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SWITCHED RELUCTANCE DRIVE AS FAULT TOLERANT DRIVE

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ABSTRACT

Nowadays, the switched reluctance motor (SRM) is gaining increasing interest, mainly due to its simple and robust construction with low cost and higher reliability. These good features and others such as high efficiency, fault tolerance and variable speed capabilities make the motor one of the so called tomorrow motors.
The main object of this paper is to explain why the switched reluctance motor (SRM) drives are perceived to have a degree of fault tolerance not found in other motor drives. The critical operating conditions and the principal electromagnetic faults which may occur within the drive are explained. The fault tolerant drive requirements and the needed design modifications are discussed briefly. Various electrical configurations of winding and controller circuits are discussed under fault conditions. Comparisons with other drives are explained in many situations to explain advantages of SRM drives in safety critical applications.

KEYWORDS

Electric Machines, Switched Reluctance Motor and Fault Tolerant Drives.

1. INTRODUCTION

Military, aerospace, and harsh environment applications require drives with both high reliability and large specific power density. Many authors claimed that the SRM drives are fault tolerant drives [1]. In this paper [1] we will examine these claims and explain fault conditions from electrical, mechanical and thermal points of view. The authors discuss many of design

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considerations like the number of phases the slot shape and others from the fault tolerance point of view.

2. FAULT AND CRITICAL OPERATING CONDITIONS

As all electric drives, the SRM drive consists of the following:
(i) The electric circuits or the paths of electric current.
(ii) The magnetic circuit or the path of magnetic flux.
(iii) The thermal circuit or the path of heat flow.
(iv) The dielectric system or insulation.
(v) The mechanical parts.
Thus, the designer must deal with these circuits which are interlinked in a very complex fashion. A successful design brings out a compromise for a machine volume which is occupied by iron, copper, insulation and air. Actually, the designer must face the general design limitations in choosing the suitable amount, shape and type of materials for the fabrication of the required machine parts. These limitations include the consumer's requirements, the saturation level, the allowed temperature rise, the value of power factor, the efficiency and mechanical design limitations. For safety critical operations many additional requirements must be satisfied by the designer.
The principal electromagnetic faults which may occur within the machine are: winding open circuit, winding short circuit, winding short circuit at the terminals, switching device open circuit and switching device short circuit. The critical operation conditions include the operations at high temperature, the operation at very high speed conditions, the operation at dusty and dirty conditions and the operation at wet conditions.

3. FAULT TOLERANCE DRIVE REQUIREMENTS

Clearly, the drive which can continue to operate with any of the above faults and critical operation conditions must satisfy the following conditions:
(i) It must be a polyphase drive in which each phase may be regarded as a single module. The operation of one phase must be independent on the others, such that in the event of one phase failure, the others can continue to operate unaffected [2].
(ii) It must have robust rotor design and high efficiency especially for high speed drive applications.
(iii) Its enclosure must have high degree of protection especially for motors that operate at wet and dusty conditions.
The above modular approach requires that there should be minimal electrical, magnetic, thermal and physical interaction between phases of the drive. Because, without the magnetic isolation, fault currents in one phase induce large voltages in other phases, preventing adequate control of them, and without thermal and physical isolation, the possibility of fault between phases is maximum. Of course the minimal electrical interaction will prevent the fault current transferring from the faulty phase to the healthy phases.

4. CONSTRUCTION OF FAULT TOLERANCE DRIVE

The requirements of fault tolerance drive affect the design of the SRM drive in many aspects. The SRM motor construction can be modified to satisfy the minimum thermal and magnetic interaction, while the drive circuit can be selected to satisfy electrical isolation between phases. These design limitations will be discussed for the motor and its controller separately.

4.1. Motor construction

(i) Normal construction

The normal SRM is electromagnetically identical to a single stack variable reluctance stepper motor VRSM as shown in Fig. 1. There are, of course, important design and control differences which reflect the different objectives, but otherwise the two mechanisms are identical. However, the stepper motor has been designed first and often for open loop control i.e. without shaft position feedback, the SRM is designed for self synchronising operation with shaft position feedback to synchronise the commutation of phase currents with precise rotor positions. Also, SRM is normally designed for efficient conversion of power, while VRSM is normally designed to maintain step integrity rather than to achieve efficient power conversion. The rotor has no windings or permanent magnets and the stator poles carry simple coils which are energised by a unidirectional current pulses. The opposite pole coils are usually connected in series or parallel to form a phase winding.

