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Finite Elements Coupled to Electrical Circuit Equations in the Simulation of Switched Reluctance Drives: Attention to Mechanical Behaviour

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Abstract **— A method to model the switched reluctance motor is presented in this paper. The methodology is based on the simultaneous solution of the magnetic field, represented by the two dimensional Finite Element Method, with electrical circuit equations. With this model the currents in the windings are calculated and the force distribution on the stator teeth is obtained. The mechanical response to magnetic forces is calculated by a Finite Element code.**

I. INTRODUCTION

The switched reluctance motor (SRM) shown in Fig. 1 presents short pitch concentrated windings and doubly salient structure. These characteristics provide this machine with certain advantages like simple and robust motor and converter structures, good efficiency and high speed capability [1], [2].

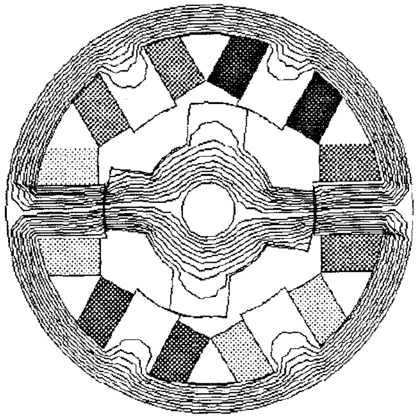


Fig. 1. Switched reluctance motor structure and field distribution.

A common method used to simulate the SRM, here named indirect approach, is to predict the flux linkages with a phase as a function of angle and current, neglecting coupling between phases. Circuit equations, which incorporate a model of the converter, are then used to calculate the phase current as a function of time, assuming constant speed. Torque can be derived from the rate of change of co-energy [2], [4]. Another indirect approach is based on the use of nonlinear magnetic field solutions and state space models, including the speed equation [5].

In this work a direct approach is made to simulate the SRM drive system. The interaction of the magnetic and electrical circuit is taken into account by adding the external circuit equations into the Finite Element matrix [6]. The whole system is then solved step by step with respect to time. Movement is taken into account by means of the Moving Band technique [7].

II. SRM WORKING PRINCIPLE AND ELECTRICAL RESULTS

The power circuit for the SRM is presented in Fig. 2, where T_i and D_i are respectively transistors and diodes. The motor phases are switched in turn and the phase excitation is controlled by means of a rotor position sensor.

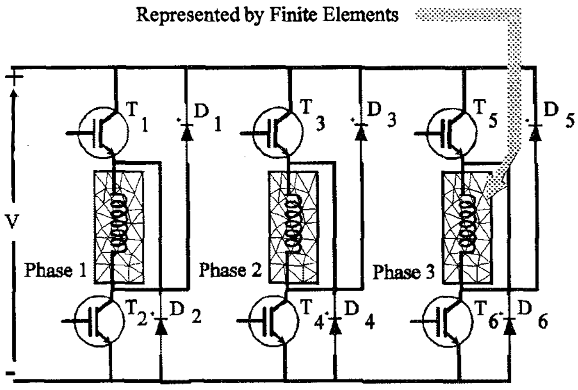


Fig. 2. Power circuit configuration for the SRM shown in Fig. 1.

The phase current calculated by means of the direct approach for the SRM shown in Fig. 1 is compared with the one obtained by the indirect approach in Fig. 3. The slight difference is due to the fact that in the indirect approach the coupling between phases is neglected.

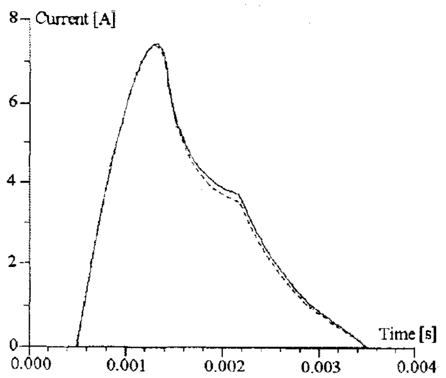


Fig. 3. Calculated phase current. Continous line: direct approach. Dotted line: indirect approach

In order to validate the calculation method based on the simultaneous solution of the field and circuit equations the SRM presented in Fig. 4 was chosen. The machine presents 8 stator and 6 rotor teeth.

