DYNAMIC PERFORMANCE OF FOUR POLE PER PHASE 12/8 SWITCHED RELUCTANCE MOTOR

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ABSTRACT

In this paper, the dynamic performance of four pole/phase switched reluctance motor (4PSRM) is investigated analytically and experimentally. Different dynamic conditions are considered which include motor starting under load, step change in load, load perturbation, and a step change in the supply voltage. A laboratory prototype of 4PSRM has been designed and built. An asymmetric power converter along with the drive circuit has been designed and built to excite the motor. A mathematical model of the dynamic operation has been developed and numerically simulated. Both the measured and calculated results are found to be in good correlation.

INTRODUCTION

During the last few years, switched reluctance motor (SRM) became a serious competitive to the other types of conventional well established electric motors. The importance of SRM is emerged from its capability of providing a high level performance over a wide range of specifications in a robust form. The motor has salient poles on both its stator and rotor sides. Stator poles are wound with simple concentrated coils, while the rotor has no windings of any kind. By this construction the motor is characterized by its simplicity and robustness.

The high operating performance of the SRM introduced it tó find its way to the market of electric motor drives and to become a challenge competitive for certain industrial applications. It can has been used in the battery-powered vehicles due to its high efficiency and controllability. Its high speed is suitable for fan, pump and certain types of cutting tools. The high starting torque is suitable for traction and hoist applications. The robust brushless construction and good thermal features made the motor attractive for hazardous environments such as mining and petrochemical industries. The motor simplicity and its low cost have implications for domestic appliances. Also, its controllability is suitable for machine tools and robotic systems[1].

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Torque production in SRM is very simple, where the magnetic flux set-up by the stator winding tries to pull the rotor poles into alignment with those of the excited stator phase. One of the important features of the motor is that the direction of the produced torque is independent of the current direction. This feature allows the use of a simple unidirectional electronic power converter in contrast of that used by the induction motor.

The conventional SRM is usually introduced as two poles/phase. Recent studies were directed to develop other motor configurations, among them is the motor of four poles per phase. Some studies have been found in literature and are discussed here.

The SRM of four poles per phase (4PSRM) was introduced and compared with the conventional SRM from the point view of flux linkage and static torque[2]. Three switched reluctance motors of the same size with 4-phase, 16/12 were investigated [3]. These motors differ from each other by using steel laminations of different magnetic characteristics for them and also in their cooling methods. Good performance was obtained from these motors with the drawback of high iron losses when they were operated at high speed. This problem can be limited if lower number of phases is used. A three phase, 12/8 of four poles per phase SRM was introduced in reference [4] to be used for traction applications. The steady state as well as the control characteristics were introduced in that work, to achieve fixed torque levels over the entire speed range. The commutation interaction on the operating performance of a three-phase 12/8,4-pole, 4PSRM was introduced in [5]. In that reference the study was carried-out to get the optimum commutation ratio for maximizing the motor torque. It should be noted that most of the previous studies were limited to the motor steady-state operation. The study of the motor dynamics is important to trace the current and speed changes at starting and load torque or supply voltage disturbances.

In this paper, the dynamic performance of 4PSRM is investigated analytically and experimentally. Different dynamic conditions are considered which include motor starting under load, step change in load, load perturbation, and a step change in the supply voltage. A laboratory prototype of 4PSRM has been designed and built. An asymmetric power converter along with the drive circuit has been designed and built to excite the motor. A mathematical model of the dynamic system was also developed. Both the measured and calculated results are found to be in good correlation.

SYSTEM DESCRIPTION

The system under investigation consists of a 4PSRM, an electronic power converter, control and gate driver circuits and auxiliary circuits for measuring the rotor position, speed and motor input current. The different parts will be illustrated.

The proposed 4PSRM consists of two main parts, the stator and rotor. The stator is built by modifying a stamped stator of an induction motor to become a twelve salient-pole member. This stator is wound with twelve concentrated coils, where each two diametrically opposite coils are connected in series to form a branch. Each two perpendicular branches are connected in parallel to form the winding of one phase.

An 8-pole steel laminated rotor has been designed and built for the proposed motor. The number of rotor poles has been chosen to ensure that, there is always a single magnetic flux path of minimum reluctance for each pole pair. A cross section of the proposed configuration is shown in Fig 1 in which the rotor is aligned to phase "A". The arrows on each stator pole of phase "A" represent the flux direction when this phase is energized. The motor data are given in the appendix

In contrast with the 6/4 motor, this configuration is characterized by its small step angle, short magnetic path and short coil overhang. By increasing the number of poles per phase the forces are split up evenly around the rotor periphery. These features are positively reflected on the motor performance.