As all electric machines whose operation is based on reluctance variations, the airgap should be as small as mechanically acceptable for obtaining the best electromagnetic performance. Thus, to maximise the specific torque and minimise the volt-ampere requirements in the controller the, airgap length is usually given as:

$$l_g = \frac{D}{2} \quad \text{mm} \qquad (1)$$

Where, D is the bore measured in meter.

This relation is restricted with a minimum value of 0.2 mm [3]. Both the stator and the rotor poles and cores are made normally from standard silicon steel laminations which can be used satisfactorily in small and medium speed applications.

The majority of SRMs are totally enclosed motors with no cooling mechanisms, because the main losses are generated in the stator which is cooled by natural conduction, radiation and convection. Although, external self ventilation may be used on some highly-rated motors.

This normal construction satisfies small mutual coupling and small thermal interaction between phases where the magnetic iron reluctance is negligible and the end windings do not overlap. However, it must be noted that different two phase coil sides occupy the same slot, so that thermal isolation between phases is limited [2].

(ii) Modified construction

Because a phase to phase fault disables two phases, it is necessary to increase the physical and thermal isolation between phases. For well cooled stator frame machines, the dominant temperature rise is within each slot and hence, by ensuring that each slot contains one coil side, the thermal and physical interactions between phases are minimised [2].

The effective solution may be done by filling the unused triangular area between the two coil sides of each slot by the lamination itself as shown in Fig. 2.b. This solution also facilitates the fitting of coils and increases the thermal contact between the coil and stator steel and hence more output power can be achieved.

The magnetic interaction between phases can be decreased by increasing the permeance of the yoke. This can be done by increasing the yoke thickness to about 0.75 of the stator pole width. This solution decreases the mutual coupling between phases, eases yoke saturation and reduces iron losses, but with the penalties of more volume and capital cost.

The shaft of a SRM is short and stiff to maintain the necessary small airgap. The use of ball and roller bearings makes accurate centring of the rotor readily possible. For high torque and high speed applications, the increase of the shaft stiffness may be done by [4]:

(i) Placing the rotor laminations under heavy precompressed construction so that the stack contributes the overall thickness of the shaft.

(ii) Placing the bearings as closely as possible to the rotor stack.

(iii) Using the largest possible shaft diameter permitted by the electromagnetic design of the rotor core.

Although, the shaft is not designed from consideration of pure torsion only, the conventional formula is usually based upon such consideration. For a solid shaft diameter d_{sh}, the usually used expression is:

$$d_{sh} = c \cdot \sqrt[3]{\frac{P}{n_r}} \quad \text{cm} \qquad (2)$$

Where, P is the output power in KW and n_r is the rotor speed in r.p.m.

For induction motor which has cylindrical rotor with short airgap length, the constant c is usually taken as 25. For SRM, the weight of the salient rotor structure is often less than that of the induction motor, and so, the constant c may be taken as fraction of 25, but for high speed and for safety it is useful to take it as that of induction motor.

Also, the airgap may be increased to decrease the unbalance magnetic pull, which arises from any small deflection or eccentricity of the rotor shaft especially at high speed operations.

For high power and high speed applications the following relation may be proposed based on the relation of the airgap length of induction motor and may also be usefully used for SRD:

$$l_g = 0.3 + D \quad \text{mm} \qquad (3)$$

Where, D is the bore measured in meter.

This relation permits relatively larger airgap length and hence more safe and quiet high speed operation, but with the penalty of lower specific torque.

Recently, For high speed and high efficiency applications, standard silicon steel is replaced by the amorphous iron [5]. The importance of amorphous iron is its ability to limit the stator and rotor tooth flux density to about 0.55 tesla and hence, the torque per unit volume can be improved using the benefit of tooth saturation. The tensile strength of amorphous iron is about three times that of the standard silicon steel a matter that increases the possible maximum speed of the motor.

4.2. DRIVE CIRCUIT CONSTRUCTION

The choice of drive circuit depends on many factors such as:
(i) The number, voltage and current rating of the working switches which determine the whole cost of the drive.
(ii) The ability to utilise the stored magnetic energy by returning it to supply after switching off the motor phase and before re-energising it again.
(iii) The cost and complexity of auxiliary circuits such as gate/ base driving arrangements, commutation circuits and snubbers.
(iv) The ease of packaging and controllability. The controllability reflects an overall weighting of dynamic response, speed range, stability, accuracy, regulation and smoothness of torque production
(v) The ability to create current wave form as close as possible to the ideal shape of rectangular pulse.
(vi) The power loss and efficiency of the drive circuit.
(vii) The serviceability and maintenance.

