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Transient modelling and simulation of a switched reluctance machine in different operating modes

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Data Tables

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ABSTRACT

An appropriate numerical computational method and simplest model captures the performance of Switched Reluctance Machines (SRMs). Several papers and computer software-based simulation models are reported in the literature. Each model has its own merits and demerits. This paper proposes a mathematical model, based on a combination of voltage and mechanical equations, suitable for the transient running of a switched reluctance machine. The simulation results of current, torque and speed profile of SRM are produced under current chopping control and voltage pulse width modulation control. The proposed work has used experimental data of flux linkage and static torque in the mathematical model for best performance and control of the machine. The obtained simulation results are verified with experimental results. This model can be extended to a range of rotor position where the machine can be switched at decreased and increased inductance region which gives motoring and generating operation mode.

1. Introduction

The presence of switched reluctance motor in a variety of applications such as industry, railways, biomedical engineering, medical has recently diverted attraction of researchers and designers from other machines, due to its simpler construction, effective performance, and flexibility of converter topologies. Despite, the machine owns non- linear characteristics, torque ripples, and acoustic noise. The quantity of copper required for the machine windings is less as compared to other machines since rotor in the SRM does not carry windings on it. For a proficient performance of the machine, the knowledge of appropriate converter [1], excitation and control strategy are important. The input data tables method is recently well reported in the literature [2].

In this work, the mathematical model and numerical computation of transient analysis of a 4-phase SRM are presented in current chopping control, in which frequency is varying and pre- set limits for current are introduced, and voltage pulse width modulation, where frequency is fixed, and control is acquired by varying the pulse width) of the machine operation. If control methods not selected, then machine will run in a single pulse operating mode. Fig. 1 shows a 4-phase switched reluctance machine with 8/6 poles, appropriate converter and one phase connections for the illustrations. A-a corresponds to phase A, B-b for phase

B, C-c for phase C and D-d for phase D. The rotation in the machine is created when an energized stator pole attracts a nearest rotor (un-energized) pole to align where inductance is more and reluctance is less, as a result a reluctance torque is produced and SRM rotates [3]. When both the poles approaching close due to magnetic attraction, as a result, the reluctance starts decreasing and inductance starts increasing, and if both poles advance away from each other, the reluctance magnitude increases, and inductance decreases as given in relation below. This happens during each cycle of the operation and excitation of succeeding pole. Therefore, selection of a particular stator pole for the excitation is important in terms of the rotation in the machine, i.e., clockwise, and anticlockwise.

$rel = \frac{NI}{\varphi}\left(\frac{Ampere-turn}{Weber}\right)$ and $L = \frac{N\varphi}{I}\ (Henry)$

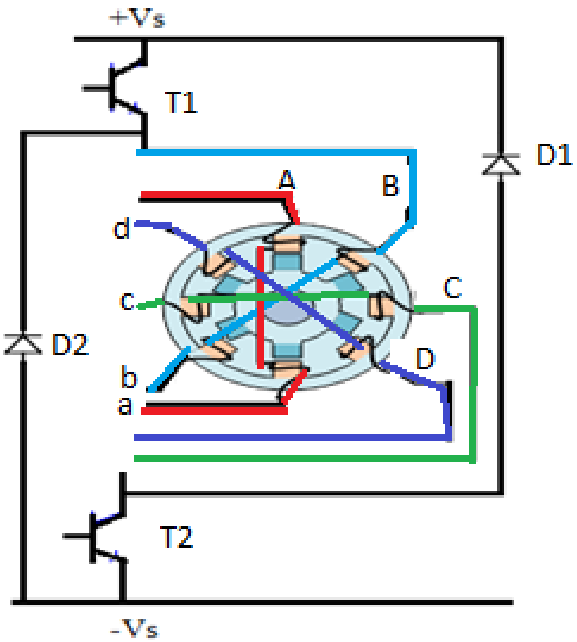

Fig. 1. 8/6 pole switched reluctance machine with representation of one phase connections

