A GENERALIZED SWITCHING MODEL FOR ANALYSIS OF STATIC CONVERTERS

BY

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ABSTRACT

This research project presents a generalized circuit model suitable for the analysis and evaluation of performance characteristics of different power electronic converter circuits. The proposed matrix representation of the generalized switching model allows one to understand easily the process of voltage, current, frequency, phase and amplitude transformation of the converters. The model will be very useful to power electronics designers. Results obtained with this model conform with standard converter circuits.

The theory of spectrum multiplication is used to analyse the different type of converter, e.g. ac to dc, dc to ac, dc to dc, ac to ac converters. Simple switching functions are used to test the validity of proposed generalized switching model. Analytically predicted results are verified by computer aided analysis. Advanced pulse width modulation switching function can be used to improve the quality of the converters.

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APPROVAL

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LIST OF SYMBOLS AND ABBREVIATIONS

$V_o(w_o t)$ = Output voltage of the converter.

$I_i(w_i t)$ = Input current of the converter.

w_i = Angular frequency of input voltage

w_s = Angular switching frequency.

w_o = Angular frequency of output voltage.

V_i = Amplitude of the input voltage.

I_i = Amplitude of the input current.

V_o = Amplitude of the output voltage.

I_o = Amplitude of the output current.

$F_d(w_s t)$ = Switching function of the converter.

$V_i(w_i t)$ = Input voltage of the converter.

$I_o(w_o t)$ = Output current of the converter.

$S_{11}, S_{12}, S_{13}, S_{21}, S_{22}, S_{23}$ = Six bileteral switches of the converter.

f_o = frequency of the output voltage.

f_{11}, f_{12} ..... = elements of switching functionmatrix

f_i = frequency of the input current

F_1, F_2, F_3 = Three switching function

V_{an}, V_{bn} V_{cn} = Input phase voltages

V_{ab}, V_{bc}, V_{ca} = Input line voltages

I_a, I_b, I_c = Input phase currents of the converter

Z_{AB} = Load Impedence

I_A = Load current

δ = Width of the switching function

M_f = Modulation index

V_{AB} = Voltage across the load

Z_A, Z_B, Z_C = Load impedences of three phases

I_A, I_B, I_C = Output line current of the converter

A_n = The n-the harmonic Fourier coefficients of the switching function

P.U. — Per unit

% =Percentage

f = Chopping frequency

T = Chopping period

t_1 = On-time of the chopper

t_2 = Off-time of the chopper

CHAPTER 1

INTRODUCTION

1.1 Introduction:

Power electronics deals with conversion and control of electrical power in various industrial, commercial, residential, municipal and aerospace applications. The motivation for using solid-state switching mode power electronics compared to conventional techniques is in the cost and in space savings, elimination of large audio noise, reduction of maintenance, improvement of reliability and high-quality performance, etc. An important aspect of power electronics applications is energy saving. The history of power electronics [1] started with the invention of mercury-arc rectifiers at the beginning of this century. Gradually, other types of gas tubes, such as phanotrons, thyratrons and ignitrons were introduced in the 1930's. Much of todays converter technology, i.e., phase-controlled rectifiers, inverters, and cycloconverters originated in that era. Then came the era of saturable reactor magnetic amplifiers which essentially appeared during World War II. The real revolution in power electronics started when the thyristors, or silicon-controlled rectifier, was invented by Bell Laboratories in 1956 and commercially introduced by General Electric Company in 1958. Modern power electronics uses various semiconductor devices in switching mode for rectification (ac-dc), inversion (dc-ac), cycloconversion (frequency changing), dc-dc conversion, and ac power control (at the same frequency).

The evaluation in power electronics over the years has occurred by the synthesis of multiple technological disciplines. Today, a true specialist in this areas is supposed to have expertise not only in power semiconductor devices, converter circuits, electrical machines, analog/digital electronics, and control theory but also in computer-aided design, microcomputers and the newly emerging VLSI/ULSI electronics (Fig. 1.1). Each of these component disciplines is moving rapidly and therefore offering a tremendous challenge to the expertise of a power electronics specialist.

The applications of power electronics have grown tremendously, and it is almost impossible to review these independently. Fig. 1.2 summarizes the principal application areas of power electronics. At one end of the spectrum, these areas include switching mode regulated dc and ac power supplies for electronics, computers, instrumentation, and aerospace applications. The demand for compact and cost-effective power supplies at the low end is bringing resonant conversion technology (at several megahertz) in this area. A bulk of power electronics is routinely used in electro-chemical processes, such as metal refining, electroplating, anodizing, and production of chemical gases. Electrical method has been used for a long time. More recently, the high-frequency fluorescent lamp ballast is showing promise for energy saving and dimming. The electronic welding area uses a thyristor ac switch for fast and precision control of electrical power. Solid-state active power filters are used for harmonics filtering and VAR compensation on utility lines. High-voltage dc (HVDC) transmission and asymmetrical frequency inter-tie systems use thyristor converters at both end. Photo-voltaic and fuel cell generators produce dc power, which is then converted to ac by solid-state inverters. In aircraft power supply, a variable-speed constant frequency (VSCF) system converts variable frequency power from the engine alternator to the fixed 400-Hz power supply. Solid-state dc and ac circuit breakers have been used in low to medium power capacity. Heating, melting, and heat treatment of metals use an induction heating method using a solid state inverter. Motor drive is the largest applications. Covering the range of machine tools and robot drive applications, the spectrum goes to paper mill, textile mill, pump, and blower-type

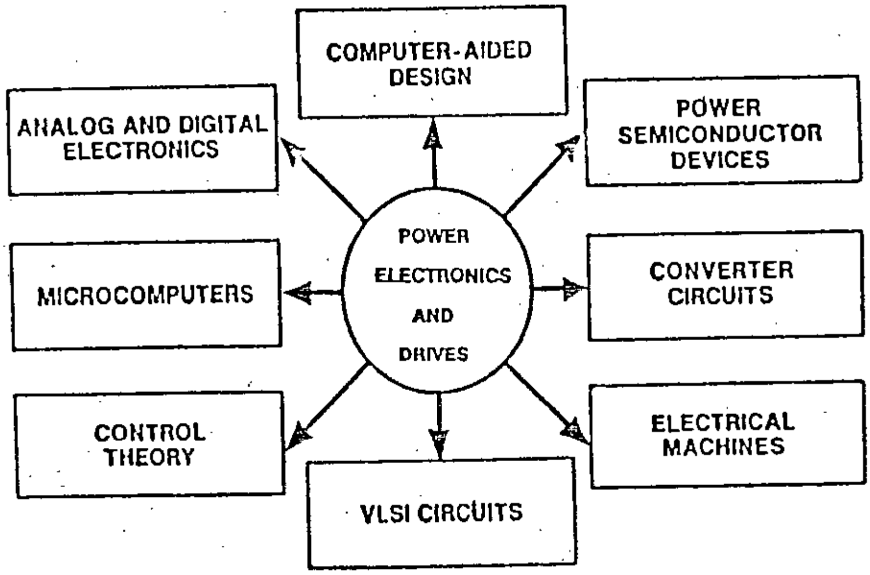


Fig. 1.1 Power electronics-an interdisciplinary technology.

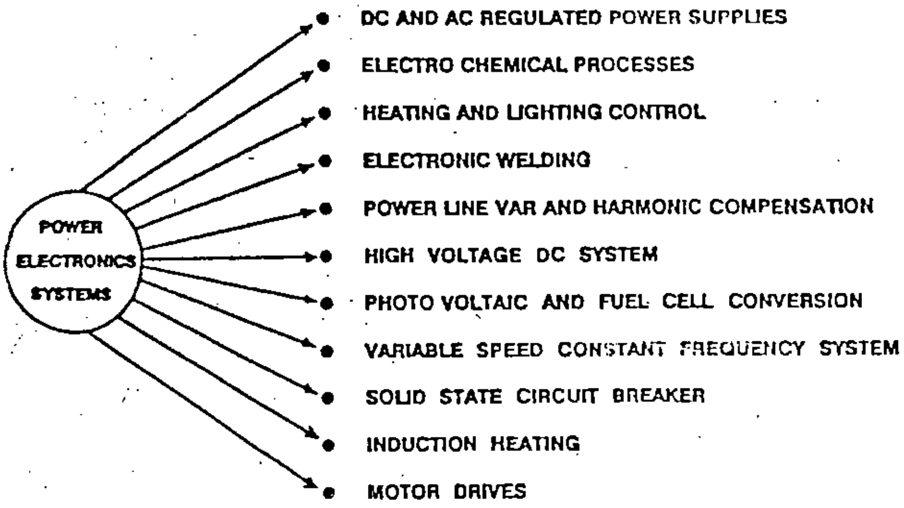


Fig. 1.2 Power electronics systems-applications.

applications in the medium power range. In the high power range, the spectrum covers multimegawatt power for gas line compressors, boiler, ID/FD fans and feed pumps, ship propulsion, and cement mill applications.

Proper application of these converters demands the understanding of the working principles of these converters. Individual analysis of different converters are done by different authors. This project work proposes a single switching model from which all different converters can be analysed.

1.2 Review of Previous Works

There are many literatures [2] - [4] dealing with individual solution and analysis of each type of converter which make it difficult for beginners to understand the analysis and design and thereby improve their performance. A few work has been reported [5] - [6] on simulation of power semiconductor circuits. But these programs are the collection of individual converter circuit analyses stored by a common name. This project proposes a simple switching model consisting of static switches which are interconnected between polyphase input ports and polyphase output ports. Depending on the number of input and output ports/phases and the purpose of the converter (AC-DC,DC-AC, etc.) the exact circuit can be realized. Once the individual circuit topology is found, the analysis of the circuit becomes very simple. This model can also be used as a self-learning tool by nonexperts.

1.3 Scope of the Project

The literature available shows that no single, concise mathematical model is reported for the analysis and evaluation of whole family of static converter. This project proposed a simple switching model which can be used to analyse any type of converter circuit. In particular, the content of this project have been organized as follows:

A generalized switching model with N-phase inputs and M-phase outputs is developed in Chapter 2. The model is next used to provide analytical generalized expressions for different types of converter circuits for the dependent input /output variables such as outputs voltages, input currents. The same model is used to evaluate transfer characteristics such as voltage and current gains.

In Chapter 3, the performance of the rectifiers is investigated by using the analysis method developed in Chapter 2. The predicted results are verified by simulation as well as experimentally on laboratory prototype units.

In Chapter 4, the inverter circuits are analysed using the proposed model. The input and output variables such as output voltages and input currents are analysed and verified with conventional methods.

In Chapter 5, the chopper circuits are analysed and evaluated in detail. The predicted results using the models are verified by experimental results. The frequency changer is also analysed in this chapter. Chapter 6 reviews the entire work presented in this project report and presents relevant conclusions. It also focuses on the future potential for a computer package for the analysis of the whole family of static converters.

CHAPTER 2

DEVELOPMENT OF THE GENERALIZED SWITCHING MODEL

2.1 Introduction

The objective of this chapter is to develop a generalized switching model suitable for the analysis and evaluation of performance characteristics of different types of static converters. To achieve this objectives, the converter circuit is modelled as circuit matrix consisting of [NXM] switching elements (Fig. 2.1). The proposed matrix representation of this generalized converter allows us to understand easily the process of voltage, current, frequency, phase and amplitude transformations. This model is used throughout this project to study the performance characteristics of different converters. Elements of this circuit matrix modelling the converter represents switching element of an actual converter.

In addition to the modelling of converter, this chapter also analyses the representative model of converter. Input-output waveforms of such converters are dependent function of actual switching patterns. The switching functions are determined by various pulse width modulation (PWM) techniques and accordingly the switches operate in ON/OFF mode rather than continuous mode for higher power conversion efficiency.

Consequently, the resulting input/output current/voltage waveforms are periodic and contain numerous harmonics and for analysis purpose be ,represented by respective Fourier series expressions. The fundamental and dominant harmonics of this waveform are dependent on respective output requirement and the type of converter. This spectral information is essential for the design of converter as well as input-output filters.

2.2 Development of the Generalized Switching Model

The generalized switching model of a converter structure capable of performing the voltage, current, frequency, phase and amplitude transformation is shown in Fig. 2.1.

This switching model comprises of an "input matrix" of [NX1] dimension, "converter switching matrix" of [MXN] dimension and an "output matrix" of [MX1] dimension. The principle [7] states that "the multiplication of a set of [NX1] sinusoidal quantities (e.g., input voltage matrix) by a compatible set of [MXN] balanced sinusoidal quantities (e.g., converter transfer matrix) yields a third set of [MX1] sinusoidal quantities (e.g., output voltage matrix) that are also balanced". This model can be used readily to realise a practical converter circuit once the nature of the input/output quantities and phase (N, M) have been specified. Therefore, the analytical statement of this model, regarding converter voltage $[V_o (W_o t)]$ and input current $[I_i (W_i t)]$ are shown in equations (2.1) and (2.2), where

W_i = is the input frequency

W_s = is the switching frequency and

W_o = $W_s - W_i$ is the output frequency of the converter

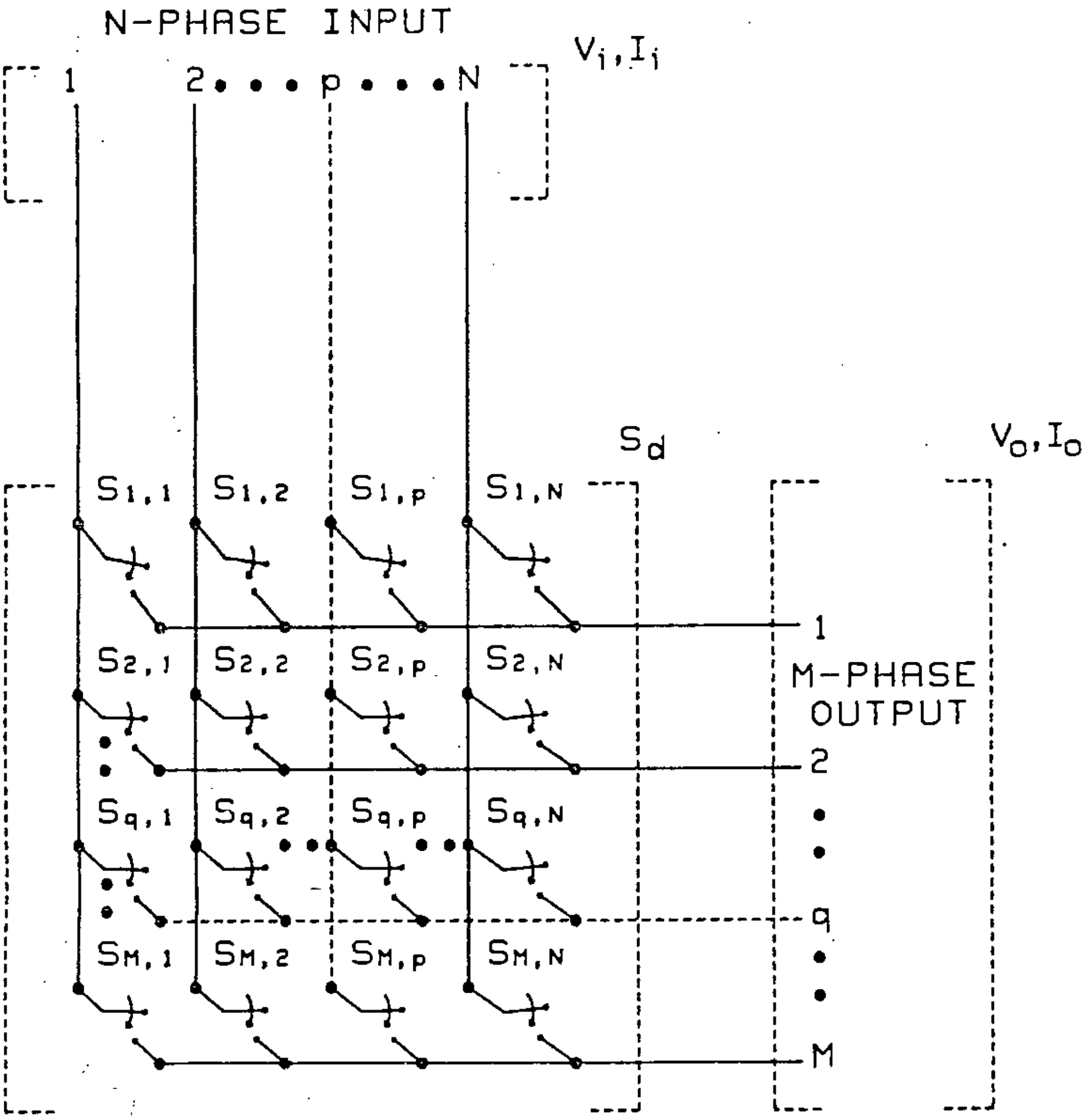


Fig. 2.1 Generalized Switching Model for analysis of static converters.

