CHAPTER 5

DIRECT AC-AC CONVERTER WITH REDUCED NUMBER OF SWITCHES

Contents

5.1 Introduction:

Initially the study of direct AC-AC converters started with electromechanical motor generator set as mentioned in Chapter 1. With advancement in semiconductor industry SCRs were introduced to the market in nineteen sixties. Researchers, taking the advantage of SCRs, introduced a complex structure, which was capable of frequency conversion. The major disadvantage of this topology was limitation of generating the frequencies lower than the input ones. Since then many complex structures were proposed by various scientist but all the topologies were suffering from same drawback of complex control mechanism. In the process to reduce the number of switches, various topologies have been studied in previous chapters and all the topologies have their own merits and demerits. Out of these topologies nine-switch topology is the most appropriate for use. Basic reason why the modulation algorithm proposed by Venturini and Alesina [2] was not accepted widely by the researches is the difficulty to implement PWM switching strategy. The main disadvantage is the commutation of the bi-directional switches, which if not proper may lead to destruction of the static AC-AC converter. A complicated commutation scheme and an elaborate clamp circuit typically must be added for safe operation [3]. As an alternate solution various attempt have been made to reduce number the switches in past.

Space vector PWM (SVPWM) for the conventional matrix converter circuit is explained in [4], [5]. In [6], this topology is treated as a rectifier/inverter, in which line side and load side switches are controlled separately. In one of the papers using topology called direct frequency changer (DFC), the zero current commutation of line side switches is proposed [7]. There are numerous processes where the bi-directional flow of power is not required i.e. the power flow is from the line side to the load side. Also the electrical isolation is not mandatory requirement. For such processes the topology proposed in the earlier chapter is not suitable. As discussed in the earlier previous chapter, the Direct AC-AC converter with high frequency link requires twelve bi-directional switches. The modified version requires six bi-directional switches plus 10 unidirectional switches. The power circuit still is complex and also makes control more complicated. Also one has to be conscious while designing the control for maintaining 50% duty cycle necessary for maintaining flux balance in case high frequency transformer is being used. For the usage in many simple processes, the only requirement is variable voltage having an added feature of arbitrary frequency setting. In this chapter, a new topology with reduced number of switches and simple control algorithm without compromising for the unity displacement factor is proposed. The advantage of the proposed topology is the input current characterized by low harmonic content.

5.2 Switch Reduction in Direct AC-AC converters

Figure 5.1 shows the basic configuration of nine-switch direct AC-AC converter topology. If the switching function of a switch, S_{jk} in Fig. 5.1 is defined as '0' when open and '1' when closed, the output voltage of this converter is directly obtained in (5.1). Here j Є {a, b, c} and k Є {A, B, C}. The relation between the output voltage and the input voltage can be expressed in Matrix form as follows:

$$\begin{bmatrix} V_{AB} \\ V_{BC} \\ V_{CA} \end{bmatrix} = \begin{bmatrix} F_1V_{ab} + F_2V_{bc} + F_3V_{ca} \\ F_3V_{ab} + F_1V_{bc} + F_2V_{ca} \\ F_2V_{ab} + F_3V_{bc} + F_1V_{ca} \end{bmatrix} \tag{5.1}$$

where F_1, F_2 and F_3 are the direct switching functions.

Considering the constraint followed by the three phase line voltages i.e.

$$V_{ab} + V_{bc} + V_{ca} = 0 \tag{5.2}$$

The direct switching function F_1, F_2 & F_3 can be modeled in such a way that they perform a single step direct conversion equivalent to two steps conversion. So Eqn (5.1) can be expressed as

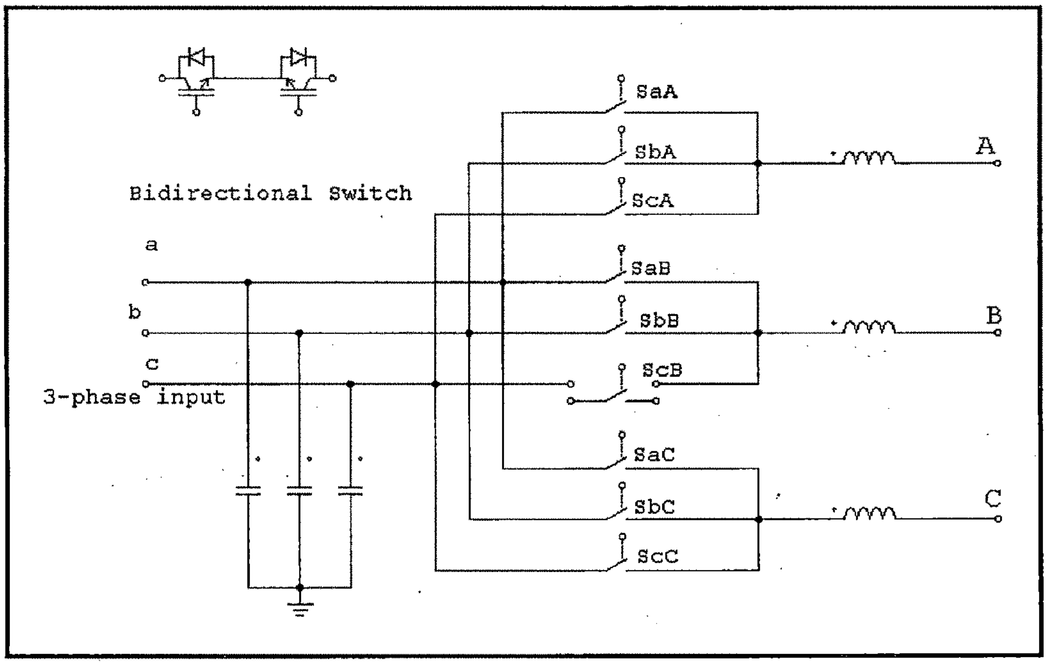


Fig 5.1 Three-phase to three-phase direct AC-AC converter

$$\begin{bmatrix} V_{AB} \\ V_{BC} \\ V_{CA} \end{bmatrix} = \begin{bmatrix} S_{AP} & S_{AN} \\ S_{BP} & S_{BN} \\ S_{CP} & S_{CN} \end{bmatrix} \begin{bmatrix} S_{ap} & S_{bp} & S_{cp} \\ S_{an} & S_{bn} & S_{cn} \end{bmatrix} \begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} \tag{5.3}$$

Above equation indicates the possibility of addition of two points [p, n]. Equation 5.3 supports the possibility of reduction of semiconductor switches but at the cost of comprise with some features. An ideal static three-phase to three-phase converter presented in chapter 2 requires nine bi-directional switches i.e. in all eighteen unidirectional switches with equal number of diodes. As discussed earlier this topology involves more complex control and commutation of switches is more critical. Also the voltage transfer gain (i.e. ratio of output voltage to that of input voltage) is less than 0.8. Chapter 3 mentions that a conventional AC-AC converter can be used to generate high frequency voltage pulses. Thus a high frequency link can be implemented for full utilization of input voltages with an added advantage of electrical isolation. Here the usage of high frequency link tends to increase the number of bi-directional switches to twelve. Already an attempt to reduce from twelve bi-directional switches to six bi-directional switches plus ten unidirectional switches is illustrated in chapter 3.

The block model of converter based on Eqn 5.3 is shown in figure 5.2. The concept shows that it requires in all 12 bi-directional switches. In practice, 24 unidirectional current conducting switches, capable of blocking bi-directional voltage can be implemented in a number of simpler realizations by appropriate assumptions.

