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OPERATION AND PERFORMANCE OF THE UNIVERSAL MOTOR
" A Comparative Study "

by

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ABSTRACT

This paper introduces a comparative analytical and experimental study for the performance of the universal motor when fed from different power sources namely; sinusoidal ac supply, square wave inverter, and a dc chopper. Throughout the present study, running performance of the motor with a variable frequency inverter as well as a d.c. chopper with different mark - space ratios are investigated. A very wide range of output characteristics are obtained using the dc chopper. Inverter is a well known efficient tool for speed control in conventional ac machines, however, this concept is not straight forward true for the universal motor A highly improved output characteristics are possible via improving the motor current waveform. An extensive analytical and experimental study are carried out and results are presented. An acceptable agreement between measured and calculated results is obtained.

1. INTRODUCTION

Universal motors are one of the series commutator machines family, and can operate satisfactorily from either a dc or ac supply. They are normally manufactured in fractional-horse-power sizes for domestic and hand tool machine applications. Such type of motors has been efficiently used to drive the portable apparatus such as vacuum cleaners ,electric drills,..etc. This is due to the comparable torque/speed characteristic produced with both dc and ac power sources of the same r.m.s. value [1].

Although the output characteristic of universal motors is suitable for the majority of the mentioned applications, sometimes it becomes essential to regulate their speed for certain loads. It is interesting to state that, the present universal motor-based drive applications uses speed regulation methods which often derate the motor output power. In one specific application, the speed of some vacuum cleaners is being regulated by an elementary variable voltage technique. With such technique it is difficult to improve the current waveform which results-in a significant reduction in the motor output torque. With the great progress in the field of power electronics and microprocessors it became both easy and cost effective to control the operation of conventional as well as most of special electrical machines to suit the requirements of their specific applications . However, it is hard to find a recent published material to study the performance of a such universal motor with the new techniques of power electronics and control applications.

The present study introduces a new technique to control the speed of the universal motor. This technique is based on the use of a dc chopper with different mark-space ratios. High output torque is obtained by the improvement of the current waveform. The motor performance is also studied when fed from a square wave inverter. A comparative study between the motor behaviour when excited from a pure ac supply and from the inverter output is investigated.

Theoretical analysis is presented to describe motor behaviour for different power sources. The results show that, the proposed technique would produce a potential variable speed high output torque universal motor suitable for a wide range of applications.

2. MATHEMATICAL REPRESENTATION

The uncompensated universal motor is represented as shown in Fig. 1. The voltage equation can be written as [2]:

$$\begin{vmatrix} V_F \\ V_a \end{vmatrix} = \begin{vmatrix} R_F + L_F P & 0 \\ - M \dot{\theta} & R_a + L_a P \end{vmatrix} \begin{vmatrix} i_F \\ i_a \end{vmatrix} \qquad (1)$$

where the field and armature currents are related by the following eqn.

$$\begin{vmatrix} i_F \\ i_a \end{vmatrix} = \begin{vmatrix} 1 \\ 1 \end{vmatrix} [i(t)] \qquad (2)$$

Also, the voltages across the field and armature windings are related by :

$$[V(t)] = [1 \quad 1] \begin{vmatrix} V_F \\ V_a \end{vmatrix} \qquad (3)$$

From equation 2 and 3 the voltage equation can be rewritten as :

$$V(t) = (R + LP - M\dot{\theta}) \, i(t) \qquad (4)$$

where,

$$R = R_a + R_F \quad \text{and} \quad L = L_a + L_F \qquad (5)$$

The motor performance has been obtained for three different power sources namely ;pure sinusoidal supply, square wave inverter and a square- wave chopper output. Representation of the universal motor under investigation will be presented subsequently .

2.1 Inverter Output

In this case the motor is excited through a single phase inverter designed specially for the present study. The construction of such inverter will be explained in the experimental sections.The output voltage waveform of the proposed inverter is shown in Fig 2. Such waveform is represented by Fourier series as follows :

$$V(t) = \sum_{n=1}^{\infty} V_n \sin(\omega_n t) \qquad (n = 1,3,5,\ldots.) \qquad (6)$$

where $\omega_n = n\omega$

Equation 4 can be rewritten for the nth component as:

$$V_n(t) = [R + LP - M\dot{\theta}] i_n(t) \qquad (7)$$

To solve equation 7, Laplace transform technique can be applied where the result equation is :

$$\frac{V_n \omega_n}{S^2 + \omega^2} = [R - M\dot{\theta} + LS] \, i_n(S) \qquad (8)$$

The nth current component can be obtained using the inverse Laplace transform for equation 8 , where,

$$i_n(t) = A_n \cos \omega_n t + B_n \sin \omega_n t + \frac{C_n}{L} e^K \qquad (9)$$

where $K = \frac{M\dot{\theta} - R}{L} t$ (10)

An , Bn and Cn are the partial fraction expansion constants defined by:

$$A_n = \frac{-V_n \omega_n L}{(R - M\dot{\theta})^2 + \omega_n^2 L^2} \tag{11}$$

$$B_n = \frac{V_n (R - M\dot{\theta})}{(R - M\dot{\theta})^2 + \omega_n^2 L^2} \tag{12}$$

$$C_n = \frac{V_n \omega_n L^2}{(R - M\dot{\theta})^2 + \omega_n^2 L^2} \tag{13}$$

the steady state value of the n<u>th</u> excitation current can be obtained from equation 9, where,

$$i_n(t) = \frac{V_n \sin(\omega_n t - \phi_n)}{\sqrt{(R - M\dot{\theta})^2 + \omega_n^2 L^2}} \tag{14}$$

and,

$$\phi_n = \cos^{-1} \frac{R - M\dot{\theta}}{\sqrt{(R - M\dot{\theta})^2 + \omega_n^2 L^2}} \tag{15}$$

The total instantaneous excitation current will be :

$$i(t) = \sum_{n=1}^{\infty} i_n(t) \tag{16}$$

The n<u>th</u> torque component is given by :

$$T_n = \frac{-MV_n^2 [1 - \cos 2(\omega_n t - \phi_n)]}{2[(R - M\dot{\theta})^2 + \omega_n^2 L^2]} \tag{17}$$

The total instantaneous torque will be :

$$T(t) = \sum_{n=1}^{\infty} T_n \tag{18}$$

Equations 6 to 18 can be applied to predict the motor performance when excited from an inverter out put. Also, using the same equations and considering the fundamental only, the motor characteristic can be obtained for a pure ac supply.

