CHAPTER 2

MODELING AND ANALYSIS

OF

DIRECT AC-AC CONVERTERS

Contents

Modeling and Analysis of Direct AC-AC Converters

2.1 Introduction:

Recently there has been considerable interest in the development and usage of direct AC-AC conversion for numerous industrial applications where transformation of voltages, currents, frequency and phase are process requirements. The circuit shown in figure 2.1 offers an all silicon solution for AC-AC power conversion. Figure 2.1 shows a typical generalized static transformer, with MxN bi-directional switches capable of transformation of voltage, current, frequency, phase and amplitude [23]. The circuit consists of an array of bi-directional switches arranged so that any of the output lines of the converter can be connected to any of the input lines. The switches allow any input phase to be connected to any output phase. The output waveform is then created using a suitable PWM modulation pattern similar to a normal inverter, except that the input is N-phase supply instead of a fixed DC voltage. This approach removes the need for the large reactive energy storage components at the DC intermediate stage used in conventional inverter based converters. An input line filter is included to circulate the high frequency switching harmonics. This static transformer has many advantages over traditional topologies. It is inherently bi-directional so can operate in regenerating mode and feed energy back to the supply. It draws sinusoidal input currents and depending on the modulation technique, it can be arranged that unity displacement factor is seen at the supply side irrespective of the type of load. The size of the power circuit has the potential to be greatly reduced in comparison to conventional technologies since there are no large capacitors or inductors to store energy.

This objective of this chapter is to give an introduction to static AC-AC converter technology by developing a suitable switching model. This chapter also contains detailed analysis of a 3 x 3 converter and also investigates the suitability and design of matrix converters for industrial applications. The potential advantages of static AC-AC converter technology are examined and the factors that have so far prevented commercial exploitation of the circuit are discussed. To evaluate the performance, simulation for various topologies of converter has been carried out and results of simulation study are included in this chapter.

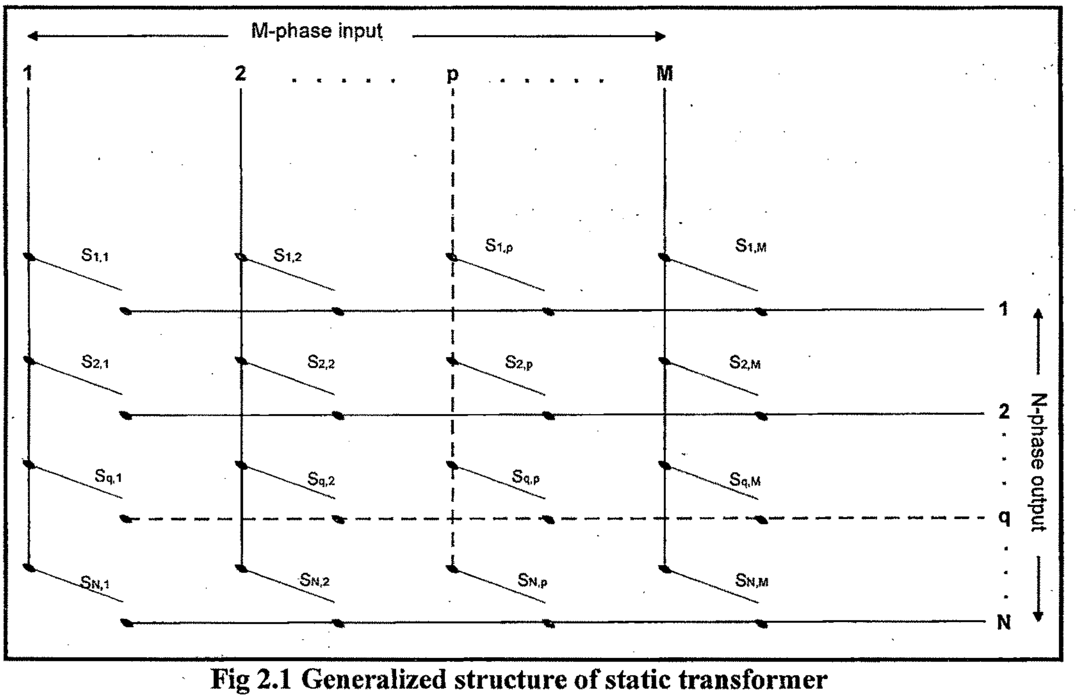


Fig 2.1 Generalized structure of static transformer

2.2 Practical Implementation Of Three-Phase To Three-Phase Direct AC-AC Converters

Generalized M-input, N-output static transformer explained in previous section can be readily used to construct a practical AC-AC converter for defined input/output phases (M, N). The most common requirement of an industrial consumer is three phase to three phase conversion i.e. M=3 & N=3, shown in figure 2.2 and is explained henceforth. L. Gyugi, and B.

Pelly had published the concept of matrix converter for the first time in 1976 [24]. The proposed circuit was considered to be a cycloconverter where the devices were fully controllable; hence the matrix converter is sometimes called a Forced Commutated Cycloconverter. A lot of research interest followed the publication of Venturini's papers of 1980 [25][26] and the following landmark paper [27], which put the matrix converter control algorithms on a strong mathematical foundation.

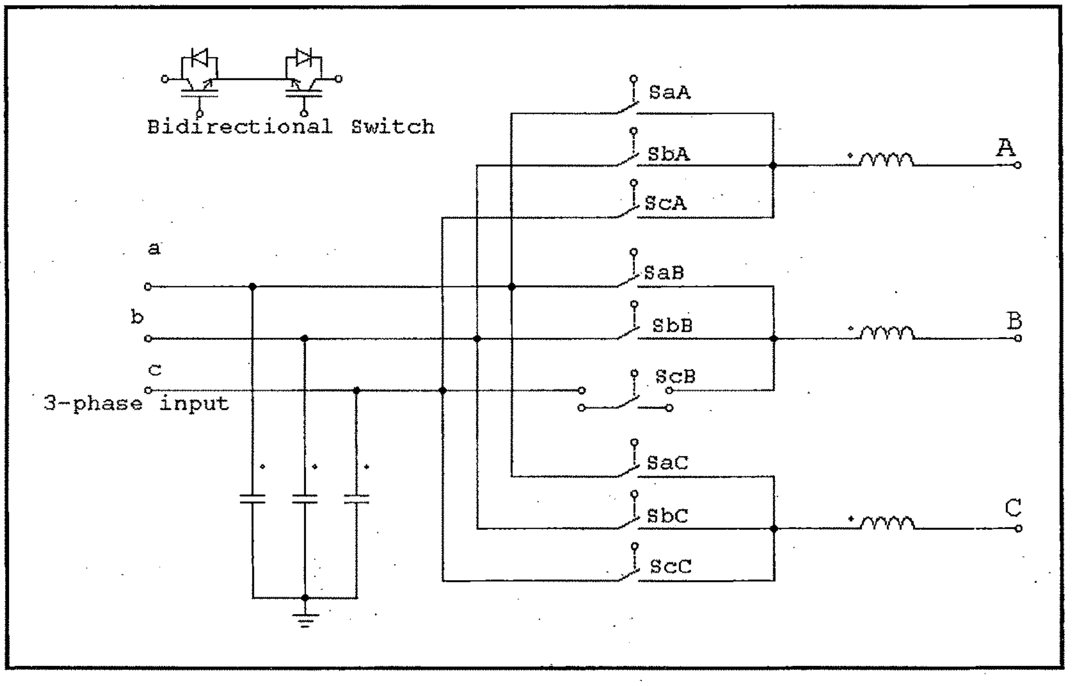


Fig 2.2. Circuit scheme of a three phase to three-phase matrix converter, where a, b, c are at the input terminals and A, B, C are at the output terminals.

At that time industrial interest in the converter was very limited due to the device count, the problems of current commutation between switches and the perceived complexity of the control algorithms. Now these limitations are no longer valid.

Since the static converter is supplied by the voltage source, the input phases must not be shorted and due to the inductive nature of the load, the output phases must not be open. These constraints are illustrated for the switch set connected to the output phase A in Fig 2.3.

If the switch function of a switch S_{ij} in Fig. 2.3 is defined as [3]

S_{ij} (t) = 1, S_{ij} closed $i \varepsilon \{a, b, c\}$, $j \varepsilon \{A, B, C\}$

= 0, S_{ij} open

The constraints can be expressed as

$$S_{aj} + S_{bj} + S_{cj} = 1, \quad j \varepsilon \{A, B, C\} \quad (2.1)$$

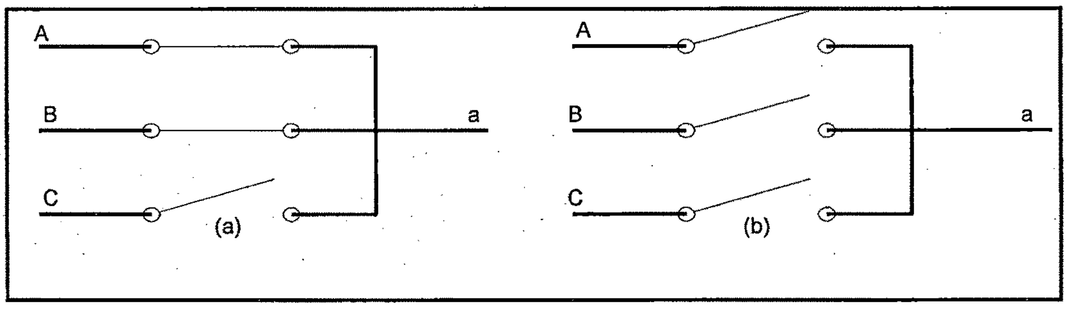


Fig 2.3 Switching constraints (a) short circuit between input phases (b) open circuit for output phase

Realization of AC-AC converters can be achieved only if solutions for following three basic problems can be found:

- Bi-directional switch problem
- Modulation algorithm problem and its implementation
- Commutation problem

2.2.1 Bi-directional switch configurations:

Practical realization of a Matrix Converter requires the use of a bi-directional switch. A bi-directional switch should be capable of blocking voltage and conducting current in both directions. Recently few manufacturers have introduced bi-directional switches in the market. But cost of such devices is very high and second thing is that the performance and reliability of such switches is questionable. Until device technology progresses to the point where such a device with high performance and reliabile is made commercially available, this bi-directional switch must be fabricated using discrete components. The switches may be constructed using diodes and transistors. IGBTs have been chosen as the controllable devices due to their high switching speeds and current handling capabilities. There are five possible configurations for this bi-directional switch:

- Diode Bridge with a Single IGBT
- A Pair of Back-to-Back IGBTs in Common Collector Mode
- A Pair of Back-to-Back IGBTs in Common Emitter Mode
- A Pair of Back to Back Series connected IGBT/Diodes with Emitters connected to anode of Diode
- A Pair of Back to Back Series connected IGBT/Diodes with Collectors connected to cathode of Diode.

Diode Bridge with a Single IGBT

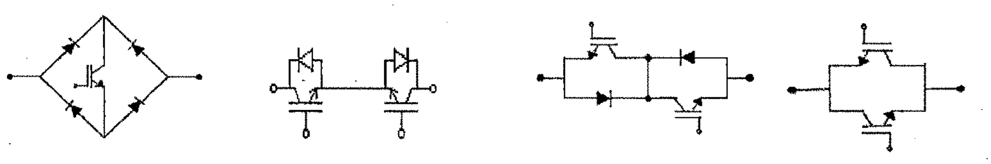
A diode bridge arrangement with one switching device providing the current path at all times is shown in figure 2.4 (a). This style of bi-directional switch has the advantage of requiring only one IGBT and its associated gate driver circuit. The main disadvantage of the diode bridge arrangement is that three devices are conducting at any given time giving rise to relatively high conduction losses.

Common Emitter Anti-parallel IGBT, Diode Pair

This bi-directional switch arrangement consists of two diodes and two IGBTs connected in anti parallel as shown in figure 2.4 (b). The diodes are included to provide the reverse blocking capability. It should be noted that it is possible to independently control the direction of the current in the bi-directional switch. Each bi-directional switch requires an isolated power supply for the gate drives, but both devices can be driven with respect to the same voltage – the common emitter point.

Common Collector Anti-parallel IGBT, Diode Pair

This arrangement is similar to the previous one but the IGBTs are arranged in a common collector configuration as shown in figure 2.4 (c). The conduction losses are the same as the common emitter configuration. The disadvantage of this method is that eighteen isolated power supplies are needed to supply the gate drive signals. Therefore the common emitter configuration is often preferred for creating the matrix converter bi-directional switch cells.



a) Diode bridge with a single IGBT

b) Two anti-paralleled IGBT in common emitter mode

c) Two anti-paralleled IGBT in common collector mode

d) Two anti-paralleled NPT-IGBT's with series diodes with reverse blocking capability

Fig 2.4 Bi-directional switch configuration

2.2.2 The Modulation Problem and Basic Solution

Following methods of control applied for achieving AC-AC conversion and allow effective elimination of harmonics from output voltages:

Direct mode of operation

Indirect mode of operation

Direct mode operation (DMO) for AC-AC conversion

Control is based on the principle that a set of Nx1 balanced output sinusoidal quantities, free from harmonics, can be constructed or obtained by multiplying a set of Mx1 sinusoidal input quantities with a balanced set of MxN sinusoidal quantities.

Here set of Nx1 quantities is henceforth termed as output matrix, set Mx1 is termed as input matrix and the MxN is termed as converter transform matrix.[23]

$$\boxed{[Nx1]=[MxN][Mx1]} \qquad (2.1)$$

Thus, the analytical representation of the DMO technique of control in terms of output and input quantities is:

$$[V_o(\omega_o t)] = [F_s(\omega_s t)][V_i(\omega_i t)] \tag{2.2}$$

$$\begin{bmatrix} V_{o,1} \\ \cdot \\ V_{o,l}\cdot \\ \cdot \\ V_{o,N} \end{bmatrix} = \begin{bmatrix} f_{1,1} & \cdot & f_{1,p} & \cdot & f_{1,M} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ f_{q,1} & \cdot & f_{q,p} & \cdot & f_{q,M} \\ \cdot & & \cdot & & \cdot \\ f_{N,1} & \cdot & f_{N,p} & \cdot & f_{N,M} \end{bmatrix} * \begin{bmatrix} V_{i,1} \\ \cdot \\ V_{i,p} \\ \cdot \\ V_{i,M} \end{bmatrix} \tag{2.3}$$

$$[I_i(\omega_i t)] = [F_s(\omega_s t)]^T [I_o(\omega_o t)] \quad \&$$

$$\begin{bmatrix} I_{i,1} \\ \cdot \\ I_{i,p}\cdot \\ \cdot \\ I_{i,M} \end{bmatrix} = \begin{bmatrix} f_{1,1} & \cdot & f_{q,1} & \cdot & f_{M,1} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ f_{1,p} & \cdot & f_{q,p} & \cdot & f_{M,p} \\ \cdot & & \cdot\ \cdot & & \cdot \\ f_{1,N} & \cdot & f_{q,N} & \cdot & f_{M,N} \end{bmatrix} * \begin{bmatrix} I_{o,1} \\ \cdot \\ I_{o,p} \\ \cdot \\ I_{o,M} \end{bmatrix} \tag{2.4}$$

where ω_i is the input frequency in radian per sec.

ω_o is the output frequency in radian per sec.

ω_s is the switching frequency in radian per sec.

