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ABNORMAL HARMONICS GENERATED BY MODIFIED HVDC CONVERTER

التوافقيات غير الطبيعية الناتجة عن استخدام المحولات المحدثة في نقل الكهرباء بواسطة التيار المستمر الضغط العالي

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ملخص

إن عدم الاتزان في عمل مغيرات التيار المتناوب ثلاثي الاوجه الى تيار مستمر يؤدي الى زيادة كبيرة نسبيا في التوافقيات غير الطبيعية المصاحبة لتيار المصدر بالاضافة الى التوافقيات الطبيعية المتولدة اصلا في تيار المصدر . لذا فإن هذا البحث يقدم تحليلا رياضيا لهذه التوافقيات مع التركيز على دراسة تاثير المعاوقة الحثية التي توصل مع موحدات التيار المحكومه على نقاط التفرع لملفات المحول الثانوية . تمت مناقشة تاثير التحكم في زاوية القدح وتاثير تغير هذه الزاوية في التحكم بمقدار هذه التوافقيات وبالتالي تحسين اداء هذا المغير، بعض النتائج العملية والتي تدعم النتائج النظرية قد زودت في هذا البحث.

ABSTRACT

Unbalance in the operation of AC/DC converters gives rise to abnormal or uncharacteristic current harmonics, in addition to the characteristic harmonics in the supply current waveforms. This paper concentrates on the analysis of uncharacteristic harmonics caused by unbalanced AC supply voltages. Attention is given to modified converter operation which uses thyristors connected to tapping points on the secondary windings of the transformer. Control of by-pass thyristor for reducing abnormal harmonic generation are discusses, and some experimental results supporting the theoretical calculations are also included.

Keywords: Modified HVDC Converter, Abnormal Harmonics, Unbalance operation

INTRODUCTION

Many applications are being found for semiconductor devices in electrical power systems. Thyristor AC/DC converters are widely used for obtaining an adjustable direct voltage from three-phase mains which is used in HVDC systems. Major problems associated with these applications are the harmonic current injection into power supply and volt-ampere absorption. The generation of normal harmonics as well as several methods for harmonics reduction are well explained in the existing literature [1-6].

In practical systems perfect conditions for analysis of characteristic harmonics of a converter are never met, and as a result harmonics of uncharacteristic orders can arise which are not explainable by existing theory yet they do appear in the AC power system. The generation of abnormal harmonics of an AC/DC converter caused by system imperfections, (i.e. firing angle errors, asymmetry in commutation impedances, AC voltage unbalance and AC voltage distortion),

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has been studied in several papers [7-9]. Many methods of control based on symmetrical firing [10-11] have been proposed to overcome the problem of abnormal operation, these methods however, cannot totally eliminate the uncharacteristic harmonics during unbalanced conditions.

The conventional bridge is modified [12-15] in such a way that it has additional thyristors which form by-pass thyristors on each phase. In this configuration, fast and continuous control of the DC voltages is possible, and the need for an on-load tap-changer may be removed. The direct voltage can be controlled by controlling the firing angles of the by-pass thyristors. Harmonic generation into the AC system and the converter reactive volt-ampere absorption may be reduced, but more switching devices and therefore control circuit are required compared with the conventional converter requirements.

This paper presents both of operation principles and control processes of a modified three-phase thyristor converter under unbalanced supply conditions. The analysis described is concerned with uncharacteristic harmonics arising from two sources, namely, firing angle and supply voltage unbalance, which are considered individually.

BASIC OPERATION OF THE MODIFIED BRIDGE CONVERTER

The basic modified bridge circuit is shown in Fig. 1, has additional thyristors which form a ' by-pass' thyristor. All three phases are similarly modified and the number of thyristors in a by-pass thyristor is related to section voltage. The firing logic for the by-pass thyristors is symmetrically arranged for the three phases, and under normal operation is independent of the main thyristor firing logic [16]. In the rectifier mode, the main thyristor firing angle is kept at a small value and the DC voltage is controlled by the firing angle of by-pass thyristors. In the inverter mode of operation, by-pass thyristors fired before main thyristors because commutation occurs from a higher voltage to a lower voltage. The control of the DC voltage is achieved by the variation of the angle of advance β_m with a minimum safe extinction angle δ.

Converter performance analysis

The method of control in the rectifier mode is to keep the main thyristor firing angle α at a small value, and the DC voltage is controlled by variation of by-pass firing angle α_b. Both voltage and current waveforms are shown in Fig. 2. There are two commutation processes are considered, current transfer between the main thyristors and current transfer between the bypass thyristors S2 and the section of main thyristor designated S1. The reactance of the main-thyristor circuit during commutation is the conventional commutation reactance X_c with additional reactance X_b due to the tapped section turns. After firing a by-pass thyristor, the rate of increase in current through the thyristor is controlled by the section voltage nV_m and the reactance X_b. Natural commutation is delayed by an angle α_0 owing to the difference between the main and by-pass thyristor voltages. The DC voltage V_d for $(\gamma+\alpha) \le \alpha_b < (2\pi/3) - \gamma_b$ is defined by the following expression:

$$V_d = \frac{3\sqrt{2}V}{\pi}\left[\frac{\sqrt{3}(n+2)}{4}\cos(\alpha+\alpha_0) + \frac{n}{4}\sin(\alpha+\alpha_0) + \frac{\sqrt{3}}{2}n\cos(\alpha_b+\alpha_0+\gamma_b) - \frac{n}{2}\sin(\alpha_b+\alpha_0+\gamma_b) + \frac{\sqrt{3}(n+2)}{4}\cos(\alpha+\alpha_0+\gamma_b) + \frac{n}{4}\sin(\alpha+\alpha_0+\gamma_b)\right] - 2V_{th} - 2I_d R_{mt} \tag{1}$$

where

$\alpha_0, \alpha, \alpha_b, \gamma$ and γ_b are angles as shown in fig.2

$$R_{mt} = R_m\left(1-\frac{3\gamma}{4\pi}\right) + R_b\left[1+\frac{3}{2\pi}\left(\frac{\gamma}{2}+\alpha-\alpha_b\right)\right]$$

The overlap γ is related to the output current I_d (assumed constant), then

$$I_d = \frac{\sqrt{6\left(1+n+n^2\right)}}{Z_1}\left[\cos\left(\frac{\pi}{6}+\alpha+\alpha_0+\theta_2\right)e^{-\gamma R_t/X_t} - \cos\left(\frac{\pi}{6}+\alpha+\alpha_0+\gamma+\theta_2\right)\right] \tag{2}$$

where

$\theta_2 = \tan^{-1}(R_t / X_t)$,

$R_t = 2R_m + R_b$

$X_t = 2X_m + X_b$,

$Z_1 = \sqrt{R_t^2 + X_t^2}$

Also, the overlap angle γ_b is related to I_d

$$I_d = \frac{\sqrt{2}nV}{Z_2}\left[\cos(\alpha_b+\alpha_0+\pi/6+\theta_3)e^{-\gamma_b R_b/X_b} - \cos(\alpha_b+\alpha_0+\pi/6+\gamma_b+\theta_3)\right] \tag{3}$$

where $Z_2 = \sqrt{R_b^2 + X_b^2}$ and $\theta_3 = \tan^{-1}(R_b / X_b)$

For the inverter mode of operation, the by-pass thyristor S2 is fired with the main thyristor S3, and the DC voltage is controlled by the angle of advance β_m of device S1. Fig. 3 shows the voltage profiles and current waveforms. The angle at which natural commutation occurs is β_0 due to the difference between the main and by-pass voltages.

