MENOUFIYA UNIVERSITY
FACULTY OF ENGINEERING
ENG. RESEARCH BULL.
Vol. 17 Part I, 1994

P.P. : 121 : 136
Received at : 19/ 1 / 1994
Accepted at : 13/ 2 / 1994

A FIVE PHASE SWITCHED RELUCTANCE MOTOR
PART 1: DESIGN AND PERFORMANCE

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ABSTRACT

This paper presents a design procedure for switched variable reluctance motors with low torque ripple content. A five phase configuration with high overlap ratio is proposed to minimize torque pulsations. The proposed scheme integrated with a special inverter are suitable for low power variable speed applications. A prototype system has, already been built and experimentally investigated. Its merits and demerits are highlighted.

1. INTRODUCTION

The concept of Switched Reluctance SR motor is more than 150 years old and in fact the first electrical motor or *electromagnetic engine,* as was called, of the 1830's was a reluctance motor [15]. Due to its early days poor characteristics, it gave way to its competitor, the induction motor. The motor could not realize its full potential until the modern era of power electronics and computer aided design techniques.

SR motors have been developed for electric propulsion [2,3], fan, pump, home appliances [11] and even for servo and robotic applications [10]. The operating principles of SR motors have been established in literature [4]. It consists of a doubly salient structure of steel laminations. Diametrically opposite stator poles carry simple concentrated coils connected, generally, in series. There are no windings of any kind on the rotor. Torque is produced by the attraction of rotor poles into alignment with appropriate group of stator poles constituting an excited phase according to a signal from a shaft encoder. It is different from conventional reluctance machines, which have distributed three-phase windings on the stator and energised from sinusoidal supplies. SR motors offer a number of potential advantages which mainly originate from simplicity of both the motor structure and the driver configuration.

In spite of the growing interest of SR machine, it still has urgent problems need to be dealt with before being fully accepted. Torque pulsations is one of these problems. Torque pulsations are dependent on various interrelated factors among them number of phases, number of poles, pole geometric dimensions, operating speed and converter control parameters. There are serious attempts to overcome this problem by generating a pre-tailored current waveforms[14]. It might be better to analyze the problem on the basis of its origin, the motor design itself. SR motor, to some extent, is a variable reluctance stepping machine with number of torque pulses per revolution given by;

$$S = \frac{N_s N_r}{N_s - N_r} \qquad (1)$$

and this number equals only 12 pulses for 3-phase motor with 6/4 poles and equals 24 pulses for 4-phase one with 8/6 poles. In an attempt to develop a SR drive system with higher number of torque pulses per revolutions and consequently lower torque ripple content a forty pulse, 5-phase SR motor with 10/8 pole configuration is presented here. This paper is devoted, mainly, to motor design and performance and another accompanying one,[Part 2], for power converter and switching control.

2. DESIGN PROCEDURE:

At the design stage, data could be known are motor power rating, full load speed, magnetic characteristics of core material and some parameters of the intended electronic commutator. Starting from these data, a certain formula is required to obtain basic core dimensions. One such formula is developed in [8]. It is closely similar to those of conventional ac machines,

$$P_d = \eta . k_d . k_1 . k_2 . B . A_{sp} . D^2 . L . N \qquad (2)$$

where

$$k_1 = \frac{\pi^2}{120} \tag{3}$$

$$k_2 = 1 - \frac{1}{\sigma . \lambda_u} \tag{4}$$

$$\sigma = \frac{L^s{}_a}{L^u{}_a} \quad , \quad \lambda_u = \frac{L^u{}_a}{L_u} \tag{5}$$

Until today, SR motor is still in its infant age. There is no well established guide lines for choosing certain parameters like bore diameter to axial length ratio and specific electric and magnetic loadings. It might be useful to start these values with those applied to similar conventional ac machines and check the result against essential specifications required for SR motor.