F_s is the switching matrix element

$V_{i,1}$, $V_{i,p}$...... $V_{i,M}$ are the input phase voltages

$V_{o,1}$, $V_{o,q}$...... $V_{o,N}$ are the output phase voltages

$I_{i,1}$, $I_{i,p}$...... $I_{i,M}$ are the input phase currents

$I_{o,1}$, $I_{o,q}$...... $I_{o,N}$ are the input phase currents

$f_{1,1}$, $f_{q,p}$ .... $f_{N,M}$ are switching matrix elements corresponding to each switch

Generalized converter structure capable of transforming voltage, current, frequency, phase and amplitude given in above equations (2.3) & (2.4) is shown in figure 2.1. The figure clearly indicates the converter circuit as a matrix of MxN elements. Here the active elements are active in nature and hence the matrix formed is known as active elements matrix. Figure 2.1 also depicts that there is one to one correspondence between the entries of converter transfer matrix and the active element matrix.

$$f_{q,p}(t) = A\sin(\omega_s t - \frac{(p-1)}{N}360° + \frac{(q-1)}{M}360°) \quad (2.5)$$

where p varies from 1, 2, ...M; q varies from 1, 2, ...N

This correspondence is clear from the above-mentioned equation (2.5)[81], where each entry of transfer matrix describes the transfer characteristics of the active element of the converter switch matrix.

Moreover one to one correspondence between the converter transfer matrix and the active element matrix result in:

- A straightforward derivation of the transfer matrix from the element matrix.
- The direct synthesis of the converter circuit from respective transfer matrix.

Advantages of the above-mentioned results are

- Formulating a transfer matrix when the converter circuit is known in advance.
- Vice versa an appropriate circuit can be worked out for any specified transfer matrix.

Detail Explanation of Direct Mode Operation:

The Venturini modulation method (Direct mode operation), proposed by Venturini in 1980, is a direct transfer function approach to find relationship between input and output quantities. The output waveforms of the matrix converter are formed by selecting each of the input phases in sequence for defined periods of time. Generally the sequence for each output phase is the same [26]-[27].

As stated earlier, the output voltage for each phase consists of segments made up from the three input voltages. The input phase current consists of segments of the three output phase currents plus blank periods during which the output current freewheels through the switch matrix. To determine the behavior of the converter at output frequencies well below the switching frequency a modulation duty cycle can be defined for each switch (eg. $m_{aA}(t) = t_{aA}/T_{seq}$ - where t_{aA} refers to the switch on input line 'a' and output line 'A', see figure 2, and T_{seq} is the sequence time of the PWM pattern).

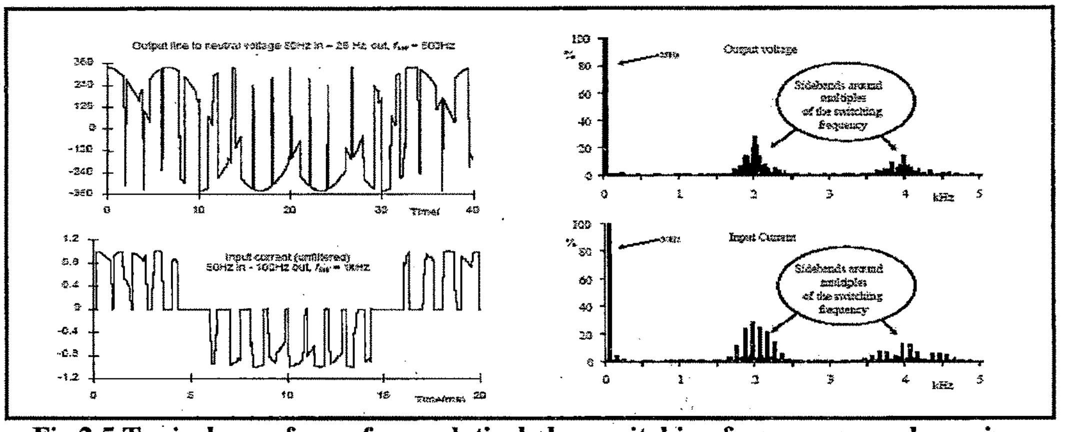


Fig 2.5 Typical waveforms for a relatively low switching frequency are shown in figure above

These continuous time functions can then be used to define and compare the modulation strategies, as set out in Equation 2.6 & 2.7

$$\begin{bmatrix} v_A(t) \\ v_B(t) \\ v_C(t) \end{bmatrix} = \begin{bmatrix} m_{aA}(t) & m_{bA}(t) & m_{cA}(t) \\ m_{aB}(t) & m_{bB}(t) & m_{cB}(t) \\ m_{aC}(t) & m_{bC}(t) & m_{cC}(t) \end{bmatrix} \begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} \tag{2.6}$$

$$\begin{bmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{bmatrix} = \begin{bmatrix} m_{Aa}(t) & m_{Ba}(t) & m_{Ca}(t) \\ m_{Ab}(t) & m_{Bb}(t) & m_{Cb}(t) \\ m_{Ac}(t) & m_{Bc}(t) & m_{Cc}(t) \end{bmatrix} \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} \tag{2.7}$$

Equations (2.6 & 2.7) can be presented in a more compact notation where M(t) is known as the modulation matrix:

$$[v_o(t)] = [M(t)][v_i(t)] \quad \& \quad [i_i(t)] = [M(t)][i_o(t)] \tag{2.8}$$

Brief Derivation:

The modulation problem is usually posed assuming that a sinusoidal output voltage and a sinusoidal input current are required as follows.

For a given a set of input voltages and an assumed set of output currents

$$[v_i(t)] = V_{im}\begin{bmatrix}\sin(\omega_i t)\\ \sin(\omega_i t + 2\pi/3)\\ \sin(\omega_i t + 4\pi/3)\end{bmatrix} \qquad [i_o(t)] = I_{om}\begin{bmatrix}\sin(\omega_i + \Phi_o)\\ \sin(\omega_i t + \Phi_o + 2\pi/3)\\ \sin(\omega_i t + \Phi_o + 4\pi/3)\end{bmatrix} \quad (2.9)$$

The basic problem is to find a modulation equation (here a matrix) such that

$$[v_o(t)] = qV_{im}\begin{bmatrix}\sin(\omega_o t)\\ \sin(\omega_o t + 2\pi/3)\\ \sin(\omega_o t + 4\pi/3)\end{bmatrix} \qquad [i_i(t)] = q\frac{\cos(\Phi_o)}{\cos(\Phi_i)}I_{om}\begin{bmatrix}\sin(\omega_o t + \Phi_i)\\ \sin(\omega_o t + \Phi_i + 2\pi/3)\\ \sin(\omega_o t + \Phi_i + 4\pi/3)\end{bmatrix} \quad (2.10)$$

Where q is the voltage transfer ratio, ω_i and ω_o are the input and output angular frequencies and Φ_i and Φ_o are the input and output phase displacement angles. There are two possible solutions of this problem. One of the solutions for this problem is derived as under:

Assuming that the input voltages are essentially constant during the switching interval the average output voltage can be found during any switching interval by the equation

$$\begin{aligned} v_{o1} &= V_o \sin(\omega_o t) = \frac{1}{T_s}(V_{i1}t_1 + V_{i2}t_2 + V_{i3}t_3)\\ v_{o2} &= V_o \sin(\omega_o t + 2\pi/3) = \frac{1}{T_s}(V_{i2}t_1 + V_{i3}t_2 + V_{i1}t_3)\\ v_{o3} &= V_o \sin(\omega_o t + 4\pi/3) = \frac{1}{T_s}(V_{i3}t_1 + V_{i1}t_2 + V_{i2}t_3) \end{aligned} \quad (2.11)$$

Where $t_1 + t_2 + t_3 = T_s$

The times t_1, t_2, and t_3 are switching interval variables in seconds. In Eq. (2.11) it is assumed that the output voltage is, in effect, the average value the three switching events weighted by the time of "dwell" on each of the input. In matrix form

$$\frac{1}{T_s}\begin{bmatrix}V_{i1} & V_{i2} & V_{i3}\\ V_{i2} & V_{i3} & V_{i1}\\ V_{i3} & V_{i1} & V_{i2}\end{bmatrix}\begin{bmatrix}t_1\\ t_2\\ t_3\end{bmatrix} = \begin{bmatrix}V_{o1}\\ V_{o2}\\ V_{o3}\end{bmatrix} \quad \text{or} \quad \left(\frac{1}{T_s}\right)[V_i][t] = [V_o] \quad (2.12)$$

Above equation can also be interpreted as the sum of three space vectors taken over the three time intervals. By definition

$$\overline{V_o} = \frac{2}{3}(V_{o1} + \overline{a^2}V_{o2} + \overline{a}V_{o3})$$

During the time interval t_1 $\qquad V_{o1}=V_{i1}$

$V_{o2}=V_{i2}$

$V_{o3}=V_{i3}$

Multiplying the second of above three equations by " a^2" and the third by " a " and adding the resulting three equations yields, for the output voltage during the fractional time interval t_1,

$$\boxed{\overline{V_o} = \frac{2}{3}(V_{i1} + \overline{a^2}V_{i2} + \overline{a}V_{i3})} \quad \text{or} \quad \boxed{\overline{V_o}(t_1) = \overline{V_i}(t_1)}$$

(2.13)

where $\qquad V_i(t_1)$ is the input space vector at the time t_1

$V_o(t_1)$ is the output space vector at the time t_1

Similarly for the second interval of time t_2 $\quad V_{o1}=V_{i2}$

$V_{o2}=V_{i3}$

$V_{o3}=V_{i1}$

Again multiplying the second of these two equations by "a^2" and the third by "a" and summing the resulting three equations we have,

$$\boxed{\overline{V_o} = \frac{2}{3}(V_{i2} + \overline{a^2}V_{i3} + \overline{a}V_{i1})} \tag{2.14}$$

Factoring out "a" from the above equation we get

$$\boxed{\overline{V_o} = \frac{2}{3}a^2(V_{i1} + \overline{a^{-1}}V_{i2} + \overline{a}V_{i3})} \tag{2.15}$$

It is well known that $a^{-1}=a^2$, so that the output voltage over the interval t_2 becomes

$$\boxed{\overline{V_o}(t_2) = a^2\overline{V_i}(t_2)} \tag{2.16}$$

Similarly, the output voltage vector over the time interval of t_3 can be expressed as

$$\overline{V_o}(t_2) = a\overline{V_i}(t_3) \quad (2.17)$$

Thus the output voltage averaged over the total time T_s will be

$$\overline{V_o}(t_1) = \overline{V_i}(t_1)\frac{t_1}{T_s} + \overline{a^2}\overline{V_i}(t_2)\frac{t_2}{T_s} + \overline{a}\overline{V_i}(t_3)\frac{t_3}{T_s} \quad (2.18)$$

Hence, the output voltage is made up of three space vectors,

1) The input voltage vector itself,

2) The input voltage vector phase shifted forward by 120° and

3) The input voltage vector phase shifted forward by 240°.

And hence the modulation equation is given by

$$[M_1(t)] = \begin{bmatrix} F_1 & F_2 & F_3 \\ F_3 & F_1 & F_2 \\ F_2 & F_3 & F_1 \end{bmatrix} = \frac{1}{3}\begin{vmatrix} 1+2q\sin(\omega_m t) & 1+2q\sin(\omega_m t+\frac{4\pi}{3}) & 1+2q\sin(\omega_m t+\frac{2\pi}{3}) \\ 1+2q\sin(\omega_m t+\frac{2\pi}{3}) & 1+2q\sin(\omega_m t) & 1+2q\sin(\omega_m t+\frac{4\pi}{3}) \\ 1+2q\sin(\omega_m t+\frac{4\pi}{3}) & 1+2q\sin(\omega_m t+\frac{2\pi}{3}) & 1+2q\sin(\omega_m t) \end{vmatrix};$$

Where $\omega_m = \omega_o - \omega_i$ (2.19)

Matrix representation of output voltage from equation 2.6 & 2.19 is

$$\begin{bmatrix} V_{AB} \\ V_{BC} \\ V_{CA} \end{bmatrix} = \begin{bmatrix} F_1V_{ab} + F_2V_{bc} + F_3V_{ca} \\ F_3V_{ab} + F_1V_{bc} + F_2V_{ca} \\ F_2V_{ab} + F_3V_{bc} + F_1V_{ca} \end{bmatrix}; \quad (2.20)$$

Indirect mode of operation (IMO) for AC-AC converter

As the name suggests, it is an indirect method of conversion. Instead of using one transfer matrix for AC-AC conversion as in case of direct mode control, the transfer matrix is divided in two-steps for performing AC-AC conversion. It can be viewed as conventional AC-DC-AC conversion with a difference that here a virtual DC link is generated and only nine bi-directional switches are used without any DC link elements.

Therefore, the output voltages and input currents of the matrix converter can be represented by the transfer function T and the transposed T^T such as

$$\boxed{V_o = T * V_I}$$

&

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ab} & S_{Ac} \\ S_{Ba} & S_{Bb} & S_{Bc} \\ S_{Ca} & S_{Cb} & S_{Cc} \end{bmatrix} \cdot \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \quad (2.21)$$

$$\boxed{I_I = T * I_o}$$

&

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ba} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{Cb} \\ S_{Ac} & S_{Bc} & S_{Cc} \end{bmatrix} \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (2.22)$$

where V_a, V_b and V_c are input phase voltages, V_A, V_B and V_C are output phase voltages, I_a, I_b and I_c are input currents and I_A, I_B and I_C are output currents. The elements in the transfer matrix T_{ij} represent the switch function from the instantaneous input voltage V_i to the instantaneous output voltage V_j and have to be assigned values that assure output voltages and input currents to follow their reference values. Defining a modulation strategy is actually filling in the elements of the transfer matrix. Although several modulation strategies have been proposed since Venturini announced a closed mathematical solution for the transfer function T in early 1980, [28]-[33] the indirect space vector modulation is gaining as a standard technique in the matrix converter modulations.

The indirect space vector modulation (indirect SVM) was first proposed by Borojevic et al in 1989 where matrix converter was represented by an equivalent circuit combining current source rectifier [34] and voltage source inverter connected through virtual dc link as shown in Fig. 2.6.

Inverter stage has a standard 3φ voltage source inverter topology consisting of six switches, *S7 ~ S12* and rectifier stage has the same power topology with another six switches, *S1 ~ S6*.

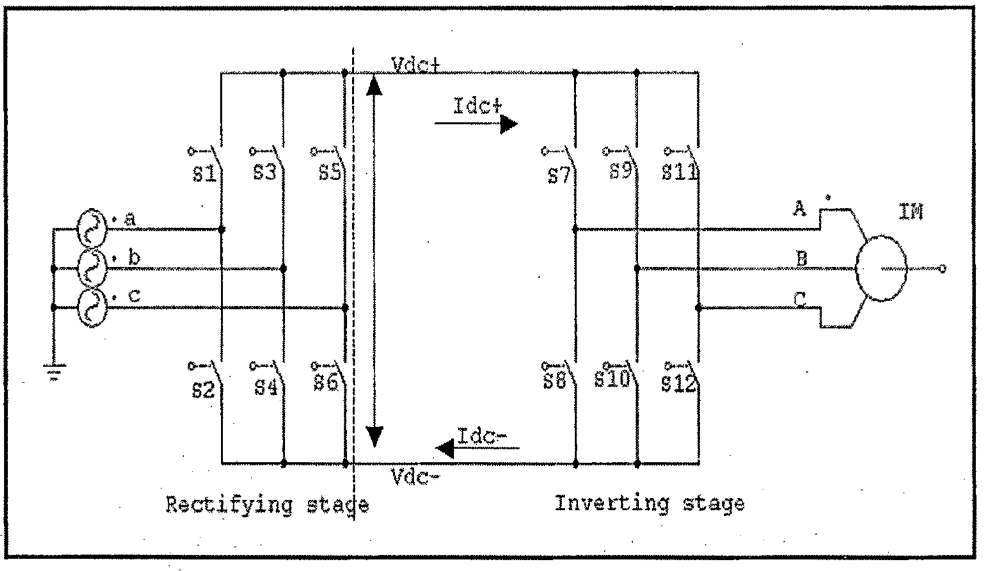


Fig 2.6 Equivalent model of matrix converter for indirect mode operation

Both power stages are directly connected through virtual dc-link and inherently provide bidirectional power flow capability because of its symmetrical topology. Although this equivalent circuit has provided a strong platform to analyze and derive several extended PWM strategies specified in a certain application since then, it is still ambiguous for a beginner to grasp its operating principle. The operating principle of the indirect SVM will be illustrated with graphical approach.