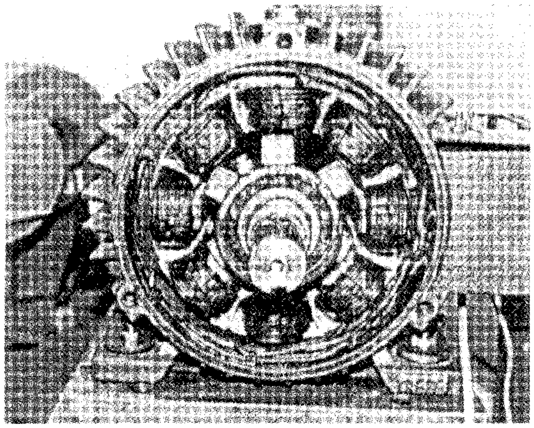


Fig. 4. Industrial SRM with six rotor teeth.

The comparison of the calculated and measured current waveforms at 2500 rpm presented in Fig. 5 and 6, which agree well, shows the validity of the adopted methodology to simulate the whole SRM and feeding circuit.

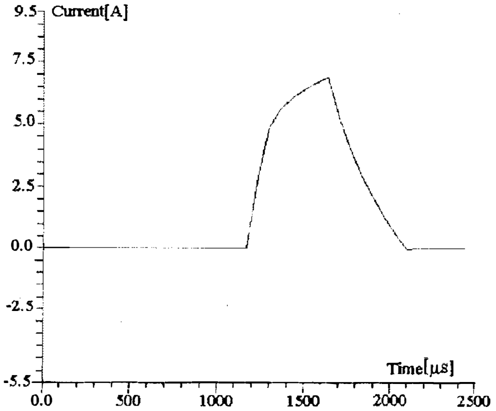


Fig. 5. Calculated phase current for the SRM of Fig. 4.

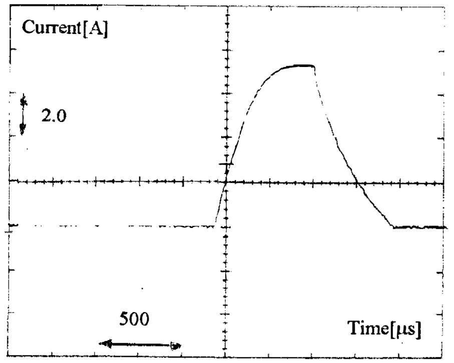


Fig. 6. Measured phase current for the SRM of Fig. 4 (2A/div.)

When working at low speeds a hysteresis current control is used in order to avoid high current levels. This current control strategy was implemented in the simultaneous solution of the field and circuit equations scheme. The so obtained phase currents are presented in Fig. 7 for the SRM presented in Fig. 1.

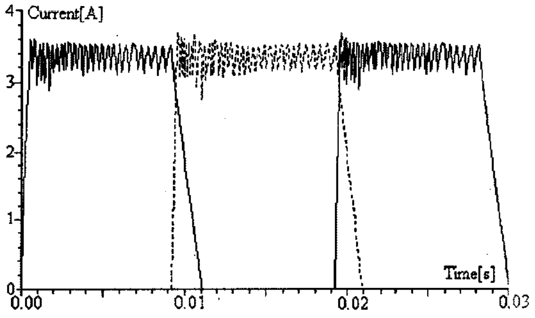


Fig. 7. Calculated phase currents with hysteresis current control.

Despite of its positive attributes the SRM does exhibit higher levels of vibration than most competing drives, like induction and permanent magnet motors [3]. It has been shown by experimental results that the dominant source of the vibrations in the SRM is the radial vibration of the stator [3], [8]. One of the most important kinds of vibrations is that of magnetic origin, which is due to the fluctuations of magnetic force inside the motor. Here we present a possible calculation of this vibration.

III. COMPUTATION OF MAGNETIC FORCES

In order to have a good evaluation of the distribution of magnetic forces along the stator, forces exerted on teeth and conductors are evaluated.

A previous paper has shown experimentally that the integration of the surface force density given by the Maxwell's stress tensor over a surface covering partially a tooth leads to the magnetic force applied on it [9].

To obtain the force evolution in time domain, the evolution of the magnetic field inside the motor must be calculated. In SRM, as in synchronous motors with no damper windings, induced currents can be neglected. Under steady state condition, their dynamic operation can be assimilated to a succession of magnetic states governed by magnetostatic equations. In this condition the forces were calculated. The electrical excitation was given by the current waveforms presented in Fig. 7 with the high frequency oscillations filtered. The evolution of the radial and tangential magnetic forces applied on three stator teeth versus the rotor position are shown in Fig. 8. Forces on conductors are not shown because their amplitudes are very weak compared to those applied on teeth. The frequency of the magnetic force is equal to twice the frequency of the supply currents. On Fig. 9 and 10 the spectra of respectively the tangential force and the radial force on one tooth are shown. It can be seen that the spectra are very rich.