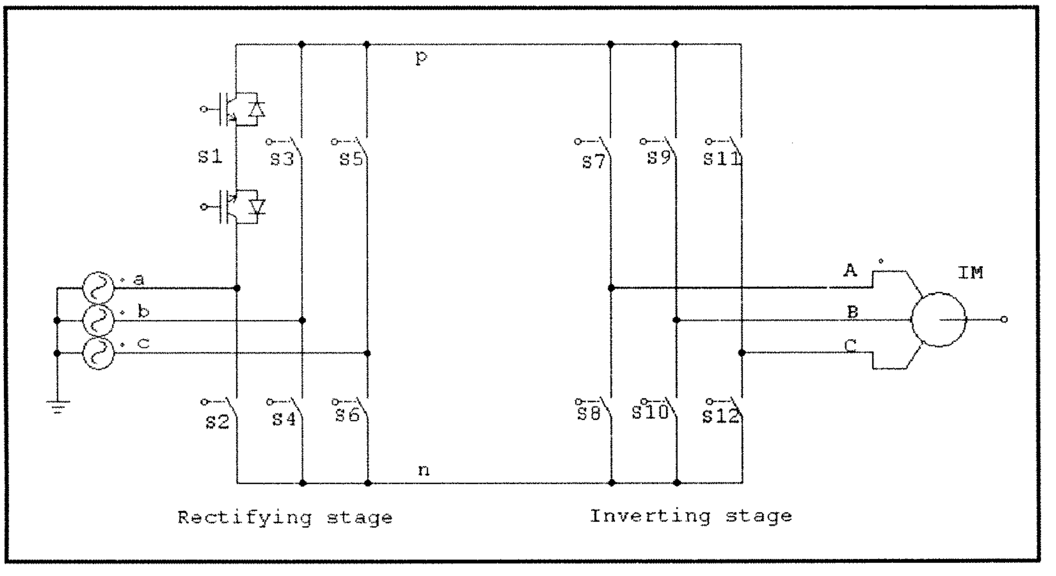


Fig 5.2 Block model of Direct AC-AC converter using IMO mode

Consider a system where if V_{pn} is always positive i.e. p is always at higher potential compared to point n. in such cases load side switches can be unidirectional in nature. Thus the reduction of switches to eighteen unidirectional switches from twenty-four switches can be implemented as shown in figure 5.3 below

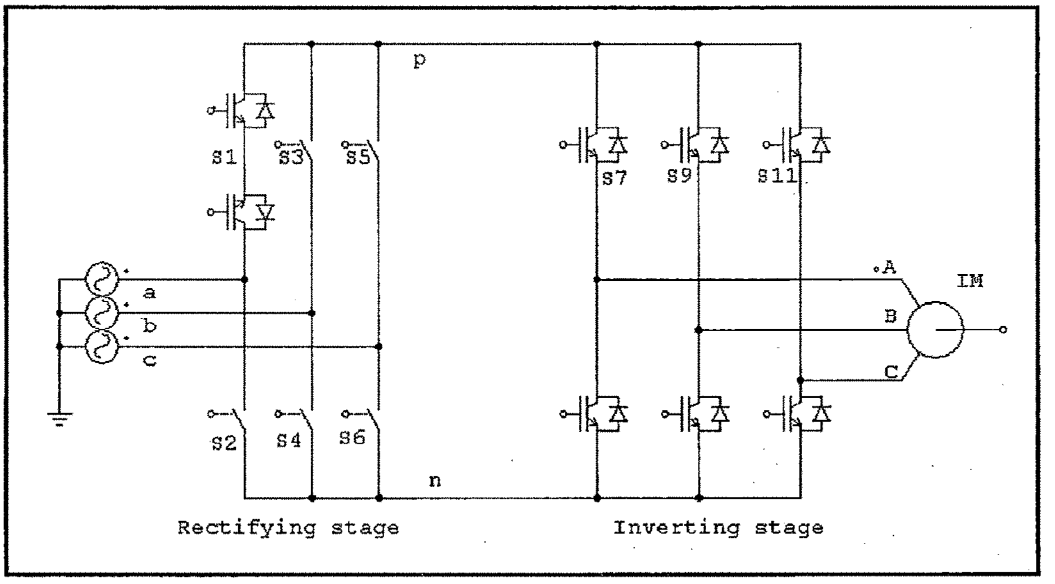


Fig. 5.3 Topology with 18 unidirectional voltage blocking switches

Consider a system where it is guaranteed that i_{dc} is always positive (No regeneration). In such a case the number of switches can be further reduced and it can be viewed as a standard current source inverter (CSI) and a voltage source inverter (VSI) connected directly to each other. Thus the numbers of unidirectional switches are reduced to twelve as shown in figure 5.4 below.

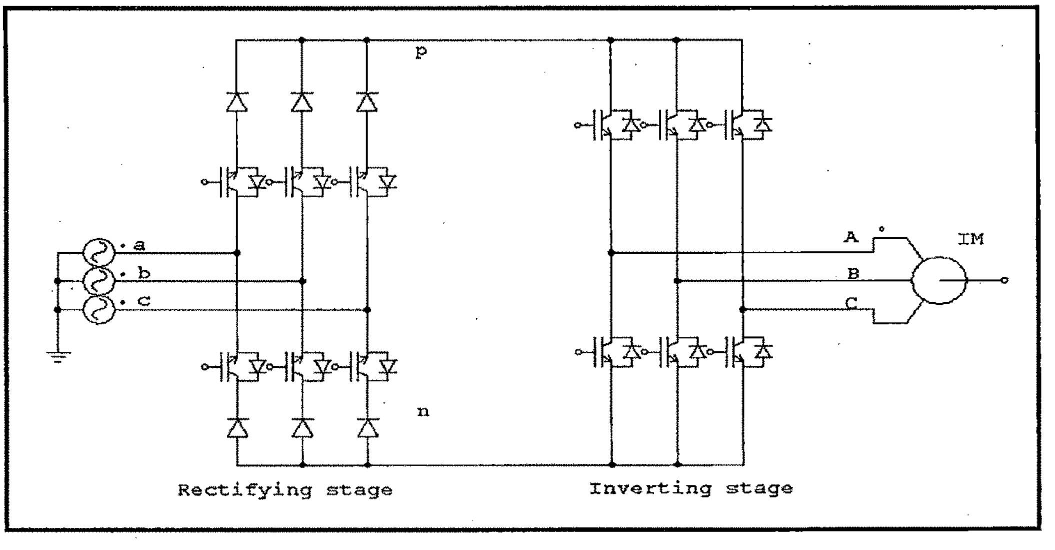


Fig. 5.4 Topology with 12 unidirectional voltage blocking switches

By appropriate PWM modulation, the DC side current i_{dc} is determined by the three-phase output current and the DC side voltage V_{dc} is obtained by the three input voltages.

The twelve-switch topology can be further modified into nine-switch configuration by slight modification as shown in figure 5.5 below.

