A NEW APPROACH TO THE SPEED CONTROL OF WOUND-ROTOR INDUCTION MOTORS

A. E. Lashine, S.M.R Tahoun and F.A. Safaan

Department of Electrical Engineering, Faculty of Engineering,
Menoufiya University, Shebien El-Kom, Egypt

ABSTRACT

In this paper a new approach to the speed control of the wound rotor (W.R) induction motor is presented. The speed can be varied from zero to the rated value but not on the expense of extra power loss in the rotor circuit. Unlike the slip power recovery control system, which gives limited speed range, switched capacitors in the rotor circuit are used. The speed can be varied smoothly by varying the duty cycle of the fast acting switches. The switching operation results in three phase voltage source in the rotor circuit with voltage levels which vary with the duty cycle and of the same rotor frequency. Theoretical and experimental results for open and closed loop operations are presented and shown to be in good agreement.

Keywords: Switched capacitors, Variable speed drives, Induction Motors

INTRODUCTION

Three phase induction motors are widely used in industrial drives. This is due to their simple and robust construction. Also, when compared with DC machines, they are inexpensive and have a high power-to-weight ratio added to lower manning cost. Various methods have been employed to obtain the variable speed operation of those motors. Stator voltage control as well as varying supply frequency have replaced most of classical schemes efficiently. Apart from the complexity of such drives, the major disadvantage of these systems is the harmonic distortion which they introduce on both the motor input and the power supply [1-3].

The simplest and more reliable speed control scheme for a wound-rotor induction motor is achieved by using external variable rotor resistance. This method can provide high starting performance and variation of speed over the whole range [4-6]. However, using this method, the system becomes poor in efficiency particularly at lower speeds. Nevertheless, a variable speed operation can be achieved by recovering the slip power from the rotor circuit to the supply [7]. The major disadvantage of this system is that, the speed range is limited and the power factor is low, especially at low speeds. Many attempts have been made to improve the performance of the slip power recovery schemes. These schemes enabled the overall power factor of the drive to be improved but on the expense of increased complexity and cost [8-10]. However, controlling the speed of the wound-rotor motor can be achieved by resonating the rotor circuit using reactive rotor networks [1]. This system provides high starting torque and improved power factor, but the capacitance needed to resonate the rotor circuit is exceptionally large. Using a fixed inductance, the per phase capacitance can be reduced to a practical value, but on the expense of using extra components and sharpening the torque-speed curve. In addition, closed loop speed control may not be possible due to the large capacitance required [1].

The recently developed field oriented and/or vector control approaches, although efficient in controlling the speed, but the final action is applied upon the inverter feeding the motor [11and 12]. This implies

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that, those techniques have the same drawbacks, e.g., the harmonic effect on the motor performance besides the need for an ac / dc converter at the input mains, as well as the complicated inverter control circuitry [11and 12].

This paper proposes a new approach of speed control for wound rotor induction motor. The speed can be varied smoothly from zero to the rated value using external capacitors in the rotor circuit. Small capacitance controlled by electronic switches can be used to vary the speed. High starting torque and improved power factor can be achieved. Also, an improvement in efficiency can be obtained compared with the conventional speed control by variable rotor resistance or slip power recovery. Motor speed can be controlled and varied using simple control circuit. Performance characteristic and analysis of this system are given together with results of an experimental set up.

SYSTEM DESCRIPTION AND OPERATION

Figure 1 shows the circuit diagram of the proposed system. It consists of a three phase wound rotor induction motor and three equal capacitors (C_1,C_2 and C_3) controlled by four IGBT switches. The three capacitors are star connected to the rotor winding as shown in Figure 1. Parameters of the employed motor are listed in Appendix A. Four IGBT switches (S_1,S_2,S_3 and S_4) of type"25Q101" are used. In order to conduct in either directions, each transistor is fed through a fast recovery diode bridge. The switches are arranged to connect or disconnect the capacitors in the rotor circuit. Therefore, the switches ($S_1$and S_3) operate simultaneously. Also switches (S_2 and S_4) operate together such that when (S_1 and S_3) are ON (S_2 and S_4) are OFF. If (S_1 and S_3) are continuously ON the motor rotates at its maximum speed (rated value). While when the switches (S_2&S_4) are continuously ON the capacitors are permanently connected to the rotor.

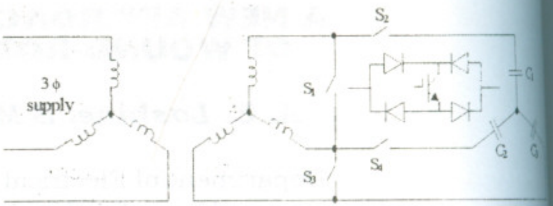


Figure 1 The proposed diagrammatic representation for capacitor controlled three-phase induction motor

Varying the pulse duration (ON time o each switch) the motor speed is changed. In order to vary the motor speed over the whole range, the value of the capacitors C_1,C_2 and C_3 is chosen such that by varying the duty cycle of S_2 and S_4 from zero to 100%, the motor speed changes from its rated value to zero. For the employed motor this value is about 22 μF/phase.

