論 文
36～12～3

마이크로 프로세서를 이용한 인버터 전압제어와 고조파 제거에 관한 연구

A Study on Inverter Voltage Control and Harmonics Elimination Using Microprocessor

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요 약

전력전자 분야에 대한 마이크로 프로세서의 응용은 제품생산과정, 실현, 정비 및 서비스와 그제어의 융통성에 있어서 이용범위가 확장되고 있는 추세이다.

본 연구는 인버터의 점호각 관계식을 다항식 근사 시킴으로서 마이크로 프로세서로 온—라인 계산을 할 수 있게 한것으로, 인버터 출력의 고조파 제거와 출력전압제어를 위한 스위칭의 이론적 분석을 하고 HP-1000 컴퓨터에 의하여 시뮬레이션을 실행 하였다.

또한 마이크로 프로세서에 의한 인버터 출력전압 및 주파수 제어의 실제적 방법이 제시되고, Z-80 마이크로 컴퓨터에 의한 단상 인버터 출력제어 실험을 하였다.

본고에서 고찰한 단상인버터 경우의 Implementation은 3상으로 확장 할 수 있으며, 얻어진 제 결과들은 실제적으로 인버터 응용에서 단상 및 3상 인버터 출력파형을 얻는 융통성 및 보다 높은 정밀성을 갖는다.

ABSTRACT

Microprocessor control of power-electronic equipment offers the possibility of improvements in manufacture, realizability, maintenance and servicing, and increased control flexibility. In this paper, simple microprocessor control with a view to approximating the polynomial equations which govern the commutation angles was consisdered.

The theoretical analysis of this principle which govern the commutation of power switches in order to cancel any predetermined harmonics and vary the fundamental rms voltage of the inverter output is described. Also the spectrum and harmonics were analyzed by HP-1000 computer. Practical aspect of the realization of a voltage controller based on a microprocessor and a suitable system for variable frequency inverter were also presented. The experimental test has been carried out on a Z-80 microcomputer and a single phase transistor inverter. The various results show the feasibility of obtaining practically a single phase and a three phase inverter waveforms, which are highly desirable in most inverter applications.

I. Introduction

It is always demanded for output voltage of inverter to be controlled in the industrial applications, whether its value has to be varied in a wide range or it must be kept constant despite the variafion of the load or of the DC voltage at the inverter. The various methods have been developed for the control of PWM voltage inverters. Such control was initially based on a analog methods, described extensively in references 1) ~ 3) and the corresponding set up was implemented either by analog[4] or by digital methods. [5], [6] The advent of digital components such as microprocessors and high speed memories opened the way for advanced control devices based on novel algorithm ; elimination of harmonics in the output voltage[7], [8] and optimization involving different performance index.[9]

Also the reference (10) has shown the approach to minimize the rms value of the current harmonics in the load by a proper choice of the commutation angles.

Another approach which can be satisfactory utilized for a quasi-continuous control of a PWM inverter output voltage by interpolation method had been described in 1980.[11]

The general procedure followed by conventional circuitry is to determine the instants at which the power switches should open and close by the intersection of two difference of reference waveforms. By the use of this techniques and analog circuitry, the total harmonic content of the out put voltage can be reduced at the complexity of great control, commutation devices.

In this paper, simple microprocessor control with a view to approximating the polynomial equations which govern the commutation angles was studied.

Thus microprocessor on-line control of transistor inverter is to make possible the implementation of the digital techniques where a predetermined number of unwanted harmonics can be canceled and the inverter frequency, voltage can be control simultaneously. Because the output filter can be used to attenuate the remaining higher harmonics, the use of this method in inverter cotrol presents various advantages, so as to attenuate the harmonics components and, therefore, approximate the sinusoidal waveform.

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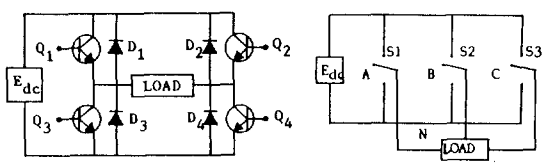
II. The Control Technique of the Inverter Output Voltage and Harmonics Elimination

Fig. 1 shows the basic structure of a fixed DC voltage inverter and the output voltage waveform where the switching angles α_i, are usually modulated so as to minimize the harmonics components in the voltage waveform which are least acceptable, usually the low order harmonics.[2]

A periodic voltage waveform as shown in Fig. 2 is expected to satisfy the following requirements ;

$$V_{AN}(wt) = V_{AN}(wt + 2\pi) \quad (1)$$

$$V_{AN}(wt) = V_{AN}(\pi - wt) \quad (2)$$



(a) single phase (b) three phase

Fig. 1. Basic structure of inverters with constant voltage source E_{dc}.

