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Control of AC/DC Converter under Unbalanced System Conditions

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Abstract**—** Unbalance in the AC/DC converters produce uncharacteristic current harmonics, in addition to the characteristic harmonics in the AC waveform not expected from the balanced operation. In this paper, a three-phase AC-DC converter is fully analyzed and the performance of the converter under balanced and unbalanced conditions is evaluated. Also, the relationship between the unbalance factor and the resultant harmonics is investigated. The method of reducing uncharacteristic harmonic generation through firing angle modulation is discussed. A digital trigger scheme control circuit for valves with individual control circuit for each device has been designed and built. A digital computer simulation program based on this method is developed; and some experimental results are also given.

Keywords**—** AC/DC converter, firing angle modulation, non-characteristic harmonics.

I. INTRODUCTION

The tremendous advancement in high power semiconductors technology over the last three decades has created a variety of industrial applications. The major problems associated with these loads are the harmonic current injection into power supply and volt-ampere absorption.

The ideal operation of AC/DC converters produces characteristic current harmonics in the associated AC system of the order $kp\pm1$, where p refers to the number of pulses in each cycle and k is any positive integer. Some techniques to simulate and study thyristor controlled converter networks under steady-state operating conditions have been reported in the literature [1]-[5].

In practical systems, perfect conditions for the analysis of characteristic harmonics of a converter are never met; as a result harmonics of uncharacteristic orders can arise. Though they are not explainable by existing theory, they do appear in the AC power system. The possible cause of these non-characteristic harmonics, which result from system imperfections (e.g. imbalance of AC supply voltage, asymmetry in commutation impedances, unequal rating of reactors and firing angle errors), has been studied in several papers [6]-[10]. Many methods of control that are based on symmetrical firing [11, 12], have been proposed to overcome the problem of abnormal operations. These methods, however, cannot totally eliminate uncharacteristic harmonics during unbalanced conditions.

Analysis in this paper presents a study of the operation and control of three-phase thyristor converters under balanced and unbalanced conditions. Two sources of unbalance, namely, commutation impedance and supply voltage unbalance are considered individually.

The Firing angle modulation technique is presented to reduce abnormal harmonics; and a computer program that is based on this method is developed. However, the technique analyzed in this paper only involves the modification of the thyristor gating which requires no changes to the power circuit.

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II. ANALYSIS OF THE BRIDGE CONVERTER

The converter valves configuration under consideration is the 3-phase full-wave controlled bridge shown in Fig. 1 which has star/star connections for alternative winding. Its thyristors are numbered in their normal conducting sequence. The bridge circuit is connected to the three-phases of AC system, where L_a, L_b and L_c are the commutation inductances per phase. A large DC choke L_d is connected in series with the converter on the DC side to keep the load current very smooth and constant. The same bridge can be used for either rectifier or inverter modes of operation by a gradual variation in the firing angle of the controlled bridge. Therefore the analysis of the phase controlled rectifier is the same as that of an inverter. To simplify the analysis, it is assumed that the transformer resistance is negligible.

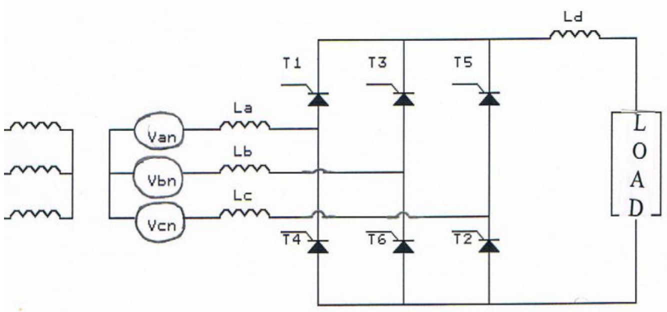


Fig. 1. Three phase bridge

A. Balanced Operation

For the purpose of the simplification of the method used to analyze harmonic power flow, the following assumptions are made during balanced operations:

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

Fig. 2 shows the voltage and current waveforms for balanced operations. There are 12 operation states per cycle in a balanced 6-pulse converter circuit when the commutation angle γ is less than 60°. Table 1 lists these states, along with their corresponding intervals and conducting valves, where α is the delay angle. This is an ideal condition, which assumes equal firing angles of all valves.

The calculation of the spectrum of harmonic current under steady-state conditions is carried out by Fourier analysis. The AC circuit is balanced in this section, so only one phase current is analyzed.