2.2 A Chopper Output

In this case the universal motor is fed by a square wave chopped voltage through an electronic circuit specially designed for this purpose. More details about this circuit will be given in the experimental section. The output of such circuit is shown in Fig. 3. The voltage waveform can be analyzed by using Fourier series as follows:

$$V(\omega t) = V\alpha + \sum_{n=1}^{\infty} \frac{2\ V}{n\ \pi} [\sin(n\alpha\pi)\ .\ \cos(n\omega t)] \qquad (19)$$

$n = 1,2,3,...$ and, $\alpha = \tau / T$ = mark-space ratio

Equation 19 can be rewritten as :

$$V(\omega t) = V_{dc} + \sum_{n=1}^{\infty} V_n(\omega t) \qquad (20)$$

$$\text{where} \quad V_n(\omega t) = \frac{2\ V}{n\ \pi} \sin n\alpha\pi \qquad (21)$$

The current and torque will be obtained for the dc component as follows:

$$I_{dc} = \frac{-\ V_{dc}}{R - M\dot{\theta}} \qquad (22)$$

and the dc torque component is:

$$T_{dc} = \frac{V_{dc}^2\ M}{(R - M\dot{\theta})^2} \qquad (23)$$

The ac current component can be obtained by taking Laplace transform of equations 7 and 21 , where the current is :

$$i_n(S) = \frac{A_n S + B_n\ \omega_n}{(S^2 + \omega_n^2)} + \frac{C_n}{(R - M\dot{\theta} + LS)} \qquad (24)$$

where;

$$A_n = \frac{V_{mn}(R - M\dot{\theta})}{(R - M\dot{\theta})^2 + \omega_n^2\ L^2} \qquad (25)$$

$$B_n = \frac{V_{mn}\omega_n L}{(R - M\dot{\theta})^2 + \omega_n^2\ L^2} \qquad (26)$$

$$C_n = \frac{-\ V_{mn}(R - M\dot{\theta})L}{(R - M\dot{\theta})^2 + \omega_n^2\ L^2} \qquad (27)$$

The steady state current can be obtained by applying the inverse Laplace transform technique to equation 24 leading to,

$$i_n(\omega t) = \frac{V_{mn} \cos(\omega_n t - \phi_n)}{\sqrt{(R - M\dot{\theta})^2 + \omega_n^2 L^2}} \qquad (28)$$

ϕ_n can be calculated using equation 15.

The total instantaneous current will be:

$$i(\omega t) = I_{dc} + \sum_{n=1}^{\infty} i_n(\omega t) \qquad (29)$$

The n<u>th</u> torque is then given by :

$$T_n = \frac{-MV_{mn}^2 \cos^2(\omega_n t - \phi_n)}{(R - M\dot{\theta})^2 + \omega_n^2 L^2} \qquad (30)$$

and the total instantaneous torque will be :

$$T = T_{dc} + \sum_{n=1}^{\infty} T_n \qquad (31)$$

2.3 Computer Simulation

A computer simulation program has been built to study the steady state performance of the universal motor. This program solves the system equations for different power sources. Calculation of motor performance in the case of both the inverter and dc chopper is carried out taking into consideration the effect of harmonics up to the 29<u>th</u> harmonic component. The simulation results are shown accompanied with the corresponding experimental measurements.

3 EXPERIMENTAL SET-UP

The experimental rig consists of a universal motor coupled with a dc generator employed as a mechanical load. The motor parameters are given in the appendix. Two electronic power converter circuits are built . One of them acts as a single phase inverter, while the other is a dc chopper. Another electronic circuit have been designed and built for current sensing and waveform chopping to ensure high output torque. More discussion will be given in the following sections.

4 THE SINGLE PHASE INVERTER

The inverter was built to excite the motor with a a variable frequency square wave voltage. This enables studying the effect of changing supply frequency on the motor performance. The inverter circuit is shown in Fig. 4. Four IGPT transistors of type "BUP203" are used as main switches to excite the motor through dc supply. Transistors 1 & 4 are turned on and off simultainously and followed by 2 & 3. The gate reference signals are generated using the counter "MN4017B". The output signals of the counter are connected to transistor gates via a NAND gate "7400" and an open collector inverter "74C06" with 2.4 Kohm pull up resistor. Such construction is designed to protect the transistor gate and to raise the pulse amplitude to 12 volt. The two upper transistors are triggered through an opto -coupler "TLP250" to isolate the ground of their gate signals from the power circuit common connection.

The recorded voltage and current waveforms are shown in Fig.5. It is clear that, the two waveforms alternate between positive and negative values. This means that the inverter circuit operates in the right order. The noise in the current waveform may be attributed to the commutator-brush contact effects. The variation of excitation current when exciting the motor from an ac supply is also shown in Fig. 5-b. There is a good matching between the calculated instantaneous current waveform for both the ac supply and the inverter ,shown in Fig. 5-c, and the recorded results. The calculated instantaneous torque using both the two supplies is also shown in Fig 5-d. It is clear that the torque variation is approximately the same. These results are obtained with a rms supply voltage equals the amplitude of that of the inverter. The difference in the instantaneous values is attributed to the difference in the voltage amplitudes. For the same rms values the inverter would produce a higher instantaneous torque due to the contribution of the time harmonics in the total developed torque.

The measured and calculated torque/speed characteristics are shown in Fig. 6. The difference in the average torque is due to the difference in voltage amplitude as explained earlier. There is a great possibility to get a higher torque value if the motor is excited through a square wave inverter output provided its rms voltage equals that of the ac source. This is attributed to the harmonic contents which add more torque to the fundamental. Also, the results illustrate clearly good matching between the experimental and simulated perfornmance. Through out the present study it has been observed that, the universal motor is working quite well with the inverter output and produces an output torque/speed characteristics comparable with those obtained with either dc or pure ac power supplies. As it was expected, [1], it has been found that, no benefit can be obtained from varying the inverter frequency, and there is no direct relation between power source frequency and running speed. The decisive factor on the motor speed is the supply voltage. Yet, frequency has adverse effect on speed due to transformer emf and inductive reactance drop.

5. THE CHOPPER CIRCUIT

The motor is excited from a square wave chopper circuit with different mark - space ratios through only one IGBT transistor switch as shown in Fig.7. To change such ratio a saw tooth signal is compared with a reference dc voltage by an operational amplifier "741" . The output of the amplifier is then a square wave with mark - space ratio varies with the reference voltage. As discussed in the inverter section the NAND gate "74C00" and the inverter "7406" are used with the pull up resistor to protect the transistor and to fed it with the required gate voltage. Since, this circuit is also employed to improve the current waveform, as will be discussed later, a snubber circuit is designed and constructed to protect the transistor switch against the spikes of voltage modulation. The employed snubber circuit consists of a resistor and series capacitor , connected across the drain and source of the transistor.

The excitation voltage and current waveforms are recorded for different mark-space ratios as shown in Fig. 8. It is emphasized that the excitation voltage as well as the current increase with increasing this ratio. This leads to an increase in motor speed for constant load torque. The same conclusion can be observed from the calculated results, Fig. 9 a , b which in phase with the experimental. Also a higher instantaneous torque is obtained with increasing the mark-space ratio .

Due to the possibility of exciting the motor with a square voltage waveform at different mark - space ratios, a family of torque/speed characteristic can be obtained as shown in Fig. 10. This gives the ability to change the motor speed while the load is maintained constant. This will permite utilization of the universal motor in many applications which require a variable speed drive. On the other hand, at lower values of mark - space ratio, the motor current does not reach its rated value which in turn decreases the developed torque. Also for each value of this ratio, increasing motor speed decreases its torque. Improving the excitation current wave shape may be useful in obtaining high torque high speed universal motor as will be discussed in the following section.

6. EXCITATION CURRENT WAVE SHAPE IMPROVEMENT

The technique of improving the current waveform is summarized in exciting the motor at twice value of its rated voltage [3]. This will ensure that, the rated current level would be reached at lower time compared with that would be taken with rated voltage. This technique is implemented as follows;, a signal voltage corresponding to the motor current (V_{sence}) is compared with a reference value ($V_{ref.}$) corresponding to the rated current. If the motor current tends to exceed the rated value , the comparator ,"LM311", output will be at low level and in turn the gate signal becomes low and temporally turns off the power transistors. The current will then decay until it becomes lower than the rated value which causes a decrease in V_{sence} leading to high comparator output. This turns the transistors on and the current tends to increase again , Fig.7. In this technique, the motor current swings about its rated value. Moreover, the current is maintained at its rated value at lower mark space ratio and at high speeds. This produce a higher output torque .

