ANALYSIS AND CONTROL OF SWITCHED RELUCTANCE MOTORS

by

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Electric motors.

गुरू गोविंद दोऊ खड़े, काके लागो पांय
बलिहारी गुरू आपने, जिन गोविंद दियो बताय

- संत कबीर

CERTIFICATE

Certified that the thesis entitled "**Analysis and Control of Switched Reluctance Motors**" which is being submitted by Mr. Virendra Kumar Sharma, for the award of the Degree of Philosophy in the Department of Electrical Engineering of the Indian Institute of Technology Delhi, is a record of the student's own work carried out by him under our joint supervision and guidance. The matter embodied in thesis has not been submitted for the award of any other degree or diploma.

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ABSTRACT

Technological breakthrough in the field of power semiconductor devices, digital signal processors and microcontrollers have resulted in increased interest in design, control and analysis of high performance electric drive systems using electronically commutated motors. Switched Reluctance Motor (SRM) is one such recent entrant to the competitive field of variable speed drives. Although the first acknowledged application of SRM dates back to the 19th century, its development then was hampered by the unavailability of fast switching devices. With the technological explosion in power semiconductors, VLSI, ASIC etc. there has been an steady growth in SR drive technology involving the motor, power converter and associated controller. Over the last two decades continuous research and development efforts have led to evolution of SRM drive systems for commercial production. But the subject is still deeply researched to tie up several loose ends and also due to scope for further improvement. Areas of interest for researchers and designers relate to the analysis, design, sensor reduction/elimination, torque ripple minimization, control, vibration/noise reduction, instrumentation and application aspects of SRM.

The advantages of SRM drive, over other conventional drives are that the motor is simple requiring few manufacturing steps, low moment of inertia and quick response. Stator is simple to wind with short turns and no crossovers. Bulk of losses appear in stator which is relatively easier to cool. The absence of rotor excitation leads to higher operating temperature. Electromagnetic torque is independent of the polarity of current which leads to reduced number of power devices and control complexity. Motor winding is in series with the semiconductor switch thereby eliminating the possibility of shoot through faults. Very high speeds are possible and the torque-speed characteristics can be tailored to the application. The robust brushless construction and good thermal features make the SRM drive attractive for mining, flame proof and traction applications. Simplicity and low cost have implications for domestic applications. Other application areas include electric vehicle propulsion, aerospace industry and traction.

Based upon these attractive features, and increased scope of SRM as an adjustable speed drive, the following aspects are covered in the present research work.

The areas identified for this research are the measurement and instrumentation technique, modeling, performance simulation, design based analysis, and improvement in excitation source of

SRM drive system. This work has led to certain new findings, observation and outcome categorized below:

i) Simplified, improved and new measurement procedures for parameter estimation for SRM and comparison with design based data.

ii) Developing a new mathematical model for magnetization characteristics of the SRM.

iii) Modeling, simulation and performance analysis of the motor and its electronic controller.

iv) Implementation of a practical controller.

v) Performance analysis of SRM drive under abnormal and fault conditions.

vi) Modeling and simulation of converter-inverter system to overcome the deterioration in quality of power and grid pollution created by SRM drive system.

vii) Simulation of switched reluctance machine operating as a generator.

The work is broadly divided in following aspects: instrumentation, modeling, performance analysis, design based analysis, performance prediction, power quality considerations to improve power factor at input ac mains of SRM controller, and analysis of switched reluctance machine for generator operation.

The major contribution of the present work is summarized as below.

1. Improved Instrumentation and Measurement Technique and Modeling of Non-linear Magnetization Characteristics

Experimental determination of magnetization characteristics of a SRM is very important for accurate performance prediction. Over the last decade, various experimental procedures have been used to obtain these characteristics. Every evolved method has its own limitations and constraints. In this investigation, an improved, simple and cost-effective experimental procedure, and an equally simple post-experimental data processing methodology is developed. To obtain the family of magnetization curves use of magnetic flux sensors is not only expensive but also requires their installation in motor assembly. Integration of the emf induced in the search coil mounted in the excited phase is equally cumbersome. Hence, the indirect method of obtaining the flux-linkage is used to obtain magnetization curves of the SRM. In order to determine the flux-linkage, it is required to sense only two electrical quantities: (i)the voltage across SRM winding, and (ii)the current flowing through the winding starting from zero till it reaches a steady state value higher than full load current, typically 120% of full load current. The use of a pure dc source (lead acid battery) eliminates the problem of poor voltage regulation and RLC oscillations caused by the dc obtained by a diode bridge rectifier with electrolytic capacitor filter. It also eliminates the requirement of digital low pass filter, interpolation techniques and removal of skew from measured data. The use of a battery also eliminates the requirement of a voltage sensor or voltage attenuator, and supply isolation required for digital storage oscilloscope. In one recording of voltage and current, sufficient number of data points are available for intermediate values of current thereby avoiding the repetition of experiment for different values of current at a given rotor position. There are many other simplifications in experimentation and data processing reported in the thesis.

The experimental results illustrate the effectiveness of the proposed method. The improved method eliminates most of the problems reported earlier in the literature. The data processing is simple and straight forward. Results compare well with the previously published data of similar and higher rating SRMs.

Due to doubly salient structure of SRM, its inductance profile has an important bearing on the motor performance. This information is required in design verification, performance analysis and rotor position sensing. A simple frequency response method to estimate the inductance profile is proposed. Here, an equivalent circuit is proposed which takes into account the core loss taking place while the test is conducted with blocked rotor. The inductance profile by the proposed experimental method is critically compared with the results obtained by using FEM based electromagnetic software, and flux-linkage method.