Any periodic waveform can be expressed by Fourier series as:

$$F(\omega t) = a_0 + \sum_{m=1}^{\infty} \left[a_m Cos(m\omega t) + b_m Sin(m\omega t)\right] \tag{1}$$

where a_0 is the DC value of the waveform, which is given by:

$$a_0 = \frac{1}{T}\int_{-T/2}^{T/2} F(t)dt \tag{2}$$

and a_m, b_m are the Fourier coefficients, which are given by:

$$a_m = \frac{2}{T}\int_{-T/2}^{T/2} F(t)\cos(2m\pi t/T)\,dt \tag{3}$$

$$b_m = \frac{2}{T}\int_{-T/2}^{T/2} F(t)\sin(2m\pi t/T)\,dt \tag{4}$$

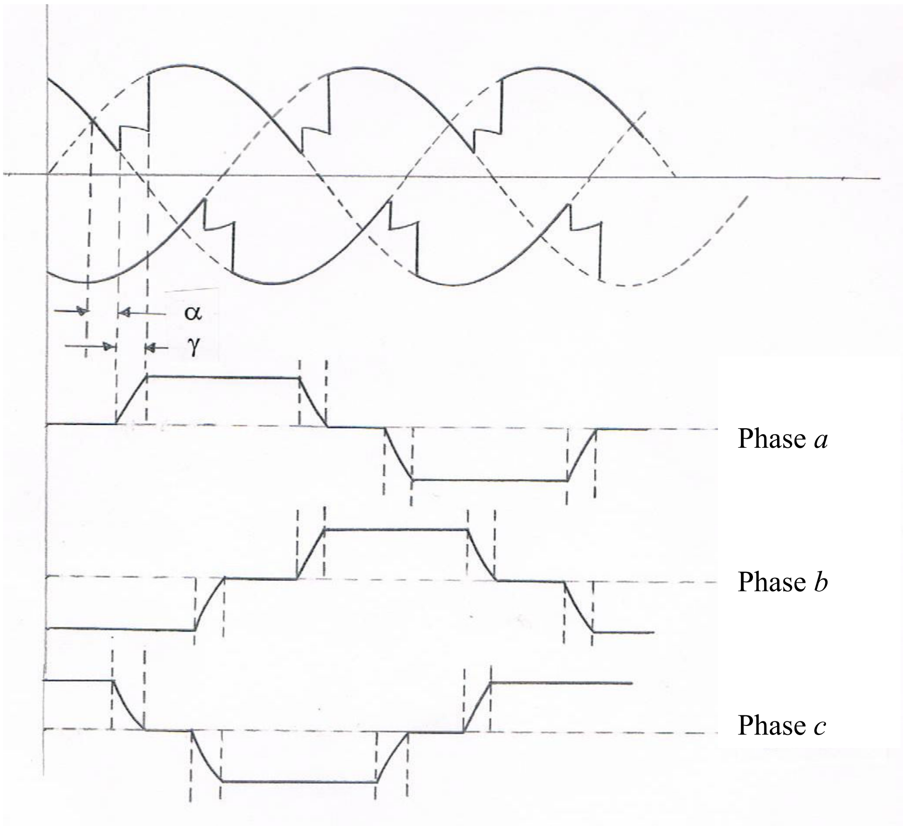


Fig. 2. Voltage and current waveforms for balance operation

A *p*-pulse converter generates characteristic current harmonics of order $m=pn\pm1$, where $n=1$, 2, 3 ... In the case of zero commutation reactance, rectangular AC waveforms are produced as shown in Fig. 3 for phase *a*. AC current harmonics arise of magnitudes which are functions of direct current only, i.e.:

$$I_1 = \frac{\sqrt{6}}{\pi} I_d \tag{5}$$

and

$$I_m = (1/m)\frac{\sqrt{6}}{\pi} I_d \tag{6}$$

TABLE 1
OPERATING STATES OF 6-PULSE BRIDGE RECTIFIER

Valve conducting	Period of conduction	State
5, 6	$\pi/6 \le \omega t \le (\pi/6)+\alpha$	1
5, 6, 1	$\pi/6+\alpha \le \omega t \le (\pi/6)+\alpha+\gamma$	2
6, 1	$(\pi/6)+\alpha+\gamma \le \omega t \le (\pi/2)+\alpha$	3
6, 1, 2	$(\pi/2)+\alpha \le \omega t \le (\pi/2)+\alpha+\gamma$	4
1, 2	$(\pi/2)+\alpha+\gamma \le \omega t \le (5\pi/6)+\alpha$	5
1, 2, 3	$(5\pi/6)+\alpha \le \omega t \le (5\pi/6)+\alpha+\gamma$	6
2, 3	$(5\pi/6)+\alpha+\gamma \le \omega t \le (7\pi/6)+\alpha$	7
2, 3, 4	$(7\pi/6)+\alpha \le \omega t \le (7\pi/6)+\alpha+\gamma$	8
3, 4	$(7\pi/6)+\alpha+\gamma \le \omega t \le (3\pi/2)+\alpha$	9
3, 4, 5	$(3\pi/2)+\alpha \le \omega t \le (3\pi/2)+\alpha+\gamma$	10
4, 5	$(3\pi/2)+\alpha+\gamma \le \omega t \le (11\pi/6)+\alpha$	11
4, 5, 6	$(11\pi/6)+\alpha \le \omega t \le (11\pi/6)+\alpha+\gamma$	12