To examine the motor behaviour with the proposed excitation technique , the current waveform is recorded at different values of mark-space ratios, Fig. 11. It is emphasized that at low ratio the current is swinging about its rated value. Comparing the current waveform shown in Fig. 11 with that in Fig.8., its clear that the motor would produce a higher torque / speed characteristic with improved current wave shape. The measured torque/speed characteristic at different values of mark-space ratio and improved current wave shape is shown in Fig. 12. A comparison between this result and the torque/speed characteristic, shown in Fig. 10, illustrate potential current waveform improvements with different mark - space ratio . This produces a high torque high speed universal motor.

7. DISCUSSIONS

The output waveform of an electronic power converter are generally distorted and may be analyzed into numerous components. There is a unique power factor associated with each of these components; however they can not be evaluated into a simple expression. This adds a complexity to either analytical prediction or measurement of the motor power factor. It might be easier evaluate the power factor at the ac source from which the power is obtained, however it would be the overall power factor of both the motor and the converter. The fact that there is a certain reactive power associated with most electronic power converters would hinder any usefulness of such idea.

The sparking on the commutator-brush contact has been observed for different power sources. The best commutation has been obtained with the dc source followed by the dc chopper then the pure ac source and the worst was the square wave inverter. These observations might be explained as follows ; the dc chopper has a significant dc component and its harmonics are of low amplitude compared the inverter output. The significant number of harmonics contained in the output of the square wave inverter might explain its severe sparking compared with other power sources. All these observations have been obtained at a frequency of 50 Hz which is recommended for the motor under consideration. The effect of changing the frequency on the commutation has not subjected to investigation, however the available results give an idea about this effect at least over the range from zero to 50 Hz. It can be claimed that, over this frequency range, the lower frequency gives better commutation. The torque pulsations associated with ac excitation might impose some restriction on the lower limit of the working frequency. This working frequency is usually a compromise between the torque pulsation and the quality of commutation process.

8. CONCLUSIONS

In this paper a comprehensive study about the excitation techniques of a universal motor have been introduced. The study explores more information about the possibility of efficient use of such type of motors. Throughout this study it has been found that, the universal motor can operate from dc , ac power source as well as inverter output at approximately similar torque/speed characteristics. In spit of the notable success of variable frequency inverters in changing the speed of conventional ac motors, it was confirmed that it is useless with universal motors.

The paper also presents a technique of controlling motor speed with high developed torque. The proposed technique depends on exciting the motor by a square voltage chopper output with different mark-space ratios. A current waveform chopping technique which supplies the motor with approximately square current pulses would ensure higher torque at lower values of such ratio.

A complete theoretical investigation is presented to describe the motor behaviour using different excitation power sources. This study has been verified experimentally and an acceptable agreement between measured and calculated results have been reached.

9. LIST OF SYMBOLS

$V(t)$	supply voltage
V_a	armature voltage
V_F	field voltage
R_a	armature resistance
R_F	field resistance
L_a	armature self inductance
L_F	field self inductance
M	mutual inductance
$\dot{\theta}$	speed
$i(t)$	motor current
T	motor torque
ϕ_n	phase angle between the nth voltage and current

10. APPENDIX

The universal motor has the following data:

Rated ac voltage = 220 V
No. of poles = 2
Armature resistance = 2.46 ohms
Field resistance = 4.00 ohms
Armature leakage inductance = 0.120 henry
Field leakage inductance = 0.110 henry
Mutual inductance = 0.380 henry
Full load speed = 3000 rpm

11. REFERENCES

[1] " The Performance and Design of A.C. Commutator Motors " (Book), E.OPENSHAW TAYLOR, 1958.,Pitman

[2] " The Unified Theory of Electrical Machines" (Book), CHARLES V. JONES , 1968., Plemun Publishing Corp.

[3] M.M.EL-Shanawany " Excitation Current Improvement For A Two-Phase Stepping Motor" UPEC'89 , 19 - 21 Sept. 1989 , Belfast, Northen Ireland, pp. 321 - 325.

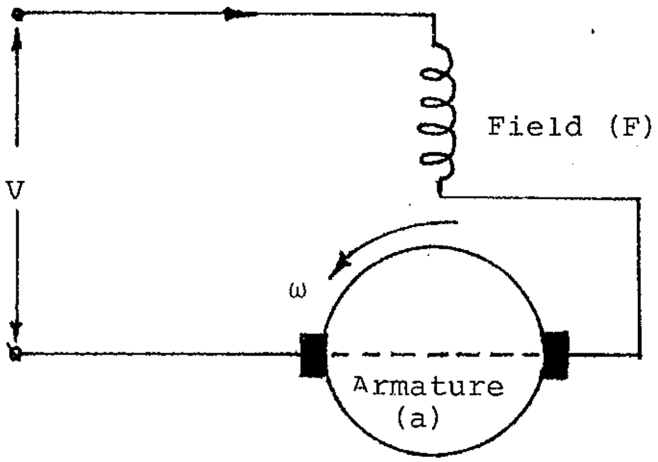


Fig. 1. The universal motor.

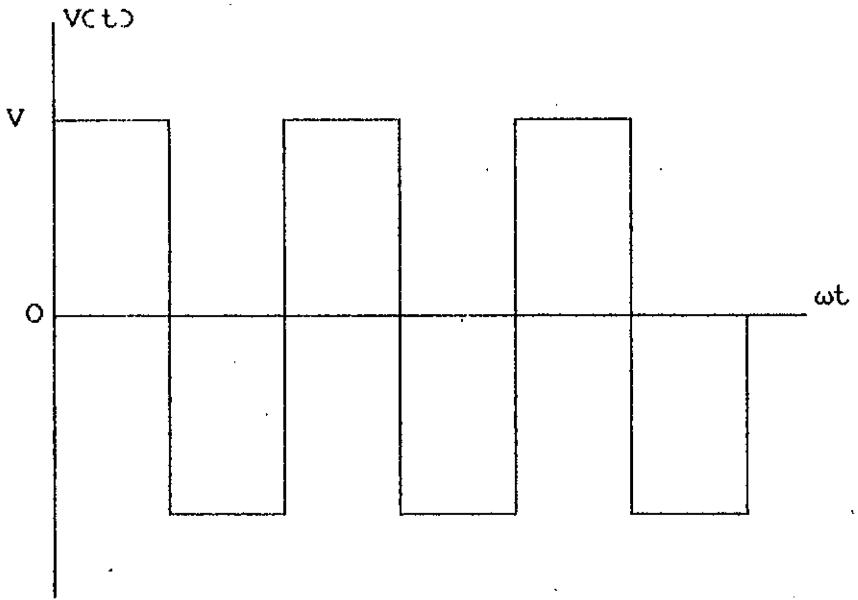


Fig.2 Inverter output voltage waveform

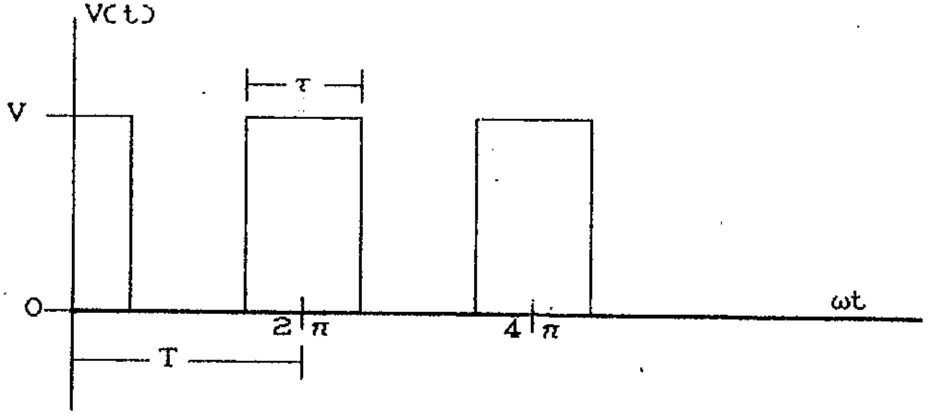


Fig. 3. Square Wave Chopper Voltage Output.

