ANALYSIS AND DESIGN OF A BALANCED

OUTPUT STATIC CONVERTER

BY

MD. SHAFIQUL ISLAM

A THESIS

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ABSTRACT

Static power converters are designed to work under balanced supply condition. In many instances static converters are subject to unbalanced condition. Conventional static converters may not work under such condition. Special unbalanced converter are required for such cases. An unbalanced converter topology is analysed and design procedure is fully discussed in this thesis.

The contribution of the thesis is the development of a technique to correct the input unbalance. The proposed technique states that inorder to generate balanced output voltage and current from unbalanced (amplitude) input voltages, the magnitude of the fundamental component of the switching functions are inversely proportional to the amplitude of the corresponding unbalanced input phase voltage. The dependency of the width of switching function on the Fourier_coefficient is established by harmonic analysis. Input currents and output voltage are fully analysed both under input balanced and unbalanced conditions. The analytically predicted results are verified by computer aided analysis.

Finally, a complete design procedure is described for this three phase to single phase unbalanced converter.

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APPROVAL

Accepted as satisfactory in partial fulfillment of the requirements for the degree of Master of Science in Engineering(Electrical and Electronic).

BOARD OF EXAMINERS :

1. (Dr. Shahidul Islam Khan) — Chairman (Supervisor)
Associate Professor,
Department of Electrical & Electronic Engineering, BUET, Dhaka.

2. (Dr. Md. Abdul Matin) 29.6.1989 — Member (Ex-Officio)
Professor and Head,
Department of Electrical & Electronic Engineering, BUET, Dhaka.

3. (Dr. Md. Mujibur Rahman) — Member
Professor and Dean,
Faculty of Electrical & Electronic Engineering, BUET, Dhaka.

4. (Dr. Enamul Bashar) 29.6.89 — Member
Associate Professor,
Department of Electrical & Electronic Engineering, BUET, Dhaka.

5. (Dr. A. M. Zahoorul Huq) 29.6.89 — Member (External)
391, Baitul Aman Housing Society,
Road No. 7, Shymoli, Dhaka.

CERTIFICATE

Certified that this work was done by me and it has not been submitted elsewhere for the award of any degree or diploma.

Countersigned

20/6/89

(Dr. Shahidul Islam Khan)
Supervisor.

Signature of the student

20/06/89

(Md. Shafiqul Islam)

Dedicated to my parents

and

to my Nieces Razia and Sumi.

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LIST OF SYMBOLS AND ABBREVIATIONS

W_s	=	Angular Switching frequency
W_i	=	Angular frequency of input voltage
W_o	=	Angular frequency of output voltage
I_a, I_b, I_c	=	Input phase currents of the converter
I_{AB}	=	Output current of the converter
I_o	=	Amplitude of the output current
V_{an}, V_{bn}, V_{cn}	=	Input phase voltages
V_{ab}, V_{bc}, V_{ca}	=	Input Line Voltages.
V_{An}, V_{Bn}, V_{Cn}	=	Three Unbalanced input phase voltage.
$V_o(W_o t)$	=	Output voltage of the converter
V_i	=	Amplitude of the balanced input phase voltage
$H_s(W_s t)$	=	Converter transfer function
$F(W_s t)$	=	Switching function
A, B, C	=	Amplitudes of the three unbalanced input phase voltage
F_1, F_2, F_3	=	Three switching functions
A_1, B_1, C_1	=	The amplitudes of the fundamental components of three switching functions F_1, F_2 and F_3 respectively.
A'_n, B'_n, C'_n	=	Amplitude of the n-th harmonic component of the three switching functions.
a_n, b_n	=	The n-th harmonic Fourier Co-efficients of the switching function.

K_m = The m-th harmonic Fourier Co-efficient of the switching function.

$\delta_1, \delta_2, \delta_3$ = Widths of the three switching functions under unbalanced input condition.

$S_1, S_2, S_3, S_4, S_5, S_6$. = Six bilateral switches of the converter

$g_1, g_2, g_3, g_4, g_5, g_6$. = Six gating signals for the bilateral switches.

L_{S1}, L_{S2}, L_{S3} = Three inductors in the protective circuits.

R_{S1}, R_{S2} = Registors in the protective circuits.

C_{S1} = Capacitor in the protective circuits.

PWM = Pulse width Modulation

DMO = Direct Mode of Operation

p.u. = per unit.

CHAPTER-1

INTRODUCTION

1.1 Introduction

Unbalanced a.c. electric power causes severe problem in operation of static power converters. Static power converters are usually designed to work under balanced input condition. The unbalance is usually caused due to improper loading of different phases or unbalanced phase impedance. Nature of unbalance could be i) Amplitude unbalance or ii) Phase unbalance. Unbalance in static converters causes various problems [1] - [3] like harmonic heating in motors, electromagnetic interference (EMI) in communication equipments, etc.

This thesis proposes a method for balancing the output voltage when the input voltage is amplitude unbalanced. The proposed method is applied to a three to single phase static converter.

1.2 Implementation of the Proposed Method

The method proposed in this thesis to balance the input amplitude unbalance uses switching function variation technique. According to the magnitude of the input unbalance, the switching function width is varied and it is inversely proportional to the amplitude of the input phase voltage. A simplified block diagram of the proposed unbalance phase converter is shown in Fig. 1.

The converter consists of six bilateral switches. The switches are synchronized with the input voltage and their opening and closing are determined by the percentage of input unbalance. The output voltage is balanced (Fig. 1).

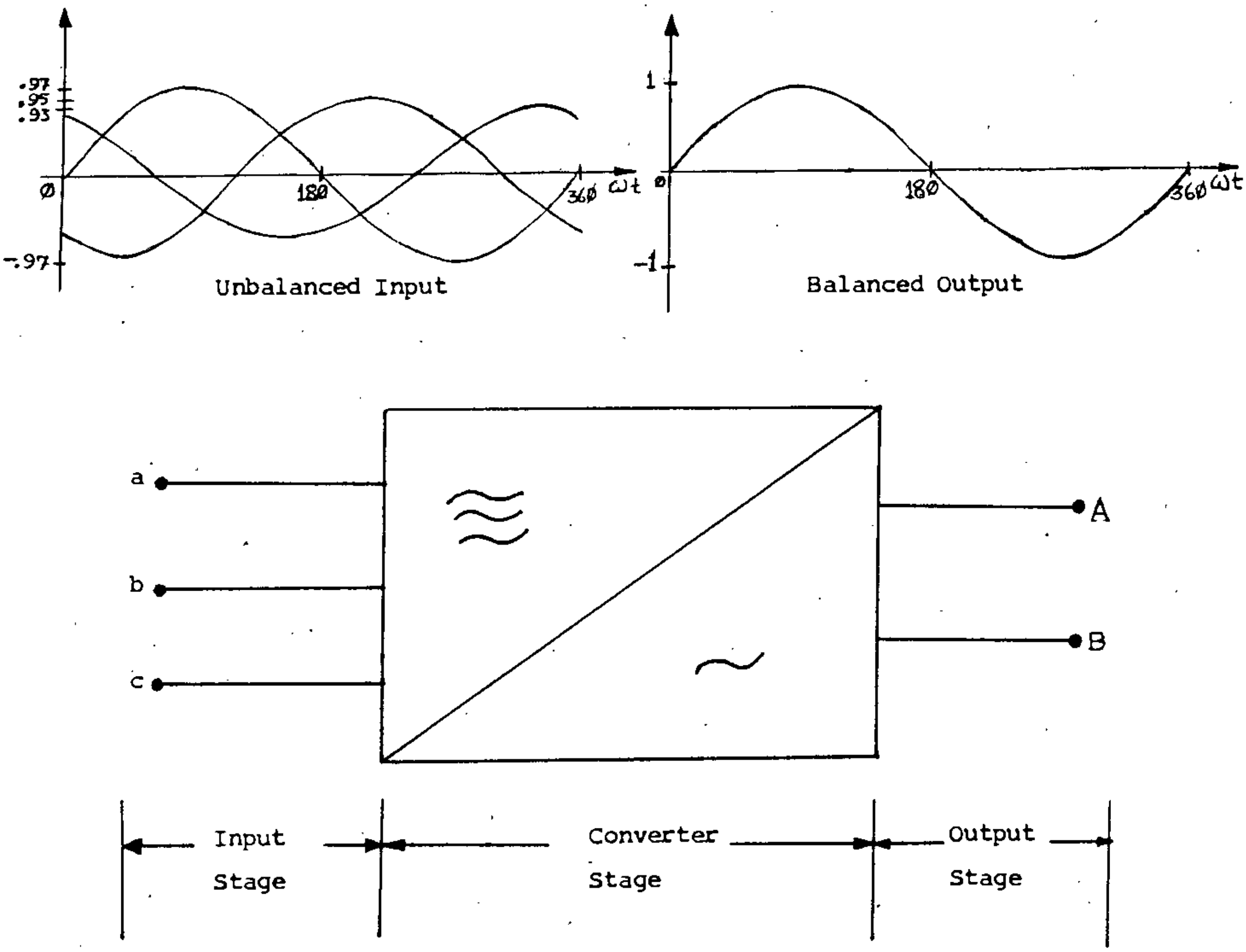

Fig. 1 : Block diagram of the proposed balanced output static converter.

1.3 Review of Previous Work

There are two types of unbalances in Three-phase supply voltages. These are amplitude unbalance and phase unbalance. Amplitude unbalance arises due to the uneven distribution of loads [4] in the three-phase circuits. Phase unbalance arises due to the difference in impedances (reactive part) of loads connected in the three-phase circuits. Amplitude unbalance can be eliminated by changing the width of the switching functions. Phase unbalance can be eliminated by shifting the switching functions to the desired positions.

The problems those were previously detected due to unbalance are harmonic generation in the converter, electromagnetic interference (EMI) in the communication equipments, harmonic heating in motor drives, and in military application. Small amount of unbalances may generate harmonics in the converter due to it's non-linear characteristics. Electromagnetic interference (EMI) in the communication equipments (receivers) due to unbalances does not allow faithful reproduction of message. In large motors, harmonic heating due to unbalances may cause insulation breakdown or damage the motors. Electromagnetic (EM) radiation from the submarine due to unbalances is used to detect the enemy submarine. This is very important in military application.

Not very many work are reported in unbalanced converters, although it has good prospect with the evolution of semiconductor technology. Power Electronics group at Concordia University, Montreal, [4] is doing some work in unbalanced converter. But those works are aimed at assessing the harmonics present in converters due to unbalance rather than finding solution. The Power Electronics group at Texas A&M University is working on unbalance converter solution by using Fortescue's theorem but their work is targeted for motor problems rather than converter problems.

1.4 Scope of the Present Work

A new technique is used to analyse the proposed static converter. Such technique was not used previously in the analysis. Switching functions are used to solved the amplitude unbalance. Amplitude unbalance is corrected by changing the width of the switching functions according to the unbalances. The magnitude of the fundamental component of the three switching functions is taken as inversely proportional to the amplitude of the three unbalanced input phase voltages.

At first a graphical technique has been developed to find out the output voltage and input currents. The graphs of the above mentioned quantities are plotted with the help of FORTRAN-IV program. A general FORTRAN-IV plotting program has been developed in the analysis.

Fourier analysis is used to prove the graphical voltage and currents. Fourier co-efficient for m-th harmonic is used to find out the output voltage and input currents. All analysis is carried out on the basis of three phase to single phase converter consisting of six-switches. The results of two methods are compared and found satisfactory.

CHAPTER 2

ANALYSIS OF THE CONVERTER

2.1 Introduction

The objective of this chapter is to analyse a converter which can handle unbalanced input voltages. To achieve this objective first a phase converter is analysed under balanced input condition. From this analysis some basic criterion is established so that the input unbalance can be made balanced in the output circuit.

Converters are usually designed to handle balanced three and single phase input power. When the input is unbalanced conventional Static converter may not work properly. Short circuiting, harmonic generation, unbalancing of the output power [5] are the major problems associated with unbalanced input.

The input voltage could be unbalanced due to different amplitudes of the three input phases or the improper phase relation. Both amplitude and phase unbalance could be corrected. Only the amplitude unbalance is treated in this thesis.

A method for correcting the amplitude unbalance is developed in this chapter which could be applied to different phase converters. A specific case of three phase to single phase converter is studied in details.

2.2 Mathematical Analysis of the Converter

The transfer function of a converter (Fig. 2.1) can be written as the ratio of output to input quantity;

$$H_s(S) = \frac{V_o(S)}{V_i(S)} \quad \text{and} \quad \left[H_s(S)\right]^T = \frac{I_i(S)}{I_o(S)}$$

$$\text{or,} \quad H_s(w_s t) = \frac{V_o(w_o t)}{V_i(w_i t)} \quad \text{and} \quad \left[H_s\ (w_s t)\right]^T = \frac{I_i\ (w_i t)}{I_o\ (w_o t)}$$

Therefore, output voltage, $\left[V_o(w_o t)\right] = \left[H_s(w_s t)\right] \cdot \left[V_i\ (w_i t)\right]$ .. .. .. (2a)

and input current, $\left[I_i\ (w_i t)\right] = \left[H_s(w_s t)\right]^T \cdot \left[I_o\ (w_o t)\right]$ .. .. .. (2b)

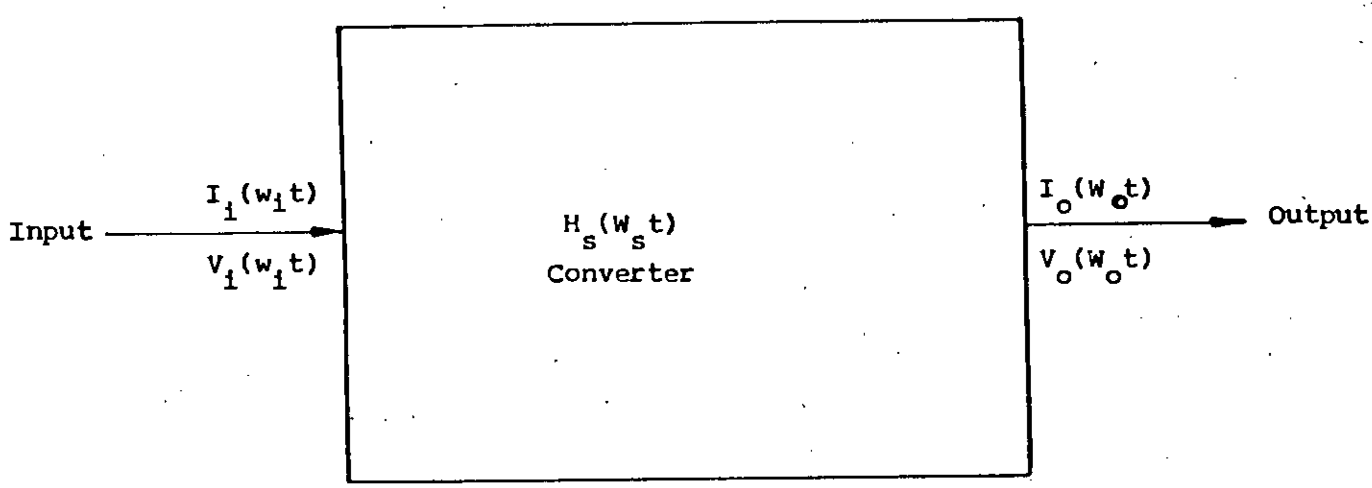

Fig. 2.1 : Representation of an ideal converter by transfer function.

Let $\left[H_s(w_s t)\right] = A\left[\text{Cos}\,(w_s t) \quad \text{Cos}\,(w_s t - 120^\circ) \quad \text{Cos}\,(w_s t - 240^\circ)\right]$ and

$$\left[V_i(w_i t)\right] = V_i \begin{bmatrix} \text{Cos}\,(w_i t) \\ \text{Cos}\,(w_i t - 120^\circ) \\ \text{Cos}\,(w_i t - 240^\circ) \end{bmatrix}$$ be the switching function

and input voltage of the converter.

From eqn. (2a),

$$\left[V_o(w_o t)\right] = \left[H_s(w_s t)\right] \cdot \left[V_i(w_i t)\right]$$

$$= A\left[\text{Cos}\,(w_s t) \quad \text{Cos}(w_s t - 120^\circ) \quad \text{Cos}\,(w_s t - 240^\circ)\right] \cdot$$

$$V_i \begin{bmatrix} \text{Cos}\,(w_i t) \\ \text{Cos}\,(w_i t - 120^\circ) \\ \text{Cos}\,(w_i t - 240^\circ) \end{bmatrix}$$

$$= AV_i \left[\text{Cos}\,(w_s t)\ \text{Cos}(w_i t) + \text{Cos}\,(w_s t - 120^\circ)\ \text{Cos}(w_i t - 120^\circ) + \text{Cos}\,(w_s t - 240^\circ)\ \text{Cos}\,(w_i t - 240^\circ)\right]$$

or, $$\left[V_o\,(w_o t)\right] = \frac{AV_i}{2}\left[\text{Cos}\,(w_s + w_i)\,t + \text{Cos}\,(w_s - w_i)\,t + \text{Cos}\left\{(w_s + w_i)t - 240^\circ\right\} + \text{Cos}\,(w_s - w_i)t + \text{Cos}\left\{(w_s + w_i)t - 120^\circ\right\} + \text{Cos}\,(w_s - w_i)\,t\right]$$

$$= \frac{3AV_i}{2}\left[\text{Cos}\,(w_s - w_i)\,t\right] + \frac{AV_i}{2}\left[\text{Cos}\,(w_s + w_i)\,t + \text{Cos}\left\{(w_s + w_i)t - 120^\circ\right\} + \text{Cos}\left\{(w_s + w_i)t - 240^\circ\right\}\right]$$

Since the second term of the above equation is the three phasors of equal magnitude and displaced 120° apart from each other, their sum i.e. the resultant is zero.

Therefore,

$$\left[V_o(w_o t)\right] = \frac{3AV_i}{2}\left[\cos\,(w_s - w_i)t\right]$$

$$= \frac{3AV_i}{2}\cos\,(w_o t) \qquad (\because w_s = w_i + w_o)$$

$$\therefore V_o\,(w_o t) = \frac{3AV_i}{2}\cos\,(w_o t) \qquad \cdots \qquad \cdots \qquad \cdots \qquad (2c)$$

From eqn. (2b), input current is given by

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

$$\text{or,}\begin{bmatrix} I_a(w_i t) \\ I_b(w_i t) \\ I_c(w_i t) \end{bmatrix} = A\begin{bmatrix} \cos\,(w_s t) \\ \cos\,(w_s t - 120^o) \\ \cos\,(w_s t - 240^o) \end{bmatrix} \cdot I_o\left[\cos\,(w_o t)\right]$$

$$= AI_o\begin{bmatrix} \cos\,(w_s t)\cos\,(w_o t) \\ \cos\,(w_s t - 120^o)\cos(w_o t) \\ \cos\,(w_s t - 240^o)\cos(w_o t) \end{bmatrix}$$

$$= \frac{AI_o}{2}\begin{bmatrix} \cos\,(w_s + w_o)t + \cos(w_s - w_o)t \\ \cos\left\{(w_s + w_o)t - 120^o\right\} + \cos\left\{(w_s - w_o)t - 120^o\right\} \\ \cos\left\{(w_s + w_o)t - 240^o\right\} + \cos\left\{(w_s - w_o)t - 240^o\right\} \end{bmatrix}$$

$$= \frac{AI_o}{2}\begin{bmatrix} \cos\,(w_s - w_o)t \\ \cos\left\{(w_s - w_o)t - 120^o\right\} \\ \cos\left\{(w_s - w_o)t - 240^o\right\} \end{bmatrix} + \frac{AI_o}{2}\begin{bmatrix} \cos\,(w_s + w_o)t \\ \cos\left\{(w_s + w_o)t - 120^o\right\} \\ \cos\left\{(w_s + w_o)t - 240^o\right\} \end{bmatrix} \cdots \qquad \cdots \qquad (2d)$$

The Second part of equation (2d) is the 3rd harmonic term. As we are considering the ideal case (free of harmonics), the second part will be considered as zero. Therefore,

$$\begin{bmatrix} I_a\ (w_i t) \\ I_b\ (w_i t) \\ I_c\ (w_i t) \end{bmatrix} = \frac{AI_o}{2} \begin{bmatrix} \cos\ (w_s - w_o\ )t \\ \cos\ \left\{(w_s - w_o)t - 120^o\right\} \\ \cos\ \left\{(w_s - w_o)t - 240^o\right\} \end{bmatrix}$$

$$= \frac{AI_o}{2} \begin{bmatrix} \cos\ (w_i t) \\ \cos\ (w_i t - 120^o) \\ \cos\ (w_i t - 240^o) \end{bmatrix} \quad \cdot\cdot \qquad \cdot\cdot\ (2e)$$

2.2.1 Three to Single Phase Converter under Unbalanced Condition

The output voltage of a three to single phase converter shown in Fig. 2.2 is given by [6];

$$\left[V_o\ (w_o t)\right] = \left[F\ (w_s t)\right] \cdot \left[V_i (w_i t)\right]$$

where, $\left[V_o\ (w_o t)\right]$ = output voltage

$$\left[V_i\ (w_i t)\right] = \text{Input voltage} = \begin{bmatrix} A\ \ \cos\ (w_i t) \\ B\ \ \cos\ (w_i t - 120^o) \\ C\ \ \cos\ (w_i t - 240^o) \end{bmatrix}$$

$$\left[F\ (w_s t)\right] = \text{Switching function} = \left[F_1 \quad F_2 \quad F_3\right]$$

Unlike three phase balanced voltages, the amplitude of the three input voltages V_{An}, V_{Bn}, V_{Cn} are unequal and given by A, B, and C respectively.