SELECTION OF DIMENSIONS

[I] *DIAMETER AND LENGTH*

From equation (2), with the stack length defined as a function of bore diameter, D is evaluated if rated speed, B, A_{sp}, k_2 and k_d are known. It is possible to start the iterative process of design with reasonable values extracted from experimental experience. At the rated operating point the range of k_2 is given in [8]

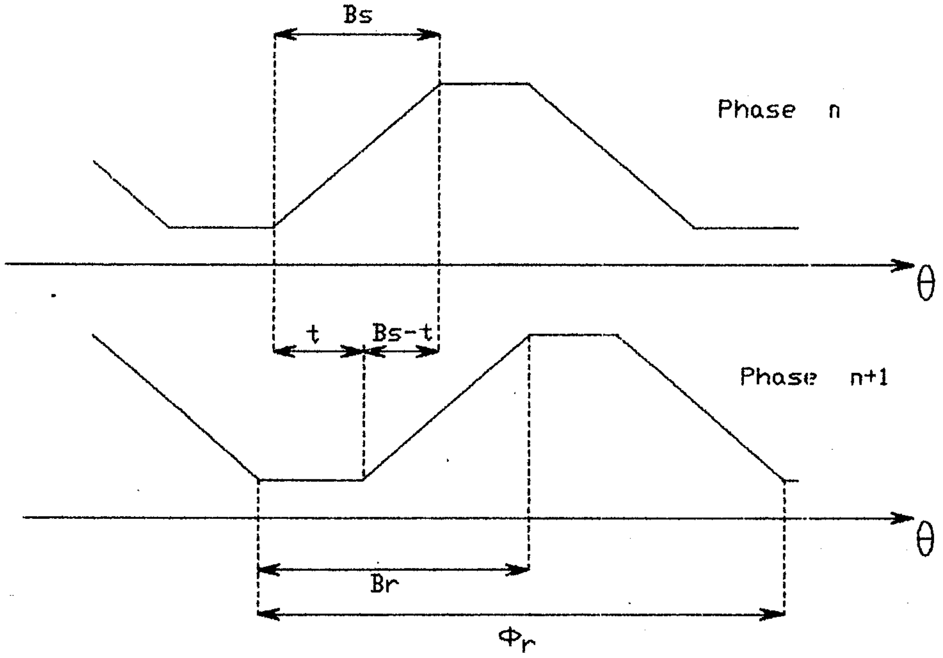
$$0.65 < k_2 < 0.75 \tag{6}$$

For effective use of magnetic circuit the value of B for the aligned position can be taken close to maximum allowable value for the core material and saturation in critical sections could be checked later.

Using the above starting values, bore diameter and axial length could be obtained. The air gap is determined by the machining tolerance and assembly techniques. Small machines have air gaps of about 0.25 mm.

[II] *POLE NUMBERS AND ARCS*

The choice of N_s and N_r has a significant implications on the instantaneous and average torque. Their choice should satisfy certain essential design requirements. Basic guidelines have been established [4], but there is an important point need to be highlighted here.



Figure(1) Unsaturated inductance profiles for two adjacent phases.

The step angle of variable reluctance motor is given by,

$$t = \frac{2\pi (N_s - N_r)}{N_s N_r} \qquad (7)$$

To minimize torque ripple content on the motor shaft, there must be an adequate overlap angle between positive sloped L(θ) variations of adjacent phases. With the aid of figure (1), if *kL* is defined as the ratio of inductance overlap of two adjacent phases to the angle over which the inductance is changing, then

$$k_L = \frac{\beta_s - t}{\beta_s} \qquad (8)$$

Defining stator pole arc as a ratio, *ks*, of stator pole pitch,

$$k_s = \frac{\beta_s}{(2\pi / N_s)} \qquad (9)$$

From equations (7),(8) and (9), *kL* can be rewritten as follows,

$$k_L = 1 - \frac{N_s - N_r}{k_s N_r} \tag{10}$$

It has been shown [9] that a typical value of *ks* would be between 0.35 and 0.5. Table (1) shows the variation of *kL* for different phase numbers. The table shows also how *kL* varies over the recommended range of *ks*.

No. of phases q	N_s/N_r	*kL*	
		ks=0.5	*ks*=0.35
3	6/4	0.00	-0.42
4	8/6	0.33	0.05
5	10/8	0.50	0.29
6	12/10	0.60	0.43
7	14/12	0.67	0.52

Table (1) Variation of inductance overlap ratio for different number of poles.

It is clear that inductance overlap ratio is highly sensitive to both number of phases and ratio *ks*. For practical SR machine it is preferred to minimize stator pole width for two reasons. The first, to be able to accommodate the winding with a reasonable stator pole height. The second, to improve ventilation and allowing enough room for good insulation specially at high voltages. From this argument, it is concluded that increasing number of phases would improve inductance overlap ratio and consequently the torque ripple content would be reduced. The penalty to be paid for the proposed scheme is its need for an inverter with more switching elements. A new inverter with minimum number of switches has been developed for these category of SR motors [Part 2 of this paper].

