A DOUBLE-FED EQUIVALENT RELUCTANCE MOTOR DRIVE SYSTEM

S.M.R.TAHOUN

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

ABSTRACT

This paper presents a new configuration equivalent to the double fed reluctance motor drives. The proposed system utilizes a three-phase salient pole reluctance motor with one group of windings fed from a dc source via a six-pulse inverter. Thus, the need for control windings in the stator is eliminated. Excitation of motor phases is performed such that, the input voltage pulses are applied at the minimum inductance position. If the load torque is varied, the proposed arrangement enables operation over a wide speed range without loss of synchronism, even if the motor is subjected to sudden load and/or voltage changes. The proposed configuration produces performance similar to that of the doubly fed motor with lower losses, since only one group of stator winding is used. Experimental and theoretical analysis for both steady state and dynamic behavior are reported. Good agreement between measured and calculated results is achieved.

LIST OF MAIN SYMBOLS

R_a	stator resistance
R_Q & R_D	rotor Q & D axes resistance respectively.
L_d & L_D	stator and rotor d axes self inductance.
L_q & L_Q	stator and rotor q axes self inductance.
M_{AD}	coupling coefficient for the d axis.
M_{AQ}	coupling coefficient for the q axis.
J	moment of inertia of the rotating parts.
K_d	friction coefficient.
T_e	the electromagnetic torque.
T_L	the load torque.
ω_m	angular velocity (rad/sec)

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INTRODUCTION

Recently, the concept of a brushless doubly fed machines has been developed[1]. Since then, such system has attracted the attention of many researchers. This may be attributed to the ability of the doubly fed machines to provide variable speed drives. However, demand for wide speed and torque applications has been achieved using a single-frame self cascaded induction machine This type of machine evolved both physically and conceptually, from two induction machines with cross-connected rotor phase windings on the same shaft. This construction can operate in either induction or synchronous mode avoiding the use of brushgear.

The progress of power electronics and control has refreshed the interest in replacing the self-cascaded induction machines by a simple system. It uses a machine, which has a stator with divided windings fed from a cycloconverter [2]. The system operates stably as a generator feeding a power grid when driven by a prime mover over a wide speed range. However, the cycloconverter is costly, due to its complicated construction and control.

Due to the defect, which always arises in using a fixed speed generation system driven by wind energy, as a stable source, the progress of doubly fed machines still, attract the attention [3-5]. A modification concerning the machine design was carried out. The stator has two windings with different number of pole pairs, where one of the two windings is used as a main or power winding, while the other is used as a control winding. The latter is excited from the mains through a bidirectional converter. Moreover, the rotor has a special cage structure with a number of identical sections equal to the sum of the pole pairs of the two stator windings. However, the appropriate combination of the number of pole pairs of the stator and rotor, which could achieve high performance, has been studied [5]. The doubly fed systems discussed in references 3-5 operate successfully, but on the expense of the total cost. The high cost is due to the requirements of special machine design as well as the use of a bidirectional converter, which has a complicated construction and control.

Regardless of the cost of the doubly fed systems work has continued to operate such systems as adjustable-speed drives; the reluctance motor was used. The steady state performance of the doubly fed reluctance motor has been studied [6]. The motor was built with two stator windings using the concept and principle of operation described in ref. 3. However, besides the high cost, the doubly fed systems suffer from higher losses due to the two magnetic fields with different frequencies as well as the converter losses.

In attempt to reduce the converter losses, converter optimisation and field oriented control on the doubly fed induction machine without sensor has been implemented [7]. Although, the losses of the converter were reduced, the machine losses were still high besides the complications of the system due to the logic circuits of the field oriented control.

The present paper introduces a new development for the doubly fed reluctance motor drive. The system consists of a conventional three-phase, four salient pole, reluctance motor fed from a dc supply through a unidirectional six pulse inverter. Excitation process is based on exciting each phase with voltage pulses at the minimum inductance positions, and follows the portion of the inductance increase. The proposed system may appear to be excited in a manner similar to that used with the switched reluctance motor (SRM). However, it must be pointed out that there are differences in construction and operation between the proposed system and the SRM. The two motor members in the proposed system have the same number of pole pairs. Moreover, the excitation current of the SRM is unidirectional and so, a dc supply which can accept reversible energy should be used. On the other hand, in the proposed system the excitation current is alternating. By varying the dc supply voltage, it is shown that, the proposed system can operate as a variable-speed drive with series characteristics. However, for constant speed operation, a closed loop control will be necessary

A theoretical model for the proposed system is developed and solved using a MATLAB SIMULINK. Good agreement between measured and calculated results is achieved.

