THE EFFECT OF CONTROLLING THE SPEED OF A SOLID ROTOR INDUCTION MOTOR ON THE AIR-GAP FIELD DISTRIBUTION

تأثير التحكم فى سرعة المحرك التأثيرى ذو العضو الحديدى الدائر
على توزيع المجال فى الثغرة الهوائية

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الخلاصة ـ يقدم هذا البحث دراسة تفصيلية لأثر تغيير سرعة المحرك التأثيرى ذو العضو الحديدى الدائر والمزود بقفص سنجابى على أدائه ، وكذلك مدى تأثر تردد توافقيات المجال الناشئة فى الثغرة الهوائية بتغيير السرعة . ولبحث ذلك فقد تم تصنيع العضو الحديدى الدائر وتم تزويده بقفص سنجابى . وفى هذا البحث تم قياس التيار واستنتاج العزم لعديد من السرعات المختلفة ، وإيضاح ذلك فى شكل منحنيات حيث أمكن بيان مدى التحسن على أداء المحرك عند اضافة ملف القفص السنجابى . كذلك فقد تم تسجيل توزيع المجال المغناطيسى فى الثغرة الهوائية عند نقط عديدة باستخدام ملفات باحثة موضوعة حول كل سنة وأيضا حول خطوة قطبية . ولدراسة خصائص هذا المجال المغناطيسى المسجل باستخدام الملفات الباحثة فقد لزم استنتاج معادلة عامة للقوة الدافعة المغناطيسية الناشئة فى الثغرة الهوائية مشتملة على تأثير توزيع ملفات وفتحات المجارى للعضو الثابت ، ومنها أمكن استنتاج درجة التوافقيات حيث تم حساب تردد هذه التوافقيات بالنسبة للعضو الدائر لعديد من السرعات المختلفة . وقد تم عمل جداول توضح مدى تأثر تردد التوافقيات الناشئة بتغيير سرعة المحرك . وقد أوضحت هذه الجداول تساوى فى التردد لبعض التوافقيات المختلفة والذى من خصائصها توليد عزم ترامنى والذى يعتبر المصدر الرئيسى لحدوث الضوضاء والاهتزازات لذا فان أهمية هذا البحث عند تصميم المحركات التأثيرية ذات العضو الحديدى الدائر متغير السرعة تتلخص فى الآتى : ـ

١ ـ التفهم العميق لسلوك التوافقيات الناشئة فى الثغرة الهوائية عند تغيير سرعة المحرك .

٢ ـ التحسن فى أداء المحرك نتيجة لاضافة ملف القفص السنجابى على العضو الحديدى الدائر .

ABSTRACT :

This paper presents the investigation of the smoothed solid rotor induction motor, equipped with a cage winding, from the point of view of speed control on the airgap harmonic field content. The rotor of this induction motor was machined and constructed at the machine's workshop to replace a conventional rotor of an induction motor rated at 1.5 kW , 3-ph , 4-pole.

This paper deals with two main parts. Firstly , an accurate measurements for the machine performance at several speeds have been measured, as well as the airgap field pulsation has been recorded at several points in the airgap by using set of search coils ; under sinusoidal excitation supply voltage. Secondly, th harmonics originating from the stator slotting , and wind distribution have been derived. Also the harmonic frequer

have been calculated relative to the stator and rotor.

The effect of machine loading has resulted in a complicated airgap field waveform. The radical waveform has been attributed to the strength of the rotor eddy current and the oscillating nature of the zig-zag leakage flux. Also, the effect of the solid rotor material nonlinearity has been revealed by comparing the output waveforms of the search coils at two levels of supply voltage.

This investigation yield useful information and understanding of the machine behaviour , as well as the airgap field pulsation. Moreover, the effect of introducing a cage winding into the solid rotor has proven to improve the machine performance. Also, it is desired to illustrate the reason for the unfavourable contribution to the machine performance, which may be existed at various speeds due to the presence of the standing waves.

INTRODUCTION :

The performance characteristics of the solid rotor induction motors show trends similar to those of machines having high-resistance rotor [1,2]. A stable operation over a wide range of speed is exhibited. Therefore, the characteristics of such induction motors are particularly suitable for solid-state power controls. Accordingly, there has been wide interest in the possible use of such solid rotor motors for ultra high-speed inverter drives with suitable high stator supply frequency , as well as variable speed drives for conventional frequencies and speed ranges [3].