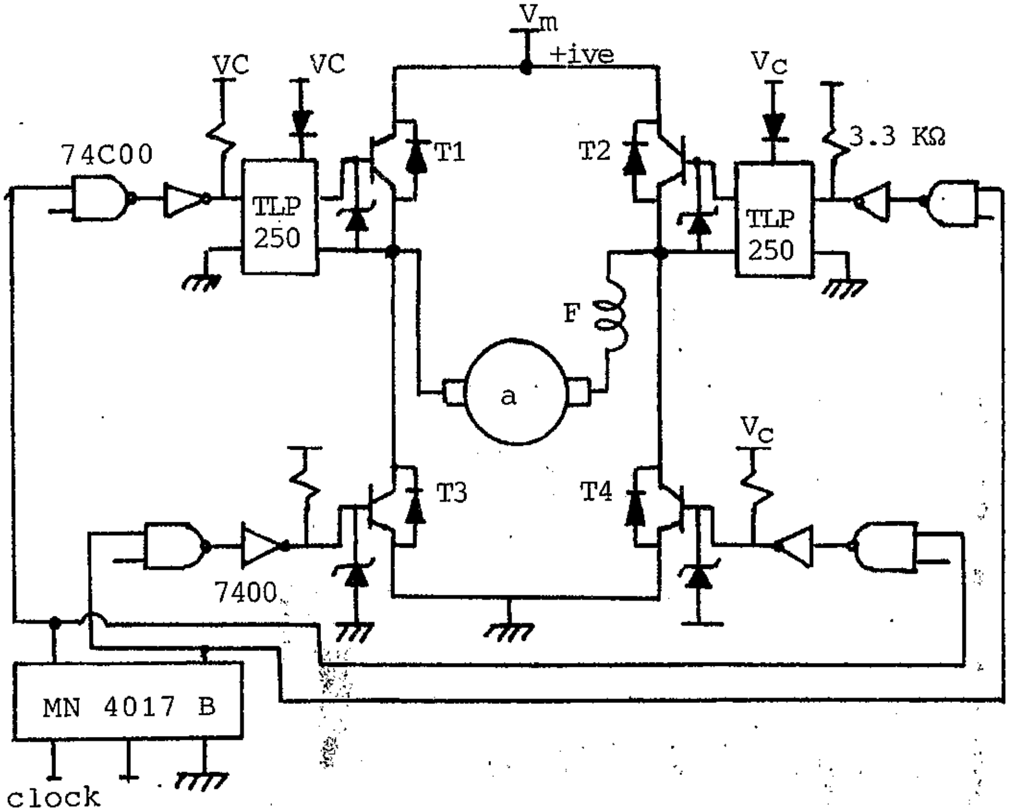


Fig. 4. The inverter circuit.

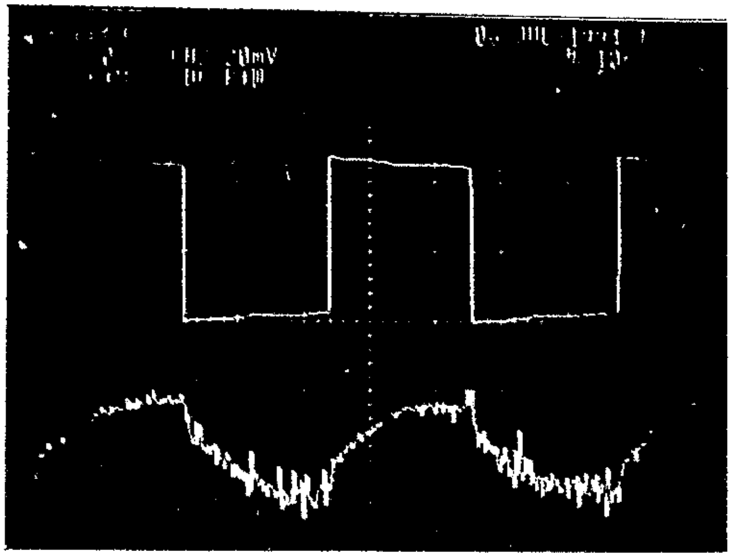


Fig.5.a. Recorded voltage and current waveforms for the inverter-supplied motor.

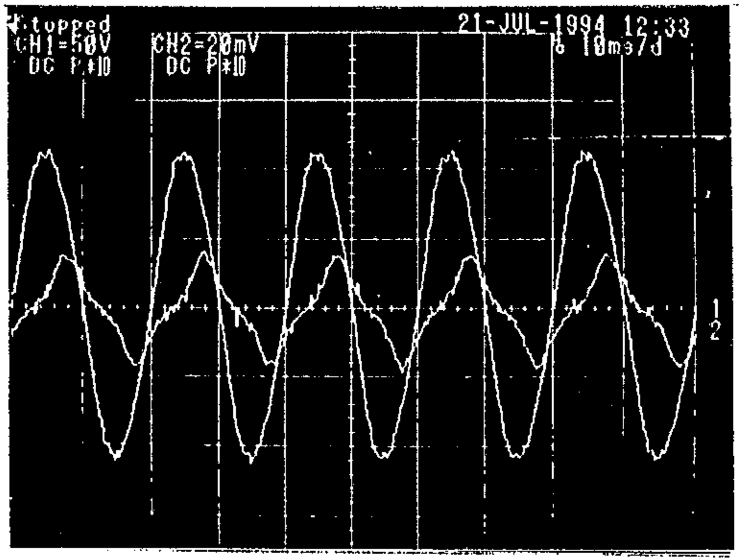


Fig.5.b. Recorded voltage and current waveforms for ac-supplied motor.

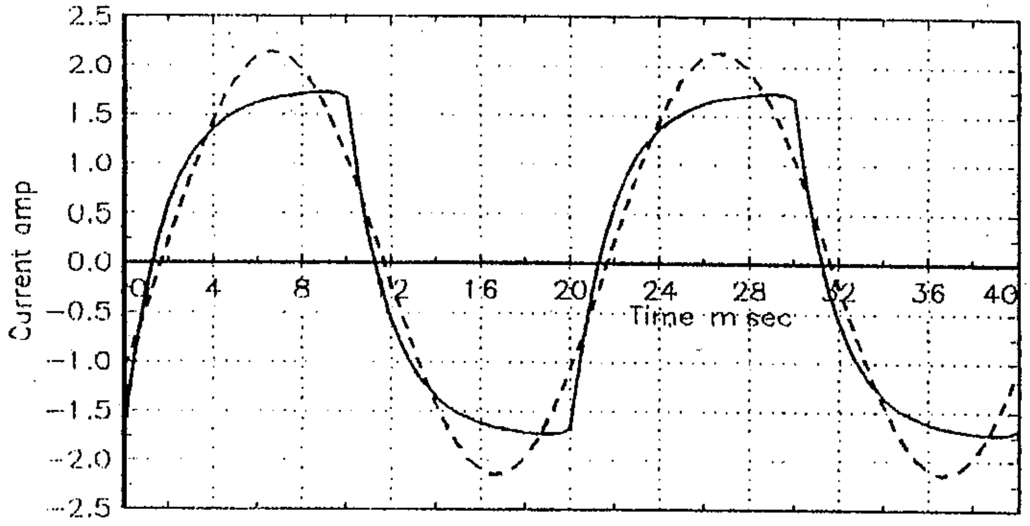


Fig.5.c. Calculated instanteneous current.