SYSTEM DESCRIPTION AND OPERATION

The experimental setup, is shown in Fig. 1, where the motor is mechanically coupled with an eddy current brake. The three-phase bridge inverter was built for the present study using six IGBTs of type CM50DY-24. The transistors were driven by square wave voltage pulses generated using a shaft position sensor. This position sensor consists of a thin slotted disc with a number of slots equals to the number of pole pairs which interrupts the light beams of three fixed opto-couplers. The slotted disc was located such that each phase winding is energized just before the corresponding active torque region. This sensor ensures that, the switching frequency is always in synchronism with the rotor speed. However, the timing diagram of the signals produced by the position sensor is as shown in Fig.(2a).

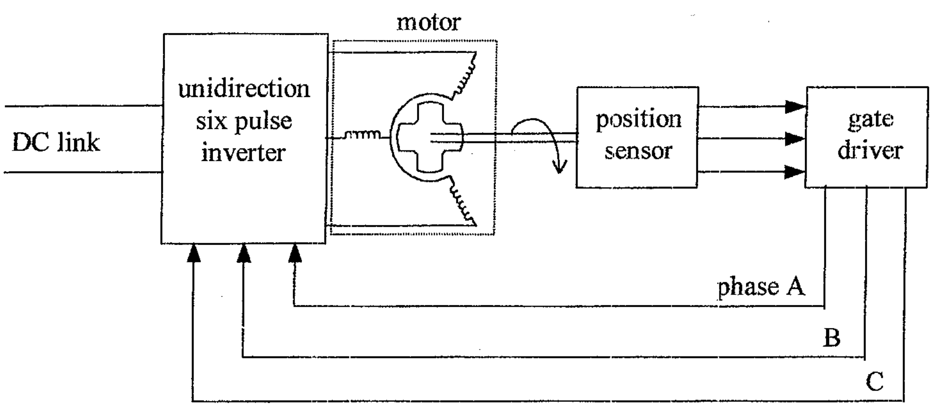


Fig. 1 Schematic diagram of the proposed system.

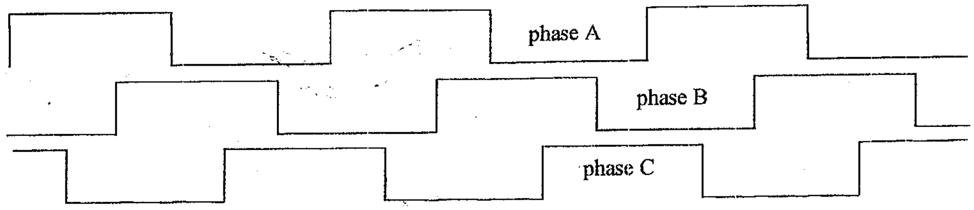


Fig.2a Timing diagram for the output of position sensor

Details of the gate driver shown in Fig.1 are as shown in Fig. 2b. It is used to adapt the output of the position sensor to the requirements of the transistor gates. In this circuit the open collector "7406" is used to protect the gates of the transistors, since no output signal is produced if the input is cleared. On the other hand, a photo-coupler "TLP250" is used to isolate the gates of the transistors connected to the positive supply terminal. However, complement signals are obtained by the logic gate "4704".

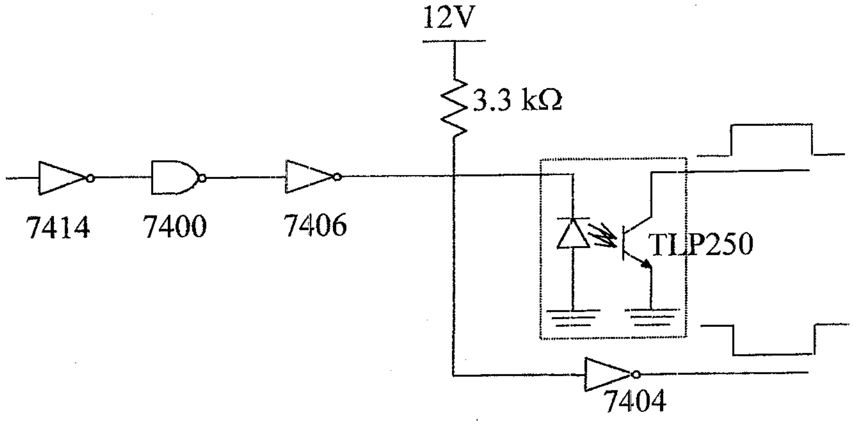


Fig 2b Per phase drive circuit

Connection of motor phases to the inverter circuit is shown in Fig. (2c). Due to the sequence of operation given in table 1, motor current is alternating. Output of the position sensor is used to operate the transistors, (A^+, B^+ and C^+) via the gate driver. However transistors A^- B^- and C^- are operated by the complement of those pulses