Let us assume,

$$F_1 = A_1 \cos\ (w_s t)$$

$$F_2 = B_1 \cos\ (w_s t - 120^o)$$

$$F_3 = C_1 \cos\ (w_s t\ - 240^o)$$

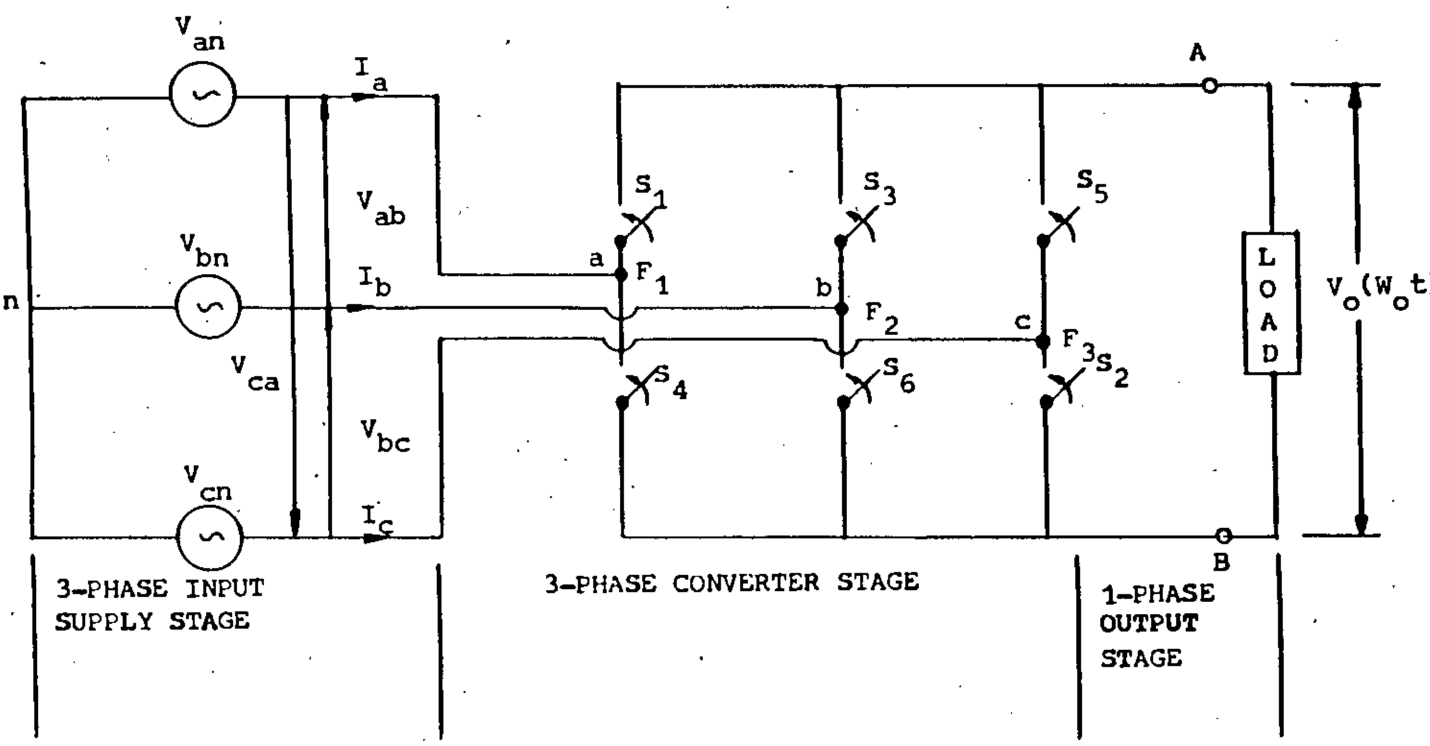

Fig. 2.2 : Simplified circuit diagram of the proposed 3-phase to 1-phase converter.

where A_1, B_1 and C_1 are the amplitudes of the fundamental components of three switching functions F_1, F_2 and F_3 respectively.

Therefore,

$$\left[V_o(w_ot)\right] = \left[A_1 \,Cos(w_st) \quad B_1 \,Cos(w_st-120^o) \quad C_1 \,Cos(w_st-240^o)\right] \cdot \begin{bmatrix} A \;\; Cos\;(w_it\;) \\ B \;\; Cos\;(w_it\;-120^o) \\ C \;\; Cos\;(w_it\;-240^o) \end{bmatrix}$$

$$= \left[A_1\,A\;Cos\;(w_st)\;Cos\;(w_it) + B_1B\;Cos\;(w_st-120^o)\;Cos(w_it-120^o) + C_1C\;Cos\;(w_st-240^o)Cos\;(w_it-240^o)\right]$$

Assuming $A_1A = 1$, $B_1B = 1$ & $C_1C = 1$

$$= \tfrac{1}{2}\left[Cos\;(w_s + w_i)t + Cos\;(w_s-w_i)t + Cos\left\{(w_s+ w_i)\;t - 240^o\right\} + Cos\;(w_s-w_i)t + Cos\left\{(w_s+w_i)t - 120^o\right\} + Cos\;(w_s-w_i)t\right]$$

$$= \frac{3}{2}\;Cos\;(w_s-w_i)t + \tfrac{1}{2}\left[Cos\;(w_s+w_i)t + Cos\left\{(w_s + w_i)t - 120^o\right\} + Cos\left\{(w_s+w_i)t-240^o\right\}\right]$$

Since the Second term in the above equation is zero, therefore,

$$\left[V_o\;(w_ot)\right] = \frac{3}{2}\;Cos\;(w_s - w_i)t$$

$$= \frac{3}{2}\;Cos\;(w_ot)\;;\text{ as } w_o = w_i \text{ and } w_s = w_o + w_i.$$

Since $A_1A = 1 \;\therefore A_1 = 1/A$

$B_1B = 1 \;\therefore B_1 = 1/B$

$C_1C = 1 \;\therefore C_1 = 1/C$

Therefore, we can conclude that in order to get a balanced output voltage from three unbalanced input voltages, the amplitude of the fundamental components of switching functions should be inversely proportional to the amplitude of three input phase voltages respectively.

2.3 Operation of the Balanced 3 to 1 Phase Converter

The operation of a 3-phase to 1-phase balanced output Static Converter can be explained with the help of Fig. 2.2. The converter output voltage is given by

$$\begin{bmatrix} V_o\ (w_o t) \end{bmatrix} = \begin{bmatrix} S_d\ (w_s t) \end{bmatrix} \cdot \begin{bmatrix} V_i\ (w_i t) \end{bmatrix}$$

$$= \begin{bmatrix} F_1 & F_2 & F_3 \end{bmatrix} \cdot \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix}$$

$$= \begin{bmatrix} F_1 * V_{an} + F_2 * V_{bn} + F_3 * V_{cn} \end{bmatrix}$$

$$\therefore\ V_o\ (w_o t) = F_1 * V_{an} + F_2 * V_{bn} + F_3 * V_{cn}$$

The switching functions can have both +1 and −1 and zero values. when

F_1 has +1 value the top switch S_1 is closed.

F_1 has −1 value the bottom switch S_4 is closed.

F_1 has 0 value both top and bottom switches S_1 & S_4 are open.

F_2 has +1 value the top switch S_3 is closed.

F_2 has −1 value the bottom switch S_6 is closed.

F_2 has 0 value both top & bottom switches S_3 & S_6 are open.

F_3 has +1 value the top switch S_5 is closed.

F_3 has −1 value the bottom switch S_2 is closed.

F_3 has 0 value both top & bottom switches S_5 & S_2 are open.

The principle of operation of the converter is explained by dividing each switching function into two switch operation as follows;

Figure 2.3 shows the input voltages and switching functions graphically. For the first 30° F_1 has a value of +1 and F_3 has a value of -1. So S_1 and S_2 is closed. The output is the combination of $F_1 * V_{an}$ and $F_3 * V_{cn}$. For 30° to 60°, F_2 has a value of +1 and F_3 has a value of -1. So S_3 and S_2 is closed. The output is the combination of $F_2 * V_{bn}$ and $F_3 * V_{cn}$. For 60° to 90°, F_1 has a value of -1 and F_2 has a value of +1. So S_3 and S_4 is closed. The output is the combination of $F_1 * V_{an}$ and $F_2 * V_{bn}$.

For 90° to 120°, F_1 has a value of -1 and F_3 has a value of +1. So S_4 and S_5 is closed. The output is the combination of $F_1 * V_{an}$ and $F_3 * V_{cn}$. For 120° to 150°, F_2 has a value of -1 and F_3 has a value of +1. So switches S_5 and S_6 is closed. The output is the combination of $F_2 * V_{bn}$ and $F_3 * V_{cn}$. For 150° to 180°, F_1 has a value of +1 and F_2 has a value of -1. So S_1 and S_6 is closed. The output is the combination of $F_1 * V_{an}$ and $F_2 * V_{bn}$.

After 180°, the operation is the same as explained earlier and the cycle is repeated.

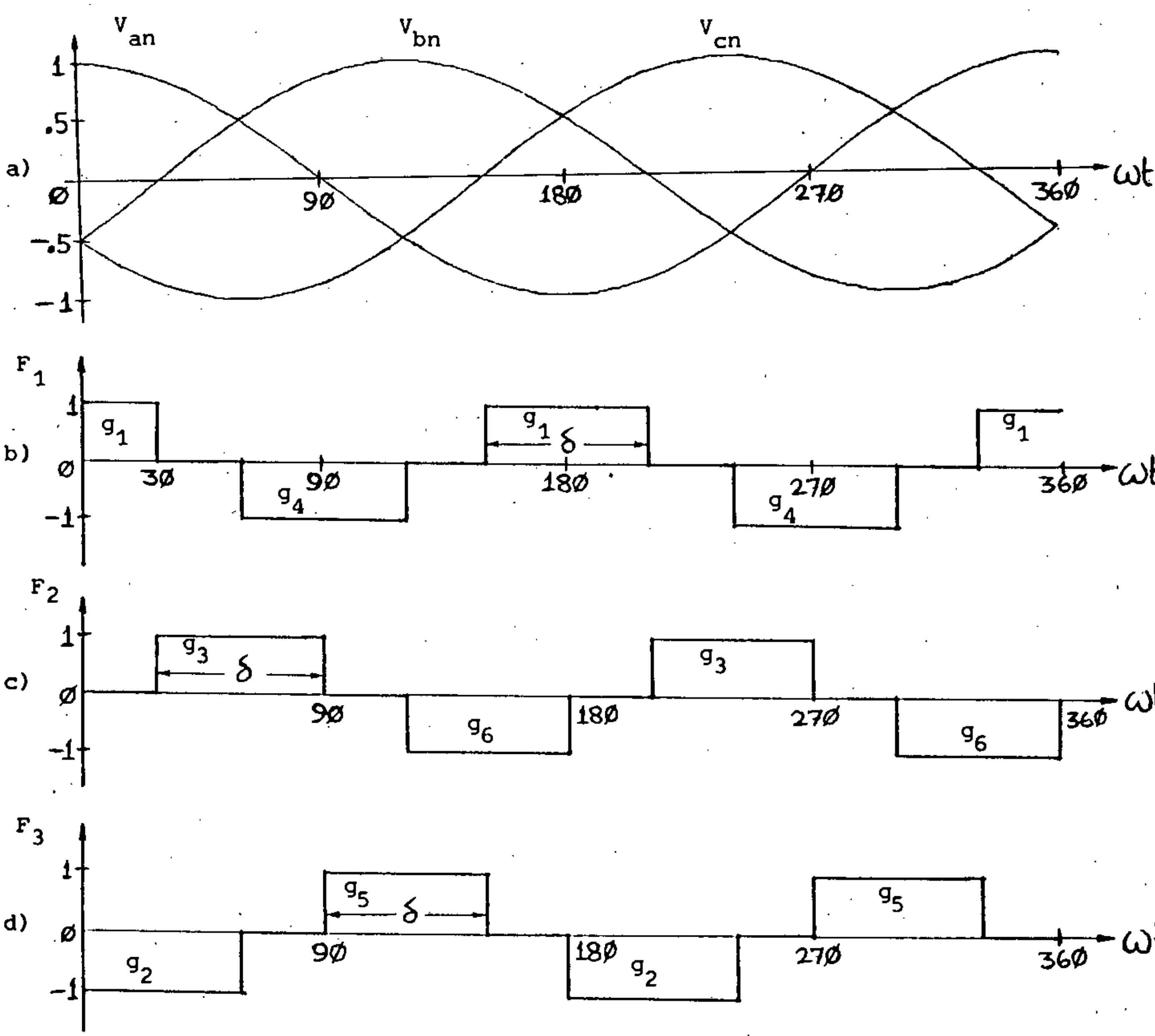

Fig. 2.3 : Switching functions for balanced case.

a)Balanced input voltages.

b)-d) Switching function components.

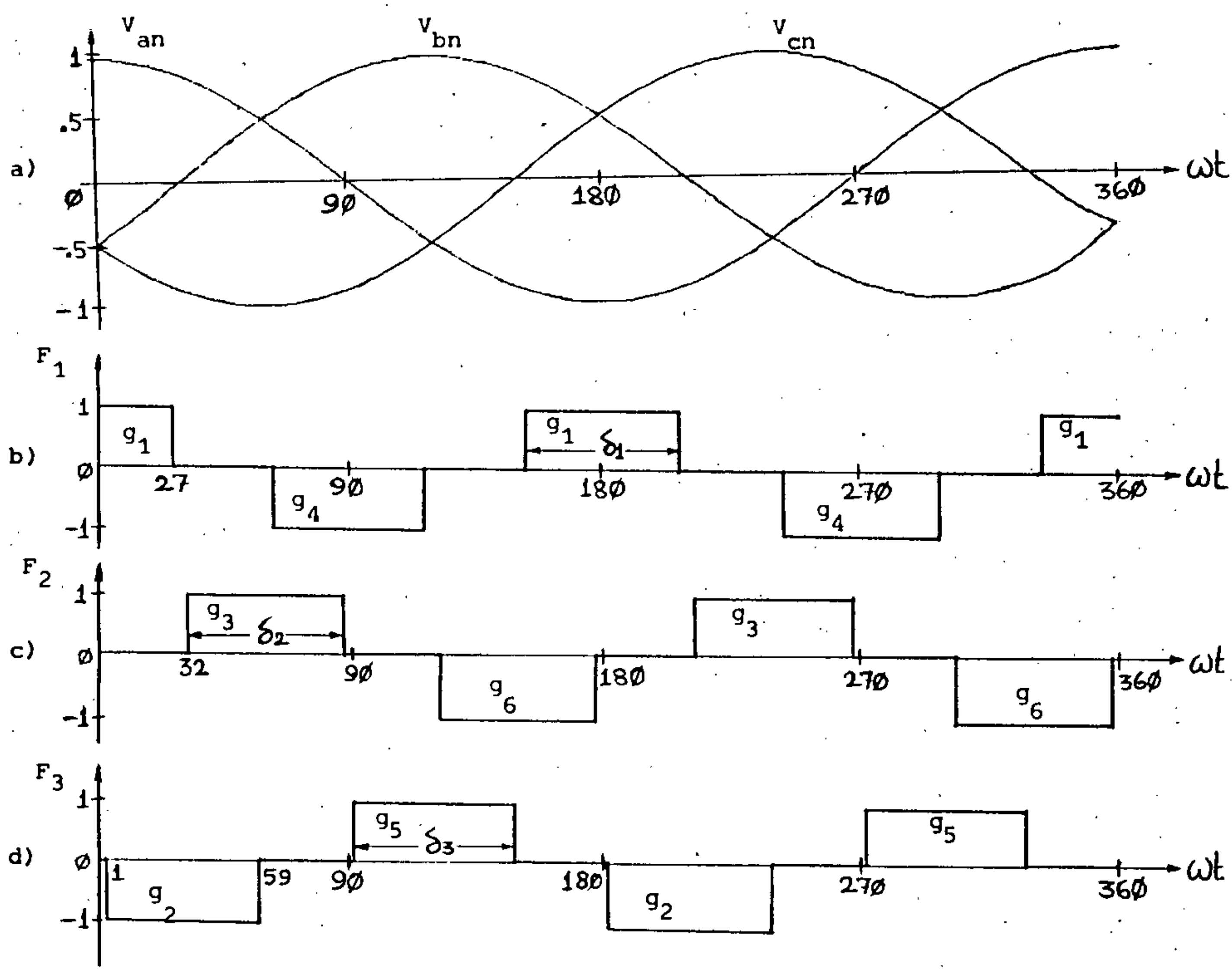

Fig. 2.4 : Switching functions for unbalanced case.

a) Unbalanced input voltages.

b)-d) Corresponding switching functions.

2.3.1 Operation of the Unbalanced 3 to 1 Phase Converter

For the unbalanced case, only the switching function widths will be different, Principle remains the same. Figure 2.4 shows the three unbalanced input voltages and three switching functions with different widths due to unbalances in the input voltages. We can explain the operation of the unbalanced converter as follows;

The unbalanced voltages are taken as

$$V_{an} = 0.97 \, \text{Cos} \, (w_1 t)$$

$$V_{bn} = 0.95 \, \text{Cos} \, (w_1 t - 120^\circ)$$

and $V_{cn} = 0.93 \, \text{Cos} \, (w_1 t - 240^\circ)$ i.e. unbalances are 3%, 5% & 7% respectively. Due to this unbalance, the widths of the switching functions are δ_1, δ_2, and δ_3 (eqn. 2.5) which is shown in Fig. 2.4. For the balanced inputs, the width of the switching function is $\delta = \delta_1 = \delta_2 = \delta_3$.

Comparing Figs 2.3 & 2.4 we see that the principle of operation of the converter remains the same under balanced and unbalanced input conditions, only the widths of the switching functions become different.