Figure 3 shows three basic power circuits configurations. The first circuit (half bridge) is perhaps the simplest of configuration which provides regeneration capability. The voltage and current rating of each switch are that of the phase winding itself. The main disadvantage of this drive is that, it needs two controlled switches per phase i.e. more cost and wiring complexity [6].
The second drive requires only a single switch and diode per phase and achieves regeneration through the use of bifilar phase windings. The disadvantages here are that the switches must be able to withstand at least double the supply voltage (assuming equal turns in primary and secondary windings) and also the winding utilisation within the motor is reduced [7].
The third drive requires only one switch per phase with a split supply and even number of phases. The phase windings are designed for half the supply voltage (and, therefore, will draw double the phase current compared with former circuits) but switches must be rated for the full supply voltage with twice the current rating compared with the former circuit switches [7].
The large ratings of the power switches of the second and third drives tend to cancel some advantages which can be gained by eliminating one switch and one diode compared with the half bridge converter.
To achieve complete electrical isolation between phases, each phase must be supplied from a separate circuit with no sharing of transistors between phases. This is naturally true for circuits which use two switches per phase as shown in Fig. 3.a.
T. J. E. Miller [1] explained that unlike all classical ac drives, the use of one half bridge per phase provides shoot through protection. In ac inverters, if both the upper and lower switches in one phase leg are switched on simultaneously, the dc supply is shorted, but in SRM, this can not happen except that, the phase winding itself is short circuited.
In fact the use of separate half bridges increases the reliability of the system with penalties of more cost and wiring complexity of the circuit.

4.3. NUMBER OF PHASES

The fault tolerant motor must be a polyphase motor, and hence all single phase motors are rejected. For constant power operation, it may be wanted to make the drive continue to produce its full load power under one phase failure fault condition. From this point of view, a fault tolerant over rating factor will defined as:

$$K_{or} = \frac{q}{q-1} \tag{4}$$

Where q is the number of phases.

If there are four phases at healthy conditions then, if one phase is faulted, the others must be overrated by 33 % in order to give full load capacity. It is clear that the value of K_{or} is decreased with the increase of the number of phases. However, on the debt side, more leads have to be brought out from the motor, more connections are needed. In practice the majority of motors have three or four phases, and it is rare to find motors with more than six phases.

From self starting and small torque ripples point of view, there must be adequate an overlap between the similar inductance variations of adjacent phases. A useful guide about the effects of overlap can be inferred from the ideal inductance variations as:

$$K_{OL} = \frac{\alpha}{\alpha_s} \tag{5}$$

$$\alpha_s = \frac{2\pi}{qn} \tag{6}$$

Where α is the stator pole arc in radians, α_s is the step angle in radians, and n is the number of rotor poles. The overlap factor must be greater or at least equal to 1.0 to achieve good starting torque from all rotor positions with only one phase conducting. For two phase motors, the overlap factor must be less than one to permit space for windings, and hence all two phase motors are rejected from reversible self starting point of view.

From efficiency point of view, the number of phases must be kept as low as possible to decrease the switching frequency and hence decrease the iron losses which may be the dominant loss in high speed operations [8].

The relationship between the stator phase frequency f and the switching frequency f_s. can be expressed as:-

$$f = n \, . \, \omega / (2 \, . \, \pi) \tag{7}$$

and

$$f_s = q \, . \, f \tag{8}$$

Where ω is the motor angular speed in (rad./s)

The switching frequency is very dependent on the number of phases and rotor poles i.e. for 3-phase SRM with n = 4.

$$f_s = 3*4*\, \omega /(2 \, . \, \pi) = 6\omega / \pi. \tag{9}$$

And for 5-phase SRM with n = 8.

$$f_s = 5*8*\, \omega / (2 \, . \, \pi) = 20\omega / \pi. \tag{10}$$

Investigation of equations (7-10) shows that, the change from 3-phase to 5-phase approximately triples the switching frequency for the same motor speed and hence increases

the iron losses and decreases the efficiency. From this point of view three phase motors are the best choice for high speed, fault tolerant drives.
However, if a low speed application is being considered, the limitation imposed by frequency will be less effective and the designer has greater freedom in choice.

