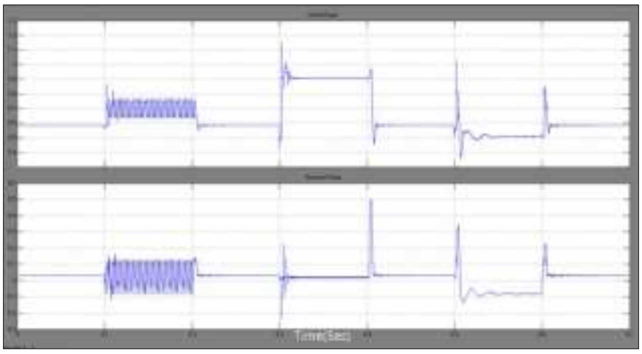


Figure 42 Active and reactive power waveform of five level cascade inverter using STATCOM

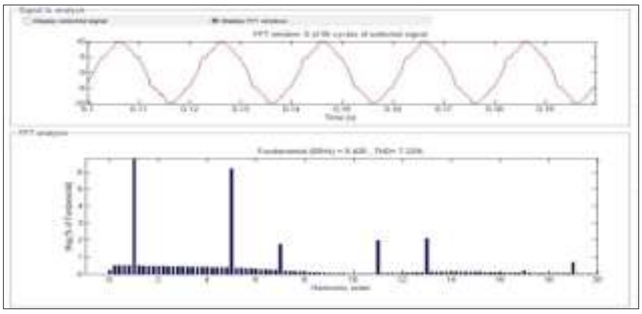


Figure 43 FFT Analysis of output voltage waveform for five level inverter using STATCOM for phase- A

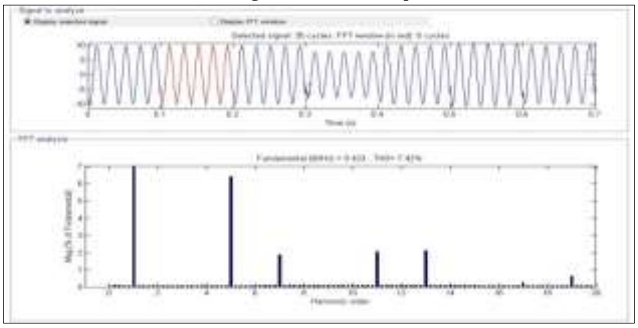


Figure 44 FFT Analysis of output voltage waveform for five level inverter using STATCOM for phase- B

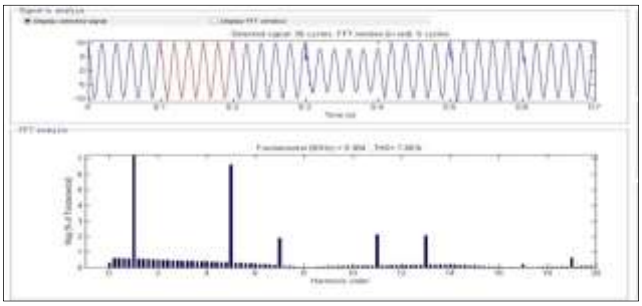


Figure 45 FFT Analysis of output voltage waveform for five level cascade inverter using STATCOM phase- C

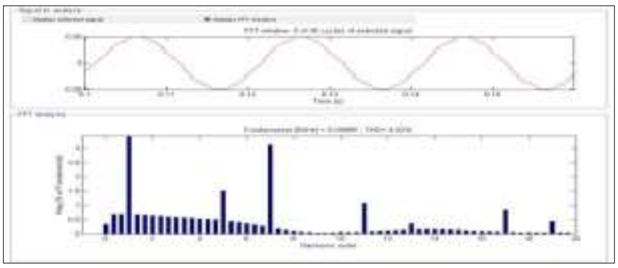


Figure 46 FFT Analysis of output current waveform for five level cascade inverter using STATCOM for phase- A

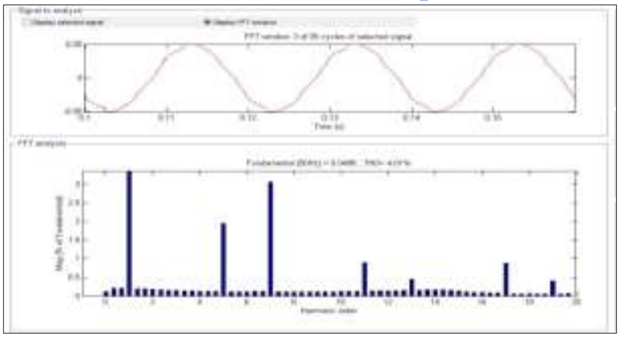


Figure 47 FFT Analysis of output current waveform for five level cascade inverter using STATCOM for phase- B