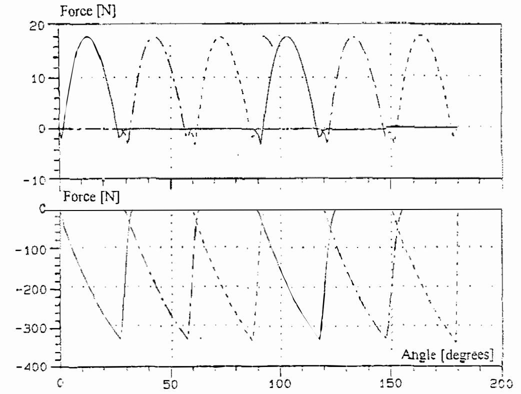


Fig. 8. Tangential and radial forces applied on the three teeth of the stator versus the mechanical position of the rotor . Upper curves: tangential forces. Lower curves: radial forces.

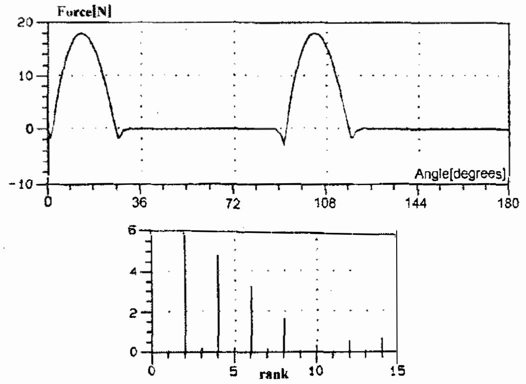


Fig. 9. Tangential force on one tooth and its spectra.

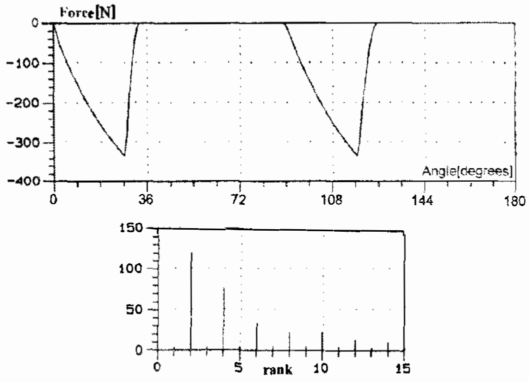


Fig. 10. Radial force on one tooth and its spectra.

For this motor it can be shown that there are only two types of distribution of the harmonics of magnetic forces along the stator [10]. These two types of distribution are represented by the distribution of harmonics of rank 1 and 3. Harmonics of rank 3k have the same type of distribution. It's the same for harmonics of rank 3k± . For instance harmonics of rank 3 and 6 have the same distribution and harmonics of rank 1 and 2 also. Fig. 11 and 12 show these two types of distribution. Fig. 12 shows that the forces on teeth have the same phase angle for harmonics of rank 3k. These harmonics, for this motor, correspond to the slot frequencies [9].

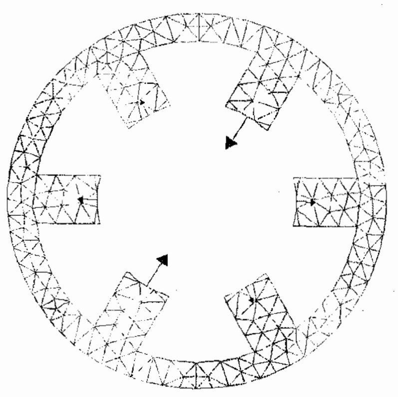


Fig. 11. Distribution of forces along the stator for harmonics of rank 3k± 1(1, 2, 4, 5, 7, 8,...).

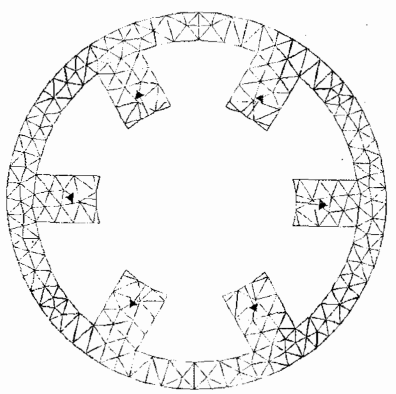


Fig. 12. Distribution of forces along the stator for harmonics of rank 3k (3, 6, 9,...).

IV. MECHANICAL RESPONSE OF THE STATOR

The frequency response of the mechanical structure to each harmonic of magnetic forces is calculated by means of the software EFMEC which solves the dynamic mechanical equation [10].