$$\beta_0 = \alpha_0 = \tan^{-1}\left[\frac{n\tan(\pi/6)}{2+n}\right]$$

The effect of β_0 is to increase slightly the angle of lag of the phase currents and the reactive volt-ampere absorption. The average value of inverter DC voltage is given by:

$$V_d = \frac{V_0}{\sqrt{3}}\left[\frac{\sqrt{3}n}{2}\cos(\beta_m+\beta_0) - \frac{n}{2}\sin(\beta_m+\beta_0) + \frac{\sqrt{3}(n+2)}{4}\cos(\beta_0+\delta) + \frac{n}{4}\sin(\beta_0+\delta) + \frac{\sqrt{3}(n+2)}{4}\cos(\beta_m+\beta_0) + \frac{n}{4}\sin(\beta_m+\beta_0)\right] - 2V_{th} - 2I_d R_{md} \tag{4}$$

where

$$R_{md} = R_m\left(1-\frac{3\gamma}{4\pi}\right) + R_b\left[1+\frac{3}{2\pi}\left(\frac{\gamma_b}{2}+\delta-\beta_m\right)\right]$$

Supply current harmonics

a- Balance operation

The following assumptions are made during balanced operation:

1) The current of the bridge includes no AC component.
2) All phases of the supply voltages are identical.
3) The transformer magnetizing current can be ignored.
4) The commutation reactances for all phases are the same.
5) Thyristor voltage drops and resistive components of the commutation circuit are negligibly small.

The phase current in the supply side of the transformer as seen in Fig. 4a consists of two rectangular components and has no even harmonics, but triples harmonics are present due to the tap-section on each phase, which are energized for a part of the main thyristor conduction period. To reduce the triples harmonics, a delta-connected primary or tertiary winding is necessary to give harmonic ampere –turn balance in the converter transformer cores. The currents flowing, at any instant in two secondary winding are equal and opposite and do not contain triples harmonics.

The supply current waveform for rectifier operation with negligible commutation reactance can be expressed by Fourier series as:

$a_0 = 0$ there is no DC component

$$a_m = \frac{2I_d}{\pi}\left(\sin m(\pi/3+\alpha_0) - \sin m(-\pi/3+\alpha_0)\right) + \frac{2I_d}{m\pi}\left(\sin m(\pi/3+\alpha_0) - \sin m(-\pi/3+\alpha_b)\right) \tag{5}$$

$$b_m = \frac{2I_d}{\pi}\left(-\cos m(\pi/3+\alpha_0) + \cos m(-\pi/3+\alpha_0)\right) + \frac{2I_d}{m\pi}\left(-\cos m(\pi/3+\alpha_0) + \cos m(-\pi/3+\alpha_b)\right) \tag{6}$$

For inverter operation , the Fourier components are obtained by replaced $\alpha_0 = \delta + \beta_0$ in equations 5 and 6.

For finite overlap angles, the main thyristor and the by-pass currents are determined by using the same analytical technique as reported in [16]. A search technique was necessary to determine values of the commutation angles γ_m and γ_b. When the two commutation periods interact as shown in a representative current waveforms Fig. 4b.

Curve ODB represents current in the main thyristor defined by

$$\frac{di_m}{dt} = \frac{\sqrt{6(1+n+n^2/3}V_{ph}}{(X_c + X_b)}\sin\left(\theta - \frac{\pi}{6} - \alpha_0\right) \tag{7}$$

Curve AB represents current in the by-pass thyristor, defined by

$$\frac{di_b}{dt} = \frac{n\sqrt{2}V_{ph}}{X_b}\sin\theta \tag{8}$$

Point B requires a search technique and is the instant at which current is completely transferred from the main thyristor to the by-pass thyristor. Curve BC is defined by

$$\frac{di_m}{dt} = \frac{di_b}{dt} = \frac{(n+1)\sqrt{6}V_{ph}}{(X_c + 2X_b)}\sin(\theta - \pi/6) \tag{9}$$

b- Unbalanced operation

As shown in the above section, the study of characteristics harmonics a perfectly operation of the conversion equipment is assumed. In practice, however, these assumptions are never met. Imbalance of the fundamental of AC bus voltages both in magnitude and phase are studied in this section. Fig. 5 shows the waveforms for unbalanced voltage operation according to the following relations:

$$\begin{aligned} v_a &= 1.2\sin(\theta) \\ v_b &= \sin(\theta - 2\pi/3) \\ v_c &= \sin(\theta + 2\pi/3) \end{aligned} \qquad (10)$$

and

$$\begin{aligned} \bar{v}_a &= 1.7\sin(\theta) \\ \bar{v}_b &= 1.4\sin(\theta - 2\pi/3) \\ \bar{v}_c &= 1.4\sin(\theta + 2\pi/3) \end{aligned} \qquad (11)$$

Any set of unbalanced AC phase voltage can now be analyzed into symmetrical components zero, positive and negative sequence according to the following well known relations [7]:

$$\begin{aligned} v_0 &= (1/3)(v_{an} + v_{bn} + v_{cn}) \\ v_1 &= (1/3)(v_{an} + av_{bn} + a^2 v_{cn}) \\ v_2 &= (1/3)(v_{an} + a^2 v_{bn} + av_{cn}) \end{aligned} \qquad (12)$$

and

$$\begin{aligned} \bar{v}_0 &= (1/3)(\bar{v}_{an} + \bar{v}_{bn} + \bar{v}_{cn}) \\ \bar{v}_1 &= (1/3)(\bar{v}_{an} + a\bar{v}_{bn} + a^2\bar{v}_{cn}) \\ \bar{v}_2 &= (1/3)(\bar{v}_{an} + a^2\bar{v}_{bn} + a\bar{v}_{cn}) \end{aligned} \qquad (13)$$

where ' a ' is an operator, and its value is $1\angle 120°$. The zero-sequence are not allowed to circulate from the AC source into the AC terminals of the converter, because the winding neutrals of the converter transformers are not ground-connected, so there is no path for zero-sequence current in the converter.

The firing angle α_b of by-pass thyristor for phase (a) is modified by modulation angle ε to reduce the abnormal harmonics

Current harmonics analysis

The general AC waveform for one-phase (positive side) is shown in Fig.6. All points of importance on the waveforms are individually identified in relation to common time reference points in the voltage-waveform. The computer approach to establishing the nature of the current harmonics is based on a complex Fourier analysis of the waveforms. These currents are determined by the periods of conduction of the corresponding converter thyristors, which, in turn depend on the phase and magnitude of the converter voltages. If the source is unbalanced, however, the lack of symmetry of voltage crossing points and the different magnitudes of the commutating voltages alter both the conduction periods and the duration of the overlap angles, thus resulting in unbalanced sets of currents.