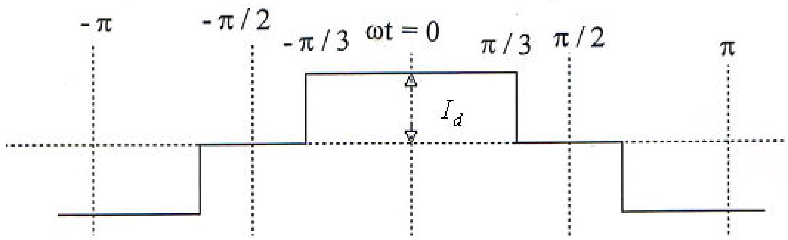


Fig. 3. Idealized phase current waveform on the primary side

The commutation reactance being introduced has the effect of rounding off the current waveforms, thereby modifying the magnitudes, but with the order of harmonics maintained as before [13]. For the conventional three phase full-wave bridge with a commutation angle, each waveform consists of eight sections as shown in Fig. 4. Thus, if i_n is the commutation current for valve n, relative Fourier coefficients for phase a are given as:

$$a_m = \int_{\alpha}^{\alpha+\gamma} i_1 \cos m\omega t d\omega t + \int_{\alpha+\gamma}^{\alpha+2\pi/3} I_d \cos m\omega t d\omega t + \int_{\alpha+2\pi/3}^{\alpha+2\pi/3+\gamma} (I_d - i_3)\cos m\omega t d\omega t$$
$$+ \int_{\alpha+\pi}^{\alpha+\pi+\gamma} -i_4 \cos m\omega t d\omega t + \int_{\alpha+\pi+\gamma}^{\alpha+5\pi/3} -I_d \cos m\omega t d\omega t$$
$$+ \int_{\alpha+5\pi/3}^{\alpha+5\pi/3+\gamma} (-I_d + i_6)\cos m\omega t d\omega t$$

$$b_m = \int_{\alpha}^{\alpha+\gamma} i_1 \sin m\omega t d\omega t + \int_{\alpha+\gamma}^{\alpha+2\pi/3} I_d \sin m\omega t d\omega t + \int_{\alpha+2\pi/3}^{\alpha+2\pi/3+\gamma} (I_d - i_3)\sin m\omega t d\omega t$$
$$+ \int_{\alpha+\pi}^{\alpha+\pi+\gamma} -i_4 \sin m\omega t d\omega t + \int_{\alpha+\pi+\gamma}^{\alpha+5\pi/3} -I_d \sin m\omega t d\omega t$$
$$+ \int_{\alpha+5\pi/3}^{\alpha+5\pi/3+\gamma} (-I_d + i_6)\sin m\omega t d\omega t$$

$$\frac{I_m}{I_1} = \frac{1}{\mathrm{m}[\cos\alpha - \cos(\alpha+\gamma)]}\left[\frac{\sin^2(m-1)\frac{\gamma}{2}}{\mathrm{m-1}} + \frac{\sin^2(m+1)\frac{\gamma}{2}}{\mathrm{m+1}} - 2\frac{\sin(\mathrm{m-1})\frac{\gamma}{2}}{\mathrm{m-1}}\frac{\sin(m+1)\frac{\gamma}{2}}{\mathrm{m+1}}\cos(2\alpha+\gamma)\right]^{\frac{1}{2}} \tag{7}$$

where I_1 is the magnitude of fundamental component, I_m is the magnitude of m order harmonic, a_0 is the DC value of the waveform, m is the harmonic order number.