$$[V_0(\omega_o t)] = [F_d(\omega_s t)][(V_i(\omega_i t)]$$

$$\begin{bmatrix} V_{o,1} \\ \vdots \\ V_{o,\ell} \\ \vdots \\ V_{o,M} \end{bmatrix} = A \begin{bmatrix} f_{1,1} & \cdots & f_{1,k} & \cdots & f_{1,N} \\ f_{\ell,1} & \cdots & f_{\ell,k} & \cdots & f_{\ell,N} \\ f_{M,1} & \cdots & f_{M,k} & \cdots & f_{M,N} \end{bmatrix} .B \begin{bmatrix} V_{i,1} \\ \vdots \\ V_{i,k} \\ \vdots \\ V_{i,N} \end{bmatrix}$$

$$= A \left[\begin{matrix} \cos(\omega_s t) \ldots\ldots & \cos(\omega_s t - \frac{(k-1)}{N}360^\circ) \ldots\ldots & \cos(\omega_s t - \frac{(N-1)}{N}360^\circ) \\ \vdots & & \\ \cos(\omega_s t - \frac{(\ell-1)}{M}360^\circ) \ldots & \cos(\omega_s t - \frac{(k-1)}{N}360^\circ + \frac{(\ell-1)}{M}360^\circ) \ldots & \cos(\omega_s t - \frac{(N-1)}{N}360^\circ + \frac{(\ell-1)}{M}36 \\ \vdots & & \\ \cos(\omega_s t - \frac{(M-1)}{M}360^\circ) \ldots & \cos(\omega_s t - \frac{(k-1)}{N}360^\circ + \frac{(M-1)}{M}360^\circ) \ldots & \cos(\omega_s t - \frac{(N-1)}{N}360^\circ + \frac{(M-1)}{M}360 \end{matrix}\right.$$

$$.B \begin{bmatrix} \cos(\omega_i t) \\ \vdots \\ \cos(\omega_i t - \frac{(k-1)}{N}360^\circ) \\ \vdots \\ \cos(\omega_i t - \frac{(N-1)}{N}360^\circ) \end{bmatrix}$$

$$= \frac{NAB}{2} \begin{bmatrix} \cos(\omega_o t) \\ \vdots \\ \cos(\omega_o t - \frac{(\ell-1)}{M}360^\circ) \\ \vdots \\ \cos(\omega_o t - \frac{(M-1)}{M}360^\circ) \end{bmatrix} \qquad (2.1)$$

and

$$[I_i(\omega_i t)] = [F_d(\omega_s t)]^T [I_o(\omega_o t)]$$

$$\begin{bmatrix} I_{i,1} \\ \vdots \\ I_{i,k} \\ \vdots \\ I_{i,N} \end{bmatrix} = A \begin{bmatrix} f_{1,1} & \cdots & f_{\ell,1} & \cdots & f_{M,1} \\ \vdots & & & & \\ f_{1,k} & \cdots & f_{\ell,k} & \cdots & f_{M,k} \\ & & & & \\ f_{1,N} & \cdots & f_{\ell,N} & \cdots & f_{M,N} \end{bmatrix} . B \begin{bmatrix} I_{o,1} \\ \vdots \\ I_{o,\ell} \\ \vdots \\ I_{o,M} \end{bmatrix}$$

$$= A \begin{bmatrix} \cos(\omega_s t) & \cdots & \cos(\omega_s t + \frac{(\ell-1)}{M} 360^\circ) & \cdots & \cos(\omega_s t + \frac{(M-1)}{M} 360^\circ) \\ \vdots & & & & \\ \cos(\omega_s t - \frac{(k-1)}{N} 360^\circ) & \cdots & \cos(\omega_s t - \frac{(k-1)}{N} 360^\circ + \frac{(\ell-1)}{M} 360^\circ) & \cdots & \cos(\omega_s t - \frac{(k-1)}{N} 360^\circ + \frac{(M-1)}{M} 360^\circ) \\ \vdots & & & & \\ \cos(\omega_s t - \frac{(N-1)}{N} 360^\circ) & \cdots & \cos(\omega_s t - \frac{(N-1)}{N} 360^\circ + \frac{(\ell-1)}{M} 360^\circ) & \cdots & \cos(\omega_s t - \frac{(N-1)}{N} 360^\circ + \frac{(M-1)}{M} 360^\circ) \end{bmatrix}$$

$$. B \begin{bmatrix} \cos(\omega_o t) \\ \vdots \\ \cos(\omega_o t - \frac{(\ell-1)}{M} 360^\circ) \\ \vdots \\ \cos(\omega_o t - \frac{(M-1)}{M} 360^\circ) \end{bmatrix}$$

$$= \frac{MAB}{2} \begin{bmatrix} \cos(\omega_i t) \\ \vdots \\ \cos(\omega_i t - \frac{(k-1)}{N} 360^\circ) \\ \vdots \\ \cos(\omega_i t - \frac{(N-1)}{N} 360^\circ) \end{bmatrix} \qquad (2.2)$$

Once the model is developed, it can be tested. For example, if a controlled rectifier is required to be analysed, then the number of input-phases is N=3 and the number of output phases is M=1 and the output frequency is $W_o = 0$, so the transfer function frequency becomes $W_s = W_o + W_i = W_i$. This AC-DC converter is discussed in next chapter in full details.

2.3 Inverter Analysis by Using the Generalized Model

In order to illustrated the usefullness and capability of the proposed model a number of representative examples are discussed throughly in the following chapters. Here only a test case of single phase inverter is discussed. The derivation of a single phase converter from this generalized model is shown in Fig. 2.2 (a) by setting the number of input phase M = 1 and N=1. The simplified converter is depicted in Fig. 2.2 (b) where f_1 and f_2 are the switching function corresponding to the switches S_{11}, S_{22} and S_{12}, S_{21} respectively. The equations for output ac voltage $V_o\ (W_o t)$ is as follows :

$$\begin{aligned} V_o\ (W_o t) &= [F_d(W_s t)] \cdot [V_i(W_i t)] \\ &= [A \cos(W_s t)] \cdot [V_i \ \cos(W_i t)] \\ &= AV_i \cos(W_o t) \qquad (2.3) \\ &[\because W_i = 0 \text{ and } W_o = W_s] \end{aligned}$$

and the corresponding input current I_i equation is

$$I_i = [F_d(w_s t)]^T [I_o(w_o t)]$$

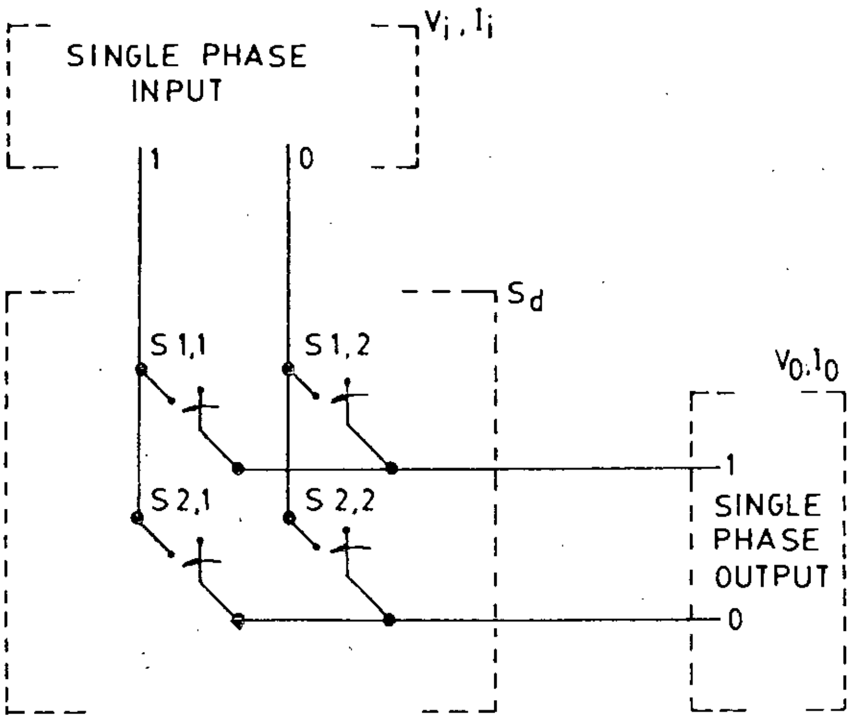
$$=[A \cos(w_s t)] \cdot [I_o \cos(w_o t)]$$

$$=[A \cos(w_o t)] \cdot [I_o \cos(w_o t)]$$

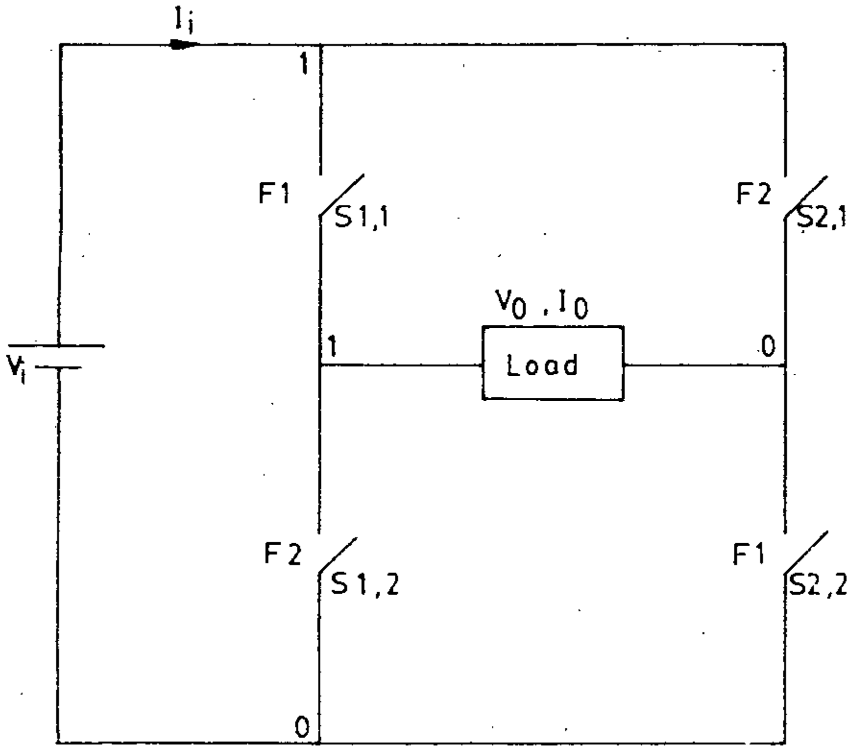
$$[\because w_s = w_o]$$

$$= \frac{AI_o}{2} + \frac{AI_o}{2} \cos(2w_o t) \qquad (2.4)$$

The output ac voltage V_o $(w_o t)$ waveform and input dc current I_i waveform are shown in Figs. 2.3 and 2.4 respectively. Corresponding spectra of voltage and current are depicted in Fig. 2.3e and 2.4e.



(a) Switching diagram derived from generalized model (Fig 2.1) for no. of input phase, N=1 and no. of output phase M=1.



(b) Corresponding simplified circuit diagram.

Fig. 2.2 Realization of Single phase inverter circuit from generalized model.

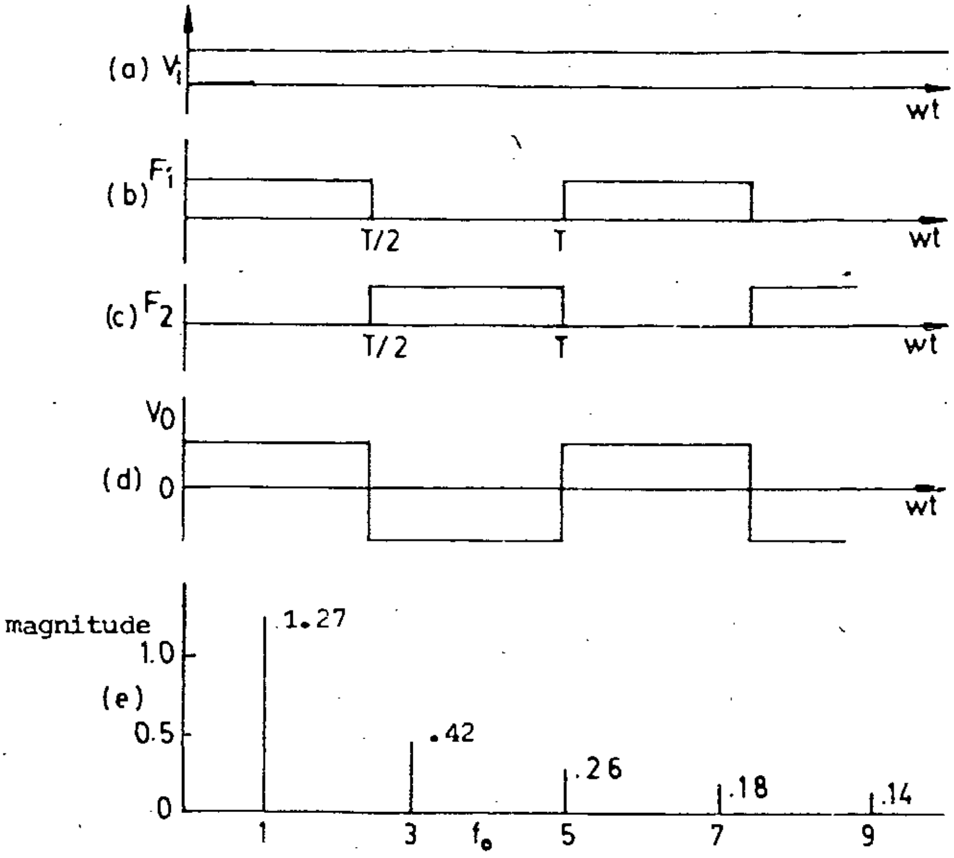


Fig. 2.3 Output voltage waveform of single phase inverter.