5. CRITICAL OPERATIONS

In this section the open circuit and short circuit faults will be studied briefly for series and parallel pole coils connections.

5.1. Open circuit condition

(i) Series connection.

Series connection is the most common arrangement at which the currents in the series coils are automatically equal under normal conditions. In this arrangement the opening of one coil leads to the opening of the whole phase.
Due to the absence of any rotor excitation, there is no generated voltage on open-circuit conditions. All torque and all forces associated with the open phase are zero. This is an advantage during fault conditions in safety critical operations or in applications with freely over running loads. This condition can be detected by the current sensors that would be included in the controller itself [1,8].
In contrast the existence of rotor excitation in all classical machines makes them produce high open circuit voltage especially at high speed operations which may necessitate the use of power full over voltage protection on the dc supply.

(ii) Parallel connection.

In this case the open circuit of one coil will double the current in the other coil for the same load power. In this condition there will be large unbalance magnetic pull which will cause serious noise and vibrations. If the healthy coil is not designed to carry double current then the fault of one coil may lead to overheating and subsequently to open circuit of the other coil. The other coil open circuit will lead to a complete phase open circuit which does not affect the operation of healthy independent phases [1,9].

5.2. Short circuit condition

(i) Series connection.

If one coil is short circuited, its voltage will be zero and applied voltage will appear in the second coil. At chopping mode of operation the controller will limit the current but with increased current ripples and chopping frequency. This fault condition
will produce unbalance magnetic pull and hence serious noise and vibrations [7].
However, we must note that due to the absence of rotor excitation there is no generated voltage to sustain or drive short circuit current into the a short circuit fault that has occurred in the controller [1].

(ii) parallel connection.

If one coil becomes short circuited, it will short the dc supply and the short circuit current will destroy the main switches. The destruction of main switches will lead to the open circuit condition and hence unbalance magnetic pull. A faster acting current regulator can protect the main switches against failure, by turning them off quickly [9].
Fuses can be used to protect the switches and phases from short circuit current, however the poor reliability of fuses usually restricts their applications.

6. SIMULATION RESULTS

The effect of the airgap lengthening, and stator yoke depth increasing in regular designs is explained for 5 KW, 190 V, 8/6, 4-phase, 1000 rpm SRM. The main results of the design and simulation are explained in table 1.

Table. 1 Main parameters of the normal and the proposed designs

Main parameters	normal design	proposed design
Rotor diameter (D)	0.114 m	0.113 m
Axial length (L)	0.167 m	0.166 m
Internal rotor diameter (D_{ri})	0.071 m	0.07 m
Airgap length (lg)	0.214 mm	0.413 mm
Stator diameter (D_s)	0.114 m	0.114 m
Stator internal diameter (D_{si})	0.176 m	0.175 m
Outer diameter (D_o)	0.2 m	0.213 m
Shaft diameter (d_{sh})	0.043 m	0.043 m
The outer volume (V_{out})	0.00596 m3	0.00669 m3
Maximum linear phase inductance L_{max}	228.059 mH	133.0 mH
Minimum phase inductance L_{min}	9.952 mH	11.31 mH
Maximum phase current I_m	36.331 A	38.114 A
Maximum staror pole flux density B_s	1.902 tesla	1.95 tesla
Per-phase ampere-turn	5945.78	5304.326
Motor full load efficiency E%	81. 2 %	83.9 %

The effect of the airgap lengthening and yoke depth increasing on values of the linear phase inductance, static magnetisation curves, full load currents, and dynamic torque curves is clear in the figures from 4 to 7. Clearly, the change in the maximum magnetic loading, maximum phase current, maximum ampere-turn per phase and full load efficiency is relatively small and depends on the whole design procedure. The increase in the airgap length increases the required current, but the increasing in the stator yoke depth tends to decrease it again. The effect of filling the unused triangular area is not included in the simulation results.

7. CONCLUSIONS

The fault tolerance requirements are naturally met in the SRM drive; where separate half bridges are used for each phase and hence the phases are electrically isolated, and where there is negligible magnetic coupling between phases. Due to the absence of rotor excitation, short circuit current will not continue to be driven into a faulted phase once the excitation of that phase is removed. Furthermore there is no overlap between phases and hence the possibility of phase to phase fault is small.