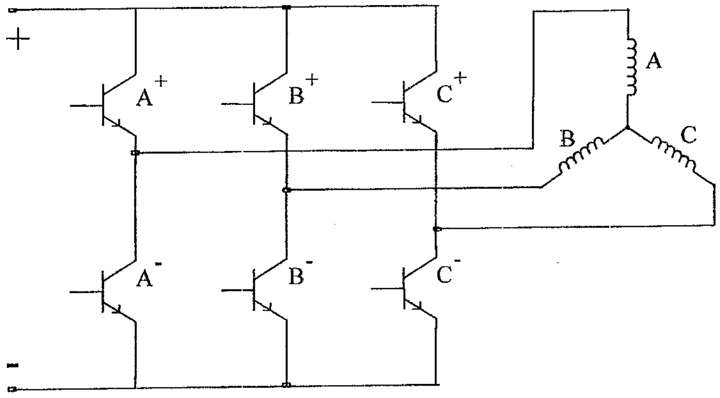


Fig 2.c Connection of motor phases to the inverter circuit

Phase A Transistor		Phase B Transistor		Phase C Transistor	
A^+	A^-	B^+	B^-	C^+	C^-
ON	OFF	OFF	ON	ON	OFF
ON	OFF	OFF	ON	OFF	ON
ON	OFF	ON	OFF	OFF	ON
OFF	ON	ON	OFF	OFF	ON
OFF	ON	ON	OFF	ON	OFF
OFF	ON	OFF	ON	ON	OFF

Table (1). Sequence of operation.

The output torque is produced due to the tendency of the rotor to align itself with the minimum reluctance position. The proposed method of excitation ensures that, each of the three transistors (A^+, B^+ and C^+) is turned ON at a position of minimum inductance for each motor phase. To achieve this, the position sensor is located such that each opt-coupler is fixed at a position of maximum reluctance of a corresponding phase. However, successful motor operation requires accurate positioning of the pulses generated from the position sensor [8&9]. Delaying or advancing those pulses causes a reduction in the developed motor torque. Nevertheless, delaying the pulses reduces the motor current. According to the proposed inverter operation, the rotor is always synchronized with the stator mmf at a fixed delay with the rotor poles.

A switched double fed synchronous motor with a shaft encoder starts due to the effect of rotor field with the applied phase pulse. The identified field current direction determines polarity of the rotor poles and accordingly the direction of rotation. However, the proposed single fed reluctance motor, may start in either direction because polarity of the rotor poles is not initially identified. This can be avoided by placing the position sensor such that the initial pulse is delayed or advanced with respect to the maximum reluctance position, according to the required direction of rotation. This can be done without affecting the motor performance using a separate shaft encoder for the start or a suitable alternative. Nevertheless, the starting operation requires only the time of one pulse after which the motor can operate normally with the main position sensor to ensure operation at maximum torque.

MODELING AND SIMULATION

The employed motor has a conventional stator of 1/3 HP, four-poles 220/380 volt, 50 Hz. The rotor was built with four salient poles. Details of the motor parameters are given in the appendix. However, methods for parameter measurements are as reported in references [10,11&12].

A reluctance motor is effectively a synchronous machine. It follows that, the mathematical model that represents this type is the same as that of the salient pole synchronous motor with damper winding on the rotor but without excitation. Thus, neglecting saturation effects the mathematical equations which represent the reluctance motor in the synchronous reference frame are as follows[13&14]:

$$v_d = R_a i_d + p\psi_d - \psi_q \omega_m \tag{1}$$

$$v_q = R_a i_q + p\psi_q + \psi_d \omega_m \tag{2}$$

$$0 = R_D i_D + p\psi_D \tag{3}$$

$$0 = R_Q i_Q + p\psi_Q \tag{4}$$

Where ψ_d & ψ_q are the stator direct and quadrature axes flux linkages respectively.

Also, ψ_D & ψ_Q are the rotor direct and quadrature axes flux linkages respectively.