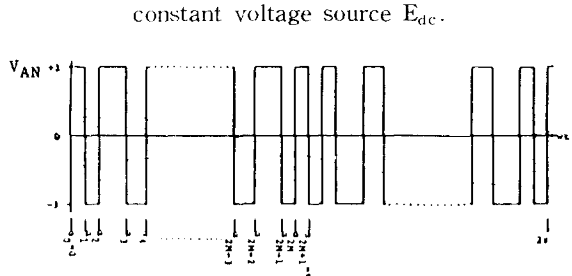


Fig. 2. General waveform of inverter output voltage.

$$V_{AN}(wt) = -V_{AN}(\pi + wt) \quad (3)$$
$$V_{BN}(wt) = V_{AN}(wt - 2\pi/3) \quad (4)$$
$$V_{CN}(wt) = V_{AN}(wt + 2\pi/3) \quad (5)$$

The above three requirements represent the character of the wave periodical, with quarter-cycle symmetry and half cycle antisymmetry ; expansion of $V_{AN}(\omega t)$ in a Fourier Series exclusively odd sinusoidal wave[12] The last two requirements represcnt the symmetric three phase character of the inverter voltage. It constitutes a succession of pulses with normalized amplitude. When the inverter is commutated M times over a quarter cycle subject tothe above requirements, the root mean square voltage of its nth harmonic is given by[13]

$$V_n = \frac{2\sqrt{2}}{n\pi}\left(1 + 2\sum_{i=1}^{M}(-1)^i \cos n\alpha_i\right) \quad (6)$$

in a Fourier Series, where the angles α_i with i=1, 2, ………, M satisfactory the following condition

$$0 < \alpha_1 < \alpha_2 < \alpha_3 \cdots\cdots \alpha_M < \frac{\pi}{2} \quad (7)$$
$$\alpha_0 = 0, \quad \alpha_{2M+1} = \pi$$

It is possible from (6) that M predetermined harmonics can be canceled by using M commutations when their respective equations are equalized to zero. And it becomes clear the rms that voltage of the fundamental has a fixed value, and is equal to

$$V_1 = \frac{2\sqrt{2}}{\pi}(1 - 2\cos\alpha_1 + 2\cos\alpha_2 - 2\cos\alpha_3 + \cdots + (-1)^M 2\cos\alpha_M) \quad (8)$$

In those applications where it is necessary to vary the output voltage, (M-1) harmonics are canceled and the appropriate commutation angles are calculated by the following equations ;

$$\frac{\pi V_1}{2\sqrt{2}} = 1 - 2\cos\alpha_1 + 2\cos\alpha_2 - 2\cos\alpha_3 \cdots + (-1)^M 2\cos\alpha_M$$
$$0 = 1 - 2\cos 3\alpha_1 + 2\cos 3\alpha_2 - 2\cos 3\alpha_3 \cdots + (-1)^M 2\cos 3\alpha_M$$
$$0 = 1 - 2\cos 5\alpha_1 + 2\cos 5\alpha_2 - 2\cos 5\alpha_3 \cdots + (-1)^M 2\cos 5\alpha_M$$
$$\vdots \qquad \vdots \qquad \vdots$$
$$0 = 1 - 2\cos A\alpha_1 + 2\cos A\alpha_2 - 2\cos A\alpha_3 \cdots + (-1)^M 2\cos A\alpha_M \quad (9)$$

where V_3, V_5, ……… are the (M-1) harmonics to be canceled. As a results, the fundamental voltage is given by

$$V_1 = V(\alpha_1, \alpha_2, \alpha_3, \cdots\cdots\cdots \alpha_M) \quad (10)$$

Therefore, the rms fundamental voltage can be varied while the chosen M-1 harmonics are canceled. The M commutation angles over a quarter-cycle permit unambiguous definition of the harmonic composition of the output voltage in the ideal inverter. Or, putting it differently, there are M degree of freedom in controlling the amplitudes of the component harmonics Mmaking it possible to eliminate M-1 of the latter and to control the amplitude of the fundamental wave between the limits ;

$$0 \leqq V_1 \leqq \frac{2\sqrt{2}}{\pi} E_{dc} \quad (11)$$

III. Polynomial approximation of Laws which Govern the Commutatipn Angles

1. Single Phase Variant

Equation (9) is nonlinear as well as transcendental in nature. There is no general method that can be applied to solve such equations. Thus, the practical method of solving these equations is a trial and error process. Taking all the factors into account, a numerical technique is the best approach in solving the equations. These methods are not practical in real time systems due to the short response times needed. On the other hand, if the microprocessor, which has to work out the correct firing pulse, is to be kept simple, for both economical and practical reasons, the resolution method of such equations must be transformed to suit the microprocessor presently available.

The solution adopted has two possibilities. In both cases the equations must be solved and the data obtained either stored in look-up tables according to the different values of the rms voltage wanted or transformed into linear equations dependent of the rms voltage. For this purpose the M equations are solved canceling M-1 harmonics and obtaining the desired fundamental rms voltage. The Damped Newton method for solving nonlinear equations was used with the aid of a computer(HP-1000).[14]

The simple example of the three pulse bidirectional wave is analyzed by the method presented and its computer algorithm is represented in Fig. 3.

