OCCASION

This publication has been made available to the public on the occasion of the 50th anniversary of the United Nations Industrial Development Organisation.

DISCLAIMER

FAIR USE POLICY

CONTACT

Please contact publications@unido.org for further information concerning UNIDO publications.

For more information about UNIDO, please visit us at www.unido.org

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org

RESTRICTED

DP/ID/SER.A/696
13 May 1986
ENGLISH

15564

SEMICONDUCTOR DEVICES AND ELECTRONIC

SUB-SYSTEMS FOR TRANSPORTATION

DP/IND/84/014

INDIA

Technical Report: Solid State AC Drives for Transportation Equipment (Part II)*

Prepared for the Government of India
by the United Nations Industrial Development Organization,
acting as executing agency for the United Nations Development Programme

Based on the work of T.A. Lipo
Expert in Solidstate AC Drives

United Nations Industrial Development Organization
Vienna

* This document has been reproduced without formal editing

V.86-56346

SUMMARY OF EXPERIENCES IN PILANI

Upon arrival in Delhi on January 1 1986, my personal affairs and necessities were again handled expeditiously by all concerned. After a briefing in the morning of January 2nd with Dr. K. Hussein, UNDP Project Director, I proceeded directly to Pilani. Upon arrival in Pilani, numerous briefings were held with the National Chief Project Co-ordinator, Dr. Amarjit Singh, the CEERI Director Dr. G.N. Acharya, Mr. U.M. Rao and Mr. R. Verma to acquaint me with progress made on the activities at CEERI related to the solid state AC traction motor drive. Discussions were also held with Dr. S.K. Lahiri who is Deputy Director. During the second week of my visit, a series of five lectures were prepared and presented. They concerned:

1. A simplified approach to Field Oriented Control.

2. Significant Research results at the University of Wisconsin related to the UNDP Project.

In parallel with the lectures, a series of meetings were held to discuss how the material presented in the lectures might be incorporated in the design of the UNDP project.

Finally, during the third week, I also attended an extensive meeting chaired by Dr. K. Hussein, the UNDP Project Director, New Delhi.

Based on these meetings, a number of important developments are evident. In particular, much of the vagueness of the description of the overall task itself mentioned in my previous report appears to have been completely resolved. The project definition, together with the project milestones, have been given proper attention and I am confident that the project is proceeding satisfactorily. Perhaps my initial concern was a result of the fact that I arrived for my first site visit only a month or two after the project was approved by UNDP and insufficient time was available to complete this most important task.

It is now clear that the development concerns a 50 KVA prototype traction system which explores device and circuit concepts at a power level which is approximately one fifth to one tenth the ultimate goal for a full scale, full rated traction drive. I agree fully, that this is a worthwhile endeavour which will enable resolution of many system and device problems at a more manageable power level, while delaying some of the more onerous converter circuit problems to a later time.

It should be noted that the laboratory for testing the completed traction drive mentioned in my first report is now essentially completed. Test beds mounted on an isolated sound deadening platform should be more than adequate for testing both the target 50 KVA system as well as future possible drives of higher rating up to 200 KVA.

Finally, a 68000 microprocessor development system is now in place which will result in rapid implementation of control concepts in software. Finally, a working current measurement and tracking filter circuit was demonstrated which will become an important integral part of the control system.

During my first visit to Pilani, two important and relatively new concepts were emphasized during my lectures, namely the need for current source inverter operation (as opposed to voltage source operation), and the necessity of field orientation. Discussions with personnel at that time, evolved a control scheme employing the regulation of the "in phase" and "out phase" components of stator current. This concept would achieve both the advantages of current source operation as well as field orientation. Over the period of the last year, the engineers at Pilani have evolved this scheme to another form which involves the real and reactive components of AC volt-amperes. While most of the benefits of the original scheme are retained, the added expense due to the extra voltage sensors and the increased difficulty of control near zero speed (particularly during braking), makes the viability of this option questionable. It is recommended that both options be retained until the control question is examined in detail when Mr. U.M. Rao spends his research sabbatical under UNDP sponsorship at the University of Wisconsin later this year.

Another subject discussed during this trip was desirability of "cross-coupling" the torque and flux producing channels, so as to eliminate the phase shift which normally occurs in pulse width modulated current regulators of the type to be employed in this project.

This subject was one of the new developments at the University of Wisconsin discussed in seminar 2 during this latest visit. A copy of the most relevant paper is attached to this report. Implementation of this concept into the software or hardware portions of the controller is recommended.

During my first visit to Pilani, three major problem areas have been identified for detailed study:

1. Pulse-Width-Modulation (PWM) Algorithms for minimizing the losses in induction motor drives.

2. Microprocessor based PWM inverter for AC Drives.

3. Adaptive control of AC Drives using PWM inverters.

It was agreed on both sides that Messrs. Rao, Verma and Perlekar will travel to Wisconsin at five month intervals, so that personnel at CEERI can become more familiar with the research at Wisconsin and extend this work as well as originate new work in directions more relevant to the UNDP project.

The visit of Mr. Perlekar to Wisconsin has now been completed. While at Wisconsin, Mr. Perlekar addressed subject area 1 involving PWM algorithms. In particular, his work at Wisonsin concerned the development of what is called a "Delta Modulator". The delta modulator is a particularly effective type of controller which can be used to perform the current source function described above as desirable. A working system was developed at Wisconsin by Mr. Perlekar and will be incorporated into the traction drive system. A copy of Mr. Perlekar's final report is attached.

RECOMMENDATIONS

1. It has already been noted that the traction system under construction is not a full-scale version but a scaled down prototype. In effect, the completed system will not be capable of its ultimate intent, i.e. an electric traction system for a rail vehicle.

A follow-on project with additional financing would be required to realize a full-scale traction drive. The immediate output of this project is only a "scale model" which has negative connotations. For the benefit of all concerned it would be very useful if another application be found to demonstrate the immediate importance of this project without regard to traction. In principle, control configurations suitable for traction can be easily modified to serve numerous useful functions including fast response servomotors, dynamometers, spindle drives and machine tool drives to name a few. The 50 KVA rating of the prototype system is ideal for such applications.

2. The work of Mr. Perlekar at the University of Wisconsin is the first of a series of three studies to be carried out here by CEERI personnel. While at Wisconsin, Mr. Perlekar did extensive simulation of the inner "current loop". This simulation work will be continued by Mr. Verma and Mr. Rao.

Unfortunately, at the present time, the simulation models developed by Mr. Perlekar cannot be utilized at CEERI since it does not possess suitable simulation software for use on their computers. The purchase of such a program for internal use at CEERI is strongly recommended. In particular, the simulation program named ACSL has been used at Wisconsin with great success. The program is available for use on many computers including IBM, DEC, Harris and Apollo computers. The minimum cost configuration is a $2,000 ACSL package for use on an IBM AT personal computer.

3. It is recommended that the "cross-coupling" described in a paper by Rowan and Kerkman be included in the inner current loop control in order to improve high frequency response.

4. It is recommended that the final decision on the control algorithm to be used, be deferred until Mr. Rao completes his studies at Wisconsin.

DELTA MODULATOR STUDY

Shekner Perlekar
January 30, 1986.

1. Static PWM inverters are used in variable speed a.c. drives and uninterruptible power supplies. In an induction motor drive the PWM inverter is required to provide:

   (1) Variable frequency output so that the induction motor can operate at desired slip frequency over a wide range of motor speed values.

   (2) Constant (v/f) ratio to maintain constant air gap flux.

Requirements (1) and (2) have been met with a variety of voltage and current control techniques. The most popular is sine wave PWM, which allows 64% utilisation of the available voltage at D.C.bus. the practical solution of this problem is gradual from PWM to SQUARE wave which results in discontinuities in inverter output voltage and also increases the control complexities.

The Delta Modulator first proposed by P.D. ZIOGAS provides a simple but effective way of generating a pwm switching sequence with smooth transition from pwm to square wave. In this method, a reference sine wave is compared with an error modulated integrated output of the pwm pattern (generated by coparator) to control the inverter switching sequence. In the proposed technique the integrated output is replaced by the actual motor current and is then modulated by error command, then compared with reference current to obtain pwm sequence. Also the work is extended for three phase operation. The system is simulated on an Applied Dynamics Hybrid Computer AD-256 at the University of Wisconsin.

2. The DELTA MODULATOR proposed by P.D. Ziogas, is shown in Fig. 1. It consists of three operational amplifiers configured with A1 as comparator, A2 an an integrator, and A3 as a modulator. Figure 2b shows the comparator output. Figure 2a indicates the reference sine wave and error command. The main feature of this method is that whenever the internal feedback voltage Vf exceeds the upper or lower limit reference waveform (which limit is set by the R2/R3 ratio) the comparator reverses the polarity of the delta modulated voltage V1 at the input of the integrator, this action reverses the slope of the Vf waveform, at the integrator output, thus forcing Vf to osillate around the reference waveform Vr.

The component values of the delta modulation control logic can be easily computed using the following equations. The integration time constant (R1*C) is given by

R1*C = (4*Vs)/(P1*Vr*Wrb) ....(1)

where

Vs .... Amplitude of comparator voltage

Vr .... Maximum ref. signal amplitude

Wrb .... "base frequency" in radians

The ratio R2/R3 is computed by

R2/R3 = 1/(2*R1*C*Ncm) ....(2)

where

Ncm .... Maximum no. of commutations per sec.

Using equations (1), (2) the circuit components were calculated. Based on these values the circuit is simulated on analog computer (Fig.3). Three such circuits are simulated to obtain three phase output.

The results obtained with simulation are indicated in Fig.4 which indicates line start with step load Figs. 6,7,8 indicates variable frequency operation of motor/inverter system with delta modulation logic from 6 Hz to 60 Hz.

3. MODIFIED DELTA MODULATOR

Figure 9 indicates that the motor phase current and the integrator output are in phase. This is because motor actually acts as an integrator because of R-L nature. Hence it was proposed to use motor current to replace integrator output or replace integrator by the actual motor.

The modified delta modulator is shown in Fig. 10. The actual motor current is modulated with error command(DT) derived from comparator (A1) to generate the pwm sequence. It has all the advantages of delta modulator listed

(1) Constant volts/hertz

(2) Smooth transition from pwm to square wave mode

(3) The switching frequency is limited by error command

The input to the motor is a switching pattern with sudden changes from zero to Edc. The motor transient time constant determines the slope of actual motor current. The transient time constant is calculated using equation 3.

$$Ta = (Ls + (Lm*L2)/(Lm+L2)) /Ps \ldots\ldots\ldots (3)$$

where

Ta .... Motor electrical transient time constant

Ls .... Stator leakage inductance

Lm .... Magnesting inductances

L2 .... Stator referred rotor leakage inductance

This time constant is replaced by the integrator time constant of the delta modulated inverter with all other parameters the same.

