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MILITARY TECHNICAL COLLEGE

CAIRO - EGYPT

DIGITAL CONTROL CIRCUIT DESIGN OF PWM INVERTERS

By

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ABSTRACT

In this paper, the hardware and the software design and also the realization of a PWM transistor inverter control circuit are given. A mathematical analysis for computing the switching angles is performed for both a single-phase and a three-phase inverters. The pre-calculated switching patterns which eliminate low order harmonics of the inverter output are stored in the EPROM. A simple digital control circuit associated with an EPROM is used to generate the control signals for the switching transistors of the inverter. The description of the designed digital control circuit for single - and three-phase inverter are included. Output waveforms for the designed circuit and the PWM inverter circuits are presented.

INTRODUCTION

Pulse Width Modulation (PWM) inverters are widely used in industrial motor drives and in Uninterrupted Power Supply (UPS) systems. The PWM technique offers control of voltage, frequency, and harmonics in only one power stage [1]. For the sake of reducing the harmonic contents, early methods [2] were confined to the generation of PWM patterns using a triangular carrier and multilevel sinusoidal reference signal. By the use of the conventional techniques and analog circuitry, the total harmonic contents of the output voltage can be reduced at the cost of great control complexity. Using of memories and microprocessors in the controllers of PWM inverters make possible the implementation of the digital techniques where a predetermined number of unwanted harmonics can be cancelled or the total harmonic contents can be reduced. In the digital modulation techniques, the conditions on the inverter output voltage constrain the switching angles by means of numerical algorithms [3]. Moreover, the solution has to be found whenever a new first harmonic has to be commanded. In this paper a simple method for calculation of switching angles for some levels of first harmonic is introduced. The calculated switching patterns are stored in an EPROM. The output waveforms

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produced on PWM inverter are controlled by proper choice of the switching patterns. This paper also includes a brief description of the designed control circuits. These control circuits generate the switching signals which control a PWM inverter output voltage.

PWM STRATEGIES

A typical waveform at the output of a PWM inverter is shown in Fig.1. It exhibits quarter-wave and half-wave symmetry, M switching angles per quarter cycle, and is normalized to a peak amplitude equal to the unity. The amplitude of the nth harmonic is given by [4]:

$$a_n = \frac{4}{n\pi}\left[1 + 2\sum_{k=1}^{M}(-1)^k \cos(n\,\alpha_k)\right] \qquad (1)$$

The fundamental of this waveform is given by:

$$a_1 = \frac{4}{\pi}\left[1 + 2\sum_{k=1}^{M}(-1)^k \cos\,\alpha_k\right] \qquad (2)$$

$\alpha_1, \alpha_2, \alpha_3 \ldots \alpha_k$ define the switching angles.

$$0 \le \alpha_1 \le \alpha_2 \le \ldots \le \alpha_M \le \pi/2 \qquad (3)$$

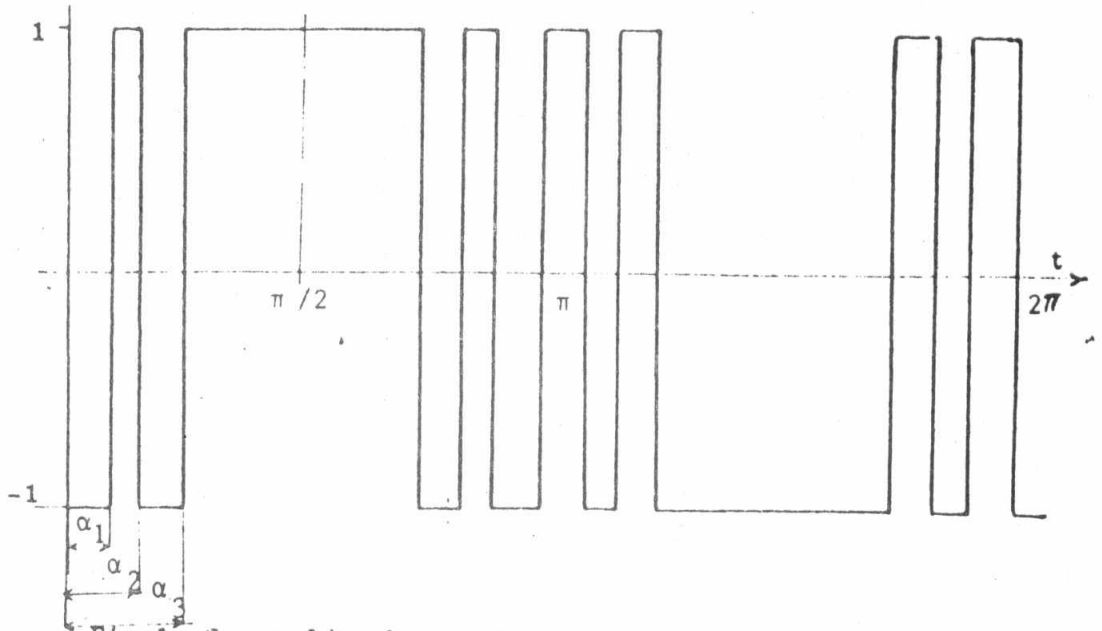


Fig.1. Generalized output waveform of a PWM inverter .