On the other hand, a solid rotor induction motor should not be simply considered equivalent to a squirrel cage rotor with high rotor resistance, such as a deep bar frequency dependent resistance rotor. Where, in the soild rotor motor , the mechanism of penetration into the bulk of the magnetic material depends only on the magnetic nonlinearity of the iron, while this is not the case for conventional wound rotors or squirrel cage rotors. Therefore, the behaviour of the iron rotors differs considerably from that of conventional rotors. Consequently, induction machine theory has proven inadequate for the solid iron rotor induction motors [4], and the need has arisen for improved methods of investigation. However, for a quantitive assessment, a knowledge of the field distribution in the airgap region is essential.

The investigation in this paper has been carried out by measuring the machine performance and calculating the airgap flux harmonic frequencies, at standstill and running conditions. Therefore , an extensive set of flux measurements has given to detect the actual field distribution that exists over each tooth in a pole pitch, under sinusoidal excitation supply, for several speeds taking into account the variation of the supply voltage and loads.

PROBLEM FORMULATION :

The interaction between the eddy currents induced in the solid rotor structure and the revolving field of the airgap produces the electromagnetic torque. Therefore, it is often desired to maximise the eddy current effect, rather than to minimise it , although it produces determintal power losses which causes heating and reduces efficiency , owing to the nonuniform of the airgap field distribution. Moreover, an excessive vibration and noise may be exhibited at certain speed. These problems are getting worse as the machine speed being controlled at high slips.

A survey of the relevant publications show no indication of tackling these problems. But the overall performance of the solid rotor has been considered under various simplifying assumptions to evaluate the solid rotor impedance at several speeds. Surprisingly , three different results for the rotor impedance phase angles have been obtained [4]. In addition, these publications have neglected the presence of the space and time harmonics [2,3,4]. Consequently, much attention has to be paid to the effects of high-order harmonic flux on the solid rotor induction motor behaviour. A precise numerical solution for the magnetic field distribution in the solid rotor is difficult , owing to complicated relationship of magnetic nonlinearity , and the unpridictable relationship between the induced and the applied magnetic fields.
Such an accurate solution is essential to predict quantitatively the airgap field harmonics which they are the fundamental source of all the trouble caused by the solid rotor induction motor. In this context , a more realistic results concerning the actual distribution of the magnetic fields in the airgap , over a wide range of speeds , are experimentally determined. In addition , the airgap field harmonic orders and their frequencies are derived , in order to bring out clearly the harmonics interaction. The actual field distribution has been measured and recorded by using several search coils situated around every tooth and over a pole

pitch. Such flux variation has various harmonics orginating from;
(a) winding distribution ;
(b) the stator slotting ;
(c) the airgap irregularity ; and
(d) the nonlinearity of the solid rotor material, which may result space harmonics.

ASPECTS OF THE AIRGAP MAGNETIC FIELD PULSATIONS :

1. The Stator Winding Harmonics and Their Corresponding Frequencies

The airgap MMF for a symmetrical polyphase winding can be expressed as ;

$$F(\theta,t) = \frac{\sqrt{2}\, m\, N\, I}{\pi} \sum_{h=1}^{\infty} (K_{dh} K_{ph}/h).\cos(w_s t - h\theta) \tag{1}$$

Where, K_{dh} and K_{ph} are distribution and coil pitch factors for the h-th harmonic respectively and are given by ;

$$K_{dh} = \sin(hq\alpha/2) \;/\; [q.\sin(h\alpha/2)] \tag{2}$$

$$K_{ph} = \sin(ah\pi/2\tau) \tag{3}$$

Harmonic EMF's induced by the corresponding harmonic MMF's in equation (1) can be obtained from :

$$e_h = -\, N\, K_{dh}\, K_{ph}\, .\, d\phi_h/dt \tag{4}$$

and ;

$$d\phi_h/dt = \frac{1}{S}\, .\, d(F_h)/dt = -\,\frac{1}{S}\, .\frac{\sqrt{2}.m.NI.ws}{\pi}.(K_{dh}.K_{ph}/h).\sin\,(w_s t - h\theta)$$

Where S is the machine reluctance and equal to $l_g/(\mu_o \mu_r \pi DL)$.