The modified delta modulator is simulated on an analog computer the results obtained are given in figure 11, 12, 13. The harmonic analysis of the current waveform at various frequencies are given in table from 1 to 7. The listing of harmonic analysis is given in Appendix 2.

4. COMMENTS AND DISCUSSION

(1) Figures 11, 12, 13 reveal that motor phase current follows the current reference. The current waveform indicates a small asymmetry which results in the presence of even harmonics in the motor current. This asymmetry becomes serious near "base frequency" of the machine, but can be minimised by controlling the error command to maintain constant switching frequency. This approach will also help to maximise inverter utilisation. In the present case the switching frequency selected is 1 KHz. Higher switching not only reduces the asymmetry but also reduces the % of individual harmonics.

(2) The number of pulses per cycle are given in table 9

TABLE 9

S.No.	Operating Frequency	No. of Pulses per cycle
1	18	23
2	24	17
3	30	12
4	36	8
5	42	4
6	48	4
7	54	2

The harmonics present near the pulse number are relatively large which support the concept of increasing the switching frequency to reduce the harmonic magnitude.

5. CONCLUSION

The application of a delta modulator for current regulated PWM inverter has been studied and implemented on an analog computer. The results indicate that this technique can be implemented using higher switching frequency to obtain reduced THD in the inverter output current and voltage to improve the inverter performance.

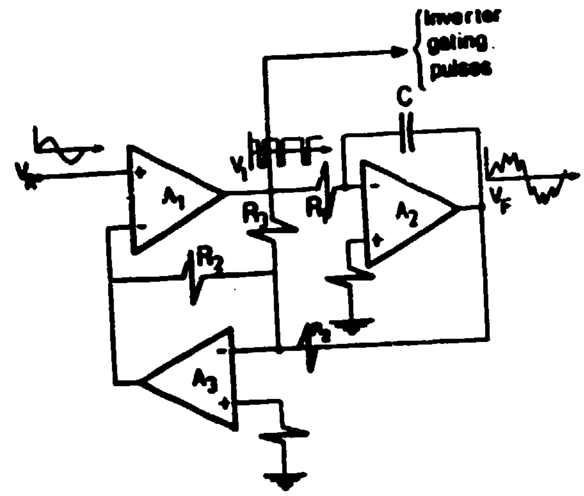


figure 1

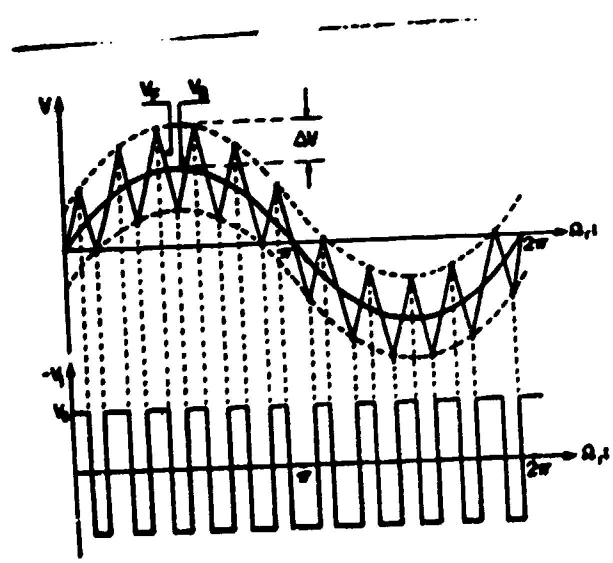


figure 2.

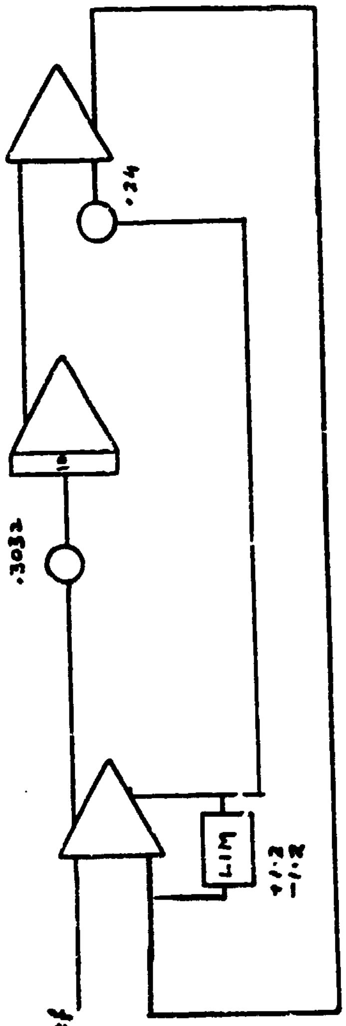
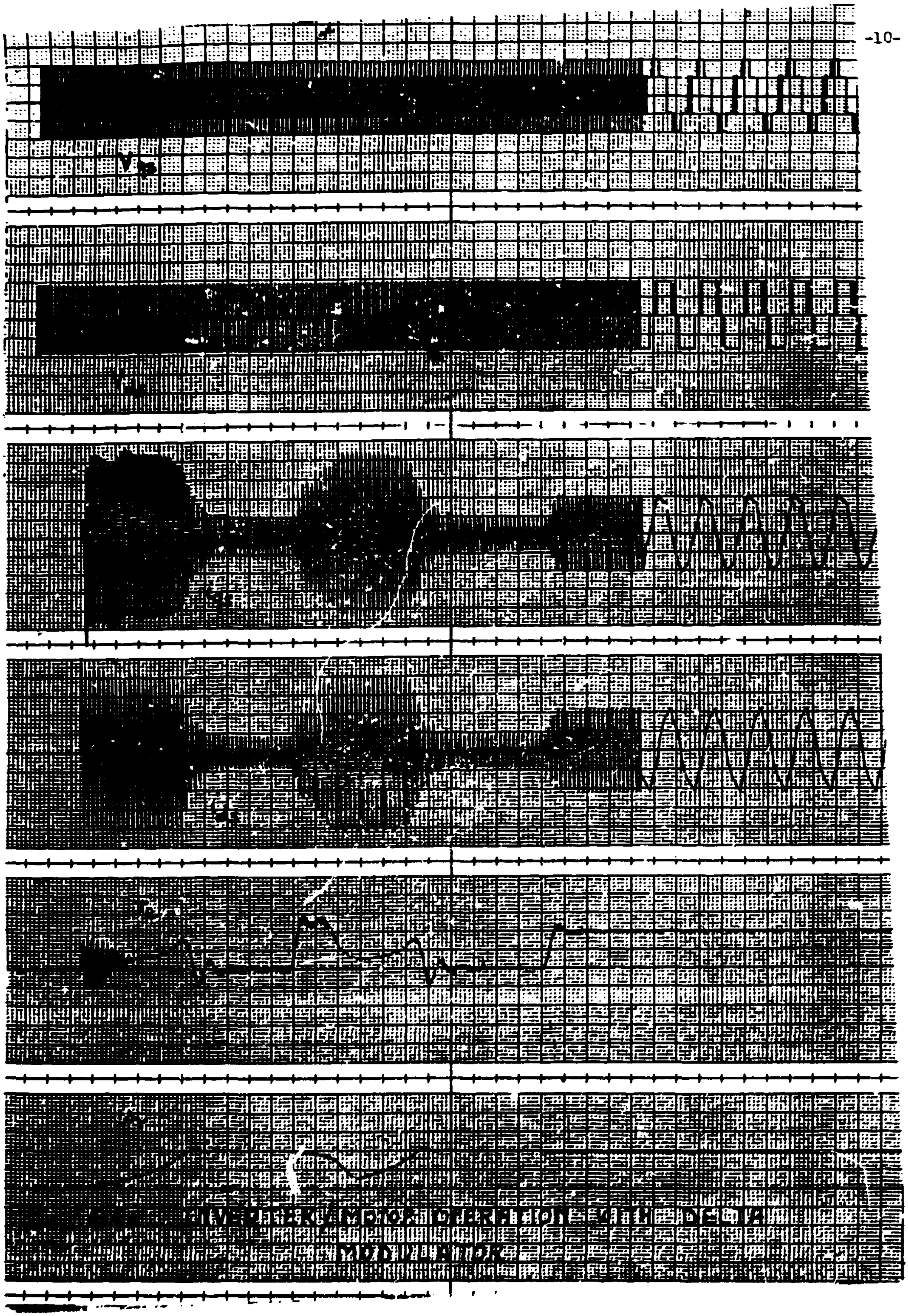


Fig 3 Anloy Simulation of delta modulator. (Phase A)