The third and fifth harmonics are canceled

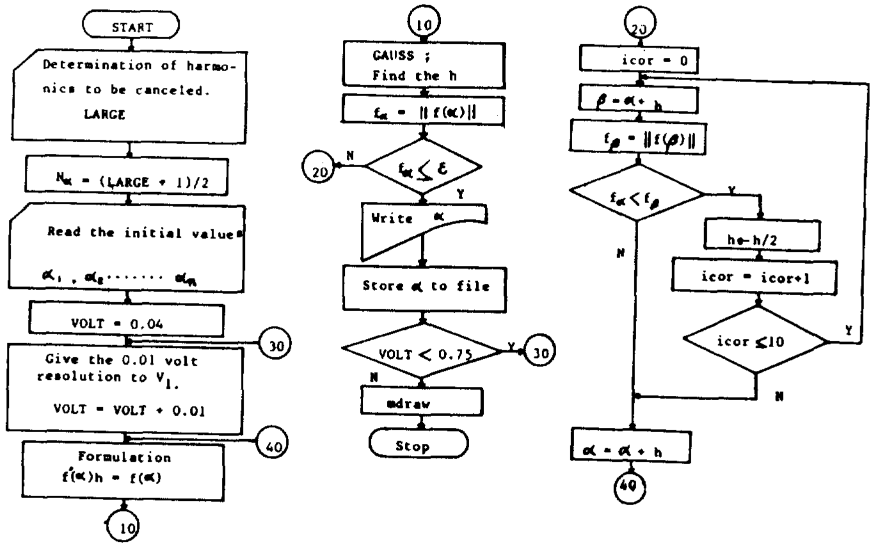
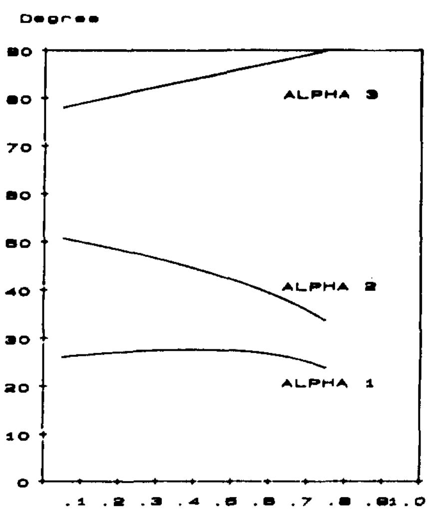
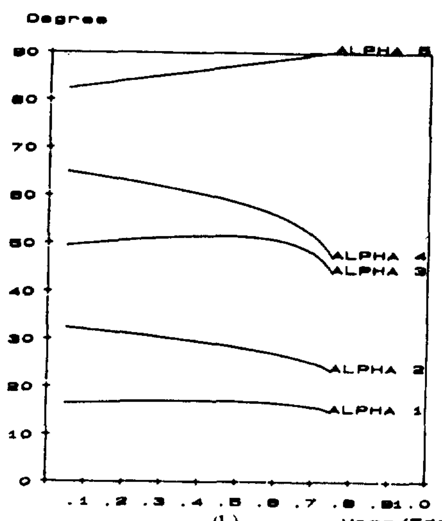


Fig. 3. Program flowchart for solving nonlinear equations(9)



(a)

Fig. 4. The switching angles for eliminating the 3rd and 5th harmonics.(single phase inverter)



(b)

Fig. 5. The switching angles for eliminating the 3rd, 5th, 7th, and 9th harmonics. (single phase inverter)

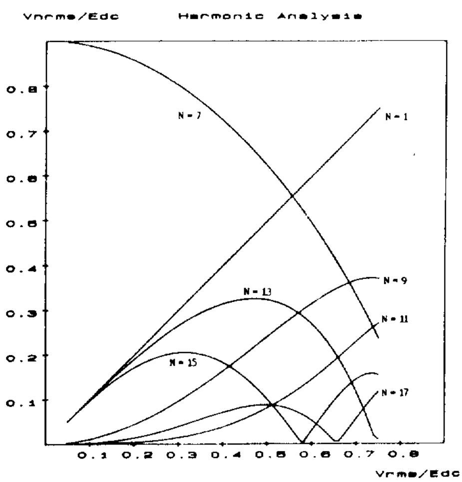


Fig. 6. Harmonic analysis. Relation between fundamental amplitude and 7th, 9th, 11th, 13th, 15th and 17th harmonics.

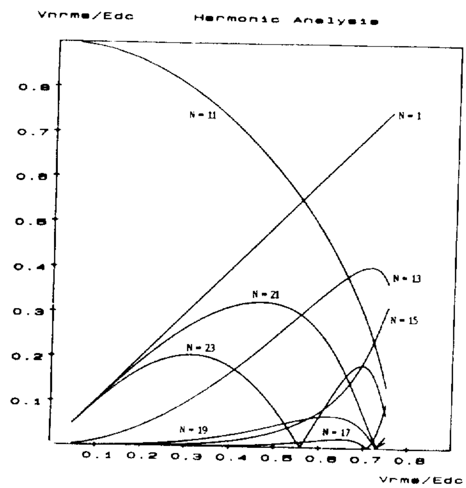


Fig. 7. Harmonic analysis. Relation between fundamental amplitude and llth, 13th, 15th, 17, 19th. 21th and 23th harmonics.

and the root of equations obtained are plotted in Fig. 4. Also Fig. 5 represents the plotting of the 3rd, 5th, 7th, and 9th harmonics elimination and the root of equations.

The relation between the relative per unit amplitude of the first six harmonics(7th, 9th, 11th, 13th, 15,h and 17th) and first seven harmonics (11th, 13th, 15th', 17th, 19th, 21th and 23th) present in the output voltage and the fundamental rms voltage are shown in Fig. 6 and Fig. 7, respectively.

A polynomial approximation dependent on the rms voltage, V_1, of the laws which govern the commutation angles previously calculated and represented in Fig. 4 and Fig. 5 is possible and the error known by using the least square approach.[14] In cases M = 3, and M = 5, the results of this methods are hereby shown in (12)-(17), where a maximum permissible error of 0.789% can be achieved using the following the third-order equations in case M = 3.

When these polyonmial approximations are used with high order equations, it might be precision to calaculate the commutation angles. Thus, the third order equations required to calculate the commutation angles are much accurater. In this paper, the control is implemented by using equations, (14).