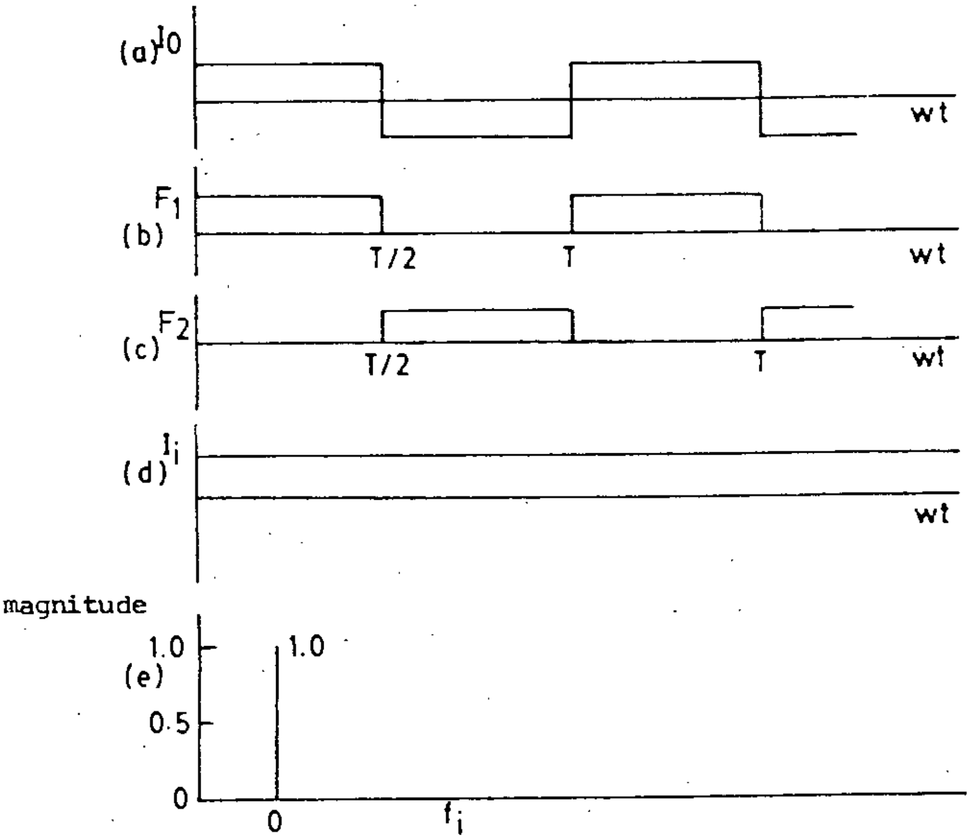


Fig. 2.4 Input current waveform of single phase inverter

2.4 Conclusions

A generalized switching model for analysis of the whole family of static converters is presented in this chapter. This model has been utilized to analyse the behaviour of converters with different operating characteristics. Furthermore, a representative example of inverter is analysed to verify the simplicity and effectiveness of the model.

CHAPTER 3

RECTIFIERS

3.1 Introduction

The AC-DC converters are commonly known as rectifiers and the diode rectifiers provide a fixed dc output voltage.

Controlled rectifiers [8] form the majority of converters employing power semiconductors. They are used to vary the average value of the direct voltage applied to a load circuit by introducing thyristors between the load circuit and a constant voltage ac source. For this purpose the thyristors are phase controlled.

Applications of controlled rectifiers include the following:

1. DC motor speed control systems, widely used in steel mills, paper mills, and so on.
2. Electro chemical and electrometallurgical processes.
3. Magnet power supplies.
4. Converters at the input end of dc transmission lines.
5. Portable hand tool drives.

Like ac voltage controllers, controlled rectifiers may be employed in closed-loop control systems, where they function as high-power operational amplifiers in which the angles at which the thyristors are turned on is varied in response to an error signal. In general a single-phase ac source is adequate for rectifier ratings of 1 to 2 kw, but for higher powers a three-phase ac source is normally used. Once again, the problem of current harmonics introduced into the supply system and load circuit arises, and their magnitude must be determined.

The phase controlled converters can be classified into two types depending on the input supply

1. Single phase converter
2. Three phase converter.

Each type can be subdivided into:

   a. Semiconverter
   b. Full converter and
   c. Dual converter.

A semiconverter is a one quadrant converter and it has one polarity of output voltage and current. A full converter is a two quadrant converter and the polarity of the output voltage can be either positive or negative. However, the output current of the full converter has one polarity only. A dual converter can operate in four quadrants and both the output voltage and current can be either positive or negative.

In this chapter, three phase diode rectifiers and three phase controlled rectifiers are analysed using the switching model developed in chapter 2.

3.2 3-Ø Diode Rectifier Circuit

Fig. 3.1b shows a simplified 3-Ø Diode rectifier circuit derived (Fig. 3.1a) from the generalized model (Fig. 2.1) by setting the number of input phases N=3 and the number of output phases M=1. As the converter is used to change the input ac (W_i = 50Hz) to output dc (W_o = 0 Hz), the switching frequency is chosen as simple single pulse (Fig. 3.2b) having a frequency $w_s = w_o + w_i = w_i$.

One of the waveforms of the switching function elements/components F_1, F_2, F_3 (corresponding to switching matrix element S_{11}, S_{21}, S_{12}, S_{22}, S_{13}, S_{23} respectively) are shown in Fig. 3.2b. The input voltage waveforms v_{an}, V_{bn} and V_{cn} and dc output voltage waveforms are depicted in Fig. 3.2a and 3.2c. Correspondingly, input current of only one phase I_a is shown in Fig. 3.3c. Other phase currents are same as I_a but displaced 120^o apart from each other.

The output voltage (dc) and input current (ac) equations derived from generalized circuit model eqns. (2.1) and (2.2) (Chapter 2) are given by :

$$V_o = [\, F_d\ (w_s t)\,] \cdot [\, V_i\ (w_i t)]$$

$$= [\, A\ [\cos\ (w_s t) \quad \cos(w_s t-120^o)\ \cos\ (w_s t-240^o)]$$

$$\cdot\ V_i \begin{bmatrix} \cos(w_i t) \\ \cos(w_i t - 120^o) \\ \cos(w_i t - 240^o) \end{bmatrix}$$

$$= \frac{3AV_i}{2} \cos(w_i - w_i)t$$

$$[\ \because\ w_s = w_i]$$

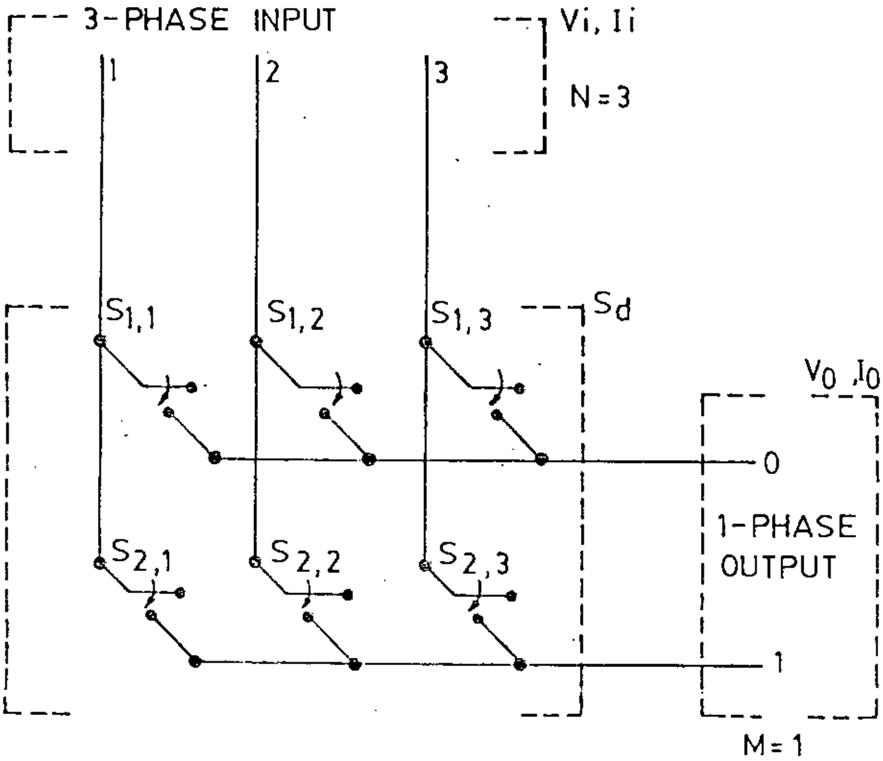
$$= \frac{3AV_i}{2} \tag{3.1}$$

and the corresponding input current equations I_i are

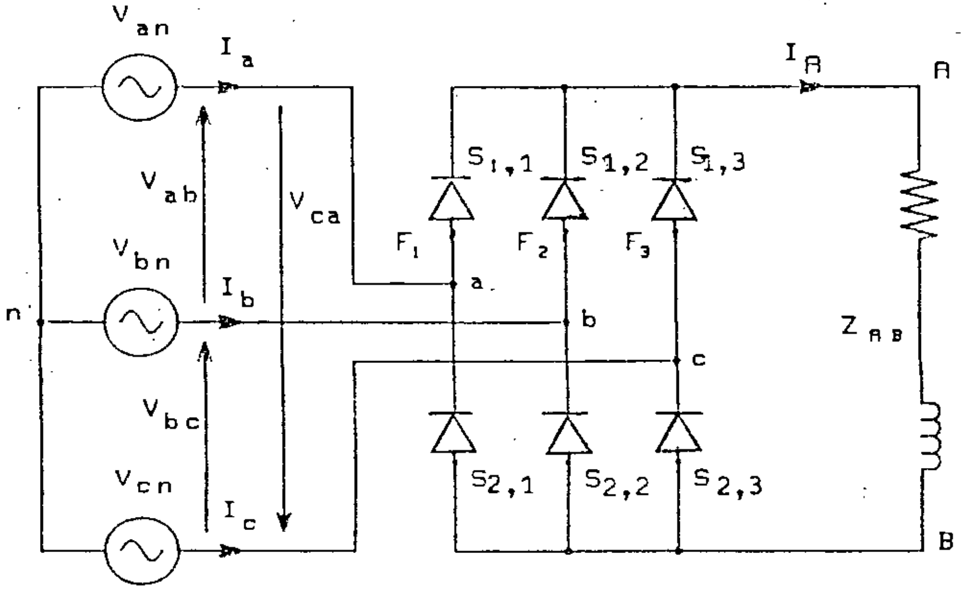
$$I_i\ (w_i t) = [F_d(w_s t)]^T\ [I_o\ (w_o t)]$$

$$= AI_o \begin{bmatrix} \cos(w_i t) \\ \cos(w_i t - 120^o) \\ \cos(w_i t - 240^o) \end{bmatrix} \tag{3.2}$$

In an actual converter, the switches operate in ON/OFF mode rather than continuous mode. For this well-known reason, however, the output voltage V_o(eqn.(3.1)) and input current I_i $(w_i t)$ (eqn.(3.2)) contains harmonics. Their respective spectra are shown in Fig. 3.2b and 3.3d.



a) Switching diagram derived from generalized model (Fig.2.1) for no. of input phases, N=3 and no. of output phases M=1



b) Corresponding simplified circuit diagram.

Fig. 3.1 Realization of 3-Ø diode rectifier circuit from generalized model.

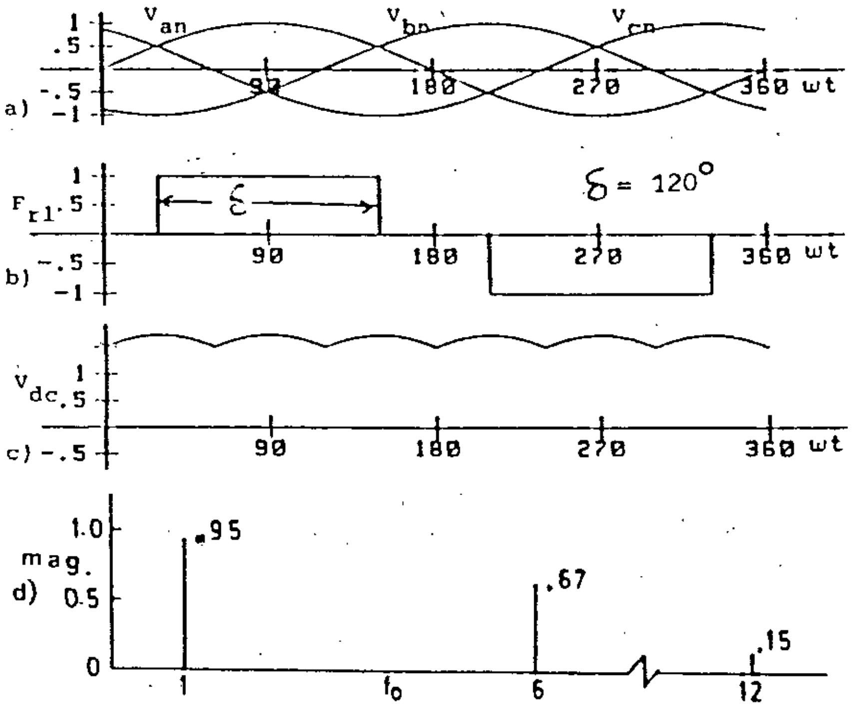


Fig 3.2 Output Voltage waveform of 3∅ diode rectifier

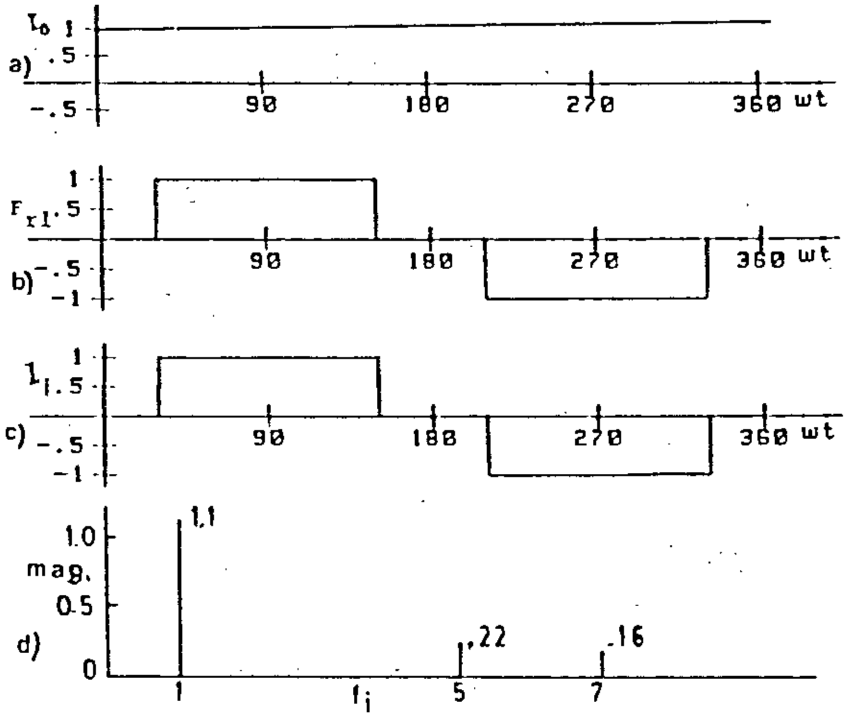


Fig 3.3 Input current waveform of 3 Ø diode rectifier

3.3 3-Ø Controlled Rectifier Circuit

The controlled rectifier shown in Fig. 3.4 is derived from Fig. 2.1. The switches in this case are SCRs as the output voltage (dc) is variable. The output voltage is varied by controlling the ON-OFF time of the switches. The output voltage V_o and input current $[I_i(w_i t)]$ equations remain the same (eqn. 3.1 and eqn. 3.2). However, the amplitude A (of the switching function) in eqn. 3.1 and 3.2 will vary as the ON-OFF time i.e., the switching function width, δ (Fig. 3.5 and 3.6) is varied. The output voltage and the input current waveform for modulation index, $M_f = 0.8$ ($\delta = 96^\circ$) is shown in Figs. Figs. 3.5 and 3.6 respectively. The corresponding spectra are depicted in Figs. 3.5d and 3.6d.

3.4 Simmulated & Experimental Results

To varify the key analytically predicted results the three phase controlled rectifier output voltage and input currents are reconstructed using the Fourier coefficients of the output and input waveforms. The output voltage and input current waveforms are shown in Figs. 3.7 and 3.8 respectively. The waveforms matches the standard six pulses rectifiers output voltage and input current.

An experimental set up is done using the equipments of power electronics laboratory. The output voltage and input current waveform are shown in Figs. 3.9 and 3.10.