Those can be expressed as follows;

$$\psi_d = L_d i_d + M_{AD} i_D \tag{5}$$

$$\psi_q = L_q i_q + M_{AQ} i_Q \tag{6}$$

$$\psi_D = L_D i_D + M_{AD} i_d \tag{7}$$

$$\psi_Q = L_Q i_Q + M_{AQ} i_q \tag{8}$$

Substituting from eqns (6,7,8,9) into eqns (2,3,4,5) yields:

$$v_d = R_a i_d + L_d pi_d + M_{AD} pi_D - \omega_m L_q i_q - \omega_m M_{AQ} i_Q \tag{9}$$

$$v_q = R_a i_q + L_q pi_q + M_{AQ} pi_Q + \omega_m L_d i_d + \omega_m M_{AD} i_D \tag{10}$$

$$v_D = R_D i_D + L_D pi_D + M_{AD} pi_d \tag{11}$$

$$v_Q = R_Q i_Q + L_Q pi_Q + M_{AQ} pi_q \tag{12}$$

The above four equations can be rearranged and put in the matrix form as follows:

$$\begin{bmatrix} pi_d \\ pi_q \\ pi_D \\ pi_Q \end{bmatrix} = \begin{bmatrix} L_d & 0 & M_{AD} & 0 \\ 0 & L_q & 0 & M_{AQ} \\ M_{AD} & 0 & L_D & 0 \\ 0 & M_{AQ} & 0 & L_Q \end{bmatrix}^{-1} \left\{ \begin{bmatrix} v_d \\ v_d \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} R_a & -\omega_m L_q & 0 & -\omega_m M_{AQ} \\ \omega_m L_d & R_a & \omega_m M_{AD} & 0 \\ 0 & 0 & R_D & 0 \\ 0 & 0 & 0 & R_Q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_D \\ i_Q \end{bmatrix} \right\}$$

$$= \begin{bmatrix} L_D/\sigma_1 & 0 & -M_{AD}/\sigma_1 & 0 \\ 0 & L_Q/\sigma_2 & 0 & -M_{AQ}/\sigma_2 \\ -M_{AD}/\sigma_1 & 0 & L_d/\sigma_1 & 0 \\ 0 & -M_{AQ}/\sigma_2 & 0 & L_q/\sigma_1 \end{bmatrix}$$

$$\times \left\{ \begin{bmatrix} v_d \\ v_d \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} R_a & -\omega_m L_q & 0 & -\omega_m M_{AQ} \\ \omega_m L_d & R_a & \omega_m M_{AD} & 0 \\ 0 & 0 & R_D & 0 \\ 0 & 0 & 0 & R_Q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_D \\ i_Q \end{bmatrix} \right\} \tag{13}$$

$$\sigma_1 = L_d L_D - M_{AD}^2 \tag{14}$$

$$\sigma_2 = L_q L_Q - M_{AQ}^2 \tag{15}$$

The developed electromagnetic torque is;

$$T_e = \frac{3}{2} \mathrm{P} \left(\psi_d i_q - \psi_q i_d \right) \tag{16}$$

Also, the shaft equation is;

$$p\omega_m = \frac{p}{J} \left(T_e - T_L - k_d \omega_m \right) \tag{17}$$

Equations (13,16&17) are the mathematical model of the drive system. Those can be solved numerically using MATLAB-SIMULINK. The digital model is initiated using three group of pulses for the three phases of the motor. Those are generated externally with a repetitive period equal to the rotor pole pitch and locked with either minimum or maximum reluctance position. For the system under consideration, they must be locked with the maximum reluctance position to produce motoring torque. However, based-on the motor dimensions variation of reluctance is computed. Once the motor starts to rotate, the external pulses are replaced by those generated due to rotor rotation and also, synchronised with the rotor. The transistors of a certain phase are turned on using the corresponding generated pulses. Therefore, the digital model can be run to obtain the required calculated results of the system.

RESULTS AND DISCUSSION

The motor under test was subjected to several tests carried out at 220-dc volt. As mentioned before, the proposed system is equivalent to the doubly fed concept for adjustable speed drives. Thus, the motor runs in synchronism with the input pulses. The torque/speed characteristics shown in Fig.3 clarify the capability of the proposed configuration to operate efficiently as the doubly fed reluctance motor. The motor has a series characteristic over a wide speed range from 100 to about 3000 rpm. However, the supply voltage level controls the motor speed, in a manner similar to that of series motor. As the motor load increases, higher current is demanded by the motor. This action forces the motor to reduce its speed, i.e. its back emf, but the rotor rotation is always in synchronism with the stator due to method of excitation employed.