Therefore,

$$e_h = (NK_{dh}.K_{ph})^2\, .\, \frac{\sqrt{2}\, m\, I\, ws}{\pi\, S\, h}\, .\, \sin\,(w_s t - h\theta)$$

Then, the RMS value is given as following :

$$E_h = (NK_{dh}.K_{ph})^2\, .\, \frac{m\, I\, ws}{\pi\, S\, h}$$

$$E_1 = (N.K_{d1}.K_{p1})^2.(m\, w_s.I)/(\pi.S) = X_{m1}.I$$

which leads to the harmonic magnetising reactance expression as given below ;

$$X_{mh} = [(K_{dh} \cdot K_{ph})/(K_{d1} \cdot K_{p1})]^2 \cdot X_{m1}/h \quad (5)$$

The speed of the h-th harmonic correspond to the stator frame is :

$$w_h = w_s/h \quad (6)$$

While h-th harmonic angular speed corresponding to the rotor is given by $[w_s/h - w_s(1-s)]$, therefore the rotor frequency is :

$$f_r = f_s \cdot [1 - h(1-s)] \quad (7)$$

Where, h = 6k+1 ; k = 0 , ± 1 , ± 2 , ± 3 , ...etc.
The calculated harmonic frequencies at different speeds are listed in Table (1).

TABLE (1) : The Airgap Field Harmonic Frequencies Relative to the Stator and Rotor ; Originating by the Stator Windings.

h	S=1		S=0.9		S=0.5		S=0.2		S=0.02	
	f_s	f_r	f_s	f_r	f_s	f_r	f_s	f_r	f_s	f_r
1	50	50	50	45	50	25	50	10	50	1
-5	50	50	50	75	50	175	50	250	50	295
7	50	50	50	15	50	-125	50	-230	50	-293
-11	50	50	50	105	50	325	50	490	50	589
13	50	50	50	-15	50	-275	50	-470	50	-587
-17	50	50	50	135	50	475	50	860	50	883
19	50	50	50	-45	50	-425	50	-710	50	-881

EFFECT OF SLOT OPENINGS :

The stator slots creates a disturbance of the MMF waveform in the airgap which is known as tooth ripple. This ripple, stationary with respect to the stator, sweeps across the solid iron surface of the rotor and sets up eddy currents. The fundamental component of the inducing field will have a wave length equal to the stator slot pitch. Therefore, the effect of slot opening needs to be taken into account in the interst of a more realistic predication.

Such effect may be represented by a Fourier series as follows ;

$$a_0 + \sum_{n=1}^{=\infty} a_n \cdot \cos ng\theta \qquad (8)$$

where a_0 , a_1 , a_2 , ... , a_n are coefficients determined from the effective slot width/slot pitch ratio , and g is the number of teeth over two pole pitches.
Combining equations (1) and (8) and including a multiplying factor $(1/a_0)$ to give the correct fundamental component results in a series of rotating fields.

$$F(\theta,t) = [\frac{\sqrt{2}\ m\ N\ I}{\pi} \sum_{h=1}^{\infty} (K_{dh}K_{ph}/h) \cdot \cos(w_s t - h\theta)] \cdot [a_0 + \sum_{n=1}^{=\infty} a_n \cdot \cos ng\theta] \qquad (9)$$

For a h-th harmonic of the stator MMF : the equation may be written as ;

$$F_h(\theta,t) = a_0 F_{hm} \cdot \{ \frac{1}{h} \cos(w_s t - h\theta) + \sum_{n=1}^{=\infty} \frac{a_n}{2ha_0} \cdot (\cos(w_s t - h\theta + ng\theta) + \cos(w_s t - h\theta - ng\theta)) \} \qquad (10)$$

Where, F_{hm} is the maximum value of the h-th stator MMF.

$$F_{hm} = \frac{\sqrt{2}\ m\ N\ I}{\pi} \cdot (K_{dh}K_{ph})$$

The corresponding rotor frequency , owing to the stator slotting may be given similar to the derivation of Eq.(7).

$$f_r = f_s \cdot [\ 1 - (\pm ng + h)(1-s)]$$

where $h = 6k+1$, $k = 0$, ± 1 , ± 2 ,..., etc , and n= 1, 2, 3, etc.