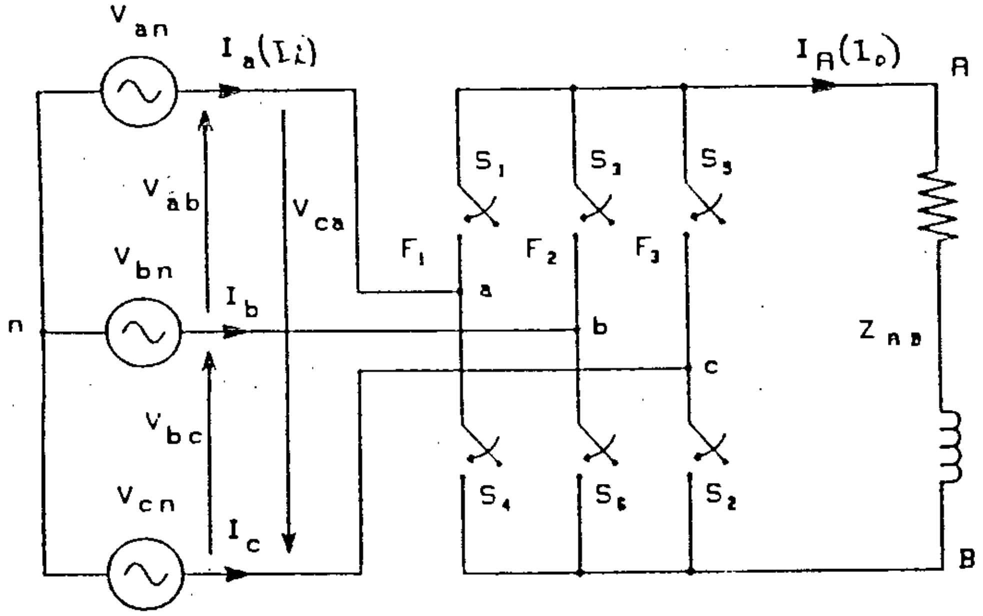


Fig.3.4 Realization of 3Ø controlled rectifier circuit from generalized model.

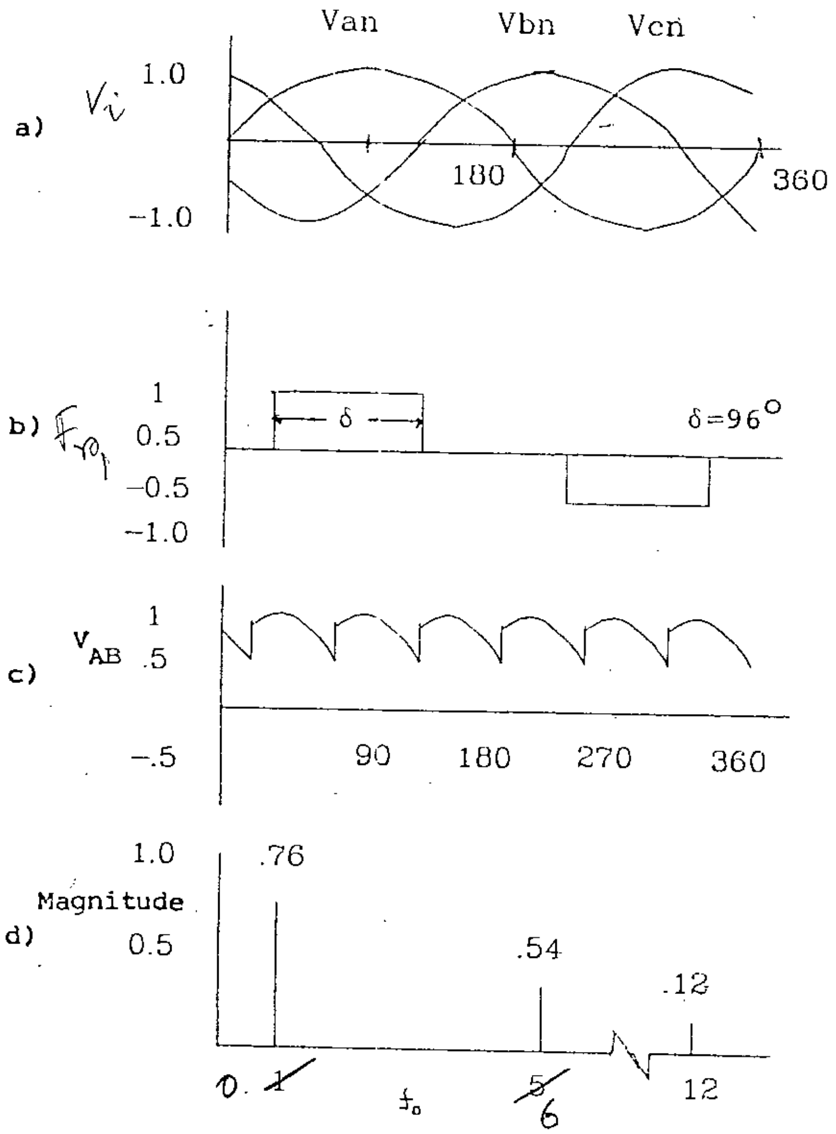


Fig.3.5 Output voltage waveform of 3Ø controlled rectifier.

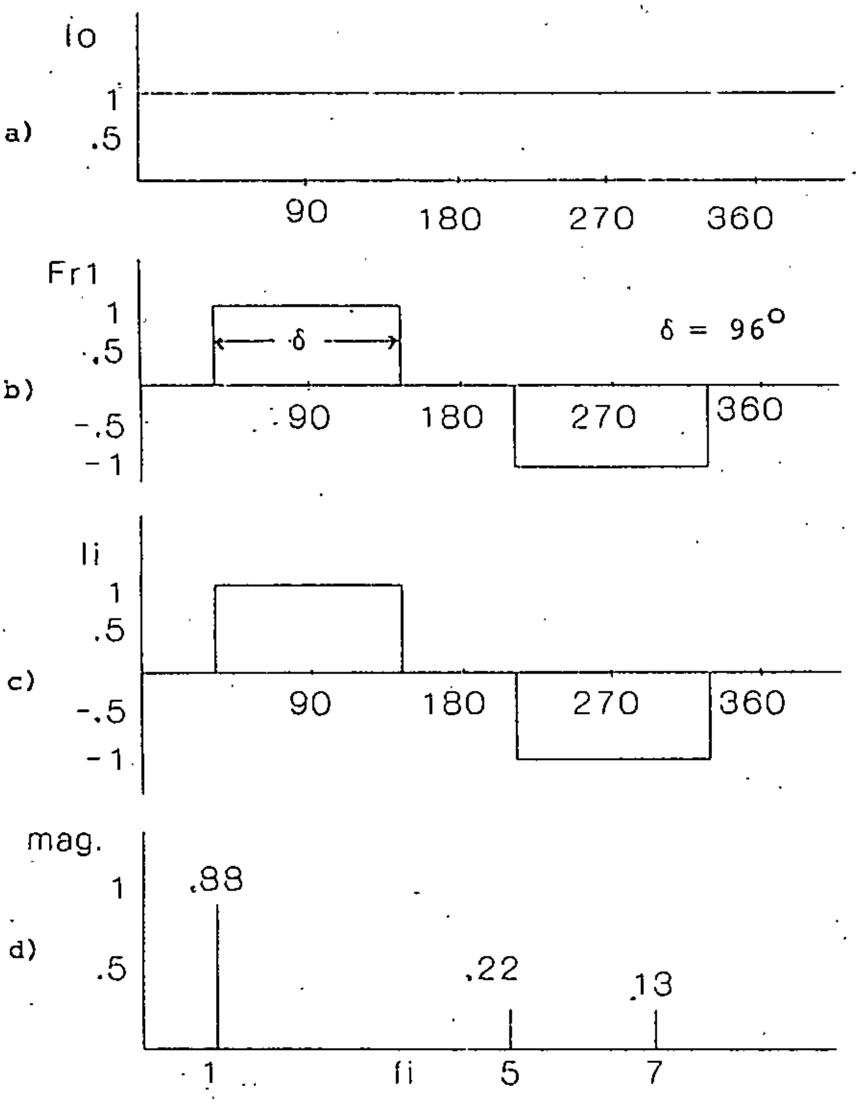


Fig.3.6 Input current waveform of 3Ø controlled rectifier.

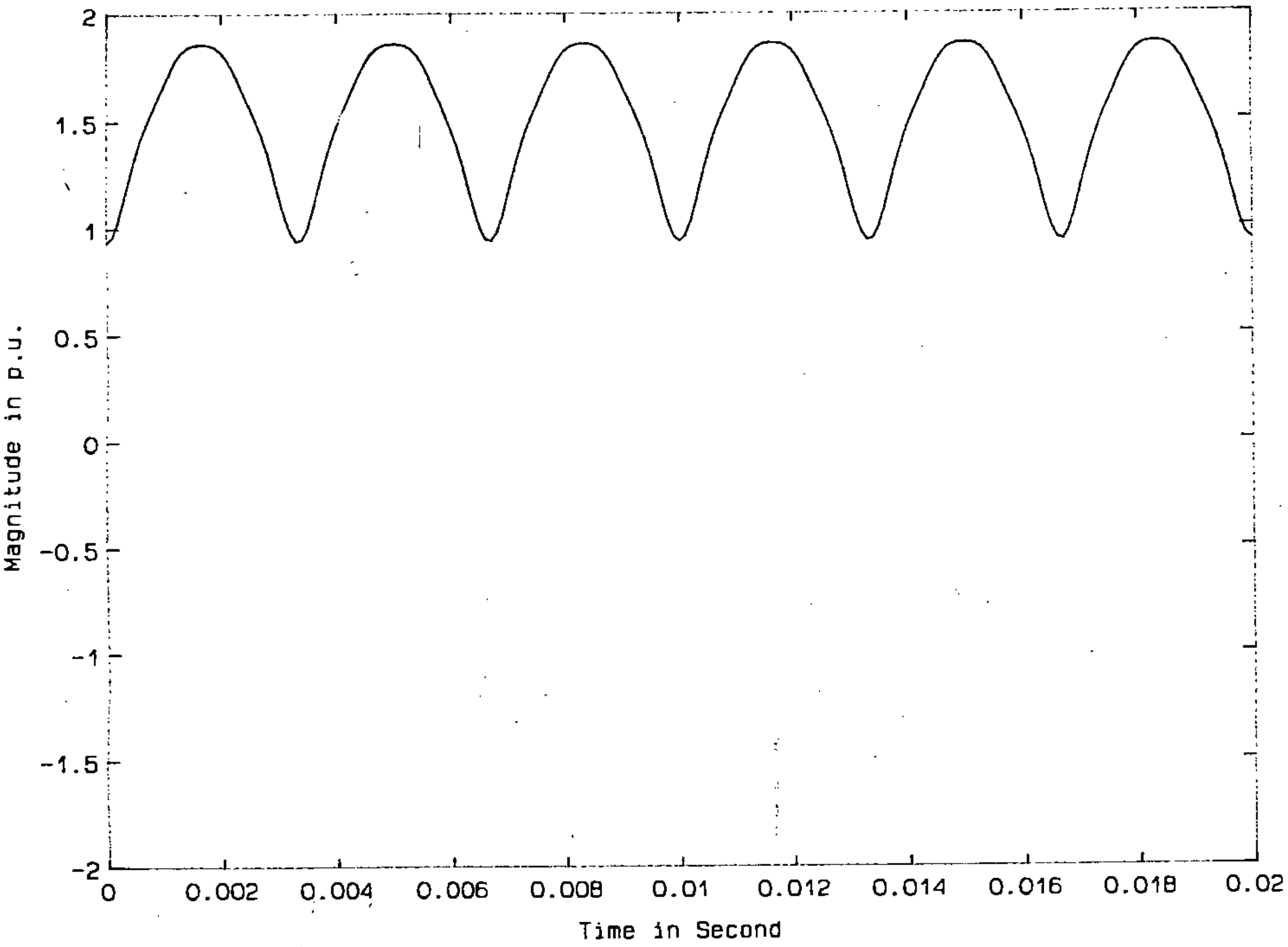


Fig 3.7: Computer simulated (from Fourier coefficients) output voltage waveform of 3-Ø controlled rectifier.

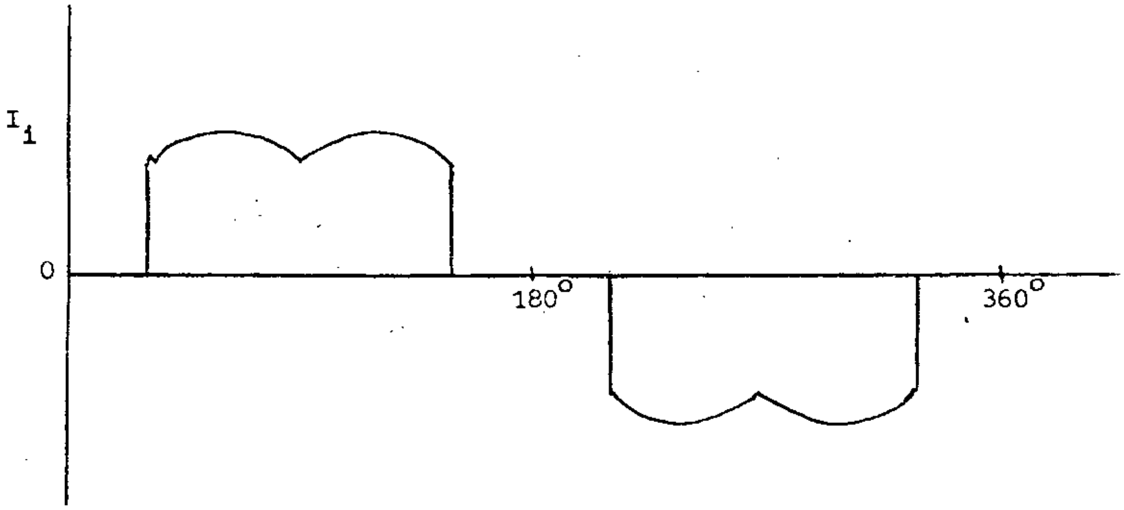


Fig 3.8. Simulated input current waveform of 3-Ø controlled rectifier.