The control of the inverter output voltage is possible if a single degree of freedom is introduced. Thus to eliminate the (M-1) harmonics and at the same time control the fundamental component, M variables are needed. With the degree of freedom introduced, it is possible to vary the output voltage from maximum value to zero continuously, eliminating the (M-1) harmonics [3,4]. The design procedure for the calculation of the switching angles $\alpha_1, \alpha_2 \ldots \alpha_M$ is usually based upon a set of M equations, the first of which determines the amplitude of the fundamental voltage and the rest of the equations are devoted to the realization of the required optimization criteria such as the elimination of M-1 predefined harmonics. The appropriate commutation angles are calculated by the following equations [5]:

$$a_1 = \frac{4}{\pi}(1 - 2\cos\alpha_1 + 2\cos\alpha_2 - 2\cos\alpha_3 \ldots + (-1)^M 2\cos\alpha_M)$$

$$0 = \frac{4}{3\pi}(1 - 2\cos 3\alpha_1 + 2\cos 3\alpha_2 - 2\cos 3\alpha_3 \ldots + (-1)^M 2\cos 3\alpha_M)$$

$$0 = \frac{4}{5\pi}(1 - 2\cos 5\alpha_1 + 2\cos 5\alpha_2 - 2\cos 5\alpha_3 \ldots + (-1)^M 2\cos 5\alpha_M)$$

$$0 = \frac{4}{k\pi}(1 - 2\cos k\alpha_1 + 2\cos k\alpha_2 - 2\cos k\alpha_3 \ldots + (-1)^M 2\cos k\alpha_M) \qquad (4)$$

SOFTWARE DESIGN CONSIDERATION

Single-Phase Inverter

The purpose of the proposed method is to minimize or to eleminate the 3rd and the 5th harmonics at certain levels of the first harmonic a_1. This level can be changed as follows:

$$a_1 = 0.1\ I \times \frac{4}{\pi} \qquad (5)$$

where:

$\frac{4}{\pi}$ ... represents the value of the maximum fundamental.

I ... controls the number of the switching patterns and takes the values from 0 to 10 (in this case we choose I = 0, 1, 2, ... 10).

The appopriate commutation angles are calculated by using the following minimization formula for the third and the fifth harmonics:

$$M\ I = \frac{1}{9}[1 + 2(-\cos 3\alpha_1 + \cos 3\alpha_2 - \cos 3\alpha_3)]^2 + \frac{1}{25}[1 + 2(-\cos 5\alpha_1 + \cos 5\alpha_2 - \cos 5\alpha_3)]^2 \qquad (6)$$

And from Equation (2) we have the fundamental a_1:

$$a_1 = \frac{4}{\pi}\left[1 - 2\left(\cos \alpha_1 - \cos \alpha_2 + \cos \alpha_3\right)\right] \quad (7)$$

From Equations (5) and (7)

$$\cos \alpha_3 = \cos \alpha_2 - \cos \alpha_1 - 0.5(-1+0.1\ I) = B \quad (8)$$

Referring to the previous published work [1,3] it is noticed that α_1 takes a value from 0.1° to 30°. So to simplify the solution we assumed that α_1 changes from 0.1° to 30° with step 0.05°. Using Equations (6) and (8) the switching patterns are obtained. The calculated switching angles for single-phase inverter are plotted in Fig.2 . The Flow Chart describing the solution is shown in Fig.3.

Three-Phase Inverter

In this case the triplen harmonics are zero. So, the purpose is to cancel the 5th and 7th harmonics. The minimization formula will be as follows:

$$MI = \frac{1}{25}\left[1 + 2\left(-\cos 5\alpha_2 + \cos 5\alpha_2 - \cos 5\alpha_3\right)\right]^2 + \frac{1}{49}\left[1 + 2\left(-\cos 7\alpha_1 + \cos 7\alpha_2 - \cos 7\alpha_3\right)\right]^2 \quad (9)$$

By using the same procedure stated before in single-phase case the switching patterns for the 3-phase inverter case are calculated. The calculated switching angles are plotted in Fig.2.