The basic idea of the indirect modulation technique is to decouple the control of the input current and the control of the output voltage. This is done by splitting the transfer function T for the matrix converter in (2.21) into the product of a rectifier and an inverter transfer function.

Rectifier transfer function:

The matrix multiplication of a fictitious rectifier transfer matrix consisting of a set of balanced sinusoidal quantities with a compatible set of Nx1 sinusoidal input quantities results a DC quantity.

i.e. $[V_{dc}]=[F_r(\omega_i t)]*[V_i(\omega_i t)]$ (2.23)

Where $F_r(\omega_i t)$ is rectifier transfer function

$V_i(\omega_i t)$ is set of input voltages

With reference to the fig 2.7, the above equation for rectifier mode can be rewritten as

$$\begin{bmatrix} V_{dc+} \\ V_{dc-} \end{bmatrix} = \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \quad (2.24)$$

Inverter transfer function:

A step further, the DC quantity resulting from the above equation (2.24) is multiplied by a set of balanced sinusoidal fictitious inverter transfer function as shown in equation (2.25) below.

$[V_o(\omega_o t)]=[F_i(\omega_o t)]*[V_{dc}]$ (2.25)

Where $F_i(\omega_o t)$ is inverter transfer function

$V_o(\omega_o t)$ is set of output voltages

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \begin{bmatrix} V_{dc+} \\ V_{dc-} \end{bmatrix} \quad (2.26)$$

The ultimate result of this matrix multiplication is a set of balanced output quantities.

$[V_o(\omega_o t)]=[F_i(\omega_o t)]*[F_r(\omega_i t)]*[V_i(\omega_i t)]$ (2.27)

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix}$$

Indirect mode operation for the static converter as described in earlier section is basically a two step process. No straight forward and simplified procedure of combining the rectifier and inverter transformer matrices has been reported in literature. In simple means, the three-phase to three-phase converter indirect transfer matrix can be derived from the generalized equation as follows:

$$[V_o(\omega_o t)] = [F_i(\omega_o t)][F_r(\omega_i t)][V_i(\omega_i t)] \quad (2.28)$$

$$\begin{bmatrix} Vab \\ Vbc \\ Vca \end{bmatrix} = K * \begin{bmatrix} \sin(\omega_o t) \\ \sin(\omega_o t - 120^o) \\ \sin(\omega_o t - 240^o) \end{bmatrix} * [\sin(\omega_i t) \quad \sin(\omega_i t - 120^o) \quad \sin(\omega_i t - 240^o)] * \begin{bmatrix} \sin(\omega_i t) \\ \sin(\omega_i t - 120^o) \\ \sin(\omega_i t - 240^o) \end{bmatrix} \quad (2.29)$$

Where K is equal to voltage or current transformation gain

Equation 2.29 above shows that the IMO transfer matrix consists of two terms.

Rectifier transfer matrix at input frequency

Inverter transfer matrix at output frequency

Hence the multiplication of three-phase input voltages with the rectifier transfer matrix can be seen as a fictitious rectification process. While the multiplication of the fictitious DC voltages with the inverter transfer matrix can be viewed as inversion.

Many researchers have made an attempt to simplify the indirect mode operation but all the efforts till date have resulted in a complex solution that is difficult to understand for implementation engineers.

Both the DMO method and IMO method can be realized using generalized converter circuit.

Functionality Explanation for DMO for Direct AC-AC conversion:

Consider switch matrix element F_1, bidirectional switches S_1, S_5 & S_9 are turned on whenever F_1 attains the value of one, resulting in the connection of input terminals a, b, c to the respective output A, B, C terminals. Whenever the value of F_1 is equal to zero, two of the previously conducting switches are turned off (in this case S_5 & S_9) with S_1 still conducting. Simultaneously the two off state switches connected to the input phase a are turned on (here S_2 & S_3) resulting in zero amplitude voltage across the load and thus inputs are disconnected from the outputs. Refer Fig 2.5.

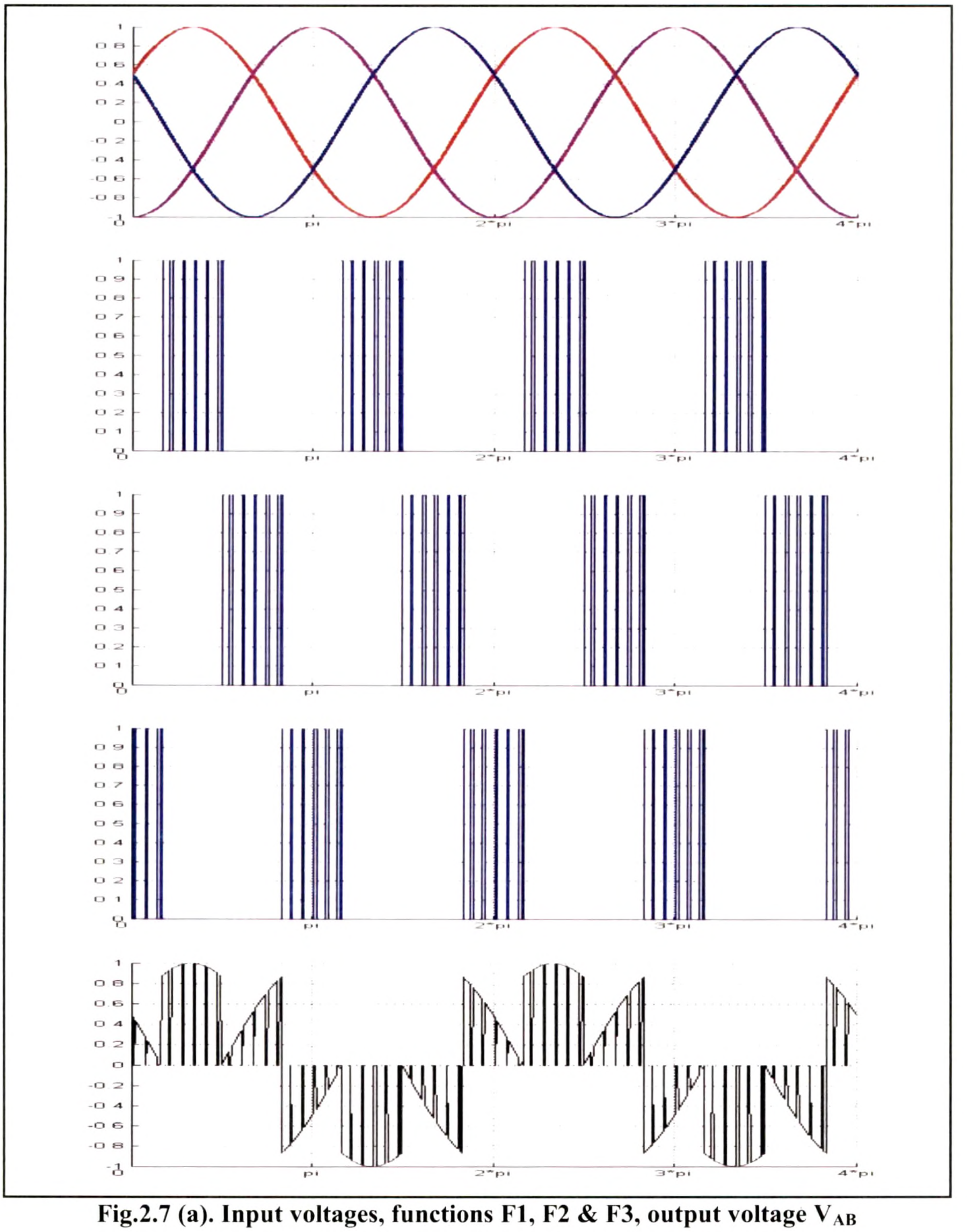


Fig.2.7 (a). Input voltages, functions F1, F2 & F3, output voltage V_{AB}

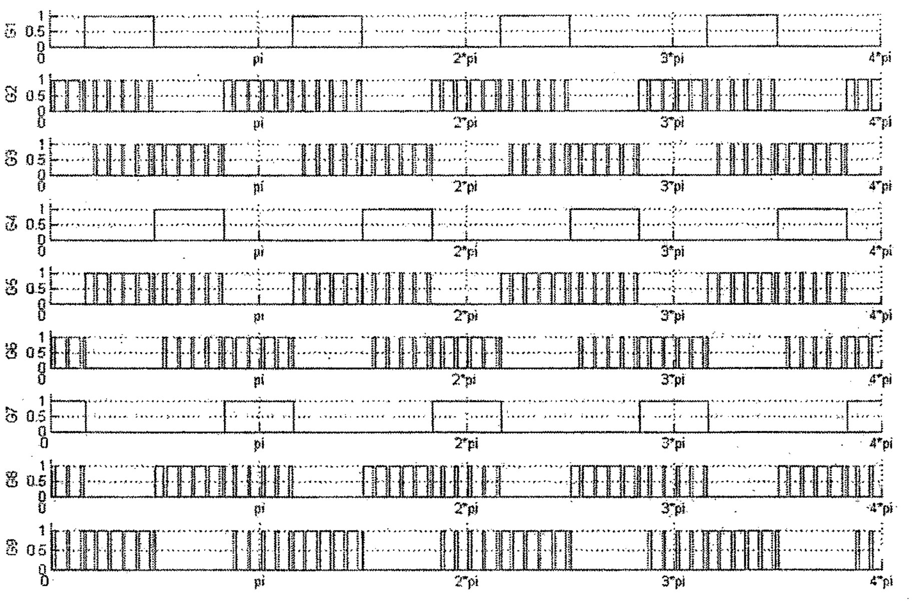


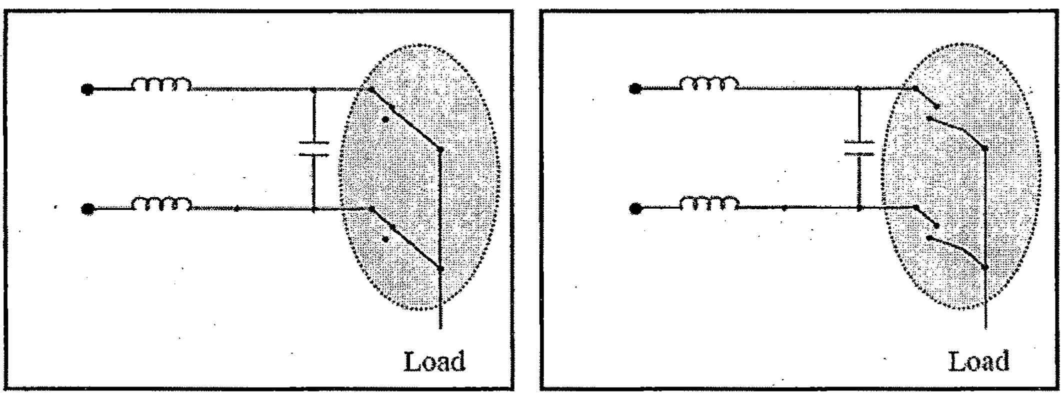
Fig.2.7 (b). Gate pulses for Bidirectional switches

This on-off operation for the switches S_5, S_9, S_2 and S_3 lasts for 120 degrees in a cycle of output voltage. During next interval of 120 degrees, operation is determined by F_2 and the functions performed by S_1, S_5 & S_9 are now performed by S_3, S_4 & S_8. The functions performed by S_2 & S_3 are done by S_5 & S_6 with S_4 still conducting.

Substitution of a switch by a switch continues in third and last interval (120 degrees) of half cycle of output voltage. On completion of the half cycle construction, the whole above-mentioned process is repeated. Thus a complete output waveform is generated (refer fig 2.7(a)). The resulting gate pulses are shown in fig 2.7(b)

2.2.3 The Commutation problem

Compared to conventional voltage source inverters, it is more difficult to achieve reliable current commutation between switches in matrix converters since there are no natural freewheel paths. The commutation has to be actively controlled at all times with respect to two basic rules. This can be visualized by considering just two switches on one output line of a matrix converter. It is important that no two bi-directional switches are switched on at any one time, as shown pictorially in figure 2.8(a). This would result in line-to-line short circuits and the destruction of the converter due to the large resulting currents. Also, the bi-directional switches for each output phase should not all be turned off at any point in time, as shown in figure 2.8(b). This would result in the absence of a path for the inductive load current, causing large over-voltages. These two considerations cause a conflict since semiconductor devices cannot be switched instantaneously due to propagation delays and finite switching times. This problem has been cited as holding back the commercial development of matrix converters. A method to tackle this problem is discussed in the following section.



(a) Short circuit condition (b) Open circuit condition

Fig 2.8 Simultaneous turning on operation leading to short circuit and turning off of two switches leading to high voltages due to breaking of inductive currents

The solution of this problem uses common emitter bidirectional switch as shown. In figure 2.9, T_A and T_B are IGBTs and D_1 and D_2 are diodes. Due to D_1 and D_2, if both transistors are off there will be no current circulation; that is, the considered topology can block voltages of any polarity. If, for example, $V_1 > V_2$, T_A is on and T_B is off, current will flow in the direction indicated in figure 2.9. In the contrary case, i.e. if $V_1<V_2$, T_B is on and T_A is off, current will flow in the opposite direction. The previous characteristics is presented using a bidirectional switch.