The switching operation of the four switches is at frequency much higher than that of the rotor. Effectively the capacitors can be considered as a voltage source in the rotor circuit and of the same frequency. Accordingly, the higher the voltage across the capacitors i.e., the higher the duty cycle of S_2 and S_4 the lower the rotor speed. This action is similar to that of S charage motor. However, super synchronous speed is not possible with the proposed system. This is because the polarity of capacitor voltages always opposes that of the rotor.

THE CONTROL CIRCUITS

Gate signals to the transistor are adjusted to suit the gate requirements. Each drive circuit receives a train of pulses from the open loop (or closed loop) control and produces the required gate pulses accordingly. Figure 2-a, shows the open loop control circuit. The comparator compares a triangular signal of frequency 1kHz with a dc reference voltage (V_{ref}). This frequency can be higher but faster diodes are then required. Its output is fed to the drive circuit through a NAND latch circuit. Such a circuit ensures that, any group of switches (S_1 and S_3) or (S_2 and S_4) is turned OFF just when the other is ON. Each switch is switched at frequency much higher than that of the rotor (twenty times the supply frequency). However, the relative pulse duration to the switches (S_2 and S_4) determines capacitor voltage level relative to that of the rotor and accordingly, the capacitor voltage required to achieve the desired motor speed. The capacitor voltage increases due to increasing the duty cycle of (S_2 and S_4) by reducing (V_{ref}).

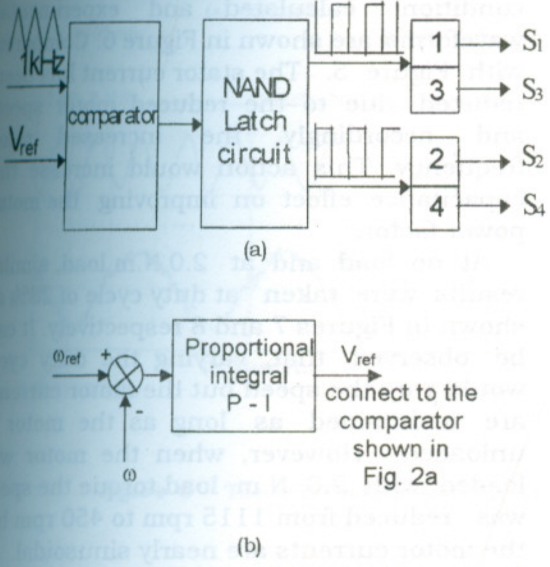


Figure 2 a) Open loop control; b) Closed loop control

To fix the motor speed at any value (from zero to its rated speed), the circuit shown in Figure 2b is used. The motor speed is detected and converted to a voltage signal (ω) which is compared with a voltage signal (ω_{ref}) representing the desired speed. The difference between (ω_{ref}) and (ω) is fed to a Proportional + Integral (P-I) controller. The output of the P-I controller is fed to the comparator shown in Figure 2-a to determine the duty cycle which achieve the desired speed.

MATHEMATICAL MODEL

Considering the per-phase equivalent circuit of the proposed capacitor controlled induction motor referred to the stator shown in Figure 3, the following motor equations can be written:

$$v_s = i_1 R_1 + L_1\, di_1/dt + i_R R_m \tag{1}$$

$$i_R R_m = L_m\, di_m/dt \tag{2}$$

$$i_2^{\copyright} = i_1 - (L_m/R_m)\, di_m/dt - i_m \tag{3}$$

$$i_R R_m = i_2^{\copyright} R_2^{\copyright}/s + L^{\copyright}{}_2\, di_2^{\copyright}/dt + v_a \tag{4}$$

$$v_a = o \quad \text{if } S_a \text{ On and } S_b \text{ OFF} \tag{5}$$

However,

$$v_a = v_b = v_c^{\copyright}/s\ , \tag{6}$$

$$s^2 C^{\copyright}\, dv_b/dt = i_2^{\copyright} \text{ if } S_a \text{ OFF and } S_b \text{ ON} \tag{7}$$

The developed motor torque is given by,

$$T_m = 3 I_2^{\copyright 2} R_2^{\copyright}/s\omega_s \tag{8}$$

The electromechanical equation is given by:

$$d\omega/dt = [T_m - T_l - f\omega]/J \tag{9}$$

where, the slip "s" is given by;

$$s = (\omega_s - \omega)/\omega_s \tag{10}$$

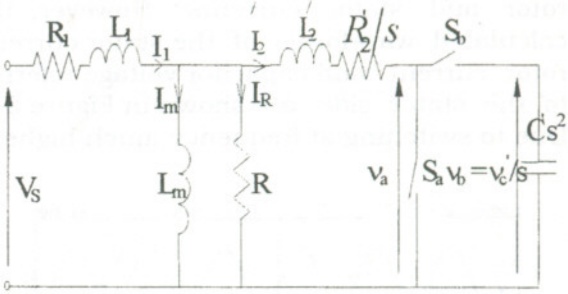


Figure 3 Per-phase equivalent circuit.