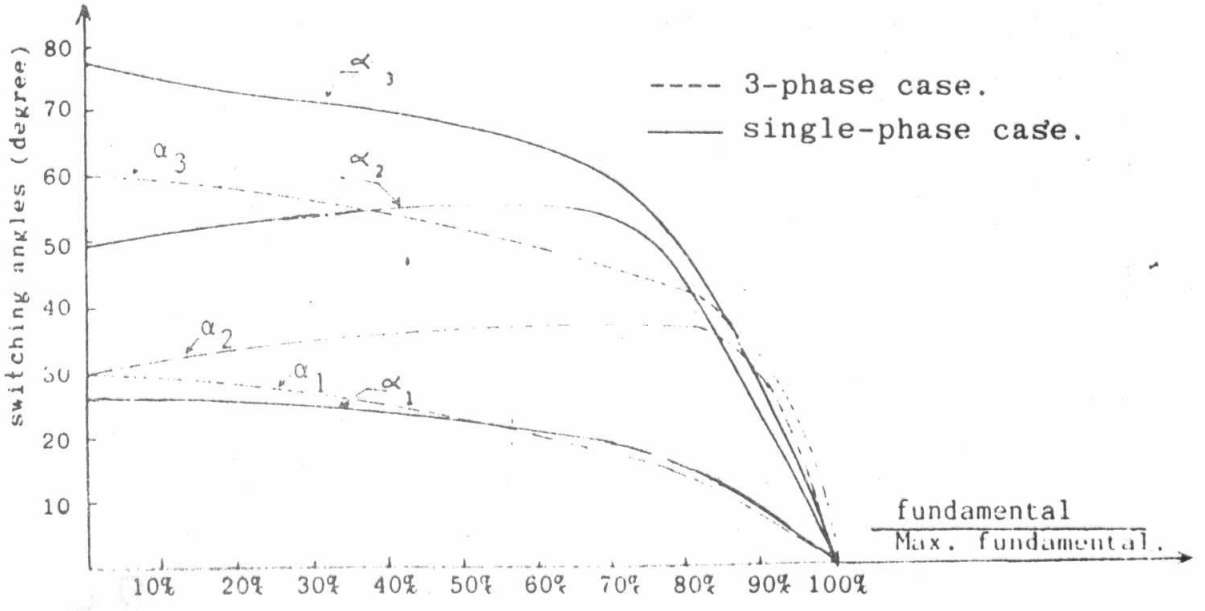


Fig.2. The calculated switching angles.

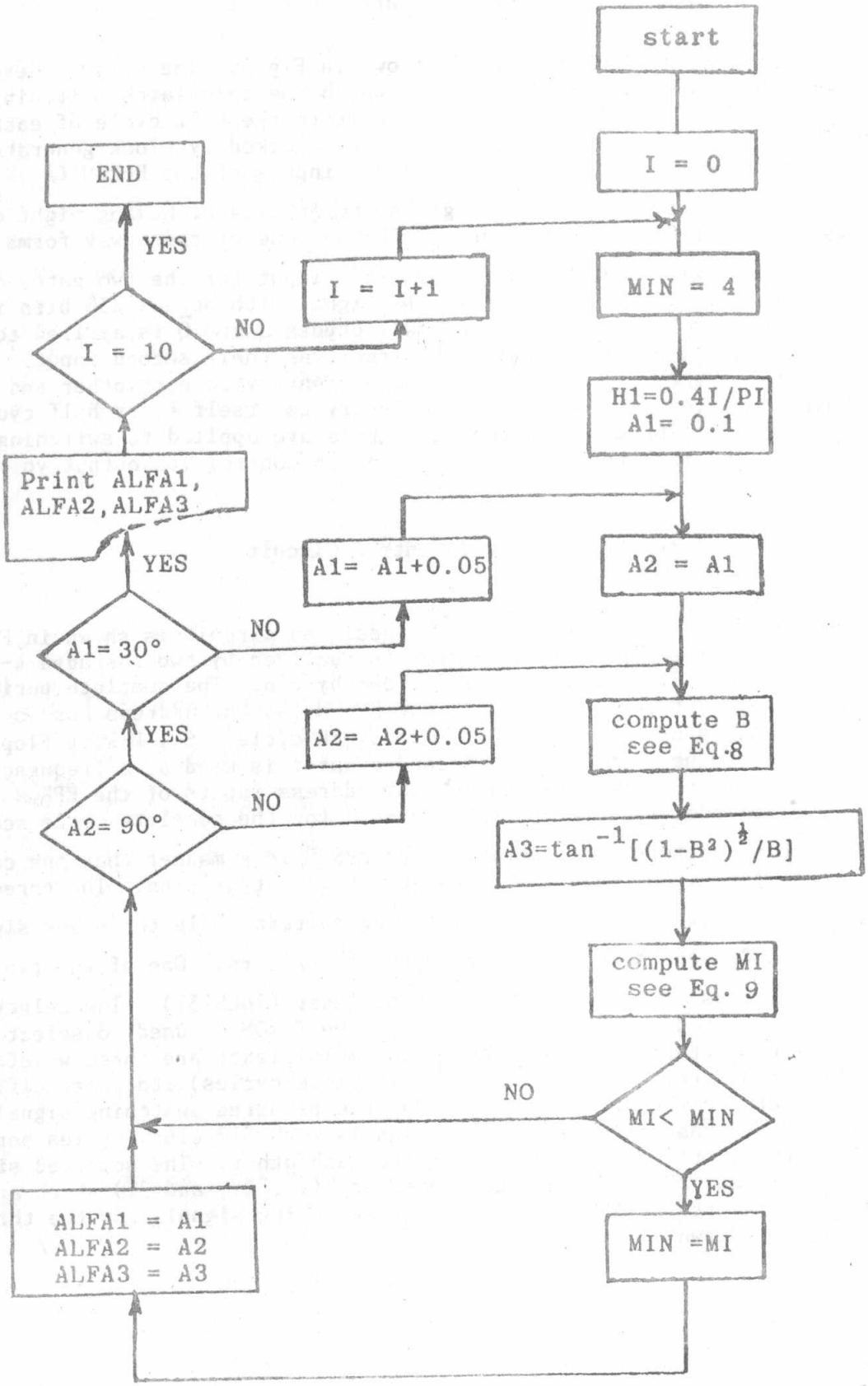


Fig. 3. Flow chart of switching patterns calculation for single-and 3-phase PWM inverter.

HARDWARE DESCRIPTION

Single-Phase Digital Control Circuit

The designed control circuit is shown in Fig.4. The circuit developed is associated with an EPROM (2716) in which the calculated switching patterns are stored. We only use 256 bits to store the half cycle of each mode of operation. Two cascaded counters [6] (clocked by clock generator) give the address of the EPROM. The address inputs of the EPROM (A_o-A_1) are used for the half cycle scan, this gives the ability of having eight different waveforms at Q_o-Q_7 outputs of the EPROM. One of these waveforms is selected by multiplexer and is used as the first input for the two gates of Exclusive OR circuit. D-Flip-Flop clocked by signal with period 256 bits is used as a divider by 2, each one of its two outputs Q and $\bar{Q}$ is applied to any one of the two gates of Exclusive OR circuit as their second input. So the two outputs of the Exclusive OR, are complementary to each other and at the same time every one is the complementary to itself every half cycle (256 bits). These two switching signals are applied to switching transistors of the inverter shown in Fig.5-a to control its output voltage.