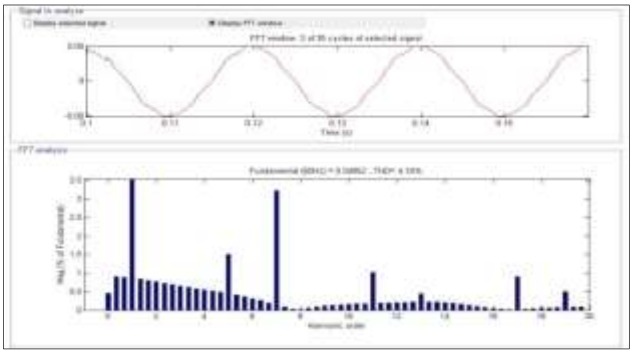


Figure 48 FFT Analysis of output current waveform for five level cascade inverter using STATCOM for phase- C

6.9 Simulink model of seven level cascade inverter using STATCOM:

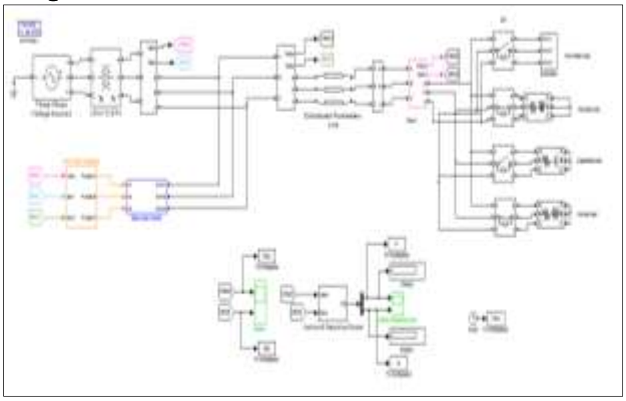


Figure 49 Simulink model of seven level cascade inverter using STATCOM

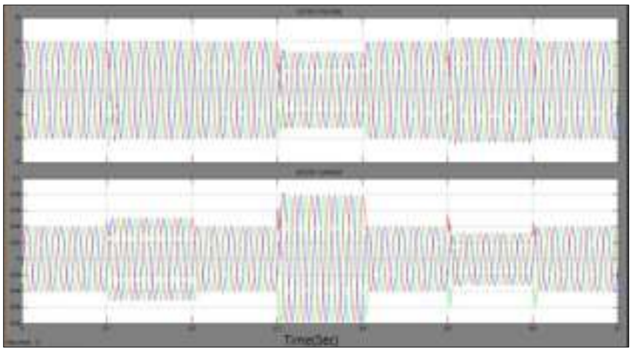


Figure 50 Output voltage and current waveform of seven level cascade inverter using STATCOM

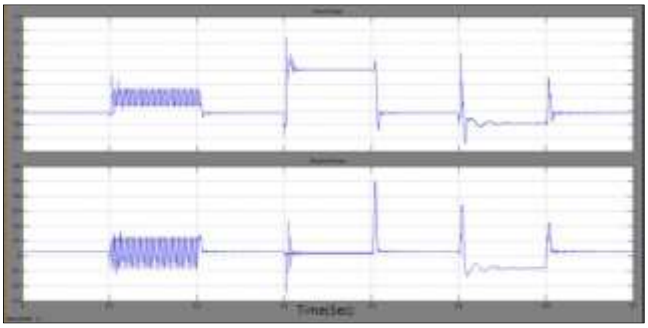


Figure 51 Active power and reactive power waveform of seven level cascade inverter using STATCOM

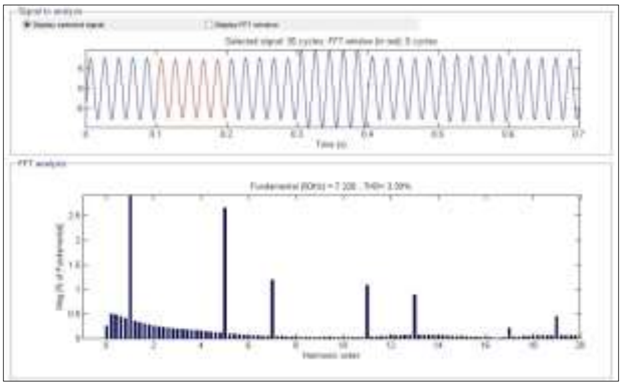


Figure 52 FFT Analysis of output voltage waveform of seven level cascade inverter using STATCOM for phase-A