[III] *NUMBER OF TURNS PER PHASE AND POLE HEIGHTS*

Number of turns per phase is calculated, for a given current, from specific electric loading defined as,

$$A_{sp} = \frac{2T_{ph} . I . m}{\pi D} \tag{11}$$

The conductor size is chosen such that current density is kept within maximum permissible value. If there is no restriction on the motor outside diameter the winding space can be calculated from the number of turns, the conductor cross-section area, and the insulation thickness. The height of the stator pole is then derived from the winding space.

The constraint on rotor pole height is to minimize phase inductance at unaligned positions. It is found, [13], that the air gap permeance is nearly constant for

$$L_{rp} \geq \frac{0.9\pi}{N_r}(1-\phi_r)\frac{D}{2} \tag{12}$$

3. PREDICTION OF INSTANTANEOUS TORQUE:

Torque is developed by the tendency for the magnetic circuit to adopt a configuration of minimum reluctance. The general equation governing the flow of stator current for one phase may be written as;

$$V(\theta) = R.i(t) + \frac{d\psi(\theta,i)}{dt} \tag{13}$$

This equation can be expressed in the following alternative form;

$$\frac{di}{dt} = \frac{1}{\frac{\partial\psi(\theta,i)}{\partial i}}\left[V(\theta) - R.i(t) - \omega\frac{\partial\psi(\theta,i)}{\partial\theta}\right] \tag{14}$$

To predict the phase current under steady state conditions, and consequently the machine performance, equation(14) need to be integrated for the appropriate switching conditions. The problem is how to formulate the flux linkage characteristics in an accurate way to implement it in the right hand side of equation(14). Various approaches are established in literature[1,2,12]. One simple method which is based only on the aligned and unaligned flux linkage data[12], and defines the flux linkage characteristics as;

$$\psi(\theta,i) = L_u.i + \frac{\psi_a(i) - L_u.i}{2}[1 - \cos(N_r\theta)] \tag{15}$$

The developed torque for each phase at certain rotor position is given by;

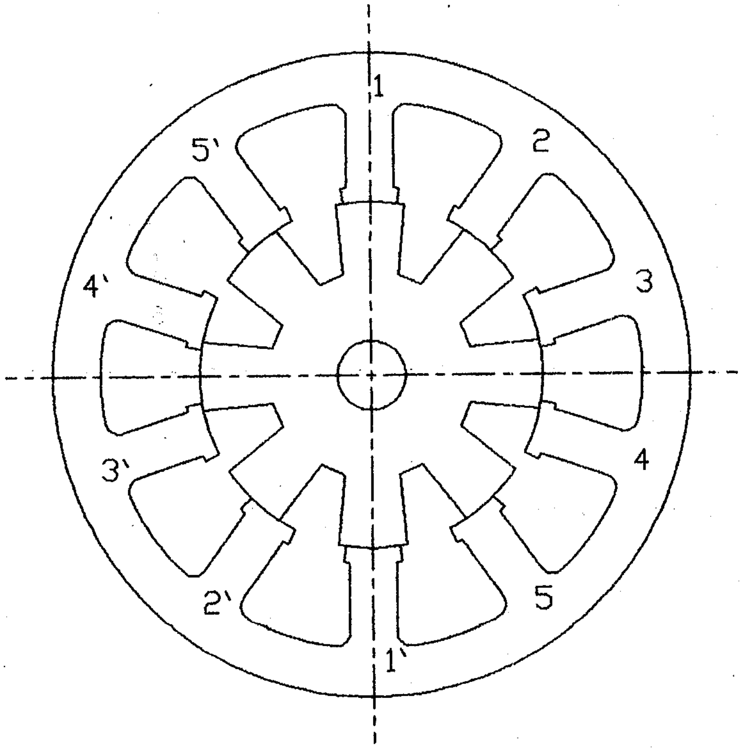
$$T(\theta,i) = \frac{1}{2}\, i^2(\theta)\frac{dL(\theta)}{d\theta} \tag{16}$$

And the total torque produced by all phases at any rotor position is given by the sum of their individual torques;

$$T_\theta = \sum_{n=1}^{q} T_n(\theta, i) \qquad (17)$$

4. PROTOTYPE DESIGN IMPLEMENTATION:

The design procedure described in section(3) has been implemented in a computer design package to obtain the detailed dimensions. The package also predicts the machine performance at design stage to be able to alter and modify the dimensions. The aligned and unaligned flux linkage data are obtained by the method described in[3]. These data are substituted in equation(15) to define the flux linkage at any rotor position and various excitation levels. Equation(14) is numerically integrated to obtain phase current pulse. The torque developed by each phase is obtained from equation(16) and the total instantaneous torque is calculated, as the positional sum of individual torque of each phase, from equation(17).