To achieve an unbalanced supply practically, an extra three-phase voltage connected with the reverse phase sequence to the primary side of the converter transformer. This voltage is supplied from another three-phase transformer (with different tap-section in each phase) which is connected to the same power supply through a variac, and the secondary side is connected to the primary side of the converter transformer. As a result of an unbalance, the magnitudes and the phase angles of the line-to-line voltages will be altered.

Analysing the current waveform shown in Fig.6 leads to the following expressions.

For phase (a) positive side

$$\phi_1 = \pi/6 + \alpha_0 + \alpha_{51}$$
$$\phi_2 = \pi/6 + \alpha_0 + \alpha_{51} + \gamma_{51}$$
$$\phi_3 = \pi/6 + \alpha_0 + \alpha_{51} + \gamma_{51} + \alpha_b$$
$$\phi_4 = \pi/6 + \alpha_0 + \alpha_{51} + \gamma_{51} + \alpha_b + \gamma_{1b}$$
$$\phi_5 = 5\pi/6 + \alpha_0$$
$$\phi_6 = 5\pi/6 + \alpha_0 + \gamma_{13} \qquad (14)$$

For phases (b) and phase (c) positive side, the same limits as above with the following modification :

$$\alpha_{13} = \alpha_{51} + 2\pi/3$$
$$\alpha_{35} = \alpha_{13} + 2\pi/3 \qquad (15)$$

and

$$\gamma_{13} = \cos^{-1}\left(\cos\alpha_{13} - \frac{(X_{C(ab)} + 2X_b)}{K(V_{m(ab)})} I_d\right) - \alpha_{13}$$

$$\gamma_{35} = \cos^{-1}\left(\cos\alpha_{35} - \frac{(X_{C(bc)} + 2X_b)}{K(V_{m(bc)})} I_d\right) - \alpha_{35} \qquad (16)$$

$$\gamma_{51} = \cos^{-1}\left(\cos\alpha_{51} - \frac{(X_{C(ca)} + 2X_b)}{K(V_{m(ca)})} I_d\right) - \alpha_{51}$$

$$\gamma_b = \cos^{-1}\left[\cos(\pi/6 + \alpha_b) - \frac{X_b I_d}{\sqrt{2} n V_{ph}}\right] - (\alpha_b + \pi/6) \qquad (17)$$

where

$$K = \sqrt{6(1 + n + n^2/3)}$$

$X_{C(ab)}$, $X_{C(bc)}$ and $X_{C(ca)}$ are the line to line reactance

$V_{m(ab)}$, $V_{m(bc)}$ and $V_{m(ca)}$ are the peak values of line to line voltage

In order to simplify the analysis, it is convenient to specify a single parameter to describe voltage unbalance. The unbalance factor (UBF) which is the ratio between negative and positive sequences is a suitable parameter. The positive sequence voltage can be taken as reference-phase, in this way any degree of unbalance as defined by v_2/v_1 is directly given by the negative-sequence voltage.

RESULTS AND DISCUSSION

With by-pass thyristor control there are significant triples harmonics, due to additional tap-section turns in the secondary side which are energized for a part of the main thyristor conducting period. This is a disadvantage of this form of control and a delta connected tertiary is then required with a star/star connected transformer to give triples harmonic ampere-turn balance in the converter transformer core. Fig.7 shows the computed results for the harmonic content of the AC phase current for modified bridge operating at a typical firing angle of 17° the harmonic content of the supply current is generally reduced with by-pass thyristor control.

A number of tests have been performed to verify the theoretical and practical results presented in this paper. Supply current harmonics were measured and plotted against the unbalance factor (UBF) together with computed values for each phase as shown in Fig.8 and Fig.9 at different values of ε. In addition to the characteristic harmonics, even and odd harmonics are generated, which enter the lines. Even harmonics in this case are of lower magnitude. Also, there is a DC component in lines which may cause transformer saturation. Uncharacteristic harmonics are always present in practice until unbalance is introduced. The triples harmonic content increases when the unbalance factor increase.

A comparison of results between the modified operation and conventional operation indicates that there is a reduction in the uncharacteristic harmonics. For conventional operation at $\alpha_b = 20^\circ$ and UBF = 0.2, the ratio of third harmonic to the fundamental component is equal to 15.4% for phase 'a' , 5.4% for phase 'b' and 12.4% for phase 'c'. The fifth harmonic is equal to 4.89% for phase 'a', whilst it is equal to the average value of about (20%) for phases 'b' and 'c'. For a modified firing angle by an $\varepsilon = 10^\circ$, the third harmonic is 5.2% for phase 'a', 1.6% for phase 'b' and 4.1% for phase 'c'. The fifth harmonic will be equal to 16.5%, 18.3% and 18.8% for the phases 'a', 'b' and 'c' respectively. Fig.10 shows the third harmonic against the change of modulation angle (ε) at $\alpha_b = 20^\circ$ for UBF=0.2 and 0.3, it can clearly be seen that the third harmonic increases when the unbalance factor increases. Fig.11 demonstrate that the uncharacteristic 3rd harmonic content vary with converter delay angle.

CONCLUSIONS

This paper addresses the problem of uncharacteristic harmonics generated in the input current for a modified converter bridge and proposes a technique of minimizing them based on modulation of by-pass thyristor firing angle. Uncharacteristic harmonics have been measured and computed for balanced and unbalanced operations. A quantitative insight has been given into the AC harmonic consequences of imbalanced input voltages. Triples harmonics are minimized by balancing the input voltage as closely as practicable for each phase.

A computer program is developed to simulate the converter. The algorithm solves for the truncated Fourier series of all line currents in a balanced and unbalanced operations.

NOMENCLATURE

V_d = DC voltage
V_{ph} = RMS value of phase voltage
V_{th} = on-state device voltage
I_d = DC current in HVDC line
i_m = instantaneous value of main thyristor current
i_p = instantaneous value of by pass thyristor current
n = transformer tap-section turns (p.u)
X_C = main thyristor commutation reactance
X_b = by-pass thyristor commutation reactance
α = delay angle of main thyristor
α_0 = delay angle due to unequal thyristor voltages
α_b = delay angle of by-pass thyristor
γ = commutation angle due to main thyristor (S1)
γ_b = commutation angle due to by-pass thyristor (S2)
β_0 = angle of advance due to unequal thyristor voltages
β_b = angle of advance of by-pass thyristor (S2) in inverter operation
β_m = angle of advance of main thyristor (S1)
δ = safety angle in inverter operation

