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DESIGN OF A HIGH-SPEED HIGH-POWER SWITCHED RELUCTANCE MOTOR

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ABSTRACT

A high speed, three phase, 12/8 pole, 225 kW switched reluctance motor (SRM) has been designed and analyzed A circuital approach has been used to find the geometry, windings parameters and electromagnetic loadings. Then, the 3D finite element method (FEM) has been used to calculate the static torque more accurately and optimize the design The efficiency of the designed SRM is almost constant over wide range of speed and its phase current is less sensitive to the speed than that of an induction motor of the same rating. Recommendations for manufacturers and users are given

Key Words · High Speed switched reluctance motor(SRM), design, FEM

1. Introduction

In many applications, as for example, compressors, pumps and machine tools, high speed motors with rotational speed well above 3600 rpm allow for elimination of mechanical gear trains No gear train means improved efficiency and reliability of the electromechanical system, reduced noise and simplified maintenance. The output *power-to-mass* ratio of high speed motors is much higher that that of motors rated at 50 or 60 Hz

The objective of this contribution is to predict the performance of a cost effective high power motor for high speed applications High speed switched reluctance motors (SRMs) can be competitive to their induction or permanent magnet brushless counterparts SRMs provide the lowest cost solution and better fault tolerance than other types of motors

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2. Choice of Construction

A three-phase machine seems to be the most economical solution from power electronics converter point of view. The stator has N_s = 12 poles and the rotor has N_r = 8 poles (Fig 1). The 12-pole stator electric circuit can be configured either as four coil winding, i e. four poles per phase, or two coil winding, i e two poles per phase. In the first case all four coils per phase can be connected in series (or sometimes in parallel) and fed from one three phase power electronics converter. In the second case each phase winding is divided into two independent windings (two coils and two poles per phase) and the motor is fed from two independent converters. Such configuration of stator windings, called sometimes *two channel* windings [1,4], makes the SRM drive more expensive since it requires two converters On the other hand, a better fault tolerance is provided A SRM, unlike its induction counterpart can operate with one damaged phase winding.

It has been assumed that the *rms* current density in the stator winding cannot exceed 4.5 A/mm^2, stator slot cross section area-to-cross section area of conductors

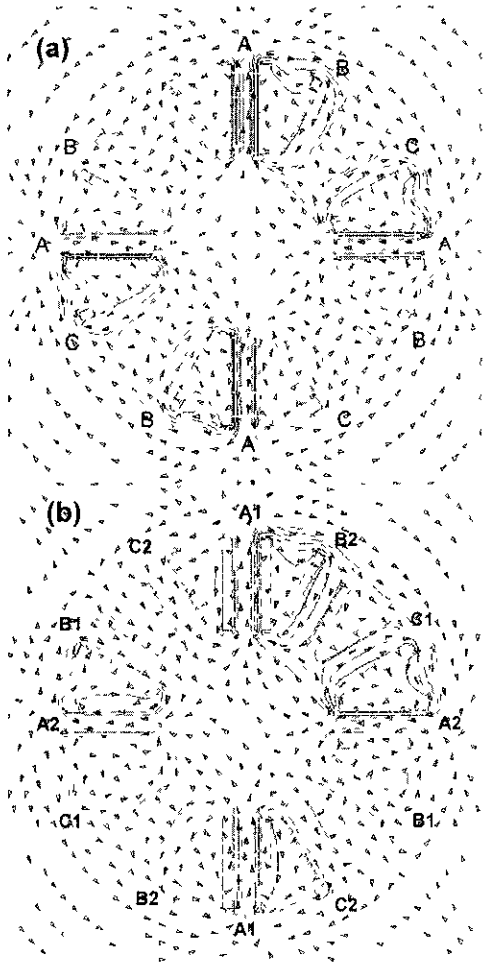

Fig 1 Magnetic flux distribution in a cross section of the designed SRM (a) standard winding configuration, phase A on, full (b) *two channel* machine, phases A1, A2 on

ratio (fill factor) 0.38, average magnetic flux density in any cross section of the magnetic circuit 1 4 T, and the power density should be minimum 1.5 kW/kg (output power per mass of active materials)

3. Design

The initial inner diameter and length of the stator core has been evaluated according to [3] To simplify the design procedure, the SRM has been first designed using a classical approach, i.e. Kirchhoff's voltage equations for the electric circuit and Ampere's circuital law for the magnetic circuit The air gap minimum and maximum permeances have been found on the basis of flux tubes.