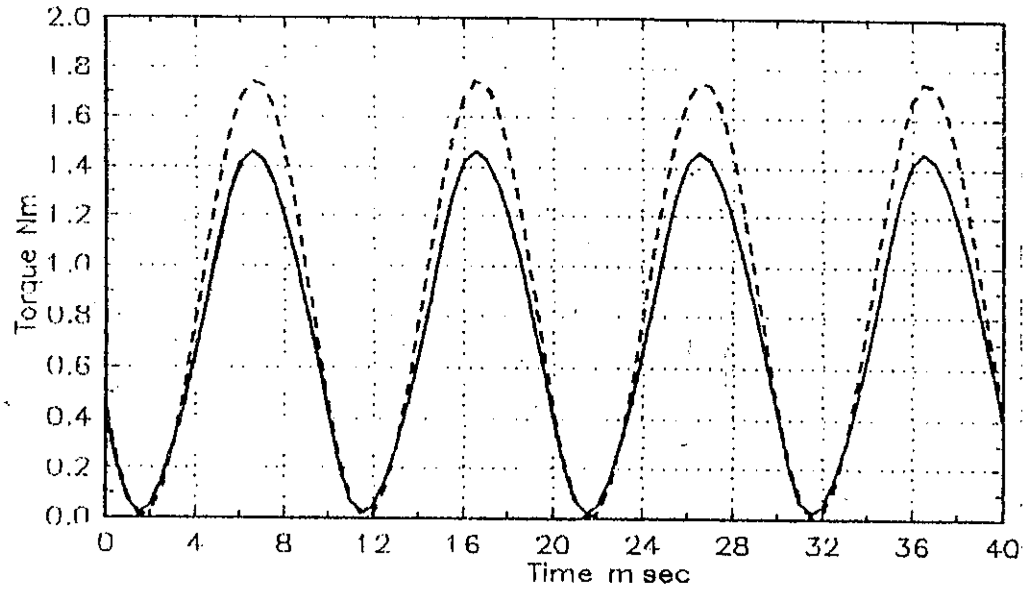


Fig.5.d. Calculated instanteneous torque.

--- ac supply.
—— the inverter.

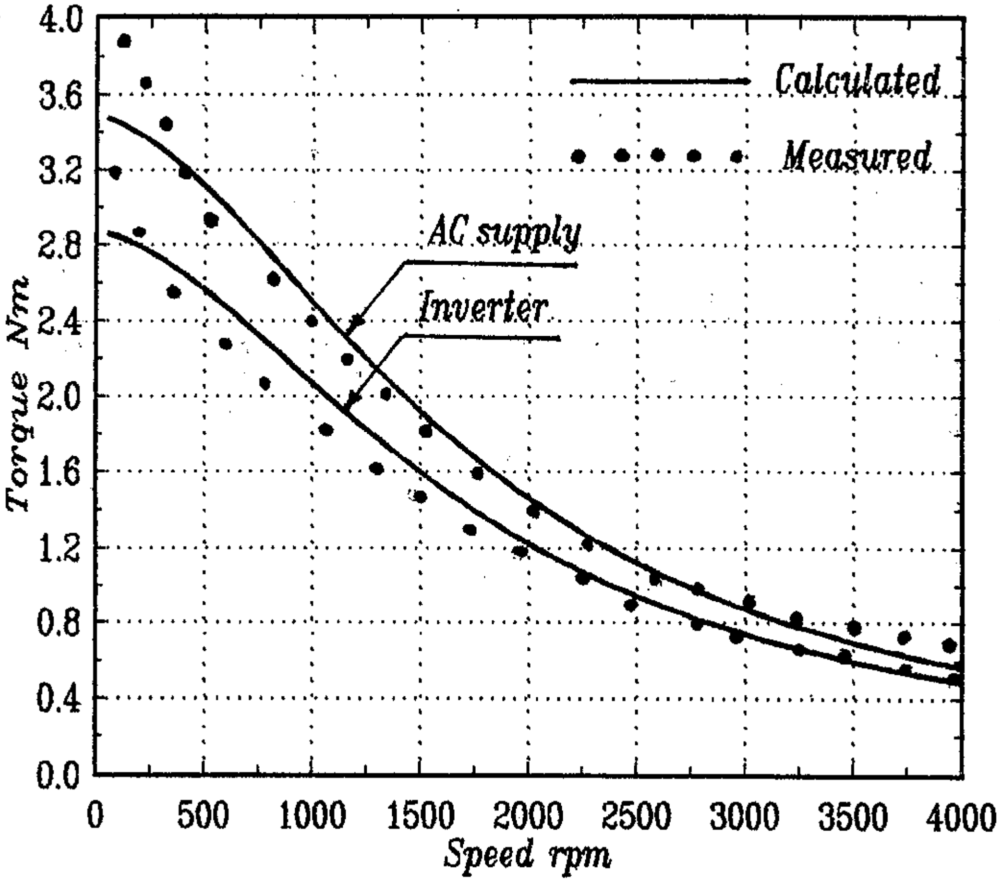


Fig. 6 Torque/speed characteristics.