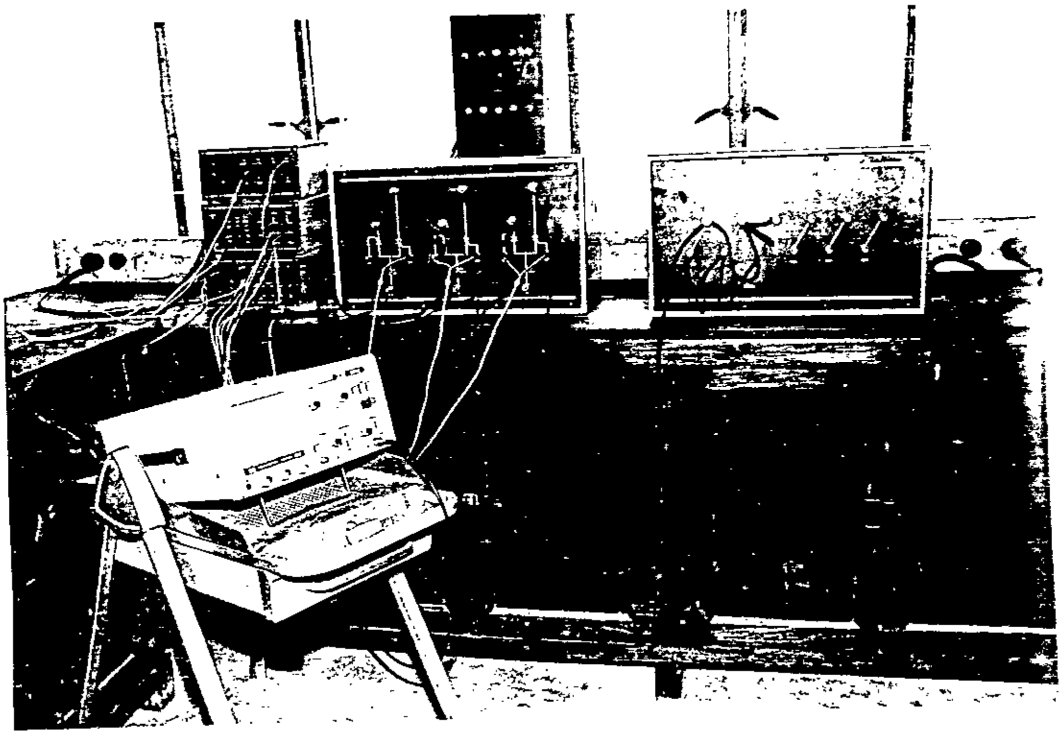
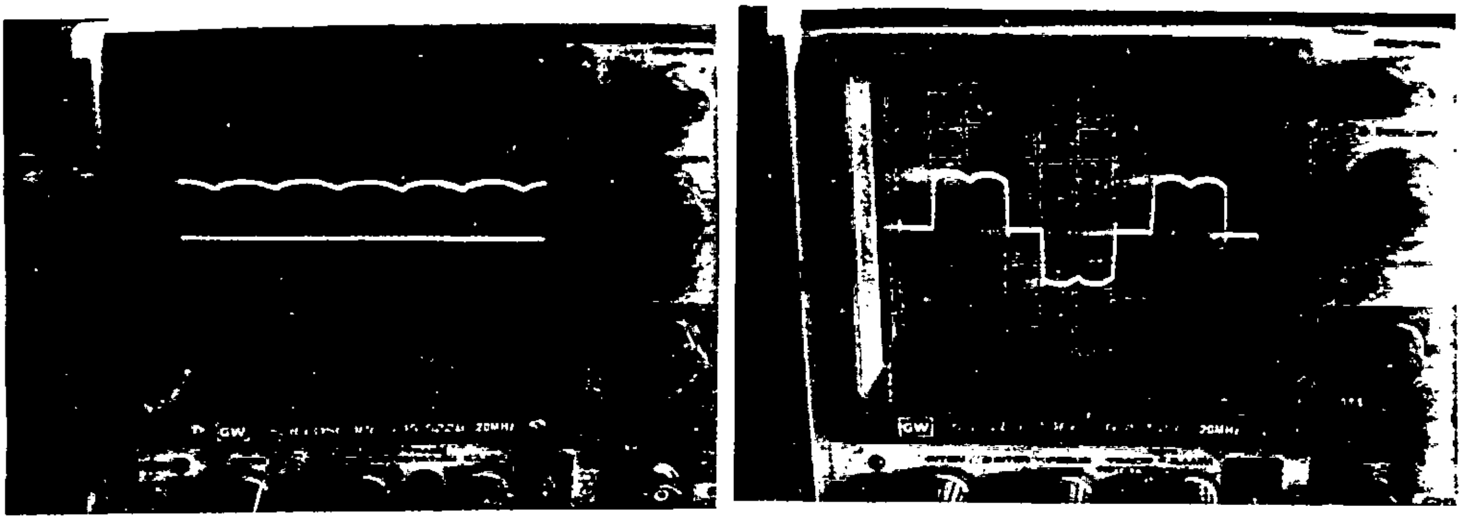


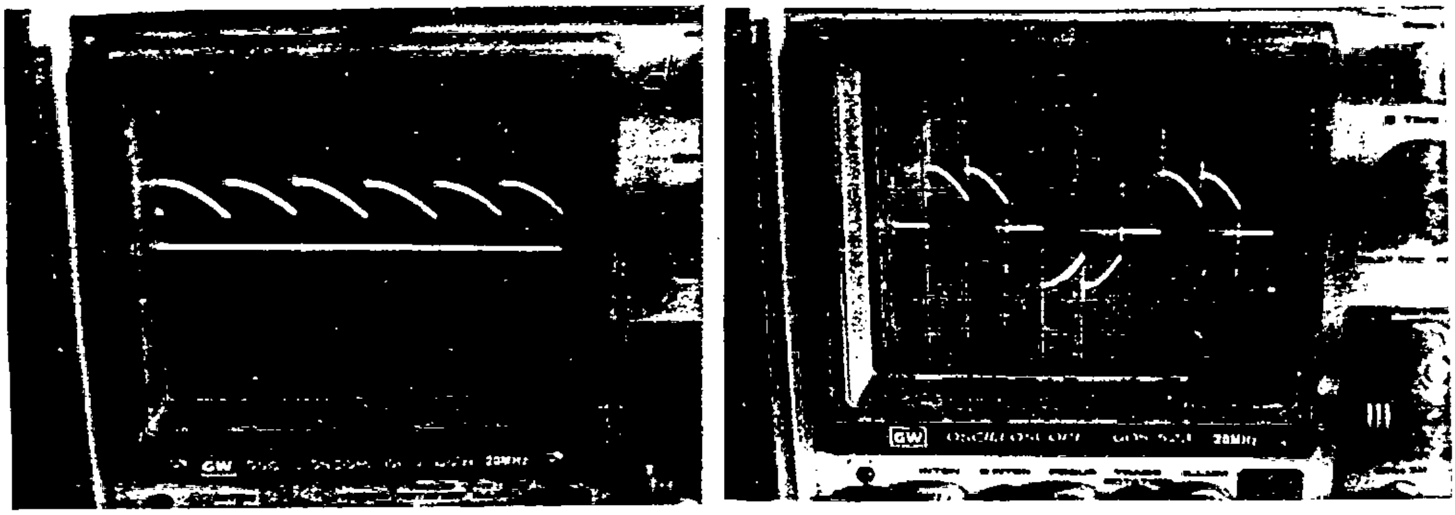
Fig. 3.9 Experimental set-up of 3-0 controlled rectifier.



a) Output voltage

b) Input current

A. Voltage & current waveforms for uncontrolled rectifier ($\delta = 120^\circ$)



a) Output voltage

b) Input current

B. Voltage & current waveforms for controlled rectifier ($\delta < 120^\circ$)

Fig. 3.10 Experimental output voltage & input current waveforms of 3-0 controlled rectifier.

3.5 Conclusions

Three phase diode and controlled rectifiers are analysed using the model developed in chapter 2. The results obtained using the developed model is same as the standard analysis. The analysis procedure is much simpler than the known procedure. Finally, these results are verified with the standard results and they are found to be similar.

CHAPTER 4

INVERTERS

4.1 Introduction

DC to AC converters are known as inverters. The function of an inverter is to change a dc input voltage to a symmetrical ac output voltage of desired magnitude and frequency. The output voltage could be fixed or variable at a fixed or variable frequency. A variable output voltage can be obtained by varying the input dc voltage and maintaining the gain of the inverter constant. On the other hand, if the dc input voltage is fixed and it is not controllable, a variable output voltage can be obtained by varying the gain of the inverter, which is normally accomplished by Pulse-Width-Modulation (PWM) control within the inverter. The inverter gain may be defined as the ratio of the ac output voltage to dc input voltage.

The output voltage waveforms of ideal inverters should be sinusoidal. However, the waveforms of practical inverters are nonsinusoidal and contain harmonics. For low-and medium-power applications, square-wave or quasi-square-wave voltages may be acceptable; and for high-power applications, low distorted sinusoidal waveforms are required. With the availability of high speed power semiconductor devices, the harmonic contents of output voltage can be minimized or reduced significantly by switching techniques.

Inverters are widely used in industrial applications (e.g. variable-speed ac motor drives, induction heating, standby power supplies, uninterruptible power supplies). The input may be a battery, fuel cell, solar cell, or other dc source. The typical single-phase outputs are (1) 120V at 60Hz (2) 220V at 50Hz and (3) 115V at 400Hz. For high-power three-phase systems, typical outputs at (1) 220/380V at 50Hz (2) 120/208V at 60Hz and (3) 115/200V at 400Hz.

Inverters can be broadly classified into two types: (1) single-phase inverters, and (2) three-phase inverters. Each type can be subdivided into four categories, depending on the type of thyristor commutations : (a) Pulse Width Modulation (PWM) inverter, (b) resonant inverter (c) auxiliary commutated inverter, or (d) complementary commutated inverter. An inverter is called a **voltage-source** inverter (VSI) if the input voltage remains constant, a current- source inverter (CSI) if the input current is maintained constant, and a variable dc linked inverter if the input voltage is controllable.

In this chapter 1-Ø and 3-Ø inverters are analysed using the generalized model developed in chapter 2; output voltage and input current Fourier analysis is done. The result obtained with this approach is same as standard analysis results.

4.2 Single Phase Inverter Circuit

The derivation of a single phase inverter from the generalized model is shown in Fig. 4.1a by setting N=1 and M=1. The simplified circuit is depicted in Fig. 4.1b. F_1 and F_2 are the switching functions corresponding to the switches S_{11}, S_{22} and S_{12}, S_{21} respectively. The equations for output ac voltage $V_o(w_o t)$ and input dc current I_i are derived from generalized eqns. 2.1 and 2.2

(of chapter 2) as follows:

$$
\begin{aligned}
v_o\,(w_o t) &= [F_d(w_s t)] \cdot [v_i(w_i t)] \\
&= A\,[\cos(w_s t)] \cdot V_i[\cos\,(w_i t)] \\
&= AV_i\,\cos(w_o t) \qquad\qquad (4.1) \\
&[\because w_i = 0 \text{ and } w_o = w_s]
\end{aligned}
$$

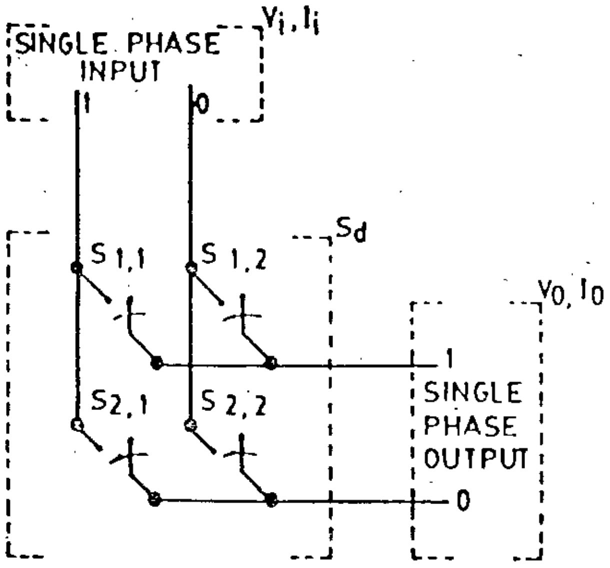
and the corresponding input current I_i equation is

$$
\begin{aligned}
I_i(w_i t) &= [F_d(w_s t)\,]^T\,[\,I_o\,(w_o t)] \\
&= A\,[\cos\,(w_s t)] \cdot [I_o\,\cos(w_o t)] \\
&= A\,[\cos(w_o t)] \cdot [I_o\,\cos(w_o t)\,] \\
&\qquad [\because w_s = w_o\,] \\
&= \frac{AI_o}{2} + \frac{AI_o}{2}\cos\,2w_o t \qquad\qquad (4.2)
\end{aligned}
$$

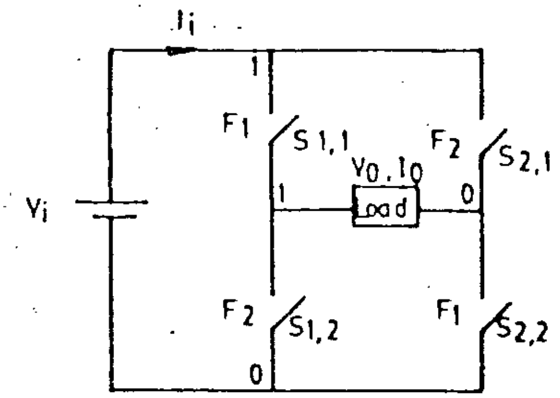
The output ac voltage $V_o(w_o t)$ waveform and input dc current I_i waveform are shown in Figs. 4.2 and 4.3 respectively. Corresponding spectra of voltage and current are depicted in Fig. 4.2e and 4.3e.

4.3 3-Ø Inverter Circuit

The simplified circuit diagram for 3-Ø inverter shown in Fig. 4.4b is derived from switching diagram in Fig. 4.4a. The switching diagram (Fig.4.4a) is derived from generalized circuit model (Fig. 2.1 of chapter 2) by setting the number of input phases N=1 and the number of output phases M=3. This is an inverter, so the output frequency is $w_i = 0$ and the corresponding switching



a) Switching diagram derived from generalized model (Fig. 2.1) for no. of input phase, N=1 and no. of output phase M=1.



b) Corresponding simplified circuit diagram.

Fig. 4.1 Realization of single phase inverter circuit from generalized model.

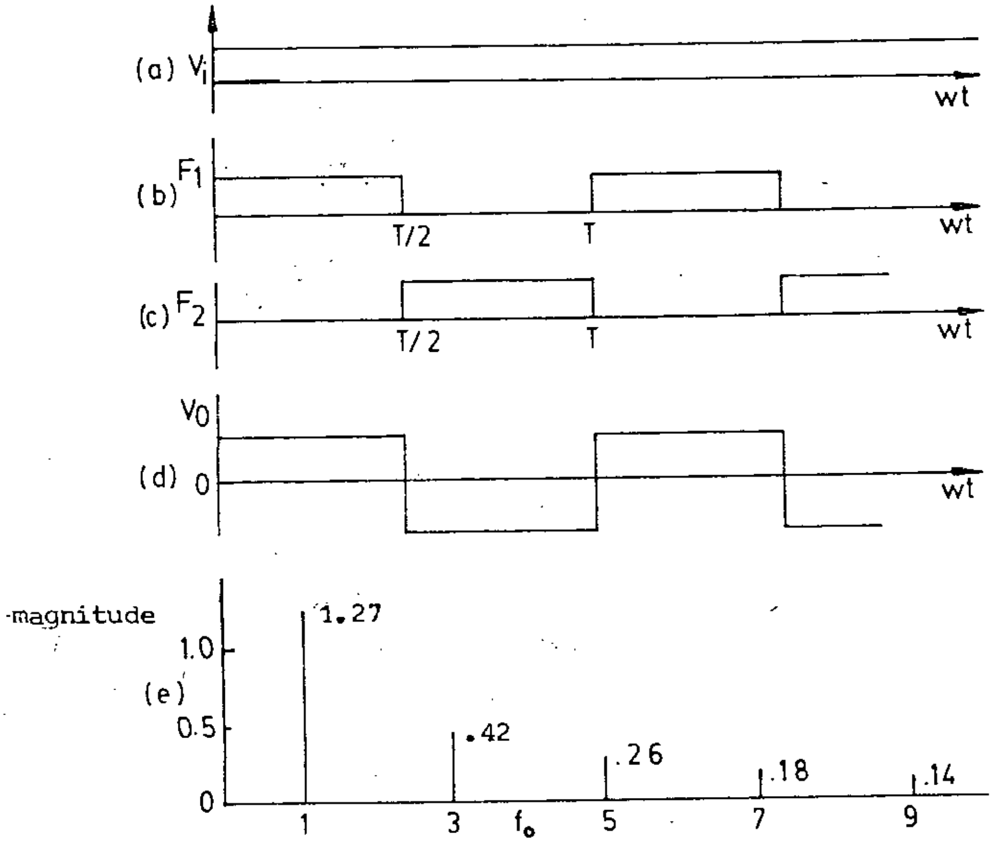


Fig. 4.2 Output voltage waveform of single phase inverter.