EXPERIMENTAL RESULTS AND DISCUSSION :

Experiments were conducted on a , 3-ph , 4-pole , 1.5 kW , induction motor, where its conventional rotor was replaced by a manufactured solid rotor equipped with a cage winding. Therefore, the performance characteristics of the smoothed solid rotor induction motor at several loading conditions are obtained : in order to explain some practical aspects especially those related to the vibration and noise problems. In this context the flux behaviour has been measured by a set of search coils situated around each tooth , and around a pole pitch. This field pulsation has been recorded at either the no-load or load conditions. Figures (1),(2), and (3) show the voltages induced in these search coils. The waveshapes of the airgap flux pulsation existed at several points in the airgap of the solid rotor induction motor are the integration of these waveforms. However, the present investigation deals with the induced voltage in those search coils. Moreover, the effect of controlling the speed, either by varying the supply voltage or the machine loading, on the performance characteristics are given in Figs.(4), and (5). As well as, the main field pulsation has been investigated.

(i) The Influence of Varying the Supply Voltage on the Main Field Pulsation :

Figure (1) illustrate the induced voltage waveforms recorded from the search coils located around the first and middle tooth of a phase belt , and the pole pitch . As well as the supply real time current and voltage waveforms are recoded. Two speeds are considered, N=0 , and N=750 rpm , with the supply voltage adjusted equal to 40 and 24.5 volt , respectively. The recorded airgap waveforms show nearly sinusoidal shape. However, Fig. (2) reveals the effect of the rotor nonlinearity , when the supply voltage has been regulated to the values of 42 , 92 , and 150 volt in order to control the machine speed at 1200 , 1430 , and 1460 rpm , respectively. Comparision between the corresponding search coils induced voltages have shown increasing in the main field pulsation as the supply voltage increased. Accordingly, this phenomenon is partly attributed to the existance of the saturation harmonics [5].

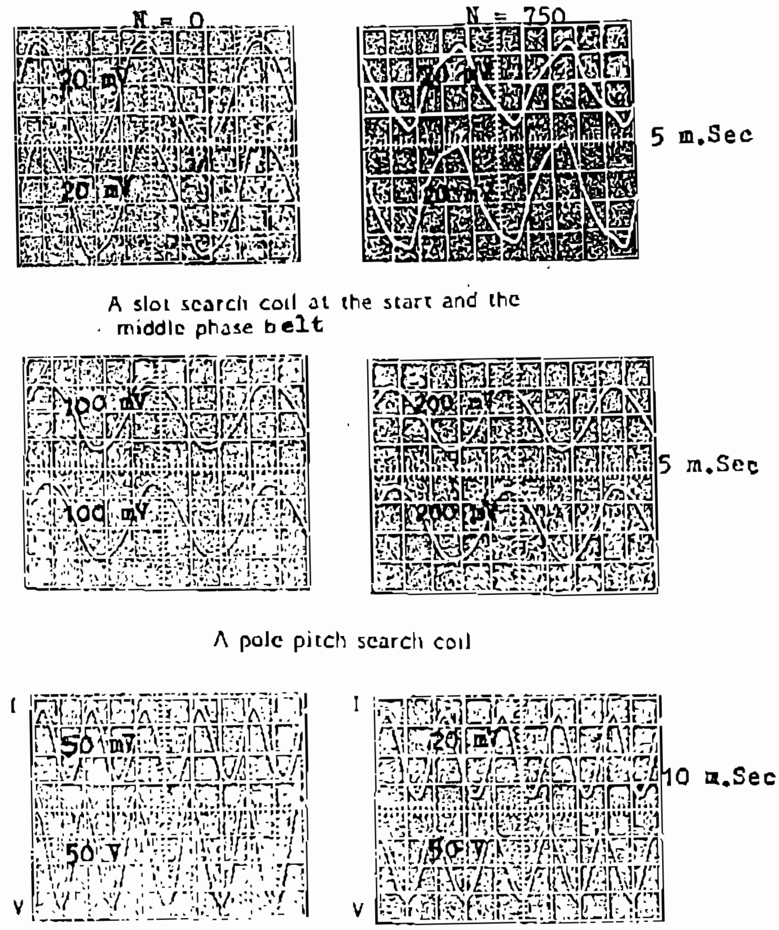
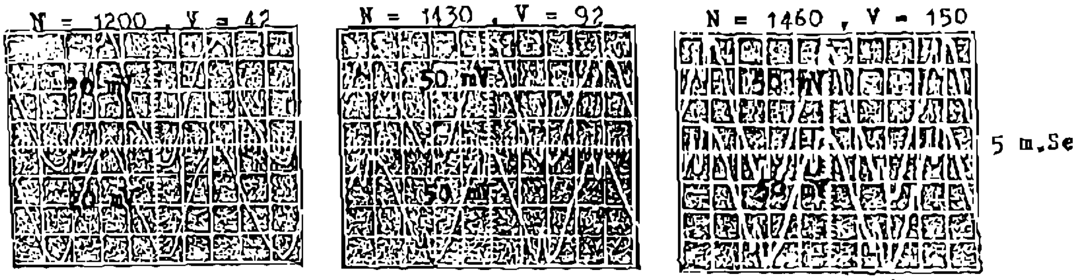
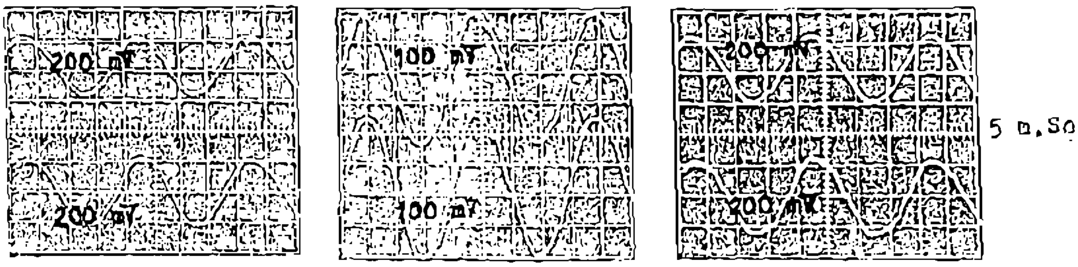