Frequency responses to harmonics of rank 1 and 3 are shown on Fig. 13 and 14. They are calculated on four positions on the stator. Each response curve presents resonance frequencies. The resonance frequencies correspond to the natural frequencies of the mechanical structure calculated by means of another software [10]. Fig. 13 shows that the harmonic of force of rank 1 excites the mode 2 whose natural frequency is equal to 2340 Hz. Fig. 14 shows that the harmonic of force of rank 3 excites modes 2 and 6. Mode 6 has double natural frequencies at 17000 Hz and 18000 Hz. The two harmonics excite slightly the mode 4 whose natural frequency is 10600 Hz.

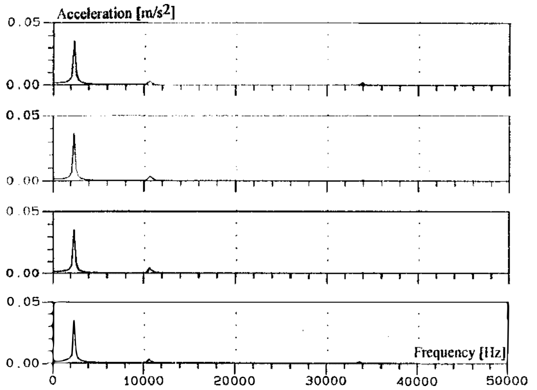


Fig. 13. Frequency response of the mechanical structure induced by harmonics of rank 3k ± 1.

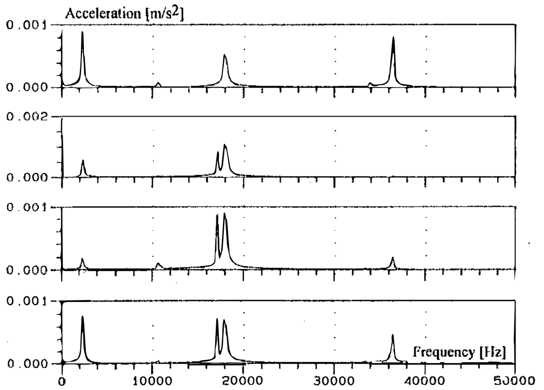
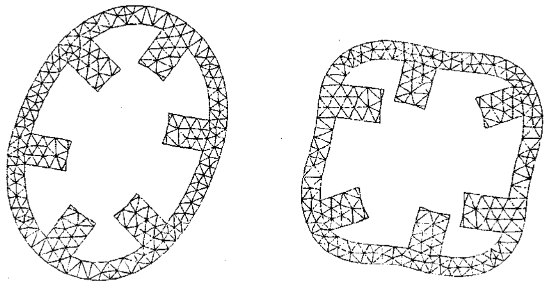


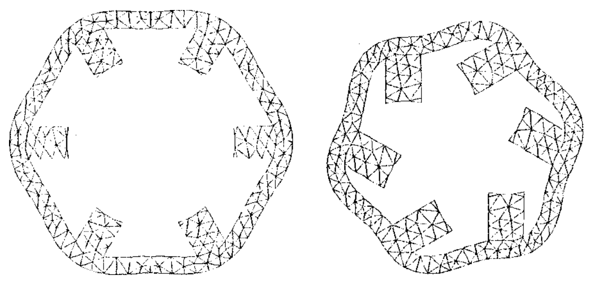
Fig. 14. Frequency response of the mechanical structure induced by harmonics of rank 3k.

Fig. 15 and 16 show the deformation of the stator submitted to magnetic forces of rank 3 when the excitation frequency is respectively equal to 2340 Hz, 10600 Hz, 17000 Hz and 18000 Hz. The shape of the deformation of the stator are very similar to those of the corresponding mode shapes.



(a) (b)

Fig. 15. Deformation of the stator magnified 10^{10} times. a) Excitation frequency equal to 2340 Hz (natural frequency of mode 2). b) Excitation frequency equal do 10600 Hz (natural frequency of mode 4).



(a) (b)

Fig. 16. Deformation of the stator magnified 10^{10} times. a) Excitation frequency equal to 17000 Hz (first natural frequency of mode 6). b) Excitation frequency equal to 18000 Hz (second natural frequency of mode 6).

V. CONCLUSIONS

A method allowing the simulation of SRM drives based on Finite Elements Method coupled to electrical circuit equations is proposed in this work. Calculated results obtained with this method with results obtained by classical analytical procedures are presented. Simulation and experimental results for a SRM are compared and show the validity of the proposed simulation scheme. Local force distribution and mechanical Finite Elements calculations are presented which allow the investigation of the vibratory behaviour of this kind of machine.

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