… MOTOR OPERATION WITH DELTA MODULATOR

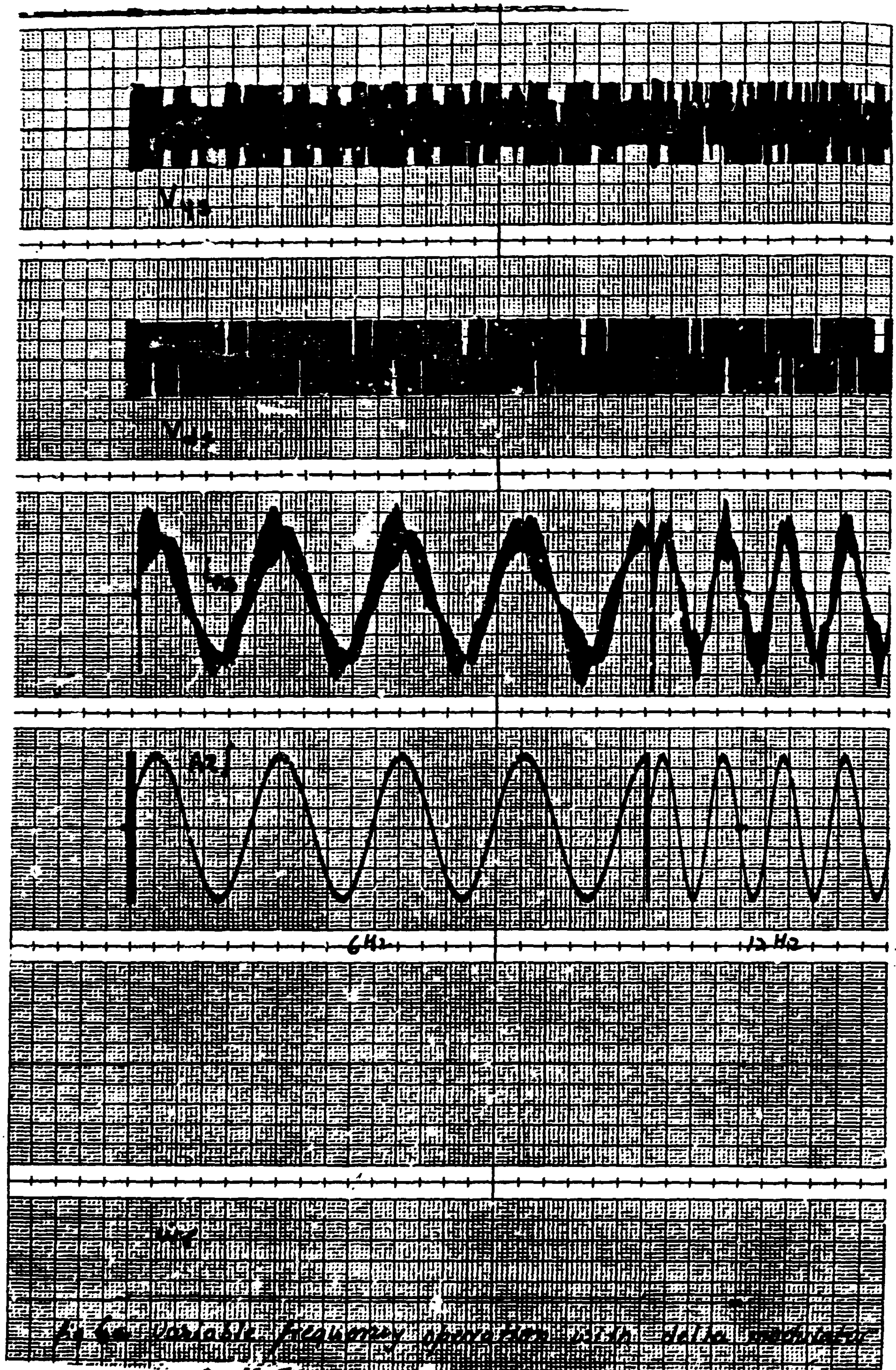


Fig 6a variable frequency operation with delta modulator

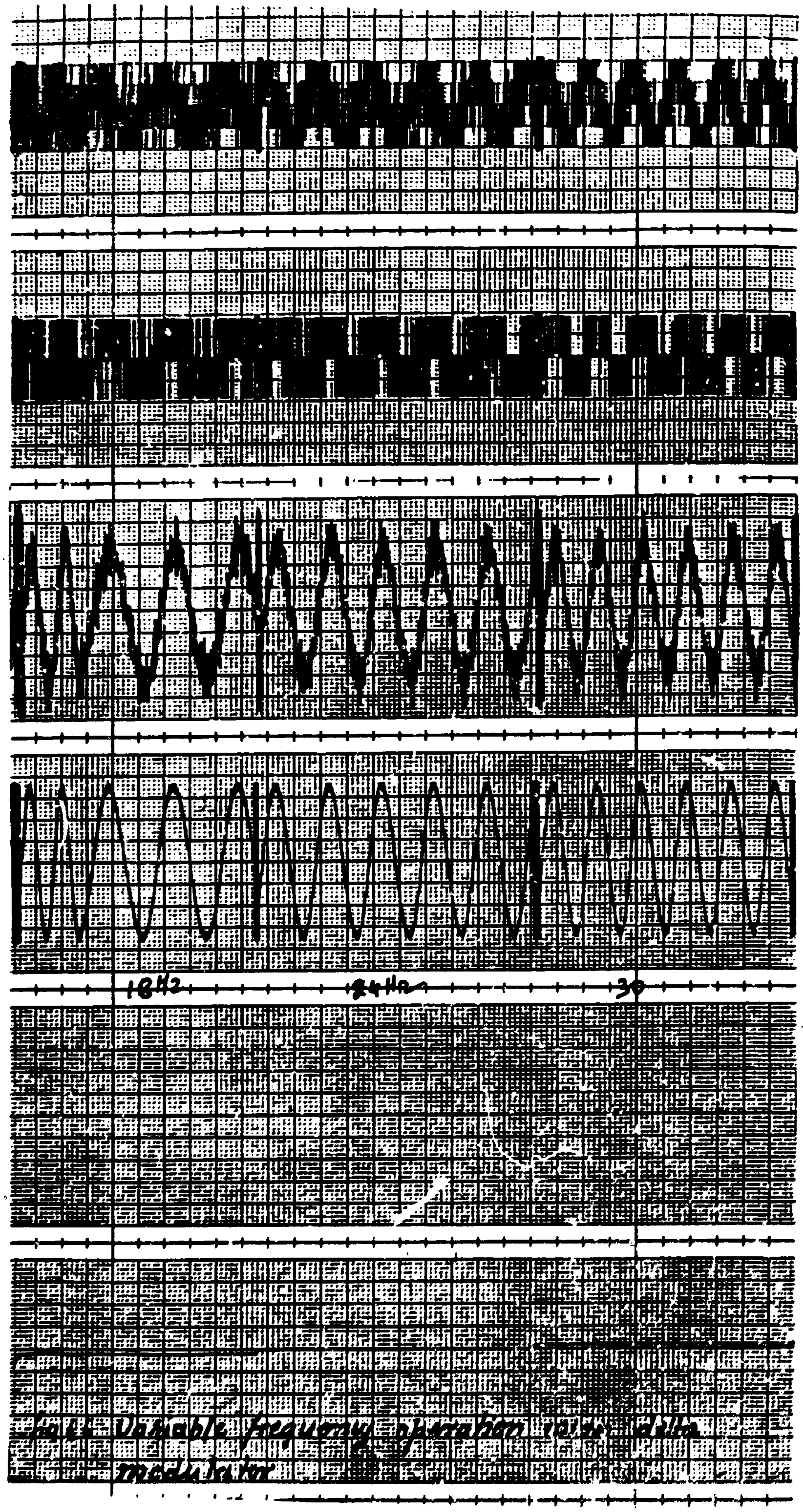
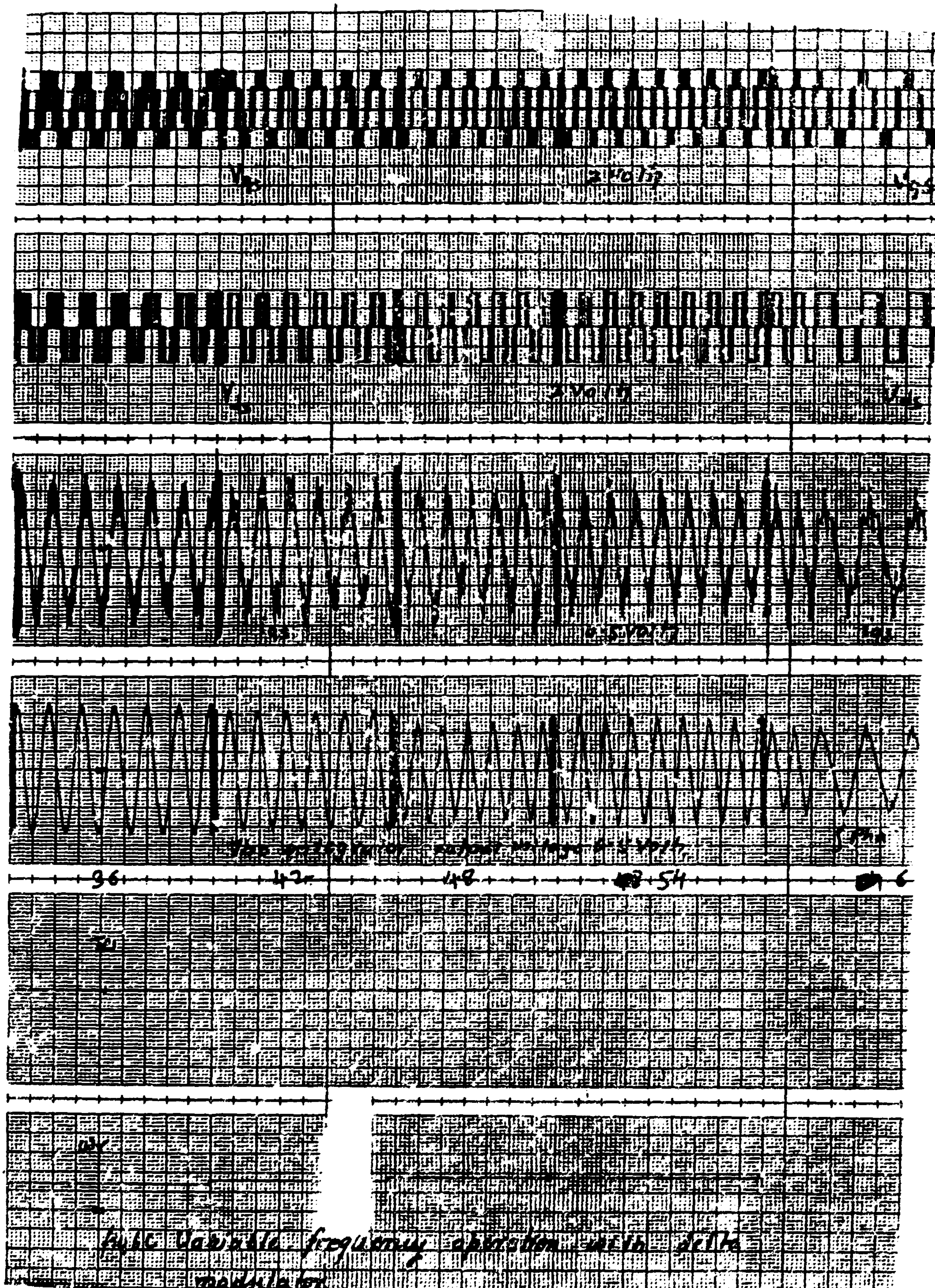
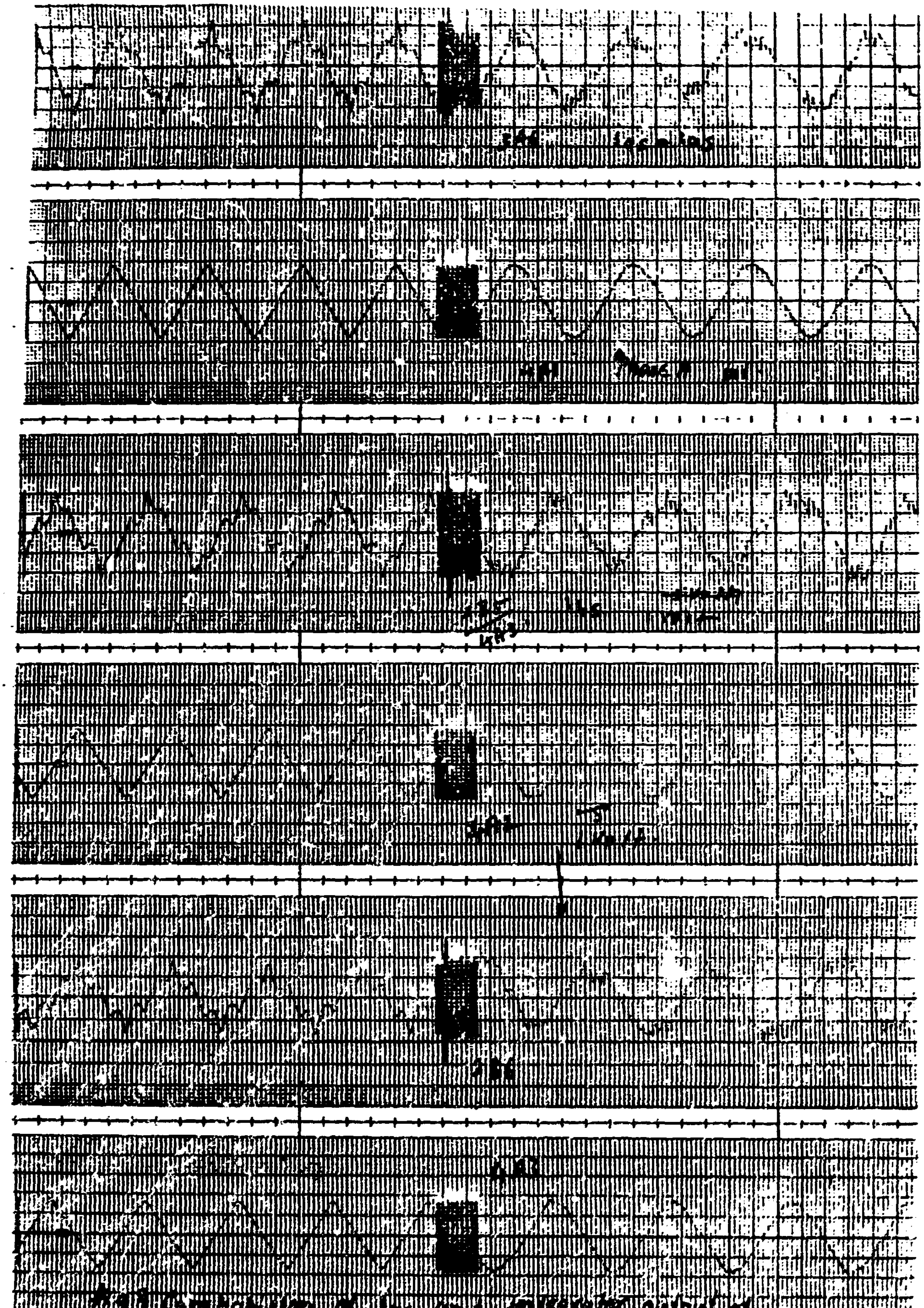