2.4 Harmonic Analysis

Practical power converters operate in ON/OFF mode rather than in continuous mode and employ static switches. Consequently, the switch elements, i.e. switching functions described earlier are actually 'trains' of rectangular pulses of uniform or sine modulated widths and as such, they posses frequency spectra comprised of infinite series of harmonic components. The harmonics associated with switching functions, output voltage and input currents are described as follows:

The Fourier-series expansion for a function F(θ) with time period 2π radians is given by

$$F(\theta) = \frac{a_o}{2} + \sum_{n=1,2,3}^{\infty} \left[a_n \, \text{Cos} \, (n\theta) + b_n \, \text{Sin} \, (n\theta) \right]$$

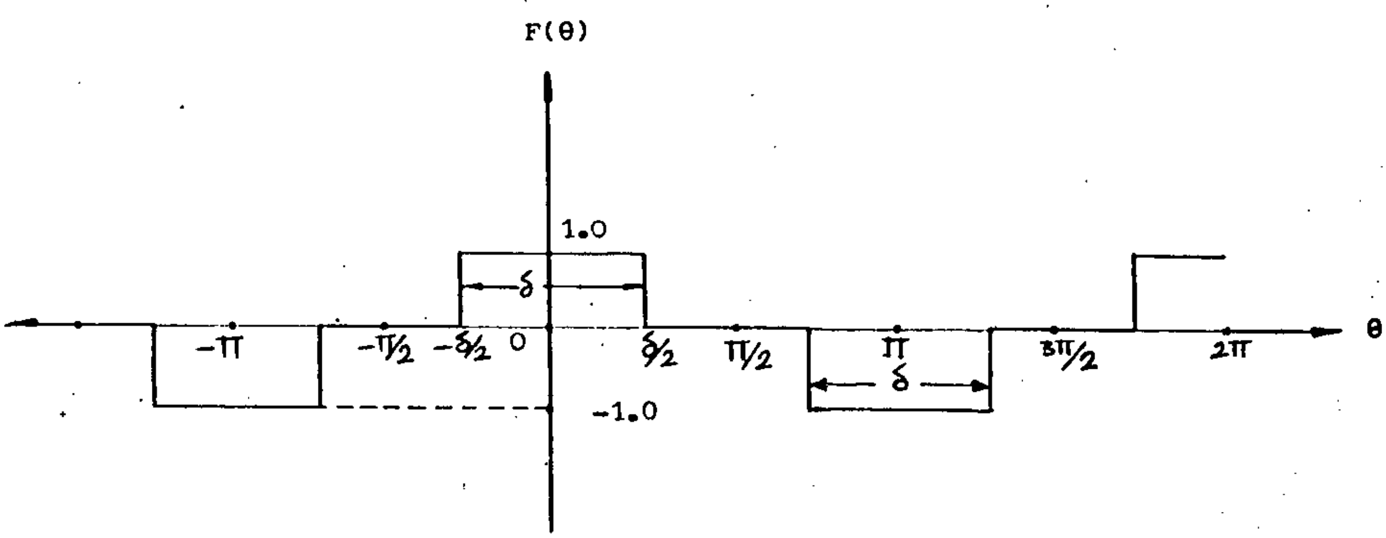

Fig. 2.5 : Switching function F(θ) with pulse width δ and time period 2π radians.

where,

$$a_n = \frac{1}{\pi}\int_{-\pi}^{+\pi} F(\theta)\ \text{Cos}\ (n\theta)\ d\theta$$

$$b_n = \frac{1}{\pi}\int_{-\pi}^{+\pi} F(\theta)\ \text{Sin}\ (n\theta)\ d\theta$$

a_o = Average value of the function $F(\theta)$

$$= \frac{1}{\pi}\int_{-\pi}^{+\pi} F(\theta)\ d\theta$$

For the switching function shown in Fig. 2.5, the Fourier coefficients are calculated as follows;

$$a_n = \frac{1}{\pi}\int_{-\pi}^{+\pi} F(\theta)\ \text{Cos}\ (n\theta)\ d\theta$$

$$= \frac{2}{\pi}\int_{0}^{\pi} F(\theta)\ \text{Cos}\ (n\theta)\ d\theta$$

$$= \frac{2}{\pi}\left[\int_{0}^{\delta/2} \text{Cos}\ (n\theta)\ d\theta - \int_{(\pi-\delta/2)}^{+\pi} \text{Cos}\ (n\theta)\ d\theta\right]$$

$$\therefore\ a_n = \frac{2}{n\pi}\left[\left(\text{Sin}\ n\theta\right)_0^{\delta/2} - \left(\text{Sin}\ n\theta\right)_{(\pi-\delta/2)}^{\pi}\right]$$

$$= \frac{2}{n\pi}\left[\text{Sin}\left(\frac{n\delta}{2}\right) - \text{Sin}\ (n\pi) + \text{Sin}\left(n\pi - \frac{n\delta}{2}\right)\right]$$

$$= \frac{2}{n\pi}\left[\text{Sin}\left(\frac{n\delta}{2}\right) - \text{Sin}(n\pi) + \text{Sin}(n\pi)\ \text{Cos}\left(\frac{n\delta}{2}\right) - \text{Cos}(n\pi)\ \text{Sin}\left(\frac{n\delta}{2}\right)\right]$$

$$= \frac{2}{n\pi}\left[\text{Sin}\left(\frac{n\delta}{2}\right) - \text{Cos}\ (n\pi)\ \ \text{Sin}\left(\frac{n\delta}{2}\right)\right] \quad \left(\because\ \text{Sin}(n\pi) = 0\right)$$

$$= \frac{2}{n\pi}\left(1 - \text{Cos}\ n\pi\right)\ \text{Sin}\left(\frac{n\delta}{2}\right)$$

$= 0$; for n = even = 2, 4, 6, ...

$$\therefore a_n = \frac{4}{n\pi} \sin\left(\frac{n\delta}{2}\right); \text{ for } n = \text{odd} = 1, 3, 5, \ldots\ldots$$

$$a_o = \frac{2}{\pi}\left[\int_0^{\delta/2} d\theta - \int_{(\pi-\delta/2)}^{\pi} d\theta\right]$$

$$= \frac{2}{\pi}\left[\frac{\delta}{2} - \pi + \pi - \frac{\delta}{2}\right] = 0$$

$$b_n = \frac{1}{\pi}\int_{-\pi}^{+\pi} F(\theta)\ \sin n\theta\ \ d\theta$$

$$\therefore b_n = \frac{1}{\pi}\left[\int_{-\pi}^{(-\pi+\delta/2)} -1.0\ \sin n\theta\ d\theta + \int_{-\delta/2}^{+\delta/2} \sin n\theta\ d\theta - \int_{(\pi-\delta/2)}^{\pi} \sin n\theta\ d\theta\right]$$

$$= -\frac{1}{n\pi}\left[-\cos n(\pi - \delta/2) + \cos(n\pi) + \cos\left(\frac{n\delta}{2}\right) - \cos\left(\frac{n\delta}{2}\right) - \cos(n\pi) + \cos n\,(\pi - \delta/2)\right]$$

$$= -\frac{1}{n\pi}\left[-\cos n\pi \cos\frac{n\delta}{2} - \sin n\pi \sin\frac{n\delta}{2} + \cos n\pi + \cos\frac{n\delta}{2} - \cos\frac{n\delta}{2} - \cos(n\pi) + \cos n\pi \cos\frac{n\delta}{2} + \sin(n\pi) \sin\frac{n\delta}{2}\right]$$

$$= 0$$

Therefore, the switching function $F(\theta)$ is given by

$$F(\theta) = \sum_{n=1,3,5}^{\infty} a_n \cos n\theta$$

$$= \sum_{n=1,3,5}^{\infty} a_n \cos(nwt)$$

and the Fourier coefficient a_n is given by

$$a_n = \frac{4}{n\pi} \sin\left(\frac{n\delta}{2}\right)\ ;\ \text{for } n = 1, 3, 5, \ldots\ldots$$

$$\text{or,}\quad K_m = \frac{4}{m\pi} \sin\left(\frac{m\delta}{2}\right)\ ;\ \text{for } m = 1, 3, 5, \ldots\ldots$$

$$\therefore \quad K_m = \frac{4}{m\pi} \sin\left(\frac{m\delta}{2}\right) \qquad \cdots \qquad \cdots \qquad \cdots \qquad (2.4)$$

From eqn (2.4) we see that K_m is dependent on δ .

$$\text{i.e. } \delta = \frac{2}{m} \left[\sin^{-1}\left(\frac{m\pi K_m}{4}\right)\right] \qquad \cdots \qquad \cdots \qquad \cdots \qquad (2.5)$$

2.4.1 Output Voltage Spectrum

The output voltage and input current equations (2a) and (2b) are for ideal case. In an actual converter, the switches operate in ON-OFF mode, therefore the practical switching function $\left[F_d\ (w_s t)\right]$ contains harmonics. Therefore, the practical expression for output voltage $\left[V_o\ (w_o t)\right]$, (2a) becomes

$$\left[V_o\ (w_o t)\right] = \left[\sum_{n=1,3,5}^{\infty} A_n' \cos n w_s t \quad \sum_{n=1,3,5}^{\infty} B_n' \cos \left\{n\ (w_s t - 120^\circ)\right\} \quad \sum_{n=1,3,5}^{\infty} C_n' \cos \left\{n\ (w_s t - 240^\circ)\right\}\right] . \begin{bmatrix} A_1 \cos (w_i t) \\ B_1 \cos (w_i t - 120^\circ) \\ C_1 \cos (w_i t - 240^\circ) \end{bmatrix}$$

$$= \sum_{n=1,3,5}^{\infty} A_1 A_n' \cos (n w_s t) \cos (w_i\ t) + \sum_{n=1,3,5}^{\infty} B_1 B_n' \cos \left\{n\ (w_s t - 120^\circ)\right\} \cos (w_i t - 120^\circ) + \sum_{n=1,3,5}^{\infty} C_1 C_n' \cos \left\{n\ (w_s t - 240^\circ)\right\} \cos (w_i t - 240^\circ)$$

$$= \tfrac{1}{2} (A_1 A_1' + B_1 B_1' + C_1 C_1') \cos (w_s - w_i) t + \tfrac{1}{2} \sum_{n=3,5}^{\infty} A_1 A_n' \left[\cos(n w_s + w_i) t + \cos (n w_s - w_i) t\right] + \tfrac{1}{2} \sum_{n=3,5}^{\infty} B_1 B_n' \left[\cos \left\{(n w_s + w_i) t - n120^\circ - 120^\circ\right\} + \cos \left\{(n w_s - w_i) t - n120^\circ + 120^\circ\right\}\right] + \tfrac{1}{2} \sum_{n=3,5}^{\infty} C_1 C_n' \left[\cos \left\{(n w_s + w_i) t - n240^\circ - 240^\circ\right\} + \cos \left\{(n w_s - w_i) t - n240^\circ + 240^\circ\right\}\right]$$

Since $w_s = w_i + w_o$ and $w_i = w_o$

$\therefore nw_s - w_i = (2n - 1)\, w_o$

and $A_1A_1' + B_1B_1' + C_1C_1' = 1 + 1 + 1 = 3$

$$\left[V_o(w_ot)\right] = \frac{3}{2}\text{Cos}\,(w_ot) + \left[\frac{1}{2}\sum_{n=3,5}^{\infty} A_1A_n'\text{Cos}\,(2n-1)\,w_ot + \frac{1}{2}\sum_{n=3,5}^{\infty} B_1B_n'\text{Cos}\left\{(2n-1)\,w_ot - (n-1)\,120^o\right\} + \frac{1}{2}\sum_{n=3,5}^{\infty} C_1C_n'\text{Cos}\left\{(2n-1)w_ot-(n-1)240^o\right\}\right]$$

$$+\left[\frac{1}{2}\sum_{n=3,5}^{\infty} A_1A_n'\text{Cos}\,(2n+1)w_ot + \frac{1}{2}\sum_{n=3,5}^{\infty} B_1B_n'\text{Cos}\left\{(2n+1)w_ot - (n+1)120^o\right\} + \frac{1}{2}\sum_{n=3,5}^{\infty} C_1C_n'\text{Cos}\left\{(2n+1)w_ot - (n+1)\,240^o\right\}\right] \quad ..(2.6)$$

From equation (2.6) it is clear that the output voltage of the converter is the sum of the fundamental component and the harmonic components.

2.4.2 Input Current Spectrum

Since the input voltages are unbalanced and switching functions are unbalanced, the input currents will also be unbalanced. The input phase currents can be calculated refering to Fig. 2.2.

The phase current I_a for resistive (R) load is given by

$$I_a = F_1 * I_{AB}$$

$$= F_1 * I_o \text{ Cos } (w_o t)$$

Since $I_o = 1.0$, therefore, we get

$$I_a = \sum_{n=1,3,5}^{\infty} A'_n \text{ Cos } (nw_s t) * \text{Cos } (w_o t)$$

$$= \frac{1}{2} \sum_{n=1,3,5}^{\infty} A'_n \left[\text{Cos } (nw_s - w_o)\, t + \text{Cos } (nw_s + w_o) t \right]$$

$$= \frac{A'_1}{2} \text{Cos}(w_i t) + \frac{A'_1}{2} \text{ Cos } (3w_i t) + \frac{1}{2} \sum_{n=3,5}^{\infty} A'_n \left[\text{Cos } (2n-1)\, w_i t + \text{Cos}(2n+1) w_i t \right]$$

$$= \frac{A'_1}{2} \text{ Cos } (w_i t) + \frac{A'_1}{2} \text{ Cos } (3w_i t) + \frac{1}{2} \sum_{n=3,5}^{\infty} A'_n \text{ Cos } (2n-1)\, w_i t$$

$$+ \frac{1}{2} \sum_{n=3,5}^{\infty} A'_n \text{Cos } (2n+1)\, w_i t \quad .. \quad .. \; (2.7)$$

From equation (2.7) it is clear that for a particular value of n the input current contains two harmonic components of order (2n-1) and (2n+1).

The phase current I_b is given by

$$I_b = F_2 * I_{AB}$$

$$= F_2 * I_o \text{ Cos } (w_o t)$$

$$I_b = F_2 * \text{Cos}\,(w_o t)$$

$$= \sum_{n=1,3,5}^{\infty} B_n' \,\text{Cos}\left\{n\,(w_s t - 120^\circ)\right\} * \text{Cos}\,(w_o t)$$

$$= \frac{1}{2} \sum_{n=1,3,5}^{\infty} B_n' \left[\text{Cos}\left\{(nw_s - w_o)t - n120^\circ\right\} + \text{Cos}\left\{(nw_s + w_o)t - n120^\circ\right\}\right]$$

$$= \frac{1}{2} \sum_{n=1,3,5}^{\infty} B_n' \left[\text{Cos}\left\{(2n-1)\, w_1 t - n120^\circ\right\} + \text{Cos}\left\{(2n+1) w_1 t - n120^\circ\right\}\right]$$

$$= \frac{B_1'}{2} \text{Cos}\,(w_1 t - 120^\circ) + \frac{B_1'}{2} \text{Cos}\,(3w_1 t - 120^\circ)$$

$$+ \frac{1}{2} \sum_{n=3,5}^{\infty} B_n' \left[\text{Cos}\left\{(2n-1)\, w_1 t - n\,120^\circ\right\} + \frac{1}{2} \sum_{n=3,5}^{\infty} B_n' \,\text{Cos}\left\{(2n+1) w_1 t - n120^\circ\right\}\right] \quad \text{.. (2.8)}$$

The phase current I_c is given by

$$I_C = F_3 * I_{AB}$$

$$= F_3 * I_o \,\text{Cos}\,(w_o t)$$

$$= F_3 * \text{Cos}\,(w_o t)$$

$$= \sum_{n=1,3,5}^{\infty} C_n' \,\text{Cos}\left\{n\,(w_s t - 240^\circ)\right\} * \text{Cos}\,(w_o t)$$

$$= \frac{1}{2} \sum_{n=1,3,5}^{\infty} C_n' \left[\text{Cos}\left\{(nw_s - w_o)t - n240^\circ\right\} + \text{Cos}\left\{(nw_s + w_o)t - n240^\circ\right\}\right]$$

$$= \frac{1}{2} \sum_{n=1,3,5}^{\infty} C_n' \left[\text{Cos}\left\{(2n-1)\, w_1 t - n240^\circ\right\} + \text{Cos}\left\{(2n+1) w_1 t - n240^\circ\right\}\right]$$

$$= \frac{C_1'}{2} \text{Cos}\,(w_1 t - 240^\circ) + \frac{C_1'}{2} \text{Cos}\,(3w_1 t - 240^\circ) + \frac{1}{2} \sum_{n=3,5}^{\infty} C_n' \left[\text{Cos}\left\{(2n-1) w_1 t\right.\right.$$

$$\left.\left. - n240^\circ\right\}\right] + \frac{1}{2} \sum_{n=3,5}^{\infty} C_n' \left[\text{Cos}\left\{(2n+1)\, w_1 t - n240^\circ\right\}\right] \quad \text{.. .. (2.9)}$$

From equations (2.8) and (2.9) it is observed that the input currents I_b and I_c contain odd harmonics only. For a particular value of n, there are two harmonic components of currents given by (2n-1) and (2n+1).

2.5 Conclusions

A three phase to single phase converter is analysed under balanced and unbalanced input conditions.

The relation between the unbalanced input voltage amplitude and the fundamental component of corresponding switching function is established. It is found that in order to make the output voltage balanced, the amplitude of the fundamental component of corresponding switching function must be inversely proportional to the amplitude of the respective input phase voltage.

The operation and analysis of the unbalanced phase converter is discussed in details. Detailed harmonic analysis of balanced output voltage and unbalanced input current is presented in this chapter.

CHAPTER 3

FOURIER ANALYSIS OF INPUT-OUTPUT VOLTAGE-CURRENT

3.1 Introduction

The analytical expressions developed for balancing the input amplitude unbalance in chapter 2 is thoroughly analysed in this chapter. Using this concept the proposed phase converter is studied for both balanced and unbalanced input conditions. Detailed Fourier analysis of input-output voltage and currents are performed. Comparison of spectrum of voltage and current for balanced and unbalanced condition is also done.

Dedicated computer programs in IBM-370-3278[2] using FORTRAN-IV is developed and respective results varified with analytically predicted input-output quantities. Agreement between analytical predicted and computer calculated results verify the validity of the proposed technique.

3.2 System Description and Mode of Operation

Fig. 3.1 shows the simplified circuit diagram of the three phase to single phase static converter. It consists of input stage, converter stage and output stage. The three phase main is assumed to be amplitude unbalanced. Switches S_1 to S_6 are ideal bilateral switches. The load could be resistive-inductive type. However, for analysis purpose only resistive load is considered.

The proposed three-phase to single-phase converter operates on direct mode of operation. The switches S_1 to S_6 are operated by the gating signals which are determined by the control scheme used.

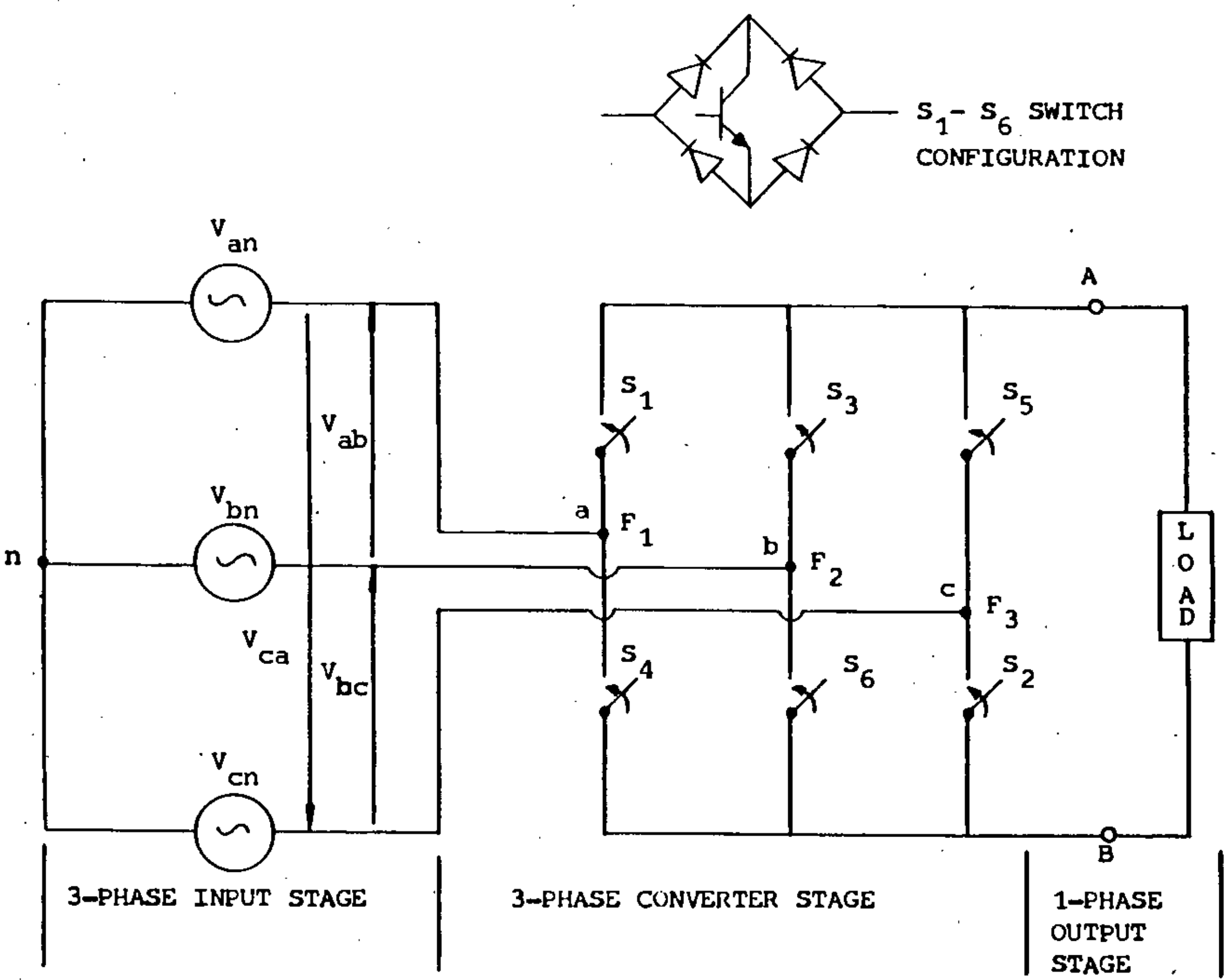

Fig. 3.1 : Simplified circuit diagram of the proposed Three phase to Single phase static converter.