To obtain the motor performance under the new technique of control, Equations 1 to 10 listed above were solved using the MATLAB Simulink. Calculated and measured results are reported and discussed below.

RESULTS AND DISCUSSION

An experimental set up for the proposed system shown in Fig. 1 has been constructed and tested. The suitable capacitance was chosen according to the test results shown in Figure 4. This figure shows the possible speed variation with the duty cycle at no load using different capacitor values. According to the test results a capacitor value of C=22μF was found suitable for the full range of speed and duty cycle variations.

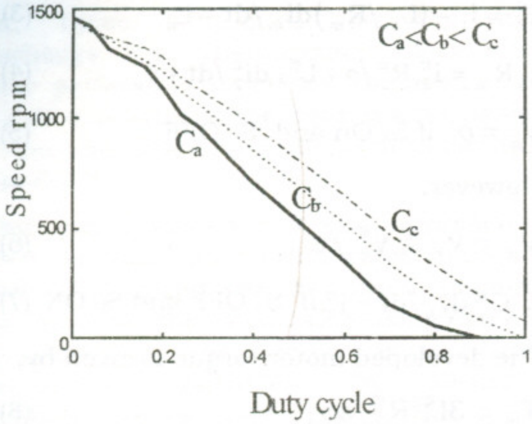
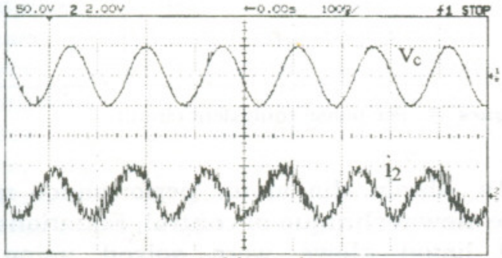


Figure 4 The effect of capacitor value on the speed range. $C_a = 11\mu F$, $C_b = 22\mu F$, $C_c = 33\mu F$.

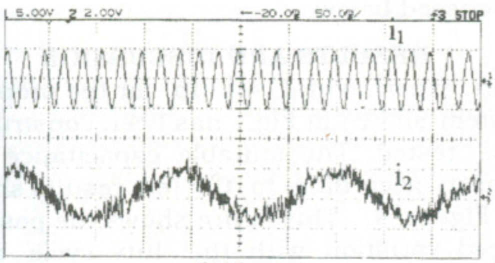
Figure 5 shows the motor voltage and current waveforms at no load and duty cycle of 12%. Figures 5-a and b, show the measured waveform of the capacitor voltage, rotor and stator currents. However, the calculated waveforms of the stator current, rotor current and capacitor voltage referred to the stator side are shown in Figure 5-c. Due to switching at frequency much higher than that of the rotor, the capacitor voltage is nearly sinusoidal. However, apart from the small high frequency ripples, the rotor current is sinusoidal. Those high frequency ripples do not appear in the stator current due to the inductive nature of the motor. At the same duty cycle the motor was loaded with 2.0 N.m load torque. At this operating condition calculated and experimental waveforms are shown in Figure 6. Compared with Figure 5. The stator current has been reduced due to the reduced motor speed and accordingly the increased rotor frequency. This action would increase the capacitance effect on improving the motor power factor.

At no load and at 2.0 N.m load, similar results were taken at duty cycle of 28% as shown in Figures 7 and 8 respectively. It can be observed that, varying the duty cycle would vary the speed but the motor currents are maintained as long as the motor is unloaded. However, when the motor was loaded with 2.0 N.m load torque the speed was reduced from 1115 rpm to 450 rpm but the motor currents are nearly sinusoidal.