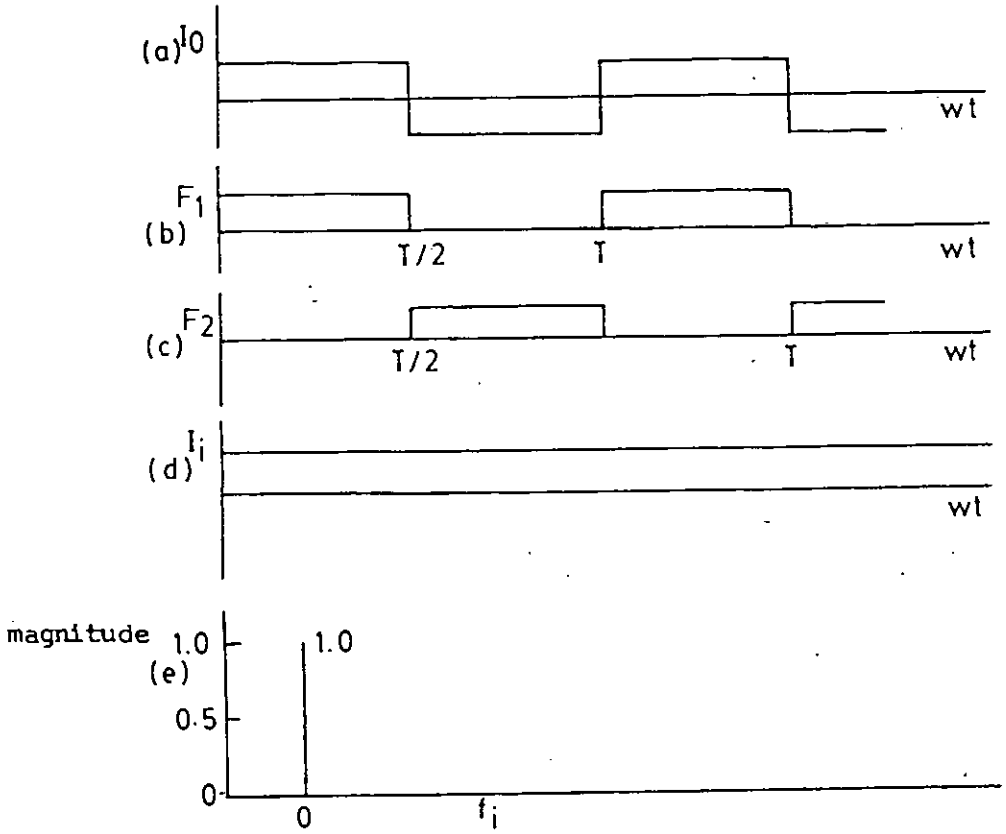


Fig. 4.3 Input current waveform of single phase inverter.

frequency is $w_s = w_i + w_o = w_o$. The output voltages and input current equations are :

$$V_o\ (w_o t) = [\,F_d\ (w_s t)\,] \cdot [\,V_i(w_i t)\,]$$

$$= A \begin{bmatrix} \cos\ (w_s t) \\ \cos\ (w_s t) - 120^{\circ}) \\ \cos\ (w_s t - 240^{\circ}) \end{bmatrix} \cdot V_i$$

$$= AV_i \begin{bmatrix} \cos(w_s t) \\ \cos(w_s t - 120^{\circ}) \\ \cos(w_s t - 240^{\circ}) \end{bmatrix} \qquad (4.3)$$

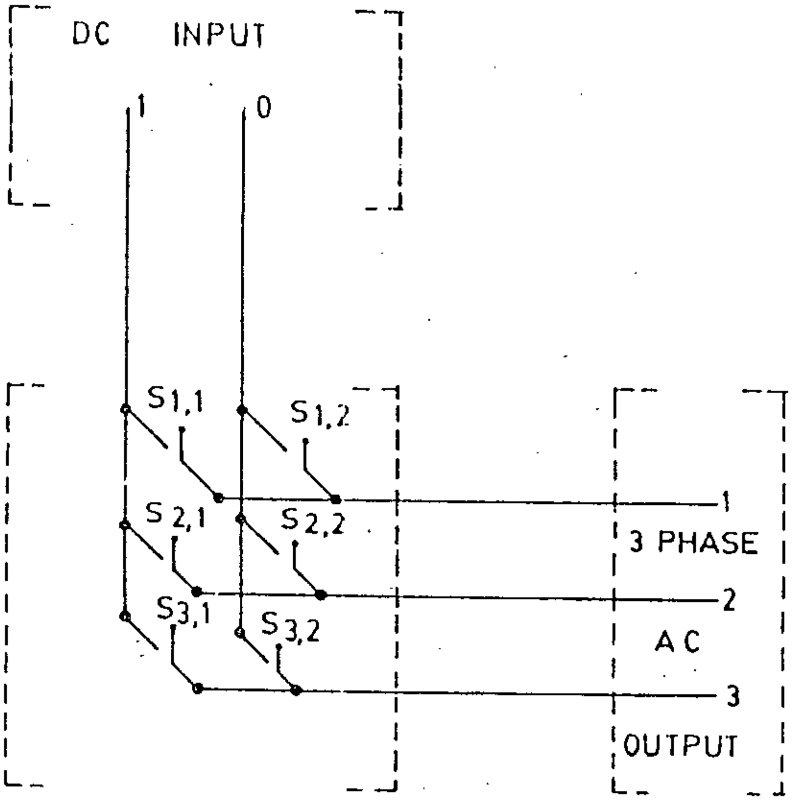
and

$$I_i = [\,F_d(w_s t)\,]^{T} \cdot [\,I_o(w_o t)\,]$$

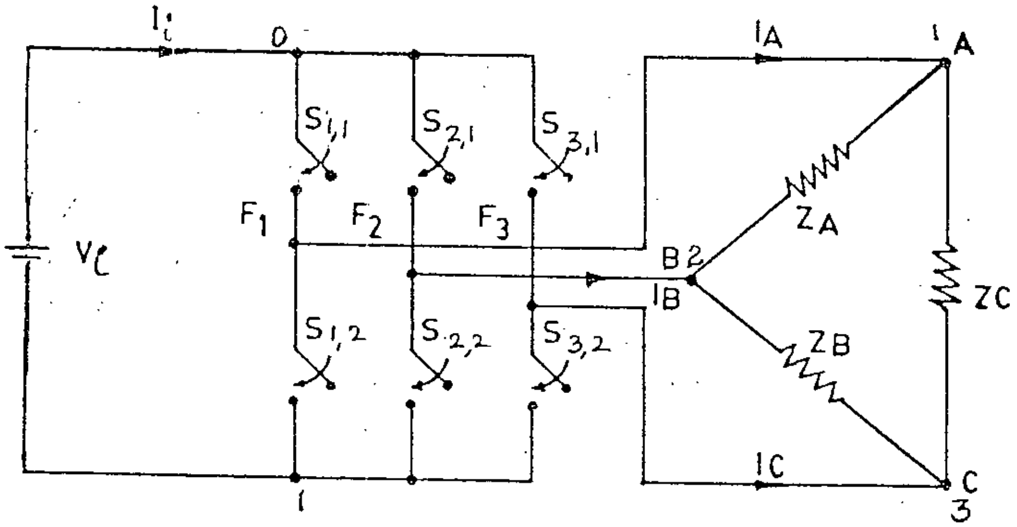
$$= A\,[\,\cos\ (w_s t)\ \cos(w_s t - 120^{\circ})\ \cos(w_s t - 240^{\circ})] \cdot I_o \begin{bmatrix} \cos(w_o t) \\ \cos(w_o t120^{\circ}) \\ \cos(w_o t - 240^{\circ}) \end{bmatrix}$$

$$= \frac{3}{2} AI_o \qquad [\ \because\ w_s - w_o = 0\ ] \qquad (4.4)$$

The output ac voltages $V_o\ (w_o t)$ waveforms and the input dc current I_i waveform for delta connected load are shown in Fig. 4.5 and 4.6 corresponding spectra of voltages and currents are shown in Figs. 4.5d and 4.6d. These waveforms and spectra conform with standard 3-0 inverter waveforms.



(a) Switching diagram



(b) Corresponding circuit diagram

Fig.4.4 Realization of 30 inverter circuit from generalized model.

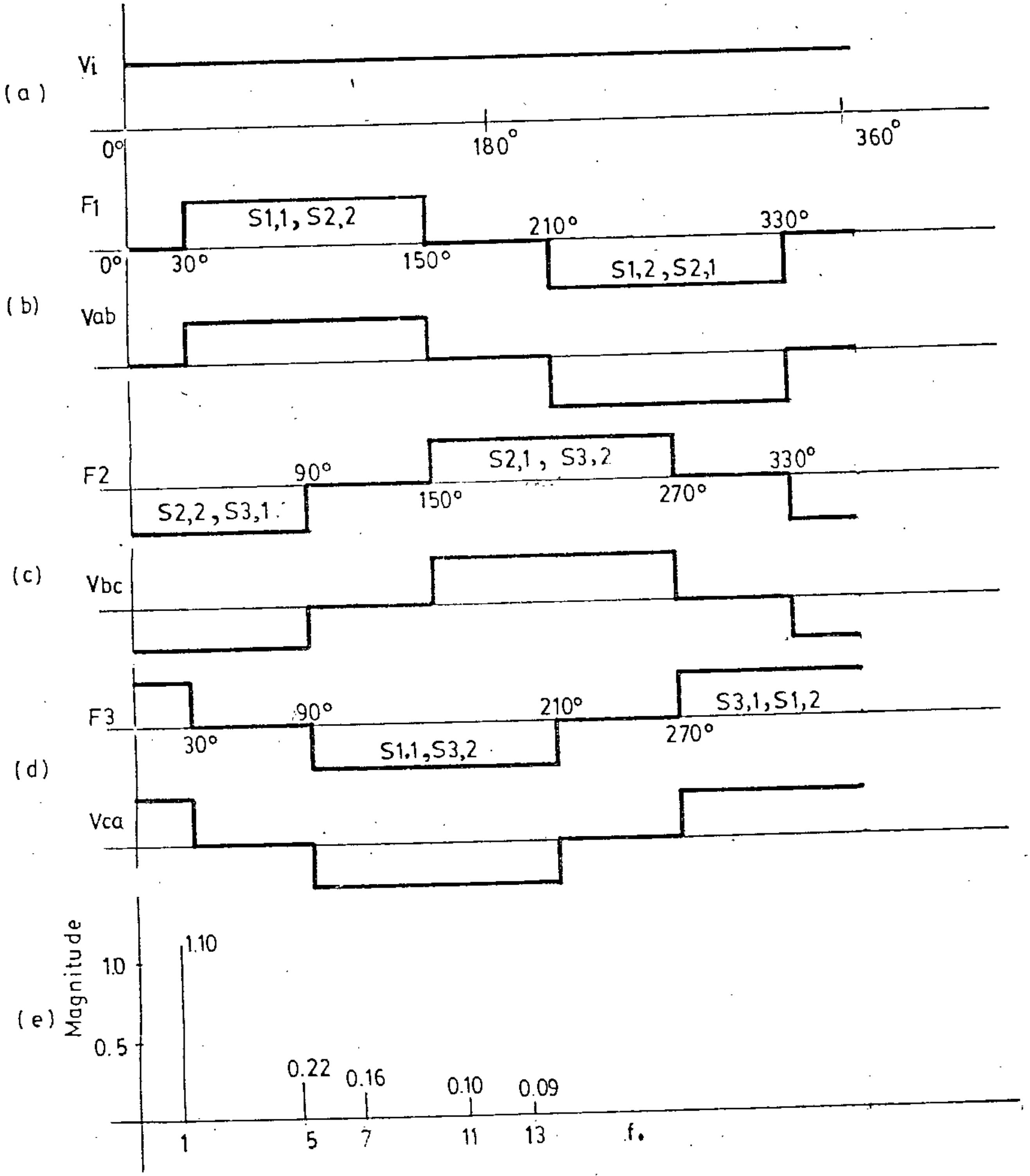


Fig 4.5 Output voltage waveform of 3Ø inverter circuit (for delta connected load).

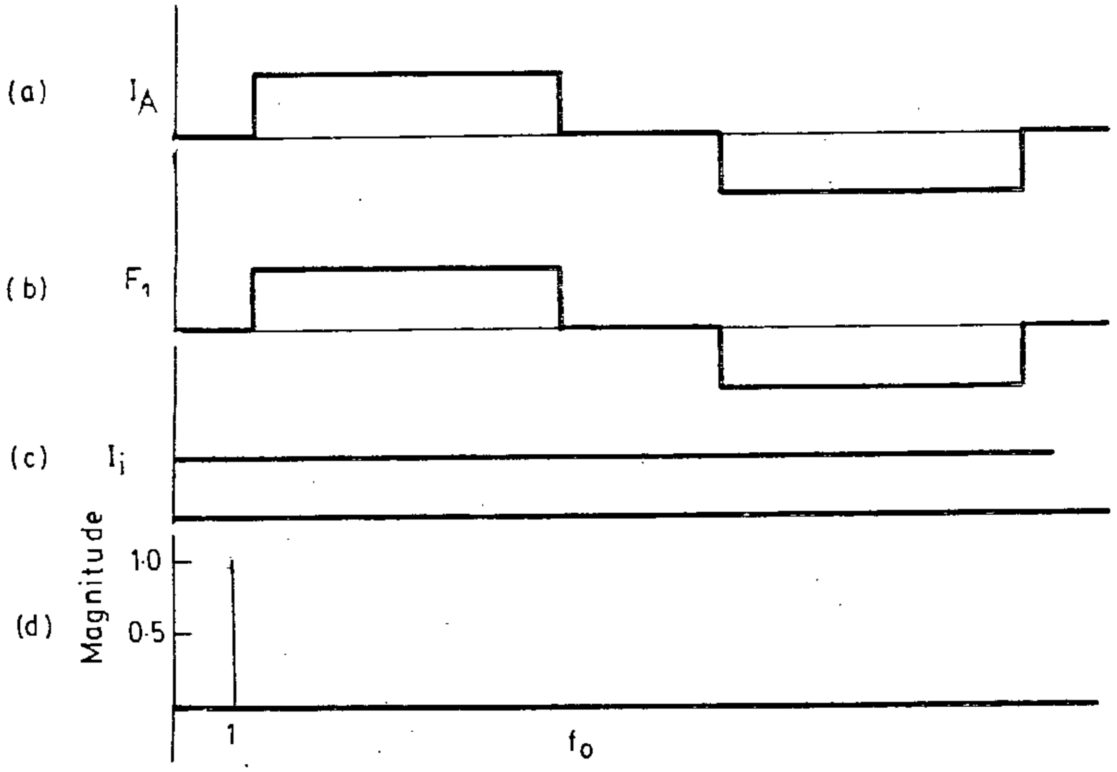


Fig. 4.6 Corresponding input current waveform of 3Ø inverter.

4.4 Harmonic Analysis of 1-Ø Inverter

The harmonic analysis of 1-Ø inverter is performed by using fourier analysis. The fourier expression for the output voltage is given by:

$$V_o(w_o t) = [F_d(w_s t)] \cdot [V_i(w_i t)]$$

$$= \sum_{n=1,3,5}^{\infty} A_n \cos n w_s t \cdot V_i$$

$$= V_i \sum_{n=1,3,5}^{\infty} An \cos n\, w_s t \tag{4.5}$$

and the input expression is given by

$$I_i(w_i t) = [F_d(w_s t)]^T \cdot [\, I_o(w_o t)]$$

$$= \sum_{n=1,3,5}^{\infty} A \cos n\, w_s t \cdot I_o \cos w_o t$$

$$= \sum_{n=1,3,5}^{\infty} AI_o \cos nw_o t \; \cos w_o t \qquad [\because w_s = w_o]$$

$$= \frac{AI_o}{2} + \frac{AI_o}{2} \cos 2w_o t + \sum_{n=3,5}^{\infty} \frac{AI_o}{2} \cos(n+1)w_o t + \cos(n-1)\, w_o t \tag{4.6}$$

The fourier coefficients of output voltage and input current are shown in Tables 4.1 and 4.2 respectively.