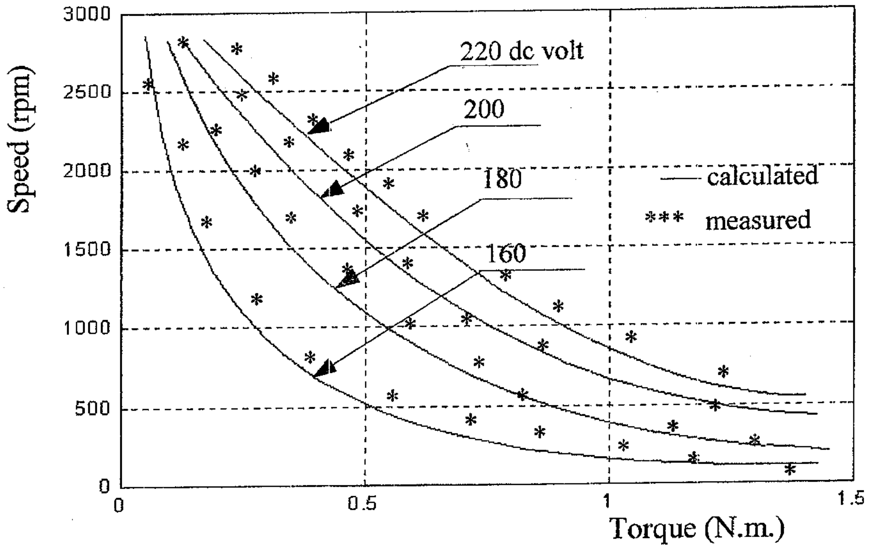
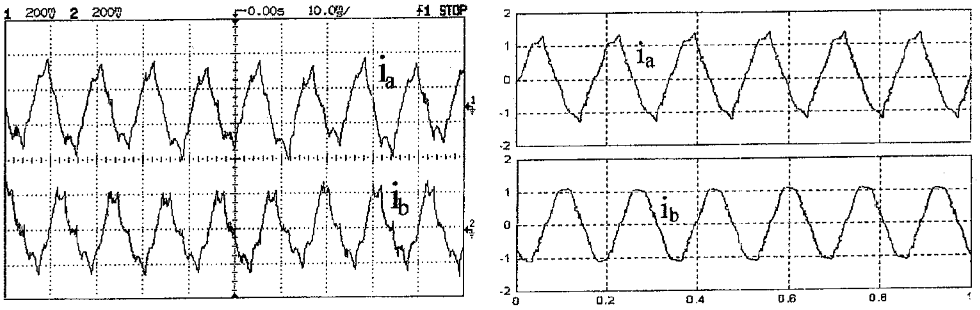


Fig 3 Torque speed characteristics at different DC supply voltages

The recorded current waveforms of the proposed configuration indicate that the currents are alternating and shifted from each other by 120 elect. degrees as shown in Fig.(4). Figures. (5-7) show the phase voltage and current waveforms at different speeds. The experimental and simulated voltage waveforms are six-stepped which confirm the logic sequence given in table (1). The distortion and voltage spikes in the experimental voltage waveforms are due to the switching process and mutual coupling between different phases. This distortion is reflected on the current waveforms.

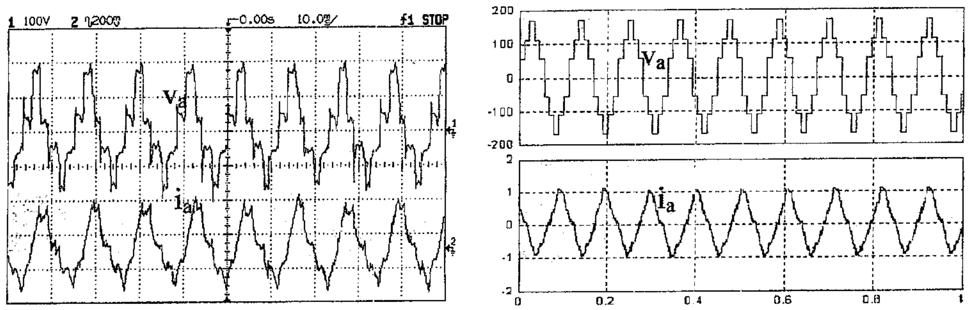


a) Experimental

b) Simulated

Scale: Current 1.0 A/div.