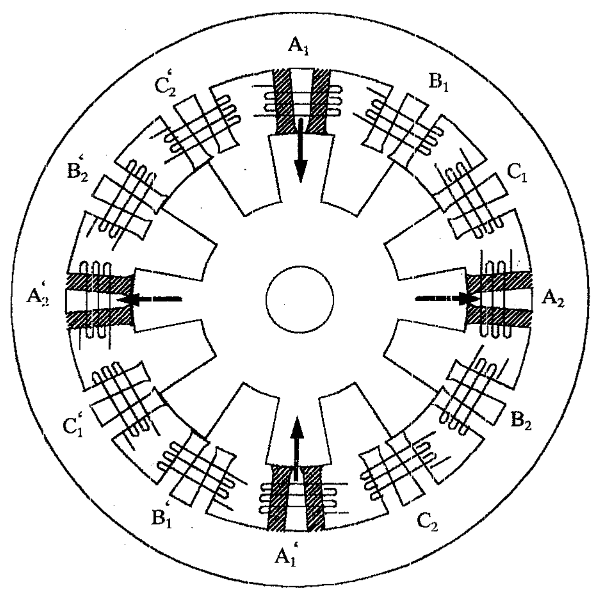


Fig 1 A cross section of the proposed 4PSRM

Since the developed torque is always independent of the phase current direction, a unidirectional electronic power converter is sufficient for the motor. A three-phase asymmetric power converter has been built using six power MOSFETs of the type IRF450FI. The power converter circuit, which is shown in Fig 2., consists of three independent switch legs, one for each phase. The upper and lower switches for each leg are switched-on simultaneously to build-up a phase current pulse. At the end of the phase duty period, the two switches are turned-off simultaneously to allow the diodes to take over the decaying current. The phase current is forced to decay rapidly by reversing the polarity of the dc supply across the phase winding through the diodes.

To maintain a positive developed torque, the current pulses should be supplied to each phase in a sequence related to the rotor position. For this reason it is important to provide the motor with some form of rotor position detector. Nevertheless, the rotor rotates in an opposite direction to the sequence of phase excitation according to the well-known stepper motor principle. In the present work, a shaft position transducer is implemented using a thin slotted disc mounted to the rotor and three optocouplers attached to the stator. The three optocouplers are fixed at space angles correspond to that of the phase windings. Each switch leg of the power converter is controlled by the signal obtained from the corresponding optocoupler. By this way, the motor and the power converter are locked together such that the stator windings are excited with the appropriate sequence to ensure continuous rotation.

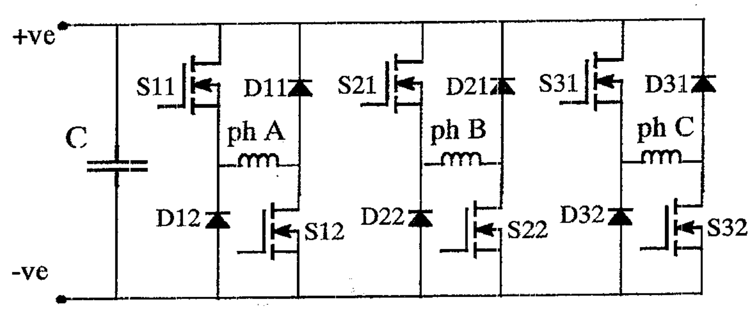


Fig 2 Power converter circuit

The 4PSRM is mechanically coupled with an eddy current brake to be used as a mechanical load. The speed signal was recorded using an electronic frequency to voltage converter circuit designed specially for this purpose. The motor current was recorded using a Hall effect current sensor. The schematic diagram for the complete experimental test rig is shown in Fig 3.

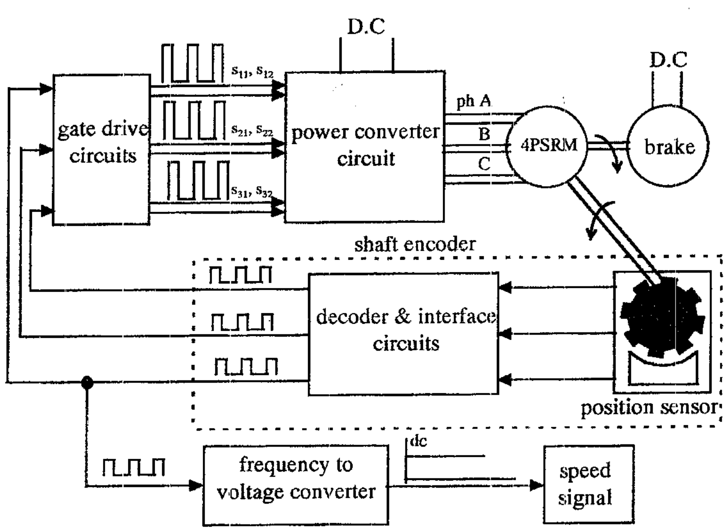


Fig 3 Schematic diagram for the experimental test rig

MATHEMATICAL MODEL

The analysis of the dynamic operation of the 4PSRM is based on simultaneous integration of the electrical and mechanical sets of differential equations representing the system. Since the present system is inherently nonlinear and operates under the influence of a switched power converter, some effort is needed for data preparation and tracing the switching actions within the time-stepping numerical solution.

The system is described mathematically by two sets of differential equations[6], the first one is the motor *electrical equations*:

$$\frac{d\psi_k(\theta_k, i_k)}{dt} = \pm V_k - R\, i_k \tag{1}$$

where R is the phase resistance, V_k is the dc supply voltage, and k=1,2,..q, where q is the number of phases.

$$\text{and } \theta_k = \theta_1 + (k-1)\,\varepsilon \tag{2}$$

where ε is the step angle expressed in tems of number of phases and rotor poles (N_r), as follows:

$$\varepsilon = \frac{2\pi}{q\, N_r} \tag{3}$$

The applied voltage alternates between three different values according to the switching states. When the MOSFETs are switched-on the applied voltage is positive and equals the dc link voltage. When the MOSFETs are turned-off while there is a current still flowing through the diodes, the applied voltage is negative and equals the dc link voltage. When both MOSFETs and diodes are turned-off the applied voltage is zero. These different states are represented by the following expression:

$$\begin{aligned} V_k &= +E \quad \text{for} \quad \theta_{on} \le \theta_k \le \theta_{off} \\ &= -E \qquad\quad \theta_{off} \le \theta_k \le \theta_{ext} \\ &= \;\; 0 \qquad\qquad\quad \theta_k > \theta_{ext} \end{aligned} \tag{4}$$

where E is the dc supply voltage, θ_{on} is the turn-on angle, θ_{off} is the turn-off angle, and θ_{ext} is current extinction angle.