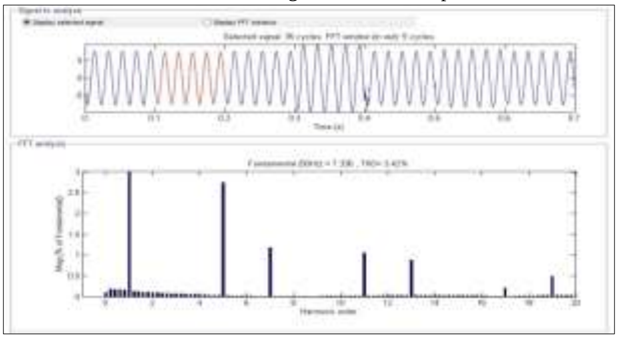


Figure 53 FFT Analysis of output voltage waveform of seven level cascade inverter using STATCOM for phase-B

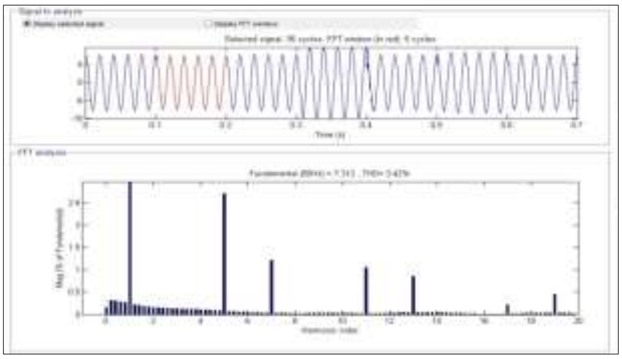


Figure 54 FFT Analysis of output voltage waveform of seven level cascade inverter using STATCOM for phase-C

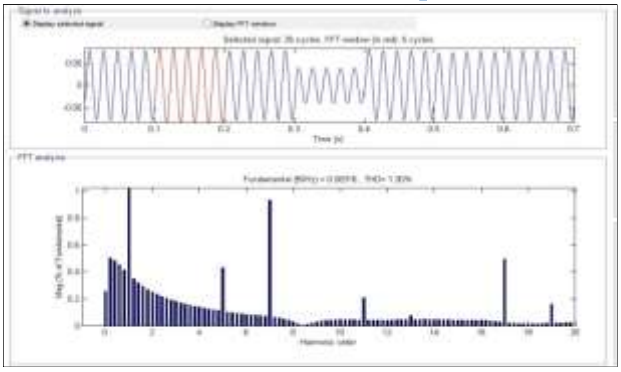


Figure 55 FFT Analysis of output current waveform of seven level cascade inverter using STATCOM for phase-A

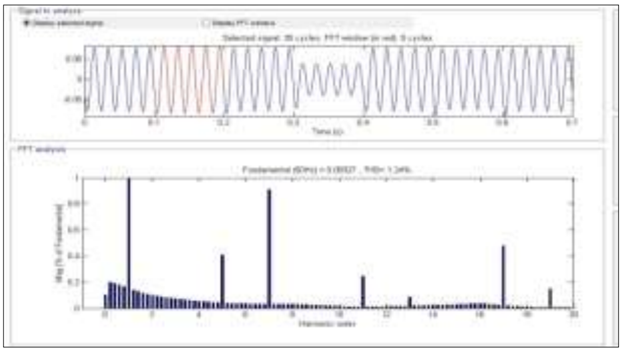


Figure 57 FFT Analysis of output current waveform of seven level cascade inverter using STATCOM for phase-B

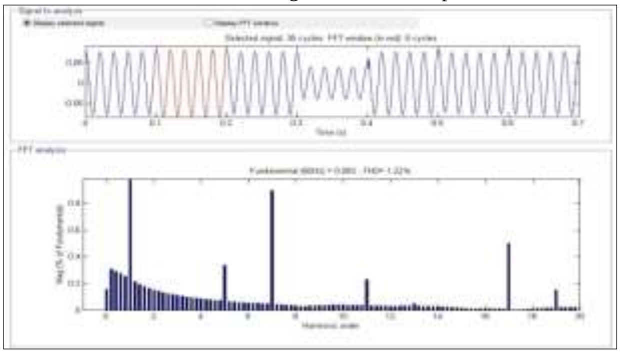


Figure 58 FFT Analysis of output current waveform of seven level cascade inverter using STATCOM for phase-C

V. CONCLUSION

Cascade multilevel inverter is one of the latest multilevel inverter that has been developed over the last few years. The output voltage of cascade multilevel inverter is in the form of pulses and also be modulated to achieve the voltage compensation. The modulation techniques available as pulse width modulation, using that generate the signals to the system through the PWM and eliminate the lower order harmonics. The STATCOM model developed with the necessary components and controller in order to determine its effectiveness in maintaining simple and fast voltage regulation at any point in the transmission line. The effectiveness of the proposed control method is validated with the help of THD calculation and is found to be lowest. 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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