3.3 Switching Functions

An electrical converter contains static switches. These switches require gating signals to change the ON/OFF states. The operation of the switches depends on a particular sequence. The functions which are required for the sequential operation of the converter static switches are termed as switching functions. Switching functions may be continuous or discontinuous type.

In the design of a balanced output three phase to single phase static converter, the switching functions are of ON/OFF type. They operate on logic levels 1 and 0. The switching pattern for a single switch assumes unit value whenever the switch is closed and a zero value whenever the switch is opened. In a converter, each switch is closed and opened according to a predetermined repetitive pattern; hence, its siwtching function will take the form of a train of pulses of unit amplitude. Neither the pulses nor the intervening zero value periods have necessarily the same duration. The requirement that a repetitive switching pattern must exist means that the function must at least consist of repetitive groups of pulses. The simplest or unmodulated switching functions have pulses of the same time duration and zero intervals with the same property. A more complex type with different pulse durations and various zero intervals, is termed as a pulse width modulated (PWM) switching function.

There are various types of modulation techniques [7] - [10] . These are single-pulse modulation, multi-pulse modulation, sinusoidal pulse modulation, sinusoidal pulse-width modulation, delta modulation, etc. The modulation technique used in this thesis is described in sub-section 3.3.1.

3.3.1 Single-Pulse Modulation

In single-pulse modulation, there is only one pulse per half-cycle. The pulse width is varied to control the converter output voltage. The switching function obtained from single-pulse modulation is shown in Fig. 3.2(a). For the purpose of analysis, it is assumed that the start of each pulse is delayed and the end of each pulse is advanced by equal angular intervals, resulting in a variation of the pulse-width δ over the range $0 \leq \delta \leq \pi$ radian.

The wave form of $F(\theta)$ in Fig. 3.2(a) may be described by the Fourier-series

$$F(\theta) = \frac{a_o}{2} + \sum_{n=1,3,5}^{\infty} \left[a_n \operatorname{Cos}(n\theta) + b_n \operatorname{Sin}(n\theta) \right]$$

where,

$$b_n = \frac{2}{\pi} \int_0^{\pi} F(\theta) \operatorname{Sin}(n\theta)\, d\theta$$

$$= \frac{4}{n\pi} \operatorname{Sin}\left(\frac{n\delta}{2}\right), \quad n \text{ is odd}$$

and $a_o = 0$, $a_n = 0$

and the corresponding harmonics i.e. b_n values are shown in Fig. 3.2(b) for $\delta = 120^{\circ}$. Width of the pulse is determined by the unbalances present in the input phase voltages.

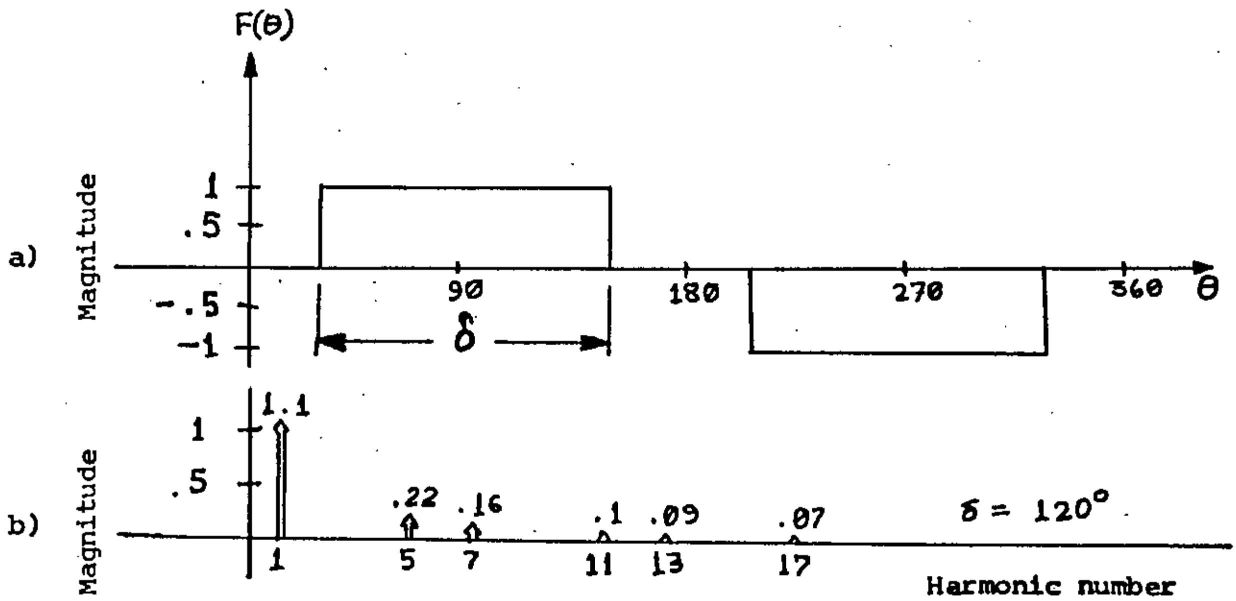

Fig. 3.2 : Single pulse modulation switching function.

a) The switching function.

b) Respective frequency spectrum.

3.4 Mode of Operation (Balanced Case)

For balanced case, the switching functions are of equal widths. The Fourier coefficients of the switching functions for this case are equal. The output voltage for balanced case is given by

$$\left[V_o(w_o t)\right] = \left[\sum_{n=1,3,5}^{\infty} A_n \operatorname{Cos}(nw_s t) \sum_{n=1,3,5}^{\infty} B_n \operatorname{Cos}\left\{n(w_s t-120^\circ)\right\} \sum_{n=1,3,5}^{\infty} C_n \operatorname{Cos}\left\{n(w_s t-240^\circ)\right\}\right]$$

$$\cdot \begin{bmatrix} \operatorname{Cos}(w_i t) \\ \operatorname{Cos}(w_i t-120^\circ) \\ \operatorname{Cos}(w_i t-240^\circ) \end{bmatrix}$$

Since $A_n = B_n = C_n$ for balanced case, therefore

$$\left[V_o(w_o t)\right] = \frac{3}{2} A_1 \operatorname{Cos}(w_o t) + \frac{1}{2}\sum_{n=3,5}^{\infty} A_n \left[\operatorname{Cos}(2n-1)w_o t + \operatorname{Cos}\left\{(2n-1)w_o t - (n-1)120^\circ\right\} + \operatorname{Cos}\left\{(2n-1)w_o t - (n-1)240^\circ\right\}\right]$$
$$+ \frac{1}{2}\sum_{n=3,5}^{\infty} A_n \left[\operatorname{Cos}(2n+1)w_o t + \operatorname{Cos}\left\{(2n+1)w_o t - (n+1)120^\circ\right\} + \operatorname{Cos}\left\{(2n+1)w_o t - (n+1)240^\circ\right\}\right] \quad \cdots \quad (3.1)$$

Equation (3.1) shows that under balanced input condition, the output voltage spectrum contains a fundamental component of amplitude $1.5A_1$ and harmonic components whose frequency is determined by $(2n \pm 1)\, w_o$ term. The amplitude of harmonic component is equal to $A_n/2$.

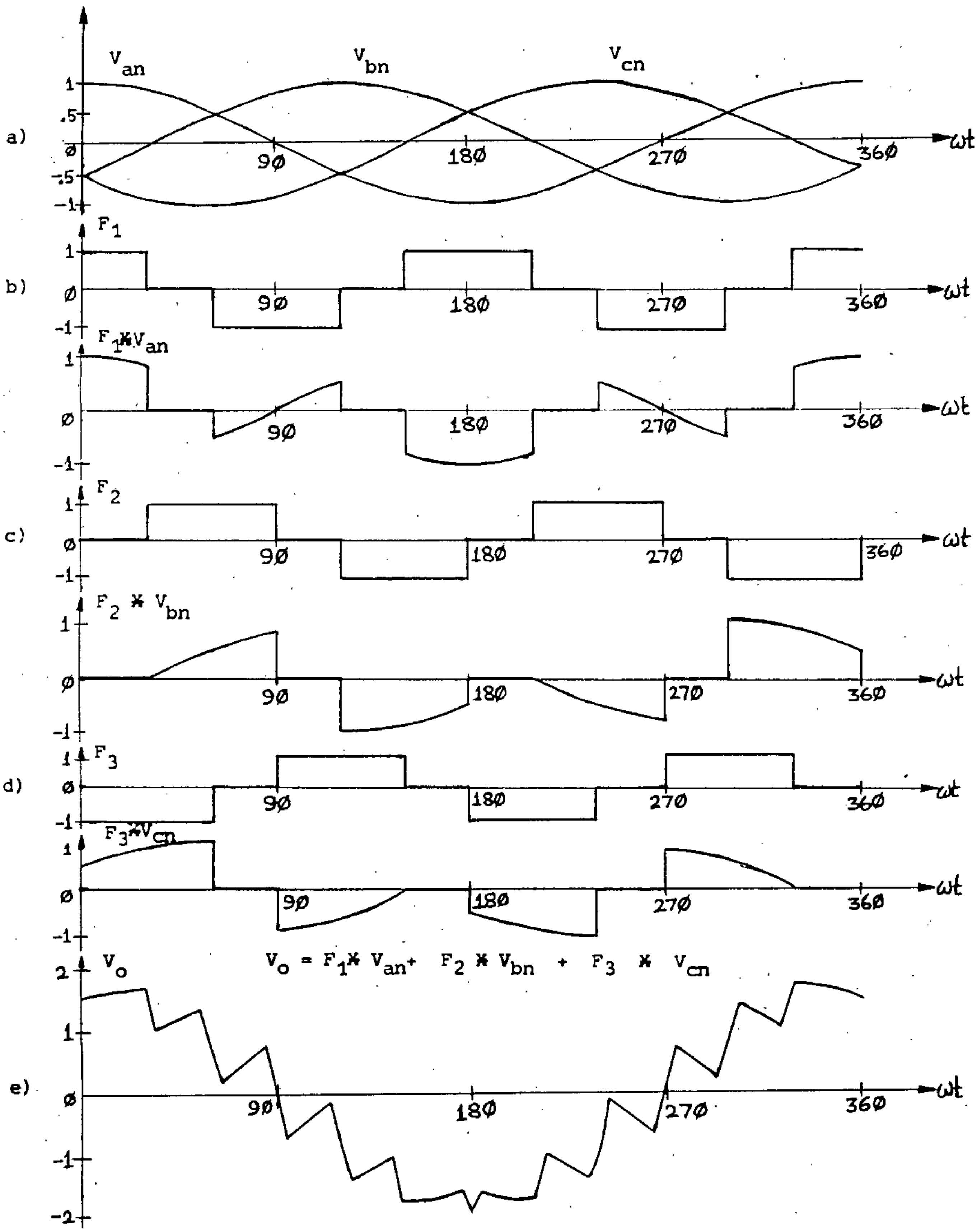

Fig. 3.3 : Output voltage waveform obtained with three to single phase converter under balanced condition.

a) Three input balanced phase voltage

b)-d) F_1, F_2, F_3 switching function components

e) Resulting output voltage.

TABLE 3.1

FREQUENCY SPECTRA OF WAVEFORMS ASSOCIATED WITH CONVERTER OUTPUT VOLTAGE SHOWN IN FIG 3.3.

Harmonic coefficients of switching function (Fig. 3.3b)		Harmonic coefficient of output phase voltage V_o, Fig. (3.3e).		
Order (n)	Amplitude (A_n)	Amplitude, V_o		
		Order (n)	p.u. (1)	% (1)
1	1.10	1	0.87	87
3	-	3	-	-
5	0.22	5	-	-
7	0.16	7	-	-
9	0.00	9	-	-
11	0.10	11	0.20	20
13	0.09	13	0.14	14
15	-	15	-	-
17	0.07	17	-	-
19	0.06	19	-	-
21	0.00	21	-	-
23	0.05	23	0.08	8

(1) Input phase voltages have been taken as 1 p.u. volt and 100% volt.

Table (3.1) shows the output voltage spectrum for balanced input conditions.

The input current equation for the practical 3-phase to 1-phase converter is expressed as follows:

$$I_a = \frac{1}{2} \sum_{n=1,3,5}^{\infty} A_n \left[\text{Cos } (2n-1)\, w_i t + \text{Cos } (2n+1)\, w_i t \right] \quad .. \quad (3.2)$$

$$I_b = \frac{1}{2} \sum_{n=1,3,5}^{\infty} A_n \left[\text{Cos } \left\{ (2n-1)\, w_i\, t - n120^\circ \right\} + \text{Cos } \left\{ (2n+1) w_i t - n120^\circ \right\} \right] .. \quad (3.3)$$

$$I_c = \frac{1}{2} \sum_{n=1,3,5}^{\infty} A_n \left[\text{Cos } \left\{ (2n-1)\, w_i t - n240^\circ \right\} + \text{Cos} \left\{ (2n+1) w_i t - n240^\circ \right\} \right] .. \; .. \quad (3.4)$$

Equations (3.2), (3.3) and (3.4) show that the input current spectrum for balanced input conditions contains harmonics at frequencies of $(2n \pm 1)\, w_i$. The amplitude of I_a, I_b and I_c are equal and is given by $A_n/2$. So the input current spreatra of I_a, I_b and I_c are same and is given in Table (3.2).

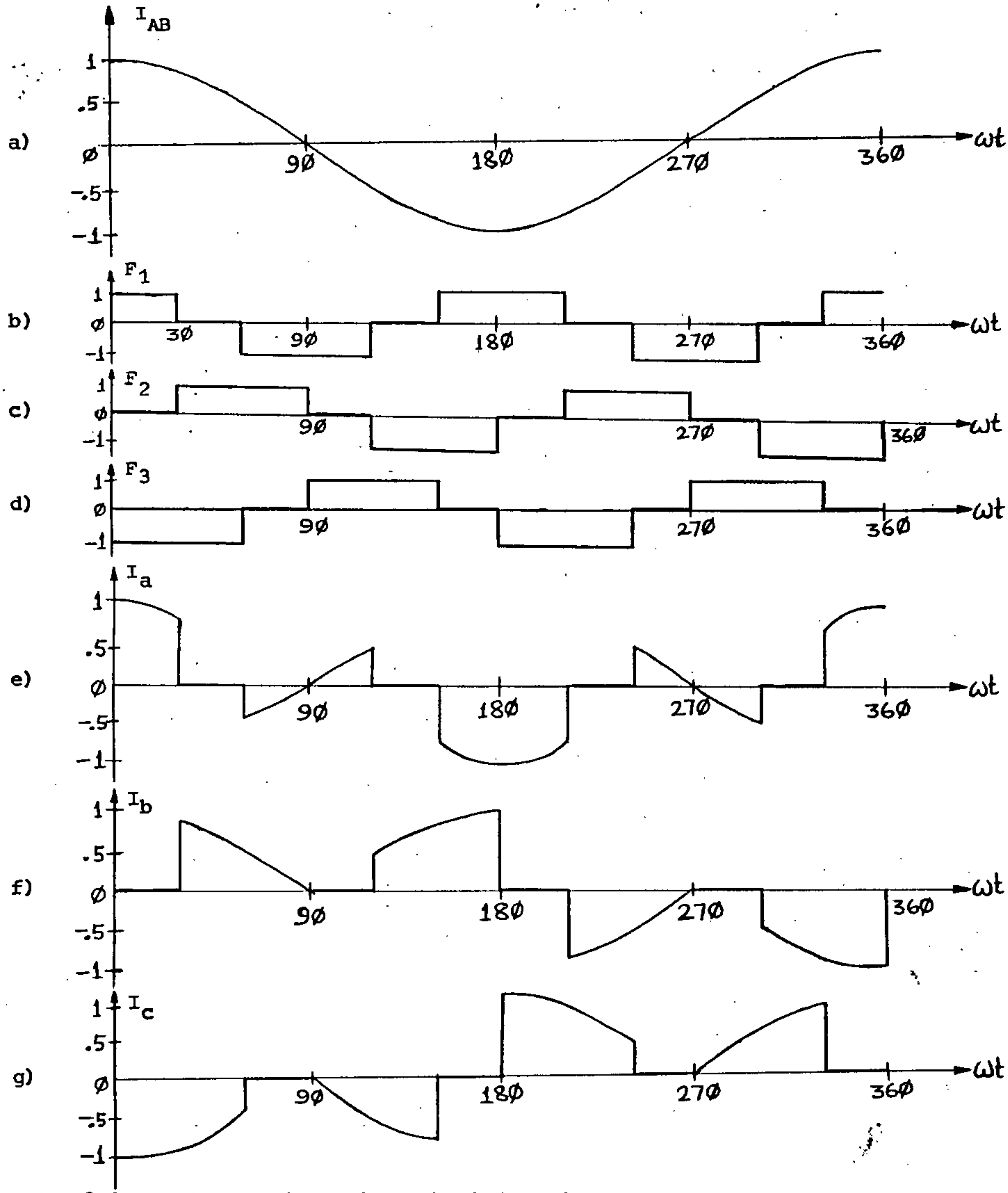

Fig. 3.4: Input current waveforms for balanced case.
a) Output current I_{AB} for balanced inputs.
b)–d) F_1, F_2, F_3 Switching function components.
e)–g) Three input phase currents.

TABLE 3.2

FREQUENCY SPECTRA OF WAVEFORMS ASSOCIATED WITH CONVERTER INPUT CURRENTS I_a or I_b or I_c SHOWN IN FIG. 3.4

Harmonic coefficients of switching function (Fig. 3.4b)		Harmonic coefficients of resulting input phase currents I_a, or I_b or I_c, (Fig. 3.4g)		
Order (n)	Amplitude (A_n)	Amplitude, I_a or I_b or I_c		
		Order (n)	p.u. (1)	% (1)
1	1.10	1	0.55	55
3	-	3	0.55	55
5	0.22	5	-	-
7	0.16	7	-	-
9	-	9	0.11	11
11	0.10	11	0.11	11
13	0.09	13	0.08	8
15	-	15	0.08	8
17	0.06	17	-	-
19	0.06	19	-	-
21	-	21	0.05	5
23	0.05	23	0.05	5
25	0.04	25	0.04	4
		27	0.04	4

(1)Output phase current has been taken as 1.p.u. current and 100% current.