In Case M – 3. (3rd, 5th harmonics elimination)

1st order equations

$$\alpha_1 = 27.4991 - 1.7795\ V_1 \qquad \text{error} \leq 9.847\%$$
$$\alpha_2 = 53.0314 - 23.2248\ V_1 \qquad \text{error} \leq 6.016\% \quad (12)$$
$$\alpha_3 = 77.2407 + 16.8670\ V_1 \qquad \text{error} \leq 0.557\%$$

2nd order equations

$$\alpha_1 = 25.0315 + 14.9498\ V_1 - 20.9116\ V_1^2$$
$$\alpha_2 = 50.8754 - 8.6007\ V_1 - 18.2714\ V_1^2$$
$$\alpha_3 = 77.2208 + 16.7580\ V_1 + 0.1363\ V_1^2$$
$$\text{error} \leq 2.780\%$$
$$\text{error} \leq 1.637\% \qquad (13)$$
$$\text{error} \leq 0.474\%$$

3rd order equations

$$\alpha_1 = 26.0063 + 3.2747\ V_1 + 13.7314\ V_1^2 - 28.8695\ V_1^3$$
$$\alpha_2 = 51.6810 - 18.2571\ V_1 + 10.3609\ V_1^2 - 23.8605\ V_1^3$$
$$\alpha_3 = 77.1429 + 17.6904\ V_1 - 2.6305\ V_1^2 + 2.3057\ V_1^3$$
$$\text{error} \leq 0.789\%$$
$$\text{error} \leq 0.470\% \qquad (14)$$
$$\text{error} \leq 0.002\%$$

In case M = 5 (3rd, 5th, 7th, 9th, harmonics elimination)

1st order equations

$\alpha_1 = 17.1645 - 1.0782\ V_1$ error $\leq$ 9.925%
$\alpha_2 = 33.6212 - 11.3495\ V_1$ error $\leq$ 7.171%
$\alpha_3 = 51.4088 - 2.5510\ V_1$ error $\leq$ 12.338%
$\alpha_4 = 67.5524 - 20.5931\ V_1$ error $\leq$ 10.461%
$\alpha_5 = 81.8257 + 11.1391\ V_1$ error $\leq$ 0.087% (15)

2nd order equations

$\alpha_1 = 15.9990 + 6.8233\ V_1 - 9.8770\ V_1^2$
$\alpha^2 = 32.3412 - 2.7190\ V_1 - 10.7882\ V_1^2$
$\alpha_3 = 47.4898 + 24.0187\ V_1 - 33.2122\ V_1^2$
$\alpha_4 = 63.9736 + 3.6699\ V_1 - 30.3287\ V_1^2$
$\alpha_5 = 81.8736 + 10.8145\ V_1 + 0.4057\ V_1^2$
error $\leq$ 4.582%
error $\leq$ 3.464%
error $\leq$ 6.317% (16)
error $\leq$ 5.285 %
error $\leq$ 0.051%

3rd order equations

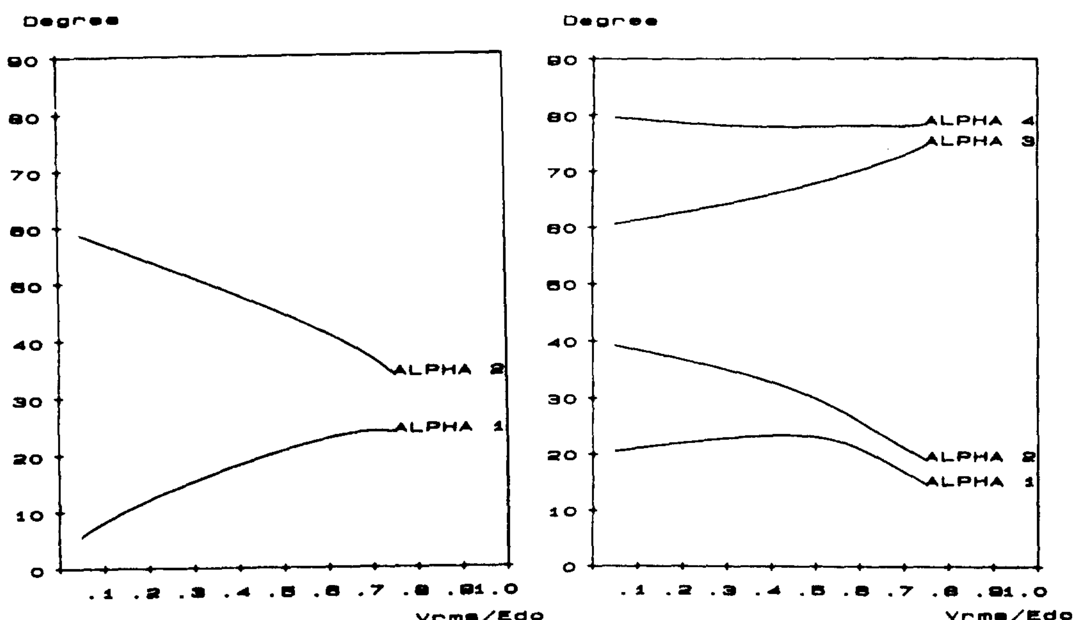
$\alpha_1 = 16.6337 - 0.7780\ V_1 \quad 12.6781\ V_1^2 - 18.7961\ V_1^3$
$\alpha_2 = 33.0608 - 11.2535\ V_1 + 14.5359\ V_1^2 - 21.1037\ V_1^3$
$\alpha_3 = 50.3446 - 10.1729\ V_1 + 63.2433\ V_1^2 - 84.5472\ V_1^3$
$\alpha_4 = 66.5848 - 27.6033\ V_1 + 62.4670\ V_1^2 - 77.3307\ V_1^3$
$\alpha_5 = 81.8038 + 11.6507\ V_1 - 2.0753\ V_1^2 + 2.0676\ V_1^3$
error $\leq$ 2.507%
error $\leq$ 1.985%
error $\leq$ 3.164% (17)
error $\leq$ 2.593%
error $\leq$ 0.014%