Table 1 Ratings, dimensions and electric circuit Parameters

Output power at 18,000 rpm	236 2
Shaft torque	125 3 Nm
Speed, n	18,000
Commutation frequency, f_c	2400 Hz
D c supply voltage to the drive, V_{dc}	460 V
Efficiency, η	94 9%
Stator current, *rms* value, I	575.8 A
Length of stack	280 mm
Air gap	1 mm
Stator inner diameter	144 mm
Stator outer diameter	355 mm
Shaft diameter	36 mm
Width of the stator pole	16 1 mm
Width of the rotor pole	16 1 mm
Mass of laminations	111 8 kg
Mass of winding	41 8 kg
Mass of shaft	23 0 kg
Turns per pole	8
Parallel paths per phase	2
Parallel conductors	96
Conductor diameter	0 95 mm
Chopping frequency	4696 Hz
Resistance per phase	0.00162Ω
Strokes per revolution	24
Air gap shear stress	14 500 N/m^2
Winding losses	1603.9 W
Core losses	10 503 4 W
Rotational losses	500 W
Current density	4 207 A/mm^2
Electric loading	149 kA/m
Power density	1.54 kW/kg
Turn-on angle	10^0
Turn-off angle	33^0

The electromagnetic torque has been calculated on the basis of instantaneous inductance. The motor ratings, dimensions and winding parameters are given in Table 1. The M19, 0 1 mm thick silicon steel laminations have been used for the magnetic circuits both the stator and rotor. The efficiency of the SRM first of all depends on the core losses as at the rated speed they are 5 times higher than all the remaining losses

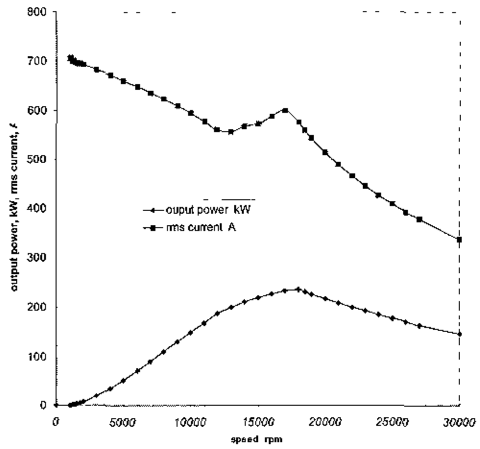

Fig 2 Electromagnetic torque and efficiency versus speed at constant d c bus voltage V_{dc} = 460 V and constant turn-on and turn-off angle (θ_{on} = 10^0 and θ_{off} = 33^0, respectively) Calculation results, circuital approach

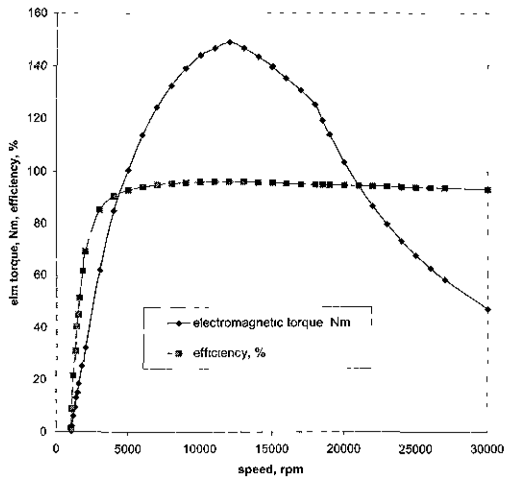

Fig 3 Output power and *rms* current versus speed at constant d c bus voltage V_{dc} = 460 V and constant turn-on and turn-off angle (θ_{on} = 10^0 and θ_{of} = 33^0, respectively) Calculation results, circuital approach

To minimize the windage losses and acoustic noise, i.e. to obtain a smooth rotor active surface the space between the rotor poles must be filled with a non-ferromagnetic, non-conducting material, i e. resin