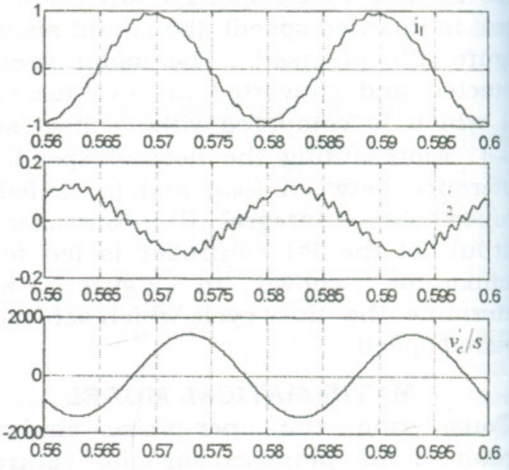
(a) Measured

Ch.1) 50 v/div Ch.2) 0.4 A/div



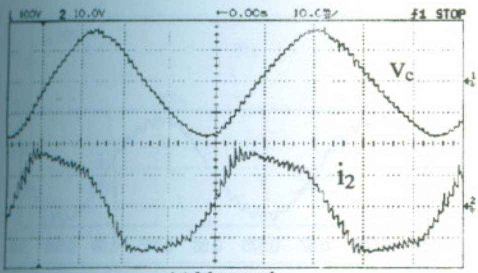
(b) Measured

Ch.1) 1.0 A/div. Ch.2) 0.4 A/div



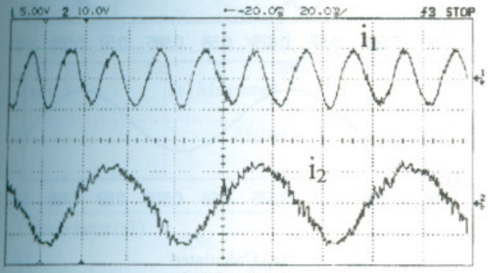
(c) Calculated

Figure 5 The motor voltage and current waveforms at no-load and duty cycle 12%



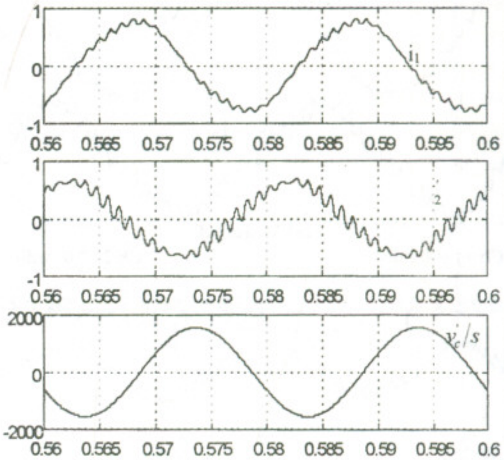
(a) Measured

Ch.1) 100v/div Ch.2) 2.0 A/div



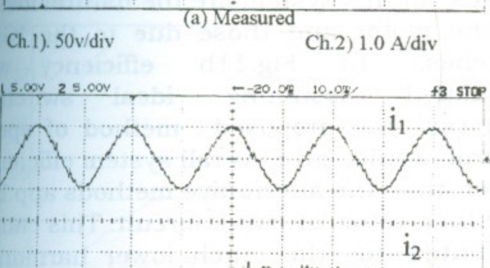
(b) Measured

Ch.1) 1.0 A/div Ch. 2) 2.0 A/div



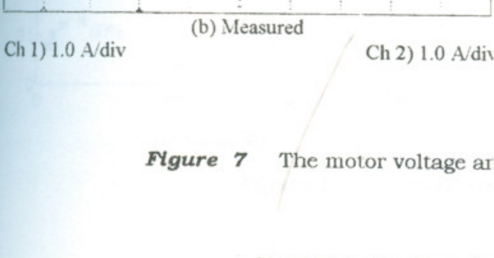
(c) Calculated

Figure 6 The motor voltage and current waveforms at 2.0 N.m load torque and duty cycle 12%