In the current chopping operating mode of switched reluctance machine, which is suitable for low-speed applications, the selection of upper limit and lower limit of phase current through the machine is intentionally set according to the requirement. The frequency of switching devices, used in the converter, is not fixed due to chopping. Whereas, in the high-speed range applications of the machine, the frequency is kept fixed to a known value [4]. Fig.2 shows the phase current, torque, and flux waveform of switched reluctance machine without presenting either control. The machine is switched-on at decreased inductance region and switched-off at increased inductance and therefore, slope of current is rising and positive. Whereas torque is positive until increasing slope of inductance, it then decreases in negative value when the slope of inductance is negative, this can be seen noticeably from illustration shown in Fig. 2. The flux is at a higher value at the instant when the electronic switches are opened.

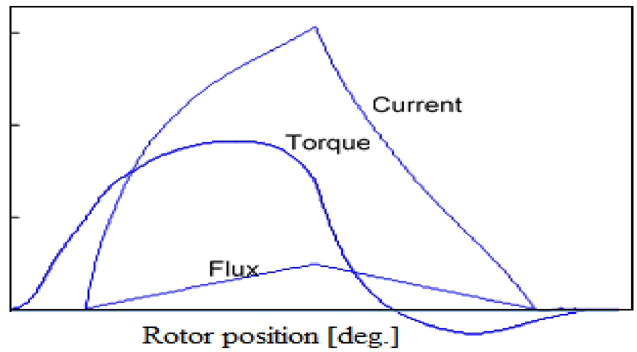

Fig. 2. Illustrations of phase current, torque and flux profile of one phase of a 4-phase switched reluctance machine

The research work related to transient modelling of SRM are reported in the literature [6-17]. An input data based, non- linear model of a switched reluctance machine in Matlab/ Simulink software is presented [5]. This model uses static characteristics. In reference [6], a simulation model based on Fuzzy PID control method is presented. The work has produced results in current chopping control of the machine with the aim to improve the static and dynamic performance of the machine. Reference [7], reports a Matlab/ Simulink model of the SRM in current chopping and voltage PWM controls is presented. In reference [8], a Matlab/Simulink and Fuzzy Logic Control based simulation model uses Finite Element Method (FEM) for torque calculations. The presented model is helpful for optimal design improvement of the machine. A nonlinear dynamic model of SRM, based on PSPICE (Personal Computer Program with Integrated Emphasis), is presented [9]. For simulations, SR machine, 300W, 12V, 8/6 was preferred. A tubular linear switched reluctance generator is preferred for the simulation in FEM [10]. The waveforms are produced in dynamic performance Dynamic performance waveforms are shown for this model. Load current, winding current of the machine. A Matlab/Simulink based models [11-13] are presented. In reference [11], the presented model relies on two data tables and does not introduce the transient model with the control strategies. FEM based models [14-17] highlights the dynamic behaviour of the machine.

2. Mathematical Modelling Equations

The proposed model is developed in Matlab software. The basic voltage equation for the machine is,

$$\frac{d\Psi}{dt} = (v - Ri) \tag{1}$$

where term on left-hand side specifies the rate of change of flux linkage. v is supplying voltage; R is resistance of motor winding, and i is stator current.

Simplifying eq.1by replacing $\Psi = Li$ and multiplying both sides of the equation by i, we get,

$$vi = Ri^2 + \frac{d}{dt}\left\{\frac{Li^2}{2}\right\} + \frac{i^2}{2}.\frac{dL}{d\theta} \quad \omega \tag{2}$$

where, term on right hand side of equation 2 is input power. Whereas, on right hand side of the equation, three terms are identified as copper loss, stored magnetic energy and output power which is multiplication of electromagnetic torque ($i^2 \frac{dL}{d\theta}$) and angular speed ($\frac{d\theta}{dt}$) respectively.