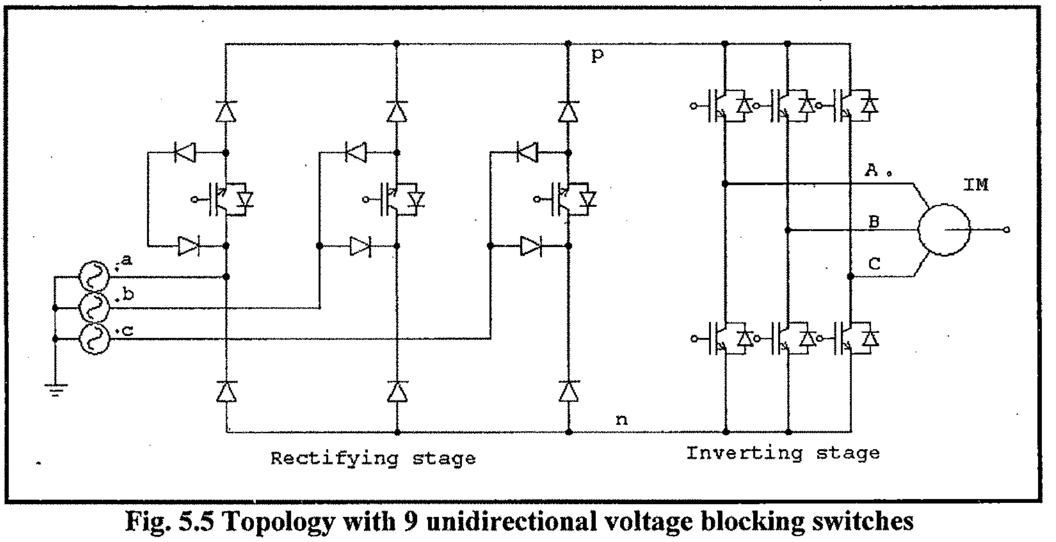


Fig. 5.5 Topology with 9 unidirectional voltage blocking switches

Generally, both the 9-switch and the 12-switch topologies show the same performance except that the 9-switch topology has somewhat larger conduction losses than the 12-switch topology. Because the 9-switch and 12-switch topologies can only be used when i_{dc} is greater than or equal to 0, the power through these two topologies can only flow from the line side to the load side. As a result, the application of these topologies is somewhat limited (applicable for permanent magnet motor drives).

5.3 PWM control Scheme

Limitation of operation of nine-switch converter in negative i_{dc} current condition is prime concern for the researcher while the designing the control scheme for the converter. Consider a balanced set of input voltages as shown below:

$$V_r = V_m \sin(2\pi f_{in} t)$$

$$V_y = V_m \sin\left(2\pi f_{in} t - \frac{2\pi}{3}\right)$$

$$V_b = V_m \sin\left(2\pi f_{in} t - \frac{4\pi}{3}\right)$$

Where V_m is the maximum value of the input phase voltage

f_{in} is the supply frequency of the source

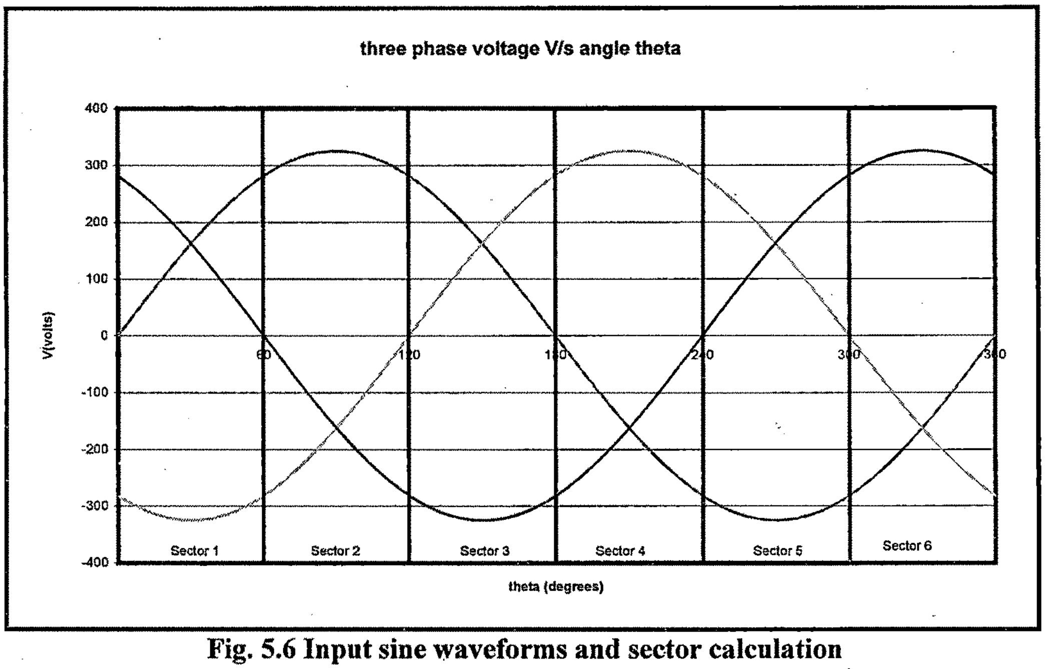


Fig. 5.6 Input sine waveforms and sector calculation

As discussed earlier in chapter 3, input three phase waveforms for one complete cycle are divided into six sectors as shown in figure 5.6. Consider sector 1, V_y has a largest absolute value compared to other two phases indicating that $V_b - V_y$ and $V_r - V_y$ are the voltages that can contribute to generate positive dc voltages during this interval. During this sector the line bi-directional switch connected to the y-phase remains continuously on. Other two line side bi-directional switches modulate as per desired dc generation. Thus the operation during interval 1 can be visualized as two-mode operation. In mode one, switch 2 is conducting along with switch 3 to generate non-negative dc current in the dc bus as shown in figure 5.7 below. In this mode switch 1 in off state thus the R phase current i_r is equal to zero.

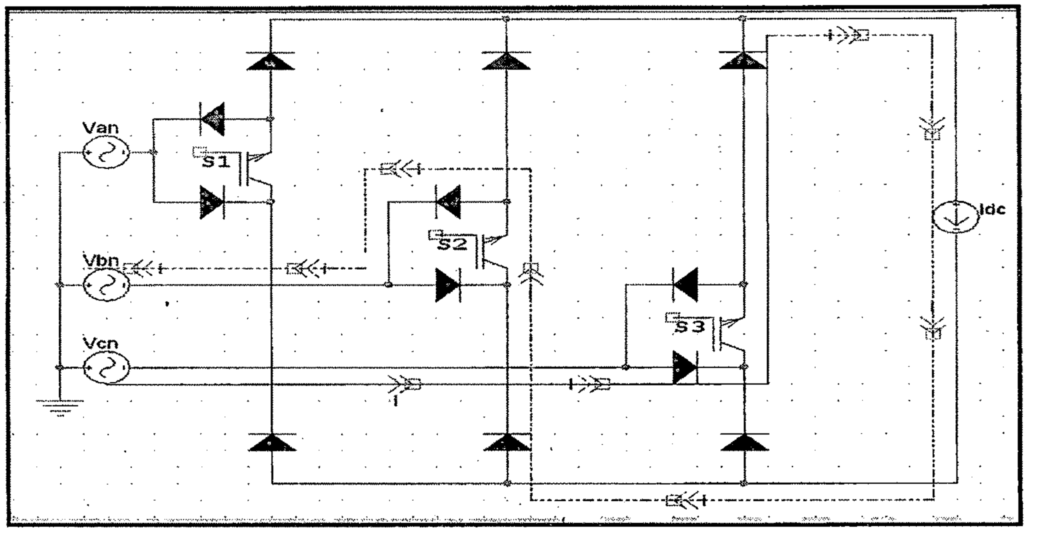


Fig. 5.7 Equivalent circuit during mode 1 of line side converter during interval 1

During mode two, switch 2 still continues to conduct while switch 2 is switched off and switch 1 is turned on. The voltage applied to the inverter section is equal to V_r - V_y. Thus the positive dc current equal to i_r and $-i_y$ is flowing through the load side as shown in figure 5.8 below.