2. Three Phase Variant

We consider the ideal half bridge three phase inverter shown schematically in Fig. 1. As in the single phase variant, in determining the M angles over a quarter-cycle with a view to eliminating M-1 harmonics, the following nonlinear set of equations-based on equations (6)- has to be solved.

$$V_1 = \text{constant}$$
$$V_5 = V_7 = V_{11} \cdots V_n = \text{zero} \qquad (18)$$

where $n = 6k \pm 1$, $k = 1, 2, 3, \cdots$ Since the load



(a) (b)

Fig. 8. The switching angles for eliminating in three phase inverter.
(a) 5th only (b) 5th, 7th and 11th

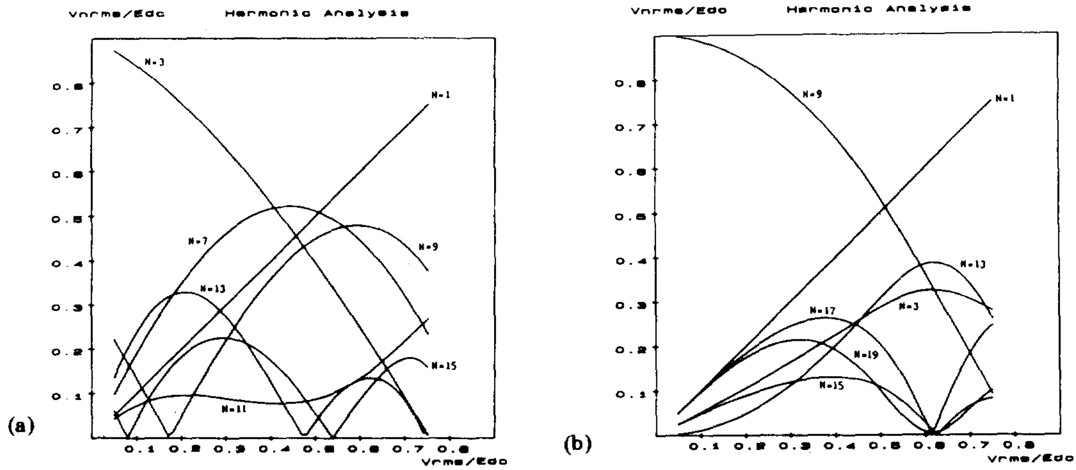


Fig. 9. Harmonics analysis in three phase. Relation between fundamental amplitude and (a) 3rd, 7th, 9th, 11th, 13th and 15th (b) 3rd, 9th, 13th, 15th, 17th and 19th

comprises three conductors, the harmonics V_{3k} ($k = 1, 2, \cdots$) produce current in it and need be eliminated. The amplitude of fundamental wave V_1 was varied from the minimum 0.05 to the maximum 0.75 with 0.01 resolution as in single phase inverter. And for each value M commutation angles were determined ensuring elimination of M-1 harmonics.

The following two cases of elimination were considers with aid of the above program Fig.3: (a) 5th harmonic only (b) 5th, 7th, and 11th

Results, α_i, are plotted in Fig. 8 (a)-(b) respectively, with the fundamental amplitude given in nomalized values and the angles in degree of arc. On the other hand, the relation between the fundamental rms voltages are shown in Fig. 9 (a)-(b) respectively.

And also, the coefficients and the error of the polynomial approximation equations whichgovern the commutation angles angles in the three phase inverter are represented in equations (19)-(24).

In case $M = 2$ (5th only harmonic elimination)

1st order equations

$\alpha_1 = 6.6929 + 26.4097\ V_1$　error $\leq$ 41.612%
$\alpha_2 = 60.7544 - 33.5362\ V_1$　error $\leq$ 5.635%　(19)

2nd order equations

$\alpha_1 = 3.6392 + 47.1131\ V_1 - 25,8792\ V_1^2$
$\alpha_2 = 59.3129 - 23.7636\ V_1 - 12.2156\ V_1^2$
error $\leq$ 4.796%
error $\leq$ 2.718%　(20)

3rd order equations

$\alpha_1 = 3.9954 + 42.8461\ V_1 - 13.2129\ V_1^2 - 10.5512\ V_1^3$
$\alpha_2 = 60.4162 - 36.9529\ V_1 + 26.9205\ V_1^2 - 32.6138\ V_1^3$
error $\leq$ 7.858%
error $\leq$ 1.128%　(21)

In case $M = 4$ (5th, 7th and 11th harmonics elimination)

1st order equations

$\alpha_1 = 23.5361 - 5.4094\ V_1$　error $\leq$ 32.917%
$\alpha_2 = 42.6442 - 28.1912\ V_1$　error $\leq$ 12.901%
$\alpha_3 = 58.7078 + 19.2771\ V_1$　error $\leq$ 2.105%
$\alpha_4 = 79.0112 - 1.7398\ V_1$　error $\leq$ 0.874%　(22)