For transient modeling, a mechanical equation is added to the given equations.

$$\frac{d\omega}{dt} = \frac{1}{J}[T - T_L] \tag{3}$$

where T is used for the torque of the machine, whereas TL represents the load torque, and J denotes moment of inertia.

The proposed model includes data tables of a static torque, the procedure of obtaining the required data tables is presented in [18]. A new topology of series connected winding in a PMSM drive system is introduced [19].

3. Necessary Data Required for Simulations

Basically, there is flexibility in opting simulations based on choice of software. But if SRM modelling is based on input data tables such as, flux, inverted flux, co energy and static torque data, all as lookup data tables, in that case model uses set of equations eq1-5 along with look u data tables where for each iteration this data is carefully and accurately utilized during computation. The graphical representation of flux, rotor position and current are shown in Fig.3. Fig.4 is ample view of co energy, rotor position and current whereas; Fig.5 depicts variation of static torque data with respect to co energy and current.

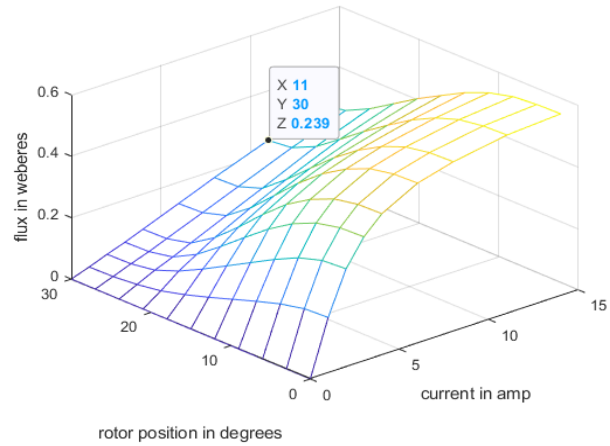

Fig. 3. Variation of Flux with rotor position and current

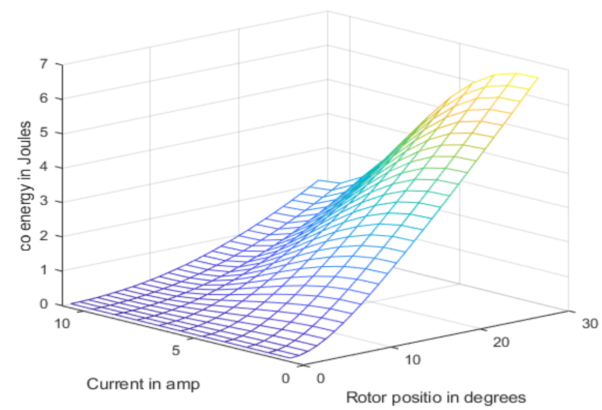

Fig. 4. Variation of Co energy with rotor position and current

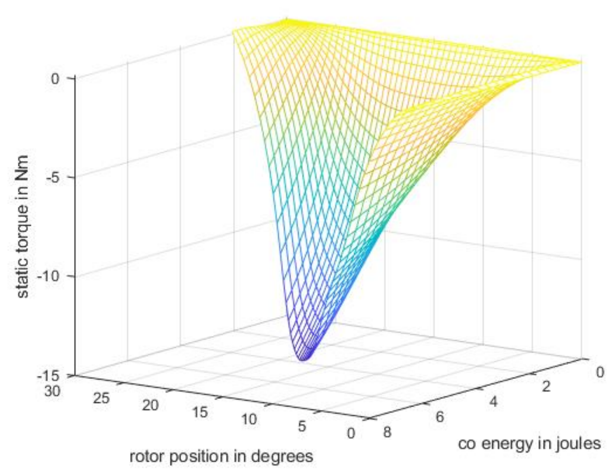

Fig. 5. Variation of Static torque with rotor position and co energy

Following steps were considered for simulations in MATLAB environment with inclusion of parameters listed in Table 1.