This paper explains that the use of single slot per phase configuration is the best configuration from physical, thermal and magnetic isolation point of view. The choice of number of phases is discussed and it is clear that three and four phase motors are the best choice for revisable self starting, high efficiency, fault tolerance drives. Some of design consideration such as the airgap length and the shaft diameter are discussed from safety operation point of view. This paper also explains that the series connection of opposite pole coils is better than the parallel connection from the fault tolerance point of view. Also it explains that the fault tolerance of SRM drives is not absolute where many hazards like unbalance magnetic pull, serious noise and vibrations can arise under faulty conditions. A motor based on these design considerations and its simulation is expected in the near future paper.

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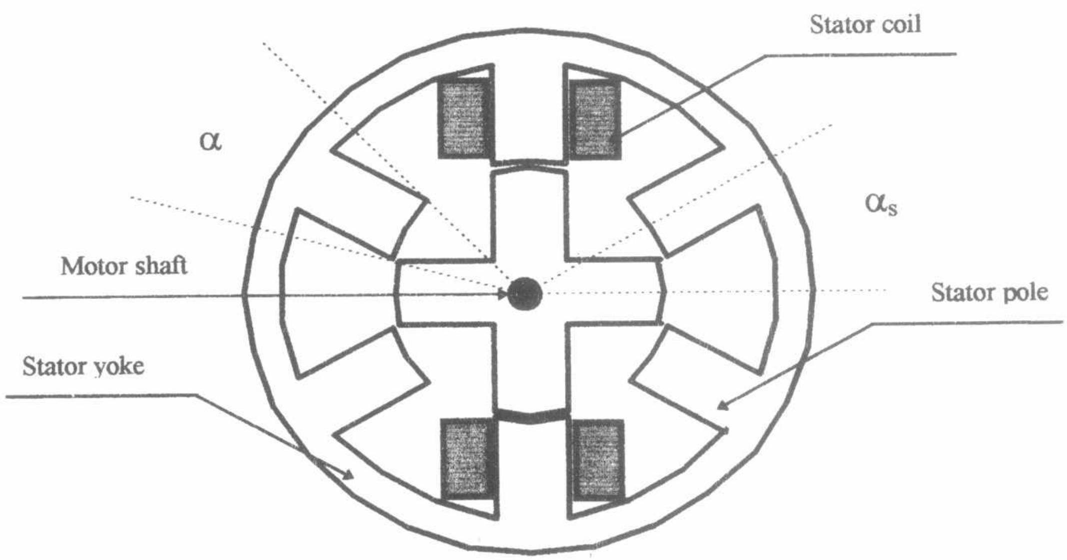
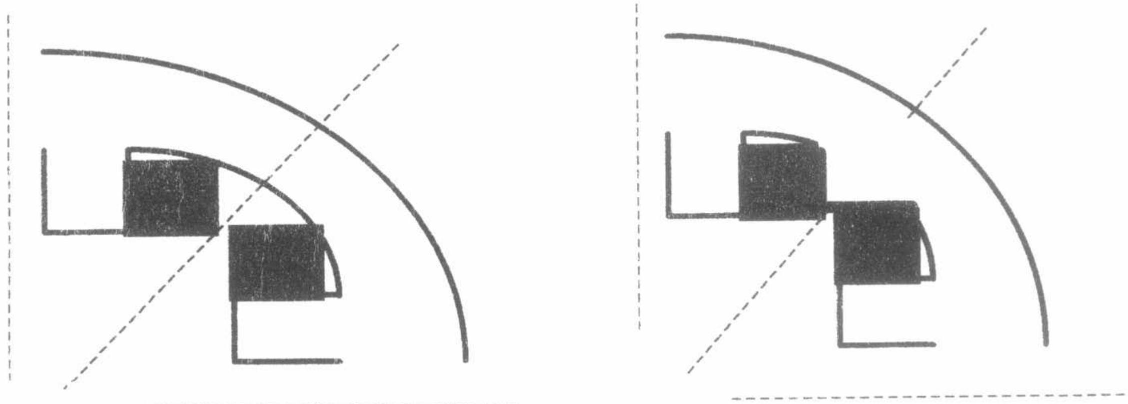
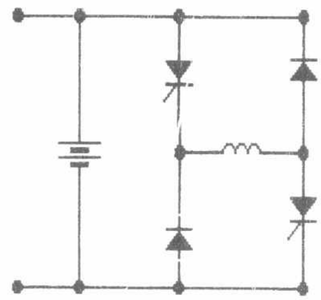