Fig. (1) : The influence of regulating the solid rotor speed on the main field pulsation and the overall performance ; at reduced voltage.



A slot search coil at the start and the middle phase bolt



A pole pitch search coil

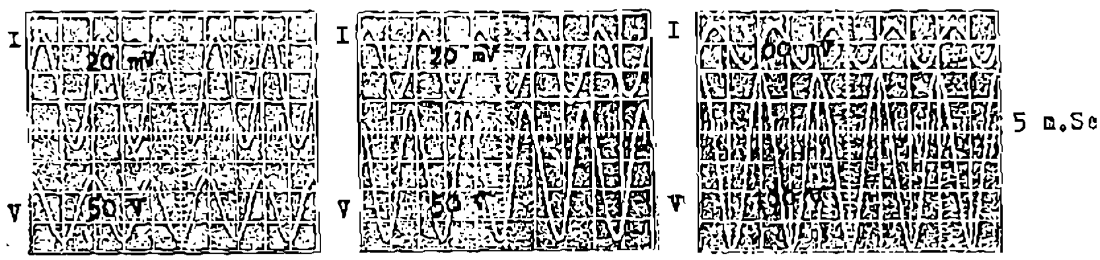
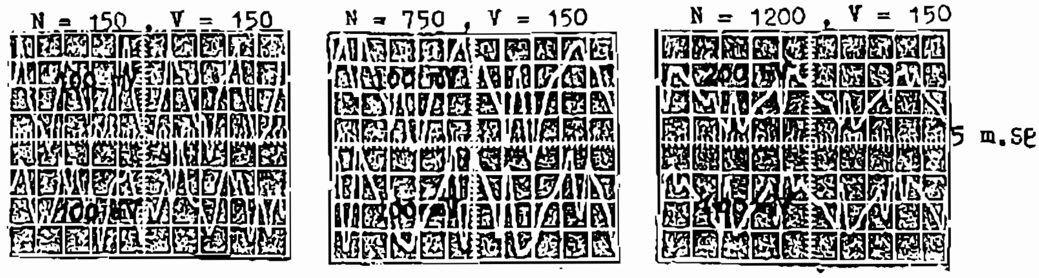
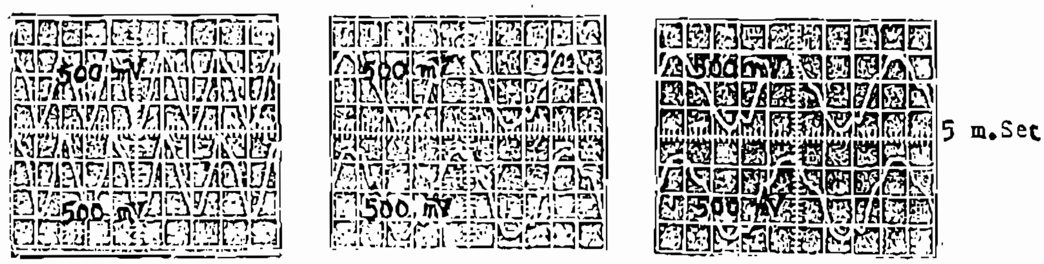


Fig. (2) : The influence of regulating the supply voltage on the main field pulsation and the overall performance.