TABLE 4.1

FREQUENCY SPECTRA OF OUTPUT VOLTAGE WAVEFORM OF 1-Ø INVERTER

Harmonic coefficients of switching function (Fig. 4.2b)		Harmonic coefficients of resulting output voltage, V_o (Fig. 4.2d)		
			Amplitude V_o	
Order n	Amplitude (A_n)	Order n	P.U.	%
0	1.0	1	1.27	127
1	1.27	3	0.0042	0.42
3	0.42	5	0.0026	0.26
5	0.26	7	0.0018	0.18
7	0.18	9	0.0014	0.14
9	0.14			

TABLE 4.2

FREQUENCY SPECTRA OF INPUT CURRENT WAVEFORM OF 1-Ø INVERTER				
Harmonic coefficients of switching function(Fig.4.3b)		Harmonic coefficients of resulting input current, I_i(Fig. 4.3d)		
Order (n)	Amplitude (Q(A_n)	Amplitude, I_i		
0	1.0	Order n	Per Unit	Percentage
1	1.27	1	1	100
3	0.42			
5	0.26			
7	0.18			
9	0.14			

4.5 Conclusions

Single and three phase inverters are analysed using the generalized model. The output voltage and input currents are drawn and their respective spectrum are also shown. The results obtained with this model conforms with standard analytical results i.e. input, output quantities of inverters.

CHAPTER 5

CHOPPERS & FREQUENCY CHANGERS

5.1 Introduction

In many industrial applications, it is required to convert a fixed-voltage dc source into a variable-voltage dc source. A dc chopper converts directly from dc to dc and is also known as a dc-to-dc converter. A chopper can be considered as dc equivalent to an ac transformer with a continuously variable turns ratio. Like a transformer, it could be used to step-down or step-up a dc voltage source.

Choppers are widely used for traction motor control in electric automobilies, trolly cars, marine hoists, forklift trucks and mine haulers. They provide smooth acceleration control, high efficiency, and fast dynamic response. Choppers can be used in regenerative braking of dc motors to return energy back into supply, and this feature results in energy savings for transportation system with frequent stops. Choppers are also used in dc voltage regulators.

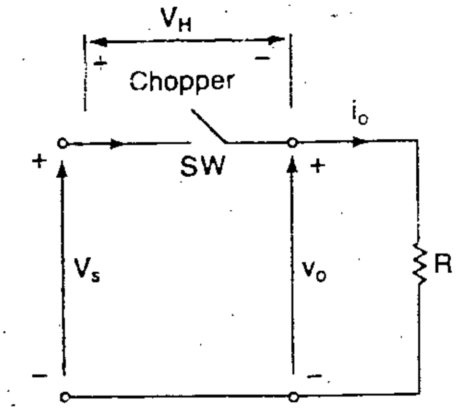
The output voltage V_o of a chopper can be varied by the following two ways:

i) Constant-frequency operation

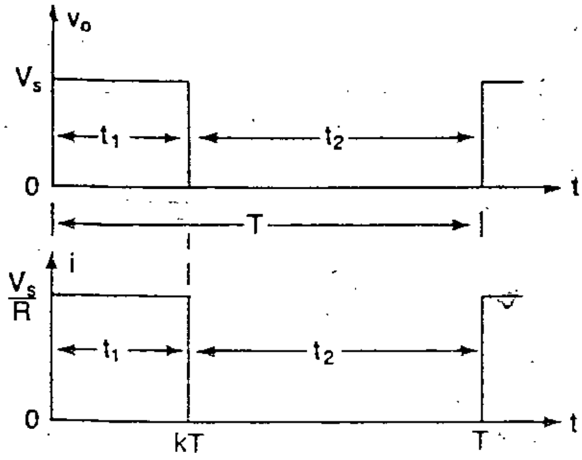
The chopping frequency, f (or chopping period T), is kept constant and the on-time, t_1, (Fig. 5.1) is varied. The width of the pulse is varied and this type of control is known as pulse-width modulation (PWM) control.

ii) Variable-frequency operation

The chopping frequency, f, is varied. Either on-time t_1, or off-time, t_2, (Fig.5.1) is kept constant. This is called frequency modulation. The frequency has to be varied over a wide range to obtain the full output voltage range. This type of control would generate harmonics at unpredictable frequency and the filter design would be difficult.



(a) Circuit



(b) Waveforms

Fig 5.1 Stepdown Chopper with resistive load.

The chopper is analysed by using the proposed model for constant frequency operation.

The frequency changer are used to convert ac to ac at variable voltage and variable frequency. There are two types of frequency changers i) Direct frequency changers or cycloconverters and ii) Indirect frequency changers or rectifier-inverter type frequency changers. Direct frequency changers are also discussed in this chapter. Frequency changer circuit and the corresponding equations are derived from the generalized switching model.

5.2 Choppers

Derivation of a chopper circuit from the generalized switching model is shown in Fig. 5.2(a) by setting n=1 and m=1. The simplified circuit is shown in Fig. 5.2(b). As this is a chopper only, one switching function is necessary. Hence only the switch S_1 ($S_{1,1}$; $S_{2,1}$) will operate and S_o($S_{1,2}$; $S_{2,2}$) will always be closed. The equations for variable dc voltage V_o and input dc current I_i are derived from generalized equations 2.1 and 2.2 of chapter 2 as follows:

$$V_o = \{F_d (w_s t)\} . V_i$$

$$= \sum_{n=0,1,3,5,}^{\infty} A_n \cos nw_s t \cdot V_i$$

$$= V_i \sum_{n=0,1,3,5,}^{\infty} A_n \cos nw_s t \qquad (5.1)$$

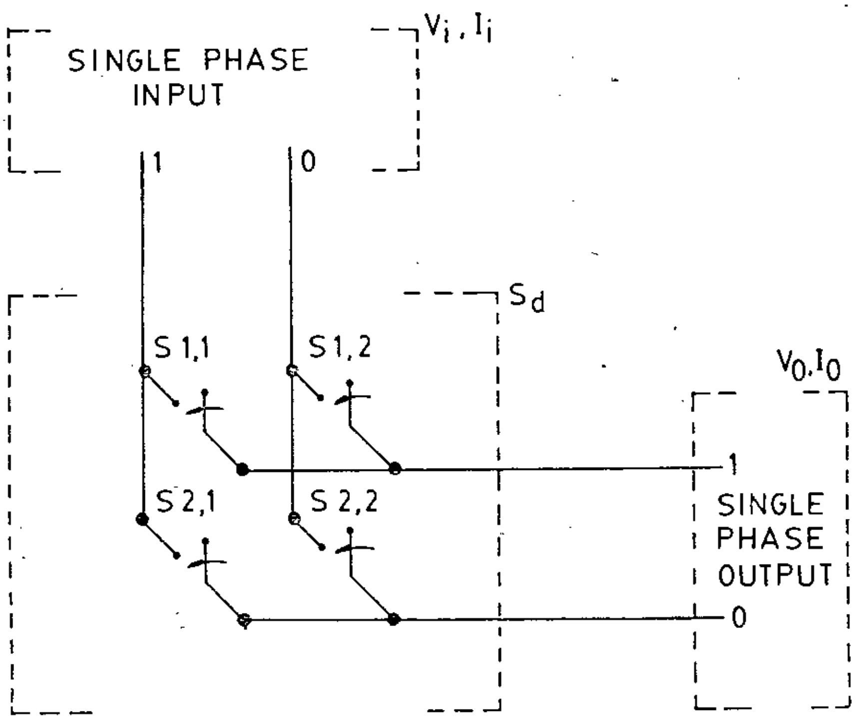
and the corresponding input current I_i equation is

$$I_i = [F_d(w_s t)]^T \; I_o$$

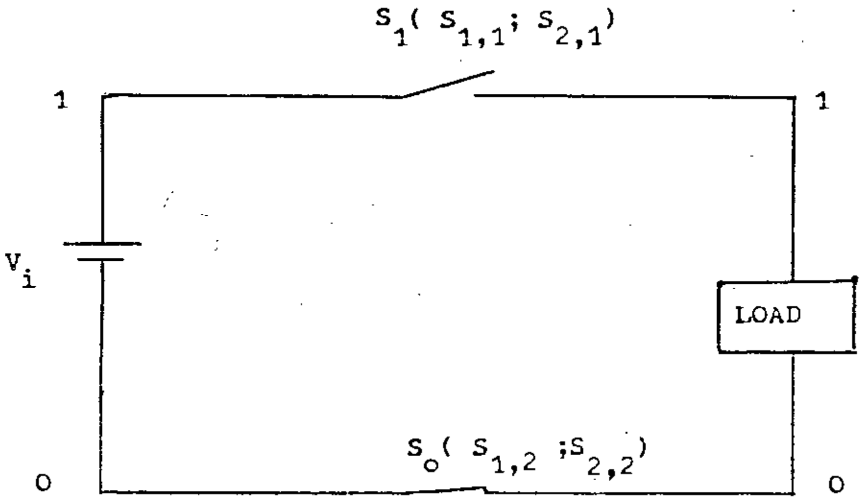
$$= \sum_{n=0,1,3,5,}^{\infty} A_n \cos nw_s t \, . \; I_o$$

$$= I_o \sum_{n=0,1,3,5,}^{\infty} A_n \cos nw_s t \tag{5.2}$$

The output dc voltage V_o waveform and input dc current I_i waveform are shown in Figs. 5.3 and 5.4 respectively. Corresponding spectra are depicted in Figs. 5.3d and 5.4d.



a) Switching diagram derived from generalized model (Fig 2.1) for N=1 and M=1.



b) Corresponding simplified diagram

Fig 5.2 Realization of a Chopper circuit from generalized model.

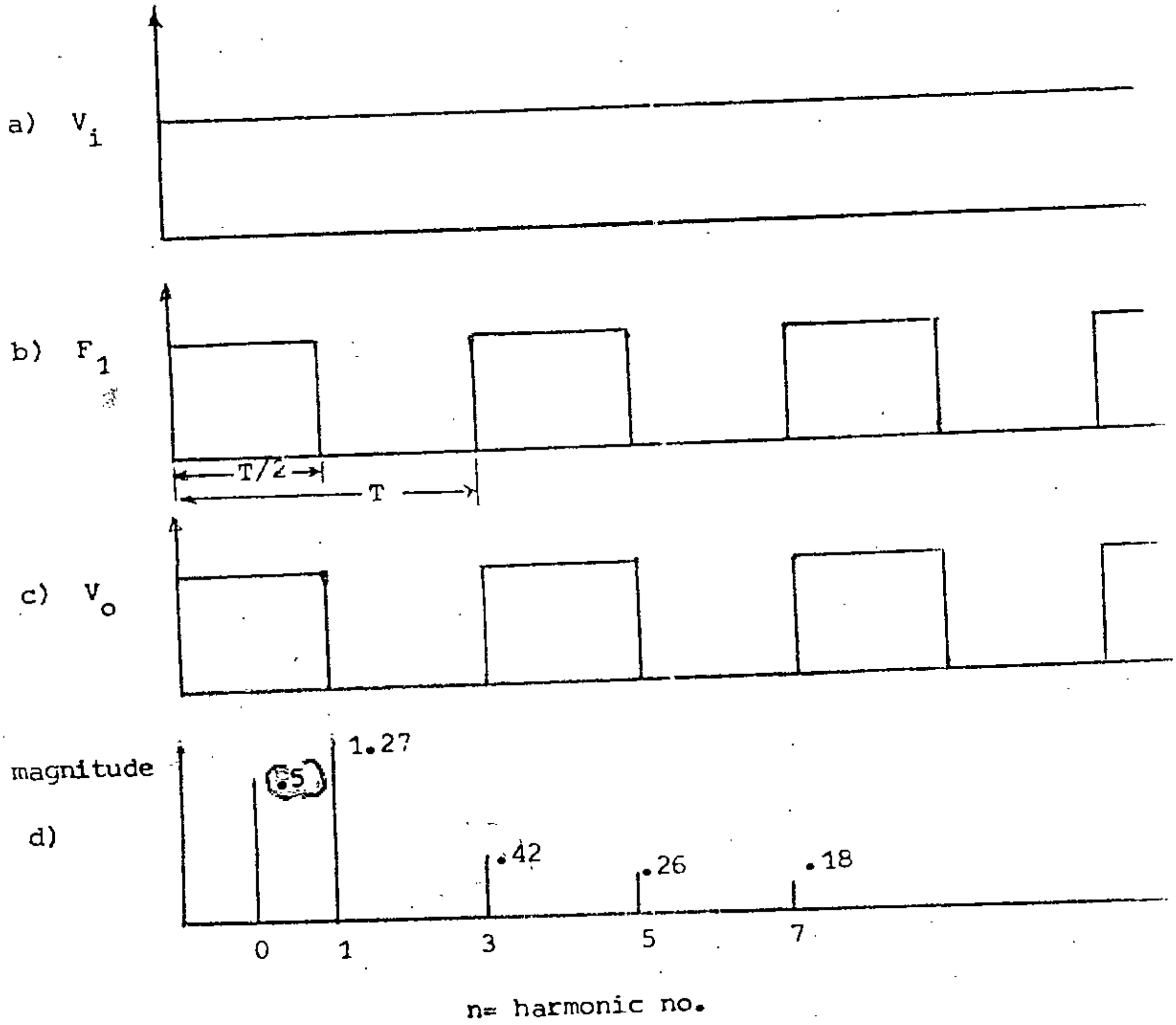


Fig 5.3 Output voltage waveform of the chopper.