Thus, a positive voltage is applied to each phase for a period equals the difference of θ_{off} and θ_{on}. It is better to express this period with commutation ratio (CR) which is defined as the ratio of the angle over which the phase voltage is positive to half the rotor pole pitch angle [7]. Since the ratio of pole arc to pole pitch equals to 0.5 (for the motor under investigation), the CR can be expressed as:

$$CR = \frac{\theta_{off} - \theta_{on}}{\tau_r / 2} = \frac{\theta_{off} - \theta_{on}}{\beta_r} \tag{5}$$

where τ_r is the rotor pole pitch, and β_r is the rotor pole arc.

The second set of equations are the *mechanical equations*:

$$\frac{d\omega}{dt} = \frac{1}{J}\left(\sum_{1}^{q} T_k(\theta_k, i_k) - T_\ell\right) \qquad (6)$$

$$d\theta = \omega \ dt \qquad (7)$$

where ω is the rotor angular speed, J is the moment of inertia of the rotating parts and T_ℓ is the load torque.

The motor dynamic performance can be obtained by simultaneous integration of the introduced two sets of differential equations. To carry out this integration process, the relation between the phase current and flux linkage should be known for different rotor position angles. A family of flux linkage-current data has been generated according to the following procedure. Two curves representing the flux linkage current at both unaligned and aligned positions are obtained from the motor geometry using the method used in[8]. The flux linkage $\psi(\theta,i)$ for a phase winding varies cyclically with rotor position θ, thus a family of flux linkage-current curves are generated at different rotor positions by the expression[9]:

$$\psi(\theta,i) = L_u.i + \frac{\psi_a(i) - L_u.i}{2}[1 - \cos(N_r\theta)] \qquad (8)$$

where L_u is the minimum (unaligned) phase inductance, $\psi_a(i)$ represents the aligned flux linkage current curve, N_r is the number of the rotor poles, and θ is the rotor position angle. Figure 4 shows these family of curves in a three dimension view. The resulted flux linkage current curves are rearranged and stored as a look-up table in the form of $i(\theta,\psi)$.

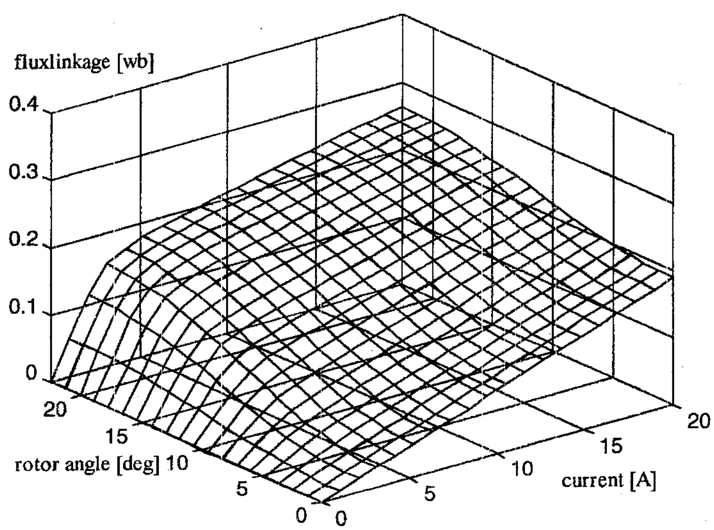


Fig 4 Flux linkage current curves for the 4PSRM

The family of flux linkage-current curves are integrated with respect to the phase current to obtain the co-energy curves:

$$W(\theta, i) = \int_0^i \psi(\theta, i)\, di \Big|_{\theta = const} \tag{9}$$

Applying numerical differentiation on phase co-energy curves relative to rotor displacement, the second look-up table T(θ,i) is obtained by:

$$T(\theta, i) = \frac{\partial W(\theta, i)}{\partial \theta} \Big|_{i = const} \tag{10}$$

The calculated static torque curves against both phase current and rotor angle are shown in Fig 5 in a three dimension view.

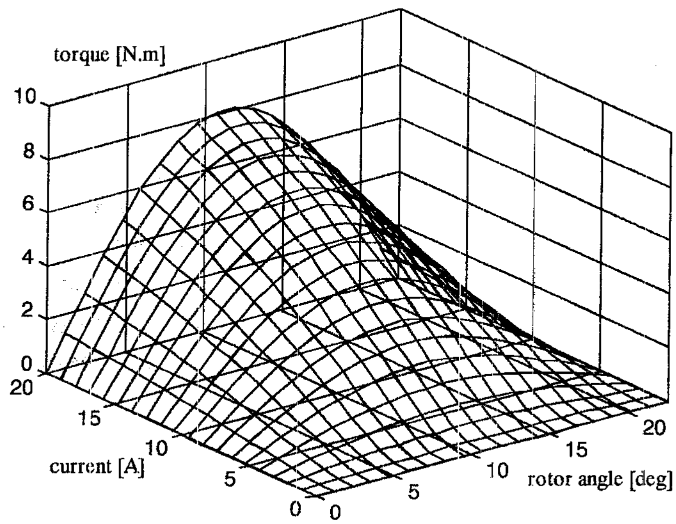


Fig 5 Calculated static torque for the 4PSRM

Numerical integration has been applied to Eqns(1,6,&7) to obtain the instantaneous values of current, torque, and speed. The flux linkage-current and torque-current look-up tables have been used to update the current and torque values after each integration step. Cubic spline interpolation has been used to obtain the intermediate values from these tables [10].