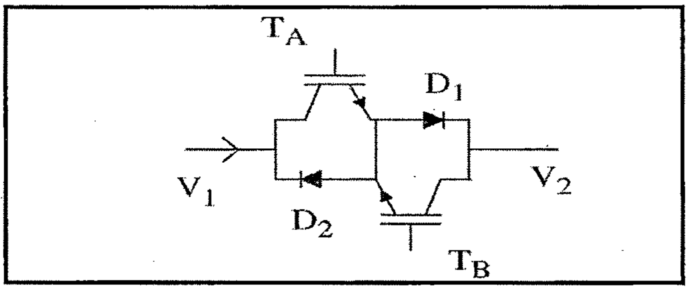


Fig. 2.9 Bidirectional Switch

It is worth noting that, although the topology of figure 2.2 is the basis of a bidirectional switch, the time required to turn on or off an IGBT, makes the commutation a nontrivial task. As an example of how the commutation actually takes place, consider figure 2.10. It should be noted that in order to obey equation (2.2), the following conditions should be avoided:

T_{A1} and T_{B2} on, with $V_A > V_B$
T_{A2} and T_{B1} on, with $V_A < V_B$ } condition A

T_{A1} and T_{A2} off, with $i_L > 0$
T_{B1} and T_{B2} off, with $i_L < 0$ } condition B

If condition A is violated, the sources will be short-circuited and, in the case of condition B, an abrupt interruption of the load current will occur and an over voltage will appear. The commutation method that is presented is based on load current measurements and is called soft switching. It works as follows:

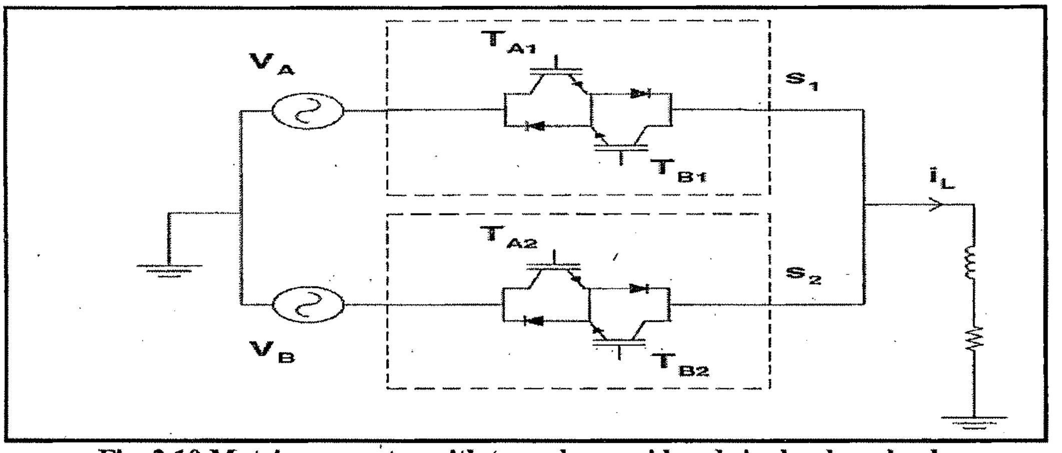


Fig. 2.10 Matrix converter with two-phase grid and single-phase load

(1) Suppose that initially s_1 is on, s_2 is off, $i_L>0$ and that it is necessary to turn s_1 off and s_2 on. From condition A and B, this implies T_{A1}, T_{B1} are on and T_{A2}, T_{B2} are off. Note that in the previous conditions neither A nor B is violated.

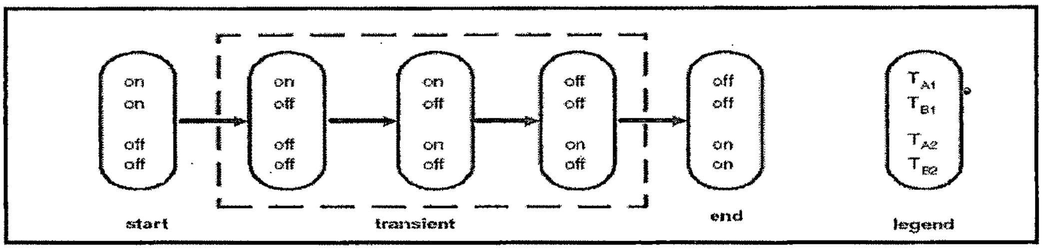
(2) Turn off T_{B1}. This brings no over voltage problems, since there is no current flow through T_{B1} and therefore the load current is not interrupted.

(3) Turn on T_{A2}. Note that there may or may not be current flow through T_{A2}, depending on the magnitudes of V_1 and V_2.

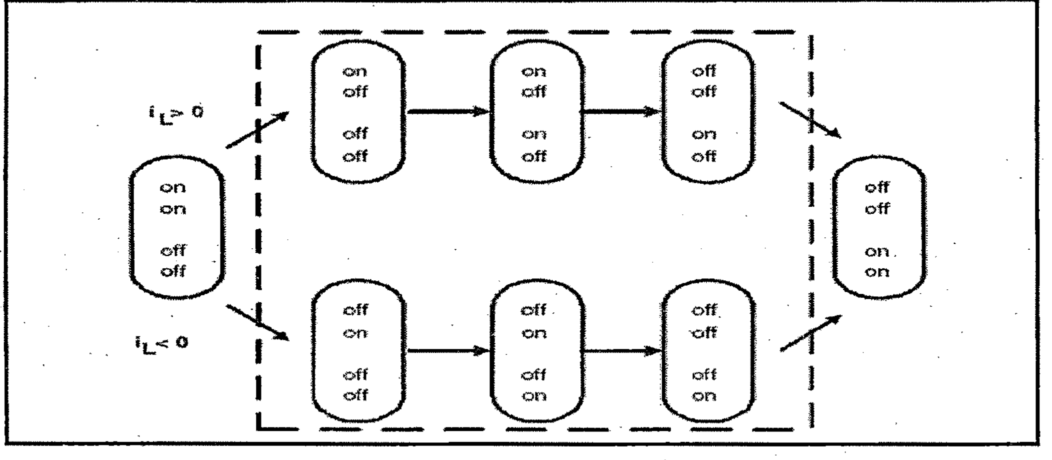
(4) Turn off T_{A1}. If T_{A2} was not actually conducting, there will be an over voltage due to the load current flow interruption, and this will turn on diode D. Since T_{A2} was on, the load will be connected to source VB, thus neutralizing the over voltage. Note that this completes the commutation: s_1 is off, s_2 is on.

(5) Turn on T_{B2}, so that s_2 can conduct in either direction.

The previous discussion can be summarised in the diagram shown in figure 2.11(a) and the general commutation strategy can be summarised as follows:



(a)



(b)

Fig 2.11 State diagram of the soft-switching commutation method:

(a) For positive load current;

(b) General case, i.e. load current of any polarity.

(1) Determine the direction of current load i_L.

(2) Depending on the direction of i_L, turn off the non-conducting transistor in the active switch (which will be turned off).

(3) Depending on the direction of i_L, turn on the transistor that should be conducting in the switch that will be turned on.

(4) Turn off the transistor that is still on in the active switch.

(5) Turn on the transistor that is still off in the switch that has just been turned on.

It is important to note that the above procedure does not violate condition (A) or (B).

Figure 2.11(b) shows the general state diagram of the commutation strategy under the assumption that initially s_1 is on and s_2 is off.

2.2.4 The input filter issue

Although the matrix converter is sometimes presented as an all silicon solution, due to the lack of the bulky and expensive DC-link capacitors of traditional indirect frequency converter, it also requires a minimum of reactive components, represented by the input filter. The input filter acts as an interface between the matrix converter and the AC mains (Fig.2.12).

Its basic feature is to avoid significant changes of the input voltage of the converter during each PWM cycle, and to prevent unwanted harmonic currents from flowing into AC mains [5], [35]. As matter of fact, due to the discontinuous input currents, the matrix converter behaves as a source of current harmonics, which are injected back into the AC mains [36]. Since these current harmonics result in voltage distortions that affect the overall operation of the AC system, they have to be reduced. The principal method of reducing the harmonics generated by static converters is provided by input filter using reactive storage elements [37].

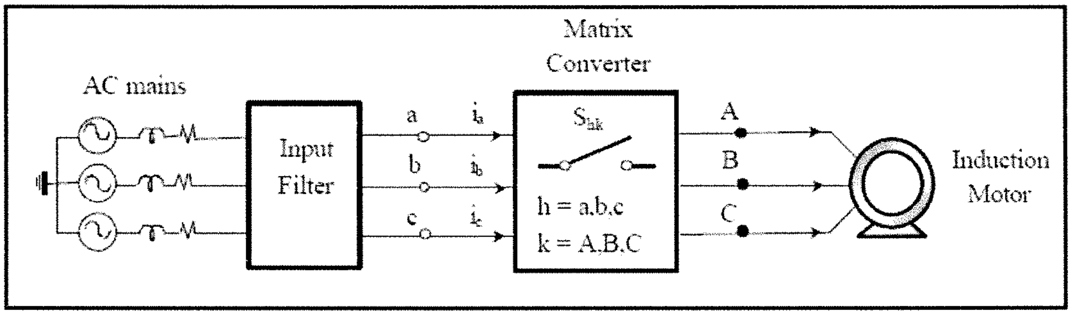
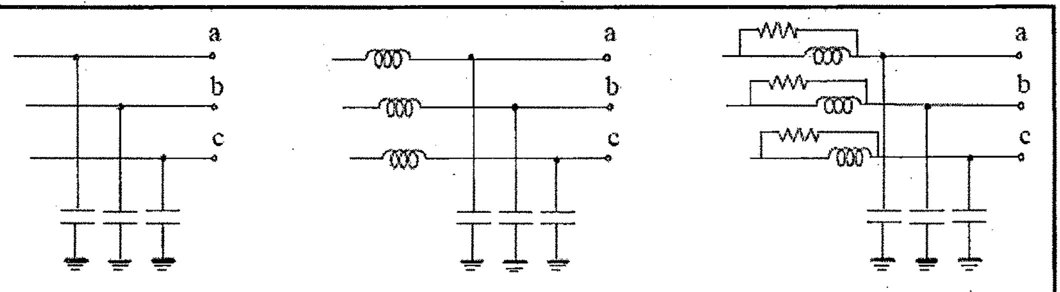


Fig 2.12 Schematic representation of a matrix converter adjustable speed drive

The problem of the input filter design for a matrix converter has been addressed in quite few papers [38], [36], [39]-[41] and looking at the literature, different configurations have been proposed for the matrix converter input filter [5], [39], [41], [42]. Such differences are a consequence of different design criteria, or at least differently weighted, different switching frequencies and different modulation strategies. In Fig. 2.13 three input filter configurations used in matrix converter prototype are shown.

In general, the design of an input filter for static power converters operating from an ac power system has to meet three main requirements:

- Carrying out the required switching noise attenuation;
- Having a low input displacement angle between filter input voltage and current;
- Guaranteeing overall system stability.



a) Capacitors star or delta

b) Second order L-C filter.

c) L-C filter with parallel connected. damping resistor.

Fig.2.13 Basic input filter configurations used in matrix converter prototypes.

In addition to these requirements, a set of considerations related to cost, voltage attenuation, system efficiency and filter parameter variation have to be made for an optimized input filter design [43], [44].

The first requirement is usually dictated by the EMI control standards: the input filter has to reduce the input current and output voltage total harmonic distortion below given values. In order to achieve this result, the resonant frequency of the filter has to be positioned accordingly to the converter switching frequency and its PWM pattern. When the input current harmonic spectrum generated by the converter is known, the filter resonance frequency is positioned where no unwanted harmonic components exist, which is usually the frequency range comprised between the fundamental and the switching frequency. In practice, due to the presence of imperfections and asymmetry in gating signals as well as implementation inaccuracies, some unwanted or uncharacteristic harmonics with small amplitude might exist in this region. If no damping is provided, these unwanted harmonics can be amplified by the filter to unacceptable level. On the other hand, a highly damped filter could not meet the harmonics attenuation requirements [43].

With regard to the matrix converter, Fig.2.13 shows that single stage filter configurations have been basically used to provide harmonic attenuation, but in the light of the new and future EMI standards such configurations are not expected either to meet the regulations or to be economically convenient [40], [44]. With regard to the second requirement, it follows by the presence in the filter of reactive storage elements. As it can be clearly seen from Fig.2.13, a phase displacement of the filter input current with respect to the line-to-neutral voltage proportional to the filter capacitance value is always present. Thus, in order to maintain high input power factor the capacitor size has to be minimized. This typically translates into an upper limit for filter capacitor value [38], [42]. Yet, the capacitor size limitation has several implications on the filter design. In order to meet the required attenuation specifications, the filter inductor size increases, which results in the overall filter size increase. Moreover, the input filter output impedance, related to the total filter capacitance, is more difficult to control, potentially resulting in converter instability [44].

As far as the matrix converter is concerned, a high displacement angle of the input line current due to the input filter capacitance component might be compensated by the matrix converter, setting as reference for the input current a lagging displacement angle. But in this way the maximum voltage transfer ratio for the converter would be significantly reduced. Therefore, even for the matrix converter, the upper limit of the input filter capacitance is set by the minimum acceptable AC mains power factor.

The last but not least requirement refers to the control of the impedance interaction between the input filter and the converter. In general, the filter output impedance should be as low as possible when compared to the converter input impedance [42], [45]. Increasing the filter capacitor size can reduce the filter output impedance. Practically the impedance interaction constraint determines the lower bound on the filter capacitor value. Additionally, proper filter pole damping is extremely important for achieving low filter output impedance for all frequencies and, thus, overall system stability. With regard to the matrix converter, although the stability issue did not appear in the relevant literature, it is not immune from this phenomenon. In conclusion, an optimized design of the matrix converter input filter is a quite difficult task, since this relies on a system level approach and in the light of the new harmonic and EMI reduction standards it can be somehow considered as an outstanding issue.

2.2.5 The protection issue

Likewise any other static converter, the matrix converter needs to be protected against the over voltages and the over currents that might be destructive for its semiconductor devices. An effective and robust protection scheme plays a important role in the implementation of a stable and reliable power converter. With respect to an AC drive application of the matrix converters, over voltages can originate externally, as voltage surge existing on the AC mains, or internally as consequence of a switch commutation error or timing inaccuracies that cause the interruption of an output motor current. This commutation-dependent risk is peculiar to the matrix converter, which does not have, differently from traditional DC link converter, any automatic static free wheeling path for the output motor currents. As discussed earlier, the commutation strategies for bi-directional switches today available do neither require, in normal operating conditions, free wheeling paths to safely commutate the output currents nor a snubber circuit. The only operating condition in which a free wheeling path is needed is when the motor is disconnected due to an emergency shutdown of the converter. In this case, to prevent destructive over voltages from appearing onto the matrix switches a free wheeling path to the motor currents has to be provided. As far as the over currents are concerned, they can rise either from a short circuit through the converter of two input voltages or from an output line-to- line or line-to-earth short circuit. In both cases the protection strategy usually adopted consists in turning all the switches off, using the fact that the currents are monitored and power semiconductors can both withstand and switch considerable over current on a non-repetitive basis [46]. It is obvious that such simply protection strategy can be used only if a freewheeling path is provided to the motor currents. Therefore, the over current protection can be considered as somehow included in the over voltage protection scheme.

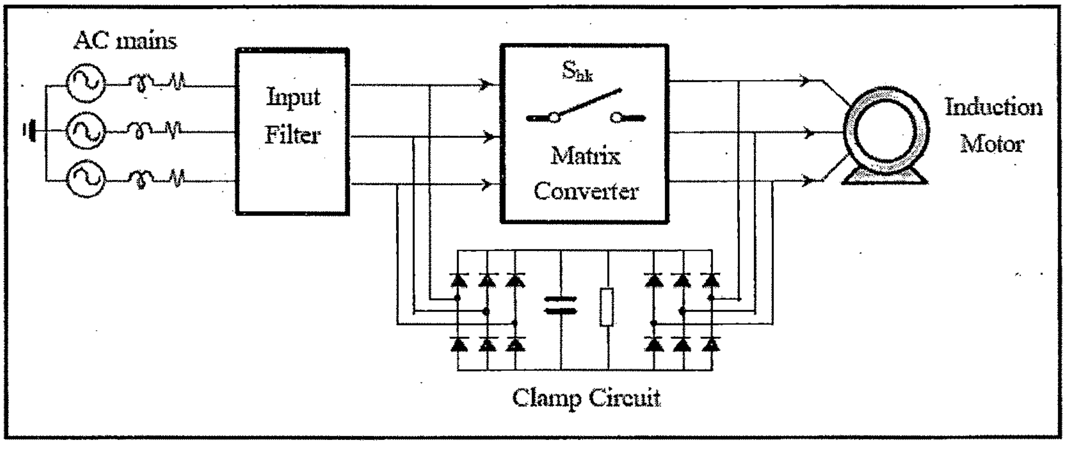


Fig.2.14 Clamp circuit as common protection for all matrix converter bi-directional switches.