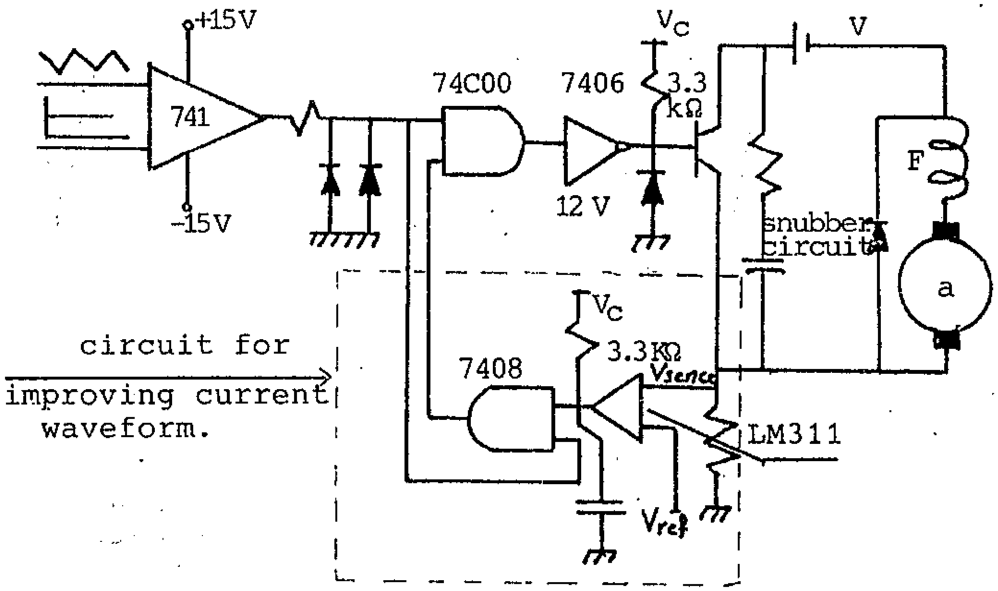
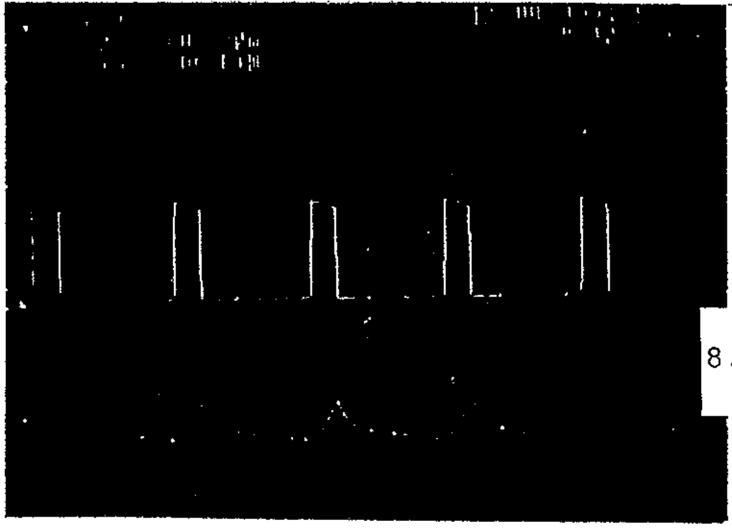
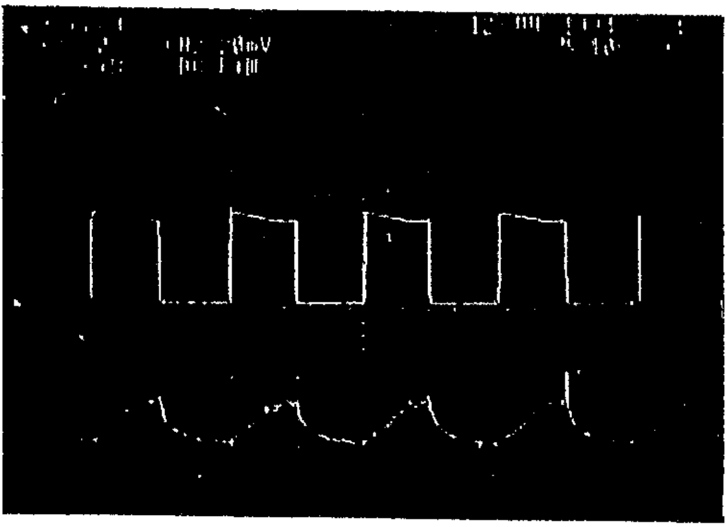


Fig.7. Shopper circuit with current level control.



8.a. α = 0.2



8.b. α = 0.5.

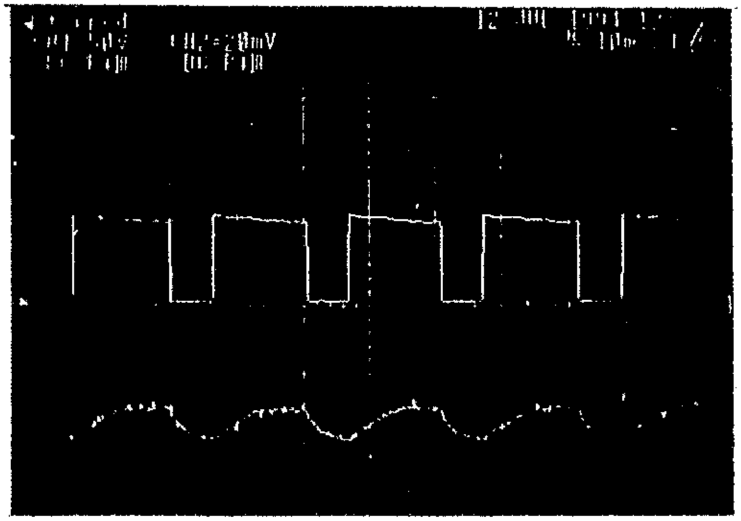


Fig. 8.c. α = 0.7.

Fig.8. Recorded voltage and current waveforms for chopper output at different values of "α".

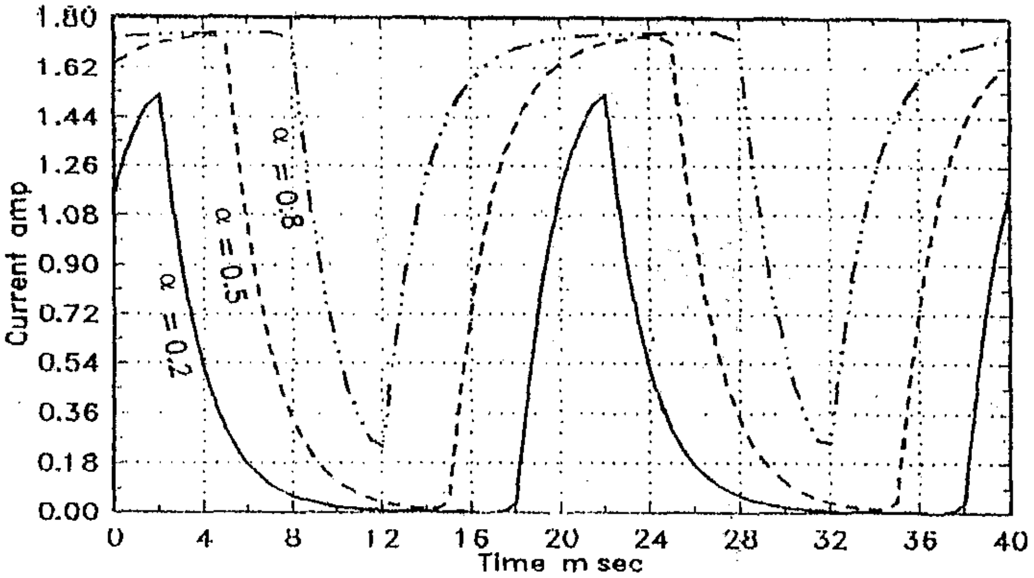


Fig.9.a. Calculated instanteneous current for chopper output at different values of "α".