Fig. 1. Normal SRM construction

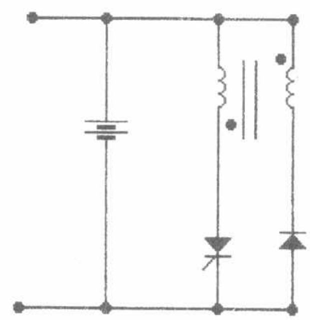


(a) (b)

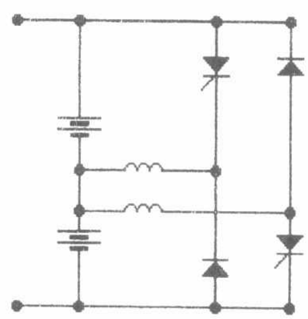
Fig. 2. Stator construction of SRM.
(a) Regular design.
(b) Modified design.



(a)



(b)



(c)

Fig. 3. Drive circuits of SRM
(a) Asymmetric half bridge converter.
(b) Bifilar winding converter.
(c) Split supply converter.

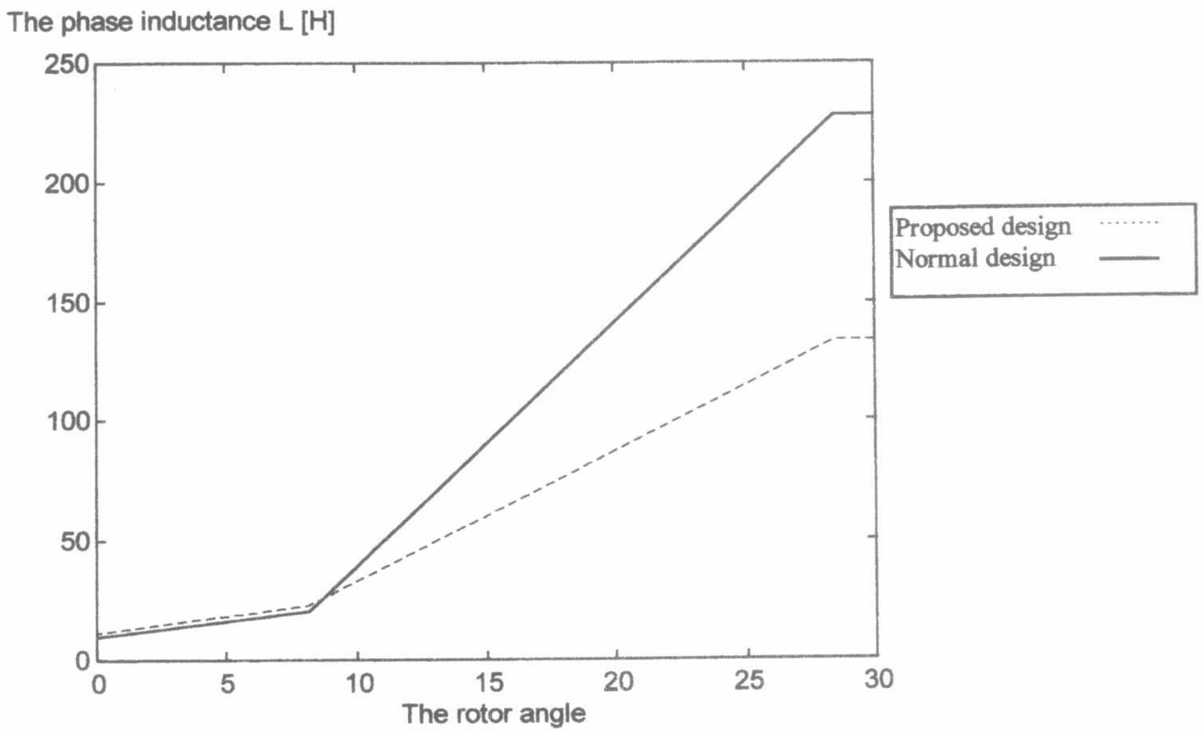


Fig. 4. Linear per-phase inductance variation.