Fig 4 Variable frequency operation with delta modulator



Variable frequency operation with delta modulator



[illegible] Comparison of [illegible] output of [illegible] modulator

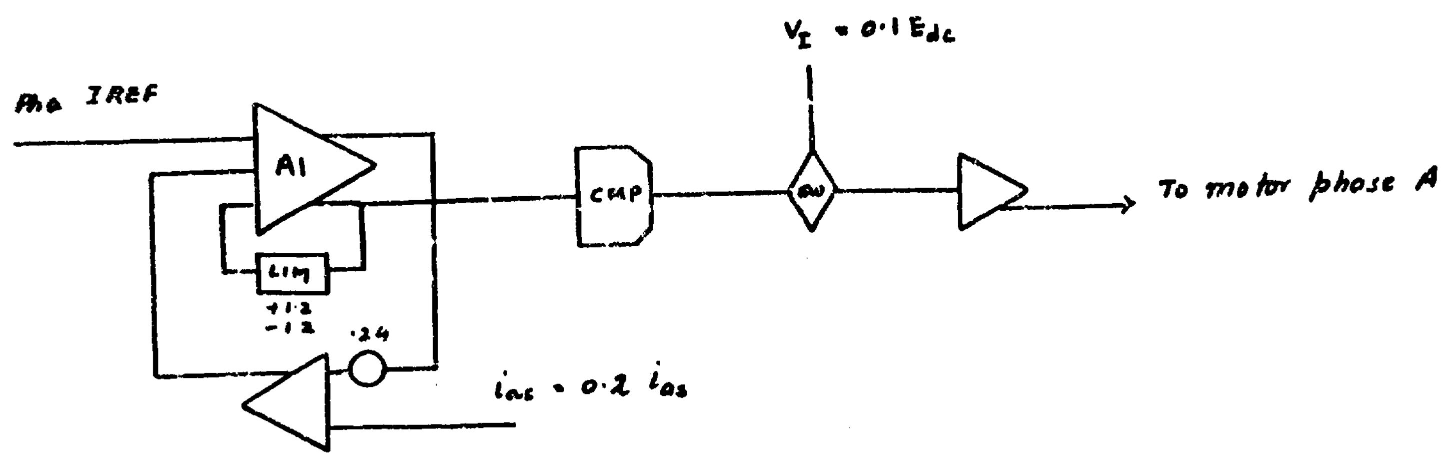
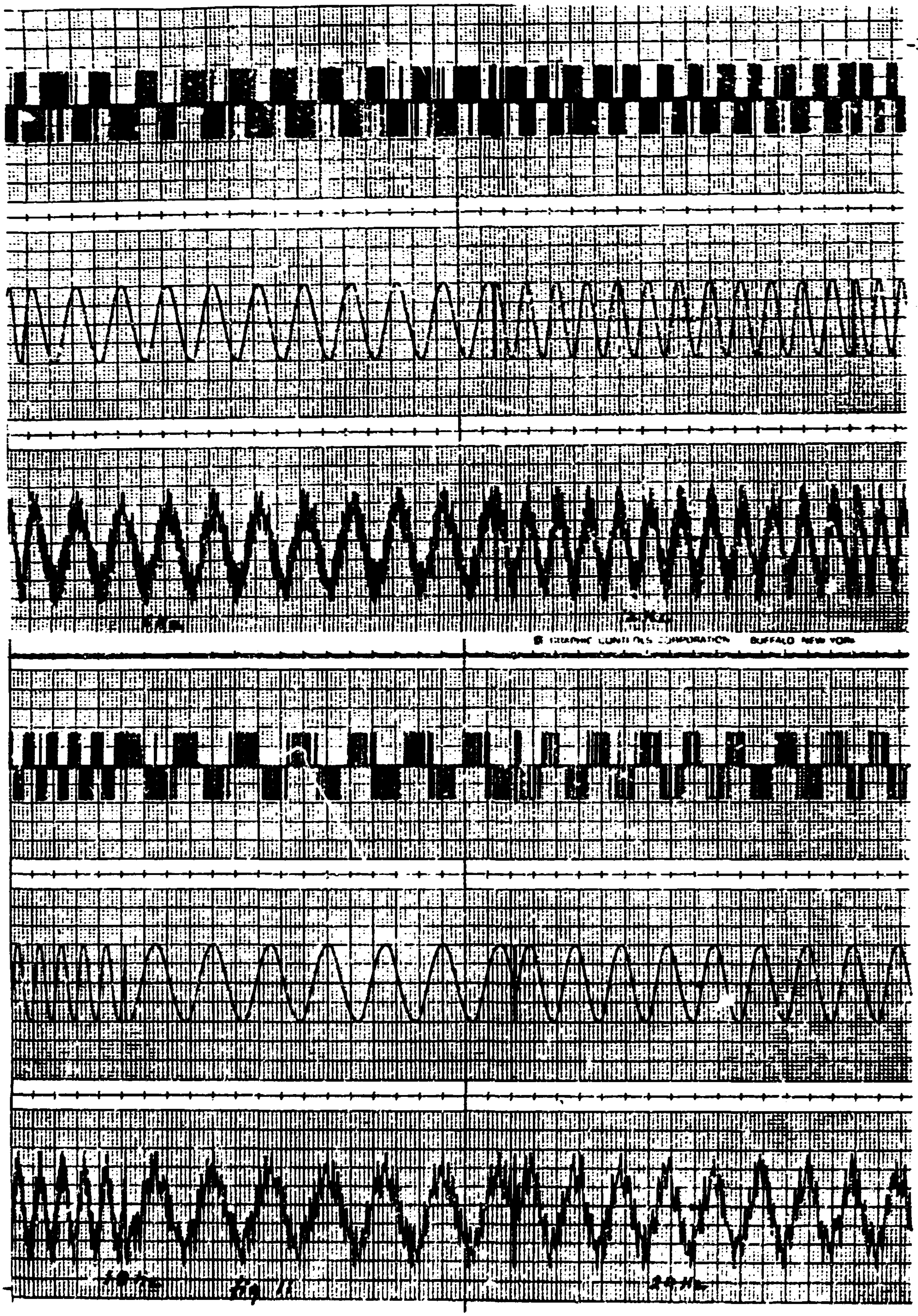
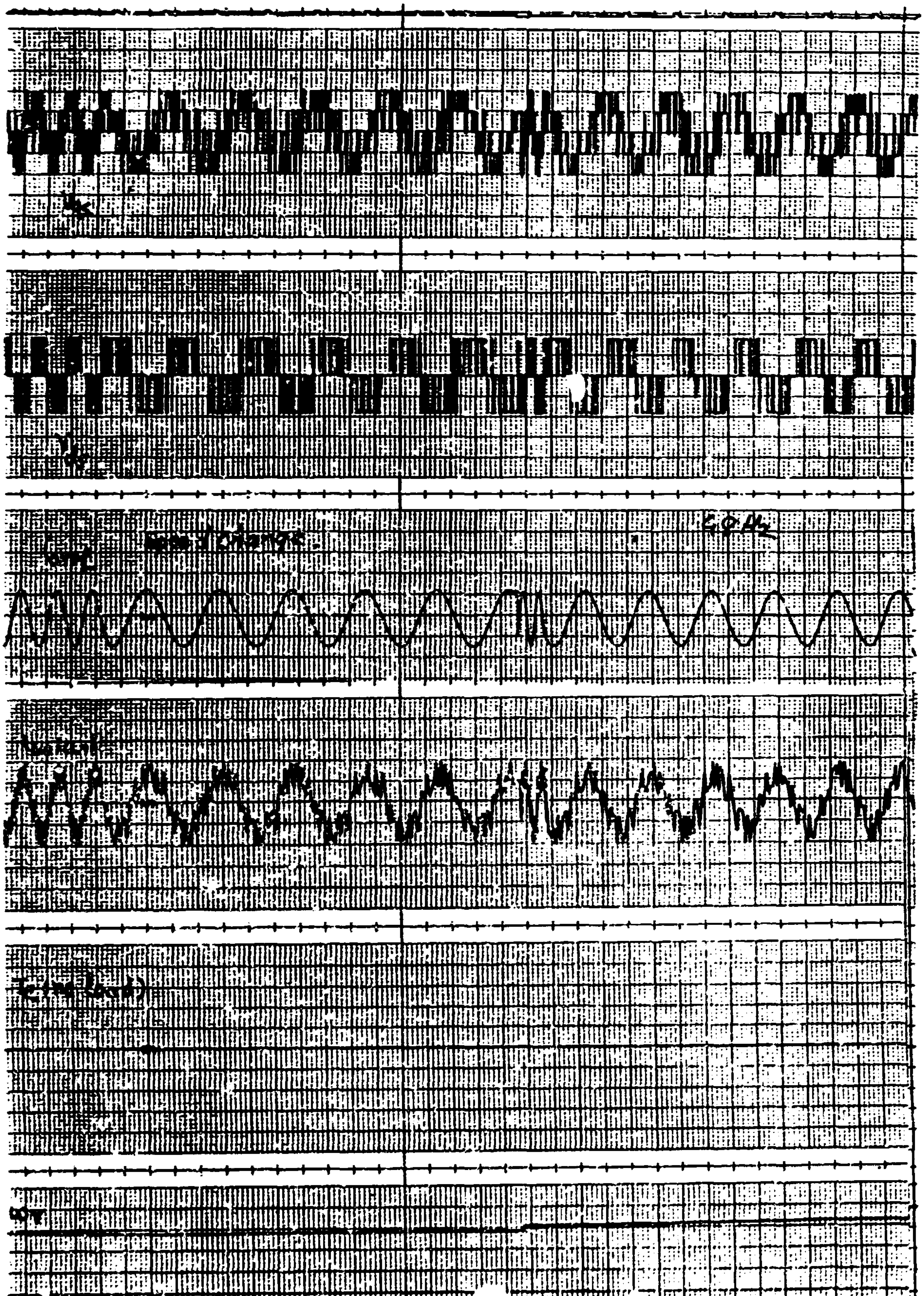