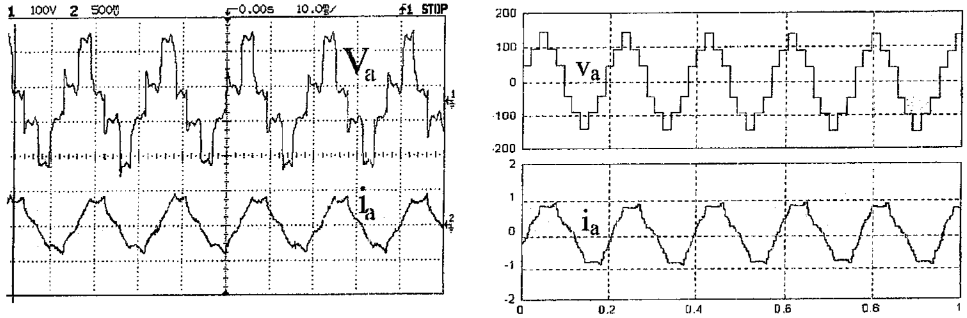
Fig.4 Phase current waveforms of the two phases a & b



a) Experimental b) Simulated

Scale: Volt 100 v/div, Current 1.0 A/div

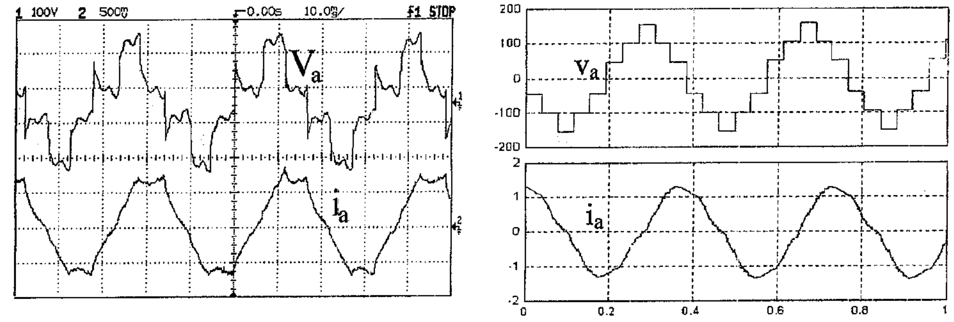
Fig.5 Phase voltage and current waveform at N=2630 rpm



a) Experimental b) Simulated

Scale Volt 100 v/div, Current 1.0 A/div

Fig.6 Phase voltage and current waveform at N=1500 rpm

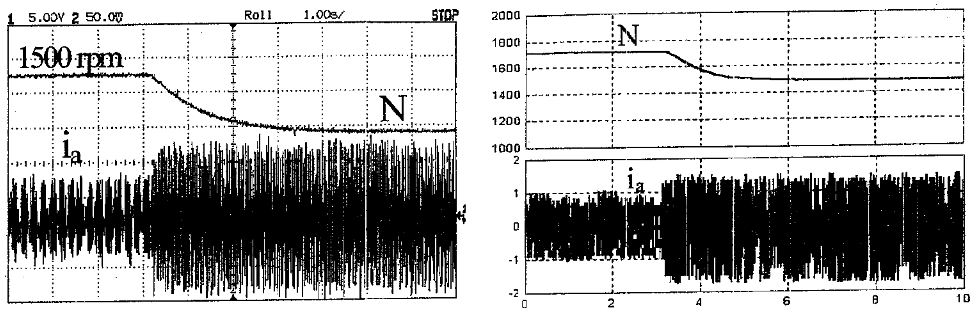


a) Experimental b) Simulated

Scale Volt 100 v/div, Current 1.0 A/div

Fig.7 Phase voltage and current waveform at N=930rpm

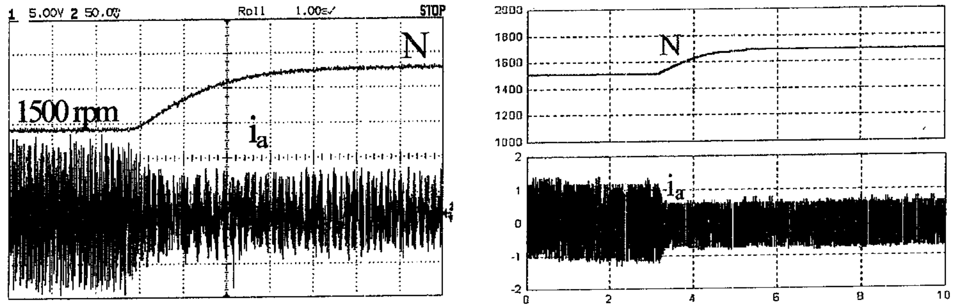
The motor behavior was examined under transient conditions. The motor response to a sudden load application is shown in Figs (8-11). In these tests the load torque was changed from 0.51 Nm to 0.67 Nm for sudden load application and it was changed from 0.67 Nm to 0.51 Nm for sudden load removal. As shown in Figs(8,9), the speed reaches steady state after about 2 seconds due to sudden loading or sudden removal of the load torque.