Three-Phase Digital Control Circuit

The complete wiring diagram of the designed circuit is shown in Fig.6. In this circuit the address generator is realized by two cascaded 4-bit counters and a D-Flip Flop is used as a divider by two. The complete period of the switching patterns is stored in the EPROM, so the address bus is 9 bit. The two counters count up from 0 to 255 clock cycle. So, D-Flip Flop which is clocked by the ripple of the second counter is used as a frequency divider by two. By this way one can get the address inputs of the EPROM (2764). The EPROM address input(A_o-A_8) are used for the complete cycle scan. The switching patterns are stored in the EPROM in a manner that one can have two different switching patterns at Q_o-Q_5 output pins. The three signals Q_o, Q_1, and Q_2 represent one switching pattern while the other signals Q_3, Q_4, and Q_5 represent the other switching pattern. One of the two switching patterns is selected by the multiplexer (74LS157). The selector circuit connected to the multiplexer and the EPROM is used to select the required pattern. The outputs of the multiplexer are three waveforms (1Y, 2Y, and 3Y) repeated every cycle (512 clock cycles)with phase difference 120° between them respectively. But the required switching signals for the three-phase inverter are six signals with 512 clock cycles period and each two of them are complementary to each other. The selected signals (1Y, 2Y, and 3Y) and their complementary ($1\bar{Y}$, $2\bar{Y}$, and $3\bar{Y}$) which are obtained by the inverter (74LS04) are the six switching signals for the three-phase inverter shown in Fig.5-b.

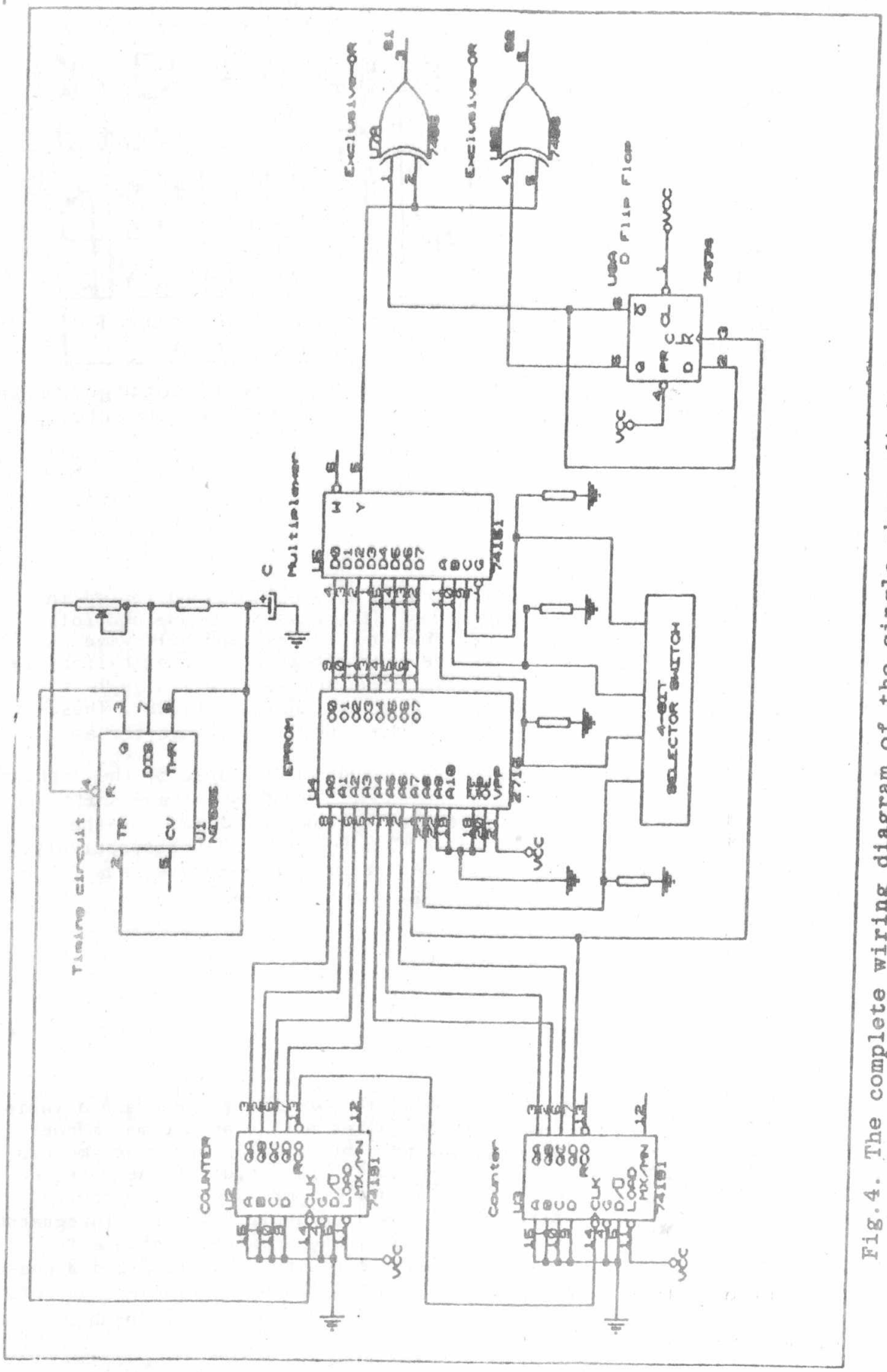


Fig.4. The complete wiring diagram of the single-phase digital control circuit.