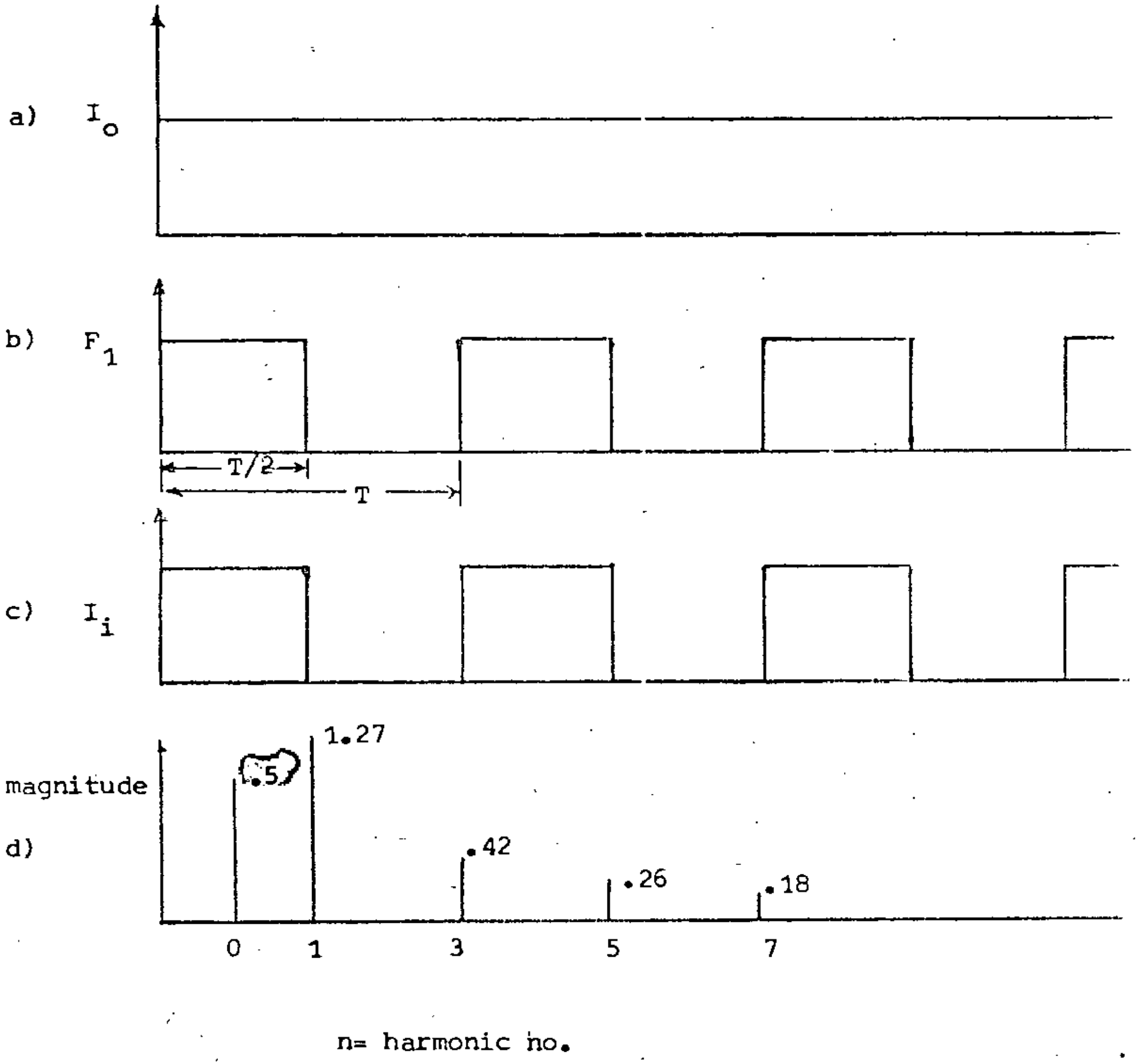
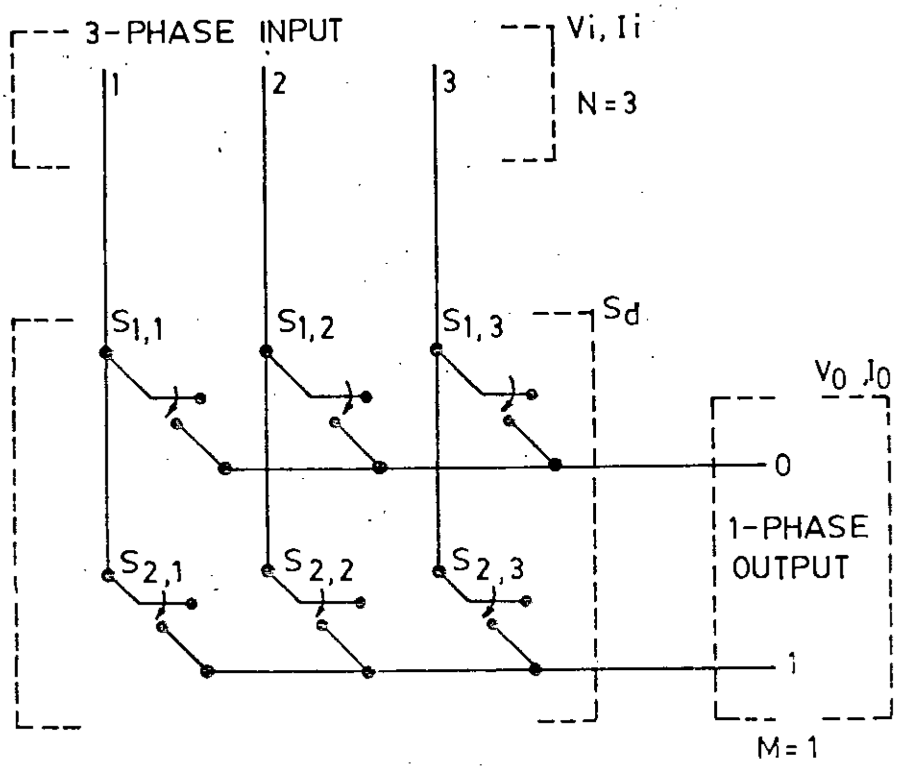


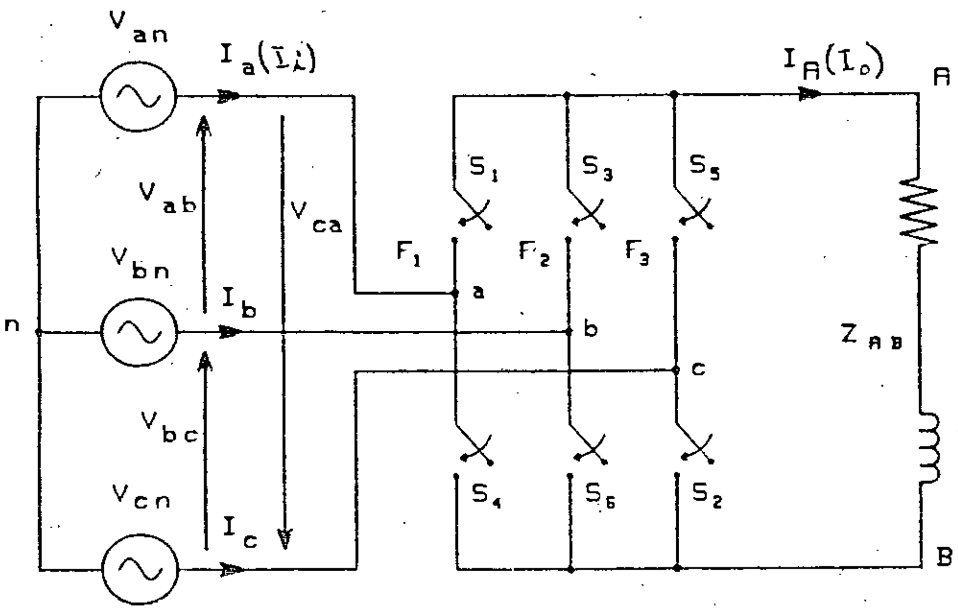
Fig 5.4 Input current waveform of the chopper.

5.3 3-Ø to 1-Ø Frequency Changer Circuit

Fig. 5.5b shows a simplified frequency changer circuit that results from the generalized model by setting the number of input phases N=3 and the number of output phases M=1 (Fig. 5.5a). As the converter is used to change the frequency with minimum harmonic distortion the converter switching function is chosen as SPWM and the switching frequency is $w_s = w_i + w_o$. The corresponding ac output voltage V_{AB} whose frequency is chosen as f_o = 100 Hz and the input ac current I_a (f_i = 50H_z) are shown in Figs. 5.6 respectively. The output voltage and input current spectra are shown in Fig. 5.6e and 5.7d. respectively. The experiemental waveform (Fig. 5.8) and spectra agree with computer simulated results (Figs. 5.6e and 5.7d).



(a) Switching diagram derived from Fig. 2.1 for N=3, M=1.



(b) Corresponding simplified circuit diagram.

Fig. 5.5 Realization of 3Ø to 1Ø frequency changer from generalized model.

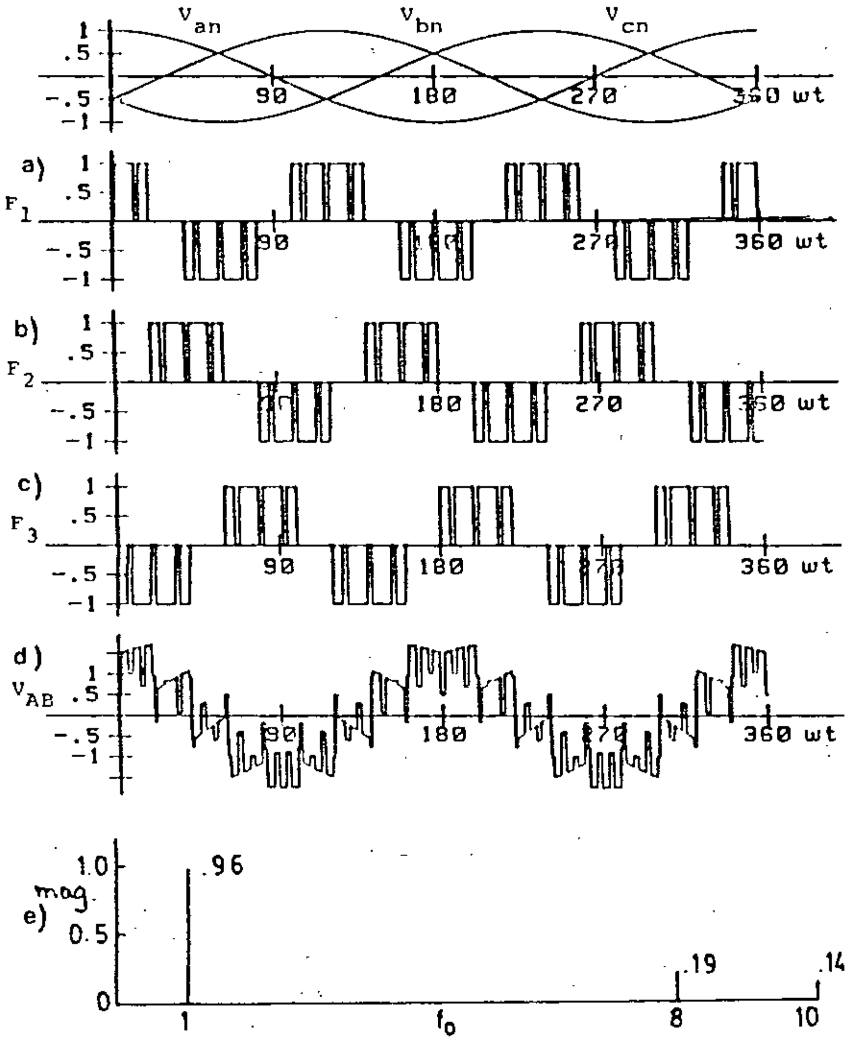


Fig. 5.6 Output voltage waveform of the frequency changer.

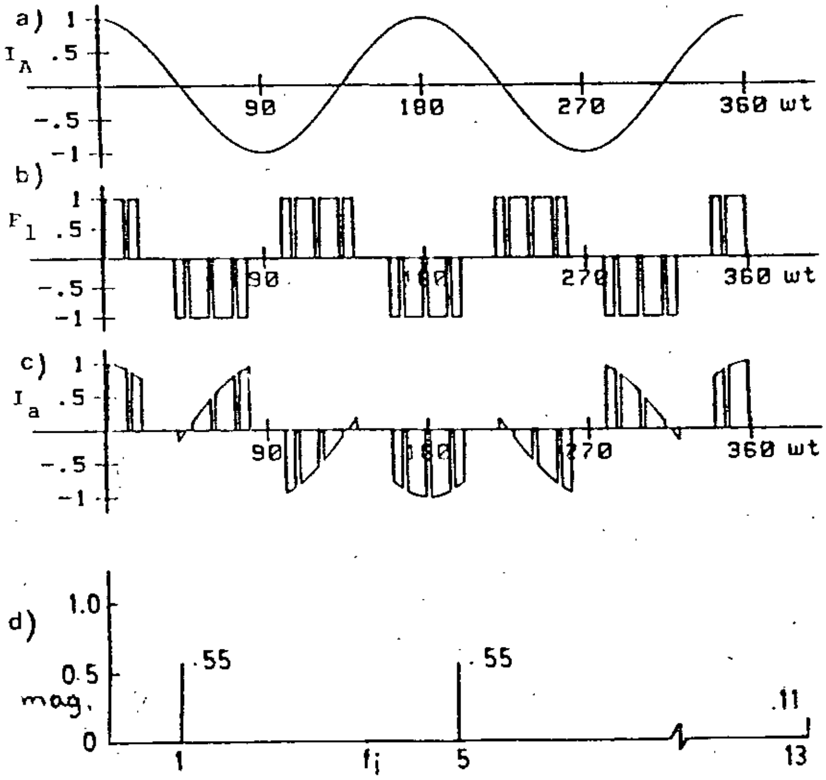
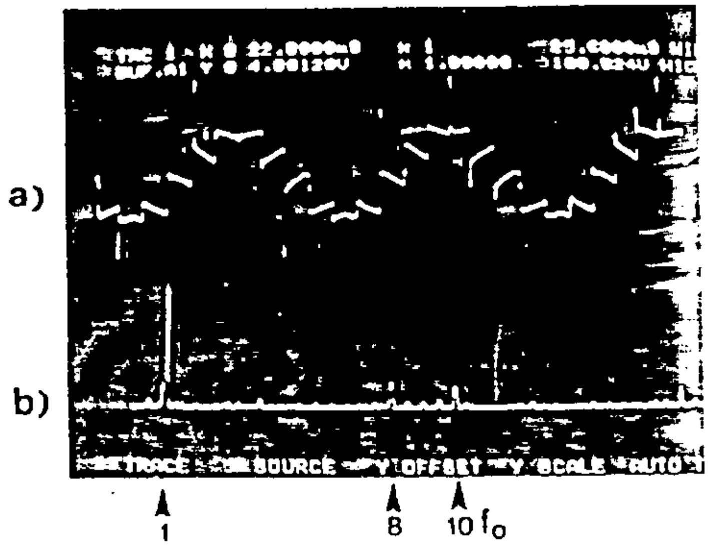
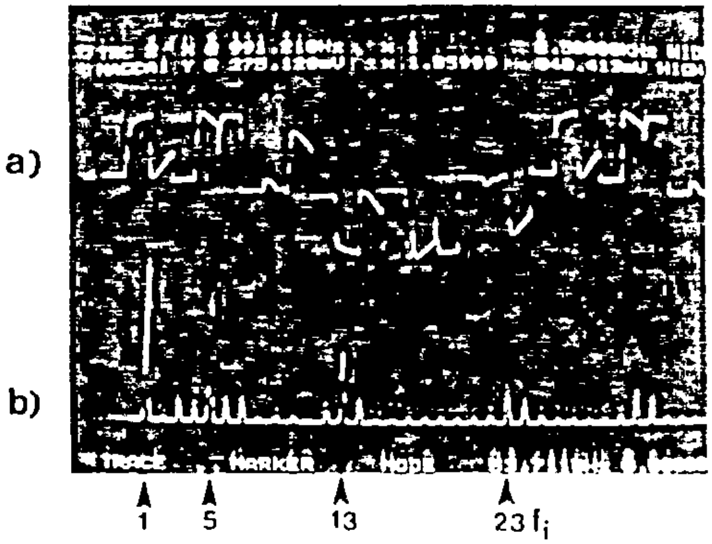


Fig. 5.7 Input current waveform of the frequency changer.



A. (a) Output voltage, V_{AB} (Fig. 5.6d)

(b) Respective frequency spectrum.



B. (a) Input current, I_a (Fig. 5.7c)

(b) Respective frequency spectrum.

Fig. 5.8 Experimental voltage and current waveform of the 3Ø to 1Ø frequency changer at f_o = 120 Hz and modulation index=1.

5.4 Conclusions

Choppers and frequency changers are analysed in this chapter using the proposed model. The output voltage and input current waveform analysis for both choppers and frequency changers are done using the generalized switching model which corresponds to standard analysis. The proposed model is much simpler than conventional methods. Finally a few experimental results are also shown.

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and Conclusions

A generalized switching model is developed in this project work. This model is used to analyse various static converters to suit different types of loads. Simple switching functions are used to analyse rectifier, inverter, chopper and frequency changer.

In particular the contributions of this project by chapter are as follows:

In Chapter 2 the switching model is developed. The necessary general equations for input-output quantities is also developed using the model. A representative case of single phase inverter is studied.

In Chapter 3 three-phase diode and controlled rectifier are studies using model. The six pulse controlled rectifier input-output waveforms are constructed using the fourier coefficient and these waveforms matches the experimental waveforms.

Inverters are studied in Chapter 4. Both single and three phase inverter equations are derived from the model. Frequency spectrum for output voltage and input current are shown in tables. These co-efficient values are same as obtain in standard single phase inverters.

Chapter 5 investigates the choppers and frequency changers. It has been shown that complex converters like direct frequency changers can also be studied by this model. Input-output voltage and current waveforms predicted by computer simulation matches the experimental results.

In summary different types of static converters are studied using the proposed switching model. It has been shown theoritically and experimentally that this generalized switching model can be successfully used for static converter analysis. Moreover, various other simple and complicated power electronics circuits (3-Ø to 3-Ø direct frequency changer, single to three phase converter) can also be simulated and analysed by the proposed model.

6.2 Suggestions for Future Work

Most of the analysis in this project are performed for simple switching functions. Advanced PWM (Pulse Width Modulation) switching function can also be used to improve the quality of the converters. Moreover, it can be further enchance to develop a package program [9] for use in home computer.

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