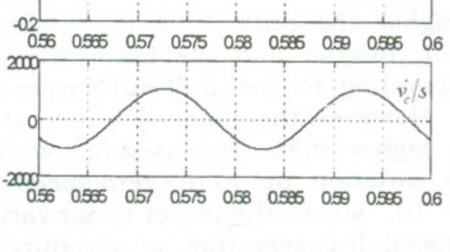
(a) Measured

Ch.1). 50v/div Ch.2) 1.0 A/div



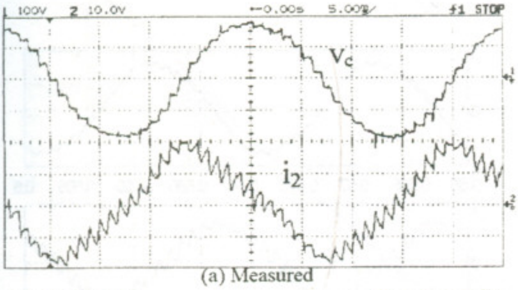
(b) Measured

Ch 1) 1.0 A/div Ch 2) 1.0 A/div



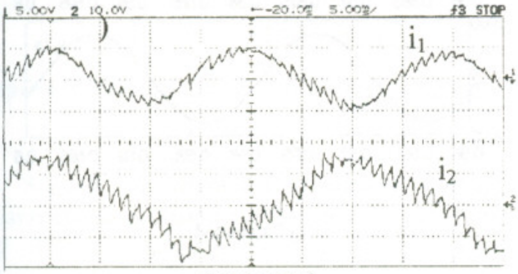
(c) Calculated

Figure 7 The motor voltage and current waveforms at no-load and duty cycle 28%



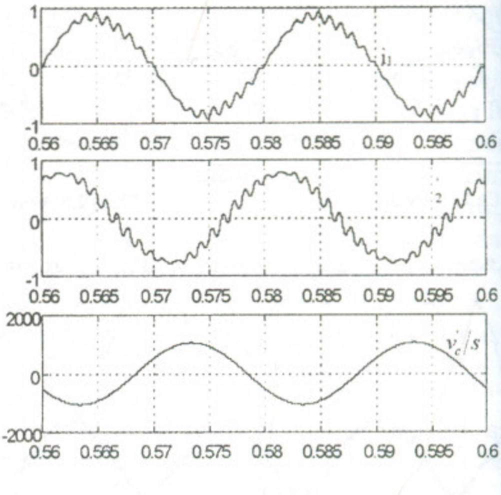
(a) Measured

Ch.1) 100v/div Ch.2) 2.0 A/div



(b) Measured

Ch.1) 1.0 A/div Ch.2) 2.0 A/div

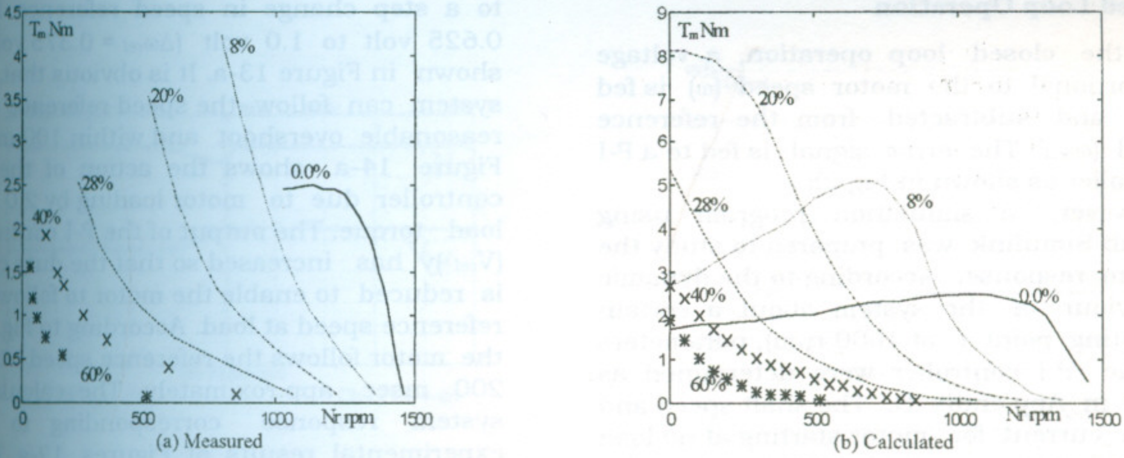


(c) Calculated

Figure 8 The motor voltage and current waveforms at 2.0 N.m load torque and duty cycle 28%