1. Start of simulation with input data tables and operating conditions as initial conditions/parameters.

2. Use of mathematical eq.1 to eq.5 along with step 1.

3. Obtain current, torque and speed profile of the SRM.

Table 1

Operating parameters

A 4-phase Switched Reluctance Machine Operation	
Supply Voltage (Volts)	100
Winding Resistance (Ohms)	2
Switch-on Angle (Degrees)	-25
Switch -off Angle (Degrees)	-5
Load Torque (N-m)	5
Upper Limit of Current (Amperes)	8
Lower Limit of Current	7.5
Carrier Frequency	2000
Temperature coefficient of	0.102
Duty Cycle (%)	70

4. Results and Discussions

The waveforms of instantaneous stator current, resulting instantaneous torque, and rotational speed, in a single pulse mode, which is default operating mode if the control is not introduced. The phase current profiles of the machine with operating conditions mentioned in the Table. Current waveforms in a single pulse, voltage PWM and current chopping are shown in Fig. 6, 7 and 8(a). Similarly, the torque of profiles is depicted in Fig. 9, Fig. 10 and Fig. 11. Whereas the speed under three operating modes is shown in Fig. 12, Fig. 13 and Fig. 14 in sequence. The blue color shows phase A, red color specifies phase B, sea green color is used to indicate phase C, whereas phase D is shown by color purple respectively. One cycle of machine operation corresponds to 60 degrees mechanical. The successive phases of the machine are individually excited after 15 degrees mechanical from the previous energized phase and so on from the dc regulated source via preferred converter. In the Figures 6-8, shown below, the negative torque of the four-phase machine is due to decreasing inductance region. The scale on the X-axis is represented in time [seconds], however, the rotor position is referenced to the degrees. A purposefully single-phase representation of current, torque profile is separately shown in a small window in which switch on and switch off the machine is shown in rotor position in degrees.

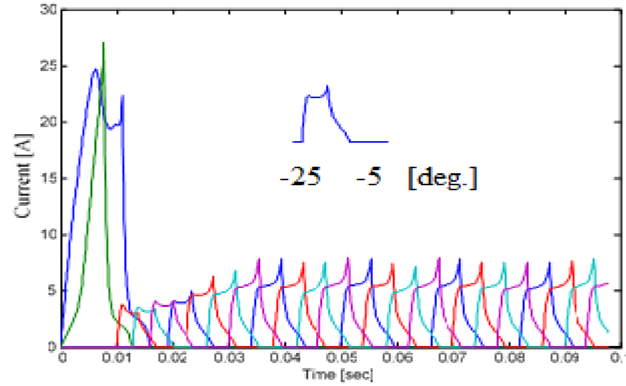

Fig. 6. Phase current waveform of 4-phase machine excluding the control

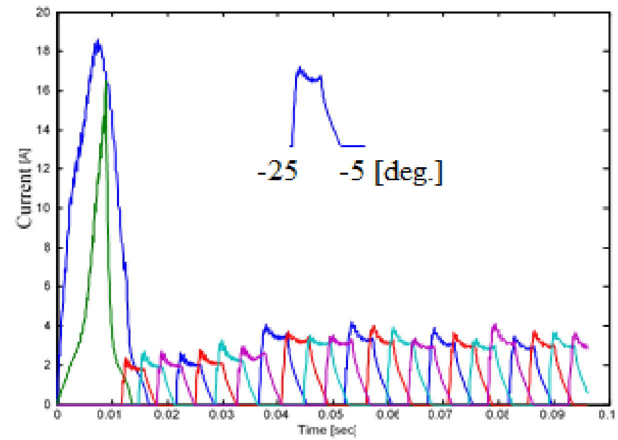

Fig. 7. Phase current waveform of 4-phase machine including the control i.e., voltage PWM