Figure(2) Cross-section of motor magnetic core.

A hundred-watt, five-phase laboratory prototype switched reluctance motor is designed, and already built, with the procedure described here. A cross-section of its steel laminated core is shown, to scale, in figure(2). The detailed dimensions are given in table(2).

Number of stator poles	10
Number of rotor poles	8
Number of phases	5
Bore diameter	50 mm
Air gap length	0.25 mm
Core axial length	54 mm
Stator pole arc	0.31 rad
Rotor pole arc	0.39 rad
Stator pole height	11 mm
Rotor pole hight	10 mm
Outer diameter	93 mm
Shaft diameter	10 mm
Number of turns/phase	320
Conductor diameter	0.5 mm
Motor power (Design value)	100 watts
Phase current amplitude	3 amp
DC voltage (series/parallel)	60/30 volts

Table(2) Summary of motor dimensions.

5. PREDICTED AND EXPERIMENTAL RESULTS:

The difficulty of experimental measuring of motor instantaneous torque is well known. On the other hand this torque is highly dependent on the rotor inertia. With no standard figures of this new family of electrical machines it would be useful to investigate the internal developed torque from the energy conversion process. Any improvement of the waveforms of this developed torque is directly reflected on the shaft output torque. In the present study the phase torque pulses are obtained with the procedure described in section(3). These pulses are added to each other to obtain the total internal developed torque.

Figure(3) shows the predicted current-fluxlinkage loop with and without chopping. The inner loop is obtained at 1600 rpm and at this speed is high enough to induce a suffient back emf to maintain the current pulse without chopping. The outer loop is obtained at 600 rpm for which phase current tends to increase and has to be limited by chopping. Both aligned and unaligned fluxlinkage characteristics are shown on the same figure.

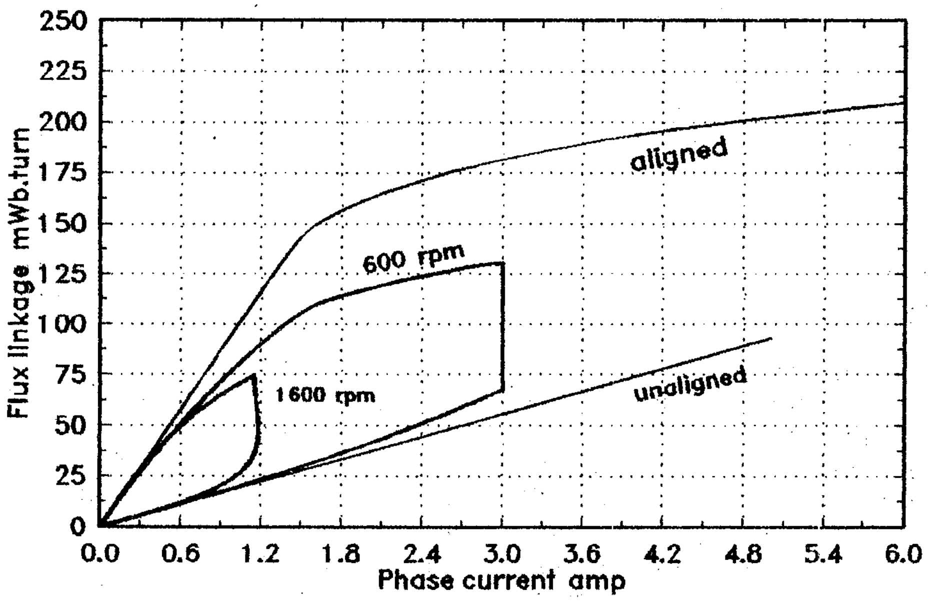
Figure(4) shows the predicted torque pulses for the five phases along one rotor pole pitch. The figure also shows the total internal torque which is the sum of the phase torque pulses. In figure(5) the internal developed torque is predicted at different speeds for the same switching conditions except that at 500 rpm current chopping becomes active. It is observed that at high speeds, without current chopping, the developed torque is approximately constant. Under chopping, the torque pulses become more flat-topped and torque variation becomes noticeable. Since current chopping is essiential at low speeds to limit the amplitude of phase currents, the straight forward solution is to increase the number of torque pulses such that the rotor inertia would be sufficient to smooth the resultant output torque on the motor shaft. The five phase configuration is proposed here to increase the frequency of the internal developed torque to forty pulse per revolution which is quite sufficient to overcome the problem.