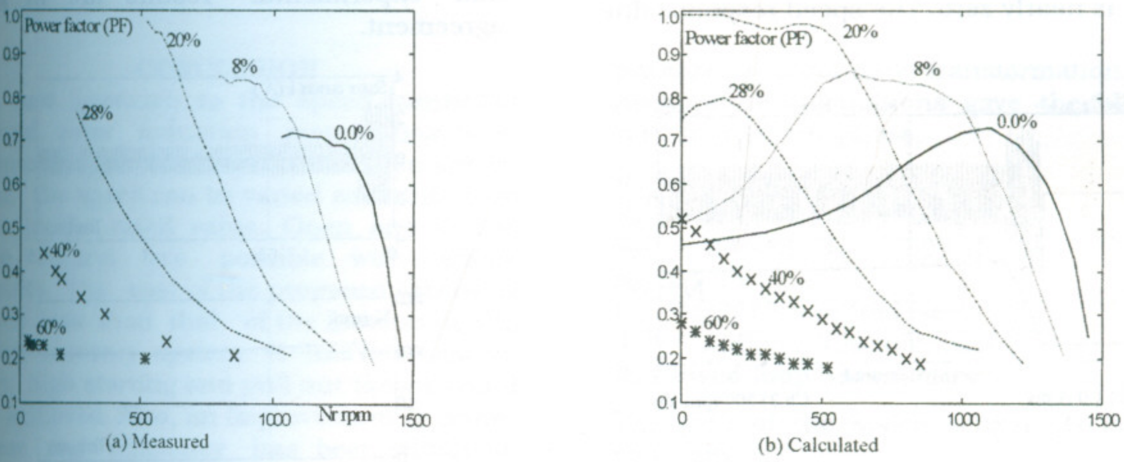
Steady State Performance

Theoretical performance characteristics of the capacitor controlled induction motor of App.endix A were calculated using the equivalent circuit of Figure 3 at various duty cycles of switch S_b. Figures 9 to 11 illustrate the variation of torque, power factor and efficiency respectively, against speed at six values for the duty cycle (Ds_b). Considering Figure 9 it is evident that, the duty cycle is the control parameter for speed variation. The higher the duty cycle the higher the pull-out torque and the lower the speed corresponding to the pull-out torque of the motor. However, the motor operation at duty cycles higher than 20% is stable with load torque variation up to the zero speed. Also, Figure 10, shows the power factor variation with speed. It is seen that, at zero duty cycle (normal operation) the maximum possible power factor which can be achieved is 0.72. However, increasing the duty cycle the capacitors are effectively introduced in the motor circuit and so improved power factor is obtained. Figure 11, shows the measured and calculated efficiency curves at different duty cycles. The presented results show that the higher the duty cycle the lower the speed at which maximum efficiency occurs. Losses in this system are the natural losses of the motor and those due to the IGBT switches.. In Fig.11b efficiency was calculated assuming ideal switches. However, the proposed method of speed control would give overall system efficiency better than the alternative methods app.lied to either rotor or stator circuit. This can be attributed to the much lower harmonics encountered with the proposed system.