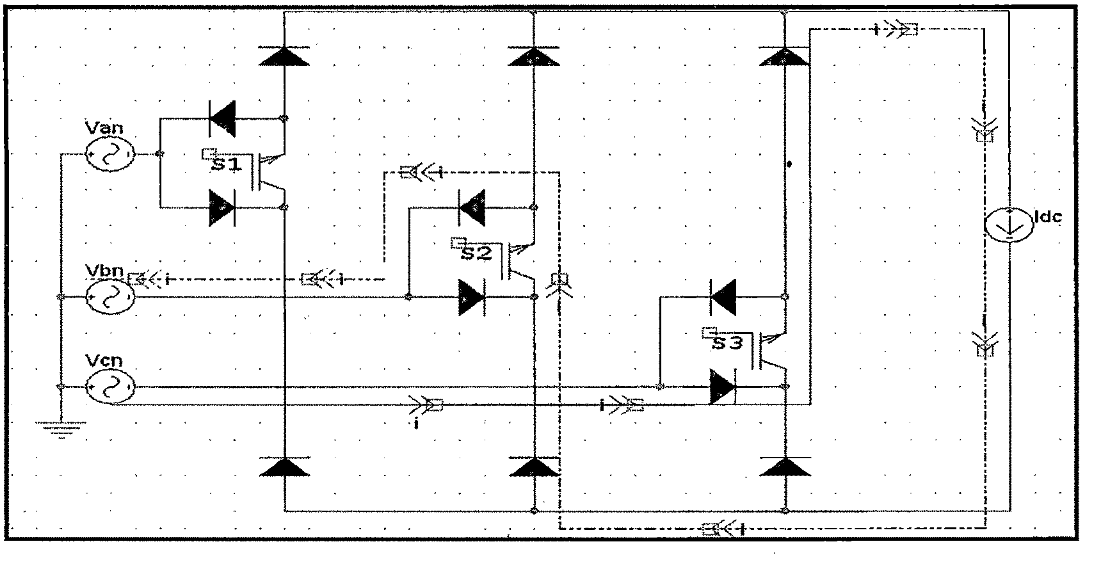


Fig. 5.8 Equivalent circuit during mode 2 of line side converter during interval 1

The inverter can be controlled based on the system requirement using any of commonly used PWM techniques as discussed in the earlier chapter. To prove the functionality of the converter, it is modeled using Simulation software. The results prove the performance of the converter under non-negative dc current condition.

5.4 Simulation and its results:

The mathematical model is simulated considering following system parameters:
System parameters:

Case I

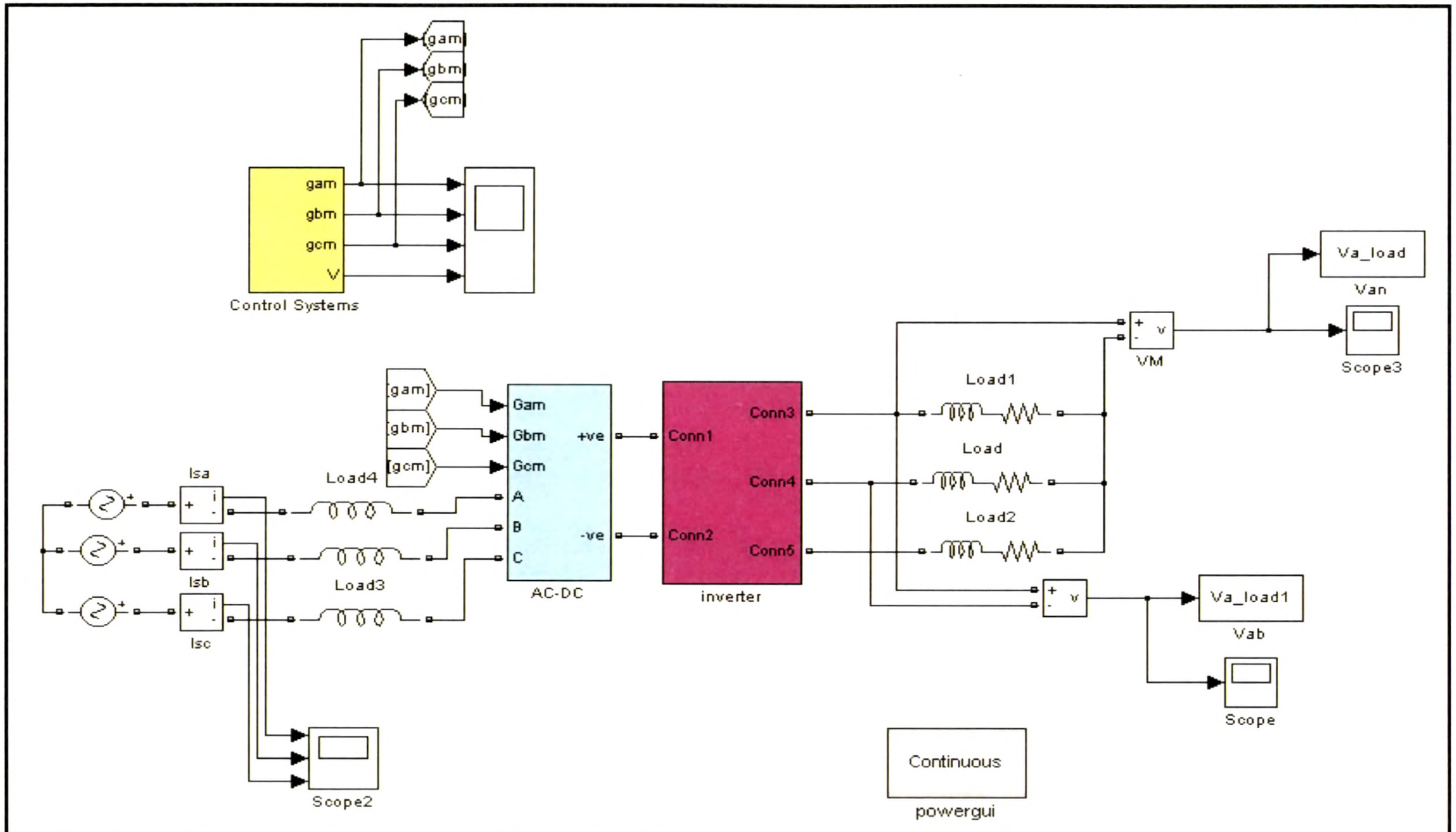
Input voltage: 415 Volts, 3-phase

Input frequency: 50 Hz

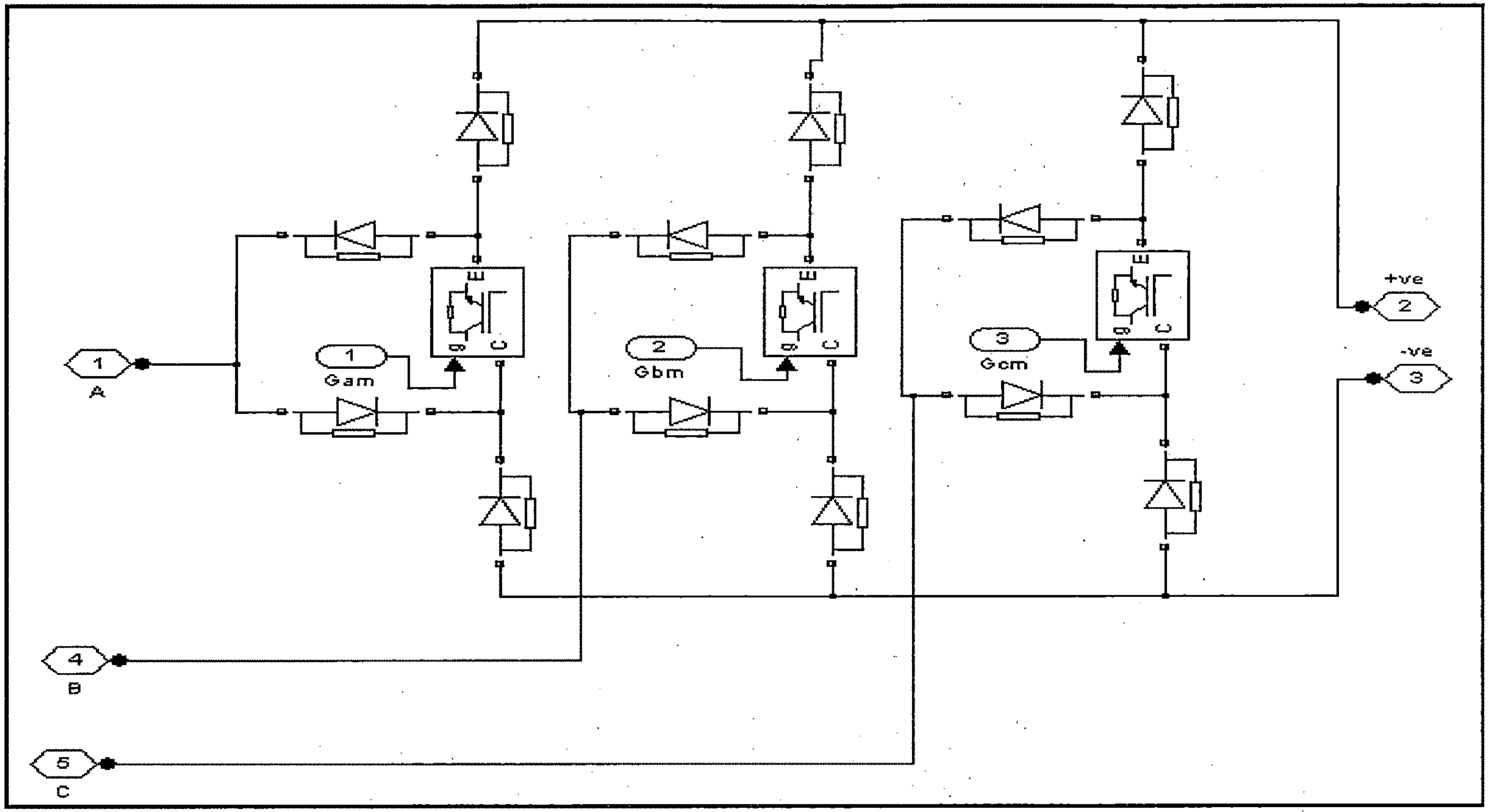
Output voltage: User selectable (0-400 volts range)

Output frequency: 30 Hz

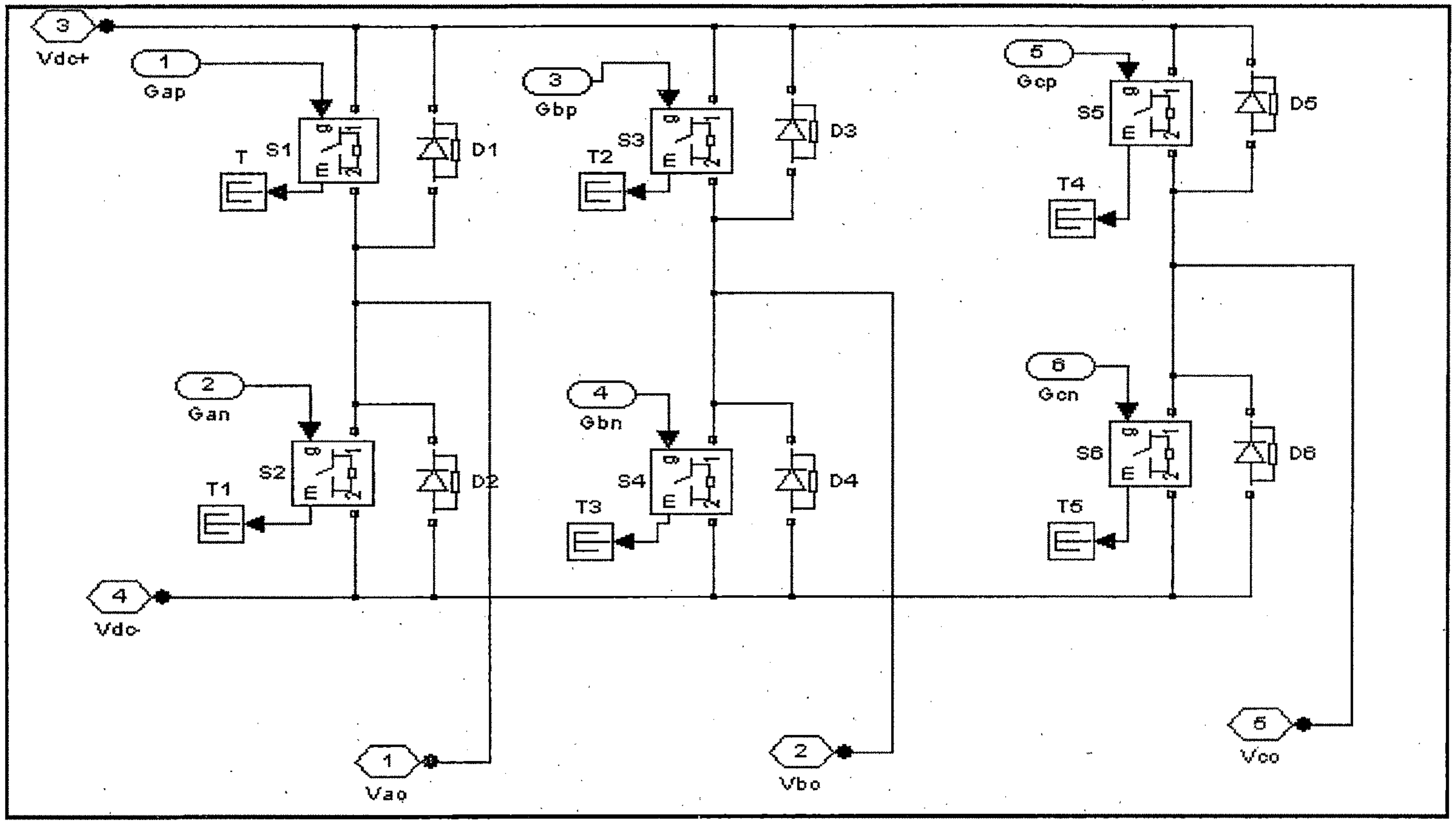
Output load parameters: R= 10 ohms, L = 19 mH



$S_{5.1}$ Block Diagram of Simulation Model of Direct AC-AC converter with reduced number of switches

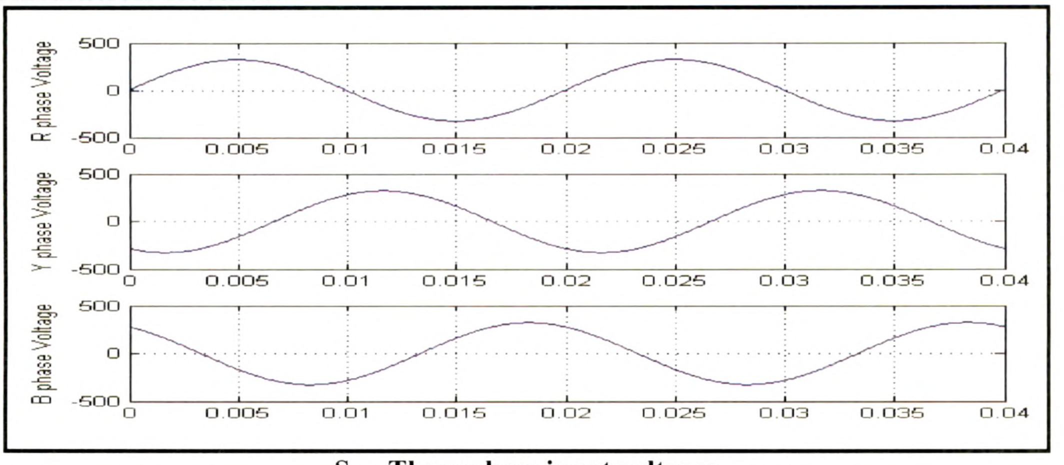


$S_{5.2}$ **Power Circuit Diagram of Primary Converter of Direct AC-AC converter with reduced number of switches**