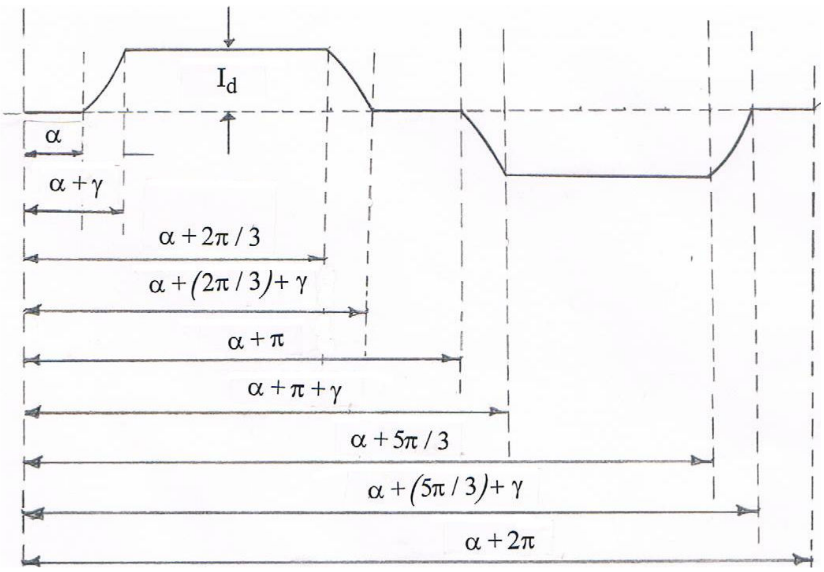


Fig. 4. Phase current with the commutation angle

Some of the basic converter equations that have been derived by others [14, 15], are to be used in this paper. As listed, these equations are valid only for a single bridge converter:

$$v_d = \frac{3\sqrt{2}}{\pi}v\left[\frac{\cos\alpha + \cos(\alpha+\gamma)}{2}\right] \tag{8}$$

or

$$v_d = \frac{3\sqrt{2}v}{\pi}\cos\alpha - \frac{3\mathrm{x_c}}{\pi}I_d \tag{9}$$

and

$$I_d = \frac{\sqrt{2}v}{2\mathrm{x_c}}[\cos\alpha - \cos(\alpha+\gamma)] \tag{10}$$

where v_d is DC voltage, I_d is the direct current, v is RMS value of AC line voltage, α is the delay angle, γ is the overlap angle during commutation.

B. Unbalanced Operation

As shown in the above section, the study of characteristic harmonics assumes a perfectly balanced operation of the conversion equipment. In practice, however, these assumptions are never met. Imbalance of the fundamental component of AC bus voltages both in magnitude and phase as well as imbalance in the angle of overlap arising from the imbalance in the leakage reactance of the converter transformer windings are studied in this section.

It is assumed that phase voltages are v_{an}, v_{bn} and v_{cn}, so that any set of unbalanced AC phase voltages can now be analyzed into symmetrical components of zero, positive, and negative sequences according to the following well known relations [16]:

$$v_0 = 1/3(v_{an} + v_{bn} + v_{cn}) \tag{11}$$

$$v_1 = 1/3(v_{an} + av_{bn} + a^2v_{cn}) \tag{12}$$

$$v_2 = 1/3(v_{an} + a^2v_{bn} + av_{cn}).. \tag{13}$$

Where a is $1\angle 120°$. The zero-sequences are not allowed to circulate from the AC system into the AC terminals of the converters because the winding neutrals of the converter transformers are not ground-connected; so, there is no path for the zero-sequence current in the converter.

To practically achieve an unbalanced supply voltage, an extra three-phase voltage is 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 Variac. The secondary side is connected to the primary side of the converter transformer, as shown in Fig. 5.

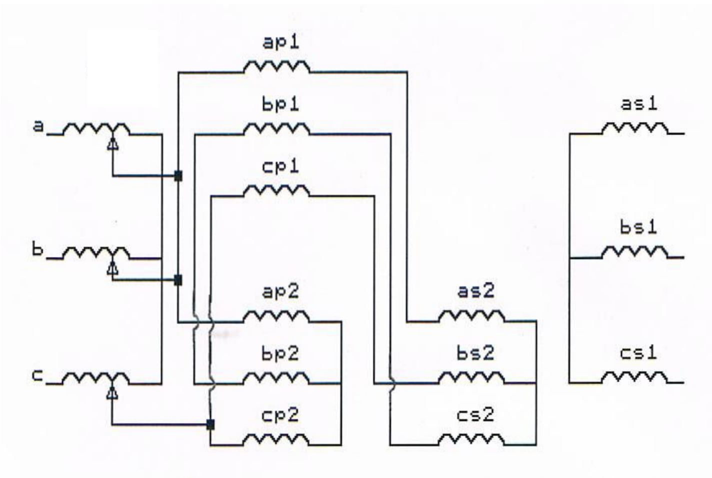


Fig. 5. Transformer arrangement for the unbalanced operation

The voltage waveform on the primary side is shown in Fig. 6. It is assumed that all firing angles remain equal for each valve with respect to the symmetrical zero voltage reference point.