RESULTS AND DISCUSSION

The system described above has analyzed and experimentally investigated. Different conditions of dynamic performance are considered, these include change in load, load perturbation, and increase and decrease in the supply dc voltage. The analysis and experimental results are given for different commutation ratios to study the effect of this ratio on the motor dynamics. The performance has been studied throughout the dc-link current and motor speed. Since the dc-link current is the instantaneous sum of the excitation pulses of the three phases, it is considered to be the total current drawn from the dc source. This explains the noisy shape of the current response observed in the experimental results.

Starting Performance

The motor started under a load torque of one Newton-meter. The analytical results are shown in Figs 6 to 10 for the different commutation ratios. It is noticed that the response is faster and the motor settles at higher speed for higher values of CR up to 0.8. This is because wider pulses are allowed to feed each phase when the CR is increased. However, any CR higher than 0.8 results- in a slower response and a lower steady-state speed. This is because much wide current pulses ,extended to the negative inductance variation, produces a negative torque component which is subtracted from the positive developed torque. For this reason the motor speed settles at a lower speed at any CR higher than 0.8.

The starting performance has been studied only analytically because the starting current is higher than the motor and power converter ratings. As it is observed from the current waveforms of Figs 6-10, the starting current is too high and increases by increasing the commutation ratio. This because at starting, the phase current is opposed solely by the low winding resistance. Switched reluctance motor in this respect is similar to dc motors which should be started with reduced armature voltage. However, SRM does not need an external means for regulating the applied voltage at starting, but regulating the CR at starting is sufficient to reduce the starting current to an acceptable level.

It should be noted that the condensed dc-link current waveforms which has been represented in this paper consist of a successive current pulses like that shown in Fig 7. This figure shows the phase voltage, current and dc-link current waveforms for a short period, about 2 ms, during the steady state. The phase current pulse increases when the applied voltage is positive. At the end of the phase duty, the applied voltage becomes negative which results in a fast decay of the phase current pulse. The dc link current is the instantaneous sum of the three phase currents.