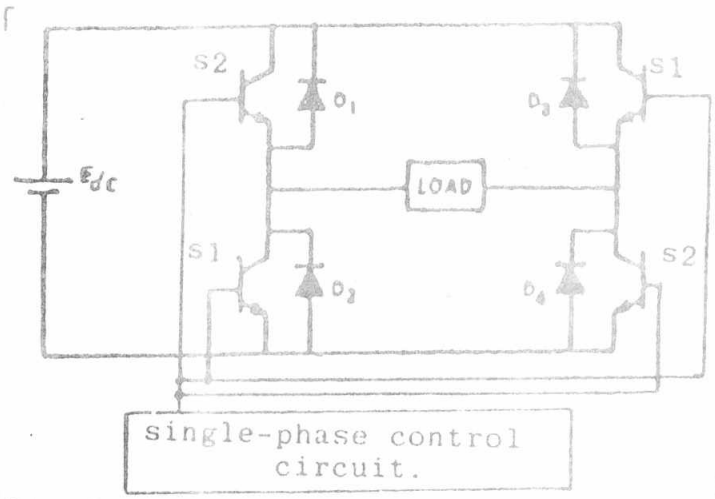


Fig.5-a. Basic configuration of single-phase inverter.

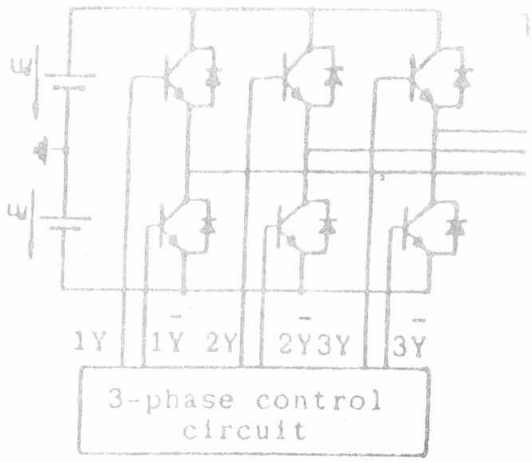


Fig.5-b. Basic configuration of 3-phase inverter.

EXPERIMENTAL WORK

The single-phase and 3-phase control circuits are realized and tested in the laboratory. An arbitrary output signal of the single-phase control circuit is shown in Fig.7. We noticed the quarter-wave and half-wave symmetry of the output waveform. Also we notice that the second half-cycle is the complement of the first half cycle. Two complementary signal generated by the single-phase control circuit are shown in Fig.8. These two signals S_1 and S_2 are used to control the single-phase inverter as shown in Fig.5-a. The output signals 1Y, 2Y and 3Y generated by the 3-phase control circuit are shown in Fig.9, where the 120° and 240° phase shift are illustrated. The oscillograms of the output voltage waveforms for the single and 3-phase inverters are shown in Fig.10 and Fig.11, respectively. The oscillograms of 3-phase inverter load current for resistive and inductive load are shown in Fig.12 and Fig.13, respectively.

CONCLUSION

The voltage control techniques derived make it possible to generate a variable - frequency variable - voltage sinusoidal output in an optimal manner. The technique has considerable practical use for variable speed ac motors drive applications where low order harmonics in the output of the inverter pose serious problems in the motor performance. Complex analog circuits are needed to generate the desired waveforms accurately. Digital integrated circuits including counters, EPROMs and logic gates can be economically combined for the transistor inverter driving circuits. The realized 3-phase digital control circuit can be also used for single-phase inverter control, by using any two complementary output signals to drive the single-phase inverter.