2nd order equations

$\alpha_1 = 17.8236 + 33.3192\ V_1 - 48.4109\ V_1^2$
$\alpha_2 = 38.8980 - 2.7930\ V_1 - 31.7477\ V_1^2$
$\alpha_3 = 60.4057 + 7.7658\ V_1 + 14.3891\ V_1^2$
$\alpha_4 = 79.9522 - 8.1196\ V_1 + 7.9748\ V_1^2$

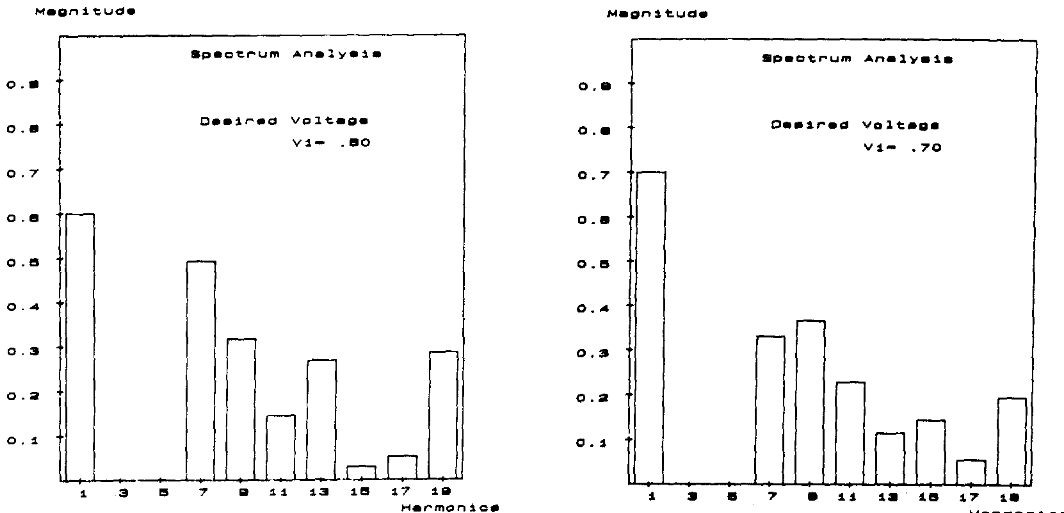


Fig. 10. Normalized voltage spectrum in single phase, 3rd and 5th harmonics elimination.
(a) $V_1=0.60(7V)$, 30Hz (b) $V_1=0.70(8.5V)$, 400Hz

$$\begin{aligned}&\text{error} \le 6.325\%\\&\text{error} \le 1.410\%\\&\text{error} \le 0.555\%\\&\text{error} \le 0.213\%\end{aligned} \qquad (23)$$

3rd order equatins

$$\begin{aligned}\alpha_1 &= 20.5375+0.8158\ V_1+48.0355\ V_1^2-80.3729\ V_1^3\\ \alpha_2 &= 39.7785-13.3382\ V_1-0.4574\ V_1^2-26.0756\ V_1^3\\ \alpha_3 &= 59.9274+13.4939\ V_1-2.6076\ V_1^2-2.6076\ V_1^3\\ \alpha_4 &= 80.2475-11.6561\ V_1+18.4684\ V_1^2-8.7447\ V_1^3\end{aligned}$$

$$\begin{aligned}&\text{error} \le 2.682\%\\&\text{error} \le 2.768\%\\&\text{error} \le 0.244\%\\&\text{error} \le 0.185\%\end{aligned} \qquad (24)$$

Ⅳ. Microprocessor Methods for Processing and Implementation

The method used to process the laws which govern the commutation angles with a microprocessor depends largely on the complexity of the expressions chosen for this purpose. Where very high order linear equations are necessary, the microprocessor will take a very long time to calculate the commutation angles and, therefore the best procedure will be to store the discrete values of the commutation angles for each value of the fundamental rms voltage. When these approximations are low order equations, it might be useful to use the microprocessor to calculate them. Here the memory requirements are greatly reduced at the expence of a more complex software. In this paper, the example previously studied, where the 3rd and the 5th harmonics are canceled, is consisdered. In this case the microprocessor calculates α_1, α_2 and α_3 from the three 3rd order linear approximation equation(14), for

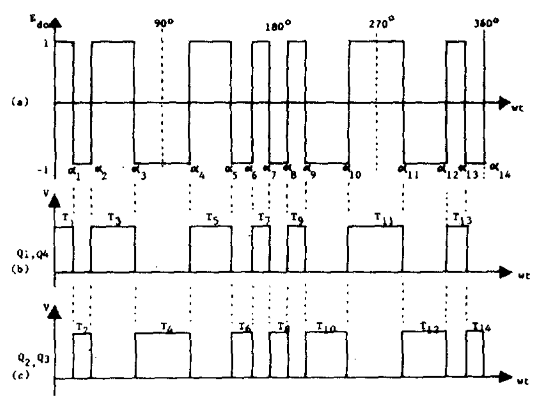


Fig. 11. Base driving time duration of the inverter.

every desired output condition.