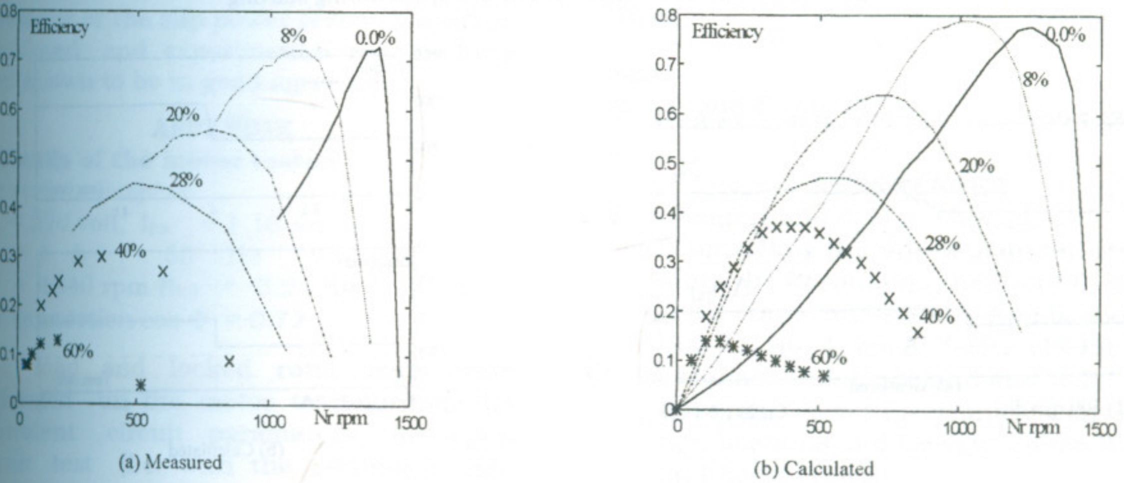
(a) Measured (b) Calculated

Figure 9 Torque/ Speed characteristics at different duty cycles



(a) Measured (b) Calculated

Figure 10 Power factor/speed characteristic at different duty cycles



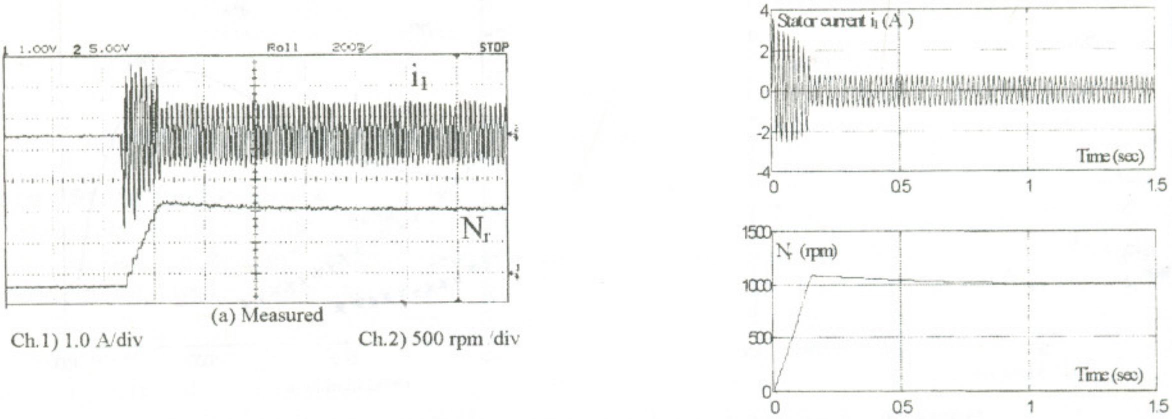
(a) Measured (b) Calculated

Figure 11 Efficiency/speed characteristic at different duty cycles

Closed Loop Operation

For the closed loop operation, a voltage proportional to the motor speed (ω) is fed back and subtracted from the reference speed (ω_{ref}). The error signal is fed to a P-I controller as shown in Fig.2b.

However, a simulation program using Matlab-Simulink was prepared to study the system response. According to the dynamic behaviour of the system about a certain operating point (at 1000 rpm), parameters of the P-I controller were determined as given in App.endix B. The shaft speed and stator current for motor starting at no load and reference speed of 1000 rpm (ω_{ref} =1.0 volt) is shown in Fig. 12a. The motor speed follows the reference and the steady state error is nearly zero. The speed response due to a step change in speed reference from 0.625 volt to 1.0 volt ($\Delta\omega_{ref}$ = 0.375 volt) is shown in Figure 13-a. It is obvious that, the system can follow the speed reference with reasonable overshoot and within 100 msec. Figure 14-a shows the action of the P-I controller due to motor loading by 2.0 N.m load torque. The output of the P-I controller (V_{ref})ý has increased so that the duty cycle is reduced to enable the motor to follow the reference speed at load. According to Fig.14a the motor follows the reference speed within 200 msec app.roximately. The calculated system response corresponding to the experimental results of Figures 12-a, 13-a and 14-a are given in Figures 12-b, 13-b and 14-b respectively. It is clear that, calculated and experimental results are in good agreement.