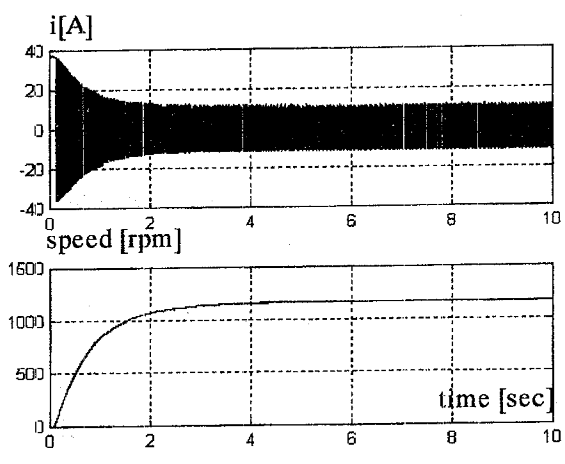


Fig 6 Starting performance at CR=0.6

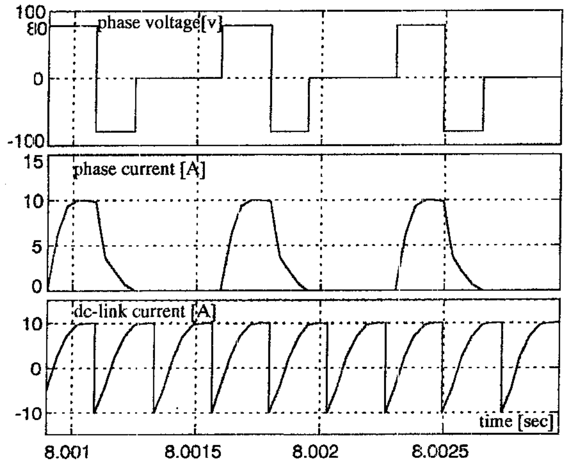


Fig 7 Narrow sector of phase voltage, current, and dc link current at CR=0.6

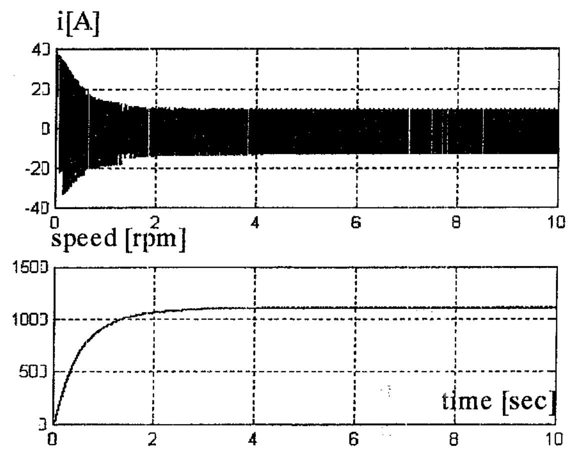


Fig 8 Starting performance at CR=0.7

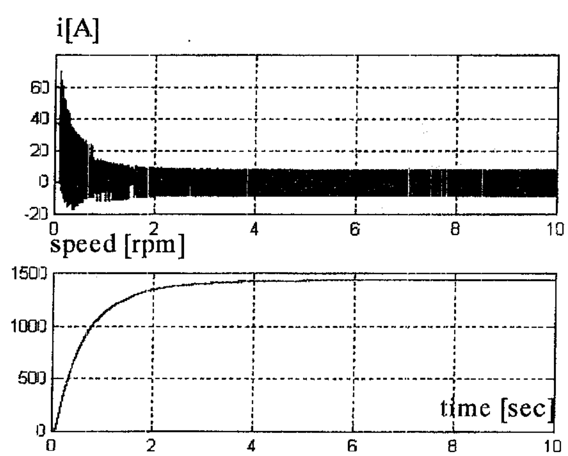


Fig 9 Starting performance at CR=0.8

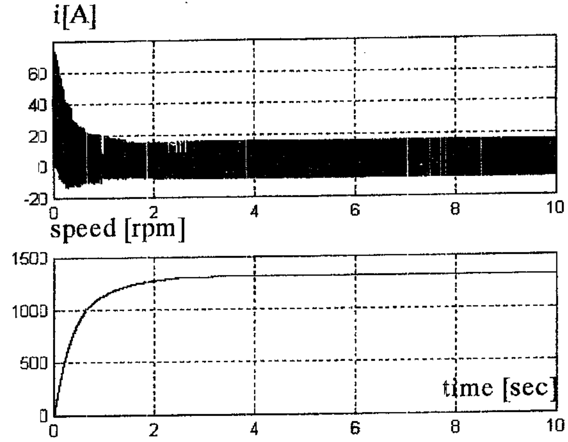
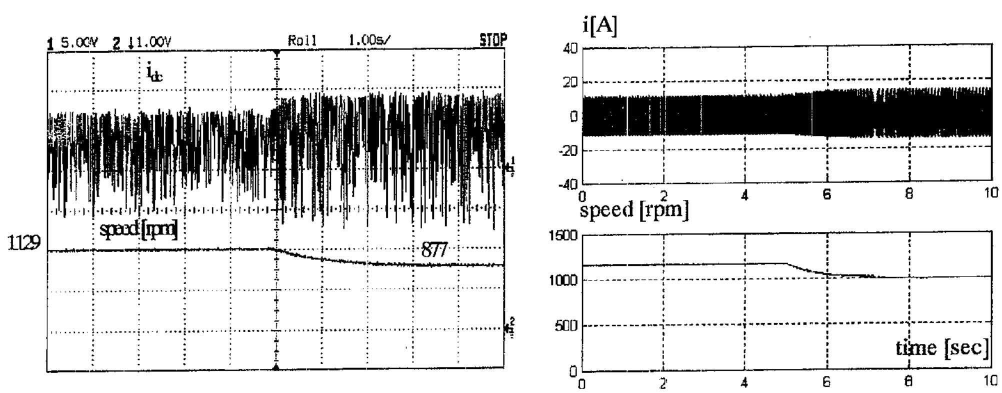


Fig 10 Starting performance at CR=0.9

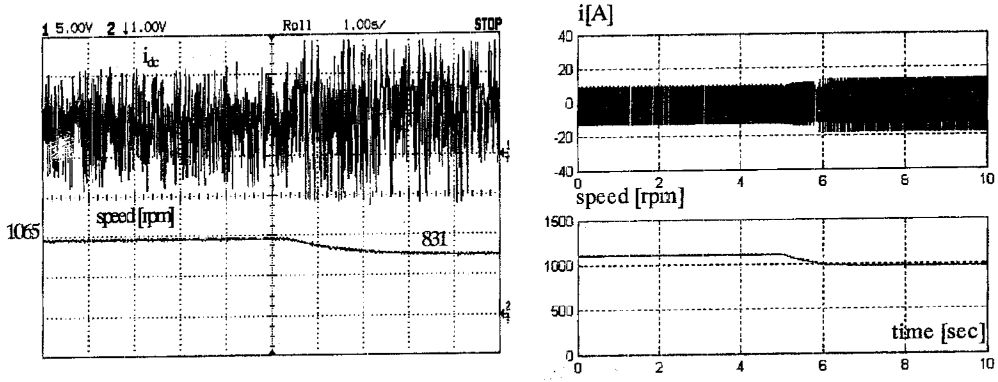
Step Change In Load

The motor has been tested for sudden load variations. Figures(11-14) show the experimental and analytical results when the load torque is changed from 1.0 to 1.5 N.m. It should be noted that there is no stability problem in this type of motors due to locking the rotor position with the excitation pulses via the rotor position sensors. As the load torque is suddenly increased, the motor settles at lower speed and draws higher current. The result is the same for different values of CR, however, the current and speed levels are different for each value. This result is a typical for open loop motor and corresponds with the series characteristics of the 4PSRM[5]. Basically, the motor is capable to operate under a sudden increase of the load torque. The only restriction on the load torque is the motor input current which shoud be within the rated value. If some means of control is implemented, the motor may sustain the load increase while keeping the current within an acceptable level.