On the other hand, Fig. 11. respresents the pulses of thebase drivihg time duration for switching in the single phase inverter(Fig.1). In order to realize pulses of Fig. 11-(a) the signals with time duration such as Fig. 11-(b), (c) have to be yielded from the computer. In this case the relationship between the switching angles, α_1 and base driving time duration T_n, (n=1, 2, 3……) and desired frequency f, in the inverter output from Fig. 11 follows as ;

$$T_n=\left[(\alpha_n-\alpha_{n-1})\frac{10^4}{3\ 6f}-d\right]f_c \qquad (25)$$

where f_c denotes the system clock frequency and d is the dead time for protecting the power transistor in switching. In implementation the time d is consisdered with 10 micro seconds but this time is very small compare with switching time T_n.

Consequently, in such as inverter voltage 8. 5V, desirous frequency 400Hz, unwanted harmonics are 3rd, 5th order, the error rate of switching angles α_n is 1. 71772%maximum, or 0. 334584% minium. Thus,the error that is produced by dead time could be ignored and the goal of the harmonics elimination and the voltage control is accomplished.

On the other hand, Fig. 12. is the flowchart for generating the time duration of Fig. 11.—(b), (c). In flowchart Fig. 12, the calculation process of the swiching time T_n, was programed with the aid of the aid of a FORTRAN language and the processing which transmit the consequent data T_n to inverter circuit was programmed by Z-80 assembly language in order to the real time processing.

The notation V_P denotes the DC power source and V_d is the desired rms voltage value of the inverter output.

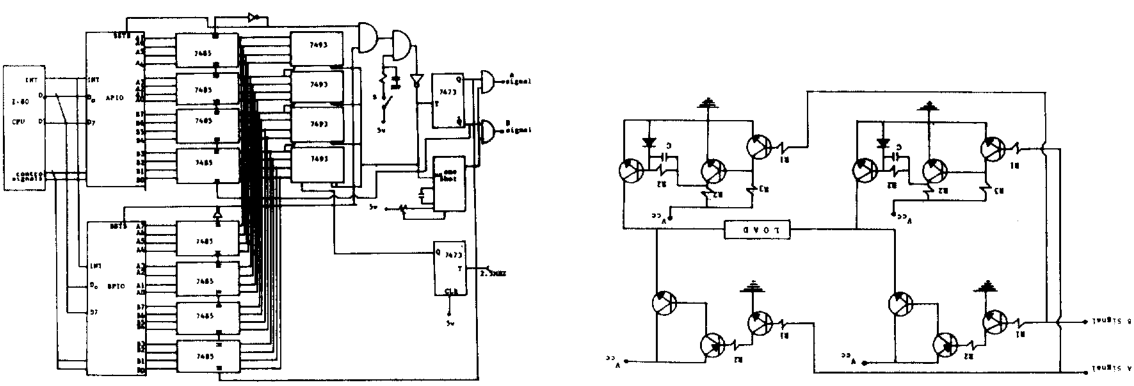
In addition, the control circuit and harsware developed in based on Zilog's Z-80 microcomputer is represented in Fig. 13. The clock of the microcomputer was adjusted to 2. 5 Mhz.

The practical scheme used in the experimental test is shown in Fig. 13.-(b). It is based on the circuit, as shown in Fig. 1. and employs the 7 watt lamp as resistor load and DC 12 V as V_{cc}.

Photo 1-(a), (b) show the voltage waveforms at inverter output. These waveforms represents the desired voltages 7 volt (30 Hz) and 8. 5 volt (400 Hz) while the 3rd and the 5th harmonics are canceled in single phase inverter output, respectively.

As a practical result of calculation, the photo 1-(a), (b) rms voltage are 6. 957644491 V and 8. 520 089438 V respectively. Thus they take 0. 6 percent and 0. 236 percent in error rate.

As assumming, previously studied in section II, they have the three commutations within the each quadrant and show they are odd-quarter



(a) (b)