fig. 10 Anlog Simulation diagram for modified delta modulator


GRAPHIC CONTROLS CORPORATION BUFFALO NEW YORK



12 Stator phase current with modified delta modulator for F = 42 Hz and F = 48 Hz.

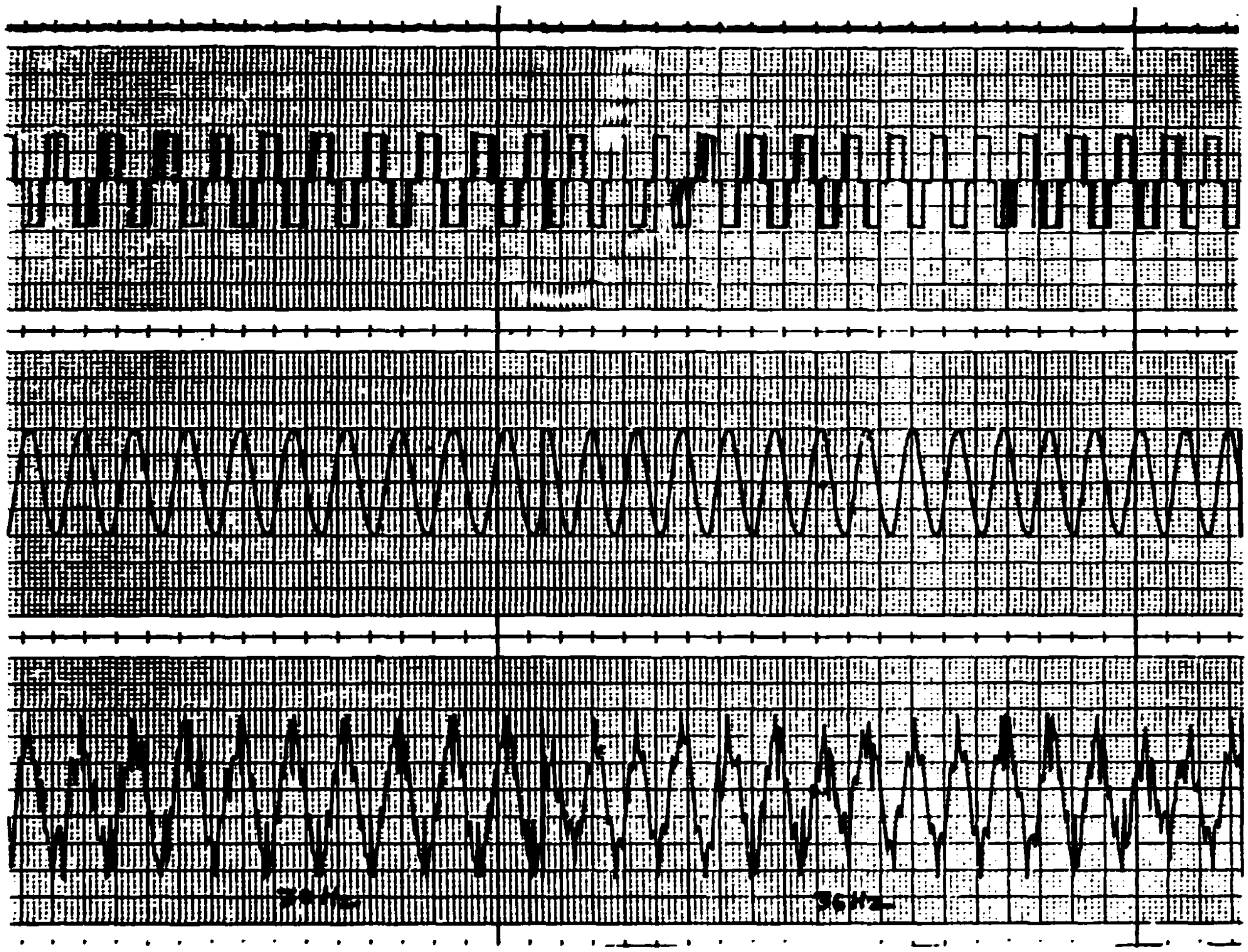
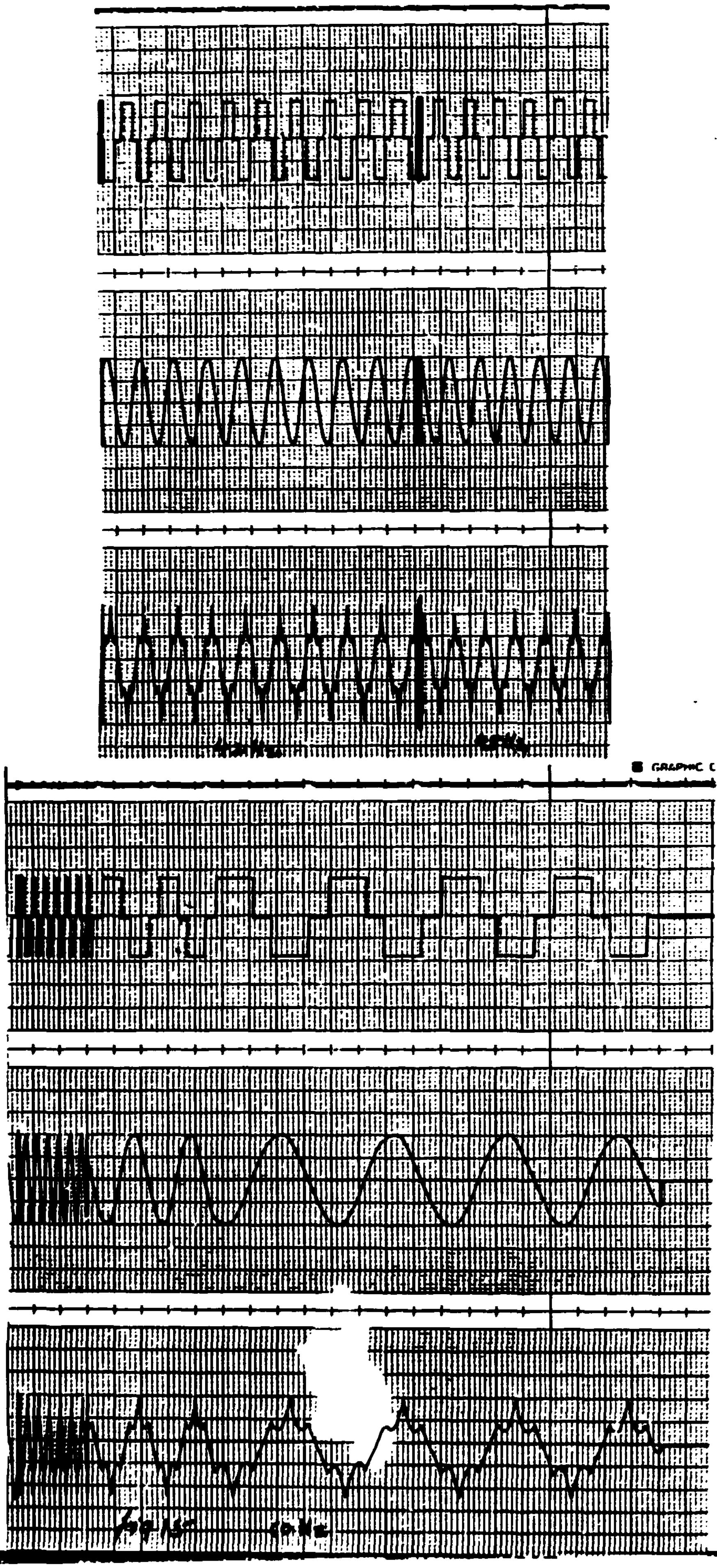