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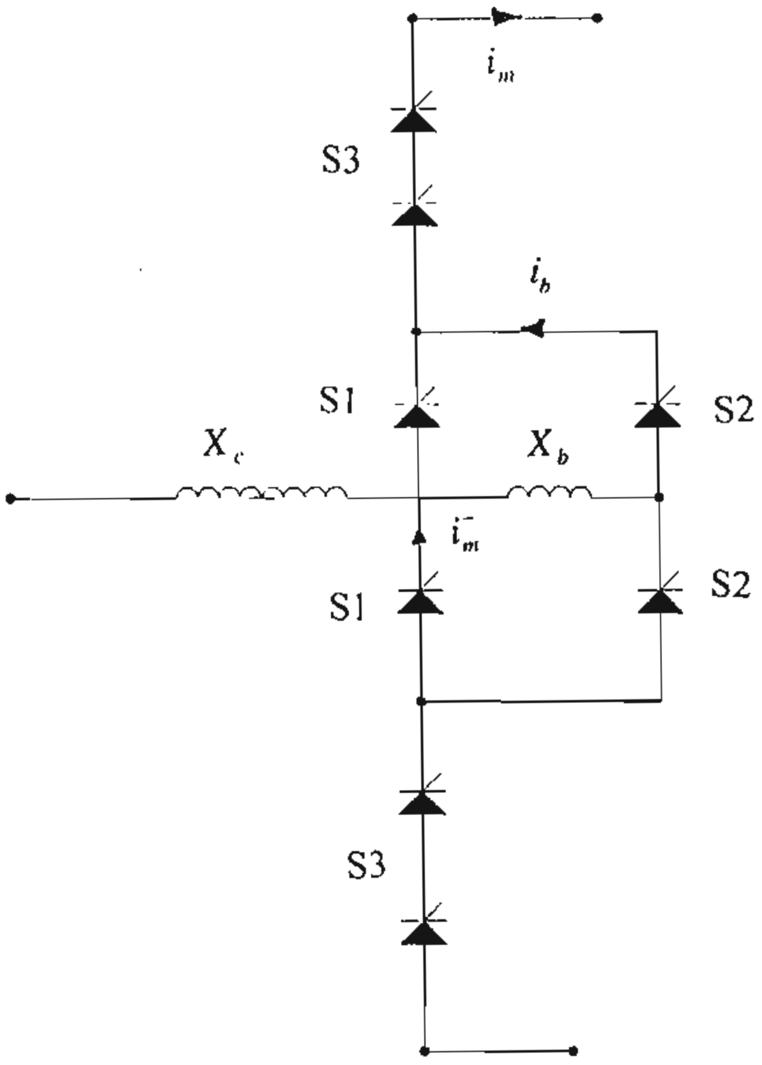


Fig.1 Modified bridge arrangement (one phase shown)
S1 (part of main valve) and S2 (by-pass valve)