a) Experimental b) Simulated

Scale Speed 165 rpm/div, Current 1.0 A/div

Fig.8 Motor response due to load application

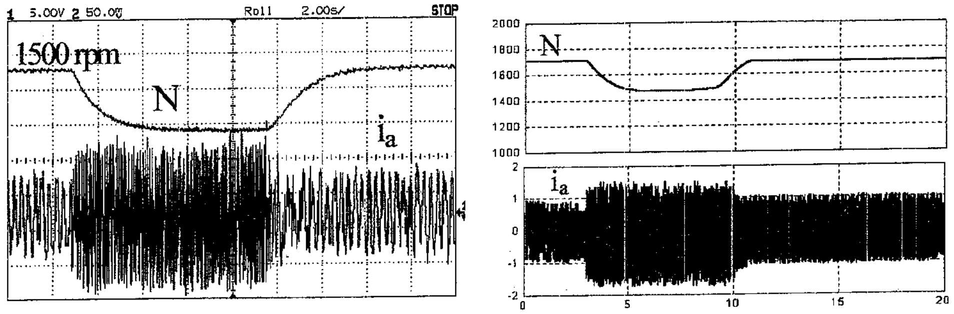


a) Experimental b) Simulated

Scale Speed 165 rpm/div, Current 1.0 A/div

Fig.9 Motor response due to load removal

The motor response to sudden loading followed by load removal was also recorded as shown in Fig(10). The load torque was changed from 0.51Nm to 0.67 Nm and then changed to 0.51Nm. The motor operates synchronously with the input pulses at sudden change in loading. However, such behavior may not be possible with the conventional reluctance motor. Nevertheless, reluctance motors may need to be loaded smoothly to keep in synchronism.

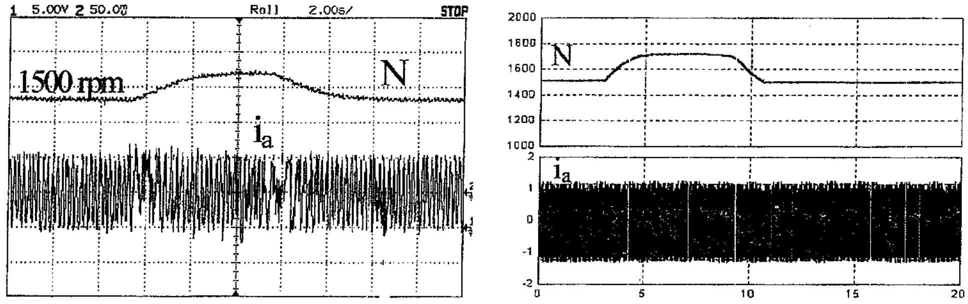


a) Experimental b) Simulated

Scale: Speed 165 rpm/div, Current 1.0 A/div

Fig.10 Motor response due to sudden load changes

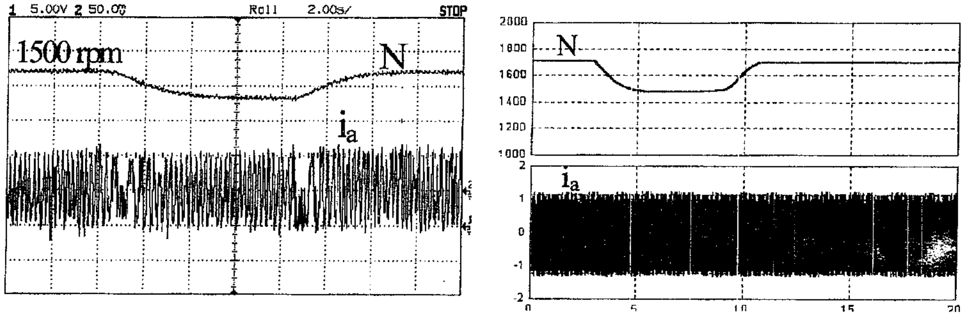
The motor response due to supply voltage change has also been considered. Figs(11,12) show the response of motor speed and phase current as a result for increasing and decreasing the supply voltage by about 20% under loading conditions. The results confirm the capability of controlling the speed by the supply voltage. Such result is compatible with the performance of both switched reluctance and universal motors. However, such test may give undesirable behavior if it is carried out on the conventional reluctance motor.



a) Experimental b) Simulated.