The first protection scheme proposed in [5] and [47] is a clamp circuit made up of one or two capacitors connected to all input and all output lines through two diodes bridges (Fig.2.14). This clamp circuit is operative for all nine bi-directional switches. It protects the switches from the surge coming from the input AC line as well as from the surge on the output side that would be otherwise produced whenever an emergency shutdown of the converter is required. As a matter of fact, in the latter case, when the inductive currents of the motor are interrupted, the energy stored in the load is transferred to the clamp capacitor and no critical over voltage is caused if the capacitor is large enough. Furthermore, the clamp circuit prevents output voltage spikes caused during commutation of switches by the parasitic inductance of the power switch matrix and by the unavoidable timing inaccuracies. Since the capacitor voltage increases at each switching operation, some means to discharge the capacitor is required. An efficient energy removal method is to use the clamp energy to power system auxiliaries [47], even though a back up power supply would be probably needed due to the short term ride-through capability of the matrix converter [48]. This protection scheme has the advantages of being very simple; it has small hardware requirements and it is safe in all operating conditions. But it has also some drawbacks: it increases the number of the required semiconductor devices by 12 fast-recovery diodes, that might be reduced at 6 using some diodes of the power bi-directional switches [49]; it increases the amount of reactive components needed; and last but not least the optimum design of the clamp capacitor requires the knowledge of the equivalent circuit parameters of the motor [38]. A second recently proposed [50] passive protection scheme for low power applications relies on the use of three varistors, in triangle configuration, added at the input and output side of the converter, as shown in Fig.2.15.

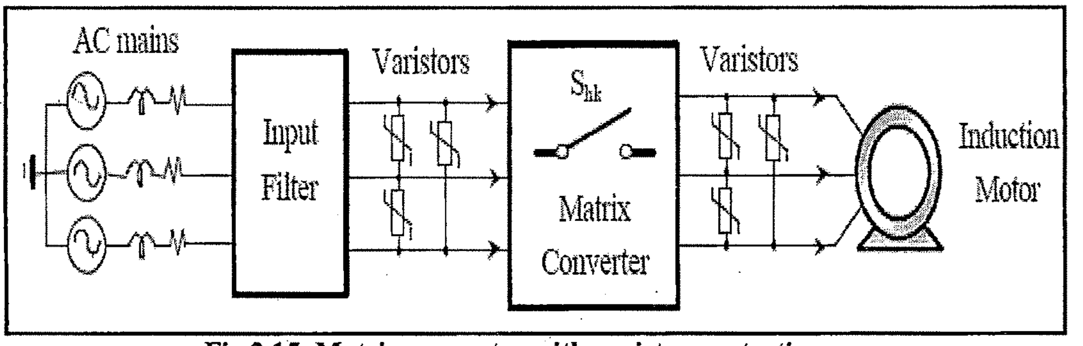


Fig.2.15. Matrix converter with varistor protection.

The input triangle has to protect the converter switches from the voltage surges coming from the AC mains. With regard to the output side, the risk of over voltages originates, once more, from a hard converter shutdown due to an emergency stop or a converter error. In order to avoid that the output voltages rise to destructive level, the energy stored in the motor leakage inductances has to be managed, providing a free wheeling path to the motor currents. Since this stored energy is rather small, the varistors can be the devices that provide the freewheeling path to the motor currents and absorb the relevant energy.

During normal operations, the losses caused by the varistors are not worth mentioning. But the varistors triangles, by themselves, are not sufficient to guarantee, during a converter shut-down, a reliable protection of the matrix IGBTs: a problem occurs when a turning-off bi-directional switch reaches its blocking capability with a certain delay with respect to the others. In this case, the already turned off switches may experience the full over voltage and being destroyed. In order to protect the single IGBT, a simple circuit made up with a suppressor diode is added to any IGBTs. The basic scheme of the added circuit is shown in Fig.2.16.

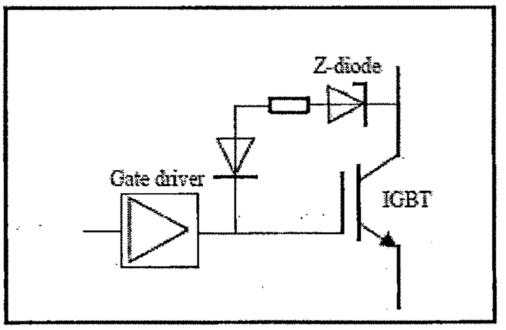


Fig.2.16 Gate driver with suppressor protection.

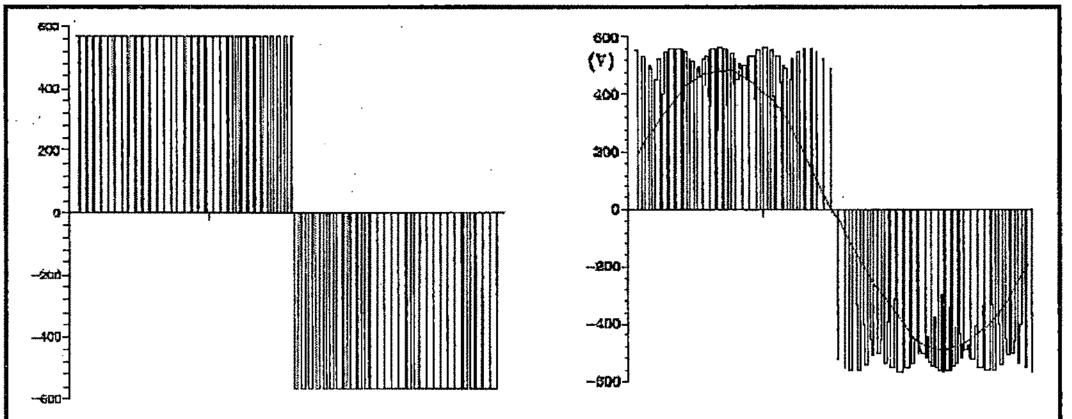
The inserted diode has the characteristic of a Zener diode with a high breakdown voltage. When the collector emitter voltage of the IGBT rises above the breakdown voltage of the suppressor diode, the IGBT is charged again and becomes conductive in its non-saturated region. This operation causes high losses in the IGBT, but it lasts only until all IGBTs are off and so it does not harm the chip. Compared to the clamp circuit solution the varistor/suppressor diode protection scheme demands for some hardware modifications but it has the advantage of not requiring additional power semiconductor devices and reactive storage component, yielding a more compact and costly effective solution. As for the clamp circuit, the equivalent circuit parameters of the motor have to be known in order to select the suitable varistor.

2.3 The Performance:

Since no energy storage components are present between the input and output side of the matrix converter, the output voltages have to be generated directly from the input voltages. Each output voltage waveform is synthesized by sequential piecewise sampling of the input voltage waveforms. The sampling rate has to be set much higher than both input and output frequencies, and the duration of each sample is controlled in such a way that the average value of the output waveform within each sample period tracks the desired output waveform [5]. As consequence of the input-output direct connection, at any instant, the output voltages have to fit within the enveloping curve of the input voltage system. Under this constraint, the maximum output voltage the matrix converter can generate without entering the over- modulation range is equal to $\sqrt{(3/2)}$ of the maximum input voltage: this is an intrinsic limit of matrix converter and it holds for any control law [5], [38].

The Output Voltage

Entering in the over- modulation range, thus accepting a certain amount of distortion in the output voltages and input currents, it is possible to reach higher voltage transfer ratio [23], [51], [52]. In Fig.2.17 the output phase to phase voltage waveform of a matrix converter is shown and compared to the output waveform of a traditional voltage source inverter (VSI). The output voltage of a VSI can assume only two discrete fixed potential values, those of the positive and negative DC-bus. In the case of the matrix converter the output voltages can assume either input voltage a, b or c and their value is not time-invariant: the effect is a reduction of the switching harmonics [38].



a) VSI b) Matrix converter

Fig.2.17 Output voltage waveforms generated by a VSI and a matrix converter

The Input Current:

Likewise to the output voltages, the output currents, synthesized by sequential piecewise sampling of the output current waveforms, directly generate the input currents. If the switching frequency of the matrix converter is set to a value that is much higher than the input and output frequency, the input currents drawn by the converter are sinusoidal: their harmonic spectrum consists only of the fundamental desired component plus a harmonic content around the switching frequency.

In Fig.2.18 the input current drawn by a matrix converter for a 2 kHz switching frequency is shown. It can be noted that the amplitude of the switching harmonic components is comparable to the fundamental amplitude. It is then obvious that an input filter is needed in order to reduce the harmonic distortion of the input line current to an acceptable level. It follows that care should be used in speaking about matrix converters as an "all silicon" solution for direct AC/AC power conversion, since some reactive components are needed.

The matrix converter performance in terms of input currents represents a significant improvement with respect to the input currents drawn by traditional VSI converters with a diode bridge rectifier, whose harmonic spectrum shows a high content of low-order harmonics.

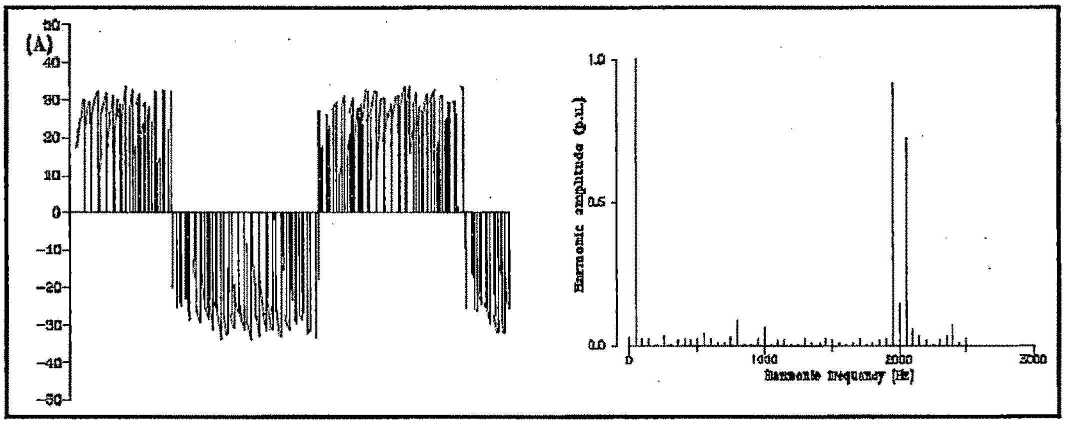


Fig.2.18 Matrix converter input current and harmonic spectrum. Switching frequency 2kHz.

In the light of the standards related to power quality and harmonic distortion of the power supply this is a very attractive feature of matrix converter.

The input power factor control

The input power factor control capability is another attractive feature of matrix converters, which holds for most of the control algorithms proposed in literature [5], [56], [47], [54]-[56]. Despite of this common capability it is worth noting that a basic difference exists with respect to the load displacement angle dependency. For instance, the algorithm proposed in [24] does not require the knowledge of the load displacement angle in order to fully control the input power factor. On the contrary, the algorithm in [25] does require the knowledge of the load displacement angle whenever the reference input power factor is different from unity. From an algorithm computational burden point of view this is a drawback, since it implies additional quite heavy calculations.

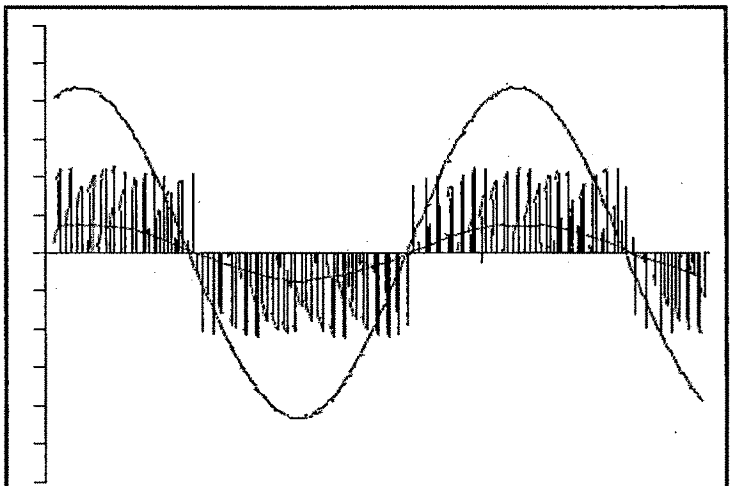


Fig.2.19 Matrix converter input line-to-neutral voltage, instantaneous input current and its average value

2.4 Comparison

A comparison in terms of number of components utilized by matrix converter, a conventional AC-DC-AC converter having an inverter with diode bridge rectifier and a PWM VSR- PWM VSI (functional characteristics of bi-directional power flow and sinusoidal input currents) is summarized in table 2.1. It can be seen that the DC link capacitor and input inductors associated with the back-to-back inverter circuit are replaced with the extra six switching devices in the matrix converter solution.