fig 14 Motor phase current with modified delta modulator for F = 30 and 36 Hz



SPECTRUM OF CURRENT WAVEFORM

N	A(N)	B(N)	C(N)	P(N)
1	-8.6987158E-03	0.1001712	0.1005482	100.000
2	1.1767861E-03	-2.8318195E-03	3.0665987E-03	3.04988

^C
^C

.R RPER

M= 5116 F = 18 Hz

SPECTRUM OF CURRENT WAVEFORM

N	A(N)	B(N)	C(N)	P(N)
1	-1.1634945E-02	0.1022752	0.1029349	100.000
2	2.1636316E-03	-2.1357536E-04	2.1741472E-03	2.11215
3	1.5195308E-03	2.9815666E-03	3.3464481E-03	3.25103
4	3.3056650E-03	9.0094650E-04	3.4262408E-03	3.32855
5	1.4044496E-03	1.1490700E-03	1.8146186E-03	1.76288
6	1.0442125E-03	-1.9037551E-03	2.1713276E-03	2.10941
7	-1.5669371E-03	1.2778892E-04	1.5721393E-03	1.52731
8	-3.2178231E-03	2.8683776E-03	4.3106815E-03	4.18777
9	-2.1311059E-03	5.2403397E-04	2.1945897E-03	2.13201
10	3.3838162E-03	-7.6944571E-06	3.3838248E-03	3.28734
11	1.4726432E-03	2.1903743E-03	2.6393973E-03	2.56414
12	4.3230779E-03	-2.0564995E-03	4.7872951E-03	4.650791
13	2.0336956E-03	1.4002383E-03	2.4691264E-03	2.39872
14	3.1577583E-04	-7.1921252E-04	7.8548142E-04	0.763085
15	-3.6099111E-04	3.9572585E-03	3.9736899E-03	3.86039
16	4.3260894E-04	-8.3093799E-04	9.3680760E-04	0.910097
17	2.8471800E-03	-4.5419219E-03	5.3605493E-03	5.20770
18	-3.8742896E-03	-3.7268368E-03	5.3758193E-03	5.22254
19	-4.0991534E-03	8.3171115E-05	4.0999972E-03	3.98309
20	1.2549533E-03	-2.6992937E-03	2.9767591E-03	2.89188
21	2.2707498E-03	2.6727444E-03	3.5071168E-03	3.40712
22	-1.5293706E-03	1.3474157E-03	2.0382600E-03	1.98014
23	-1.2364633E-03	-2.2061823E-03	2.5290477E-03	2.45693
24	-1.2559464E-03	-3.4187003E-03	3.6421029E-03	3.53825
25	-2.5277506E-04	2.6306135E-03	2.6427303E-03	2.56738
26	-8.5341395E-04	-3.5239926E-03	3.6258569E-03	3.52247
27	6.3160324E-04	-2.8707301E-03	2.9393903E-03	2.85558
28	-2.5872248E-03	-2.9166328E-04	2.6036128E-03	2.52937
29	5.3757019E-03	3.5126728E-03	6.4216075E-03	6.23851
30	-3.9587948E-03	1.3210363E-03	4.1733910E-03	4.05439
31	-1.5327911E-03	5.7693087E-03	5.9694536E-03	5.79925

SPECTRUM OF CURRENT WAVEFORM

N	A(N)	B(N)	C(N)	P(N)

=B
^C

.R RPER

M= 5116

SPECTRUM OF CURRENT WAVEFORM

N	A(N)	B(N)	C(N)	P(N)
1	-8.4905056E-03	9.8726459E-02	9.9090882E-02	100.0000
2	1.6992004E-03	-1.4889134E-03	2.2592356E-03	2.279963
3	-5.3789787E-05	3.5077743E-03	3.5081869E-03	3.540373
4	2.8119318E-03	-1.2523538E-03	3.0782057E-03	3.106447

^C
^C

.R RPER

M= 3831 F = 24Hz

SPECTRUM OF CURRENT WAVEFORM

N	A(N)	B(N)	C(N)	P(N)
1	-1.1119190E-02	0.1005604	0.1011733	100.0000
2	8.2686299E-04	2.7177865E-03	2.8407862E-03	2.807843
3	-1.2825064E-03	2.8067250E-03	3.0858594E-03	3.050074
4	-9.9547766E-04	-6.147872E-04	1.1700144E-03	1.156446
5	-2.4277223E-03	1.8434888E-03	3.0483252E-03	3.012975
6	-1.7431142E-03	1.0686611E-03	2.0446233E-03	2.020913
7	1.0471565E-03	6.0484494E-04	1.2092866E-03	1.195263
8	-2.9441556E-03	-1.6992763E-03	3.3993518E-03	3.359931
9	-2.7092689E-04	-1.2013230E-03	1.2314944E-03	1.217213
10	-1.1841161E-03	7.0847588E-04	1.3798801E-03	1.363878
11	3.8565928E-04	-3.4703626E-03	3.4917260E-03	3.451234
12	-1.1238814E-03	-5.8728986E-04	1.2680768E-03	1.253372
13	-6.7278469E-04	-1.7336551E-03	1.8596235E-03	1.838058
14	1.2092243E-03	1.9316371E-04	1.2245553E-03	1.210355
15	-3.9880761E-04	-5.9144725E-03	5.9279031E-03	5.859160
16	4.3718070E-03	-8.3751511E-03	9.4475318E-03	9.337973
17	9.6710800E-04	-2.9095728E-03	3.0660906E-03	3.030535
18	-4.5231213E-03	5.7523698E-04	4.5595532E-03	4.506678
19	5.2500085E-04	8.4643404E-04	9.9603040E-04	0.9844799
20	-9.4060111E-04	-6.8532755E-03	6.9175223E-03	6.837303
21	-7.4118981E-03	-1.2607045E-03	7.5183515E-03	7.431165
22	-4.7865724E-03	-2.6997132E-03	5.4954281E-03	5.431700
23	3.2140121E-03	-2.9810474E-03	4.3836650E-03	4.332829
24	-2.5043685E-03	-6.8774645E-04	2.5970864E-03	2.566969
25	5.0263149E-03	1.8104389E-03	5.3424276E-03	5.280474
26	-2.9650771E-03	6.8371685E-04	3.0428853E-03	3.007598
27	2.9093560E-03	-2.7834703E-03	4.0264204E-03	3.979728
28	2.2729748E-04	-5.2941625E-04	5.7614734E-04	0.5694661
29	8.9280488E-04	6.0046241E-03	6.0706353E-03	6.000237
30	6.6366169E-04	-1.4895004E-03	1.6306619E-03	1.611752
31	1.3582013E-03	4.0493766E-03	4.2710844E-03	4.221555

R RPER

M= 3064

SPECTRUM OF CURRENT WAVEFORM

N	A(N)	B(N)	C(N)	P(N)

^C

.R RPER

M= 3065 F = 30Hz

SPECTRUM OF CURRENT WAVEFORM

N	A(N)	B(N)	C(N)	P(N)
1	-1.0482918E-02	9.9074572E-02	9.9627621E-02	100.0000
2	-2.2690368E-03	4.7111092E-04	2.3174284E-03	2.326090
3	-2.6551327E-03	2.1693509E-04	2.6639802E-03	2.673937
4	-2.6935185E-03	-3.5268825E-04	2.7165108E-03	2.726664
5	6.8595173E-04	4.0445658E-03	4.1023218E-03	4.117655
6	-1.7414845E-03	-1.0040263E-03	2.0101834E-03	2.017697
7	-5.1446434E-04	-5.6218076E-04	7.6205039E-04	0.7648987
8	-3.2341788E-03	1.3574844E-03	3.5075170E-03	3.520627
9	2.7508314E-03	-3.2125935E-03	4.2294008E-03	4.245209
10	-1.0131472E-03	7.1860766E-03	7.2571458E-03	7.284271
11	7.5920619E-04	7.6437560E-03	7.6813670E-03	7.710077
12	2.3987137E-03	6.3756346E-03	6.8119415E-03	6.837402
13	-7.3305271E-03	3.5156948E-03	8.1299907E-03	8.160378
14	-1.2509052E-03	6.0981628E-03	6.2251389E-03	6.248406
15	-4.5056973E-04	-2.6144604E-03	2.6530016E-03	2.662918
16	-2.3220999E-04	5.9924298E-03	5.9969276E-03	6.019342
17	2.4612942E-03	9.8832296E-03	1.0185097E-02	10.22317
18	1.0873459E-03	1.5653953E-03	1.9059862E-03	1.913110
19	1.5924908E-03	6.0452305E-05	1.5936379E-03	1.599594
20	-3.0536214E-03	-3.6030496E-03	4.7229836E-03	4.740637
21	5.0607943E-03	-1.2668475E-03	5.2169478E-03	5.236447
22	-3.0659812E-03	-1.4583829E-03	3.3951616E-03	3.407852
23	-8.4996200E-04	-5.2244342E-03	5.2931230E-03	5.312907
24	-2.4771744E-03	-2.4625282E-03	3.4929127E-03	3.505968
25	4.0387153E-03	7.2822911E-03	8.3272438E-03	8.358369
26	1.0566504E-03	9.8124205E-04	1.4419939E-03	1.447384
27	1.4934149E-04	-2.2041621E-03	2.2092157E-03	2.217473
28	1.7245049E-03	-2.0337526E-03	2.6664708E-03	2.676437
29	-7.7445534E-04	7.9213106E-04	1.1078152E-03	1.111956
30	-4.3956866E-04	-2.4630444E-04	5.0387147E-04	0.5057548
31	1.4069428E-03	-2.5338207E-03	2.8982298E-03	2.909062

M= 2551

SPECTRUM OF CURRENT WAVEFORM

N	A(N)	B(N)	C(N)	P(N)
1	-1.0814926E-02	0.1011799	0.1017563	100.0000
2	-3.1553290E-03	-2.0001044E-03	3.7338426E-03	3.671363
3	-5.3912001E-03	-9.7264936E-05	5.3920774E-03	5.299011