As a result of an unbalance, the magnitudes and phase angles of the line-to-line voltages will be altered. It should be noted that the changes in the phase position of line-to-line voltages are responsible for the instants of commutation; hence, they are also responsible for the phase and magnitude of the alternating currents. An application of the well known analysis to the case of a three-phase voltage source and the case of the terminologies shown in Fig. 6 leads to the following expressions [17]:

$$\gamma_{13} = \cos^{-1}\left(\cos\alpha_{13} - \frac{2x_{ab}}{v_{m(ab)}} I_d\right) - \alpha_{13} \tag{14}$$

$$\gamma_{35} = \cos^{-1}\left(\cos\alpha_{35} - \frac{2x_{bc}}{v_{m(bc)}} I_d\right) - \alpha_{35} \tag{15}$$

$$\gamma_{51} = \cos^{-1}\left(\cos\alpha_{51} - \frac{2x_{ca}}{v_{m(ca)}} I_d\right) - \alpha_{51} \tag{16}$$

where

$$\alpha_{13} = \alpha_{51} + 2\pi / 3 \pm \Delta\alpha \tag{17}$$

$$\alpha_{35} = \alpha_{13} + 2\pi / 3 \pm \Delta\alpha \tag{18}$$

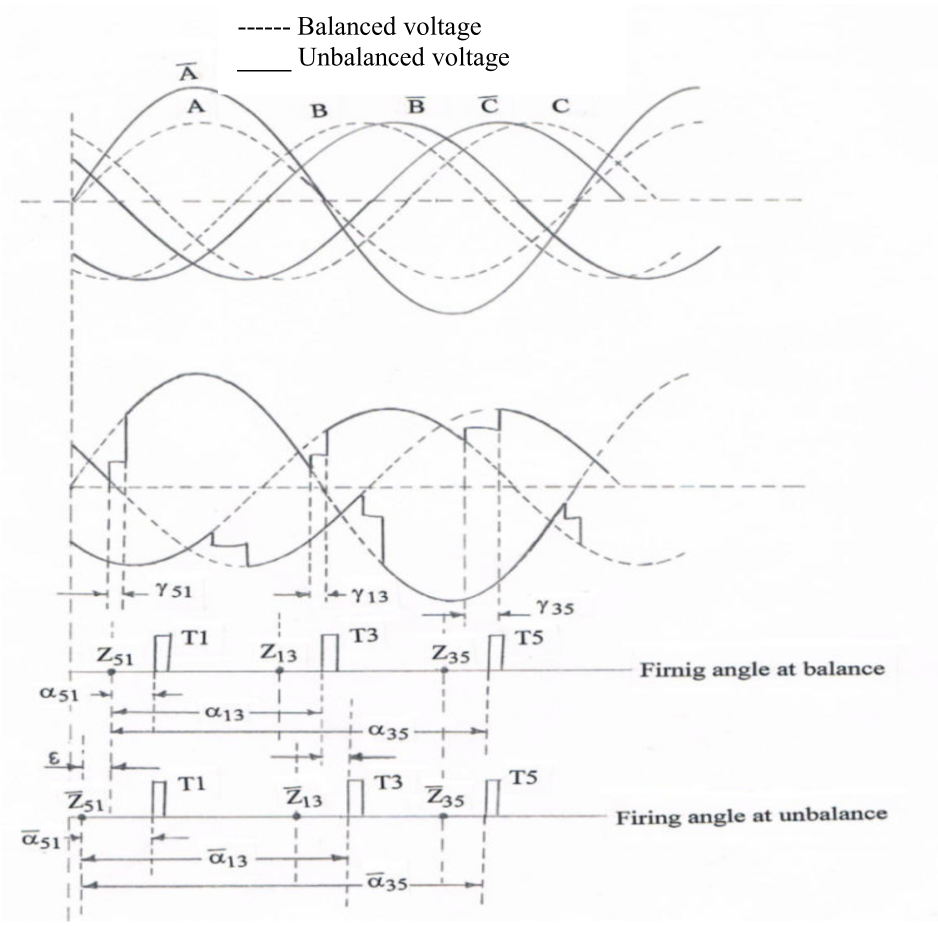


Fig. 6. Voltage waveforms and firing angles at balanced and unbalanced voltages

In general, the overlap angles between valves on the same side of the bridge unit are different, i.e. $\gamma_{13} \neq \gamma_{35} \neq \gamma_{51}$, but the commutation between the same phases in the upper and lower halves of the bridge are equal, i.e. $\gamma_{13} = \gamma_{45}$, $\gamma_{35} = \gamma_{62}$ and $\gamma_{51} = \gamma_{24}$.
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 a reference-phasor. In this way, any degree of unbalance as defined by v_1/v_2 is directly given by the negative-sequence voltage.