Table 2.1 Comparison of different topologies used for AC-AC conversion

Topology	Controlled semiconductor devices	Fast switching diodes	Rectifier diodes	Large electrolytic capacitors	Large inductors
Inverter with diode bridge	06	06	06	01	01*
PWM WSR-PWM VSI	12	12	00	01	03
Matrix converter	18	18	00	00	00

2.5 Simulation of Static AC-AC using IMO mode of operation

System parameters:

Case I

Input voltage: 415 Volts, 3-phase

Input frequency: 50 Hz

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

Output frequency: 50 Hz

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

Case II

Input voltage: 415 Volts, 3-phase

Input frequency: 50 Hz

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

Output frequency: 100 Hz

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

Explanation: Simulation of 9 switch Static AC-AC conversion is carried out using Indirect mode of operation. An analog approach is applied wherein a fictitious DC voltage is being generated using various combination of nine bidirectional switches based on the sector selection and then the same switches are used in inversion mode for generating AC output. Then the both the controls algorithms are merged and final gate pulses are generated. FFT analysis is also carried out for the input current signal and output voltage signals. The output frequency is varied from 50 Hz to 100 Hz and the difference is harmonic spectrum is observed

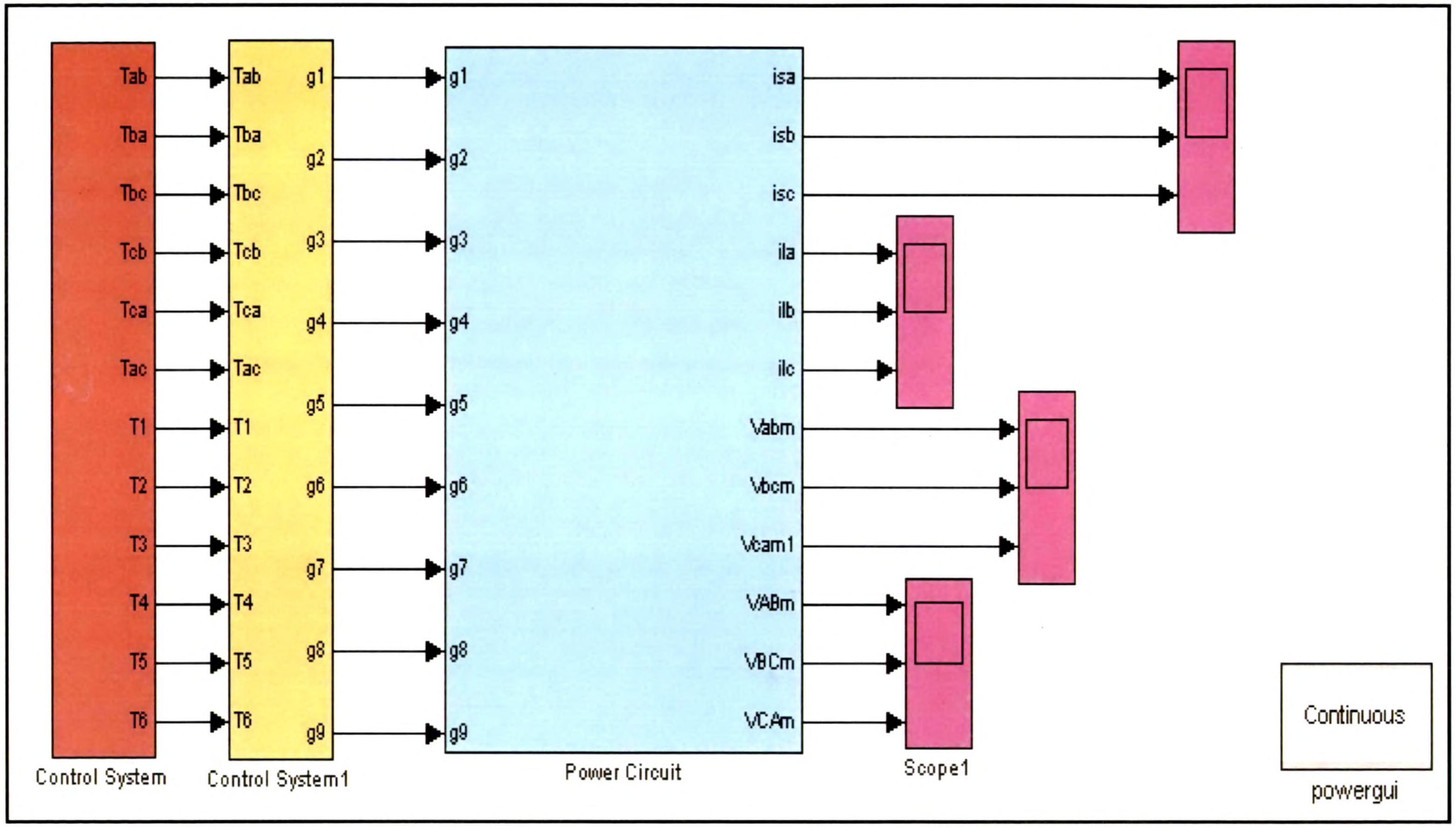


Fig. $S_{2.1}$. Simulation Block Diagram of Three-phase to Three-phase AC-AC converter using IMO mode of operation.

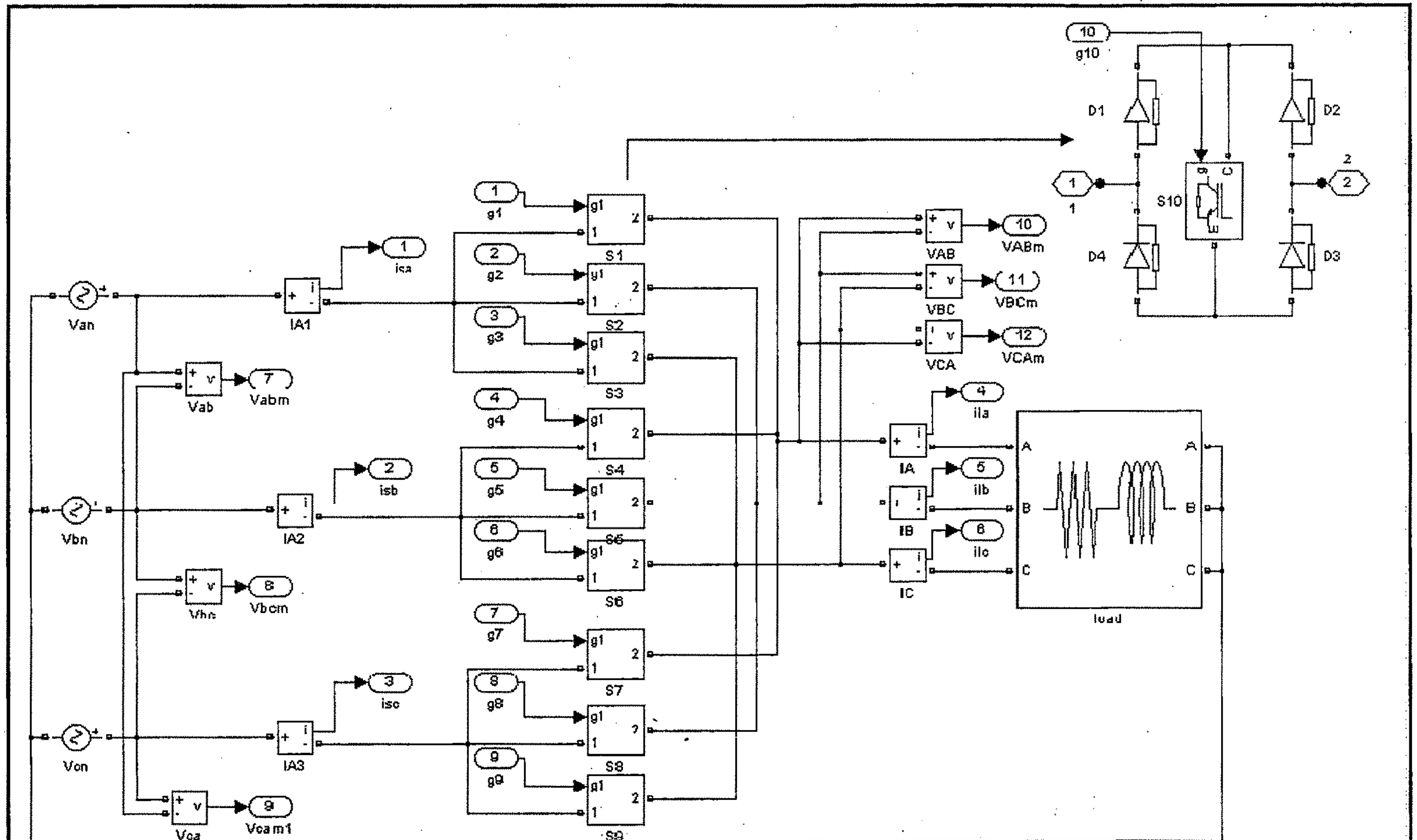
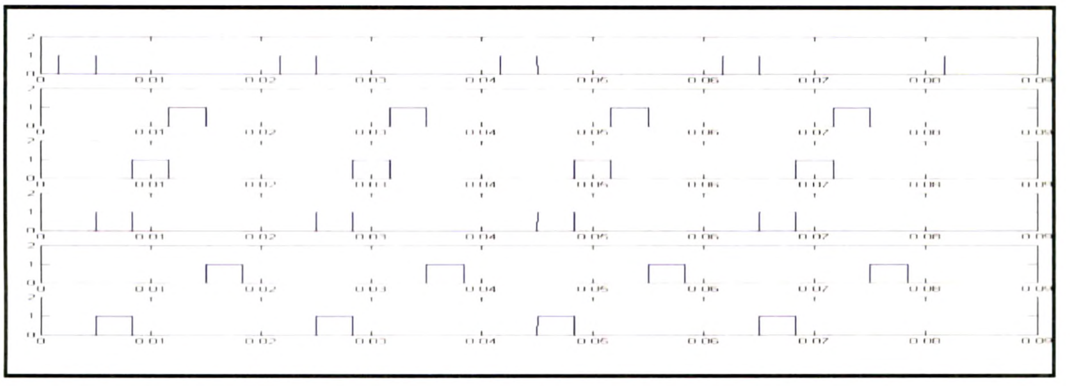
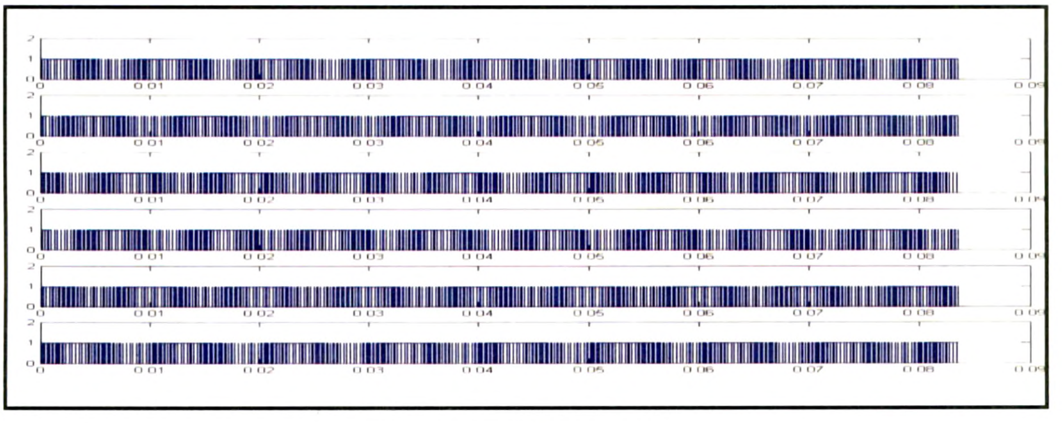


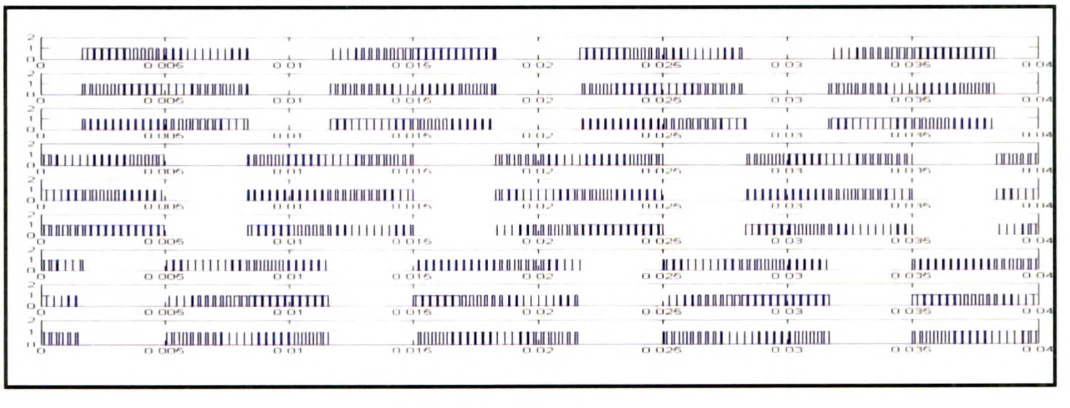
Fig $S_{2.2}$. Power Circuit layout for the Direct AC-AC converters using IMO modulation technique



(a)



(b)

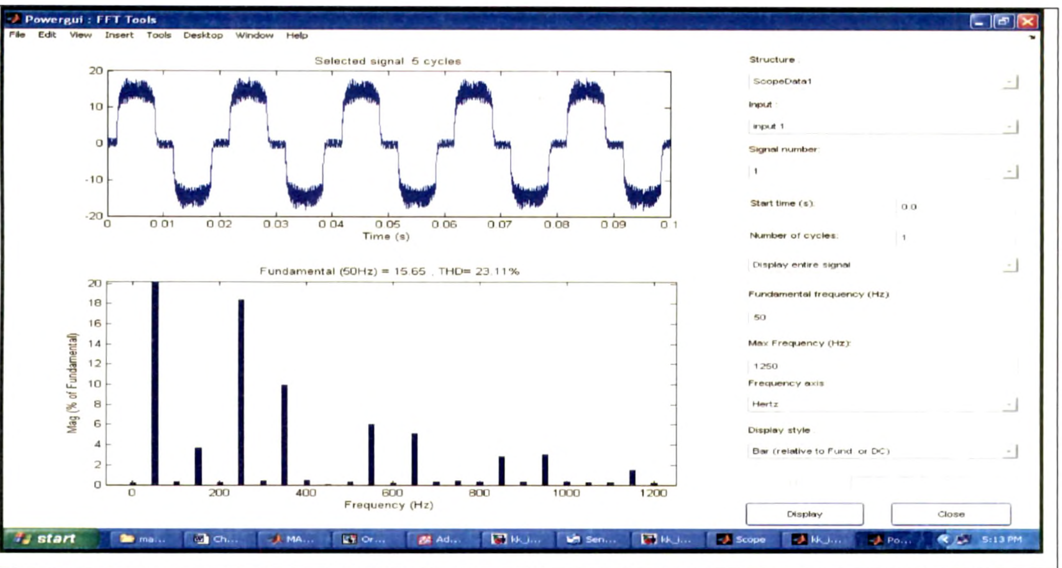


(c)

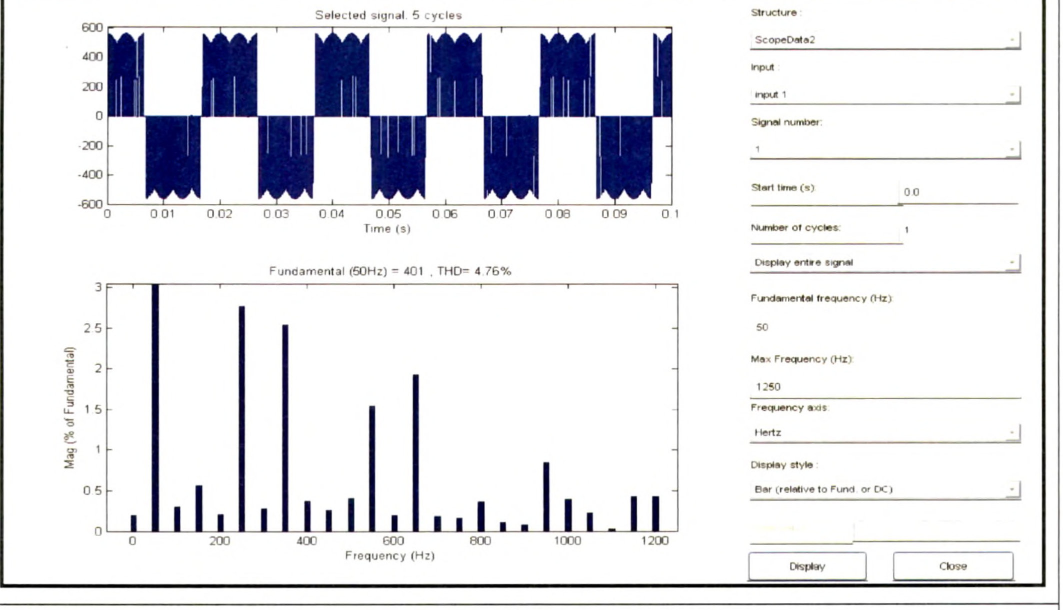
Fig $S_{2.3}$(a) Rectifier pulses for the generation of fictitious DC voltages