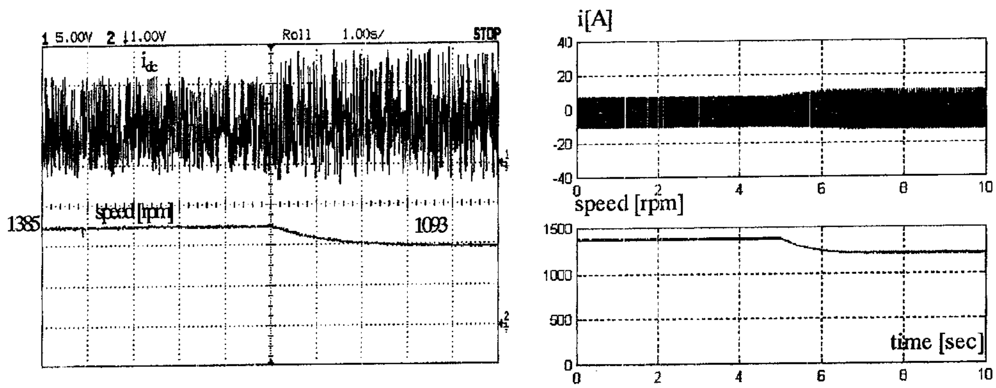
a) Experimental b) Analytical

Fig 11 Dynamic response for sudden change in load torque at CR=0.6



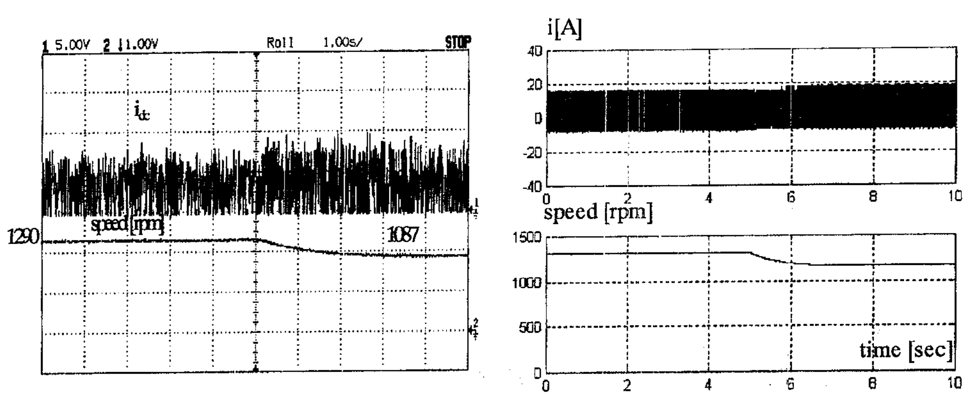
a) Experimental b) Analytical

Fig 12 Dynamic response for sudden change in load torque at CR=0.7



a) Experimental b) Analytical

Fig 13 Dynamic response for sudden change in load torque at CR=0.8

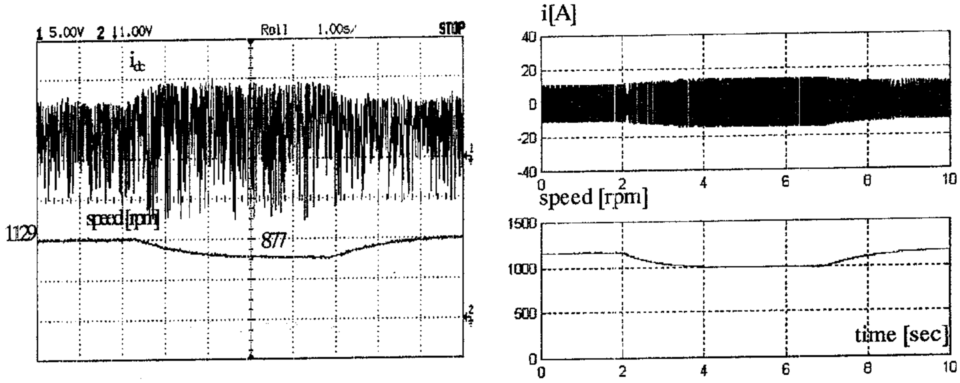


a) Experimental b) Analytical

Fig 14 Dynamic response for sudden change in load torque at CR=0.9

Load Perturbation

Load perturbation is usually encountered by the motor in its different applications. In the present study a condition is chosen in which the motor is initially running at steady-state under its full load and then its load torque is suddenly increased by 50% for a short time. The experimental and simulation results are shown in Figs 15 to 18 for different commutation ratios. It is noticed that, the dc-link current and motor speed values respond to the load variations. The dc-link current increases with the load increase, while the speed is decreased, and both of them are returned to thier original values after removing the excess torque. The result is also the same for different values of CR, however, the current and speed levels are different for each value.