III. CONTROL CIRCUIT

In a controlled rectifier, the DC output voltage and the commutation angle depend on the firing angle, which in turn depends on the instant at which the gate trigger pulse appears. There are several techniques for controlling a converter firing angle: analog comparators, digital counters, phase-locked loops, etc. [17].
A firing angle controller has been designed and built with a very simplified control strategy; the firing delay angle is calculated with respect to a zero-crossing point of the input voltage waveform across the individual thyristor valve. The propagation delay of the signal is very small; thus, an accuracy of 0.05° in the firing angle value is realized. To ensure that the thyristor conducts successfully in the shortest time when triggered, it is desirable to have a current pulse, which is much higher than the minimum required for turn-on applied to its gate. In order to keep the thyristor conducting continuously, the on-state current must be positive and larger than the minimum on-state current level (latching current) for the thyristor.
All thyristors are fed with a common firing delay signal. To achieve adjustable firing delay angles and allow the converter to be operated under unbalanced firing delay angles, an individual control circuit for each device has been used. A phase-locked loop (PLL) technique has been used to produce symmetrical or equidistant spacing of firing pulses and reduce the possibility of harmonic instability and abnormal harmonics in the supply current, which is generating 7200 pulses/cycle for the switching-angle setting clock, giving an adjustment in steps of 2.7μs, i.e. 0.05° at 50Hz.
Fig. 7 shows the block diagram for the control circuit which is composed of three basic sections, namely zero crossing-detector, phase-locked loop and central processing unit. The output pulse of each zero-crossing detector and the clock pulses, which are coming from the PLL at 360KHz, are connected to the twelve-bit counter. When the thyristor becomes forward-biased, the output register of the counters begins to increase from zero at the rate of 0.05°. The output of the counter is connected into one of the inputs of a comparator. The other input comes from the output of the adder which is used to add the firing delay angle α and the firing delay error angle $\Delta\alpha$. The output pulse of the comparator takes place when the sum of α and $\Delta\alpha$ is equal to the counter output. This pulse is fed to a monostable whose output remains 6.7ms corresponding to 120°. Then, the pulse is fed to a buffer circuit, which is necessary to make the pulse strong enough to trigger the thyristor.

IV. RESULTS AND DISCUSSION

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 UBF together with computed values for each phase as shown in Figs. 8, 9 and 10 at different values of $\Delta\alpha$. In addition to the characteristic harmonics, even and odd harmonics are generated to enter the lines. Even harmonics in this case are of lower magnitude. Also, lines have a DC component, which may cause transformer saturation. Uncharacteristic harmonics are always present in practice until unbalance is introduced. The triple harmonic content increases when the unbalance factor increases.