Experimental tests are carried at both running and rest conditions to investigate the loading capability of the designed motor. Torque-speed characteristics are recorded using digital optical tachometer for measuring the speed and frictional brake for the torque measurement. These characteristics are mainly dependent on the power converter switching parameters. The curve shown on figure(6) is recorded for current pulses of $0.8\beta_s$ angle duration and turn-on points exactly at the unaligned axis for each phase. The current level is also maintained constant by chopping at 3 amps which is the current rating of motor windings. The chopping process becomes active for speeds approximately below 600 rpm and this is observed on the torque-speed curve where the torque tends to be maintained constant while phase current pulses approache the rectangular shapes.

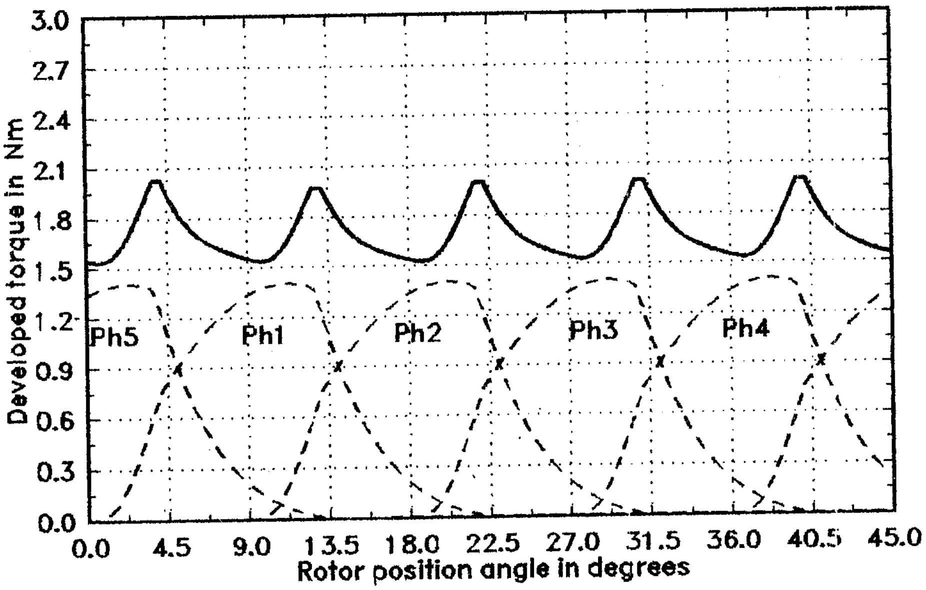
The static torque test is recorded for different excitation levels on figure(6). Generally, these characteristics match those known for variable reluctance stepping machines, but with slight flat-topped periods. This distortion is due to manual assembly of the motor which resulted in phase winding coils with a relatively large cross sections with good chances to increase the leakage flux specially at aligned positions. With more sophisticated assembly techniques it is possible to improve these characteristics which will also reflect on the motor running performance.