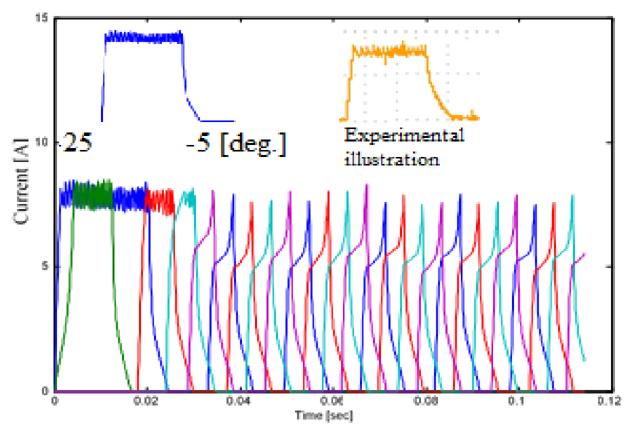

Fig. 8(a). Phase current waveform of 4-phase machine including the control i.e., current chopping with experimental waveform of one phase (small window)

For purpose of validation, a 4-phase existing prototype was run under operating conditions mentioned in Table 1 in current chopping control shown in Fig.8(b). Upper waveform shown in yellow colour is phase A, phase B is shown by sea green colour, phase D is represented by purple colour and phase D is shown by green colour respectively.

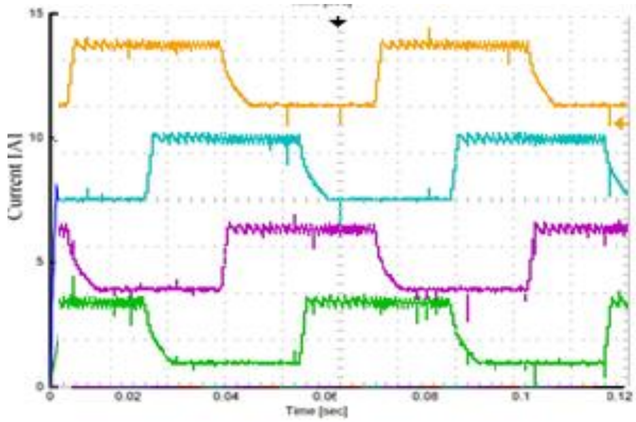

Fig. 8(b). Experimental waveform of phase current

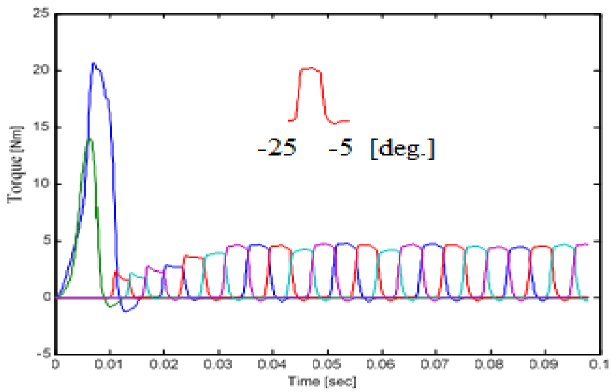

Fig. 9. Phase torque waveform of 4-phase machine excluding the control

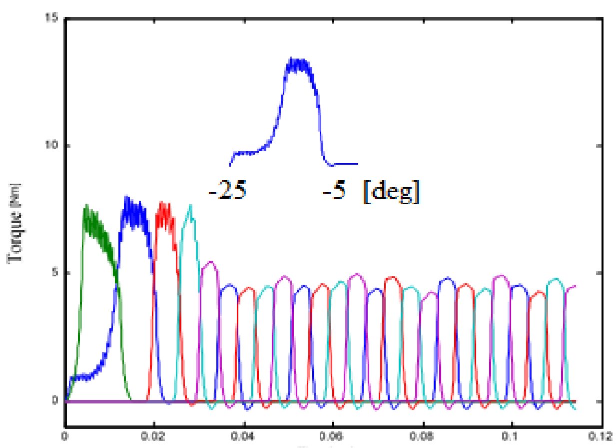

Fig. 10. Phase torque waveform of 4-phase machine including the control i.e. current chopping