The commutation (switching) frequency f_c is equal to the speed n in rev/s times the number of rotor poles N_r, i.e $f_c = n\ N_r$ The number of strokes per revolution is calculated as the number of phases multiplied by the number of rotor poles N_r

4. Performance Characteristics

Fig 2 and 3 show the electromagnetic torque, efficiency, output power and *rms* current as functions of speed at constant voltage V_{dc} = 460 V, constant turn-on angle Θ_{on} = 10^0 and turn-off angle Θ_{off} = 33^0, obtained from calculations on the basis of circuital approach The electromagnetic torque where i is the instantaneous current, L is the phase inductance unaffected by the current and θ is the angular rotor position, has a maximum value 149 Nm at the critical speed of 12,000 rpm (Fig. 2)

$$T_{elm} = 0\ 5i^2 dL/d\theta \quad (1)$$

$$i = V_{dc}/[R + 2\pi(f_c/N_r)(\Delta L/\Delta\theta)] \quad (2)$$

Unlike other motors, the efficiency of a SRM is practically constant over wide range of speed The efficiency of the designed SRM is greater than 90% at speeds from 4000 to 30,000 rpm and greater than 94% at speeds from 6000 to 24,000 rpm This makes a SRM the most efficient propulsion motor in variable speed drives. The output power increases with the speed and after achieving its maximum value, it decreases at speeds higher than the rated speed The output power is approximately equal to the product of the d c. supply voltage times *rms* current times efficiency Only one phase winding is fed at a time. The *rms* current decreases with the speed since the instantaneous current is significantly affected by $\Delta L/\Delta\theta$, where R is the winding resistance per phase, f_c is the commutation frequency and N_r is the number of rotor poles At low speed, i e about 1000 rpm, the *rms* current is still less than 1 3 of the rated value

The performance characteristics are very sensitive to the turn-on θ_{on} and turn-off θ_{off} angles (Fig. 4 to 7). Even a very small change in those angles can significantly change the electromagnetic torque, efficiency and other performance The torque ripple can be minimized by modulating the phase current or magnetic flux with respect to the rotor angle The calculated *rms* torque pulsation of the designed motor is high, i.e. 20% The acoustic noise can be reduced by the use of (a) profiled phase voltage, current or magnetic flux waveforms, (b) mechanical measures and (c) modified pole geometries

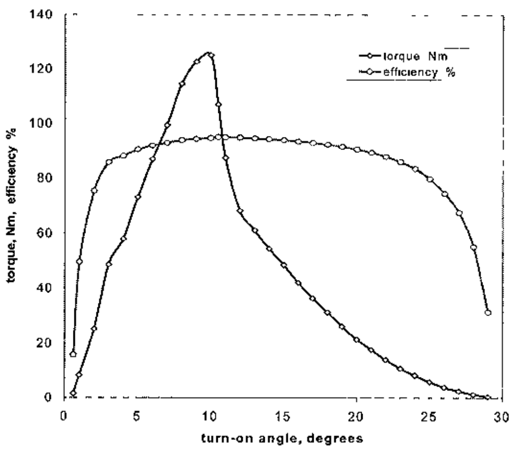

Fig 4 Torque and efficiency versus turn-on angle at constant voltage V_{dc} = 460 V, constant speed n = 18,000 rpm and constant turn-off angle $\theta_{on} = 10^0$ Calculation results, circuital approach

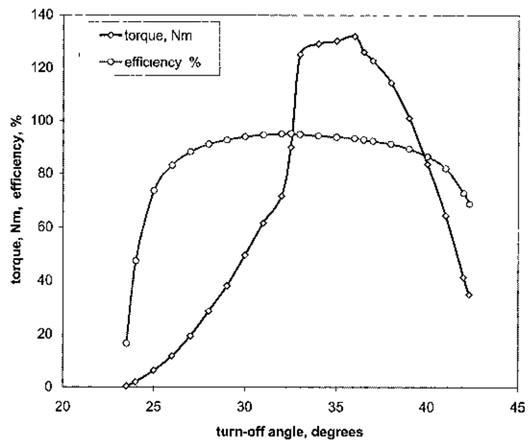

Fig 6 Torque and efficiency versus turn-off angle at constant voltage V_{dc} = 460 V, constant speed n = 18,000 rpm and constant turn-on angle $\theta_{off} = 33^0$ Calculation results, circuital approach