6. CONCLUSION

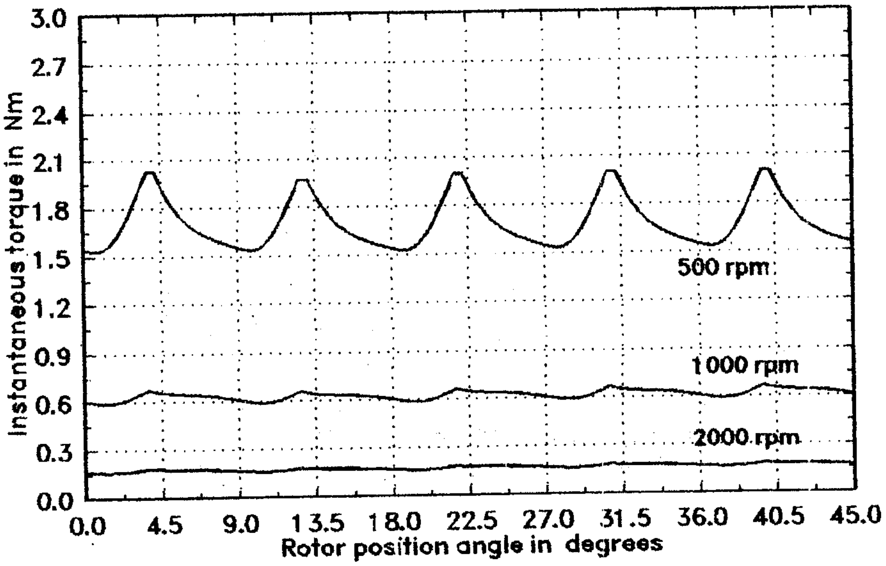
This paper provides a simple design procedure for switched variable reluctance motor with low torque ripple content. The use of high number of phases combined with the proper choice of poles geometric dimensions are proposed to increase both the number and overlap angle of successive torque pulses. The proposed scheme integrated with a special electronic converter constitute a high performance variable speed drive system. A low power prototype is extensively tested, but it is equally possible for higher power ratings.



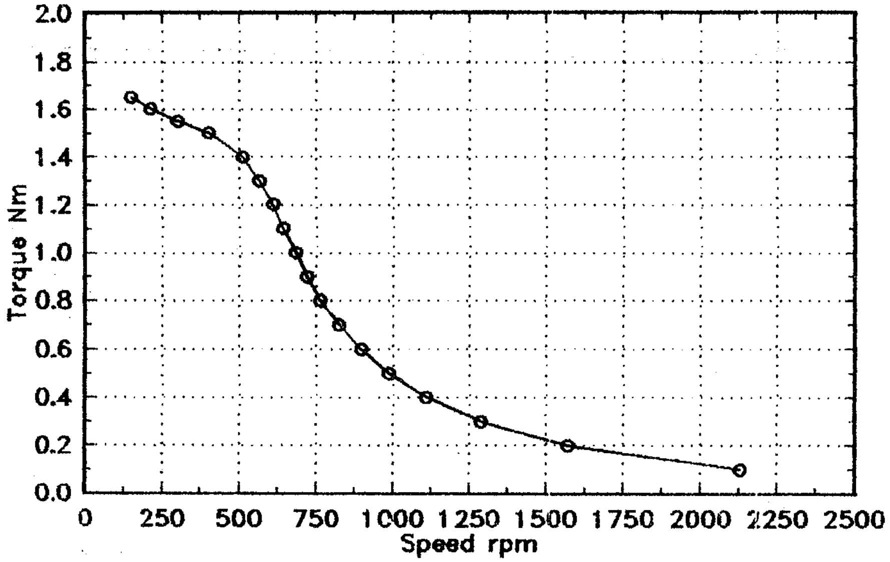
Figure(3) Predicted current-flux linkage loops at different speeds.



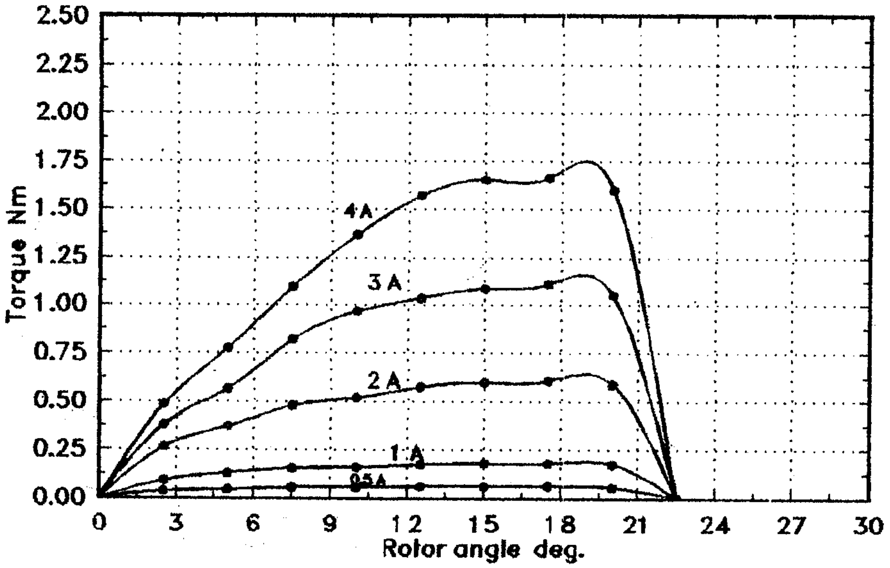
Figure(4) Predicted individual phase torques and total positional developed torque.