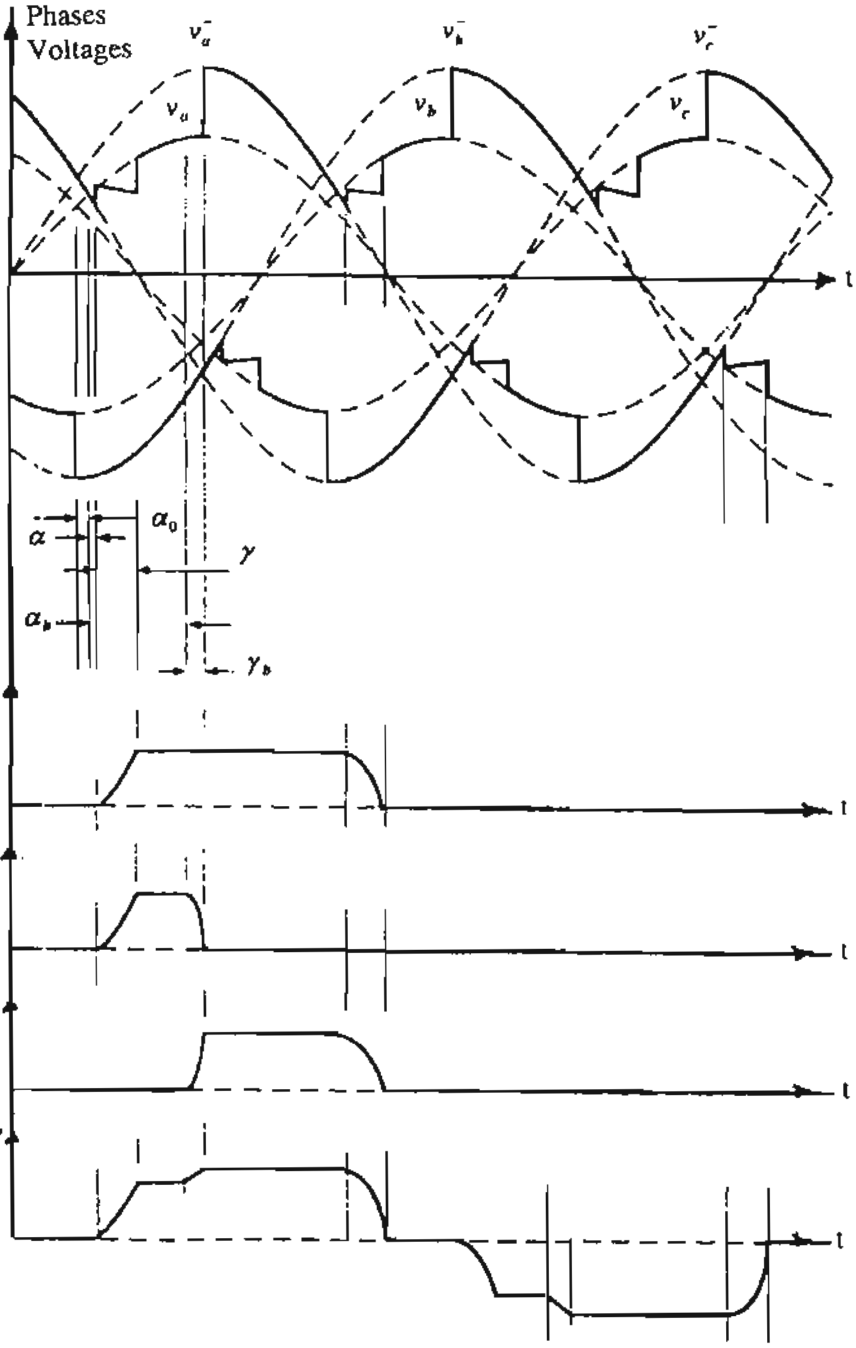


Fig.2 Voltage and current waveforms for rectifier mode

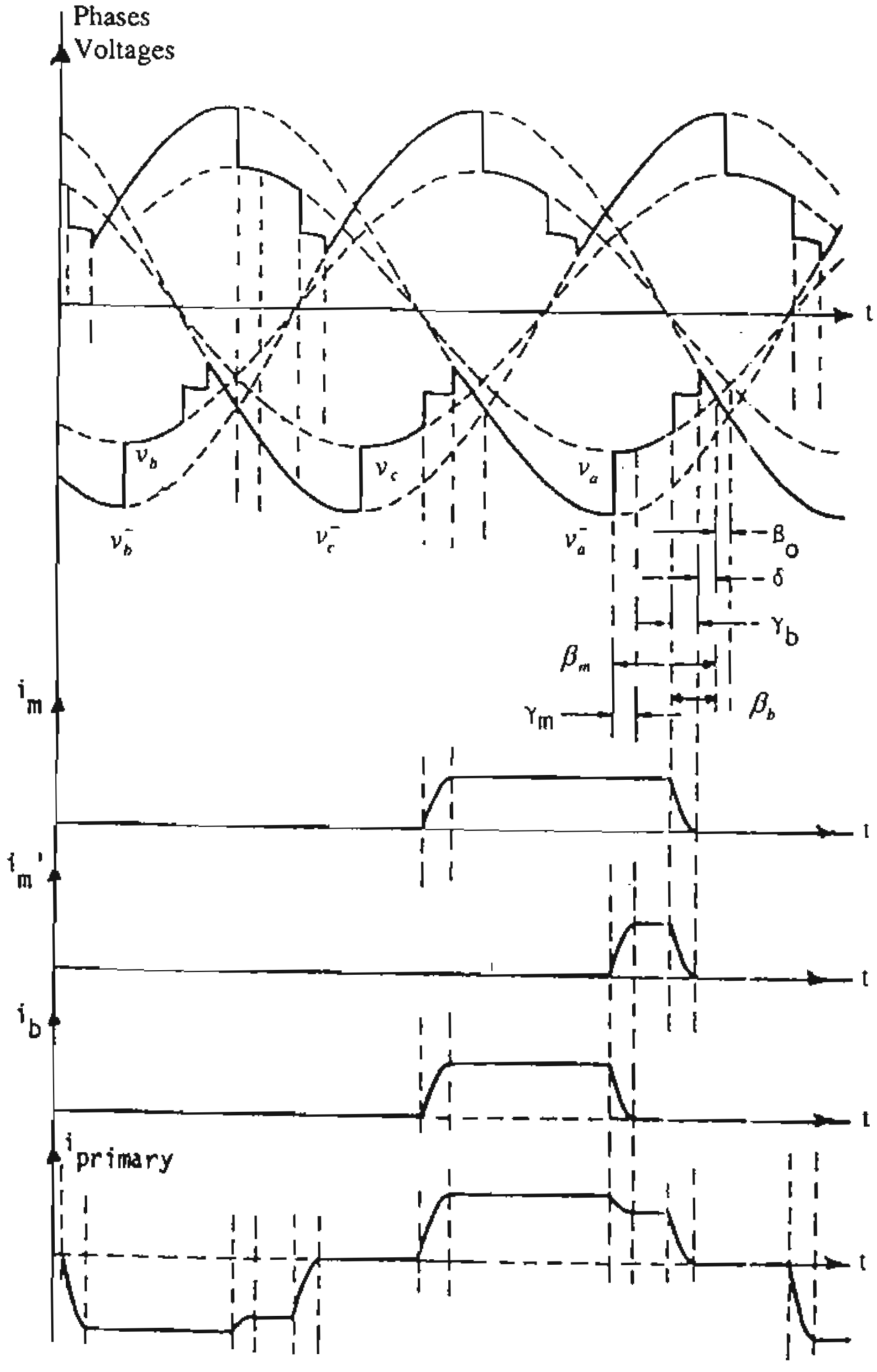


Fig.3 Voltage and current waveforms for inverter mode

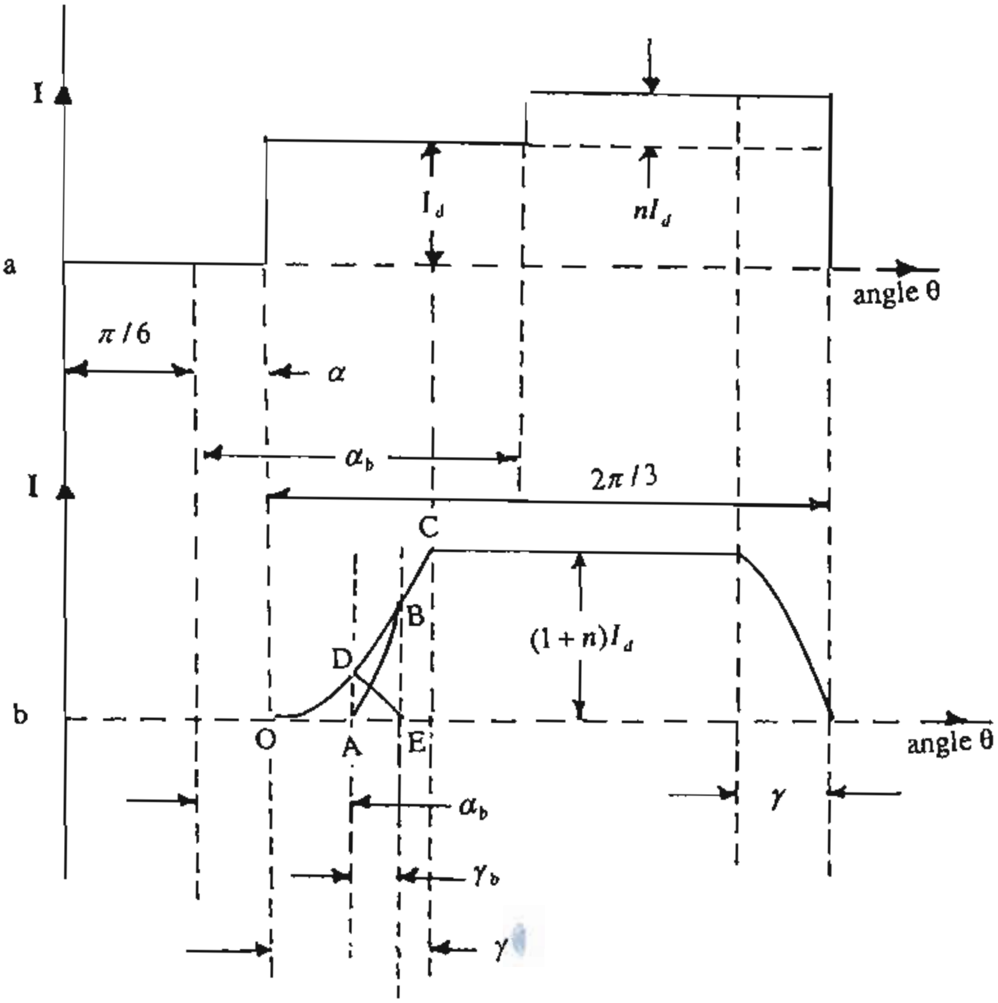


Fig.4 Supply current waveforms (star-star connections)