3.4.1 Mode of Operation (Unbalanced Case)

Output voltage is constructed by direct multiplication of input voltages by the respective converter transfer function. The practical equation for the output voltage of a 3-phase to 1-phase converter which is derived in 2.4.1, chapter 2, is once again described here to maintain continuity.

$$\left[V_o\,(w_o t)\right] = \frac{1}{2}\sum_{n=1,3,5}^{\infty} A'_n A_1 \left[\mathrm{Cos}\,(nw_s+w_i)t + \mathrm{Cos}\,(nw_s-w_i)t\right]$$

$$+\frac{1}{2}\sum_{n=1,3,5}^{\infty} B'_n B_1 \left[\mathrm{Cos}\left\{(nw_s+w_i)t - n120^\circ - 120^\circ\right\} + \mathrm{Cos}\left\{(nw_s-w_i)t - n120^\circ + 120^\circ\right\}\right]$$

$$+\frac{1}{2}\sum_{n=1,3,5}^{\infty} C'_n C_1 \left[\mathrm{Cos}\left\{(nw_s+w_i)t - n240^\circ - 240^\circ\right\} + \mathrm{Cos}\left\{(nw_s-w_i)t - n240^\circ + 240^\circ\right\}\right]$$

$$= \frac{3}{2}\,\mathrm{Cos}\,(w_o t) + \left[\frac{1}{2}\sum_{n=3,5}^{\infty} A'_n A_1 \mathrm{Cos}(2n-1)\,w_o t + \frac{1}{2}\sum_{n=3,5}^{\infty} B'_n B_1 \mathrm{Cos}\left\{(2n-1)w_o t\right.\right.$$

$$\left.\left. -(n-1)120^\circ\right\} + \frac{1}{2}\sum_{n=3,5}^{\infty} C'_n C_1 \mathrm{Cos}\left\{(2n-1)w_o t - (n-1)\;240^\circ\right\}\right]$$

$$+\left[\frac{1}{2}\sum_{n=3,5}^{\infty} A'_n A_1\,\mathrm{Cos}\,(2n+1)w_o t + \frac{1}{2}\sum_{n=3,5}^{\infty} B'_n B_1 \mathrm{Cos}\,\left\{(2n+1)w_o t - (n+1)120^\circ\right\}\right.$$

$$\left. + \frac{1}{2}\sum_{n=3,5}^{\infty} C'_n C_1 \mathrm{Cos}\left\{(2n+1)w_o t - (n+1)\;240^\circ\right\}\right] \quad .. \qquad ..(3.5)$$

Equation (3.5) shows that output voltage spectrum contains a fundamental component of amplitude 1.5 and harmonic component whose frequency is determined by $(2n \pm 1)\,w_o$ term.

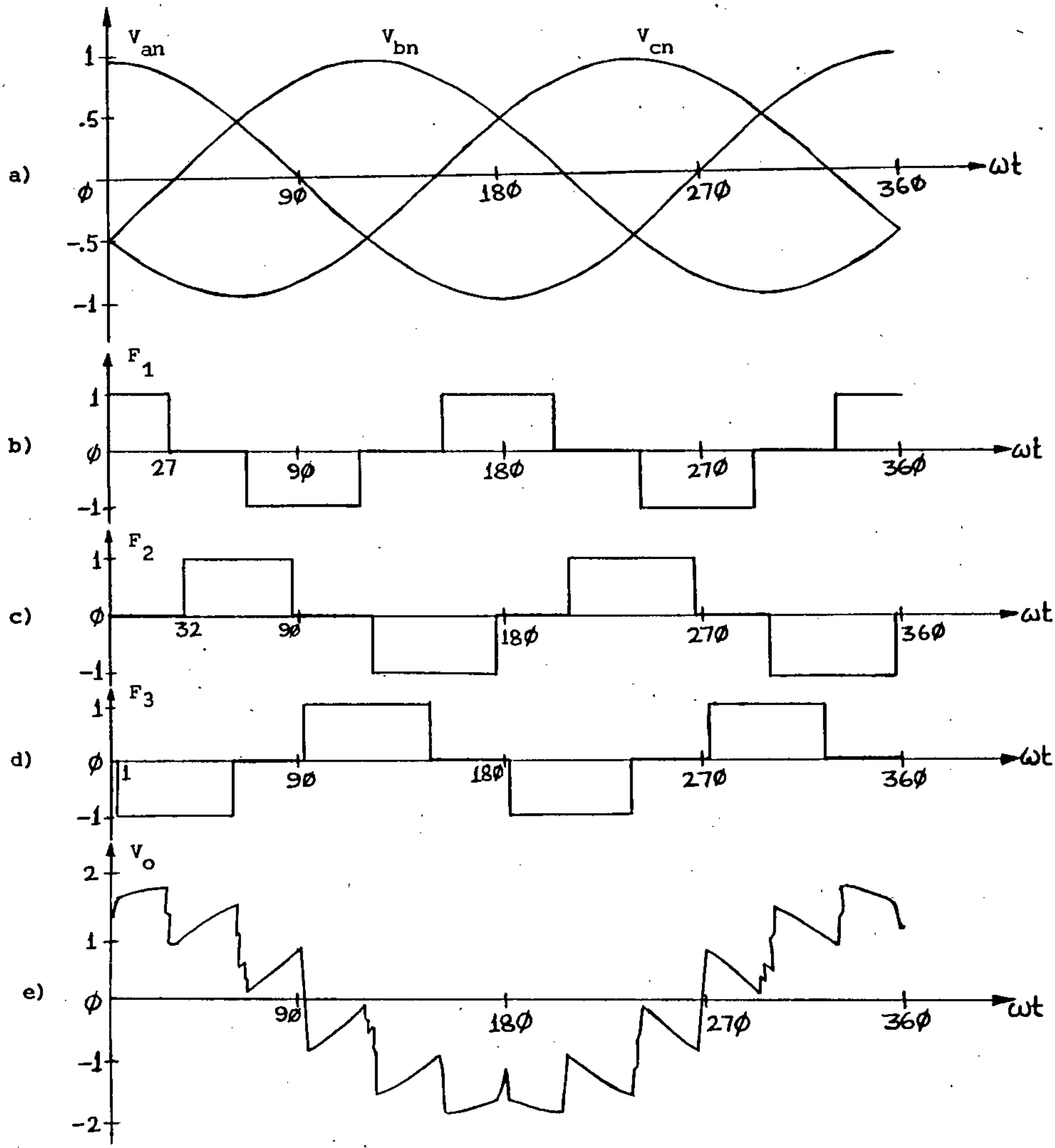

Fig. 3.5 : Output voltage waveform obtained with three to single phase converter.

a) Three input unbalanced phase voltages.

b)-d) F_1 , F_2 , F_3 switching function components.

e) Resulting output voltage.

TABLE 3.3

FREQUENCY SPECTRA OF WAVEFORMS ASSOCIATED WITH CONVERTER OUTPUT VOLTAGE SHOWN IN FIG. 3.5

Harmonic coefficients of switching function (Fig. 3.5b)				Harmonic coefficient of output phase voltage V_{out} Fig. (3.5e)		
Order (n)	Amplitude			Amplitude, V_{out}		
	A_n	B_n	C_n	Order (n)	p.u.(1)	% (1)
1	1.03	1.06	1.08	1	0.87	87
3	0.13	0.09	0.04	3	[illegible]	-
5	0.25	0.25	0.24	5	0.02	2
7	0.06	0.09	0.13	7	0.02	2
9	0.11	0.08	0.04	9	0.01	1
11	0.09	0.11	0.11	11	0.20	20
13	0.03	0.01	0.05	13	0.08	8
15	0.08	0.07	0.04	15	0.02	2
17	0.02	0.06	0.07	17	0.02	2
19	0.05	0.02	0.03	19	0.02	2

(1) Input phase voltages have been taken as 1 p.u. volt and 100% volt.

Table 3.3 shows the output voltage spectrum from where we can compare the theoritical and analytical results for different harmonics.

The input current equation for this practical 3-phase to 1-phase converter is expressed as follows;

$$I_a = \frac{1}{2} \sum_{n=1,3,5}^{\infty} A'_n \left[\text{Cos } (nw_s - w_o)\, t \; + \text{Cos } (nw_s + w_o) t \right]$$

$$= \frac{A'_1}{2} \text{ Cos } (w_i t) + \frac{A'_1}{2} \text{Cos } (3w_i t) + \frac{1}{2} \sum_{n=3,5}^{\infty} A'_n \left[\text{Cos } \left\{ (2n-1) w_i t \right\} - \text{Cos } \left\{ (2n+1)\; w_i t \right\} \right] \quad .. \quad (3.6)$$

$$I_b = \frac{1}{2} \sum_{n=1,3,5}^{\infty} B'_n \left[\text{Cos } \left\{ n\; (w_s t - 120^o) \right\} * \text{ Cos } (w_o t) \right]$$

$$= \frac{1}{2} \sum_{n=1,3,5}^{\infty} B'_n \left[\text{Cos } \left\{ (2n-1)\; w_i t - n\; 120^o \right\} + \text{ Cos } \left\{ (2n+1)\; w_i t - n120^o \right\} \right] \quad .. (3.7)$$

$$I_c = \frac{1}{2} \sum_{n=1,3,5}^{\infty} C'_n \left[\text{Cos } \left\{ (2n-1)\; w_i t - n240^o \right\} + \text{ Cos } \left\{ (2n+1) w_i t \; - \; n240^o \right\} \right] \quad .. (3.8)$$

From equations (3.6), (3.7) and (3.8) we see that the input current spectrum contains harmonics at frequencies of $(2n \pm 1)\, w_i$. The input current spectra of I_a, I_b and I_c are given in table 3.4, 3.5 & 3.6 respectively from where we can compare the theoritical & Analytical results.

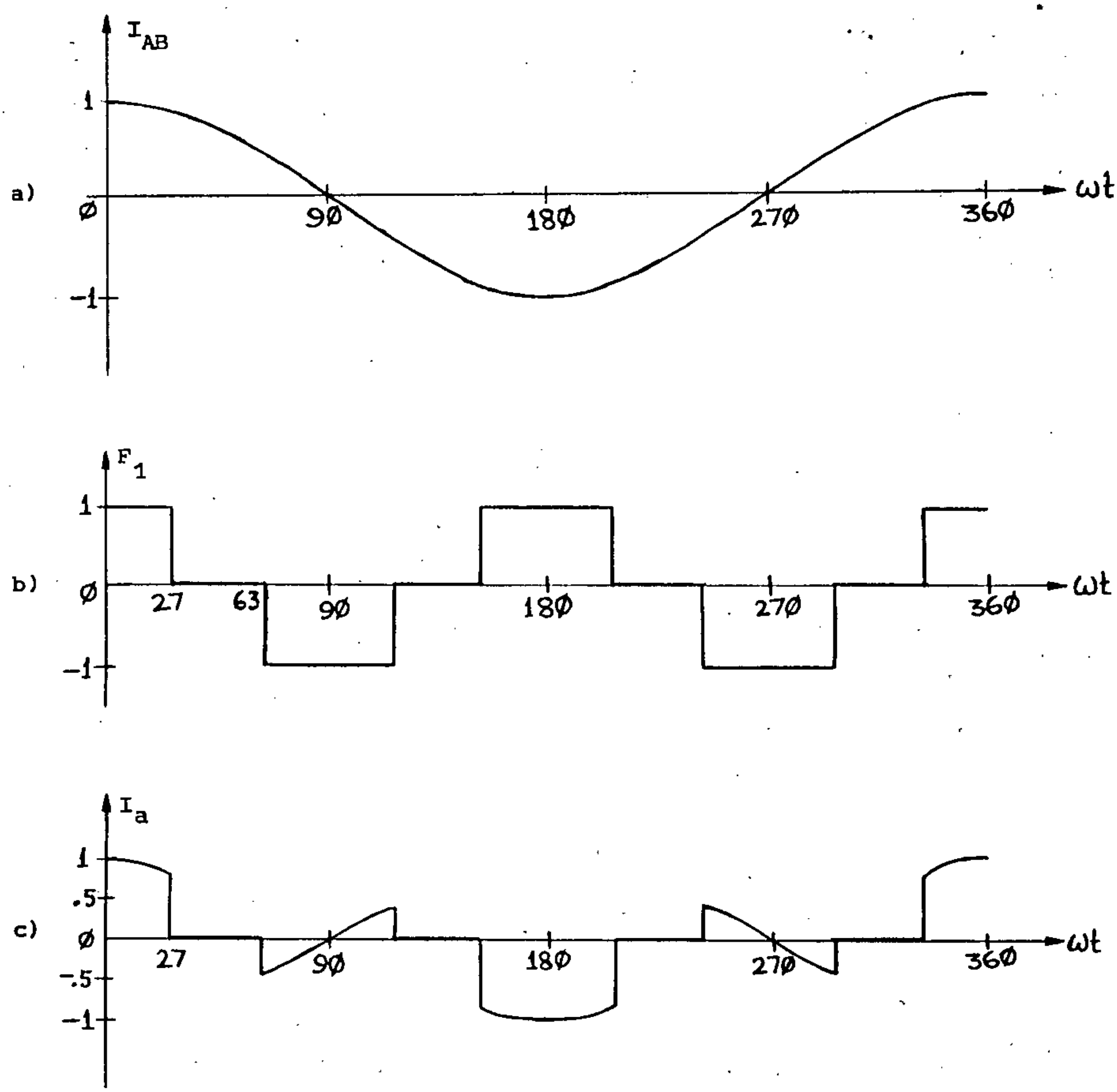

Fig. 3.6 : Input current waveform obtained with three to single phase converter.

a) Output current, I_{AB}.

b) F_1 switching function component.

c) Resulting Input current, I_a.

TABLE 3.4

FREQUENCY SPECTRA OF WAVEFORMS ASSOCIATED WITH CONVERTER INPUT CURRENT I_a SHOWN IN FIG. 3.6

Harmonic coefficients of switching function (Fig. 3.6b)		Harmonic coefficients of resulting input phase current I_a (Fig. 3.6c)		
Order (n)	Amplitude (A_n)	Amplitude, I_a		
		order (n)	p.u. (1)	% (1)
1	1.03	1	0.52	52
3	0.13	3	0.52	52
5	0.25	5	0.07	7
7	0.05	7	0.07	7
9	0.11	9	0.13	13
11	0.10	11	0.13	13
13	0.03	13	0.03	3
15	0.08	15	0.03	3
17	0.02	17	0.06	6
19	0.05	19	0.06	6
21	0.05	21	0.05	5
23	0.02	23	0.05	5
		25	0.02	2
		27	0.02	2

(1) Output phase current has been taken as 1 p.u. current and 100% current.

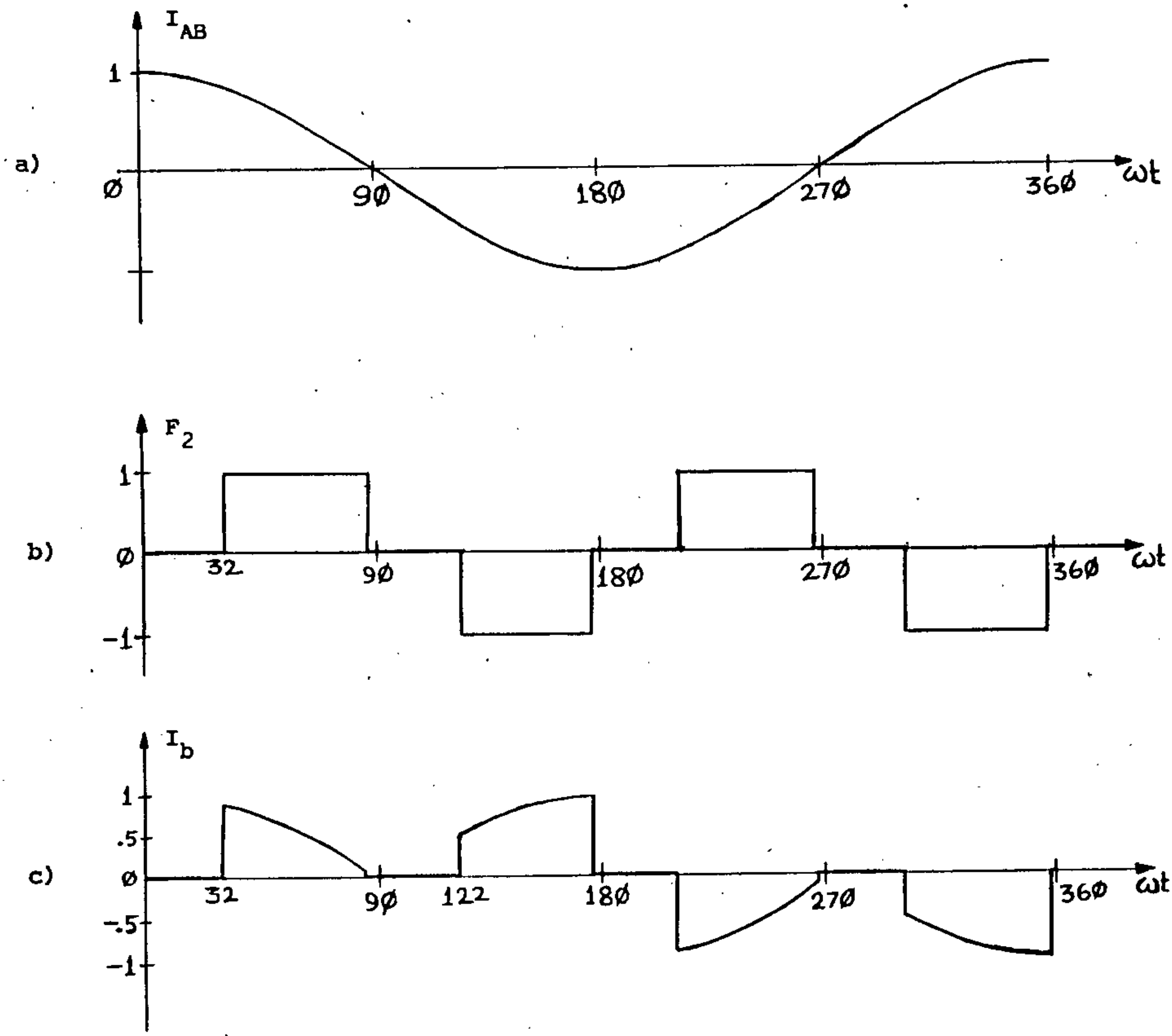

Fig. 3.7 : Input current waveform obtained with three to single phase converter.

a) Output current, I_{AB}.

b) F_2 switching function component.

c) Resulting input current, I_b.

TABLE 3.5				
FREQUENCY SPECTRA OF WAVEFORMS ASSOCIATED WITH CONVERTER INPUT CURRENT I_b SHOWN IN FIG. 3.7				
Harmonic coefficient of switching function (Fig. 3.7.b)		Harmonic coefficients of resulting input phase current I_b, (Fig. 3.7c)		
Order (n)	Amplitude (B_n)	Amplitude, I_b		
		order (n)	(1) p.u.	(1) %
1	1.06	1	0.53	53
3	0.09	3	0.53	53
5	0.25	5	0.05	5
7	0.10	7	0.05	5
9	0.08	9	0.13	13
11	0.11	11	0.13	13
13	0.01	13	0.05	5
15	0.07	15	0.05	5
17	0.06	17	0.04	4
19	0.02	19	0.04	4
21	0.06	21	0.06	6
23	0.03	23	0.06	6
		25	0.01	1
		27	0.01	1

(1) Output phase current has been taken as 1 p.u. current and 100% current.