(b) Inverter Pulses for generation of output voltages

(c) Finally development of nine gate pulses for Bidirectional Switches



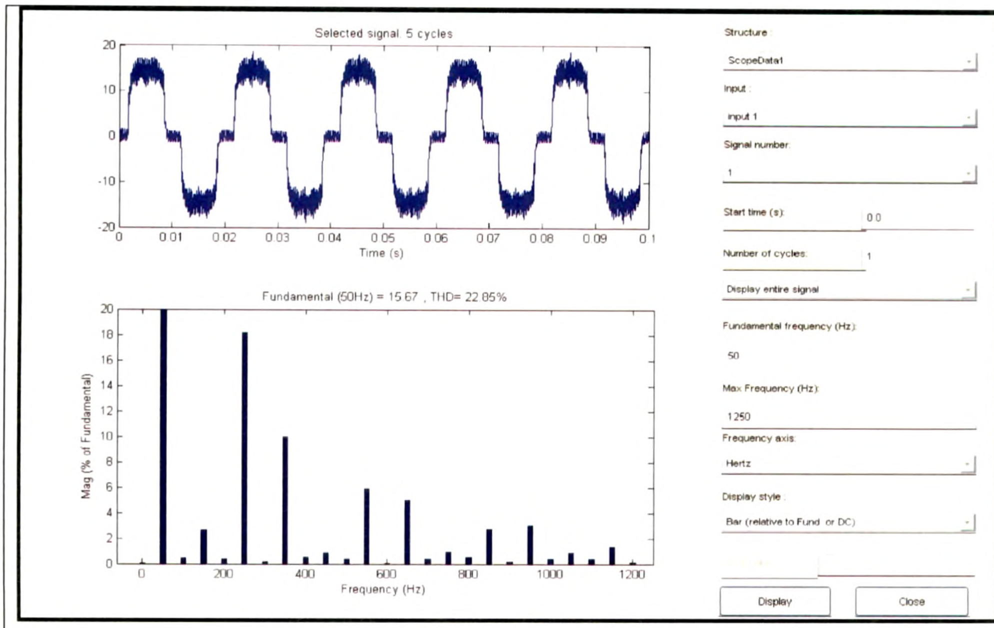
(a)



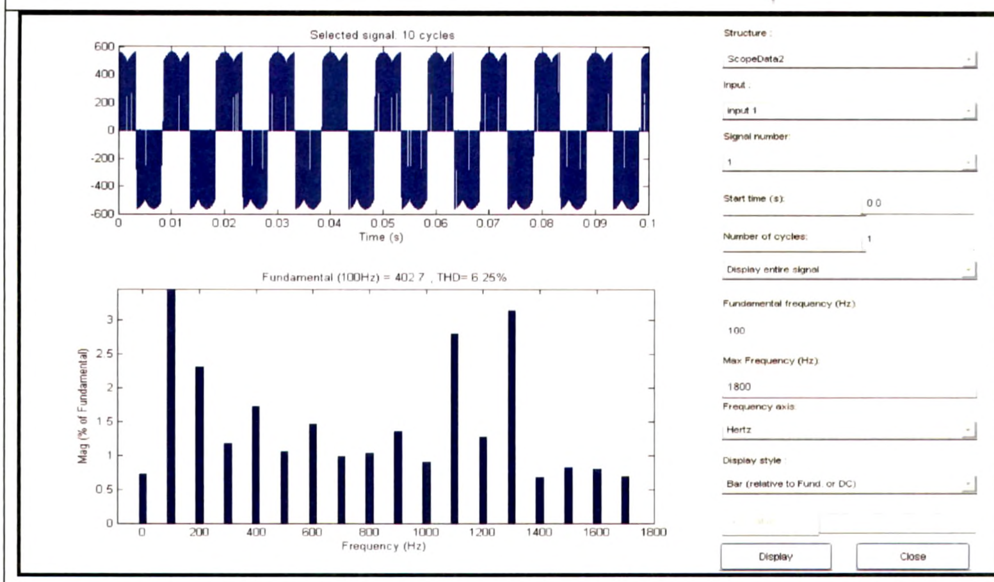
(b)

Fig $S_{2.4}$(a) Input Current and its harmonic analysis
(b) Output Voltage and its harmonic analysis at 50 Hz

Results for 100 Hz generation

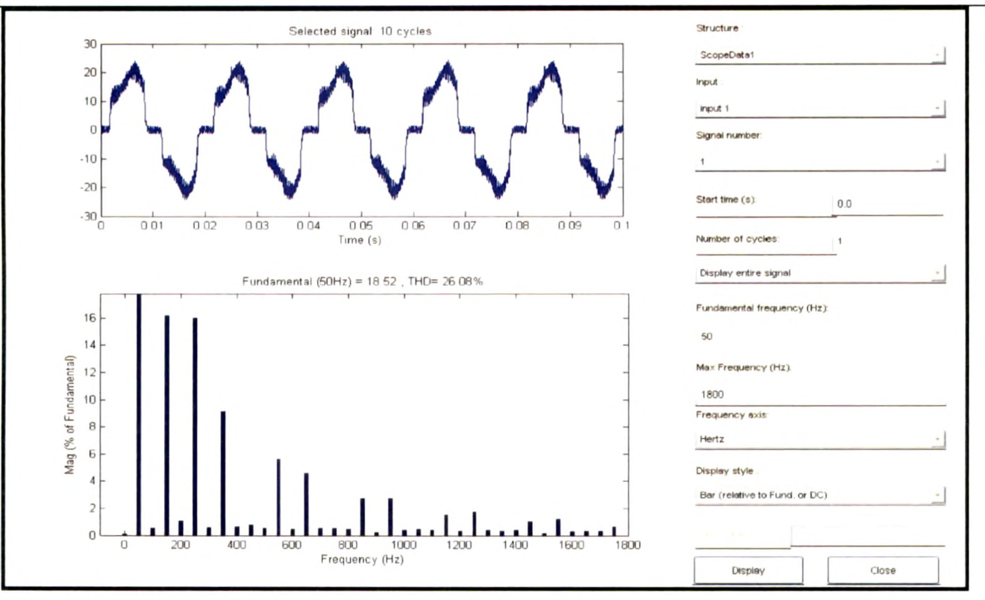


(a)

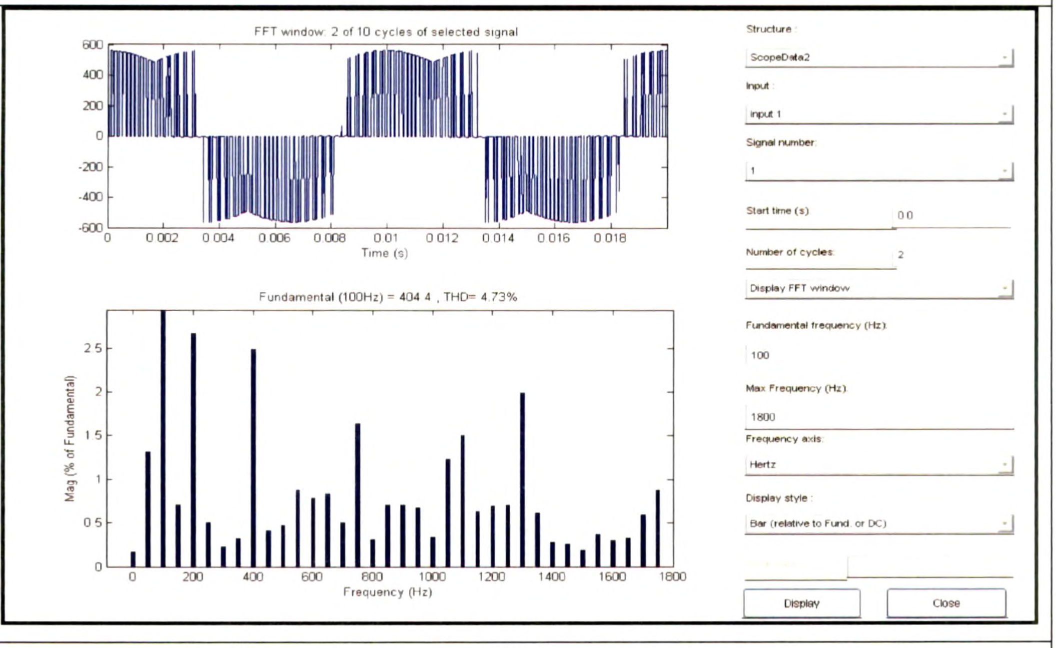


(b)

Fig S2.5(a) Input Current and its harmonic analysis
(b) Output Voltage and its harmonic analysis at 100 Hz



(a)



(b)

Fig $S_{2.6}$(a) Input Current and its harmonic analysis
(b) Maximum output Voltage and its harmonic analysis at 100 Hz

2.6 Three phase to single phase conversion

Single-phase applications, where low frequency power is required, are supplied by single phase to single-phase cycloconverter. If the power requirement for such applications is sufficiently large then this cause unbalance in mains supply system. An alternate solution to this problem is to supply such variable frequency loads through a three phase to single phase converter. Thus results in equal distribution on stress on all the input phases.

There are two possible ways of structuring three-phase to single phase static converter depending on the power conversion requirement. They are

- Full bridge Configuration utilizing six bidirectional switches
- Half bridge configuration utilizing four bidirectional switches

Half bridge configuration is simple and easy to implement but the full bridge configuration is more versatile in nature and capable of delivering more power. Generalized direct AC-AC converter configuration is used for deriving three-phase to single phase converter by setting the number of input phases to three and the number of output phases to one.

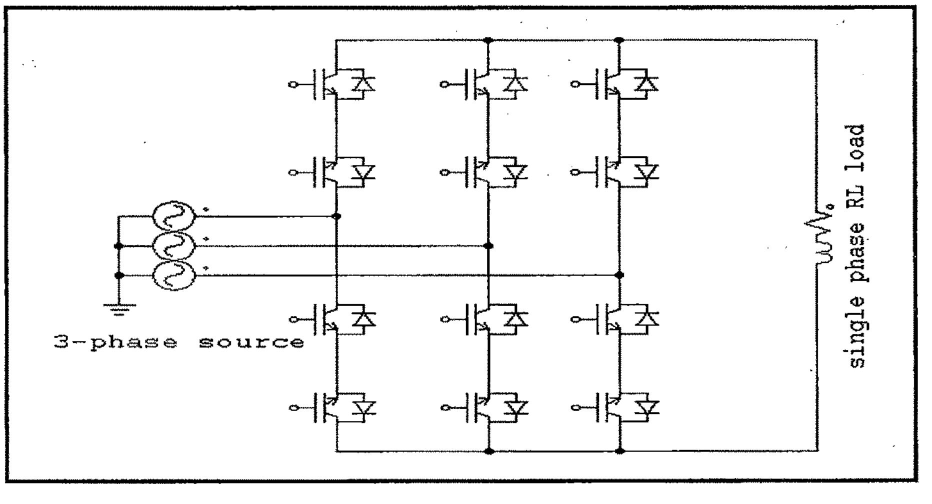


Fig 2.20 Three-phase to single-phase full bridge Direct AC-AC converter

Fig 2.20 shows three-phase to single phase converter consisting of six bidirectional switches. This configuration is most suitable for three phase three-wire applications. An alternate configuration for achieving similar performance is shown in figure 2.21. This scheme can be used for three phase four wire systems, i.e. when system neutral is available. Though simple in construction and implementation, this configuration suffers in poor input current spectrum compared to full bridge configuration.

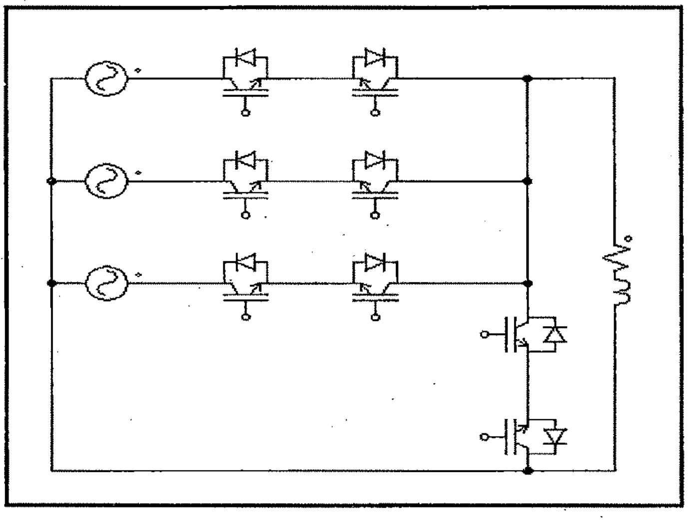
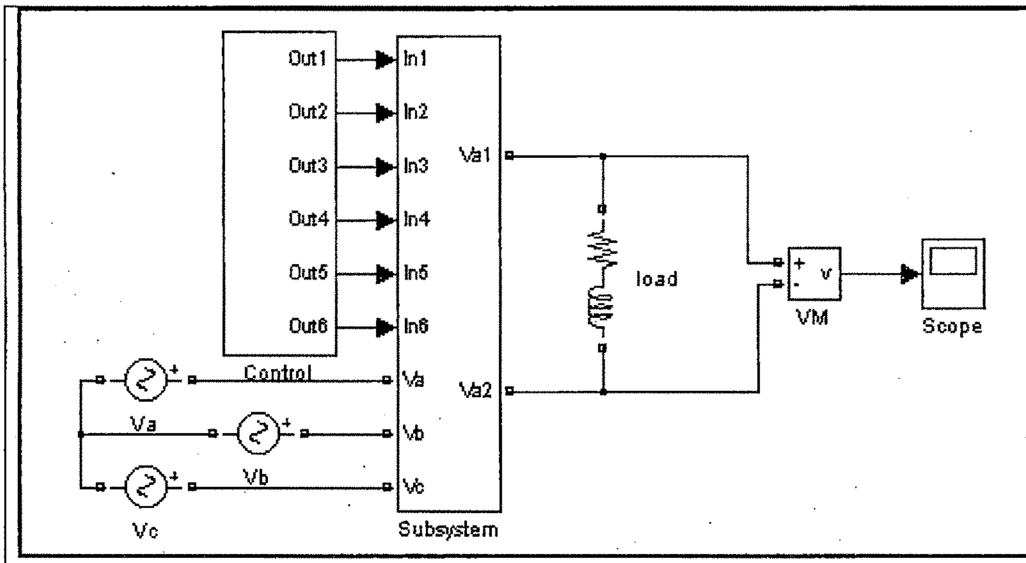


Fig 2.21 Three-phase to single-phase half bridge Direct AC-AC converter

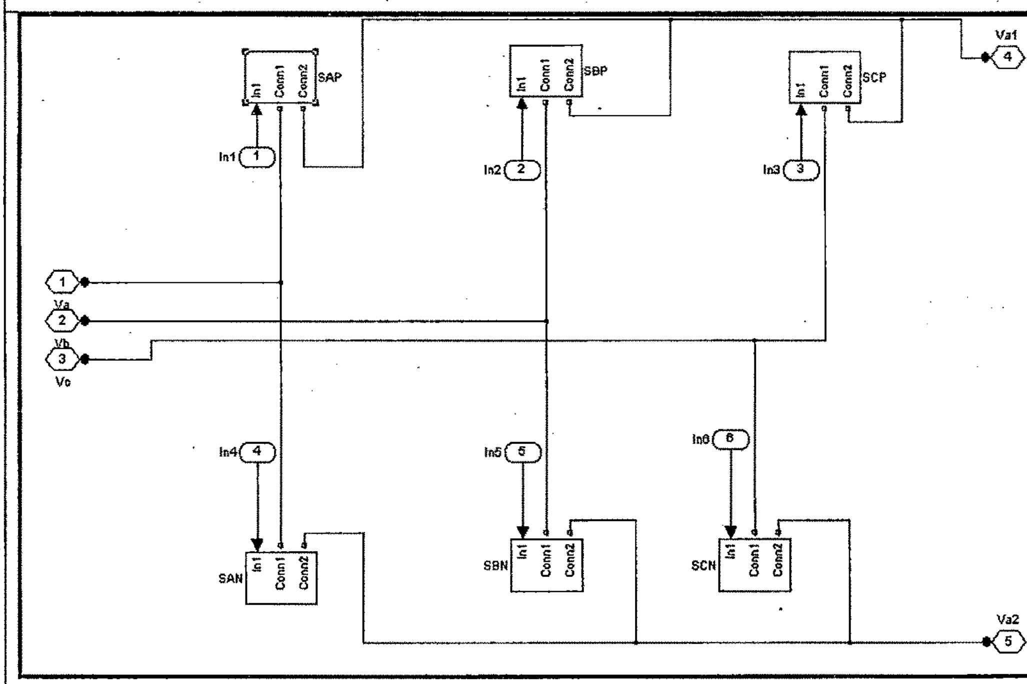
2.7 Simulation of the three-phase to single-phase converter

Input voltage: 415 Volts, 3-phase
Input frequency: 50 Hz
Output frequency: 50 Hz
Output voltage: 480 volts, 1 phase
Output load parameters: R= 10 ohms, L = 19 mH

Explanation: in this simulation model the static converter is modified and used for phase transformation. The input fed to the converter is three phase where else the output derived is single phase. The same nine switch converter power circuit is now limited to six switch power circuit. The control topology is slightly modified to yield the desired output. Harmonic spectrum for input current and output voltage is also derived from the simulation model to study the level of distortion introduced into the source due to the phase transformation.