a- Ideal case

b- Real case

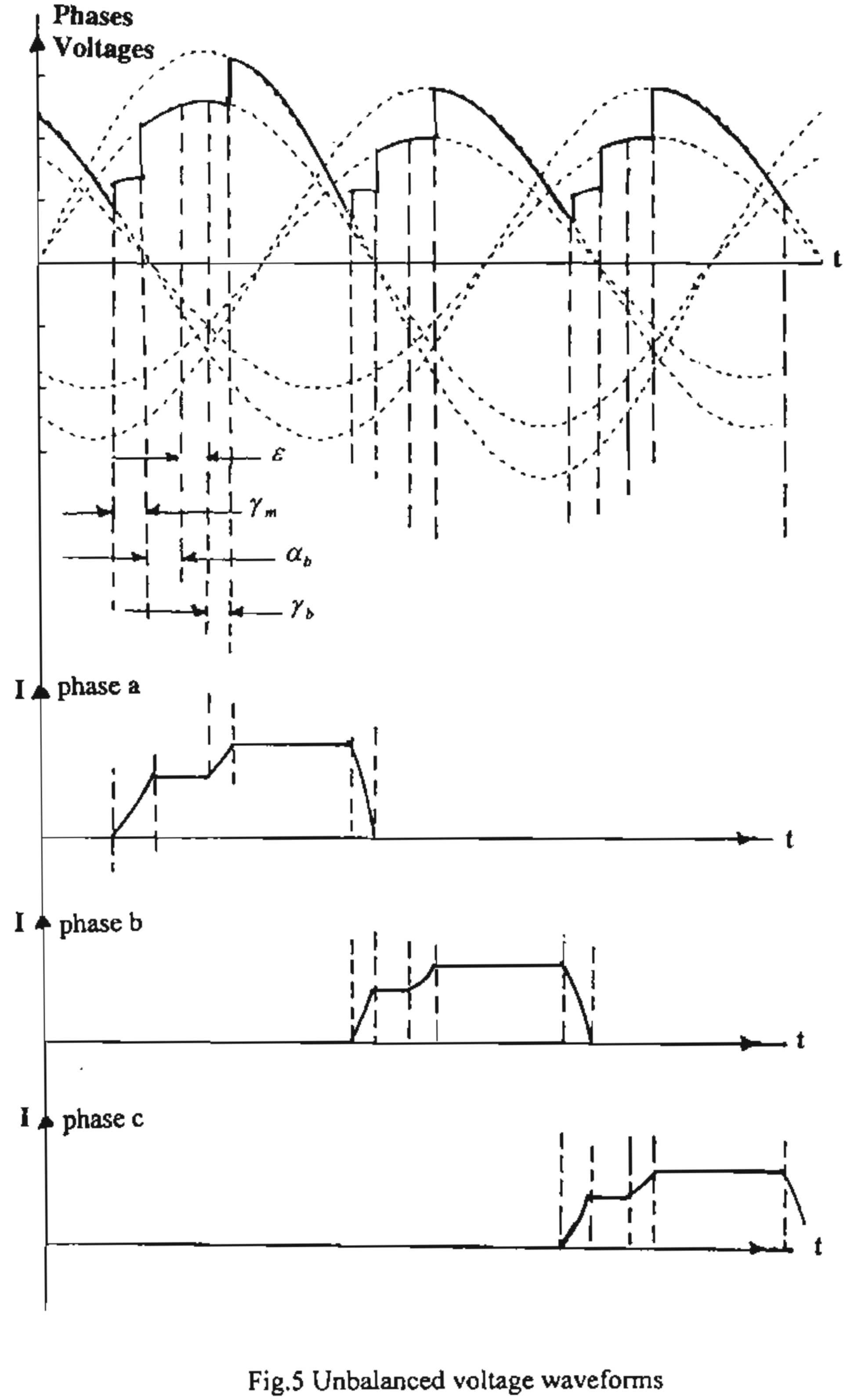


Fig.5 Unbalanced voltage waveforms

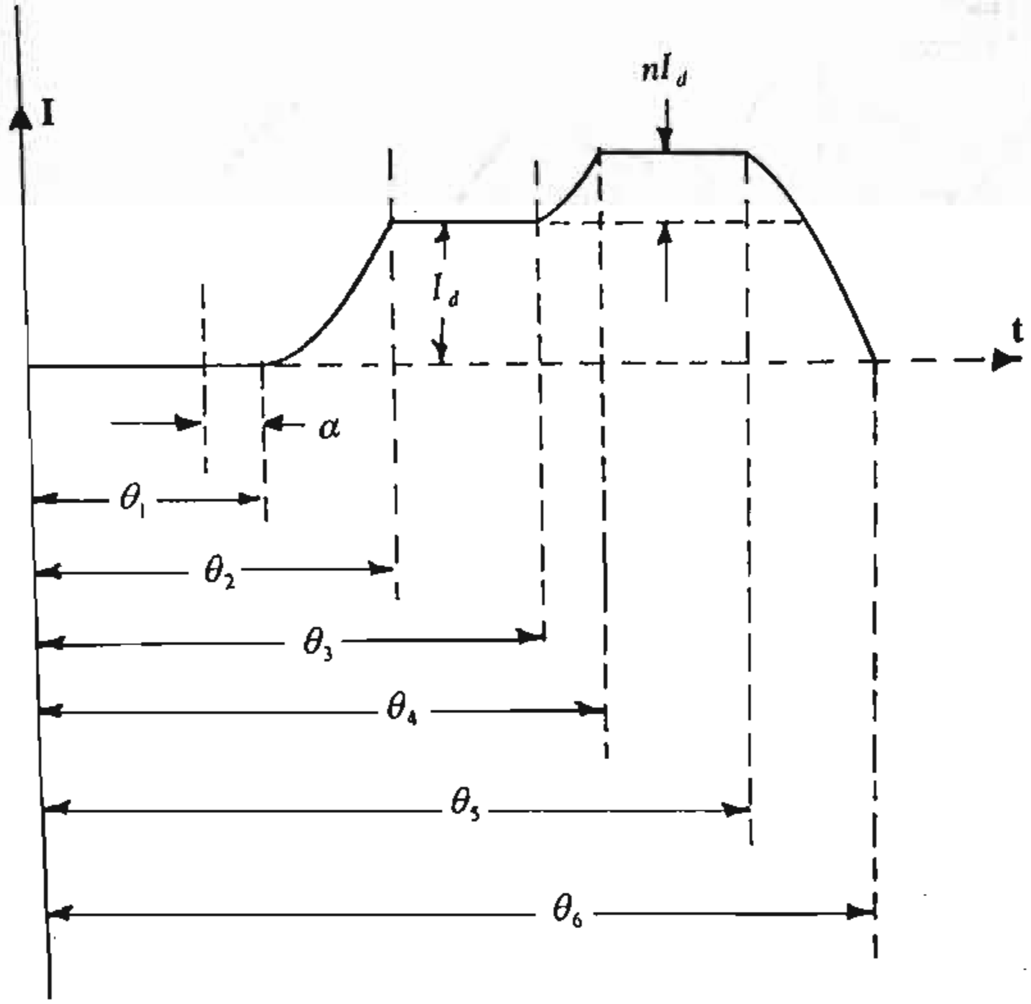
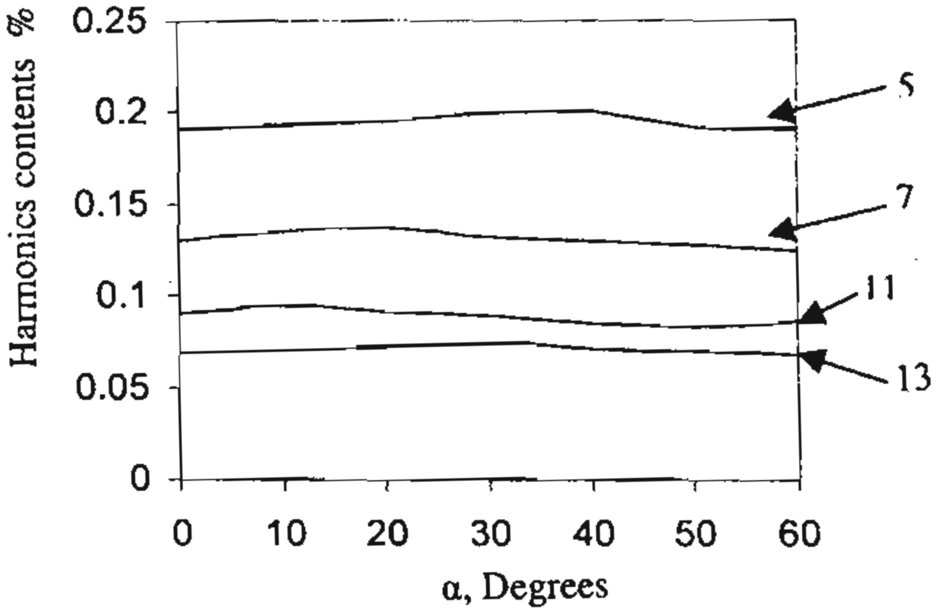
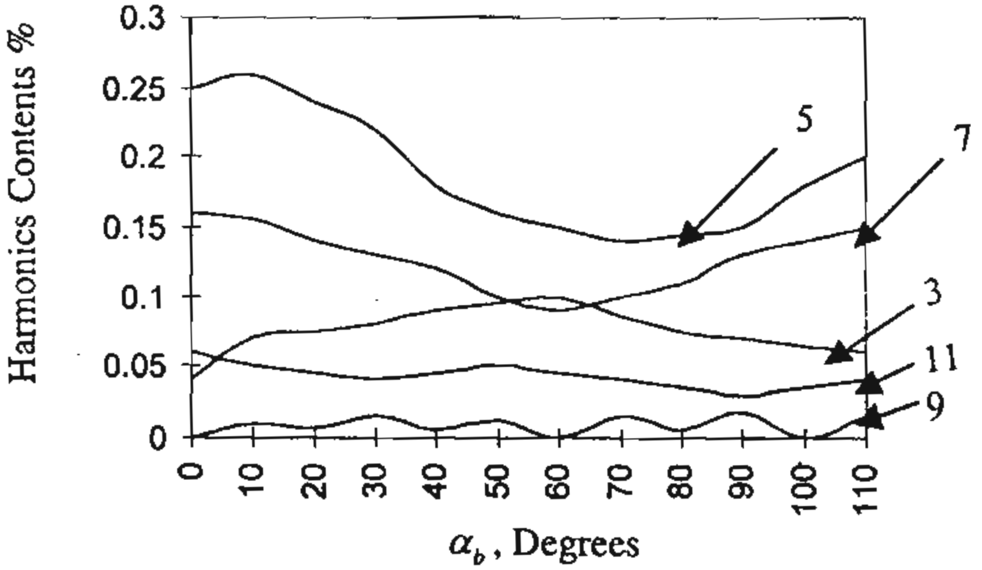