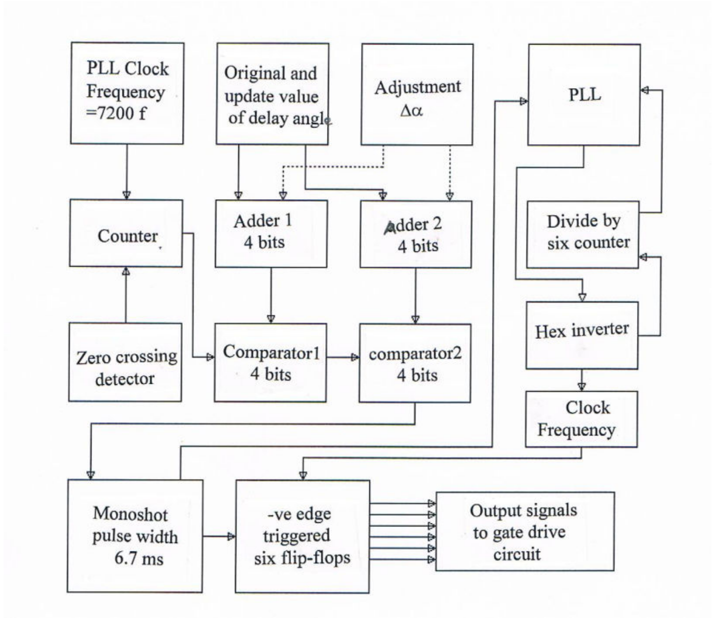


Fig. 7. Block diagram of control circuit

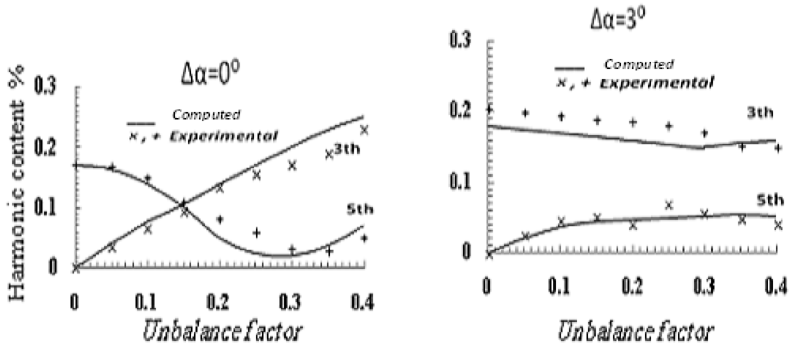


Fig. 8. Supply current harmonics for phase *a* at α=20°

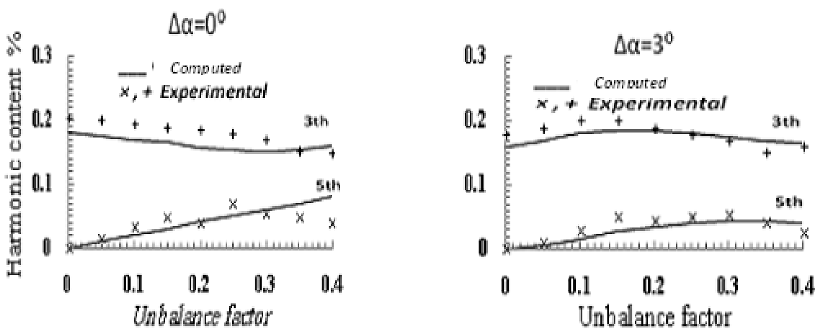


Fig. 9. Supply current harmonics for phase *b* at α=20°

A comparison of results between the modified operation and conventional operation indicates that there is a reduction in the uncharacteristic harmonic. For conventional operation at α=20°

and UBF=0.2, the ratio of the 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 20% for phases *b* and *c*. For modified firing angle by Δα=3°, 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.

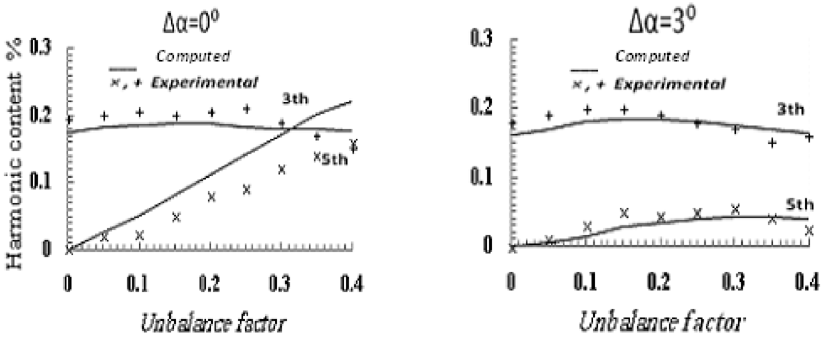


Fig. 10. Supply current harmonics for phase *c* at α=20°

Fig. 11 shows the third harmonic against the change of firing angle $\Delta\alpha$ at α=20° for UBF=0.2 and 0.3. It can clearly be seen that the third harmonic increases when the unbalance factor increases. Fig. 12 demonstrates that the uncharacteristic 3rd harmonic content varies with converter firing delay angle. A spectrum of harmonic currents for each phase at different operation cases is shown in Fig. 13, 14 and 15.