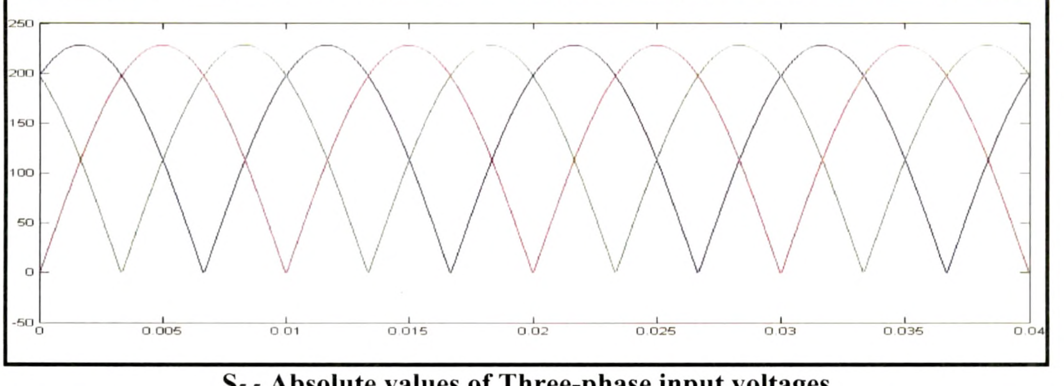


$S_{5.3}$ Power Circuit Diagram of Secondary Converter of Direct AC-AC converter with reduced number of switches

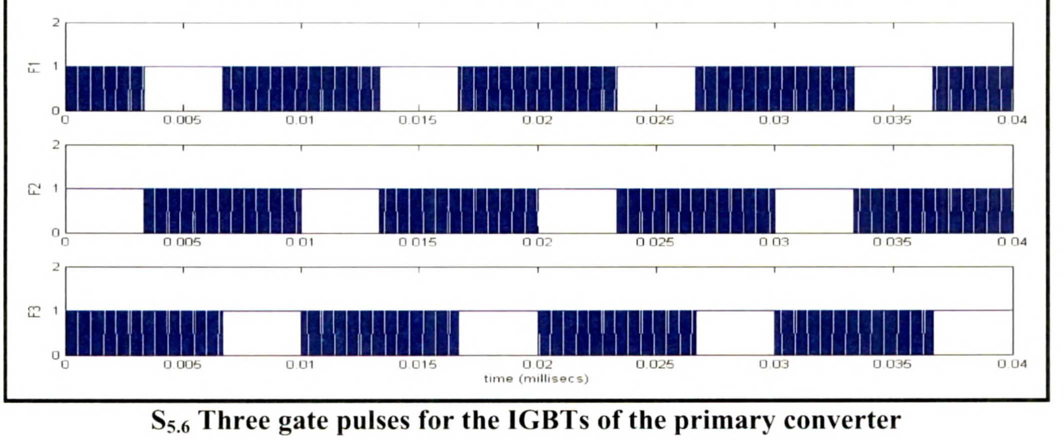
Simulation Results:



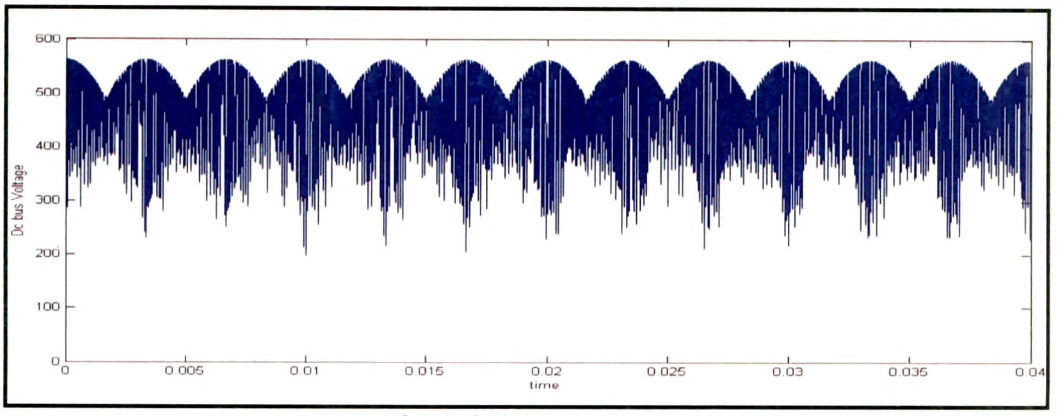
$S_{5.4}$ **Three phase input voltages**



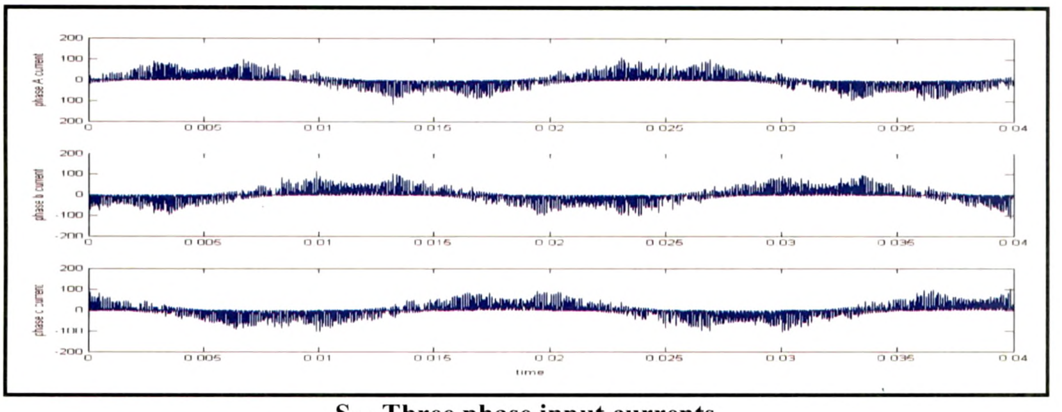
$S_{5.5}$ **Absolute values of Three-phase input voltages**



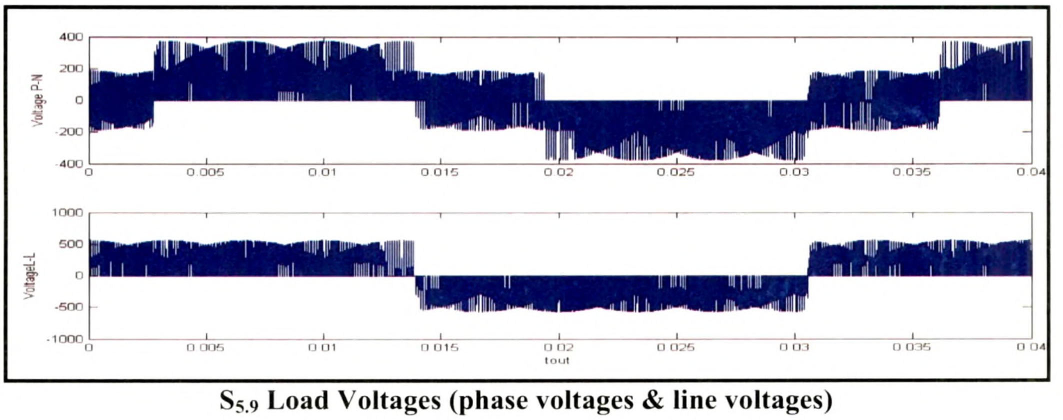
$S_{5.6}$ **Three gate pulses for the IGBTs of the primary converter**