Fig.6 General ac waveforms for one phase



a) Conventional Converter



b) Modified Converter

Fig: 7 Supply current harmonics

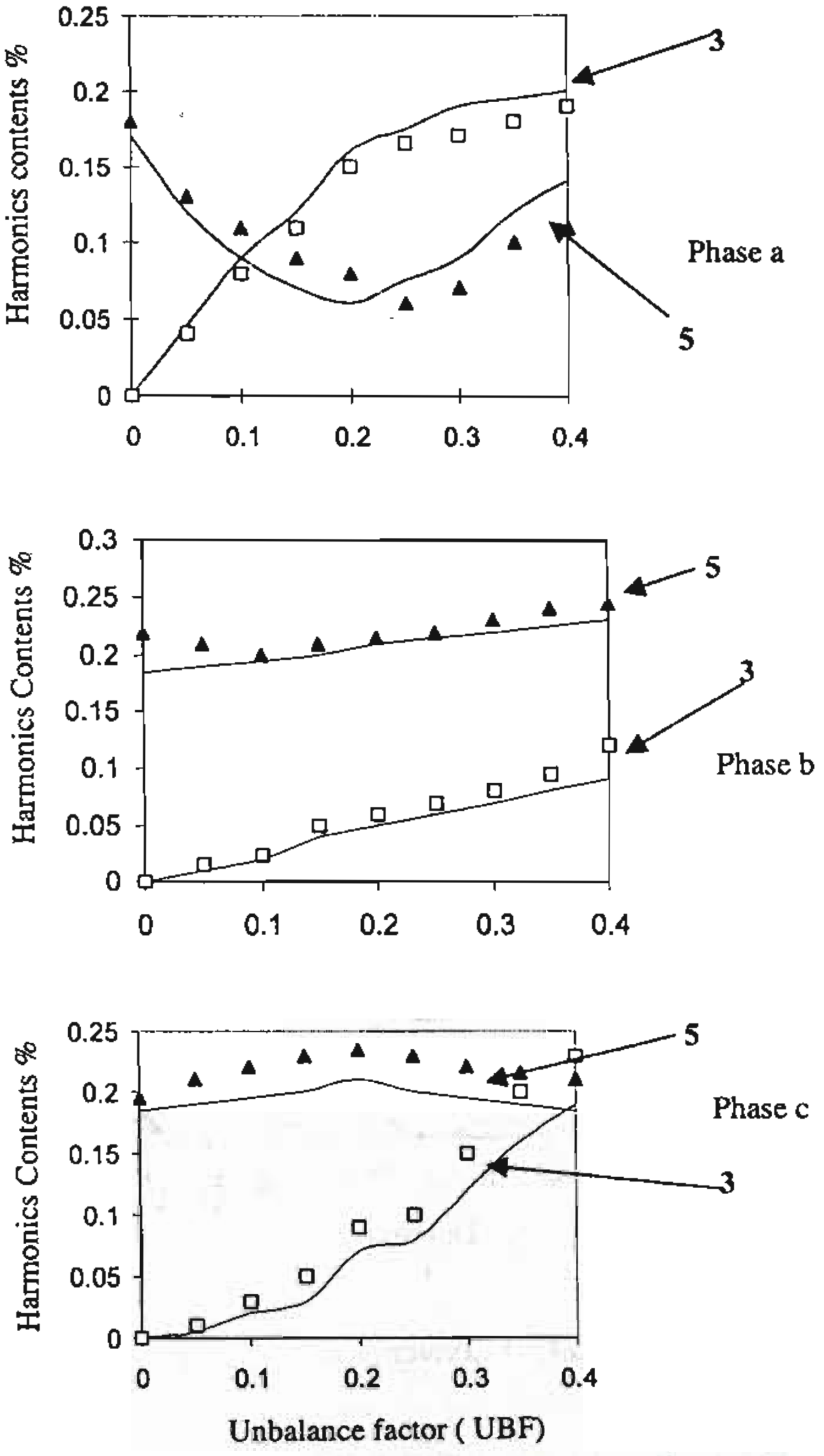


Fig: 8 Supply current harmonics at $\alpha_b = 50°$ and $\varepsilon = 0°$

□ and ▲ Experimental results

______ Computed results

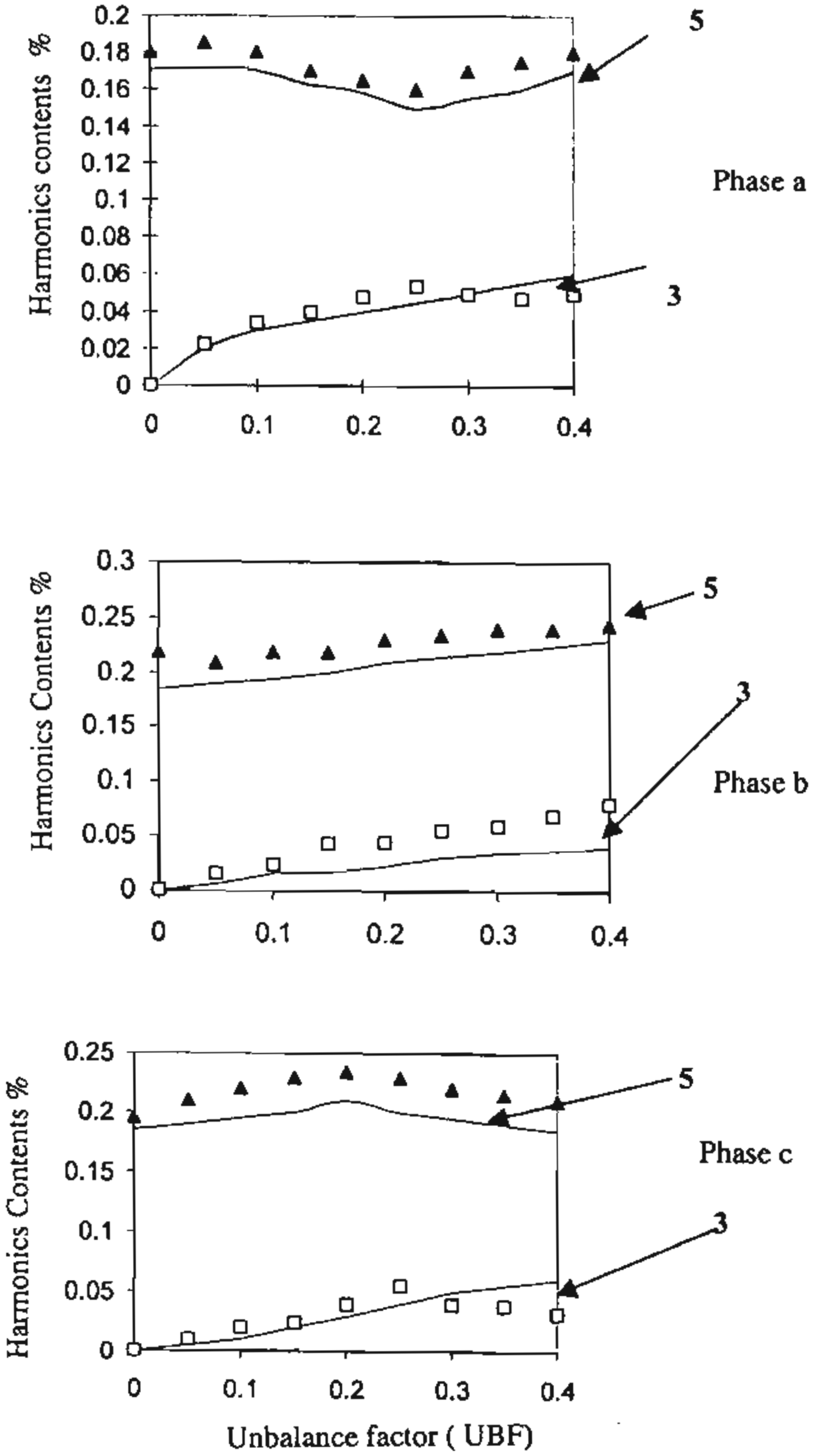


Fig: 9 Supply current harmonics at $\alpha_b = 50°$ and $\varepsilon = 10°$