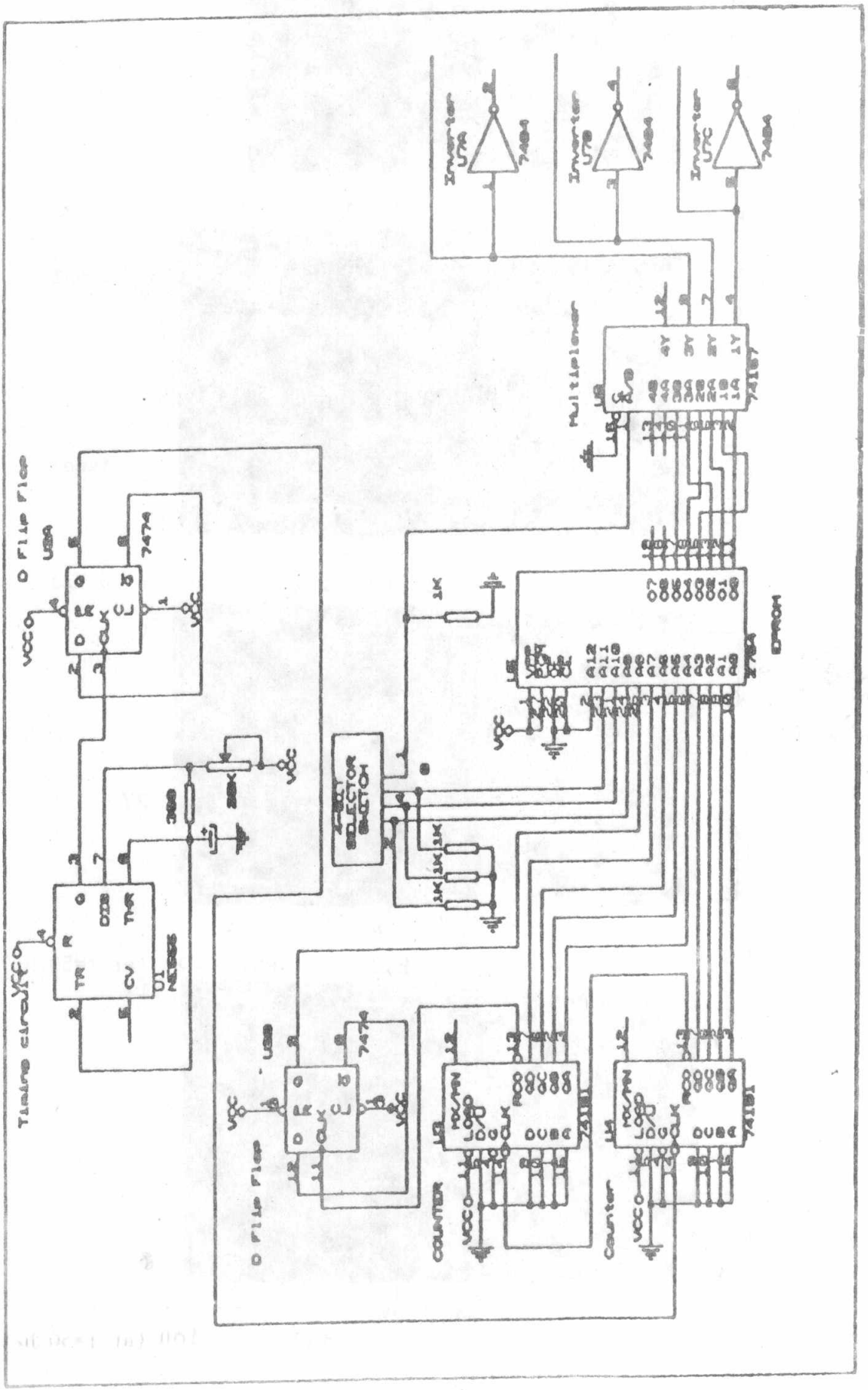


Fig.6. The complete wiring diagram of the 3-phase digital control circuit.

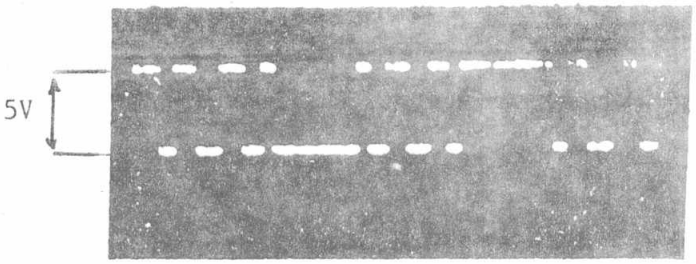


Fig.7. One generated control signal (at f = 50 Hz)

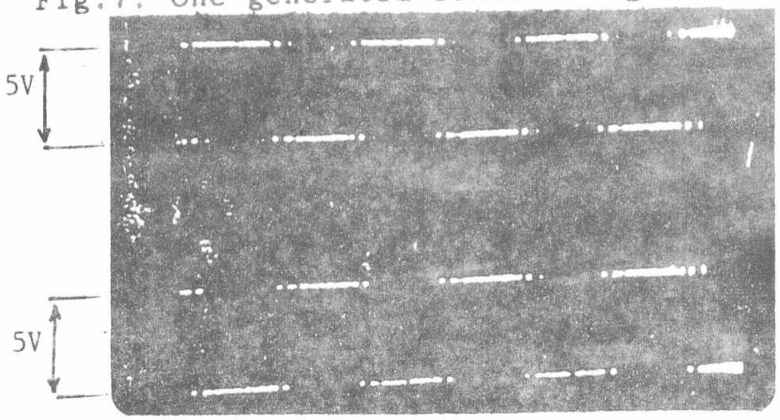


Fig.8. Two complementary signals (at f = 50 Hz)

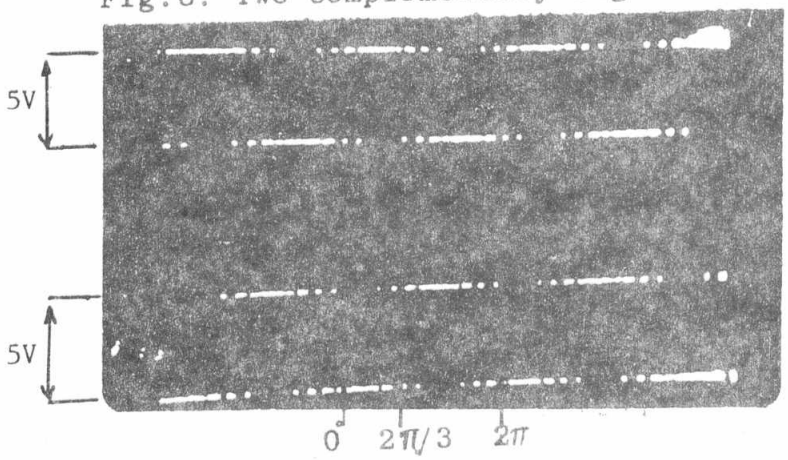


Fig.9-a. 120° phase shift illustration (at f=50 Hz)