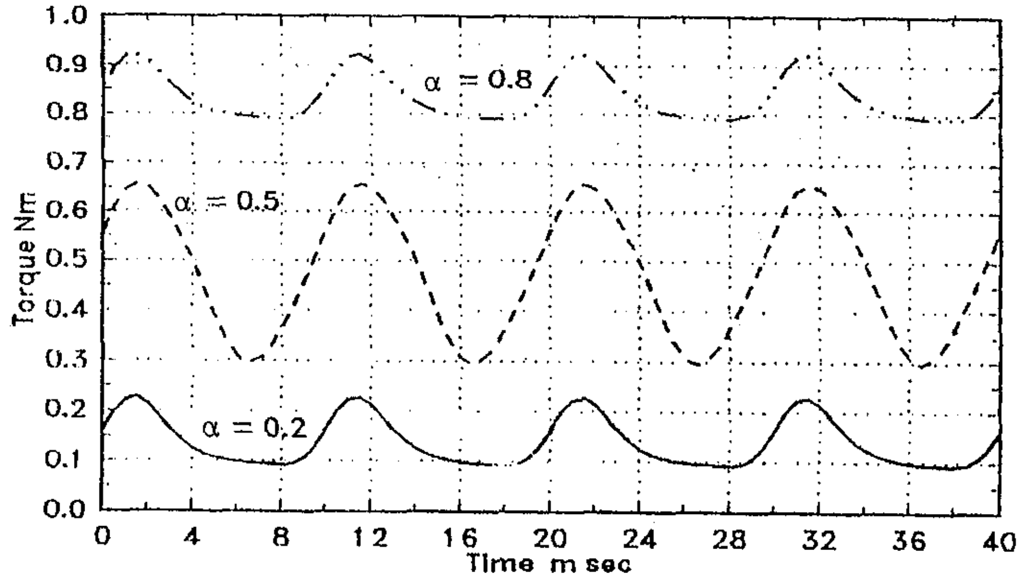


Fig.9.b. Calculated instantaneous torque for chopper output at different values of "α".

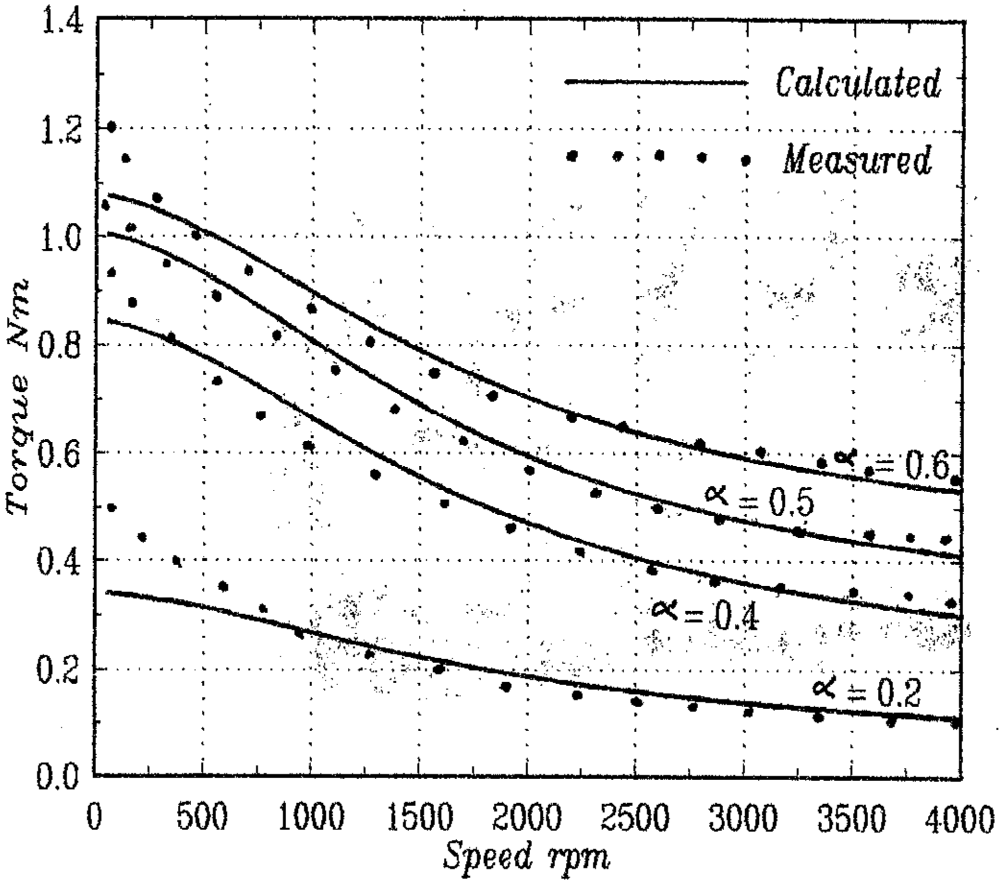


Fig. 10 Torque/speed characteristics for chopper output at different values of α

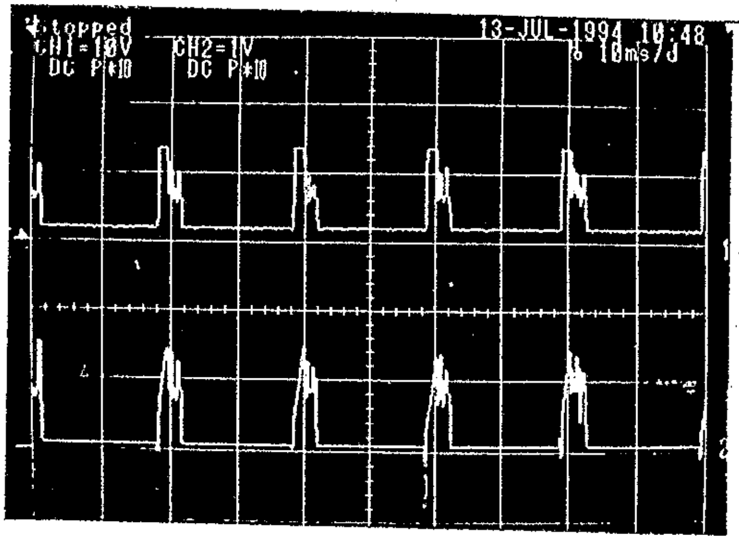


Fig. 11.a. α = 0.2.

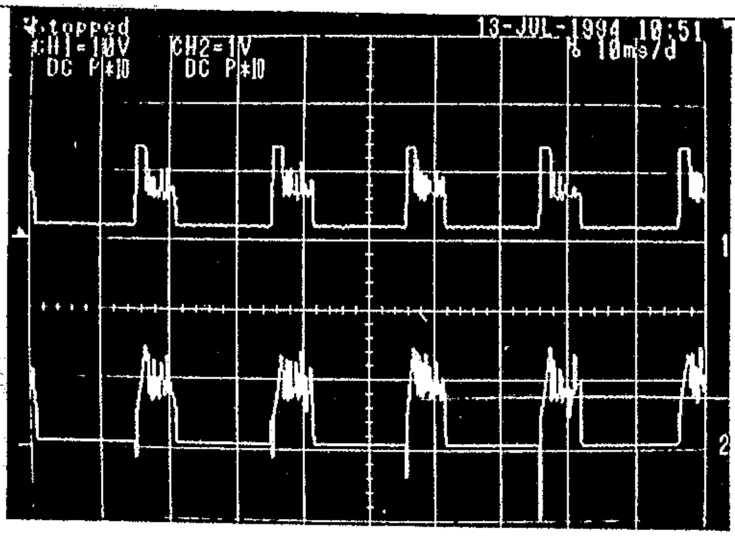


Fig. 11.b. $\alpha = 0.3$.