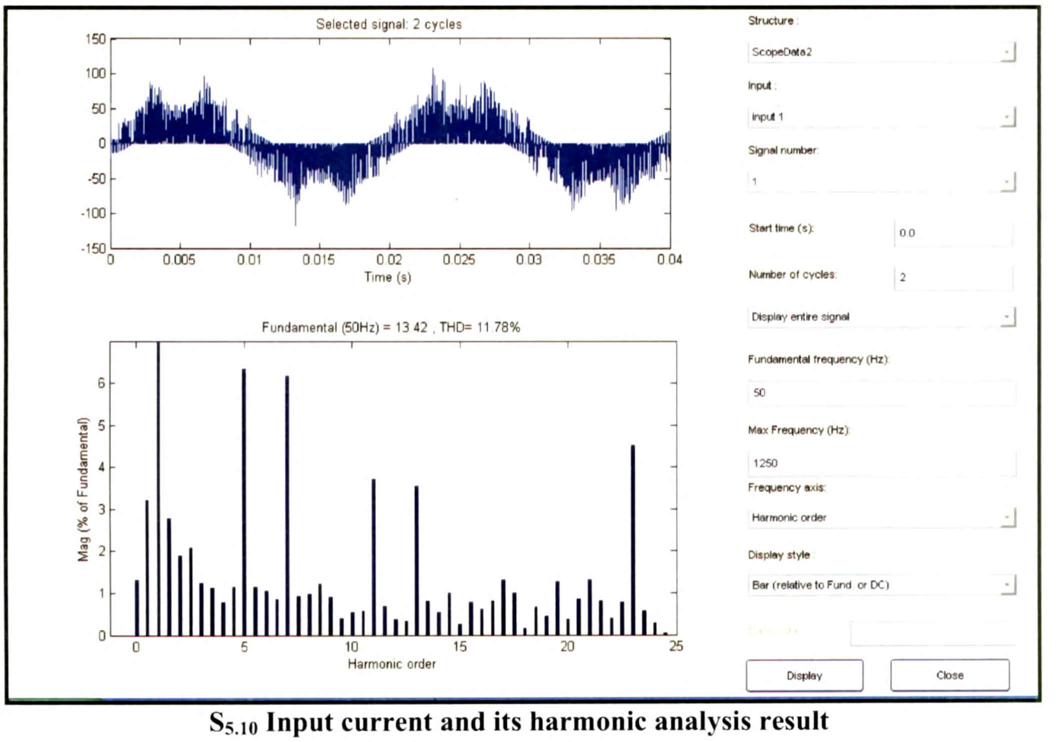
$S_{5.7}$ DC link Voltages



$S_{5.8}$ Three phase input currents



$S_{5.9}$ Load Voltages (phase voltages & line voltages)



$S_{5.10}$ Input current and its harmonic analysis result

5.5 Experimental Results:

To validate the mathematical model, an experimental model has been developed using a unidirectional switch (a MOSFET) with a diode bridge as a bidirectional switch for line side converter. Carrier based control is implemented for generation of control pulses for line side switches. The secondary converter is a conventional three-phase full bridge inverter using six unidirectional switches. SPWM control technique is used for generating required output voltage with arbitrary frequency. Control circuits are implemented using analog circuitry.

Prototype Details:

Power Circuit Design:

Input Parameters:

Input voltage: 100 V_{rms}, 3-ϕ, 50 Hz
Output voltage: 75 V_{rms}, 3-ϕ, 30 Hz
Load parameters: (40 ohms, 5 millihenry)/phase

Power circuit Design:

Unidirectional Switch details: IRF 840, 500 Volts, 6.3 amps
High frequency diodes: BY299
Design of Heat sink: 80 AD
Design of snubber components: 1μF, 600 volts snubber capacitors

Control Circuit description:

The flow of the control block is simple and to avoid the complexity in implementing the control, it is kept in line with earlier topology control sequence as explained in earlier chapter with minor modification. The functional block diagram of the control is shown in the figure below.

Stage A: Sector Determination:

With the aim of determining the appropriate switch that conducts during an interval of sixty degrees resulting in generation of maximum value of DC voltage. In order to get the knowledge of appropriate sectors using analog circuits, first step is to obtain the instantaneous maximum value of the three phase input signals.

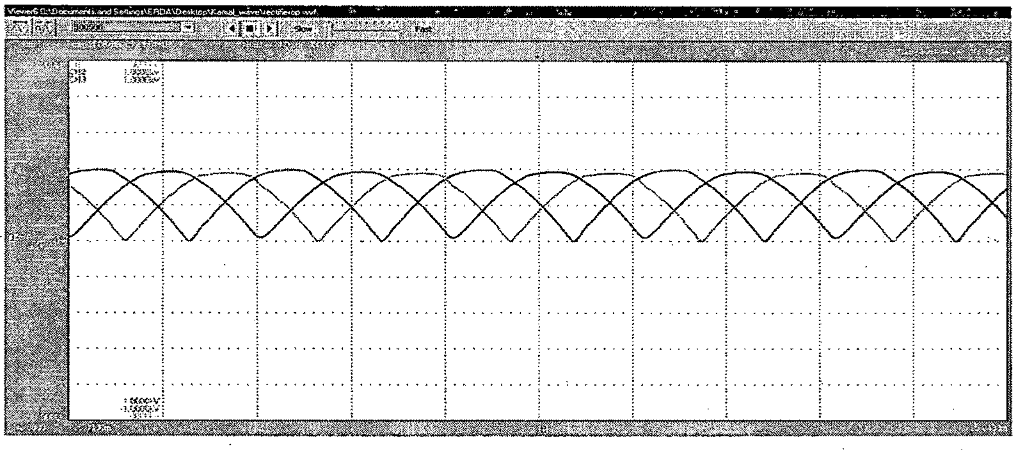


Fig 5.9 Fully rectified waveforms of Three-Phase to Neutral voltages

For this the input signals are rectified with the help of full wave rectifier circuit having a resistive load across it. This results in generation of instantaneous maximum value. Sector determination means to determine the phase that contributes more to generate the maximum value.

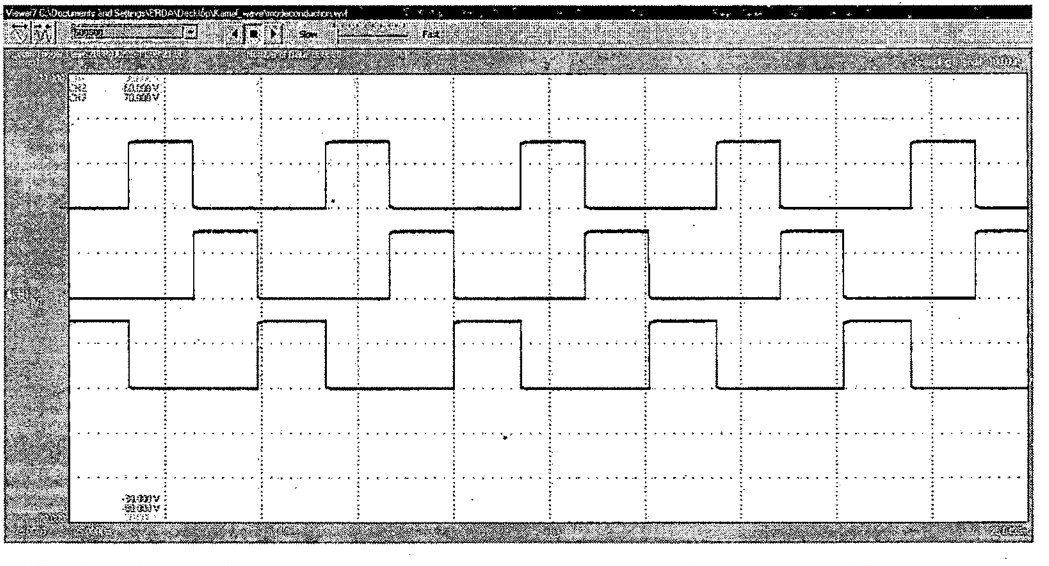


Fig 5.10 Sector determination for all the three phases for primary side converter