.R RPER

M= 2550 F = 3k

SPECTRUM OF CURRENT WAVEFORM

N	A(N)	B(N)	C(N)	P(N)
1	-1.1251559E-02	0.1016232	0.1022441	100.0000
2	-2.9837282E-03	-1.0194159E-03	3.1530689E-03	3.083863
3	-6.0042799E-03	3.2362874E-04	6.0129953E-03	5.881017
4	-8.3754736E-04	-9.9238462E-04	1.2985811E-03	1.270079
5	2.8772012E-03	3.6629089E-03	4.6578096E-03	4.555576
6	-2.5874795E-03	1.5594177E-03	3.0210651E-03	2.954756
7	4.3396498E-03	-9.3365670E-05	4.3406542E-03	4.245382
8	-5.3327653E-04	-2.4401664E-03	2.4977583E-03	2.442935
9	-1.2338572E-03	-3.4100024E-03	3.6263647E-03	3.546770
10	-1.6294083E-03	-2.2434539E-03	2.7727347E-03	2.711876
11	-4.4764644E-03	3.7095477E-03	5.8137318E-03	5.686127
12	-3.0880845E-03	-4.3171677E-03	5.3079380E-03	5.191434
13	2.4578299E-03	6.7482931E-03	7.1819490E-03	7.024313
14	-3.4979736E-03	1.5889310E-03	3.8419424E-03	3.757616
15	2.0539002E-03	-1.6596549E-03	2.6406364E-03	2.582677
16	-1.2489295E-03	-3.9730043E-04	1.3106002E-03	1.281834
17	-5.2577942E-03	2.5170459E-04	5.2638156E-03	5.148281
18	1.1893184E-03	2.1298109E-03	2.4393797E-03	2.385838
19	4.7025364E-03	-4.0185796E-03	6.1856960E-03	6.049927
20	1.2961189E-03	-1.0522145E-03	1.6694550E-03	1.632812
21	-1.2022645E-03	2.7674134E-03	3.0172863E-03	2.951060
22	1.2231006E-03	-3.3921388E-04	1.2692680E-03	1.241409
23	4.1228724E-03	2.0027974E-04	4.1277343E-03	4.037135
24	8.8519440E-04	-1.9293450E-04	9.0597622E-04	0.8860911
25	-3.2590046E-03	-9.2754548E-04	3.3884293E-03	3.314057
26	7.9436647E-04	-1.4534589E-03	1.6563699E-03	1.620014
27	2.0721391E-05	3.4146549E-04	3.4209364E-04	0.3345850
28	1.9971469E-05	8.1793644E-04	8.1818027E-04	0.8002222
29	6.3154555E-04	-1.6894201E-05	6.3177146E-04	0.6179048
30	-6.5965942E-05	-1.2272825E-03	1.2290541E-03	1.202078
31	-1.1828747E-03	-1.3734287E-04	1.1908214E-03	1.164684

.R REBR

M= 2182

SPECTRUM OF CURRENT WAVEFORM

N	A(N)	B(N)	C(N)	P(N)
1	-3.5615951E-02	7.8726918E-02	8.6408466E-02	99.99999
2	7.8222193E-03	-6.7325011E-03	1.0320547E-02	11.94391

^C
^C

.R RPER

M= 2182 F = 42 Hz

SPECTRUM OF CURRENT WAVEFORM

N	A(N)	B(N)	C(N)	P(N)
1	-3.5427235E-02	7.9254165E-02	8.6811937E-02	99.99999
2	7.8515159E-03	-6.3820682E-03	1.0118157E-02	11.65526
3	3.8805970E-03	2.1919736E-03	4.4568805E-03	5.133949

^C
^C

.R RPER

M= 2178

SPECTRUM OF CURRENT WAVEFORM

N	A(N)	B(N)	C(N)	P(N)
1	-3.6245845E-02	7.8617647E-02	8.6570755E-02	100.0000
2	7.5464784E-03	-6.2817363E-03	9.8188361E-03	11.34198
3	3.9633936E-03	2.0280846E-03	4.4521475E-03	5.142785
4	-1.4790243E-03	1.7853347E-03	2.3183902E-03	2.678029
5	-7.5651780E-03	-2.3010431E-03	7.9074027E-03	9.134034
6	-7.9363141E-05	5.6765281E-04	5.7317381E-04	0.6620871
7	5.1928693E-03	-1.8029280E-03	5.4969485E-03	6.349660
8	-1.3822408E-03	2.7828196E-03	3.1071973E-03	3.589200
9	4.1083480E-05	-2.3328513E-03	2.3332131E-03	2.695152
10	2.6784518E-03	-1.1435875E-03	2.9123696E-03	3.364150
11	7.0976871E-03	-4.8631016E-04	7.1143280E-03	8.217935
12	-5.3185452E-04	-3.1393440E-03	3.1840776E-03	3.678006
13	1.0593928E-03	-4.4118492E-03	4.5372597E-03	5.241100
14	2.0479290E-04	5.7936478E-03	5.7972660E-03	6.696564
15	-8.0678862E-04	-7.2404655E-04	1.0840440E-03	1.252206
16	1.5895955E-03	-1.2303626E-03	2.0101259E-03	2.321946
17	2.6545217E-03	-2.2168411E-03	3.4584492E-03	3.994940
18	-2.6349146E-03	-2.9735605E-03	3.9730137E-03	4.589325
19	-2.7890131E-04	-1.4649176E-03	1.4912308E-03	1.722557
20	2.1200874E-03	3.1030441E-03	3.7581450E-03	4.341125
21	5.3452927E-04	-2.6268873E-04	5.9558958E-04	0.6879801
22	1.0401787E-03	-2.7093128E-04	1.0748840E-03	1.241625
23	1.5253402E-04	-3.9267785E-04	4.2126488E-04	0.4866134
24	-2.0196489E-03	-6.0932303E-04	2.1095632E-03	2.436808
25	2.6035588E-05	6.7823892E-04	6.7873846E-04	0.7840274
26	8.8518253E-04	4.6272608E-04	9.9883112E-04	1.153774
27	7.4437354E-04	-5.2808056E-04	9.1266702E-04	1.054244
28	5.4554129E-04	1.3868256E-04	5.6289264E-04	0.6502111
29	1.1120968E-04	8.5302272E-06	1.1153655E-04	0.1288386
30	-1.5039454E-04	-1.2542629E-04	1.9583225E-04	0.2262106
31	4.7034936E-04	7.3271268E-04	8.7085564E-04	1.005947

.R RPER

M= 1905

SPECTRUM OF CURRENT WAVEFORM

N	A(N)	B(N)	C(N)	P(N)
1	-4.0286720E-02	5.6455195E-02	6.9355674E-02	100.0000
2	6.1448985E-03	2.5794175E-03	6.6643208E-03	9.608905
^C 3	-9.4711540E-05	5.0515337E-03	5.0524217E-03	7.284800

^C

.R RPER

M= 1904 F~ 48Hz

SPECTRUM OF CURRENT WAVEFORM

N	A(N)	B(N)	C(N)	P(N)
1	-4.0031269E-02	5.6568798E-02	6.9300301E-02	100.0000
2	6.0069491E-03	2.7184037E-03	6.5934178E-03	9.514271
3	-5.0109542E-05	5.1595867E-03	5.1598297E-03	7.445610
4	-1.8946037E-03	1.5618391E-03	2.4553747E-03	3.543094
5	-3.4845790E-03	-5.0595375E-03	6.1433879E-03	8.864880
6	-2.8978387E-04	1.4181739E-03	1.4474778E-03	2.088703
7	-6.8589603E-03	4.9666939E-03	8.4683755E-03	12.21983
8	3.7869844E-03	-3.3562570E-03	5.0602090E-03	7.301857
9	-1.1182741E-03	1.3996961E-03	1.7915597E-03	2.565212
10	-2.2320931E-03	-2.5881142E-03	3.4176856E-03	4.931704
11	1.2037186E-03	-8.0677141E-03	8.1570186E-03	11.77054
12	-4.1853669E-03	2.0973591E-04	4.1906186E-03	6.047042
13	-4.8319995E-04	-1.3345480E-03	1.4193311E-03	2.048088
14	9.1367221E-04	6.3690087E-03	6.4342110E-03	9.284535
15	-6.3289405E-04	5.2551448E-04	8.2263019E-04	1.187051
16	3.6668638E-04	4.6059478E-04	5.8873295E-04	0.8495388
17	1.5500562E-03	1.2930532E-04	1.5554401E-03	2.244493
18	1.4841183E-03	-2.7452079E-03	3.1207008E-03	4.503156
19	-1.5117795E-03	-7.2186039E-04	1.6752790E-03	2.417419
20	-1.4658574E-03	-6.9961941E-04	1.6242553E-03	2.343793
21	-9.9605869E-04	-1.8360242E-04	1.0128390E-03	1.461522
22	1.3170058E-04	-8.8055769E-04	8.9910900E-04	1.297410
23	6.8745372E-04	5.2220299E-04	8.6330099E-04	1.245739
24	-2.8599735E-04	8.3408377E-04	8.8175409E-04	1.272367
25	1.3924392E-03	1.6195094E-05	1.3925334E-03	2.009419
26	-6.5543340E-04	6.0294761E-04	8.9058338E-04	1.285107
27	6.7306263E-04	-6.8424508E-04	9.5979410E-04	1.384978
28	4.7730071E-05	4.2469462E-04	4.2736833E-04	0.6166904
29	-1.8654900E-04	-6.0233939E-04	6.3056586E-04	0.9099035
30	2.6380402E-04	-9.9134899E-04	1.0258487E-03	1.480295
31	-7.3165377E-04	-9.7419434E-05	7.3811092E-04	1.065091

SPECTRUM OF CURRENT WAVEFORM

N	A(N)	B(N)	C(N)	P(N)
1	-4.0150255E-02	5.1298689E-02	6.5142915E-02	100.0000
2	8.9906566E-03	-2.7351379E-03	9.3974937E-03	14.42596
3	-8.1488490E-04	1.5995208E-03	1.7951336E-03	2.755685