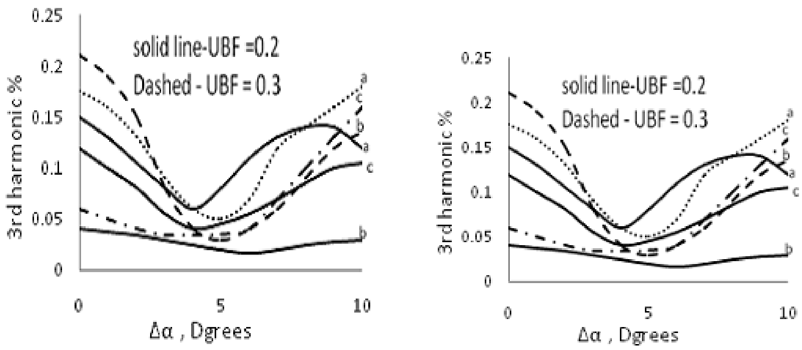


Fig. 11. Third harmonic with $\Delta\alpha$ at α=20°

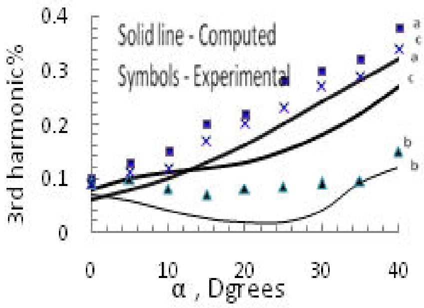
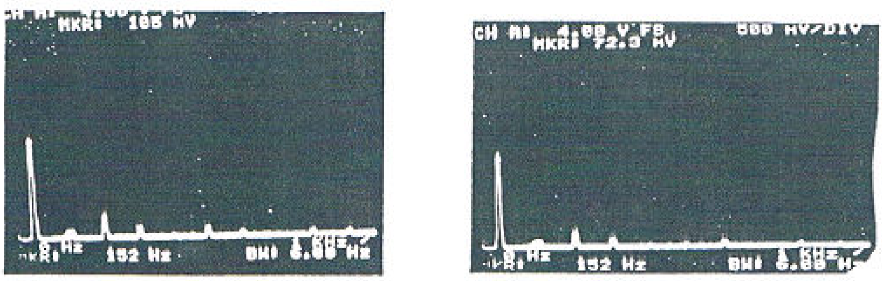


Fig. 12. Third harmonic with delay angle at UBF=0.2



$\Delta\alpha = 0°$ $\Delta\alpha = 3°$

Fig. 13. Spectra supply current harmonics for phase *a* at α=20° and UBF=0.3

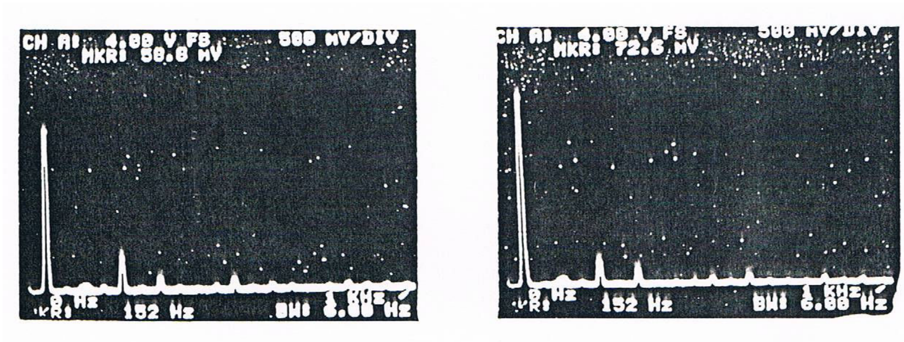


Fig. 14. Spectra supply current harmonics for phase *b* at α=20° and UBF=0.3

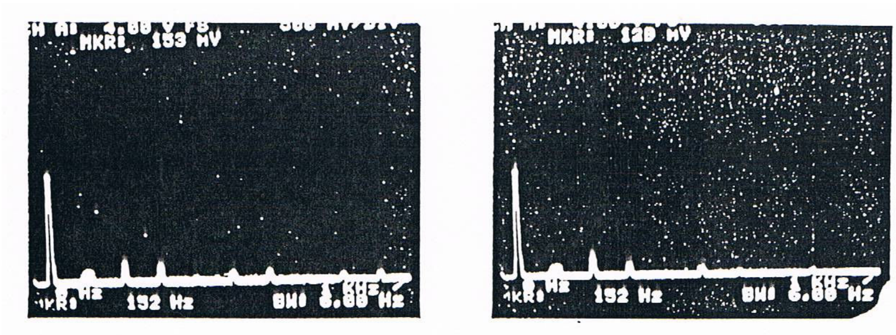


Fig. 15. Spectra supply current harmonics for phase *c* at α=20° and UBF=0.3

V. CONCLUSIONS

This paper addresses the problem of uncharacteristic harmonics generated in the input current for a six pulse phase controlled bridge and proposes a technique of minimizing them based on the modulation of the 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 unbalanced input voltages. Triple 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 the truncated Fourier series of all line currents in balanced and unbalanced operations. A digital control circuit is designed and built with high resolution by using a phase-locked loop technique to avoid the effect of frequency deviation. The accuracy of the control circuit was 0.05° at 50Hz. All valves are fed with a common firing delay angle that is individually controlled by $\Delta\alpha$=±20°. Fast and continuous control can be possible using this circuit.

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