To achieve the desired results, it is required to divide the absolute value of each phase voltage with the maximum value obtained earlier. The resultant of this division will be the trapezoidal waveform with a flat top where the phase voltages are equal to the maximum voltages. Once these waveforms are generated, the bi-directional switch selection algorithm for yielding the desired output while maintaining the input displacement factor close to unity is implemented using the PWM modulation technique. For implementation of the PWM modulation, the ramp signals are used as the carrier frequency signals and the trapezoidal waveforms generated as a result of earlier mentioned division are used as modulated signals. The resulting gate pulse waveforms for the primary converter are shown in the figure 5.11 below

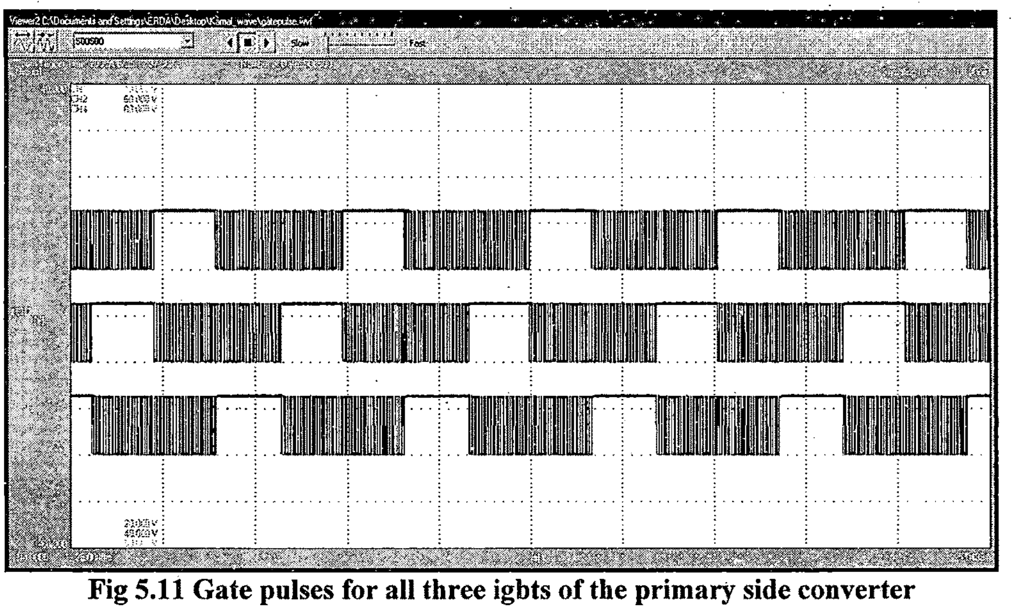


Fig 5.11 Gate pulses for all three igbts of the primary side converter

These gate pulses are given to the Primary side AC-DC converter via a driver card (required for isolation), which will generate the DC voltages and currents as shown in figure 4.12. the input voltage and current for one phase are shown in figure 4.13 below. It can be seen that the voltage and current are in phase with each other and the current waveform is having less distortion indicating that the %thd contents present in the currents is quite low.

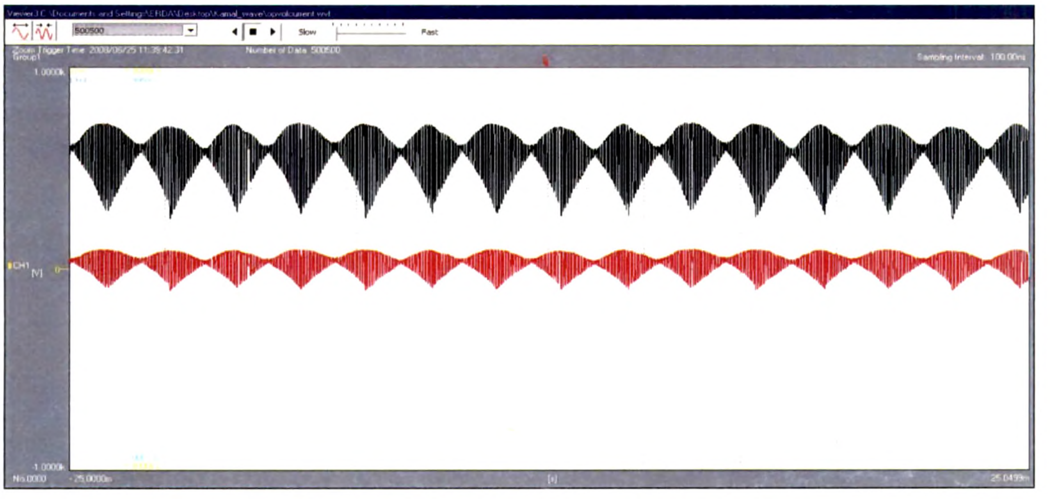


Fig 5.12 Intermediate DC voltage and current

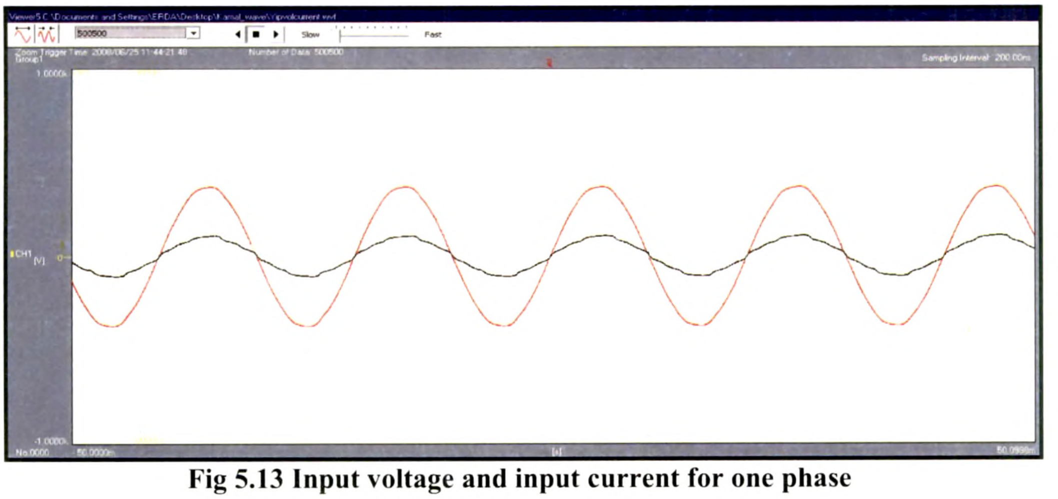


Fig 5.13 Input voltage and input current for one phase

5.6 Conclusion

One of the disadvantages of the topology proposed in chapter 3 is high value of device count. There are several applications where regenerative action is not required. In such cases it is possible to reduce the number of devices required. In this chapter a power circuit configuration is proposed wherein the number of devices used is reduced. A detailed simulation has been carried out and results are experimentally verified.