Scale: Speed 165 rpm/div, Current 1.0 A/div

Fig.11 Motor response due to sudden change in supply voltage from 180 to 220 to 180 volt



a) Experimental b) Simulated

Scale: Speed 165 rpm/div, Current 1.0 A/div

Fig.12 Motor response due to sudden change in supply voltage from 220 to 180 to 220

The above results confirm that, the proposed system is able to behave as a brushless double fed reluctance motor over a wide speed range. It is characterized by ruggedness, reliability and low cost. The torque speed characteristic of the proposed system is similar to that of the switched reluctance motor. However it is different in its construction and method of excitation.

CONCLUSIONS

The paper introduces a proposed arrangement equivalent in performance to that obtained from the doubly fed reluctance motor but with lower losses. Steady state as well as dynamic performance have been examined. The obtained results show the possibility of employing the reluctance motor for variable speed drives. Besides, it has been shown that the proposed single fed motor has a series characteristic with nearly sinusoidal phase current waveform. Considering the overall performance, the proposed system is effectively a brushless DC series motor but with electronic commutator. The proposed system is better than the conventional reluctance motor fed from the mains, since it always runs in synchronism without any stability problems. However, further work may be required to operate the motor at fixed speed in closed loop for the dc supply voltage control.

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APPENDIX

Parameters of the employed reluctance motor:

rating	1/3 hp
current	0.5/0.8 A
2P	4
K_d	0.0005
R_a	21 Ω
R_Q	24 Ω
R_D	18 Ω
L_D	0.9859 H
L_Q	0.361 H
L_d	0.995 H
L_q	0.3882 H
J	$56\text{x}10^{-4}\text{Kgm}^2$

نظام تسيير لمحرك المعاوقة مكافئ لنظام التغذية المزدوجة

د./ سلوى محمد رياض طاحون

يقدم هذا البحث شكل جديد لتغذية محرك المعاوقة باستخدام مجموعة واحدة من الملفات تكافئ نظام التغذية المزدوجة. يستخدم النظام المُقترح محرك معاوقة ثلاثي الأوجه ذو أقطاب بارزة بمجموعة واحدة من الملفات تُغذى من مصدر تيار مستمر من خلال عاكس ذو ستة نبضات أحادي الاتجاه، و بذلك تم تلافي استخدام مجموعة ملفات التحكم الموضوعة بالعضو الثابت و المستخدمة بالمحركات ذات التغذية المزدوجة. تُغذى أوجه المحرك بحيث تصل نبضات جهد الدخل دائماً عند وضع أدنى ممانعة مغناطيسية. و يتميز نظام التغذية المُقترح بأنه في حالة تحميل المحرك بحمل متغير العزم، فإنه يمكنه العمل على مدى واسع من تغير السرعة دون أن يفقد تزامنه حتى و إن تعرض إلى تغيرات مفاجئة في الحمل أو في جهد التغذية. و يعطي النظام المُقترح أداءاً مماثلاً لنظام التغذية المزدوجة و لكن بمفاقيد أقل حيث يستخدم مجموعة واحدة من الملفات.

تم في هذا البحث بناء النظام معمليا كما تم اختباره في الحالة المستقرة و الديناميكية. كما تم عمل النموذج الرياضي، و استعرضت النتائج المعملية و النظرية للنظام في كل من الحالة المستقرة و الحالة الديناميكية حيث أوضحت النتائج أن هناك توافقا جيدا بين النتائج العملية و ما يناظرها من النتائج النظرية.

أوضحت النتائج أن النظام المقترح المغذى من خلال مجموعة واحدة من الملفات يعطي خواص محركات التوالي، كما أوضحت أن تيارات أوجه المحرك لها شكل جيبي تقريبا. و باعتبار الأداء العام للنظام فإنه يمكن مماثلته بمحرك توالي بدون شربونات و لكن بمبدل إلكتروني. و يتم التحكم في سرعة نظام التسيير المقترح من خلال التحكم في جهد مصدر التغذية المستمر كما في حالة محركات التوالي، و بذلك فإنه يمكن تشغيله كنظام تسيير يعطي سرعات ثابتة مناظرة للسرعة المرجعية بنظام التحكم المغلق.