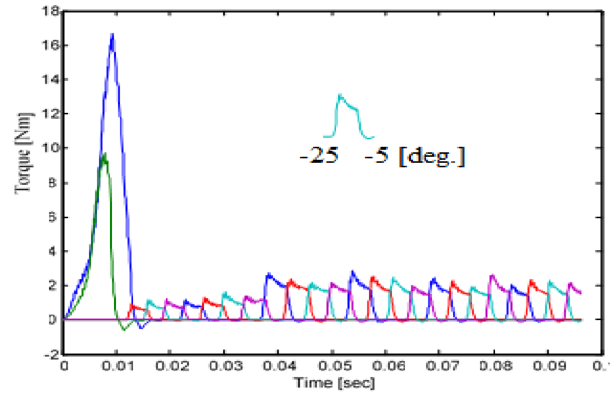

Fig. 11. Phase torque waveform of 4-phase machine including the control i.e., voltage PWM

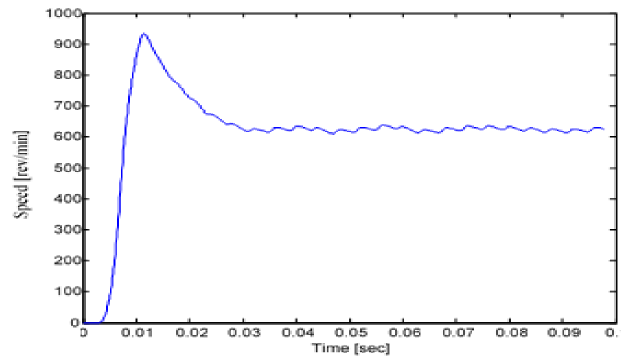

Fig. 12. Speed waveform of 4-phase machine excluding the control

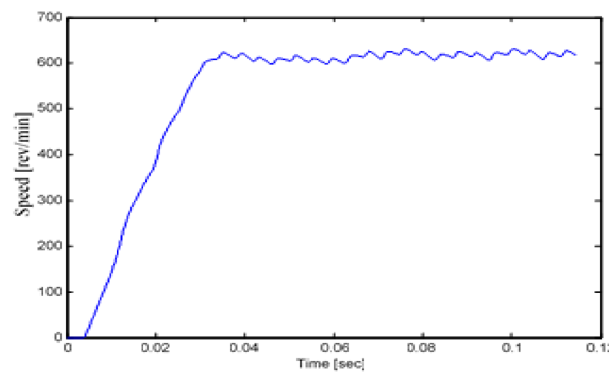

Fig. 13. Speed waveform of 4-phase machine including the control i.e., current chopping

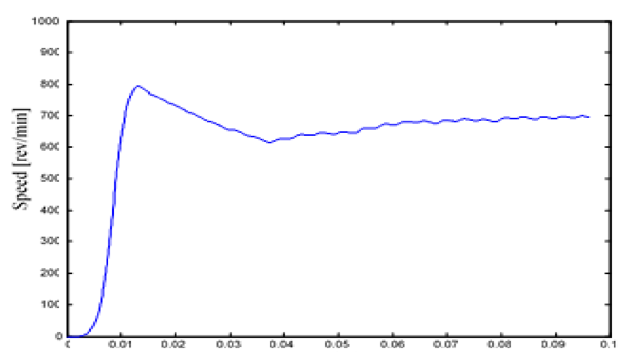

Fig. 14. Phase current waveform of 4-phase machine including the control i.e., voltage PWM

5. Conclusion

The transient performance of 4- phase switched reluctance machine is addressed. The results are produced in current chopping control and voltage PWM control with a set of operating conditions. These control schemes are suitable for low speed and high-speed application of the machine. The results are reproduced in a small window to see the clear picture of the machine at switch-on and switch- off instants. These results are compared separately with experimental obtained under same operating conditions. Proposed mathematical has produced in motoring mode. The results are produced in several cycles of the machine operation during transient and after the transient behavior of the machine can be clearly seen. The trend of current is compared with the experimentally obtained current profile.

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