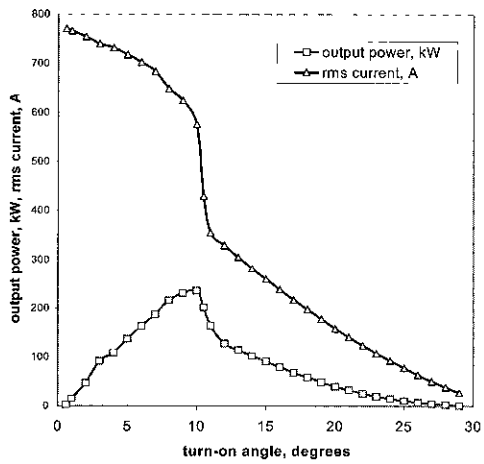

Fig. 5 Output power and *rms* current versus turn-on angle at constant voltage V_{dc} = 460 V, constant speed n = 18,000 rpm and constant turn-off angle $\theta_{on} = 10^0$. Calculation results, circuital approach

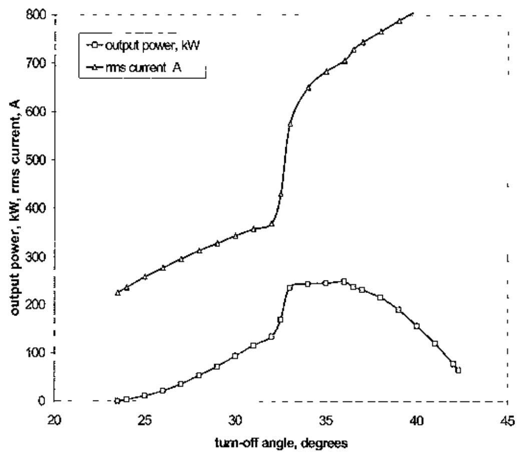

Fig 7 Output current and *rms* current versus turn-off angle at constant voltage V_{dc} = 460 V, constant speed n = 18,000 rpm and constant turn-on angle $\theta_{off} = 33^0$ Calculation results, circuital approach

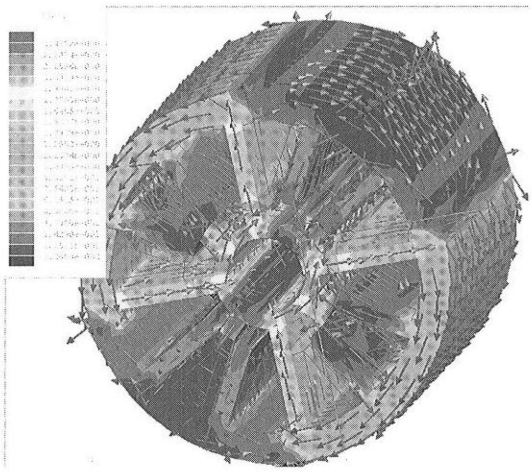

Fig. 8. Distribution of 3D magnetic flux density in the case of *two channel* windings when only phases A1, A2 are energized. Full alignment of stator phase A and rotor poles.

5. Finite Element Approach

The 3D finite element approach allows for more accurate performance prediction than a circuital approach. In addition, the shape of pole face areas can be optimized to maximize the electromagnetic torque. Fig. 8 shows the 3D magnetic flux density distribution at rated current in phase A (magnetostatic problem).
Fig. 9 shows the static torque when only phase A is energized. The average static torque per phase as obtained from the 3D FEM is 170.1 Nm. This is not the electromagnetic torque under operation given in Table 1, but the torque acting on the rotor when one phase winding is energized with a d.c. current.