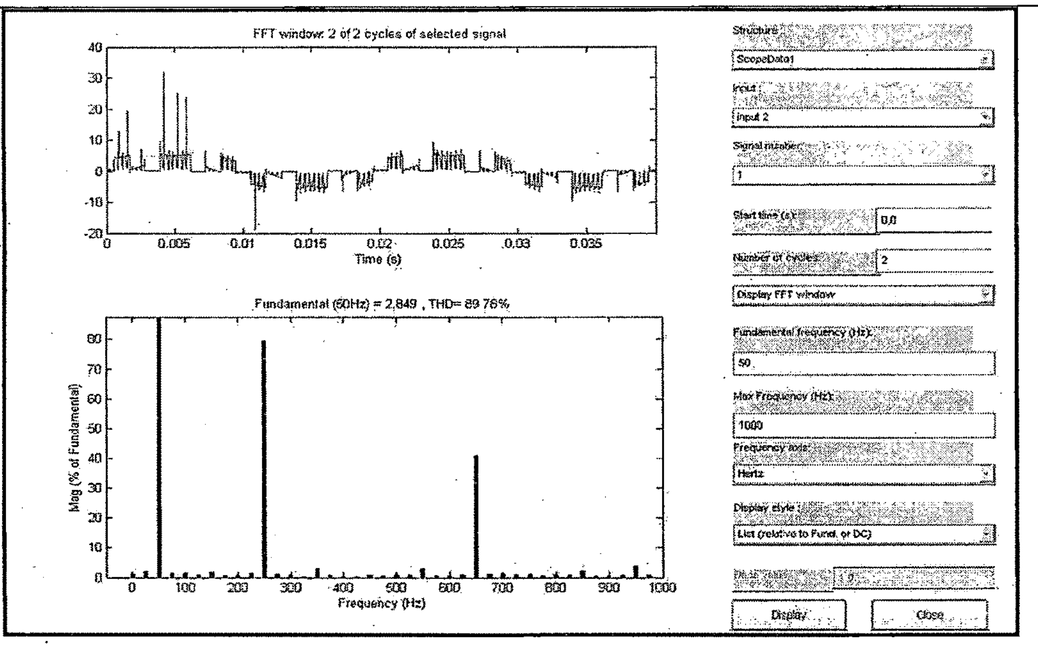
(a)



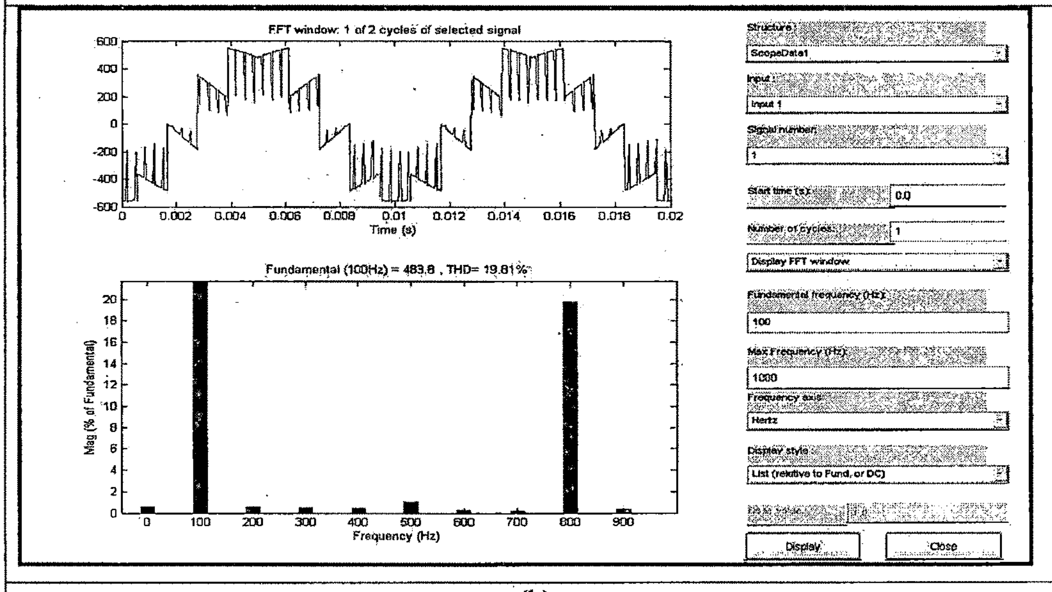
(b)

Fig $S_{2.7}$(a) System block diagram

(b) Power circuit diagram of the converter



(a)



(b)

Fig $S_{2.8}$(a) Input current and its analysis

(b) Output voltage and its harmonic analysis

2.8 Single-phase to Three-phase converter

It is well known that 80% of industrial loads are motor loads of various capacities. Major part of these motor loads is three-phase induction motors as these motor are more efficient and economical compared to their competitors and single phase counterparts. Hence the three-phase power in its original form is the most economical and efficient usage of electrical power. Exceptions are always there, in many circumstances it is seen that extension of three-phase power at certain locations is not economically viable. Alternately single-phase mains supply such areas. The cost of the single phase to three-phase conversion in such cases is comparative low compared to extension of three phase mains. Hence many schemes have been worked out and proposed in the past. Broadly these systems are rotary or static. In rotary systems, a rotary transformer along with capacitors is used. A rotary transformer is basically a poly phase squirrel cage induction motor without any shaft. In no load condition, capacitor current I_{cap} flows into the rotary transformer.

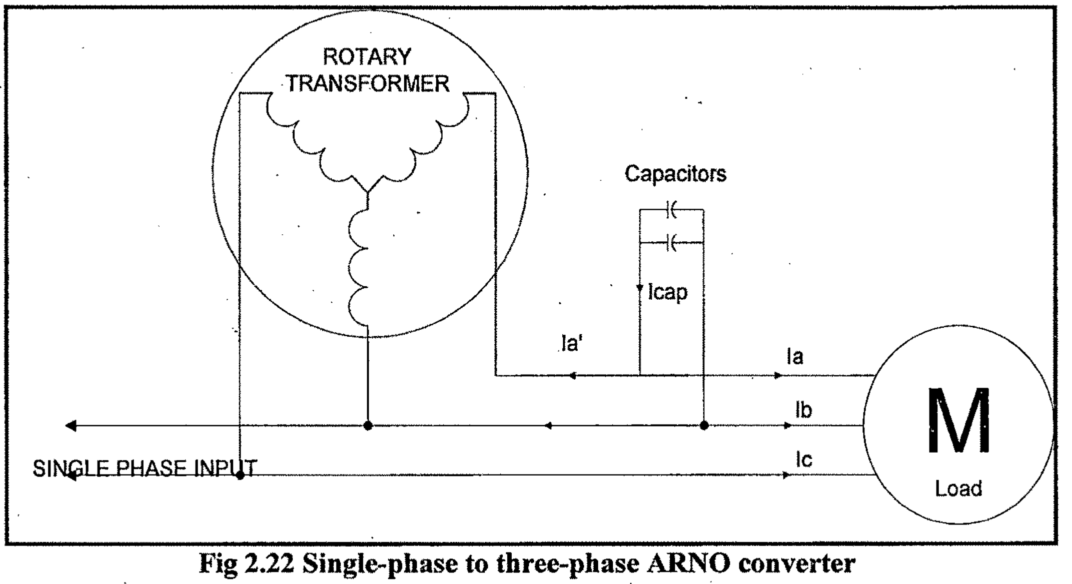


Fig 2.22 Single-phase to three-phase ARNO converter

During light loads condition a part of the capacitor current flows through rotary transformer and balance amount of capacitor current flows through the load. With the increase in the load system requirements more percentage of capacitor current flows in the external load circuit. This is commercially known as ARNO converter.

The main advantage of the above mentioned rotary converter is it is cost effective solution. A single rotary converter can supply to number of motor loads simultaneously. Initial high starting torque requiring loads are matters of serious concern for rotary transformer and also high no load losses also contribute a lot.

The static converter illustrated in fig. 2.23 employs an autotransformer with capacitors.

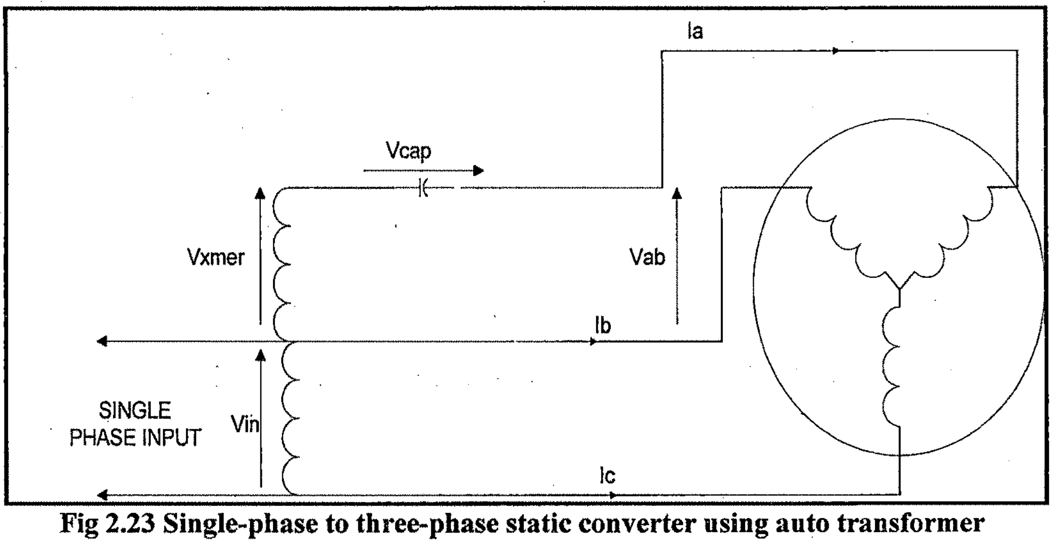


Fig 2.23 Single-phase to three-phase static converter using auto transformer

As seen from the figure, the phase A current is supplied by capacitor. A suitable design of autotransformer and appropriate selection of capacitors can aid in achieving balance in three phase output voltages. As an inherent advantage this converter exhibits property of having low no load losses. Also it capability to balance load motor currents makes it suitable to rotary transformer. But it suffers limited breakdown torque and also is sensitive to large variation in operating load point.

Both the above-mentioned converters were popular in late sixties until the introduction of thyristors to the market. After the familiarity with SCRs, the researches preferred conventional AC-DC-AC converters consisting of few diodes, thyristors and energy storage elements foe conversion of converting single phase to three phase conversions.

With an attempt to eliminate the usage energy storage elements, a static converter is discussed here. The static converter shown in figure 2.24 consists of six bidirectional switches.

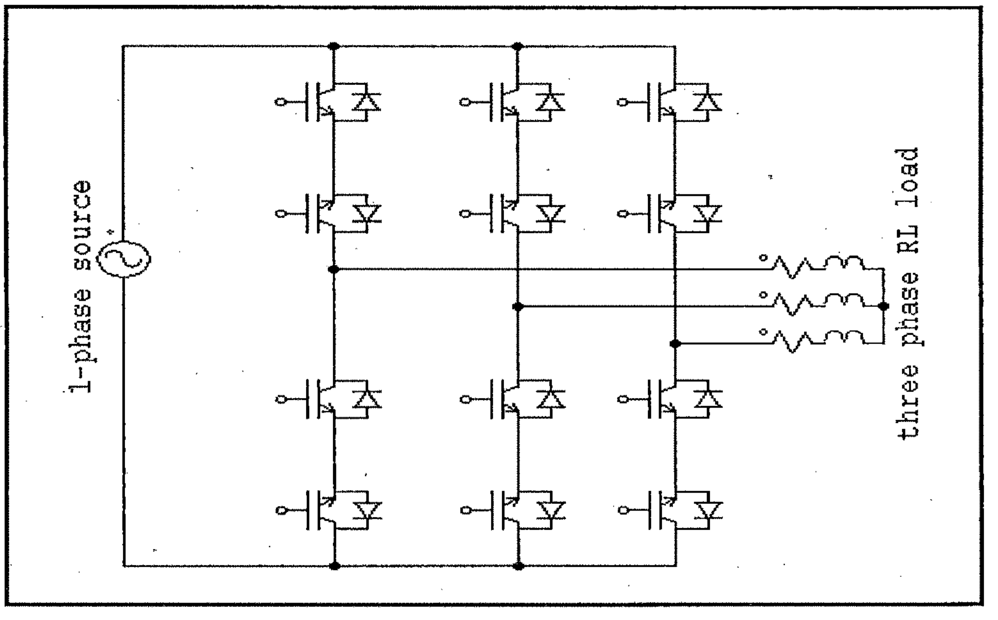


Fig 2.24 Single-phase to three-phase static converter using IGBT bridge

This converter requires six gate pulses for the control of six bi directional switches. Although the static converter is capable of generating variable three phase voltage at variable frequency, the simulation for fixed frequency generation equal to source frequency has been carried only for proving the concept.

Advantages:

It permits full control on generated voltage range from zero to rated level, which helps in achieving smooth starting of induction motors.

High quality input current is achieved.

Disadvantages:
High third harmonic content in output voltage and hence third harmonic filter required.

2.9 Conclusions

A comprehensive analysis of Direct AC-AC converter, which is capable of voltage, frequency and phase transformation, has been presented in this chapter. All the practical issues related to the implementation of Direct AC-AC converters viz. bidirectional switch configuration, commutation of the active switches and protection issues are discussed in detail. Both the modes of operation have been explained in detail.

Performance evaluation and its implementation using two distinct mode of operation have been provided. Detailed simulations have been carried out using either mode of operation showing the frequency and phase transformation along with voltage amplitude variation.