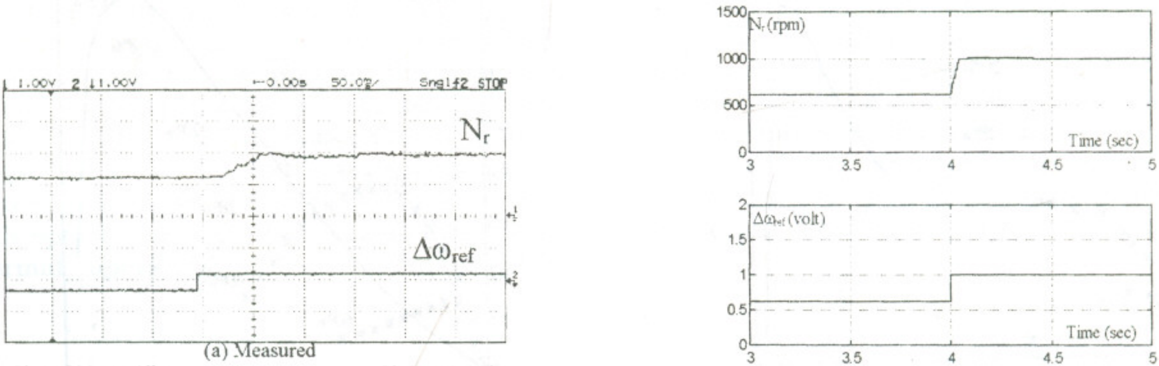


(a) Measured

Ch.1) 1.0 A/div Ch.2) 500 rpm /div

(b) Calculated

Figure 12 No-load stator current and speed during starting

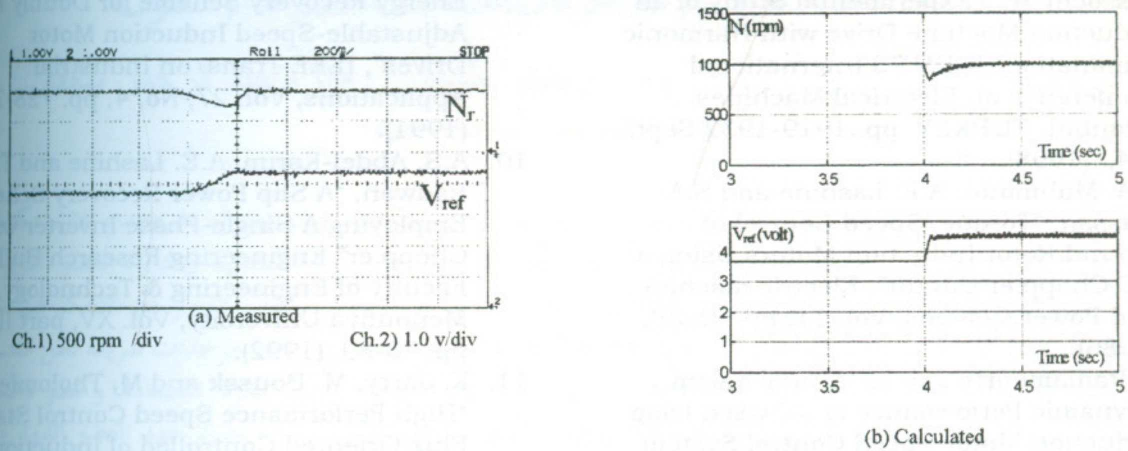


(a) Measured

Ch.1) 500 rpm/div Ch.2) 1.0 v/div

(b) Calculated

Figure 13 Speed response due to step change in speed reference



(a) Measured

(b) Calculated

Figure 14 Speed response due to sudden load application

CONCLUSION

A new approach to the speed control of wound rotor induction motors has been proposed and examined. It has been shown that, the speed can be varied smoothly from zero to the rated value. Open and closed loop control are possible with simple circuits. The cost of the proposed control is much less than that of the inverter or slip power recovery system. It has been shown that, high starting and pull out torque could be achieved. Also, an improvement in power factor and efficiency has been obtained. Additional losses with the proposed control are expected to be much less than those encountered with the use of variable rotor resistance or the slip power recovery system. Calculated and experimental results have been shown to be in good agreement.

APPENDIX

A. Details of the motor tested

The motor nameplate

V_{ph} = 220 volt, I_{ph} = 1.16 Amps
2p = 4 f_1 = 50 Hz
N_r = 1340 rpm P_{out} = 0.25 Kw
Y/Y connection cos Φ = 0.72

No load and locked rotor tests were performed on the motor to determine its equivalent circuit parameters. An open circuit test (i.e. with the secondary side open) was performed to determine the primary / secondary transformation ratio. Appropriate calculations gave the following results in ohms/phase.

R_1 = 35 Ω L_1 = 0.17 H
R_2 = 2.1 Ω L_2 = 0.0106 H
R_m = 3400Ω L_m = 0.99 H
n_p/n_s = 4
f = 0.00075 N.m/rad/sec.
J = 0.00035 N.m/rad/sec^2

B. Closed loop parameters

The gain of the speed sensor (G) is 0.001 volt/rpm.

The transfer function of the P-I controller is given as:

$$G_c(s) = \frac{k_c(1 + sT_c)}{sT_c}$$

where,

k_c = 6 and T_c = 0.08 sec.

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طريقة جديدة للتحكم في سرعة المحركات الحثية ذات العضو الدائر الملفوف

عزه محمد عزت لاشين ، سلوى محمد رياض طاحون ، فايزه عبد الرحمن سعفان
قسم الهندسه الكهربيه -جامعة المنوفيه

ملخص البحث

تم في هذا البحث اقتراح طريقة جديدة للتحكم في سرعة محرك حثي ذو عضو دوار ملفوف باستخدام ثلاث مكثفات محكومة، والتي يمكن عن طريقها تغيير السرعة من صفر إلى القيمة المقننة للمحرك بدون زيادة للمفاقيد في دائرة العضو الدوار.

تعتمد هذه الطريقة على التحكم في ثلاث مكثفات متساوية متصلة نجمة في دائرة العضو الدوار يتم التحكم فيها عن طريق أربعة مفاتيح الكترونية سريعة يمكنها تمرير التيار في كلا الاتجاهين باستخدام قنطرة من أربعة موحدات سريعة لكل مفتاح. يمكن التحكم في السرعة بنعومة بالتحكم في فترة اتصال المكثفات بدائرة العضو الدوار بالنسبة لفترة استبعادها و قصر دائرة العضو الدوار و بالتالي يمكن التحكم في جهد المكثفات والذي يعمل كمصدر جهد ثلاثي الأوجه مضاد لجهد العضو الدوار و له نفس تردده. تحتاج هذه الطريقة إلى سعة صغيرة و يؤدي استخدامها إلى تحسين عزم البدء و كذلك معامل القدرة و الكفاءة بالمقارنة بالطرق البديلة للتحكم في سرعة هذا النوع من المحركات.

أمكن أيضاً التحكم في السرعة باستخدام التحكم المغلق عن طريق دوائر بسيطة بحيث يمكن تثبيت سرعة المحرك عند السرعة المطلوبة مع تغير الحمل.

تم اختبار النظام و تحليله و استعراض النتائج العملية و النظرية حيث أعطت تطابقا مرضيا.