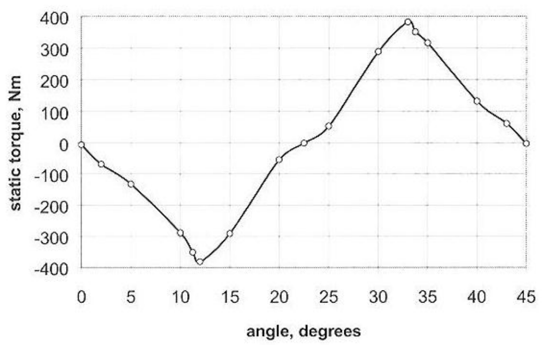

Fig. 9. Static torque versus rotor position Θ. Phase A is fed with d.c. current equal to rated *rms* current 575.8 A.

The computed maximum phase inductance (aligned position) is 0.383 mH and minimum phase inductance is 0.113 mH.

6. Control

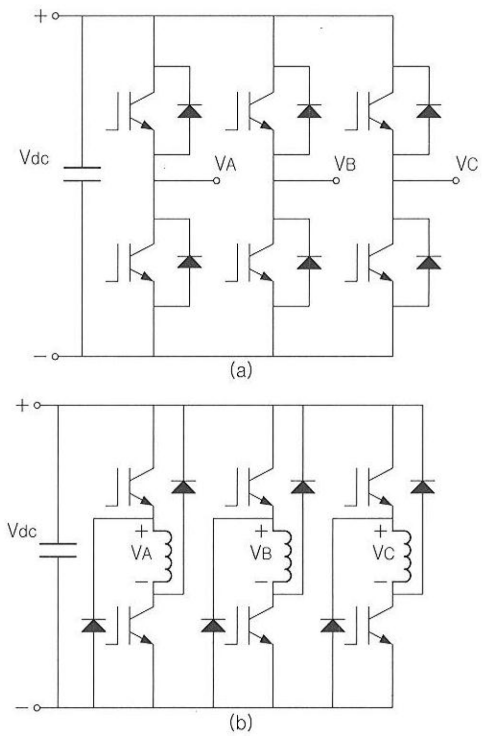

Fig. 10. PWM converters: (a) For induction motor and (b) For SRM.

For high speed SRMs only two degrees of freedom are used, i.e. turn-on and turn-off angle. Usually, an advancement of the turn-on angle well before the unaligned position is required. Most common two switches per phase topology has been designed (Fig. 10). The advantage of this topology is flexibility of control and fault tolerant operation. In the case of a three-phase SRM the number of switches are the same as in the case of a three-phase induction motor inverter (Fig. 10). It has been found that ;

- The algorithm of control is simpler than that of a vector controlled induction motor ;
- There are lower solid state switch ratings as compared with induction or permanent magnet brushless motors ;

- A low capacitance between windings and frame helps to reduce radio frequency interference.

Both rotor-mounted position sensors and sensorless inductance model based control technique has been considered. The second option has been aimed at the cost reduction of SRM drive.

7. Conclusion

The circuital approach to the simulation of a high speed SRM allows for designing the motor and prediction of all fundamental characteristics. However, to calculate the static torque more accurately and optimize the magnetic circuit, the FEM is recommended. For a quick industrial design the use of the FEM is not necessary since the lumped-parameter analysis is complete in itself [3,6]. It generates the geometry and winding designs and selects the material properties including the magnetization curve before the magnetic equivalent circuit calculation and electrical simulation are run [6].

The designed SRM has a flat efficiency versus speed curve and operates with high efficiency over a wide range of speed. At low speed about 5% of the rated speed, the phase *rms* current does not increase more than 30%.

A three-phase SRM can operate with the loss of one phase winding which reduces only the electromagnetic torque. On the other hand, the continued excitation of a shorted phase winding causes overcurrents and vibration [5].

Better fault tolerance can be obtained by designing more phases than three or *two channel* windings [1,4]. From the cost of converter point of view, more than three phases make the SRM drive less cost-effective.

The cost of power electronics converter associated with a three-phase, *single-channel* SRM is similar as that for a cage induction motor. For high power SRMs smaller ratings of solid state devices are possible because SRMs have higher *torque-to-current* ratio than induction motors.

A 225 kW, 18 000 rpm, 460 V SRM, in comparison with a cage induction motor of the same rating, has about 0.5 to 1% higher efficiency and 40% higher power density (output power per mass) [2]. On the other hand, the SRM has higher stator current density and 50% smaller air gap.

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