Fig. 13. (a) Microcomputer hardware (b) Inverter power circuit

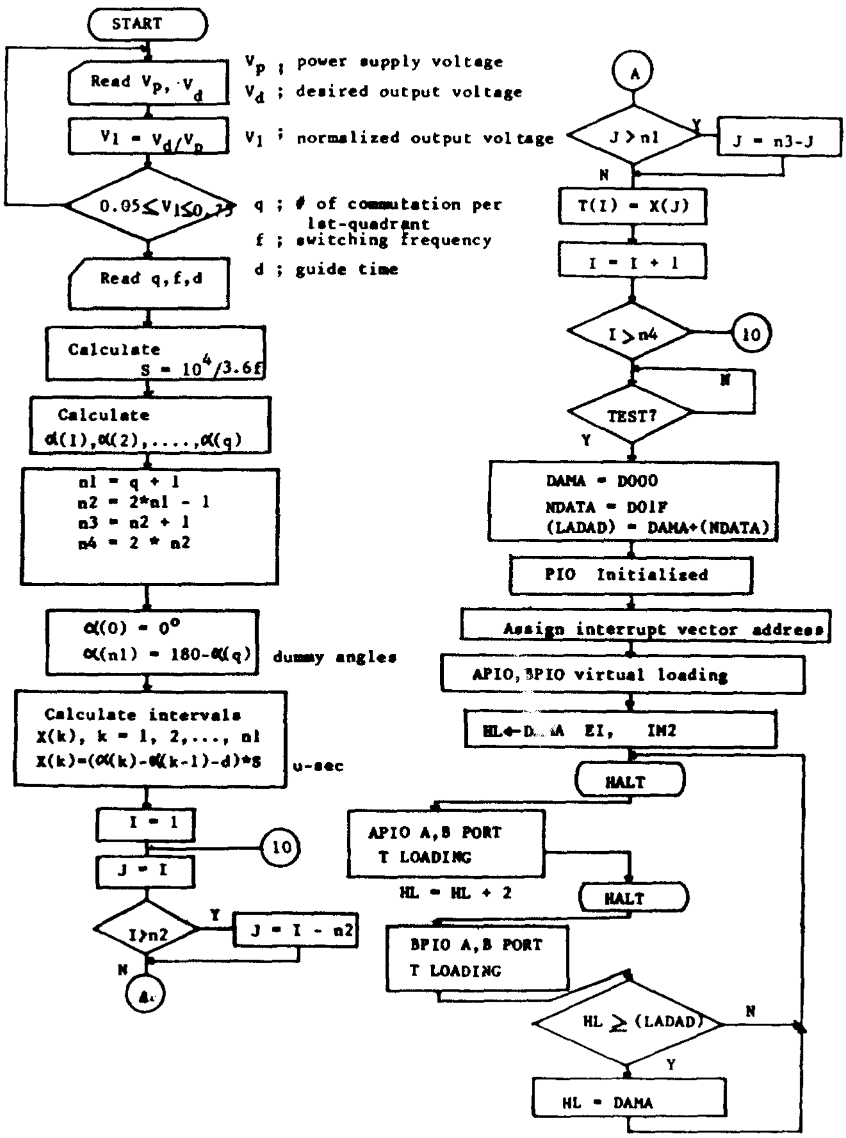


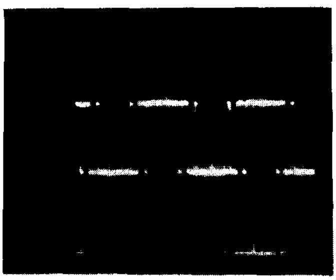
Fig. 12. Flowchart for generating the time durations of Fig. 11-(b) and (c).

symmetry wavefoms.

On the other hand, Photo 2-(a)~(d) show the spectrum analyses of photo 1-(a), 1-(b), respectively. As can be seen, we find that the predetermind 3rd and 5th harmonics are eliminated through the load.

On the other hand, the usable frequency of inverter is depended upon the number of necessary clock cycle to process the machine language of the whole program. Furthermore, the critical limit of inverter freqency is not depended upon the number of unwanted harmonicss but also the computer system clock frequency. Thus, we can not determine the relationship to regulate the

(a)



(b)

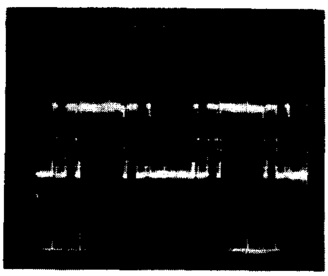
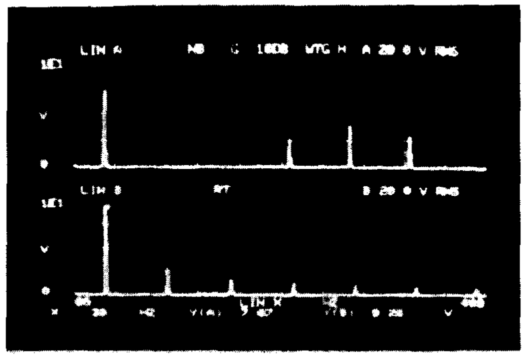
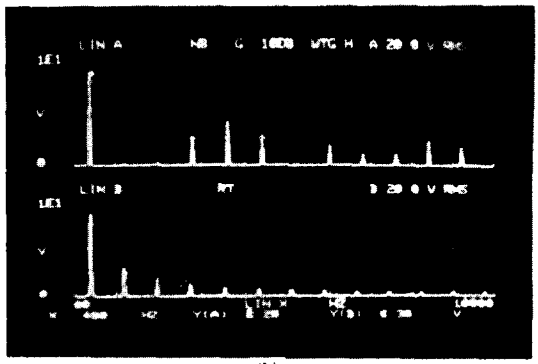


Photo. 1. Inver output waveforms versus desired voltage ahd frequency in single phase.
(a) 7V, 30Hz Hori : 10ms/div, vert ;
(b) 8. 5V, 400 Hz Hori : 0. 5 ms/div, vert : 10V/div

usable limit of inverter frequency. However, in any case, we can fix the desirous higher limit of inverter frequency by of the short program calculated. Here the inverter frequency on this experiment is higher than 100 Hz.



(a)



(b)

Photo. 2. Experimental PWM spectra results in Upper ; eliminated inverter frequency, (a) 30Hz, (b) 400Hz.
Lower : non-eliminated.

Ⅴ. Conclusion

In this paper, the analysis of the equations which govern the more accurate commutation of power switches in order to cancel any predetermined harmonics and very the fundamental rms voltage was presented and the realization of constructing such a control circuit were discussed.

The experimental test has been carried out on a Z-80 microcomputer with a view to controlling in the single phase inverter. As can be seen, the effective elimination of any order harmonics and the frequency control were able to be accomplished by using polynomial approximation equat tions. In addition, throughout the experimental investigations, it can be summerized that the inverter output control has the various features as follows to the conventional ones ;

(1) effective elimination of low order harmonics
(2) generation of the ignoble error be due to consideration of the dead time(guide time), d.
(3) adjustment of inverter output frequency that is based on the necessary clock frequency of machine language program and computer system.

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