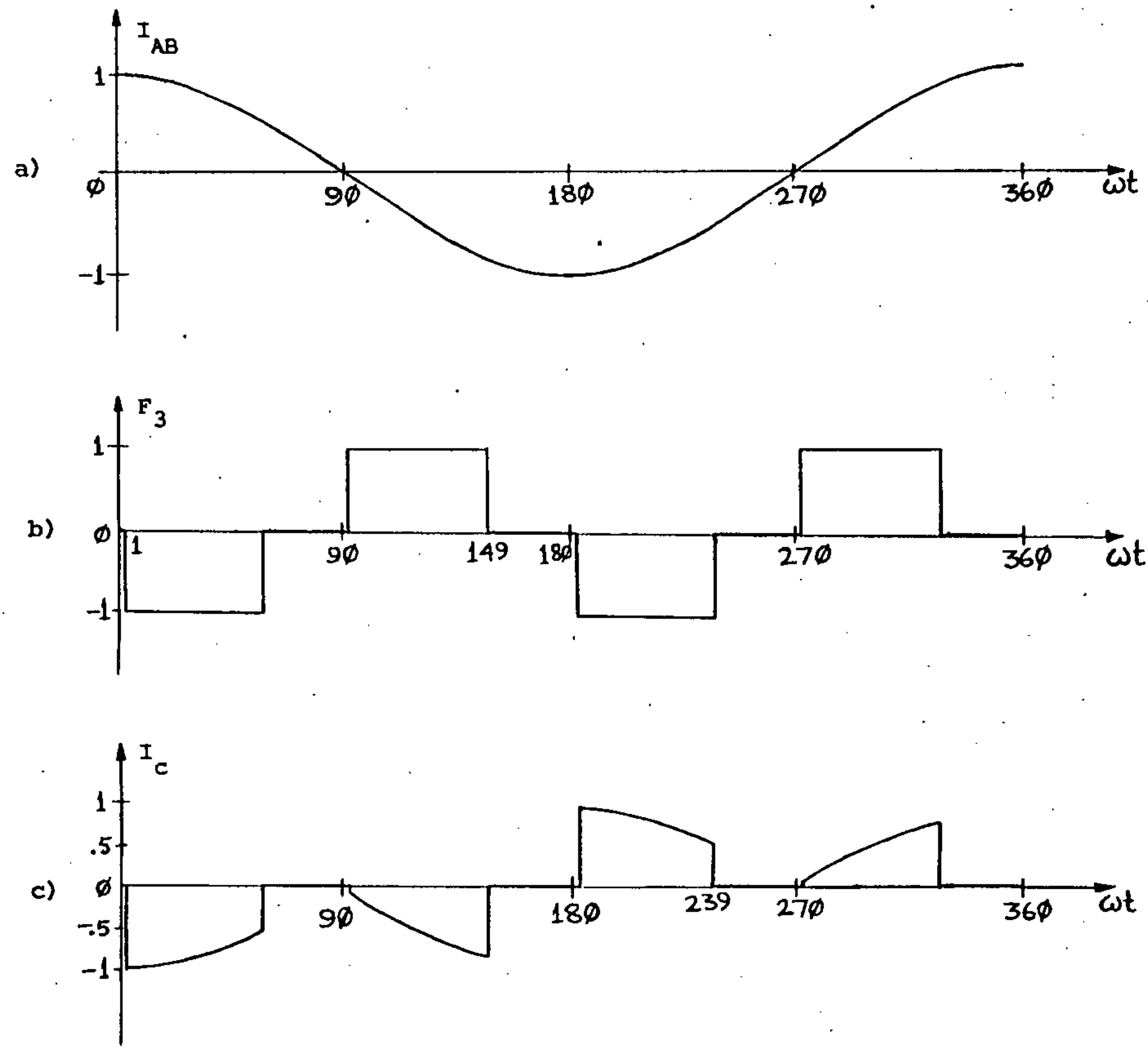

Fig. 3.8 : Input current waveform obtained with three phase to single phase converters.

a) Output current, I_{AB}.

b) F_3 switching function component.

c) Resulting input current, I_c.

TABLE 3.6				
FREQUENCY SPECTRA OF WAVEFORMS ASSOCIATED WITH CONVERTER INPUT CURRENT I_c SHOWN IN FIG. 3.8				
Harmonic coefficients of switching function (Fig. 3.8b)		Harmonic coefficients of resulting input phase current I_c (Fig. 3.8c)		
Order (n)	Amplitude (C_n)	Amplitude, I_c		
		order (n)	(1) p.u.	(1) %
1	1.08	1	0.54	54
3	0.04	3	0.54	54
5	0.24	5	0.02	2
7	0.13	7	0.02	2
9	0.04	9	0.12	12
11	0.12	11	0.12	12
13	0.05	13	0.06	6
15	0.04	15	0.06	6
17	0.08	17	0.02	2
19	0.03	19	0.02	2
21	0.04	21	0.06	6
23	0.05	23	0.06	6
		25	0.03	3
		27	0.03	3

(1) Output phase current has been taken as 1 p.u. current and 100% current.

3.5 Comparison of Spectrum of Balanced and Unbalanced phase Converter

The Fourier coefficients for balanced and unbalanced cases are different due to different widths of the switching functions. Therefore, the spectrum for the two cases will also be different. The comparison of spectrum for balanced and unbalanced phase converter is explained in the following sections.

3.5.1 Output Voltage Spectrum

Tables 3.1 and 3.3 show the output voltage spectrum of balanced and unbalanced case respectively. For the balanced case first harmonics appears as 11th harmonics and its magnitude is 20% of the fundamental. As expected in unbalanced case, the output voltage contains 5th, 7th and 9th harmonics but their magnitudes are insignificant i.e. only 2,2 and 1 percent respectively. These harmonics come from the 2nd and 3rd terms of eqn (3.5). For example, 5th harmonics is the sum of $\frac{1}{2} A_3'A_1$, $\frac{1}{2}B_3'B_1$(with 2 x 120° phase delay), and $\frac{1}{2} C_3'C_1$ (with 2 x 240° phase delay) terms. The 7th harmonics is the sum of $\frac{1}{2} A_3'A_1$, $\frac{1}{2} B_3'B_1$ (with 4 x 120° phase delay), $\frac{1}{2} C_3'C_1$ (with 4 x 240° phase delay) terms. Similarly, the 9th harmonics can be explained as above. However these harmonics can easily be filtered out by appropriate filter.

3.5.2 Input Currents Spectra

The input current spectra for balanced and unbalanced cases are depicted in Tables 3.2, 3.4, 3.5 and 3.6 respectively. In Table 3.2 the fundamental and 3rd harmonics have the same amplitude. This phenomena is expected, as shown in eqn(3.6). It also contains 9th, 11th, 13th and 15th of amplitude 11, 11, 8 and 8 percent respectively. As it is a balanced case, all the three input currents have the same spectra. For unbalanced case, the input currents are expected to be unbalanced as the input voltages are unbalanced. This is reflected in Tables 3.4, 3.5 and 3.6.

From table 3.4, we see that the 9th, 11th, 13th and 15th harmonics of input current I_a are 13, 13, 3 and 3 percent respectively. Table 3.5 shows that they are 13, 13, 5 and 5 percent respectively for input current I_b. For phase current I_c, they are 12, 12, 6 and 6 percent respectively. Therefore, the input currents spectra are different due to the unbalanced input voltages. The magnitude of harmonics are dependent on the amount of amplitude unbalance present in the corresponding input phase voltages.

3.6 Reduction of Higher Harmonics

Output voltage of the converter contains higher harmonics. These harmonics must be eliminated in order to retrieve the fundamental frequency component. The converter will supply harmonic (Table 3.4) components to the supply (source) due to its non-linear characteristics. These harmonics will disturbe other consumers connected to the same source. Particular modulation technique may be employed to eliminate the higher harmonics. Only the modulation technique is not sufficient to eliminate the harmonics completely. So low-pass filter circuits are to be added prior to and after the sampler.

The distortion factor (DF) of a filter indicates the amount of harmonic distortion that remains in a waveform after the harmonics of that waveform have been subjected to a second-order attenuation. Thus DF is a measure of effectiveness in reducing unwanted harmonics and is defined as

$$DF = \frac{1}{V_1}\left[\sum_{n=2,3,\ldots}^{\infty}\left(\frac{V_n}{n^2}\right)^2\right]^{1/2} \quad .. \qquad (3.9)$$

where V_1 is the rms value of the fundamental component and V_n is the rms value of the n-th harmonic component.

The distortion factor of an individual (or n-th) harmonic component is defined as

$$DF_n = \frac{V_n}{V_1 n^2} \quad .. \qquad .. \qquad (3.10)$$

From Table 3.3 ,we see that fundamental component of output voltage is 0.87 p.u. whereas, 3rd, 5th, 7th, 9th, 11th, and 13th harmonics are 0.00, 0.02, 0.02, 0.01, 0.20, and 0.08 p.u. respectively.

The total distortion factor is given by eqn. (3.9);

$$DF = \frac{1}{V_1}\left[\left(\frac{V_3}{3^2}\right)^2 + \left(\frac{V_5}{5^2}\right)^2 + \left(\frac{V_7}{7^2}\right)^2 + \left(\frac{V_9}{9^2}\right)^2 + \left(\frac{V_{11}}{11^2}\right)^2 + \left(\frac{V_{13}}{13^2}\right)^2\right]^{1/2}$$

$$= \frac{1}{0.87}\left[0 + \left(\frac{0.02}{25}\right)^2 + \left(\frac{0.02}{49}\right)^2 + \left(\frac{0.01}{81}\right)^2 + \left(\frac{0.20}{121}\right)^2 + \left(\frac{0.08}{169}\right)^2\right]^{1/2}$$

$$= \frac{1}{0.87}\left[3.78 \times 10^{-6}\right]^{1/2}$$

$$= 2.234 \times 10^{-3}$$

$$= 0.2234\%$$

The distortion factor of 11th harmonic is

$$DF_{11} = \frac{V_{11}}{(11)^2 V_1} = \frac{V_{11}}{121\ V_1} = \frac{0.20}{121 \times 0.87} = 0.19\%$$

From Table 3.3, we see that the 11th harmonic is 20% of input phase voltage and is dominant one. Other harmonics are negligible. So a low-pass π-section filter may be used before the load.

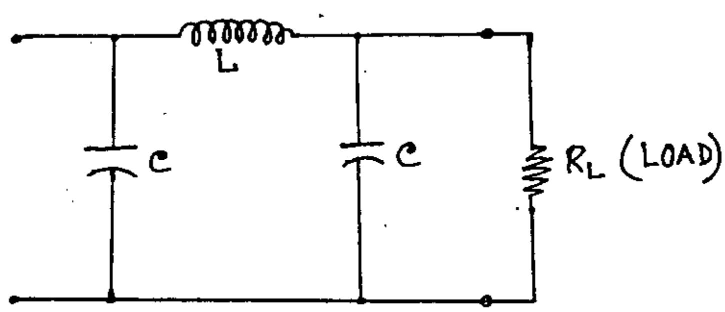

Fig. 3.9 : Low-pass π-Section Filter.

The cut-off frequency, $f_c = \frac{1}{\pi\sqrt{LC}} = 11 \times 50$ C/S. ,.. .. (3.11).

Assuming load resistance, R_L = 1000 ohms

$$\therefore \text{ load resistance } R_L = \sqrt{\frac{L}{C}} = 1000 \text{ ohms.} \quad .. \quad (3.12)$$

$$\text{or, } \frac{L}{C} = 10^6$$

$$\text{or, } L = C \times 10^6$$

Putting the value of L in eqn (3.11) we get,

$$\frac{1}{\pi\sqrt{C \times 10^6 \times C}} = 11 \times 50 = 550$$

$$\text{or, } \frac{1}{\pi C 10^3} = 550$$

$$\text{or, } C = \frac{1}{\pi \times 10^3 \times 550} = 5.78 \times 10^{-7} F$$

$$= 0.58\,\mu F$$

$$L = C \times 10^6 = 0.58 \times 10^{-6} \times 10^6 \text{ H}$$

$$= 0.58 \text{ H}$$

$$\therefore L = 0.58 \text{ H}$$

$$\text{and } C = 0.58\,\mu F$$

New from Table 3.4, we see that input current I_a contains 3rd harmonics 0.52 p.u. of output current and this is dominant. We will require a Low-pass π- Section filter before the converter to cut-off this 3rd harmonic term.

Here, cut-off frequency, $f_c = \frac{1}{\pi\sqrt{LC}} = 3 \times 50 = 150$ C/S .. (3.13)

Now load resistance $= \sqrt{\frac{L}{C}} = 1000$ ohms. .. (3.14)

$$\text{or,} \quad L = C \times 10^6$$

From eqn. (3.13) we get,

$$\frac{1}{\pi\sqrt{C \times 10^6 \times C}} = 150$$

$$\text{or,} \quad C = 2.12\,\mu F$$

$$L = C \times 10^6 = 2.12 \times 10^{-6} \times 10^6 \text{ H}$$

$$= 2.12 \text{ H}$$

$\therefore$ $L = 2.12$ H

and $C = 2.12\,\mu F$

3.7 Conclusions

The analytical expressions developed in the earlier chapter is utilized to study the phase converter under balanced and unbalanced conditions. The proposed technique produces balanced output voltage. The input current unbalance is dependent on input voltage unbalance. By choosing appropriate switching function the harmonic content of the output voltage can be reduced. Detailed input current, output voltage harmonic analysis has shown that the proposed technique produces balanced output voltage with effetive suppression of lower order harmonics.

CHAPTER 4

DESIGN OF THE CONVERTER

4.1 Introduction

This chapter focuses on the design aspects of logic-control circuit of the unbalanced phase converter. These aspects include, the derivation of the appropriate switching function,the processing of the gating signals from their respective functions and the development of the circuitry required to implement these functions and signal processing.

As the input voltages are unbalanced, the principle and process of deriving the proper gating signals is much more ecomplex[11]-[12] than deriving respective signals for a balanced phase converter. The unbalance present suggests that the implementation and performance of such phase converter depends to a large extent on their respective logic control boards. Slight mismatch of the gating signals will result in short-circuiting and blow-up of switches.

Finally, a complete design data for the converter is provided.

4.2 Control Logic Design

The design of control circuit includes the derivation of the appropriate switching functions, the processing of the gating signals from their respective functions and finally the development of the circuitry required to implement the above functions and signal processing.

To implement the schemes proper relationship between input voltages and gating signals is required. Such a gating signal relationship with balanced input for the phase converter (Fig. 4.1) is shown in Fig. 4.2. This gating signals can be realized by using digital components.

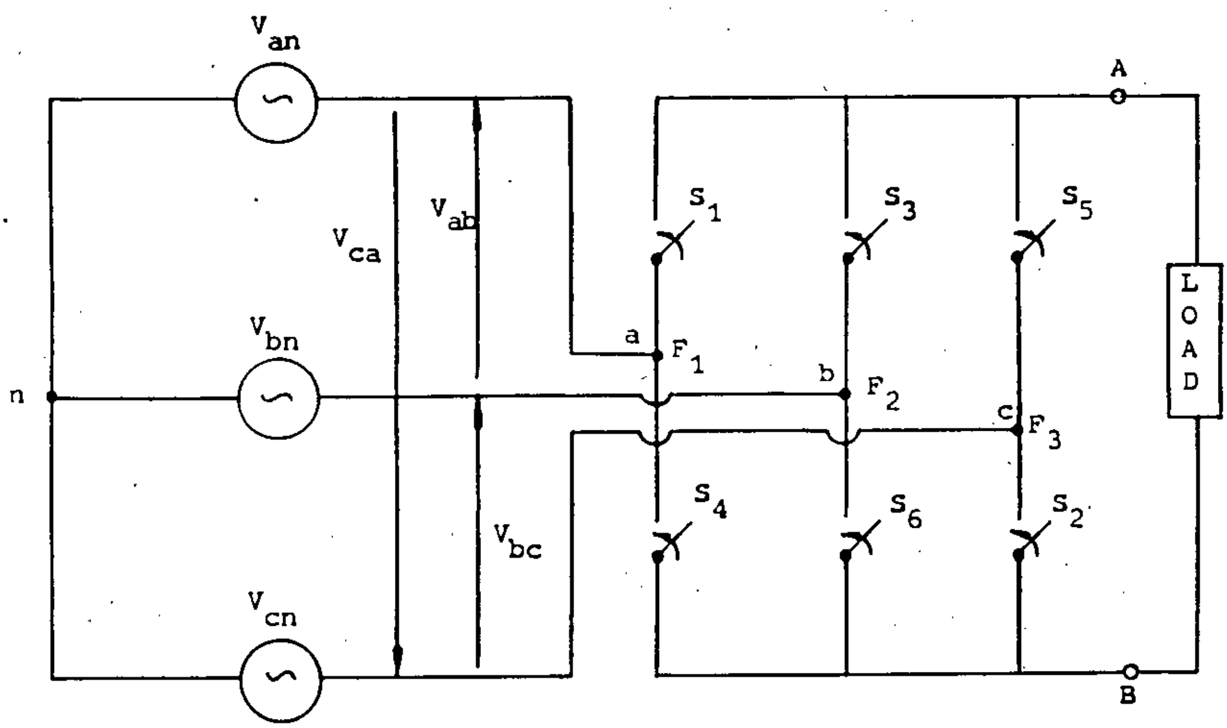

Fig. 4.1: Simplified circuit diagram of the proposed 3-phase to 1-phase converter in full-bridge configuration.

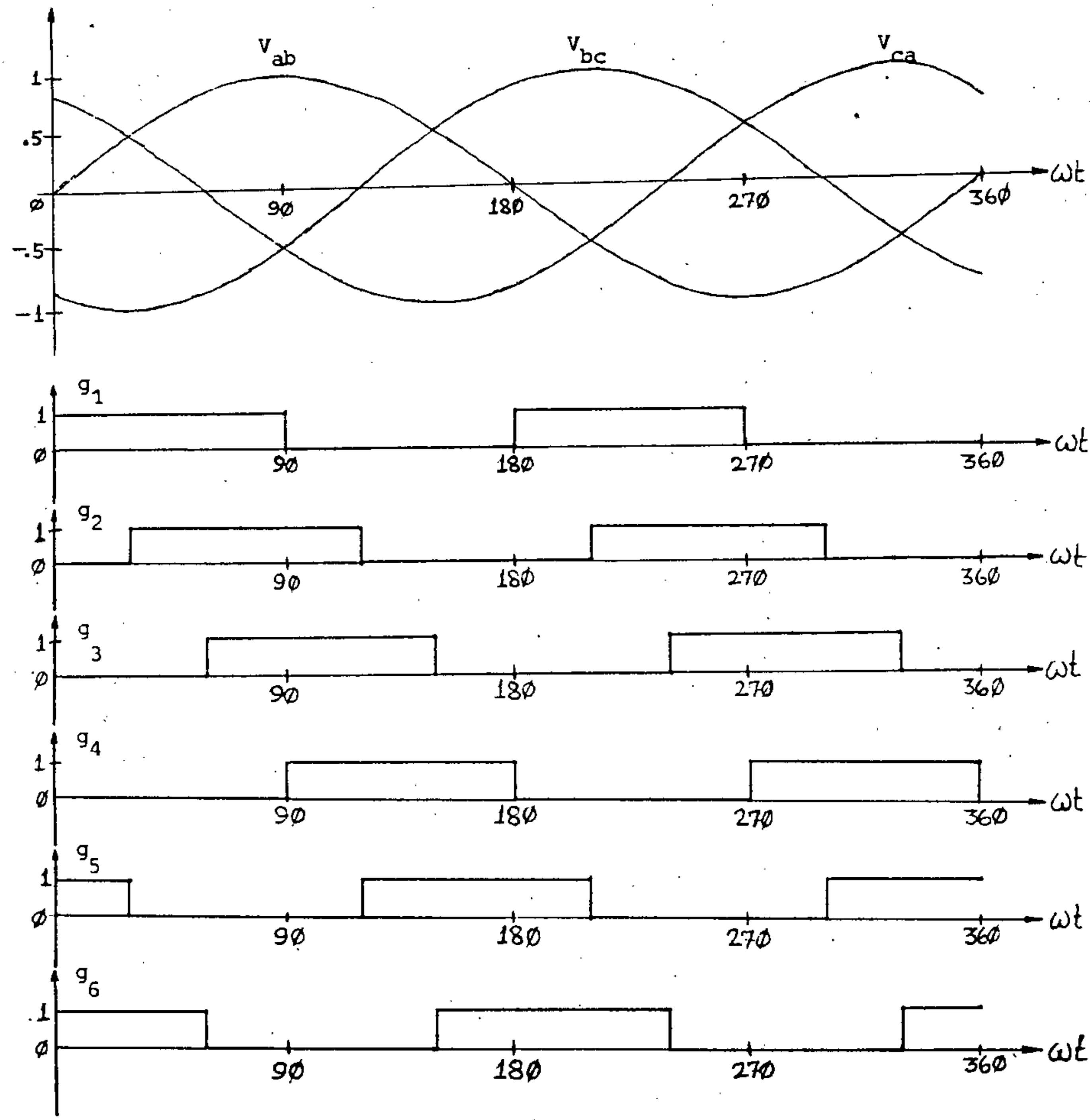

Fig. 4.2 : Six gating signals relationship with balanced input voltages for the converter.