Figure(5) Predicted instantaneous internal torque at different speeds over 45° (1/8th revolution)



Figure(6) Experimental torque-speed for turn-on angle 0.8 β_m.



Figure(7) Experimental static torque for different excitation currents.

7. LIST OF SYMBOLS

A_{sp}	Specific electric loading.
B	Air gar flux density at aligned position.
D	Stator bore diameter.
i	Instantaneous phase current.
I	Current pulse amplitude of phase winding.
k_d	Duty cycle ratio.
kL	Inductance overlap ratio.
ks	Ratio of stator pole arc to pole pitch.
L	Rotor core axial length.
L_a^s	Aligned saturated inductance.
L_a^u	Aligned unsaturated inductance.
L_u	Unaligned inductance.
L_{rp}	Rotor pole height.
$L(\theta)$	Phase inductance as a function of rotor position.
m	Number of phases conducting simultaneously.
N	Motor speed rpm
N_s	Number of stator poles.
N_r	Number of rotor poles.
P_d	Rated power of SR drive.
q	Number of phases.
R	Phase winding resistance.
s	Number of torque pulses (steps) per revolution.
t	Step angle.
T	Phase torque.
T_{ph}	Number of turns per phase.
V	DC. voltage.
β_s	Stator pole arc in rad.
β_r	Rotor pole arc in rad.
σ	Ratio of saturated to unsaturated inductances
for	aligned position.
λ_u	Ratio of unsaturated aligned to unaligned inductances.
η	Over all SR drive efficiency.
θ	Rotor position angle.
ω	Rotor angular speed.
ϕ_r	Rotor pole pitch.
ψ	Flux linkage.

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محرك الممانعة المغناطيسية المتغيرة خماسي الأوجه المغذى بنبضات

الجزء الأول: التصميم وخصائص التشغيل

تعتبر محركات الممانعة المغناطيسية المتغيرة المغذاه بنبضات من أحدث أنواع الآلات الكهربية، ورغم أن فكرة عمل المحرك معروفة منذ مايزيد على قرن ونصف - قبل الأنواع التقليدية المعروفة من الآلات الكهربية - إلا أنها لم تلق إهتماما يذكر حتى بداية العقد الماضى، ويرجع ذلك إلى حاجة هذا النوع من المحركات إلي طريقة تغذية خاصة أصبحت متاحة فقط بتوفر وحدات شرائح السيليكون والمفاتيح الإليكترونية فائقة الجودة.

وفي محاولة للتغلب علي أحد أهم عيوب هذا النوع من المحركات وهو العزم النبضى علي محور الآلة يقدم هذا البحث إقتراحا بإستخدام عدد أوجة عالي نسبيا يتيح زيادة التداخل بين نبضات العزم المتتابعة للتغلب على هذا العيب، وفى إطار الدراسة المقترحة تم إختيار تركيبة الخمسة أوجه كتركيبة جديدة لم تشملها أى دراسة من قبل، ثم تم تصميم وبناء وإختبار محرك ممانعة مغناطيسية متغيرة ذو خمسة أوجه، وقد إعتمدت طريقة التصميم علي صياغة معادلة عامة لهذا النوع من المحركات تربط بين قدرة المحرك والأبعاد الرئيسية للدائرة المغناطيسية علي غرار تلك المعادلة العامة للآلات الكهربية التقليدية، مع الأخذ في الإعتبار الطبيعة النبضية لتغذية المحرك، وقد تم صياغة طريقة التصميم في برنامج للحاسب الآلي يتيح إمكانية إستنتاج أبعاد الآلة وخصائص التشغيل في مرحلة التصميم لإمكانية التعديل لتحسين تلك الخصائص.

تخلص هذه الدراسة إلي أنه بزيادة عدد أوجه محرك الممانعة المغناطيسية المتغيرة المغذى بنبضات وبالإختيار الدقيق لأبعاد الأقطاب أمكن تقليل العزم النبضى على محور الآلة، وقد تم إختبار ذلك علي محرك ذو قدرة صغيرة علي مستوى الدراسة المعملية.