A slot search coil at the start and the middle phase belt



A pole pitch search coil

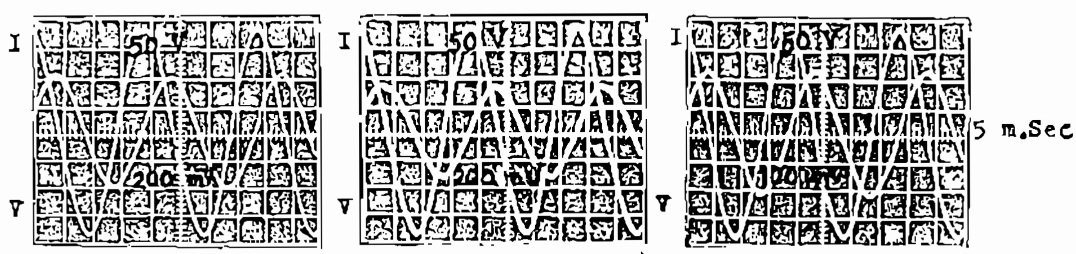


Fig. (3) : The loading effect on the main field pulsation and the overall performance ; with constant supply voltage equal to 150 volt.

Table(2) : The Airgap Frequencies Relative to the Rotor , Due to the Stator Slotting.

h	±ng	S=1	S=0.9	S=0.5	S=0.2	S=0.02
1	18	50	- 45	- 425	- 710	- 881
	-18	50	135	475	730	883
	36	50	- 135	- 875	-1430	-1763
	-36	50	225	925	1450	1765
	54	50	- 225	-1325	-2150	-2645
	-54	50	315	1375	2170	2647
-5	18	50	- 15	- 275	- 470	- 587
	-18	50	165	625	970	1177
	36	50	- 105	- 725	-1190	-1469
	-36	50	255	1075	1690	2059
	54	50	- 195	-1175	-1910	-2351
	-54	50	345	1525	2410	2941
7	18	50	- 75	- 575	- 950	-1175
	-18	50	105	325	490	589
	36	50	- 165	-1025	-1670	-2057
	-36	50	195	775	1210	1471
	54	50	- 225	-1475	-2390	-2939
	-54	50	290	1225	1930	2353
-11	18	50	15	- 125	- 230	- 293
	-18	50	195	775	1210	1471
	36	50	- 75	- 575	- 950	-1175
	-36	50	290	1225	1930	2353
	54	50	- 165	-1025	-1670	-2057
	-54	50	375	1675	2650	3235

(2) The Loading Effect on the Main Field Pulsation :

In order to gain some insight into the effect of loading on the solid rotor machine performance , the recorded airgap flux waveforms are investigated. It is noticed that , the airgap flux distortion is being affected by the machine loading. The machine loading changes the speed as well as the harmonic amplitudes and their frequencies pattern. Tables (1) and (2) give the frequencies of these harmonics as the machine speed vary.

The complicated waveforms of the airgap flux, being recorded by the stator teeth search coils, reveal the interaction between many of the harmonics generated by the stator windings, stator slotting and the nonlinearity of the rotor material. Where, a solid rotor circulate an eddy current under any harmonic EMF that is produced by the airgap flux. These harmonics penetrate the solid rotor differently according to their strength and frequency. Therefore, with the eddy currents induced in the rotor are high enough to increase the saturation effect , a more distortion on the airgap flux being recorded. Comparison between the voltage induced in the search coils reveal such phenomenen ; Fig. (3). In addition, the presence of the zig-zag leakage flux complicates the airgap field pulsation. Where this leakage component surrounding the slots going across the airgap along the tooth tip and returning back over the airgap. This component has to oscillate differently as the machine speed vary. Therefore, its effect has to be measured by using a search coils situated around each tooth. Moreover , a discontinuity phenomena have been noticed on the toothed search coil output waveforms, which may be attributed to the existance of the cage winding embeded in the solid iron rotor. On the other hand, Figs. (4) , and (5) show the improvement on the machine chracteristics due to the existance of the cage winding.