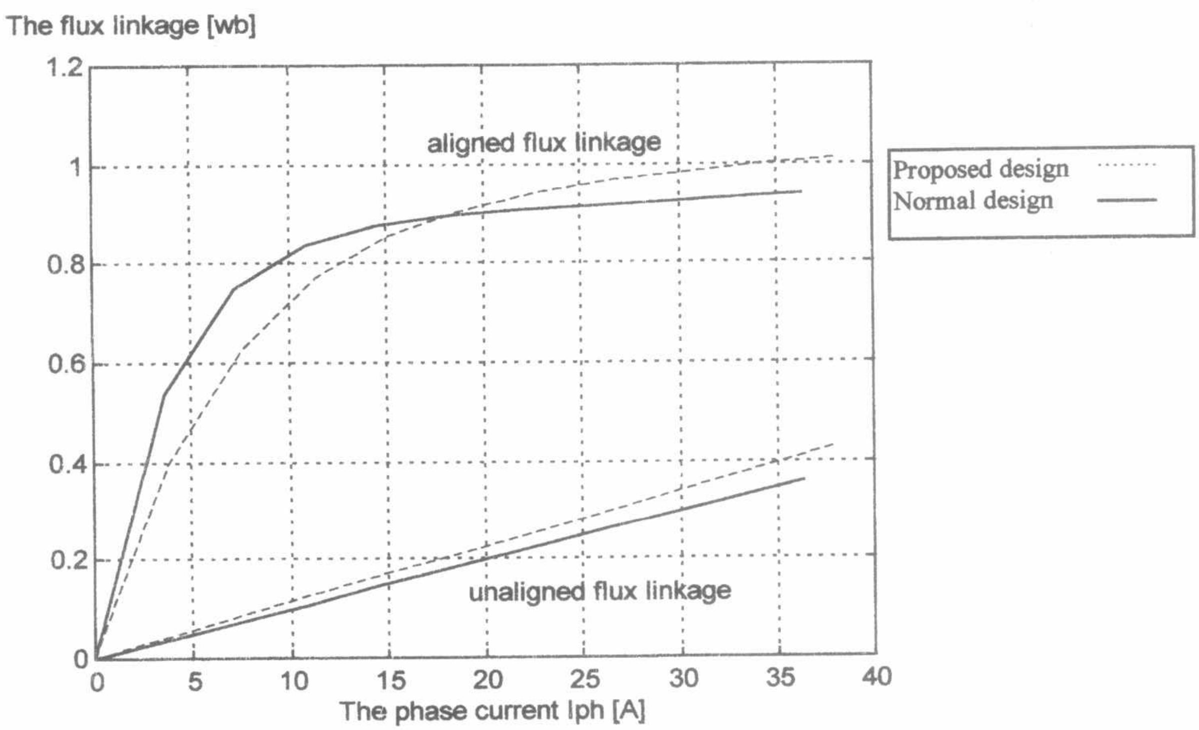


Fig. 5. Static magnetization curves.