^C
^C

.R RPER

M= 1597 F = 58Hz

SPECTRUM OF CURRENT WAVEFORM

N	A(N)	B(N)	C(N)	P(N)
1	-4.0170707E-02	5.1260829E-02	6.5125711E-02	100.0000
2	9.0203350E-03	-2.8377343E-03	9.4561717E-03	14.51987
3	-9.2781248E-04	1.6687559E-03	1.9093408E-03	2.931777
4	-4.2184428E-03	-2.9827282E-03	5.1664235E-03	7.933001
5	-1.5737924E-04	-1.7920906E-02	1.7921597E-02	27.51847
6	-1.9624743E-03	1.1418074E-03	2.2704690E-03	3.486287
7	-7.5261854E-03	1.8342733E-03	7.7464846E-03	11.89466
8	2.1591124E-03	2.1116417E-03	3.0200658E-03	4.637286
9	-5.9847604E-04	4.3276697E-05	6.0003874E-04	0.9213546
10	-5.0364609E-04	-1.7639803E-03	1.8344715E-03	2.816816
11	2.0956446E-03	-2.6460050E-03	3.3753621E-03	5.182841
12	-1.0879650E-03	-3.2780757E-04	1.1363002E-03	1.744780
13	-1.3922584E-03	-9.4307627E-04	1.6815994E-03	2.582082
14	1.3840114E-04	1.5685136E-03	1.5746078E-03	2.417798
15	-1.6186434E-04	-3.2700953E-04	3.6487711E-04	0.5602658
16	3.6745446E-04	-8.8945159E-04	9.6236530E-04	1.477704
17	1.0634972E-03	-3.6927091E-04	1.1257830E-03	1.728631
18	-3.1608681E-04	-6.6618720E-04	7.3737121E-04	1.132228
19	-1.3721376E-05	-5.4306193E-04	5.4323528E-04	0.8341333
20	-5.2319013E-04	7.6258794E-04	9.2480716E-04	1.420034
21	1.7183527E-04	-2.4102518E-04	2.9600761E-04	0.4545173
22	4.7211087E-04	-3.2011510E-04	5.7040545E-04	0.8758529
23	4.1911250E-04	1.1928552E-05	4.1928224E-04	0.6438045
24	1.6967364E-04	-5.3481053E-04	5.6108064E-04	0.8615348
25	2.1465716E-04	-8.8004628E-05	2.3199680E-04	0.3562292
26	-5.4535340E-04	1.4386962E-04	5.6401140E-04	0.8660349
27	2.8093916E-04	-2.1513439E-05	2.8176166E-04	0.4326427
28	3.3982934E-04	-1.5202902E-05	3.4016944E-04	0.5223274
29	1.7718451E-04	-5.7957390E-05	1.8642267E-04	0.2862505
30	3.6340361E-04	-2.2391904E-04	4.2790372E-04	0.6570427
31	7.6859811E-05	7.6124190E-05	1.0817728E-04	0.1661053

M= 1690

SPECTRUM OF CURRENT WAVEFORM

N	A(N)	B(N)	C(N)	P(N)
1	-4.0056661E-02	6.2430896E-02	7.4176505E-02	100.0000
2	1.2335555E-02	1.3604991E-03	1.2410354E-02	16.73084
3	-2.3269099E-03	-6.7594210E-03	7.1493774E-03	9.638331

^C
^C

.R RPER

M= 1690 F = 54Hz

SPECTRUM OF CURRENT WAVEFORM

N	A(N)	B(N)	C(N)	P(N)
1	-4.0260274E-02	6.3291132E-02	7.5011045E-02	100.0000
2	1.2340455E-02	1.1857559E-03	1.2397293E-02	16.52729
3	-2.3312483E-03	-6.4429804E-03	6.8517677E-03	9.134345
4	1.8052277E-03	5.3124214E-04	1.8817775E-03	2.508667
5	-1.0320514E-02	-1.2099984E-02	1.5903542E-02	21.20160
6	-2.0368542E-03	-6.0929526E-03	6.4243949E-03	8.564598
7	-3.4467527E-03	6.3640852E-03	7.2375196E-03	9.648605
8	-1.6418964E-04	1.8497942E-03	1.8570668E-03	2.475724
9	3.2847954E-03	-1.0221608E-03	3.4401591E-03	4.586204
10	-3.5612355E-03	1.6370635E-03	3.9194869E-03	5.225213
11	-1.0751036E-03	-6.0395845E-03	6.1345277E-03	8.178166
12	1.6275269E-03	3.3580072E-04	1.6618081E-03	2.215418
13	-2.4108987E-03	6.0828892E-04	2.4864529E-03	3.314782
14	6.2953727E-04	1.3353386E-03	1.4762948E-03	1.968103
15	-1.2923837E-04	-1.6994508E-04	2.1350384E-04	0.2846299
16	7.6632008E-05	-1.5213887E-03	1.5233174E-03	2.030791
17	1.0161098E-04	-3.8916292E-04	4.0220961E-04	0.5362005
18	-4.1650308E-04	-5.6044728E-04	6.9826643E-04	0.9308848
19	-1.6722553E-04	2.6859067E-04	3.1639426E-04	0.4217969
20	-9.2390575E-04	8.9711502E-05	9.2825107E-04	1.237486
21	1.6868288E-03	-3.5644337E-04	1.7240775E-03	2.298431
22	-3.2415424E-04	6.8256864E-04	7.5562950E-04	1.007358
23	-5.6311296E-04	-1.2868438E-03	1.4046576E-03	1.872601
24	2.6916232E-04	1.5715576E-05	2.6962074E-04	0.3594414
25	-3.9119944E-04	-2.8725390E-04	4.8533600E-04	0.6470194
26	4.3940902E-04	-3.0113701E-05	4.4043970E-04	0.5871664
27	2.1795508E-04	7.4686884E-04	7.7802152E-04	1.037209
28	-1.7181215E-04	-5.3800968E-04	5.6477770E-04	0.7529261
29	1.7535828E-04	-4.2527396E-04	4.6000921E-04	0.6132553
30	-1.5855047E-04	-3.0152505E-04	3.4066936E-04	0.4541589
31	3.2697021E-04	1.8728212E-04	3.7680792E-04	0.5023364

```
.TYPE RPER
FORTRAN IV        V02.5-2    Mon 27-Jan-86 06:50:42

        FORT/LIST:SY:/WARNINGS PER
***** C
        LINK PER,ANLIB,FORLIB
***** C
        RUN PER
***** C
        EDIT PER.FOR
***** C
      C       PROGRAM HARMONIC ANALYSIS OF CURRENT WAVEFORM
      C       DELTA MODULATED INVEWRTER,25 H.P. MOTOR AT NO LOAD
0001          M=0
0002          DIMENSION X(7000),A(50),B(50),C(50),P(50)
0003          FN=TEST(1)
0004     10   FO=FN
0005          FN=TEST(1)
0006          IF ((FO.LT.0).AND.(FN.EQ.0)) GO TO 30
0008          GO TO 10
0009     30   CALL TIMER (3,1,5)
0010          DO 40 I=1,7000
0011          FO=FN
0012          CALL WAIT
0013          CALL FADC (3,X(I))
0014          M=M+1
0015          FN=TEST(1)
0016          IF ((FO.LT.0).AND.(FN.EQ.0)) GO TO 45
0018     40   CONTINUE
0019     45   TYPE *, '                    M=',M
0020          TYPE *, '
0021          PI=3.141592654
0022          TYPE *, '             SPECTRUM OF CURRENT WAVEFORM'
0023          TYPE *, '             ----------------------------'
0024          TYPE *, '      N      A(N)          B(N)          C(N)          P(N)'
0025          TYPE *, '-----------------------------------------------------------'
0026          MAX = M - 1
0027          DO 50 N=1,31
0028          A(N)=0.0
0029          B(N)=0.0
0030          C(N)=0.0
0031          DO 70 I=1,MAX
0032          W1=(2.0*PI*(I-1)*N)/M
0033          W2=(2.0*PI*I*N)/M
0034          A(N)=A(N)+(X(I)*(SIN(W2)-SIN(W1)))/(N*PI)
0035          B(N)=B(N)+(X(I)*(COS(W1)-COS(W2)))/(N*PI)
0036     70   CONTINUE
0037          C(N)=SQRT(A(N)*A(N)+B(N)*B(N))
0038          P(N)=(100*C(N))/C(1)
0039          TYPE *,  N,A(N),B(N),C(N),P(N)
0040     50   CONTINUE
0041          TYPE *, '==================================================='
0042          STOP
0043          END
FORTRAN IV      Diagnostics for Program Unit .MAIN.

In line 0027, Warning:  Possible modification of index 'N'
In line 0043, Warning:  Non-standard statement ordering
FORTRAN IV      Storage Map for Program Unit .MAIN.

Local Variables, .PSECT $DATA, Size = 070274 (14430. words)

Name  Type  Offset     Name  Type  Offset     Name  Type  Offset
FN    R*4   070206     FO    R*4   070212     I     I*2   070216
```

```
FORTRAN IV      V02.5-2    Tue 28-Jan-86 02:17:38

          C        PROGRAM TO CALCULATE SWITCHIG POINTS PER
          C        CYCLE.WITH DELTA MODULATED INVERTER
0001               N=0
0002               FN=TEST(1)
0003         10    FO=FN
0004               FN=TEST(1)
0005               IF ((FO.LT.0).AND.(FN.EQ.0)) GO TO 30
0007               GO TO 10
0008         30       F1=TEST(2)
0009               F1=F2
0010               F2=TEST(2)
0011               F3=TEST(1)
0012               F3=F4
0013               F4=TEST(1)
0014               IF ((F3.LT.0).AND.(F4.EQ.0)) GO TO 50
0016               IF ((F1.LT.0).AND.(F2.EQ.0))  N=N+1
0018               GO TO 30
0019         50    TYPE *, 'NO OF SWITCHING POINTS=',N
0020               STOP
***** E
FORTRAN IV      Storage Map for Program Unit .MAIN.

Local Variables, .PSECT $DATA, Size = 000032 (   13. words)

Name   Type  Offset     Name   Type  Offset     Name   Type  Offset
FN     R*4   000002     FO     R*4   000006     F1     R*4   000012
F2     R*4   000016     F3     R*4   000022     F4     R*4   000026
N      I*2   000000

Subroutines, Functions, Statement and Processor-Defined Functions:

Name   Type   Name   Type   Name   Type   Name   Type   Name   Type
TEST    R*4
```

APPENDIX I

INDUCTION MOTO R SPECIFICATION

The induction motor selected for study has the following specifications

NAME PLATE SPECS

Stator line frequency.........60 Hz
Output horse power............25 HP
Line to Line voltage..........230 Volts (RMS)
Pole number...................4

Machine parameters

Stator Resistance....................0.0788 ohms
Stator referred rotor restance........0.0408 ohms
Stator leakage reactance..............0.3062 ohms
Stator referred rotor leakage
rectance.............................0.6682 ohms
Magnetizing reactance................5.5395 ohms