□ and ▲ Experimental results

——— Computed results

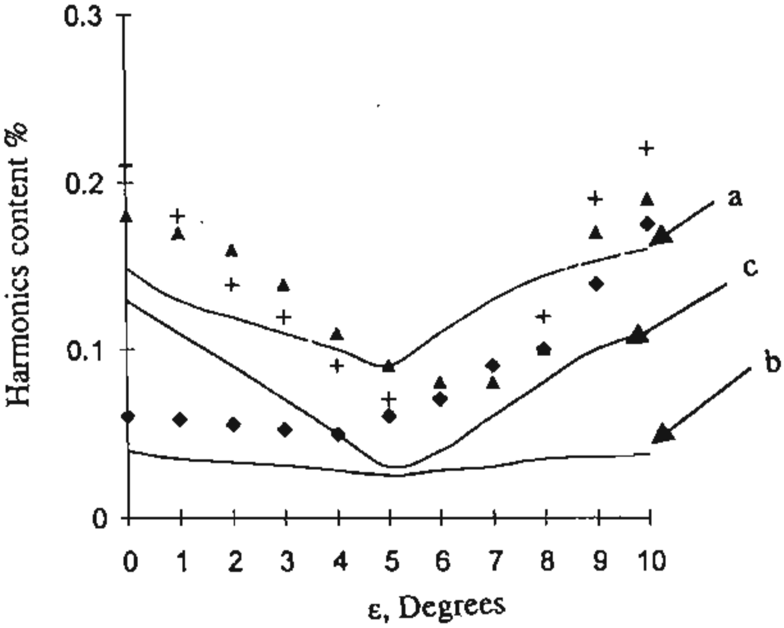


Fig.10 Third harmonic with ε ($\alpha_b = 50°$)
_____ UBF = 0.2
(+--phase a, ■—phase b, ▲—phase c) UBF = 0.3

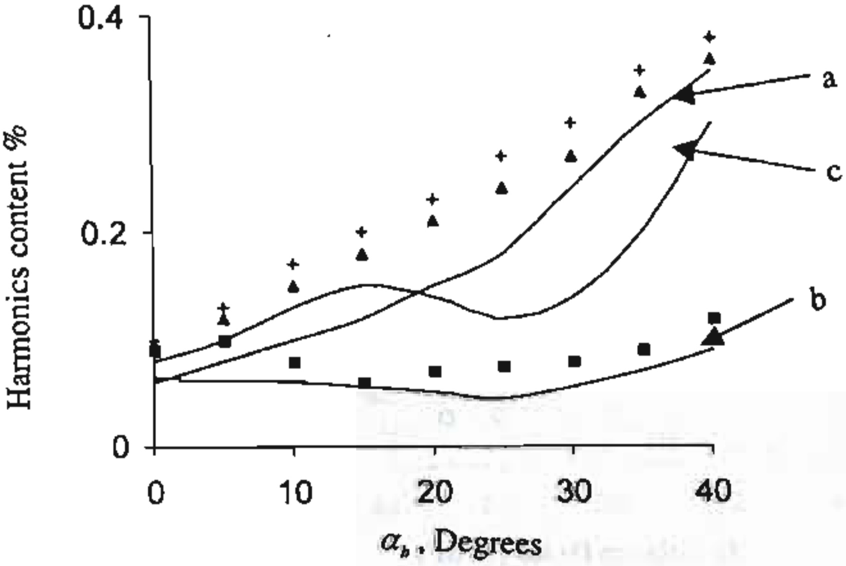


Fig.11 Third harmonic with α_b (UBF = 0.2)
_____ Computed results
(+--phase a, ■—phase b, ▲—phase c) Experimental results