In some cases exessive vibration may be set up at certain speeds due to the existance of the standing waves [7]. Such standing wave patterns will be exhibited due to the existance of the different harmonics at the same frequencey as being noticed from Tables (1) , and (2). Consequently, the field amplitude ,at a particular frequency of a standing wave, observed relative to the rotor are peripharally nonuniform which may cause noise and vibration problems.

CONCLUSION :

From the harmonic frequencies analyses derived and listed in Tables (1) and (2). As well as the direct measurements of the airgap field pulsation , and the solid rotor induction motor charateristics ; the following conclusions could be obtained.

(1) The effect of the solid rotor nonlinearity on the main field pulsation has been revealed by comparing the search coil output waveforms at low and high levels of supply voltages.

(2) The effect of the machine loading on the leakage flux pulsation has resulted in a complicated airgap field waveforms measured by a toothed search coils. This radical waveforms have been attributed to the stregth of the rotor eddy currents and the oscillating nature of the zig-zag leakage flux.

(3) From the harmonic frequencies analyses ; listed in Tables (1) and (2) , a standing wave pattern may be exhibited at low speeds [7]. These waves are peripherally nonuniform which may cause vibration and noise at certain speed.

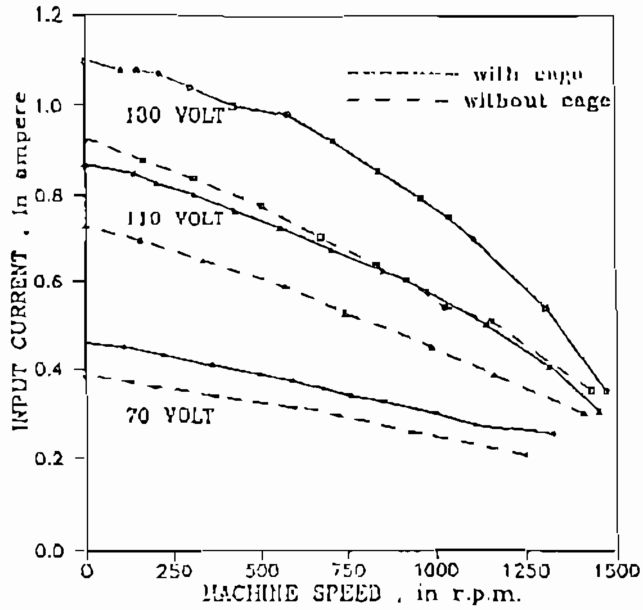


Fig. (4) : The input current-speed characteristics for the smoothed solid rotor induction motor ; with and without the cage winding.

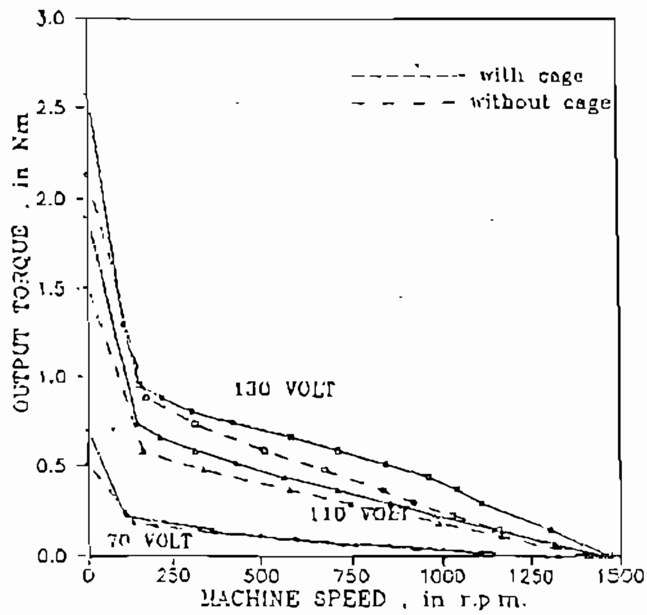


Fig. (5) : The torque-speed characteristics for the smoothed solid rotor induction motor ; with and without the cage winding.

(4) A discontinuity phenomenon have been noticed on the output waveform of the toothed search coils at high supply voltage which may be attributed to the existance of the cage winding. This phenomenon was noticed and modified to measure the penetration depth into the solid iron [8]. But the improvement has been shown on the machine performance at several levels of supply voltages due to the existance of a cage winding ; Figs. (4) , and (5).

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