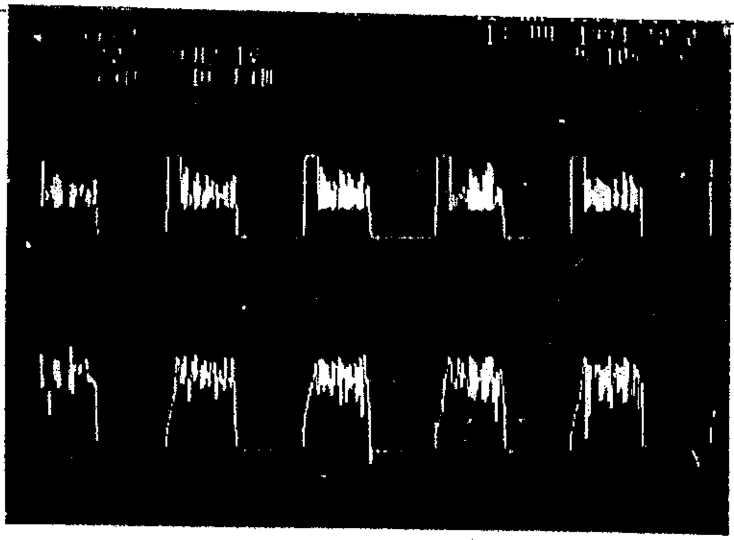


Fig. 11.c. $\alpha = 0.5$.

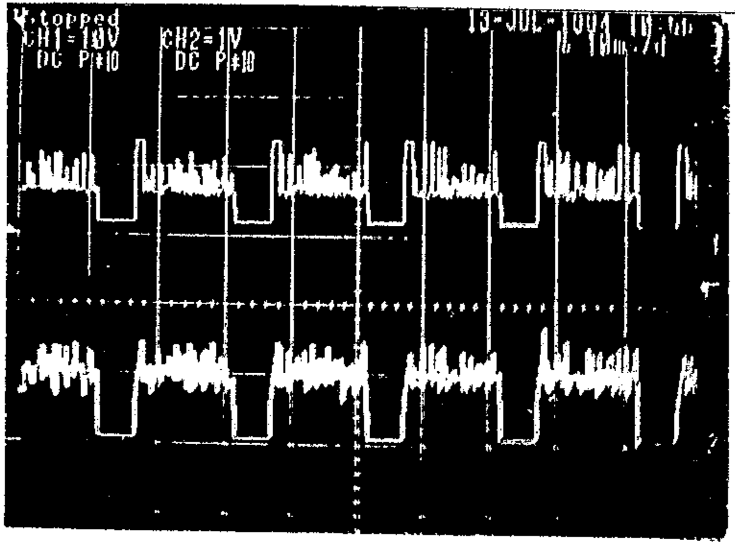


Fig. 11.d. α = 0.7.

Fig.11. voltage and current waveform at different values of "α". (with current level control).

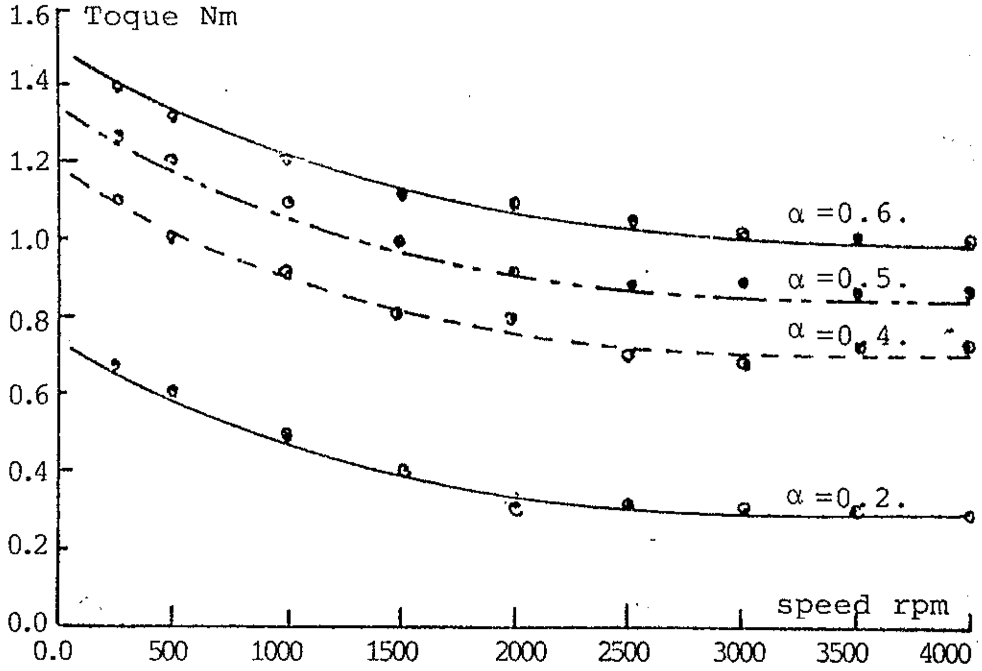


Fig. 12. Torque/speed characteristic at different values of "α". (with current level control).

خصائص تشغيل المحركات الكهربية عامة-التغذية
'دراسة مقارنة'

تنتمي المحركات الكهربية عامة-التغذية إلى مجموعة محركات التوالي التي تعطي خصائص تشغيل متقاربة على كل من المنبعين المتردد والمستمر، وهي غالبا تنتج بقدرات صغيرة في حدود الإحتياجات اللازمة للتطبيقات المنزلية والعدد اليدوية الخفيفة، ومن أهم متطلبات هذه التطبيقات الحاجة إلى تنظيم سرعة المحرك حسب طبيعة الحمل.

نظرا لأن الطرق المستخدمة في تنظيم سرعة هذه المحركات تؤدي بالضرورة إلى خفض القدرة الميكانيكية للمحرك بدرجة ملحوظة؛ ففي هذا البحث تم عمل دراسة مقارنة لعدة طرق بديلة لتغذية المحرك من خلال أنظمة تكييف القدرة الكهربية بحيث يؤدي ذلك إلى تحسين خصائص أداء المحرك.

تم بحث وتحليل خصائص تشغيل محرك كهربي عام-التغذية عند تغذيته من ثلاثة منابع كهربية مختلفة المواصفات: الأول منبع قياسي للتيار المتردد، والثاني منبع تيار متردد مشكل إليكترونيا وذو نبضات جهد مربعة وبنفس تردد المنبع الأول، والثالث منبع تيار مستمر متقطع النبضات وذو تردد ثابت يساوي تردد اى من المنبعين الآخرين ولكن بنسب مختلفة من عرض النبضة إلى دورة تكرارها، وقد تم عمل التحليل والتمثيل الرياضي لكل من الحالات السابقة وصياغته في برنامج للحاسب الآلي لإيجاد خصائص التشغيل نظريا، كذلك تم أيضا بناء منظومة إختبار معملية لكل من الحالات السابقة حيث تم بناء الدوائر الإليكترنية اللازمة لكل منبع على حدة وتشغيل وإختبار خصائص المحرك على كل منها، وتم إجراء مقارنة بين تلك الخصائص المقاسة والمستنتجة معمليا.

تم عمل دراسة خاصة لشكل موجة تيار المحرك عند تغذيته من منبع التيار المستمر متقطع النبضات، حيث أمكن إستنباط تقنية تسمح بتحسين شكل موجة هذا التيار وجعلها تقترب من الشكل المربع، والذي بدوره يؤدي إلى رفع قيمة القدرة الميكانيكية للمحرك لنفس نسبة عرض النبضة إلى دورة تكرارها، وقد تم تصميم وبناء الدوائر الإليكترنية اللازمة لذلك وإختبارها معمليا.

يستخلص من هذا البحث أن منبع التيار المستمر متقطع النبضات هو أفضل طرق التغذية للتحكم في سرعة هذا النوع من المحركات؛ إذ أنه بإستخدام التحكم الإليكتروني يمكن تحسين شكل موجة تيار المحرك لرفع قدرته الميكانيكية.