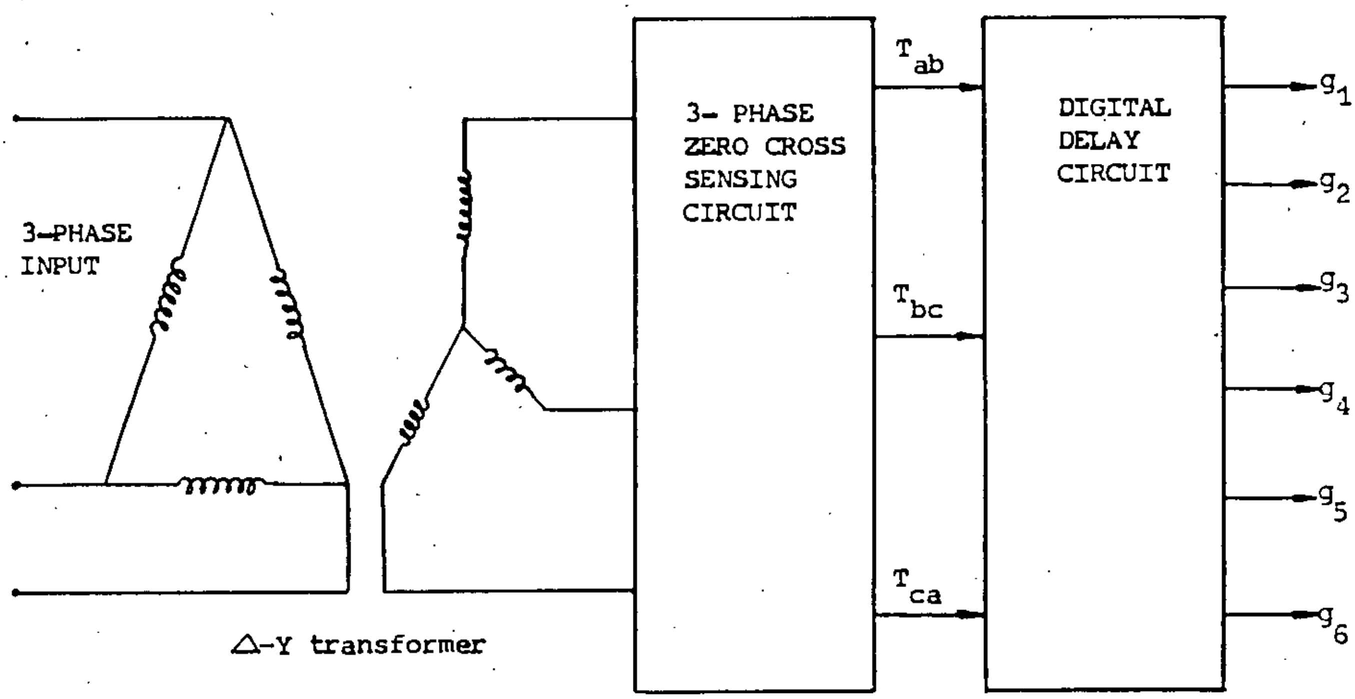

Fig. 4.3 : Logic circuit block diagram for the converter.

A delta-wye step down transformer (Fig. 4.3) is used for input line voltage sensing. The output of this transformer provides the three zero crossing points for the three input line voltages. The zero-cross sensing is implemented by employing three properly biased voltage comparators.

The six gating signals g_1-g_6 (Fig. 4.2) are then applied to the gates of the six switches S_1- S_6 in synchronization with zero crossing signals. The gating signals for balanced and unbalanced case is depicted in Fig. 4.2 and 4.4 respectively.

The derivation of unbalanced gating signals are described as follows:

Let,

$$V_{ab} = 0.97 \text{ Sin wt}$$

$$V_{bc} = 0.95 \text{ Sin } (\text{wt} - 120^{\circ})$$

$$V_{ca} = 0.93 \text{ Sin } (\text{wt} - 240^{\circ})$$

i.e. the unbalances are 3%, 5% and 7%.

The widths of the gating signal will be changed according to the amplitude of the unbalanced line voltages. The width of the gating signals are calculated as follows;

For signal g_1 & g_4, the width = $90^{\circ} \times 0.97 = 87.3^{\circ}$

For signal g_3 & g_6, the width = $90^{\circ} \times 0.95 = 85.5^{\circ}$

For signal g_5 & g_2, the width = $90^{\circ} \times 0.93 = 83.7^{\circ}$

The relationship between the gating signals and the unbalanced line voltages are shown in Fig. 4.4.

Therefore, the width of the gating signals changes according to the unbalances present in the input line voltages.

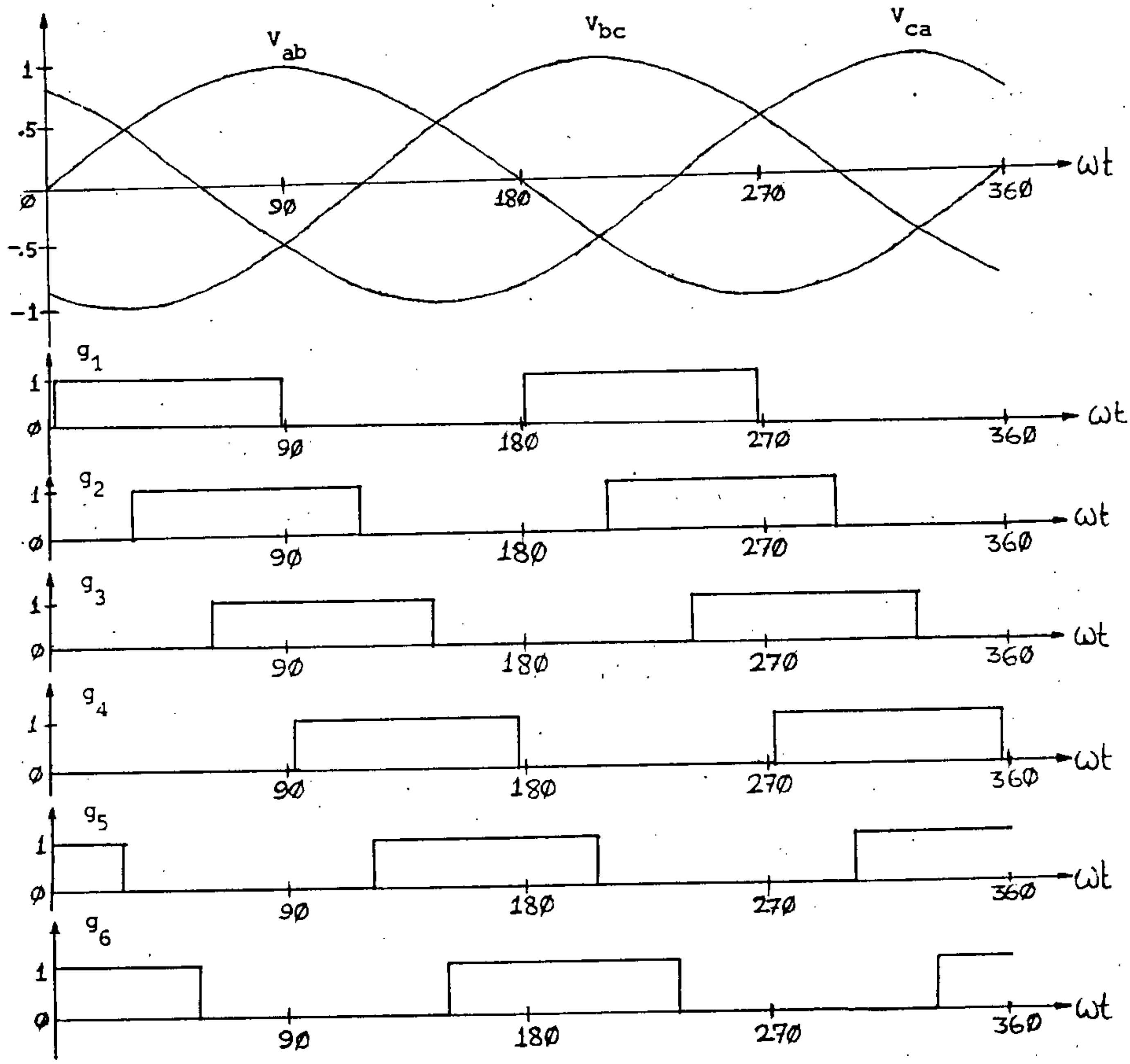

Fig. 4.4 : Six gating signals relationship with unbalanced input voltages for the converter.

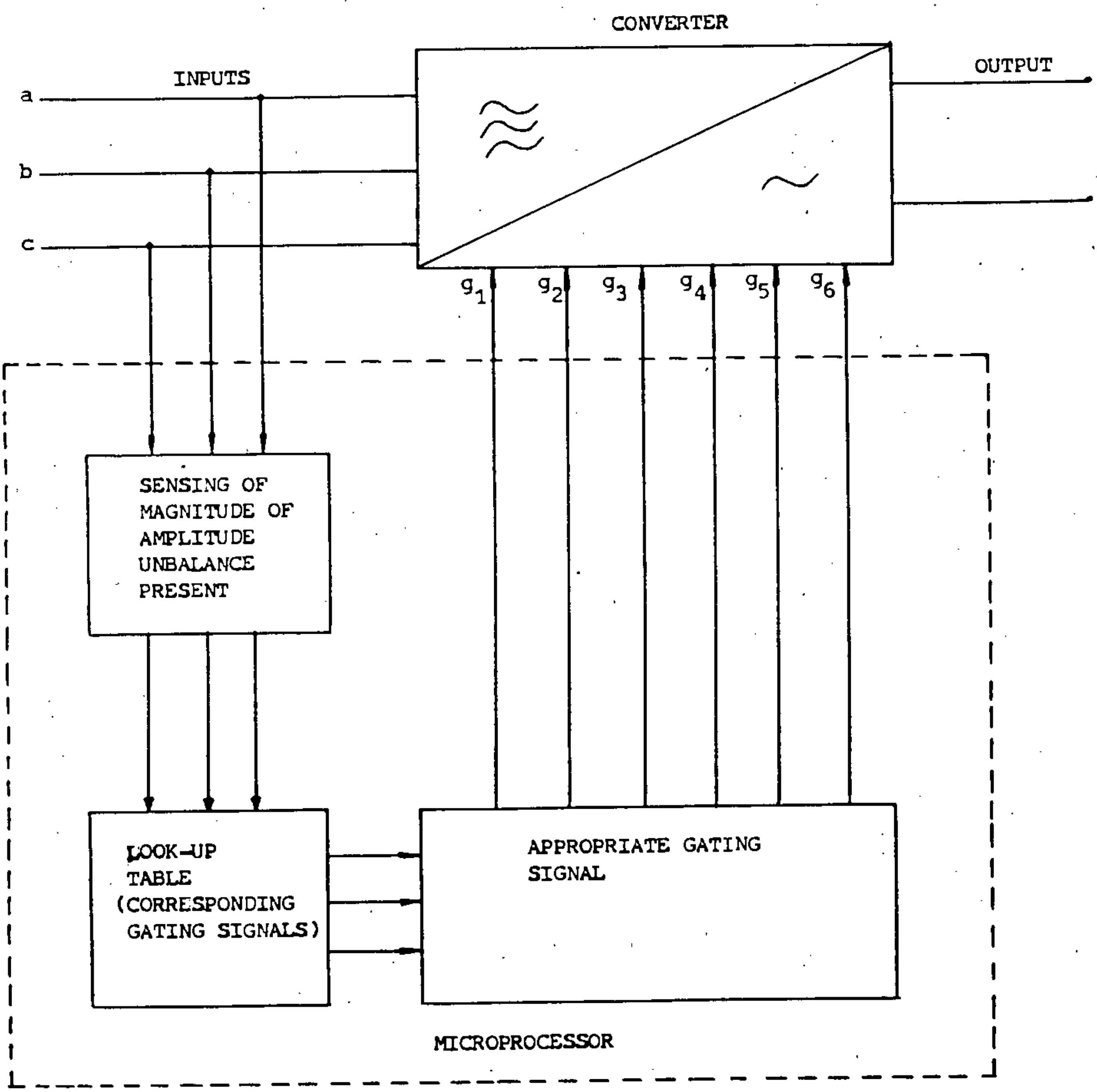

Fig. 4.5 : Microprocessor based control circuitry.

LOOK-UP TABLE

Amplitude Unbalance-present in input Line voltage V_{ab} in percent	Corresponding gating signal width g_1, g_4	Amplitude Unbalance-present in input Line voltage V_{bc} in percent	Corresponding gating signal width g_3, g_6.	Amplitude Unbalance present in input Line voltage V_{ca} in percent.	Corresponding gating signal width g_5, g_2.
1	89.1°	1	89.1°	1	89.1°
2	88.2°	2	88.2°	2	88.2°
3	87.3°	3	87.3°	3	87.3°
4	86.4°	4	86.4°	4	86.4°
5	85.5°	5	85.5°	5	85.5°
6	84.6°	6	84.6°	6	84.6°
7	83.7°	7	83.7°	7	83.7°
8	82.8°	8	82.8°	8	82.8°
9	81.9°	9	81.9°	9	81.9°

If the amplitude of the unbalanced input voltages are previously known, then the corresponding gating signals can be stored in EPROM and can be synchronized with the zero crossings. A computer program for loading (burning) EPROM for known amplitude unbalance is written in BASIC language.

When the amplitude of the input unbalance voltages change with time i.e. varying continuously, then a dedicated microprocessor can be used. Various combinations of gating signals for corresponding amplitude unbalance can be stored (Fig. 4.5) in a look-up table. According to the unbalance present the corresponding gating signals will be applied to the switches to balance the output (Fig. 4.5).

4.3 Component Ratings

To select the ratings of the switches, the worst case condition (Fig. 4.2) is considered. The worst case condition is 120° conduction and for this case the peak, rms and average switch currents I_{sp}, I_{sr} and I_{sav} are given by [13] ;

$$I_{sp} = (\sqrt{3}) * (\sqrt{2}) \quad \text{p.u. Amps.}$$

$$I_{sr} = \sqrt{3}/\sqrt{2} \quad \text{p.u. Amps.}$$

$$I_{sav} = \sqrt{6}/\pi \quad \text{p.u. Amps.}$$

with these ratings a simple design is provided here for the phase converter.

Considering the design of 30 KVA three phase to single phase converter (Fig. 4.1), it is assumed that ;

Nominal input ac voltage V_{an} = 220 volts (rms)

1.p.u. volt = 220 volts (rms)

and the fundamental component of output (Table 3.1) voltage

$V_{AB}, 1 = 220 * 0.87 = 191.4$ volts (rms)

and the load current, I_{AB} (Fig. 4.1) is given by

$$I_{AB},_1 = 30{,}000/\ (3 * 191.4\ ) = 52.25 \text{ Amps (rms)}$$

By using computed per unit voltage and current values, the actual converter switch voltage and current ratings (without safety margin) can be computed as follows:

Peak switch voltage = $220 * \sqrt{2}$ = 311 volts.

Peak switch current = $52.25 * (\sqrt{6})$p.u.

= 128 Amps.

Average switch current= $52.25 * (\sqrt{6}/\pi)$

= 40.74 Amps.

RMS switch current = $52.25 * (\sqrt{3}/\sqrt{2})$

= 64 Amps.

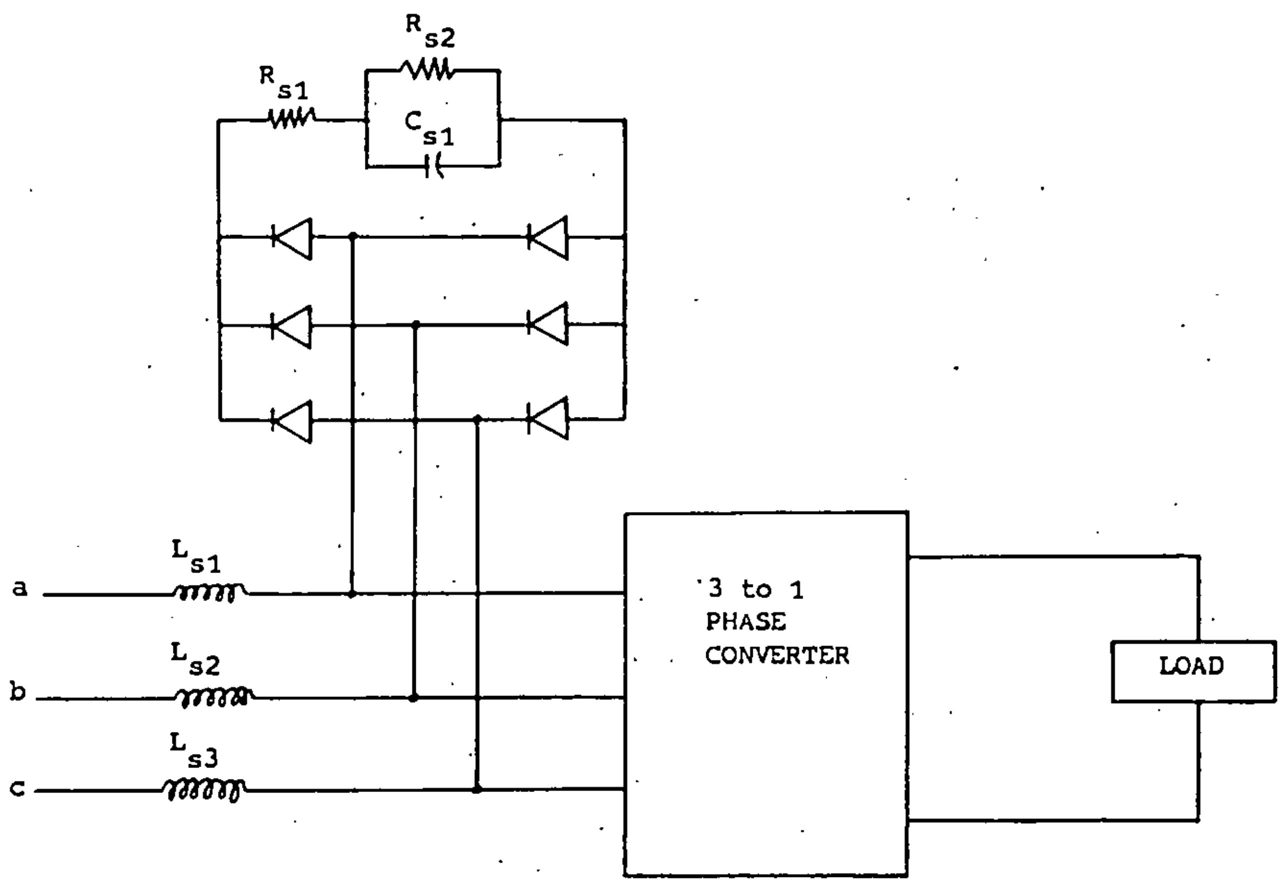

Fig. 4.6 : The converter circuit showing protective elements.

4.4 Component Protection

It is very difficult to provide effective protection for the converter shown in Fig. 4.1 as the load current commutation must be done without free-wheeling diode. Referring to [14] a snubber circuit (Fig. 4.6) which can provide adequate protection for the switches is discussed below :

1) When the switch is turned ON from the OFF condition, a current transient takes place. Reactors L_s-1-2-3 facilitate current transient (i.e. commutation) from a turning off to a turning on switch.

2) The snubber circuit consists of a full-wave diode rectifier circuit. During normal or accidental switching transient, the snubber rectifier diverts input currents to storage element C_{s1}.

3) Over-voltages occur during transient. Snubber capacitor C_{s1} limits resulting over-voltages during transients.

4) Once the storage element C_{s1} is fully charged, it must be discharged for further application. The charge stored in C_{s1} is discharged through the energy "bleeding" resistor R_{s2}.

5) During transient, a series L-R-C circuit is formed by the snubber circuit components. Resistor R_{s1} provides critical damping for L-R-C series path.

4.5 Conclusions

A complete design for the proposed unbalanced phase converter is provided in this chapter. Design for both fixed and variable amplitude unbalance is discussed. Using these design data and control logic circuitry a laboratory prototype can easily be built.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and Conclusions

A three to single phase converter is investigated under balanced and unbalanced supply conditions. A complete analytical description and relevant design data are provided. The analysis is carried out for amplitude unbalance and the load is considered as resistive. In particular the contributions of this thesis by chapter are as follows:

In chapter 2, a converter which can handle unbalanced input voltages is analysed. To make the output balanced, the converter is first analysed under balanced input condition and from this analysis some basic principle is established for unbalanced input condition.

The principle states that inorder to generate balanced output voltage (and current) from unbalanced (amplitude) input voltages, the magnitudes of fundamental component of the switching functions are inversely proportional to the amplitude of the corresponding unbalanced input phase voltage. Operational feature of the converters is described under both balanced and unbalanced input conditions. Principle of operation remains the same for both conditions; only width of the switching functions varies.

The dependency of the width of switching function on the Fourier-coefficient is established by harmonic analysis. The output voltage and input current spectra are described in this chapter. These spectra show that output voltage and input currents contain fundamental of 0.87 and 0.55 respectively and the harmonics content is not very high.

In chapter 3, complete Fourier analysis for balanced and unbalanced phase converter is done. The system description and mode of operation are described. The switching function and modulation technique of the switching function used in this thesis are presented. Computer simulated results of output voltage and input currents spectra under balanced and unbalanced conditions are compared. It is seen that the harmonic content of output voltage increases with the increase of unbalances.