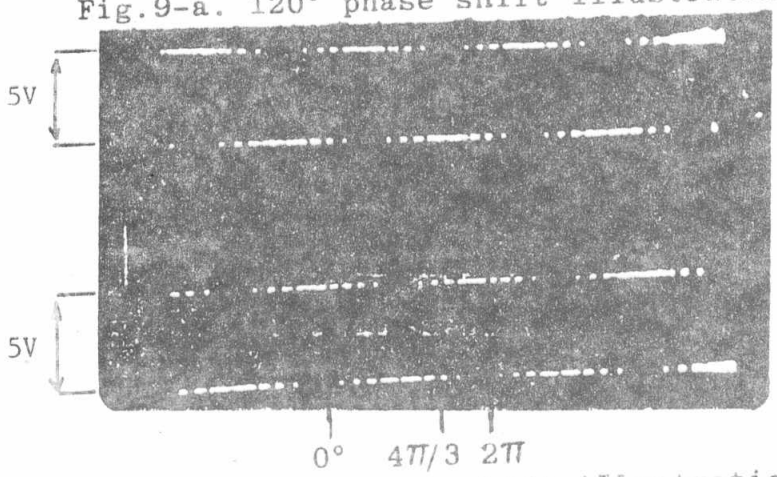
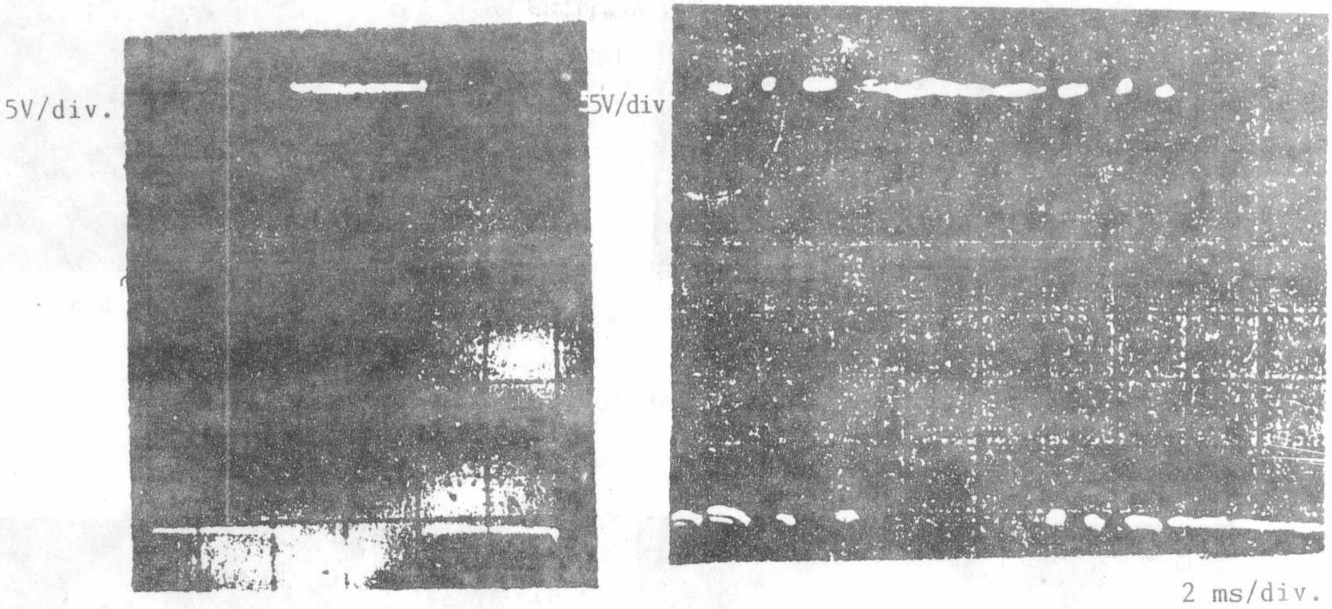