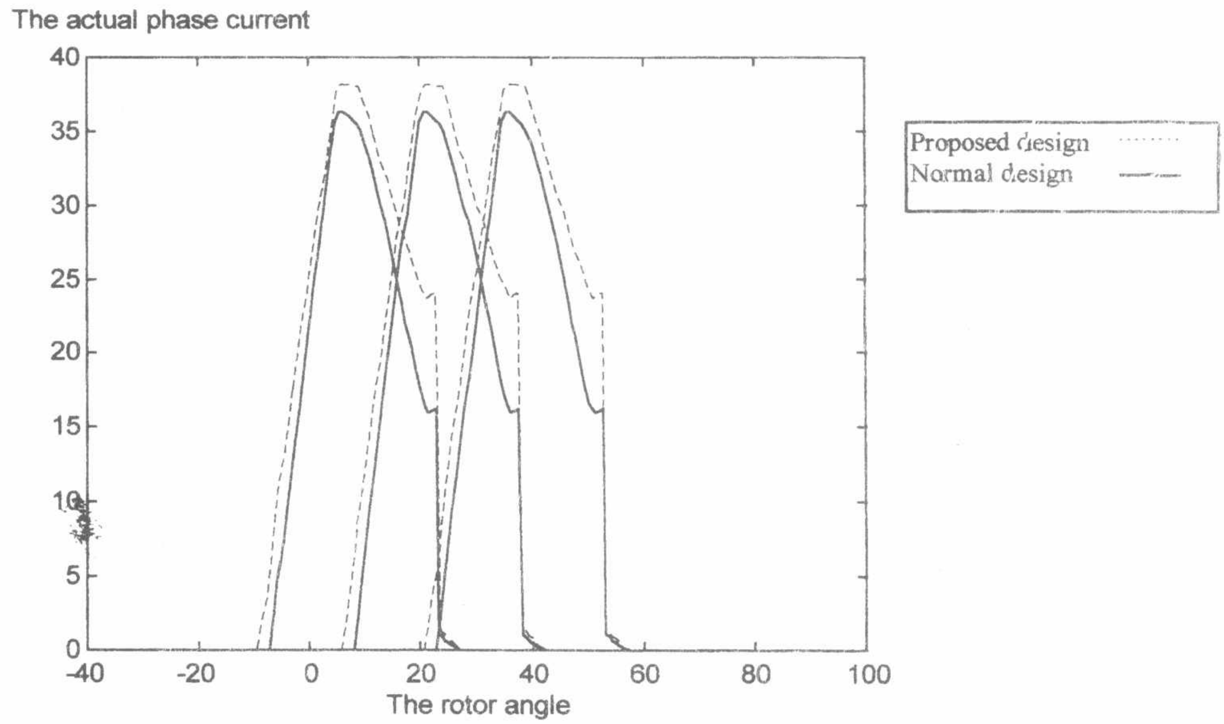


Fig. 6 Simulated full load currents.

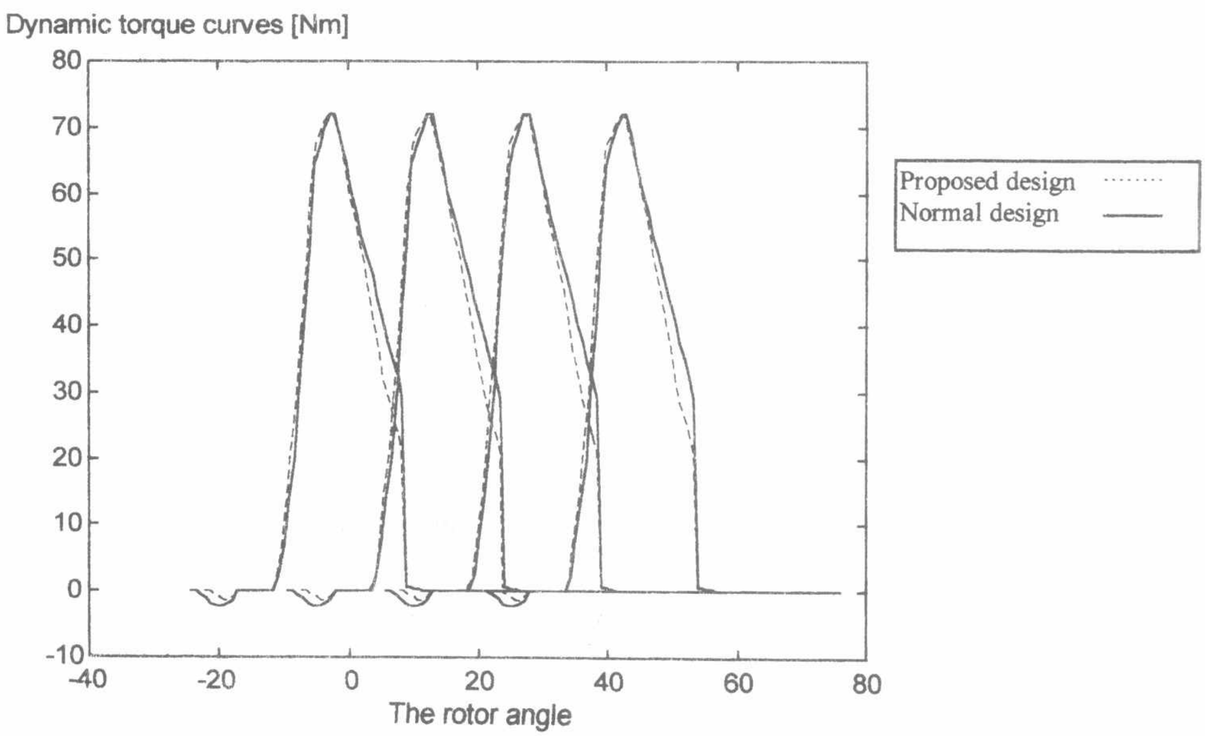


Fig. 7 Dynamic torque curves.