The fundamental component of input currents decreases with the increase of unbalances. For balanced case, the fundamental component of I_a or I_b or I_c is 55%, whereas they are 52%, 53% and 54% for I_a, I_b and I_c respectively for unbalanced case. But the harmonic content of input currents increases with the increase in unbalances.

In chapter 4, complete design data is presented. Input voltage sensing is used to synchronize the opening and closing of the converter switches. Control logic circuit using simple logic blocks is designed to handle both fixed and varying amplitude unbalance. Dedicated microprocessor is suggested to correct the continuous variation of input unbalance. Component ratings and their protection scheme are also discussed.

5.2 Suggestions for Future Work

The analysis and design of the three to single phase converter under unbalanced operating condition is presented in this thesis. As a first step simple switching function is considered for this study. More complex and advanced PWM switching functions may be used to study further the behaviour of this converter. Moreover, three phase to single phase converter study may be extended to cover the three phase to three phase unbalanced converter.

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APPENDICES

APPENDIX-A

BASIC PRINCIPLE OF CONVERTERS

The output of a converter depends on the switching pattern of the converter switches and the input voltage (or current). Similar to linear system, the output quantities of a converter can be expressed in terms of the input quantities by spectrum multiplication. The arrangement of a single-phase converter is shown in Fig. A-1a. If $V_i(W_it)$ and $I_i(W_it)$ are the input voltage and current, respectively, the corresponding output voltage and current are $V_o(W_ot)$ and $I_o(W_ot)$, respectively. The converter could be either a voltage source or a current source converter[15].

Voltage Source: For a voltage source, the output voltage $V_o(W_ot)$ can be related to input voltage $V_i(W_it)$ by

$$V_o(W_ot) = F(W_st)\ V_i(W_it) \qquad \text{(A-1)}$$

where $F(W_st)$ is the switching function of the converter as shown in Fig. A-1b. $F(W_st)$ depends on the type of converter and the gating pattern of the switches. If g_1, g_2, g_3 and g_4 are the gating signals for switches Q_1, Q_2, Q_3 and Q_4, respectively, the switching function is

$$F(W_st) = g_1 - g_4 = g_3 - g_2$$

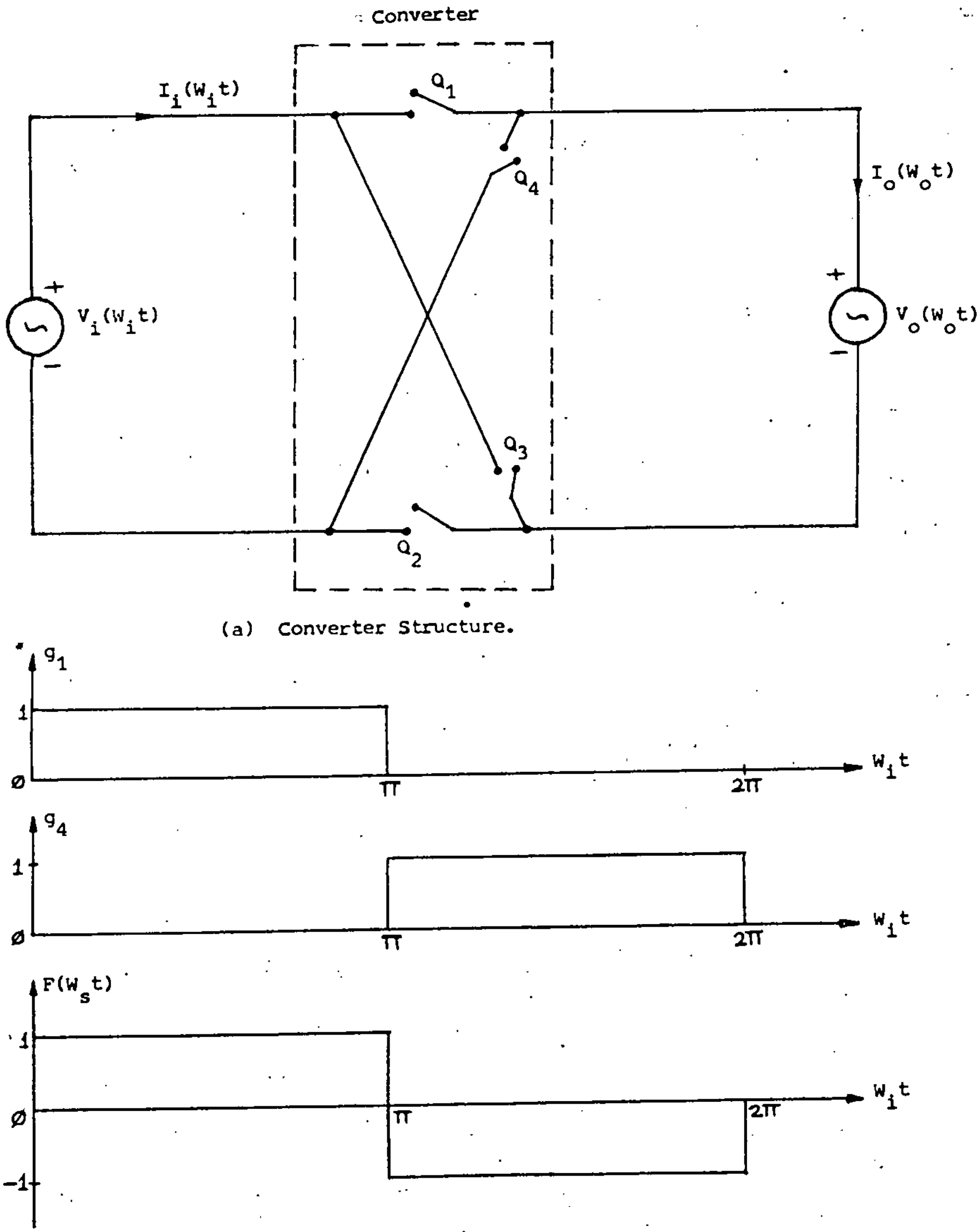
Neglecting the losses in the converter switches gives us

$$V_i(W_it)\ I_i(W_it) = V_o(W_ot)\ I_o(W_ot)$$

$$F(W_st) = \frac{V_o(W_ot)}{V_i(W_it)} = \frac{I_i(W_it)}{I_o(W_ot)} \qquad \text{(A-2)}$$

$$I_i(W_it) = F(W_st)\ I_o(W_ot) \qquad \text{(A-3)}$$

Once $F(W_st)$ is known, $V_o(W_ot)$ can be determined. $V_o(W_ot)$ divided by the load impedance, gives $I_o(W_ot)$; and $I_i(W_it)$ can be found from eqn. (A-3).



(b) Switching function

Fig. A-1 : Single-phase converter structure.

<u>Current Source:</u> In the case of current source, the input current remains constant, $I_i(W_i t) = I_i$ and the output current $I_o\ (W_o t)$ can be related to input current I_i,

$$I_o(W_o t) = F(W_s t)\ I_i \quad \cdots \quad \cdots \quad (A-4)$$

$$V_o(W_o t)\ I_o\ (W_o t) = V_i(W_i t)\ I_i\ (W_i t)$$

which gives

$$V_i(W_i t) = F(W_s t)\ V_o(W_o t) \quad \cdots \quad \cdots \quad (A-5)$$

$$F(W_s t) = \frac{V_i(W_i t)}{V_o(W_o t)} = \frac{I_o(W_o t)}{I_i(W_i t)} \quad \cdots \quad \cdots \quad (A-6)$$

A-1 SINGLE-PHASE BRIDGE RECTIFIERS

If the input voltage to the single-phase bridge rectifier is

$V_i(W_i t) = V_m \text{ Sin } (W_i t)$, then output voltage is given by

$$V_o(W_o t) = F(W_s t)\ V_i(W_i t) = \frac{4V_m}{\pi} \sum_{n=1,3,5,\ldots}^{\infty} \frac{\text{Sin } (W_i t) \text{ Sin } (nW_i t)}{n} \quad \cdots \quad (A-7)$$

$$= \frac{4V_m}{\pi} \sum_{n=1,3,5,\ldots}^{\infty} \frac{\text{Cos } \{(n-1)\ W_i t\} - \text{Cos } \{(n+1)\ W_i t\}}{2n} \quad \cdots \quad (A-8)$$

$$= \frac{2V_m}{\pi}\Big[1 - \text{Cos}\,(2W_i t) + \frac{1}{3}\text{Cos}\,(2W_i t) - \frac{1}{3}\text{Cos}\,(4W_i t) + \frac{1}{5}\text{Cos}(4W_i t)$$

$$- \frac{1}{5}\text{Cos}\,(6W_i t) + \frac{1}{7}\text{Cos}\,(6W_i t) - \frac{1}{7}\text{Cos}\,(8W_i t) + \cdots\cdots\Big]$$

$$= \frac{2V_m}{\pi}\Big[1 - \frac{2}{3}\text{Cos}\,(2W_i t) - \frac{2}{15}\text{Cos}\,(4W_i t) - \frac{2}{35}\text{Cos}\,(6W_i t) - \cdots\cdots\Big]$$

$$= \frac{2V_m}{\pi} - \frac{4V_m}{\pi}\sum_{m=1,2,3,\ldots}^{\infty}\frac{\text{Cos}\,(2mW_i t)}{4m^2-1} \qquad \ldots\text{(A-9)}$$

The first term of eqn. (A-9) is the average output voltage and the second part is the ripple constant on the output voltage.

For a three-phase rectifier, the switching functions are $F_1(W_s t)$, $F_2(W_s t)$ and $F_3(W_s t)$ respectively. If the three input phase voltages are $V_{an}(W_i t)$, $V_{bn}(W_i t)$, and $V_{cn}(W_i t)$, the output voltage becomes

$$V_o(W_o t) = F_1(W_s t)\,V_{an}(W_i t) + F_2(W_s t)\,V_{bn}(W_i t) + F_3(W_s t)V_{cn}(W_i t) \quad \ldots\text{(A-10)}$$

APPENDIX-B

COMPUTER PROGRAM - 1

```
C     THIS PROGRAM IS DONE BY MD. SHAFIQUL ISLAM
C     THESIS SUPERVISOR DR. SHAHIDUL ISLAM KHAN
C     ASSOCIATE PROFESSOR,DEPARTMENT OF E.E.E.BUET,DHAKA
C
C     DETERMINATION OF OUTPUT VOLTAGE WAVEFORM
C     UNDER UNBALANCED INPUT CONDITION
C     WITH THE HELP OF FOURIER COEFFICIENT
C
      DIMENSION B(100),BC(200),XX(360),YY(360),A(100),C(100)
      OPEN(UNIT=3,FILE='OUTPUT',STATUS='NEW')
      PI=3.1415927
      DEL1=108.*PI/180.
      DEL2=112.*PI/180.
      DEL3=116.*PI/180.
      DO 44 K=1,99,2
      A(K)=4.*SIN(K*DEL1/2.)/(K*PI)
      B(K)=4.*SIN(K*DEL2/2.)/(K*PI)
      C(K)=4.*SIN(K*DEL3/2.)/(K*PI)
   44 CONTINUE
      WRITE(3,31)(K,K,A(K),K,B(K),K,C(K),K=1,99,2)
   31 FORMAT(1X,'K=',I2,3X,'A(',I2,')=',F12.8,3X,'B(',I2,')=',F12.8,3X,
     1'C(',I2,')=',F12.8)
      A1=0.97
      B1=0.95
      C1=0.93
      DO 61 M=3,99,2
      AN=A1*A(M)
      BN=B1*B(M)
      CN=C1*C(M)
      N=2*M-1
      BC(N)=0.5*(AN*1.0+BN*COS(-(M-1)*2.*PI/3.)+CN*COS(-(M-1)*4.*PI/3.))
      K=2*M+1
      BC(K)=0.5*(AN*1.0+BN*COS(-(M+1)*2.*PI/3.)+CN*COS(-(M+1)*4.*PI/3.))
   61 CONTINUE
      WRITE(3,72)
   72 FORMAT('1',5X,'START FROM NEW PAGE')
      WRITE(3,32)(M,M,BC(M),M=3,99,2)
   32 FORMAT(2X,'M=',I2,2X,'BC(',I2,')=',F9.5)
      DO 91 I=1,360
      VOV=0.0
      RAD=I*PI/180.
      DO 92 J=3,99,2
      VOV=BC(J)*COS(J*RAD)+VOV
   92 CONTINUE
      XX(I)=FLOAT(I)
      YY(I)=3.*COS(RAD)/2.+VOV
   91 CONTINUE
      CALL ZPLOT(XX,YY,360)
      STOP
      END
C     SUBROUTINE FOR ABOVE FUNCTION
      SUBROUTINE ZPLOT(ZZ,QQ,N)
      DIMENSION ZZ(N),QQ(N),PLOT(101)
      CHARACTER G,BLANK,H,PLOT
      DATA G,BLANK,H/'#',' ','.'/
```

```
      WRITE(3,85)
   85 FORMAT('1',4X,'CONSTRUCTION PROGRAM'//4X,'XX(I)',4X,'YY(I)'//)
      DO 80 K=0,101
   80 PLOT(K)=BLANK
      QQMAX=QQ(1)
      QQMIN=QQ(1)
      DO 81 I=2,N
      IF(QQ(I).GT.QQMAX)QQMAX=QQ(I)
      IF(QQ(I).LT.QQMIN)QQMIN=QQ(I)
   81 CONTINUE
      IAXIS=1.5+(-QQMIN)/(QQMAX-QQMIN)*25.0
      DO 82 I=1,N
      PLOT(IAXIS)=H
      L=1.5+(QQ(I)-QQMIN)/(QQMAX-QQMIN)*25.0
      PLOT(L)=G
      WRITE(3,83)ZZ(I),QQ(I),PLOT
   83 FORMAT(3X,F5.2,3X,F6.3,2X,101A1)
      PLOT(L)=BLANK
   82 CONTINUE
      RETURN
      END
```

COMPUTER PROGRAM–2

```
C       THIS PROGRAM IS DONE BY MD. SHAFIQUL ISLAM
C       THESIS SUPERVISOR DR. SHAHIDUL ISLAM KHAN
C       ASSOCIATE PROFESSOR,DEPARTMENT OF E.E.E.BUET,DHAKA
C
C       DETERMINATION OF INPUT PHASE CURRENTS(IA,IB&IC)WAVEFORMS
C       UNDER UNBALANCED INPUT CONDITION
C       WITH THE HELP OF FOURIER COEFFICIENT
C
        DIMENSION B(100),XB(360),YB(360),C(100),XC(360),YC(360),A(100),XA(
       1360),YA(360)
        OPEN(UNIT=3,FILE='OUTPUT',STATUS='NEW')
        PI=3.1415927
        DEL1=108.*PI/180.
        DEL2=112.*PI/180.
        DEL3=115.*PI/180.
        DO 01 N=1,99,2
        A(N)=4.*SIN(N*DEL1/2.)/(N*PI)
        B(N)=4.*SIN(N*DEL2/2.)/(N*PI)
        C(N)=4.*SIN(N*DEL3/2.)/(N*PI)
     01 CONTINUE
        WRITE(3,51)(N,N,A(N),N,B(N),N,C(N),N=1,99,2)
     51 FORMAT(1X,'N=',I2,2X,'A(',I2,')=',F8.5,2X,'B(',I2,')=',F8.5,2X,'C(
       1',I2,')=',F8.5)
        DO 03 I=1,360
        RAD=I*PI/180.
        COA=0.0
        COB=0.0
        COC=0.0
        DO 04 N=1,99,2
        COA=(A(N)/2.)*(COS((2*N+1)*RAD)+COS((2*N-1)*RAD))+COA
        COB=(B(N)/2.)*(COS(((2*N+1)*RAD)-2*N*PI/3.)+COS(((2*N-1)*RAD)-2*N*
       1PI/3.))+COB
        COC=(C(N)/2.)*(COS(((2*N+1)*RAD)-4*N*PI/3.)+COS(((2*N-1)*RAD)-4*N*
       1PI/3.))+COC
     04 CONTINUE
        XA(I)=FLOAT(I)
        YA(I)=COA
        XB(I)=FLOAT(I)
        YB(I)=COB
        XC(I)=FLOAT(I)
        YC(I)=COC
     03 CONTINUE
        CALL APLOT(XA,YA,360)
        CALL BPLOT(XB,YB,360)
        CALL CPLOT(XC,YC,360)
        STOP
        END
C       SUBROUTINE FOR CURRENT.
        SUBROUTINE APLOT(ZA,QA,NA)
        DIMENSION ZA(NA),QA(NA),PLOTA(101)
        CHARACTER GA,ABLANK,HA,PLOTA
        DATA GA,ABLANK,HA/'*',' ','.'/
        WRITE(3,55)
     55 FORMAT('1',2X,'INPUT PHASE CURRENT IA'//2X,'XA(I)',4X,'YA(I)'//)
        DO 05 K=0,101
```

```
05 PLOTA(K)=ABLANK
   QAMAX=QA(1)
   QAMIN=QA(1)
   DO 06 I=2,NA
   IF(QA(I).GT.QAMAX)QAMAX=QA(I)
   IF(QA(I).LT.QAMIN)QAMIN=QA(I)
06 CONTINUE
   IAX=1.5+(-QAMIN)/(QAMAX-QAMIN)*50.0
   DO 07 I=1,NA
   PLOTA(IAX)=HA
   LA=1.5+(QA(I)-QAMIN)/(QAMAX-QAMIN)*50.0
   PLOTA(LA)=GA
   WRITE(3,56)ZA(I),QA(I),PLOTA
56 FORMAT(1X,F6.2,2X,F8.5,4X,101A1)
   PLOTA(LA)=ABLANK
07 CONTINUE
   RETURN
   END
   SUBROUTINE BPLOT(ZB,QB,NB)
   DIMENSION ZB(NB),QB(NB),PLOTB(101)
   CHARACTER GB,BBLANK,HB,PLOTB
   DATA GB,BBLANK,HB/'#',' ','.'/
   WRITE(3,57)
57 FORMAT('1',2X,'INPUT PHASE CURRENT IB'//2X,'XB(I)',4X,'YB(I)'//
   DO 08 K=0,101
08 PLOTB(K)=BBLANK
   QBMAX=QB(1)
   QBMIN=QB(1)
   DO 09 I=2,NB
   IF(QB(I).GT.QBMAX)QBMAX=QB(I)
   IF(QB(I).LT.QBMIN)QBMIN=QB(I)
09 CONTINUE
   IBX=1.5+(-QBMIN)/(QBMAX-QBMIN)*50.0
   DO 10 I=1,NB
   PLOTB(IBX)=HB
   LB=1.5+(QB(I)-QBMIN)/(QBMAX-QBMIN)*50.0
   PLOTB(LB)=GB
   WRITE(3,58)ZB(I),QB(I),PLOTB
58 FORMAT(1X,F6.2,2X,F8.5,4X,101A1)
   PLOTB(LB)=BBLANK
10 CONTINUE
   RETURN
   END
   SUBROUTINE CPLOT(ZC,QC,NC)
   DIMENSION ZC(NC),QC(NC),PLOTC(101)
   CHARACTER GC,CBLANK,HC,PLOTC
   DATA GC,CBLANK,HC/'#',' ','.'/
   WRITE(3,59)
59 FORMAT('1',2X,'INPUT PHASE CURRENT IC'//2X,'XC(I)',4X,'YC(I)'//
   DO 11 K=0,101
11 PLOTC(K)=CBLANK
   QCMAX=QC(1)
   QCMIN=QC(1)
   DO 12 I=2,NC
   IF(QC(I).GT.QCMAX)QCMAX=QC(I)
```

```
      IF(QC(I).LT.QCMIN)QCMIN=QC(I)
   12 CONTINUE
      ICX=1.5+(-QCMIN)/(QCMAX-QCMIN)*50.0
      DO 13 I=1,NC
      PLOTC(ICX)=HC
      LC=1.5+(QC(I)-QCMIN)/(QCMAX-QCMIN)*50.0
      PLOTC(LC)=GC
      WRITE(3,60)ZC(I),QC(I),PLOTC
   60 FORMAT(1X,F6.2,2X,F8.5,4X,101A1)
      PLOTC(LC)=CBLANK
   13 CONTINUE
      RETURN
      END
```