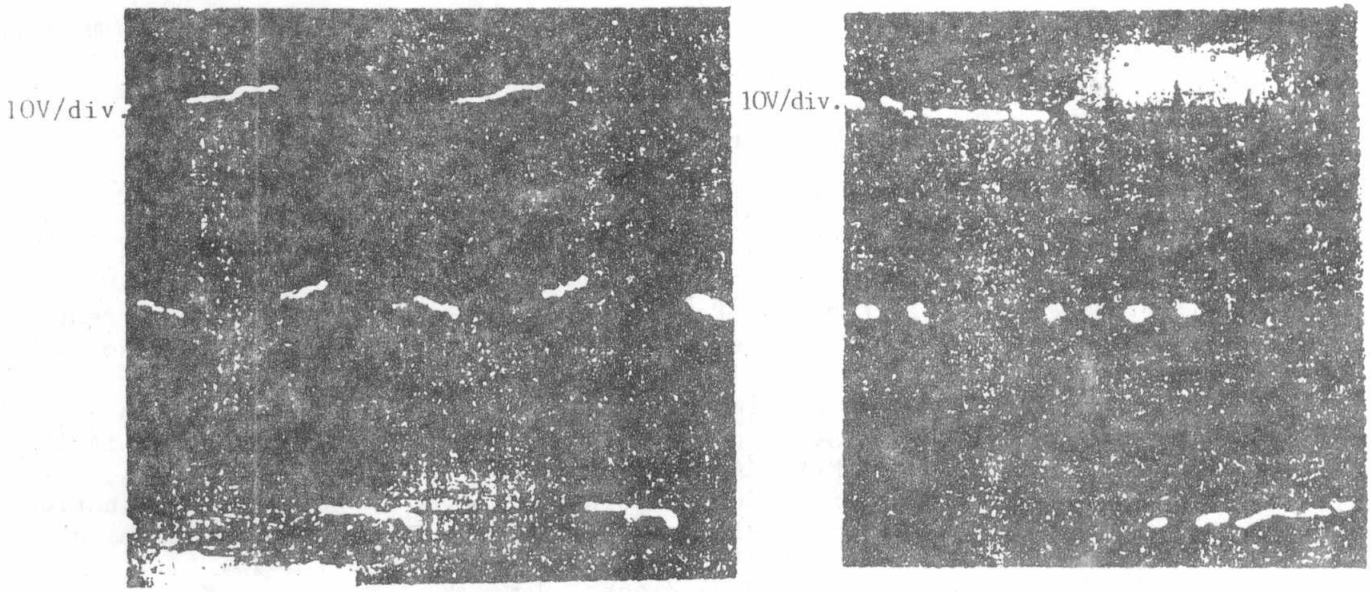
Fig.9-b. 240° phase shift illustration (at f=50 Hz)



a) Square wave operation.

b) PWM operation.

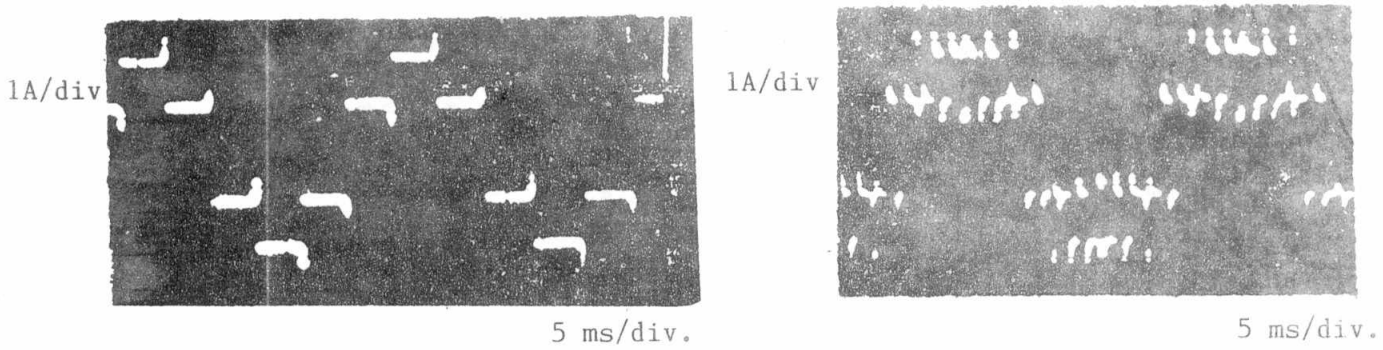
Fig.10. Single-Phase inverter output voltage waveforms.



a) Quasi-square wave operation.

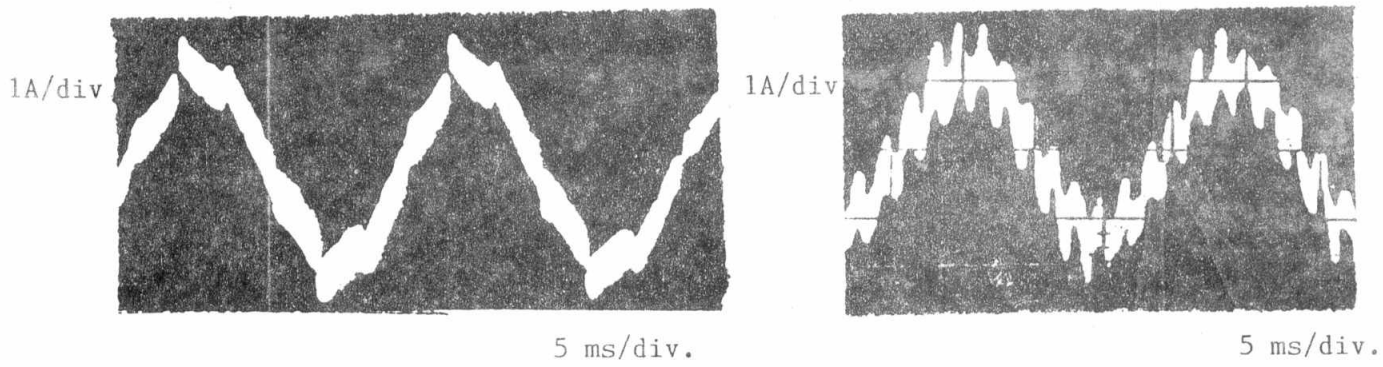
b) PWM operation.

Fig.11. 3-Phase inverter output voltage waveforms.



a) Quasi-square wave operation. b) PWM operation.

Fig.12. 3-Phase inverter load current for resistive load.



a) Quasi-square wave operation. b) PWM operation.

Fig.13. 3-Phase inverter load current for inductive load.

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