a) Experimental b) Analytical

Fig 15 Dynamic response for load torque perturbation at CR=0.6

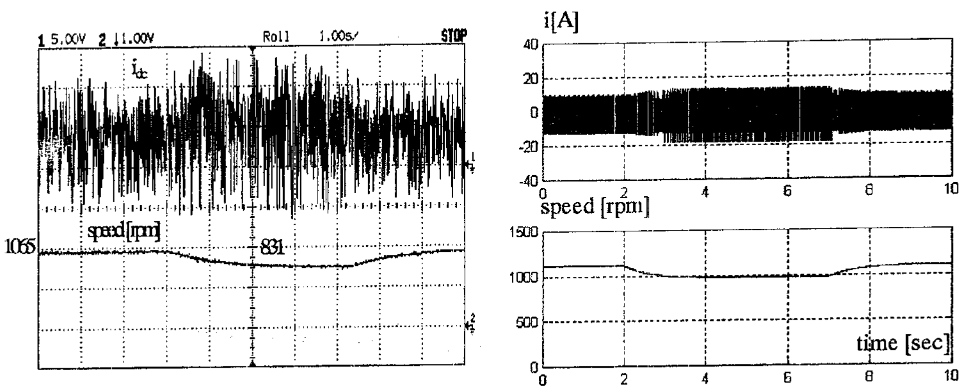


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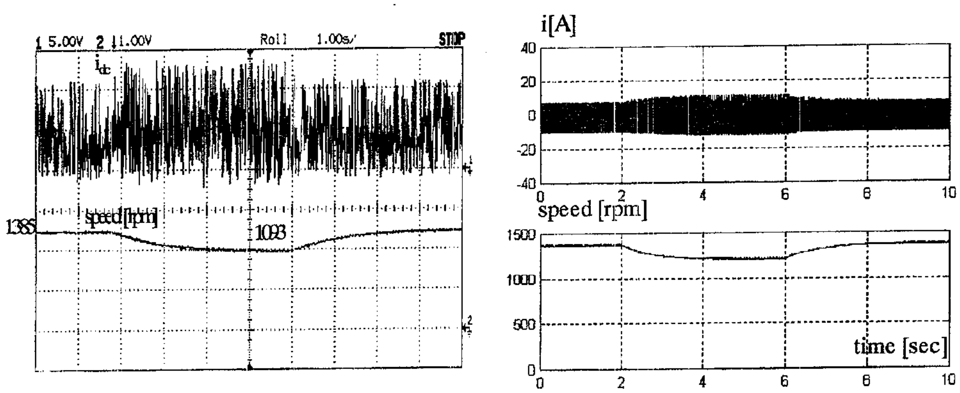
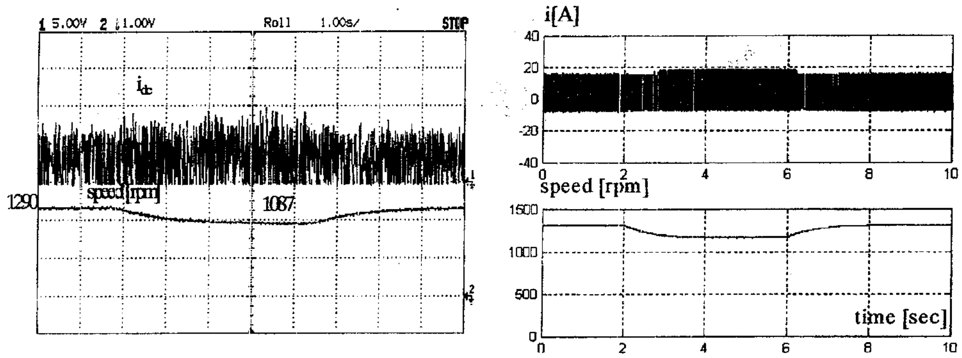
Fig 16 Dynamic response for load torque perturbation at CR=0.7



a) Experimental b) Analytical

Fig 17 Dynamic response for load torque perturbation at CR=0.8

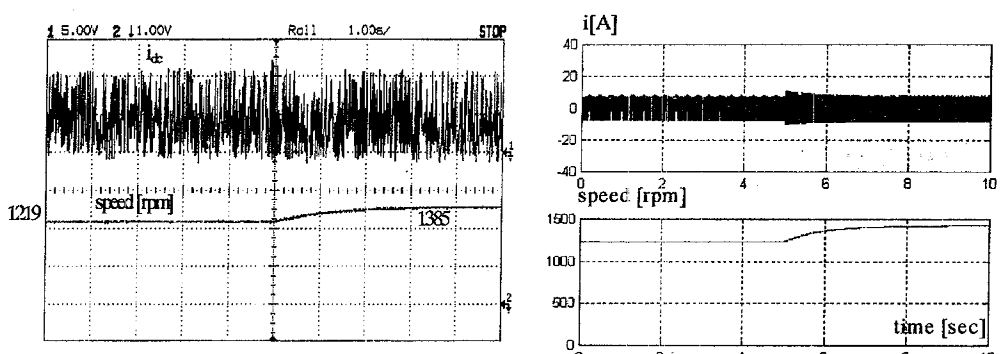


a) Experimental b) Analytical

Fig 18 Dynamic response for load torque perturbation at CR=0.9

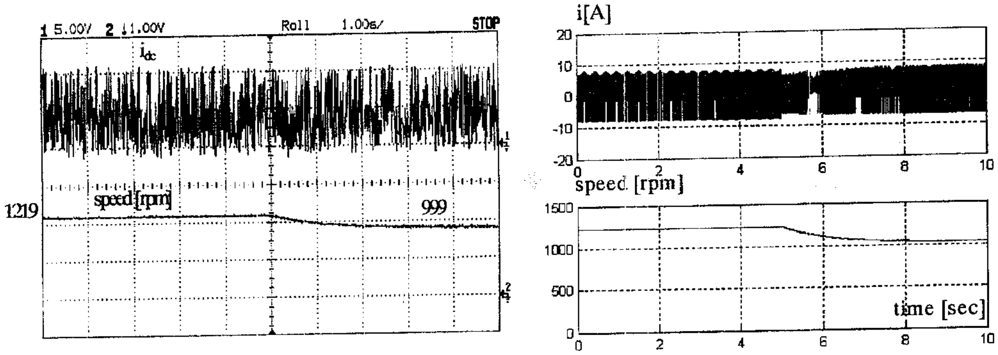
Change In The Supply Voltage

Investigating the effects of the supply voltage changes on the dynamic response is helpful to study the control characteristics of the motor. The motor operation has been tested under sudden increase and sudden decrease of the supply voltage. The experimental and analytical results of sudden increase of the supply voltage are shown in Fig 19, while those of sudden voltage decrease are given in Fig 20. In Fig 19 the motor was initially running at steady state with its full-load of 1.0 N.m and a supply voltage of 70V. The applied voltage is then increased by 15%. By increasing the applied voltage, the motor current is initially increased for some transient period and then it decreases to a lower level comparable to its original value, while the speed increases and settles at a higher level. Figure 20 represents the case of decreasing the applied voltage by 15%. In this case, the action is reversed, that is the current after the transient period is approximately the same, while the speed is decreased. It should be noted that the test was carried out for different values of CR, but the results at CR=0.8 are only presented. This is the most suitable value for CR as it has been concluded from the present study as well as a previous study [5]. It should be noted also that, the switched reluctance motor responds to the voltage changes in the same way like the dc motor. For this reason it is possible to regulate the motor speed by changing the motor applied voltage.



a) Experimental b) Analytical

Fig 19 Dynamic response for sudden incraese in supply voltage at CR=0.8



a) Experimental b) Analytical

Fig 20 Dynamic response for sudden decraese in supply voltage at CR=0.8

CONCLUSIONS

In this paper an experimental and analytical study has been carried-out to study the dynamics of the 4PSRM. The motor starting under load, step change in the load torque, load perturbation, and step changes in the supply voltage are the main conditions included in the present work at different commutation ratios. From the present study, it has been observed that the motor response is similar to that of the dc motor in two respects. The first is that the starting current is too high such that the applied voltage should be reduced at starting. The second is the motor response to changing the applied voltage, which is useful for speed regulation. In both respects, the 4PSRM is better than the dc machine since it does not need an external means for regulating the applied voltage but regulating the CR is sufficient to give the same effect like varying the applied voltage. The study reveals that 4PSRM cope with sudden changes of the load torque. The only restriction on the load torque is the motor input current which shoud be within the rated value. If some means of control is implemented, the motor may sustain the load increase while keeping the current within rated value. The study has been carried-out analytically and experimentally and good correlation has been obtained.

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APPENDIX

The motor data:

number of stator poles	12
number of rotor poles	8
number of phases	3
the active iron length	40.9 mm
the stator outer diameter	145.5 mm
the stator inner diameter	85.3 mm
apparent stator pole arc	0.309 rad
net stator pole arc	0.257 rad
stator pole height	16 mm
rotor diameter	84.8 mm
rotor pole arc	0.5 rotor pole pitch
rotor pole height	16 mm
moment of inertia	0.02 N.m.sec/rad

الأداء الديناميكي لمحرك المعاوقة المُغذى بنبضات و المكون من نسبة أقطاب ٨/١٢ و يحتوي على أربع أقطاب لكل وجه

م/ محمود أحمد عبد اللطيف، د/ سلوى محمد رياض طاحون، د/ محمود مصطفى خاطر، أ.د/ محمد مصطفى الشنواني، أ.د/ سيد أحمد حسن

يقدم هذا البحث دراسة معملية و تحليلية للأداء الديناميكي لنموذج معدل لمحرك المعاوقة ثلاثي الأوجه المُغذى بنبضات يتركب من عدد أقطاب ٨/١٢ في العضو الثابت و العضو الدوار حيث يحتوي العضو الثابت على أربع أقطاب لكل وجه. هذا التركيب يعطي توزيعاً أفضل لكل من الفيض المغناطيسي والقوى المماسية المؤثرة على العضو الدوار بالإضافة إلى قصر المسار المغناطيسي و قصر و قصر الوصلات الطرفية مقارنة بالنوع التقليدي و الذي يشتمل على قطبين لكل وجه، و التركيب المقترح ينعكس بصورة إيجابية على خصائص تشغيل المحرك. وقد تعرضت الدراسة لعدة حالات من التشغيل الديناميكي شملت بدء الحركة بوجود الحمل و تغير الحمل على محور المحرك و اضطراب قيمة الحمل و تغير جهد التغذية.

النموذج المستخدم تم تصنيعه خصيصاً لهذا البحث، وقد استخدم في بنائه العضو الثابت لمحرك تأثيري أحادى الوجه تم تعديله ليصبح به اثنا عشر قطباً بارزاً، وتم تصميم وبناء العضو الدوار من شرائح الصلب السيليكوني به ثمانية أقطاب بارزة، كما تم أيضا بناء المغذي الإلكتروني، بما في ذلك محدد موضع العضو الدوار من أجل ضبط بداية توصيل كل وجه من أوجه المحرك بحيث تكون متوافقة مع الفترة الموجبة لتغير حثية الوجه أثناء الدوران، و ذلك لضمان الحصول على عزم موجب.

تم بناء برنامج لمحاكاة أداء المنظومة حيث استُخدمت الخصائص الساكنة للمحرك في حل المعادلات التفاضلية للنظام ككل.

تم عرض النتائج المعملية و التحليلية عند قيم مختلفة لنسبة التبديل (و هي النسبة بين فترة توصيل الوجه مقدرة بالزاوية و نصف الخطوة القطبية في العضو الدوار) حيث أمكن تحديد القيمة التي تحقق أفضل أداء للمحرك.

أوضحت الدراسة أن المحرك موضوع البحث له خصائص تتشابه مع خصائص محركات التيار المستمر إذ أن تيار البدء يأخذ قيمة مرتفعة مما يستلزم إنقاص جهد التغذية أثناء عملية البدء، و كذلك فإن أداء المحرك يتوقف على جهد المنبع و هذه الخاصية يمكن الاستفادة منها في تحسين أداء المحرك. وبذلك فإن محرك المعاوقة المُغذى بنبضات يُعتبر أفضل من محركات التيار المستمر حيث أن التغير في نسبة التبديل له نفس تأثير تغير الجهد، أما من ناحية الاستقرار فإن هذا المحرك يفوق محرك المعاوقة التزامني نظراً للربط الكائن بين موضع العضو الدوار و النبضات التي تغذي أوجه العضو الثابت.