Lot of efforts have been made to represent the family of non-linear set of magnetization curves by some mathematical model. For this, mathematical modeling of magnetization characteristics of SRM is proposed by a new sigmoidal function. The validity of proposed model is confirmed with experimental magnetization data of a 4-phase and a 3-phase motor and compares well with existing analytical and piecewise linear models.

2. Performance Prediction with Different Types of Controller

A comprehensive model of SRM and its electronic controller is developed for performance prediction of the drive, working with different types of speed controllers, over a wide range of operating conditions. Design of controllers based on linear approximations around nominal operating condition does not always meet the high dynamical performance requirements of variable speed control. In general, the variable speed drives represent a class of multi-input, nonlinear system.

The SRM exhibits a coupled nonlinear multivariable control structure since (i)it primarily operates in magnetic saturation to maximize torque/mass ratio (ii)the developed torque is a nonlinear function of rotor position and excitation current and iii)the turn-on and turn-off angles, which are speed dependent, play a crucial role in developing motoring and braking torque. Speed controllers based on the conventional linear control law (PID), nonlinear control law (Sliding Mode Control) and modern control law (Fuzzy Logic Control) are analyzed for the control of SR motor. The operating conditions include starting, load perturbation, speed reversal and parameter variation. The performance of drive with different controllers is compared for defined performance indices such as starting/reversal time, dip/rise in speed, speed ripple, torque ripple and steady state error in speed.

3. Implementation of a Practical Controller

The design and implementation of a simple digital control scheme for closed loop operation of switched reluctance motor is reported. The laboratory model of the controller comprises diode bridge rectifier with capacitor filters to provide a mid-point dc link, and a power converter with a minimum number of four IGBT modules connected in split phase H-bridge configuration for 4-phase, 4kW, 1500 rpm motor. The control circuits are developed for current sensing, rotor position sensor conditioning, gate drive circuit for IGBT, and power supply unit. The position sensor signals are used for commutation of four phase windings, speed estimation and forward/reverse motion control. Current sensors are used to sense the four winding currents for individual current control. Software developed in higher level language `C' is used for closed loop control of the SRM drive by a 80486 based processor. The software developed on the host computer is tested and integrated with the hardware. Successful testing is carried out for different operating conditions such as starting, load perturbation in forward as well as reverse direction of rotation.

To validate the developed modeling strategy, the predicted speed response of a sample case of PID controlled SRM under certain operating conditions is compared with corresponding experimental results. The study has shown that the algorithm developed to analyze the performance can be used for real time implementation. The results demonstrate that the drive operates satisfactorily

4. Analysis under Fault Conditions and Supply Interference

The importance of modeling and analysis of SRM drive system under fault and supply interference conditions stems from its applications in aerospace industry where reliability of drive operation is highly desirable. Electric drive systems requiring higher degree of reliability consider and prefer SRM due to its superior fault tolerant characteristics. Because of the magnetic independence of the motor phases and the circuit independence of inverter phases, a fault in either a motor winding or an inverter phase can be conveniently detected and isolated with no effect on other phases. The motor continues to operate with reduced power output and slightly inferior speed-torque characteristics.

The dynamic behaviour of SRM operating under fault and abnormal conditions is analyzed. A generalized modeling and analysis methodology is evolved to estimate the performance of SRM drive under different types of motor and converter fault and supply interference conditions. Motor fault conditions investigated are opening of one of the phase winding. Fault on the converter side lead to short circuiting and subsequent opening of the semiconductor device. Other abnormal operating conditions analyzed are the drive operation at reduced dc link voltage due to partial failure of rectifier circuit or single phasing of three phase supply. Performance of the drive under absence of position sensor mounted on the motor is also presented. The fault conditions are simulated to occur during (i)starting (ii)steady state (ii)no load and (iii)full load at rated speed. The validity of the proposed fault modeling is verified experimentally for certain cases of fault conditions.

5. Power Quality Considerations and Unity Power Factor Operation

Solid state controlled drive systems are viewed as non-linear load by ac mains as they generate harmonic currents and create reactive power burden on the grid. The injected harmonics, reactive power burden and voltage unbalance cause low system efficiency, reduced component reliability and poor power factor.

In case of SR motor, between three phase ac mains and the motor there is a uncontrolled converter feeding power to inverter which controls the sequential excitation of four phase windings. Normally, the converter receives power from three phase ac mains, converts it to dc by a diode bridge rectifier and this dc link voltage is then used for the pulsed excitation of motor windings. Thus, the drive system draws a non-sinusoidal current from ac mains which is rich in harmonic contents and pollutes the power grid utility. A critical examination of the power quality measurements lead to proposing remedial measures and corrective actions required to reduce the harmonic contents and reactive power burden and improve the power factor at the input port of SRM controller. For this, a new controlled-converter-inverter for SRM drive system is proposed which operates at unity power factor and relieves the utility from harmonic pollution. The current controlled converter draws sinusoidal current from supply mains and maintains them in phase with supply voltage, thereby facilitating unity power factor operation.

6. Generator Operation of Switched Reluctance Machine

Normally, the controller of a SRM is energized by a three phase diode bridge rectifier which does not provide regenerative features. With the proposed controlled converter-inverter (C-I) system, the motor is driven by an external prime mover. The power developed by the motor operating as a generator is fed back to the ac mains by developing appropriate switching strategy for the integrated C-I system. The SRM driven by a prime mover draws excitation current from the C-I system and feeds power back to the ac mains as a generator. The bi-directional converter-inverter system capable of handling bi-directional power flow is analyzed. Steady state performance simulation of switched reluctance generator is performed to explore its use as SR generator, which may find possible application for renewable energy systems.

In this research work, a simple and cost effective procedure to obtain the significant parameters of SRM such as flux-linkage, inductance profile, static torque characteristics and co-energy have been developed. A comprehensive mathematical model of SRM drive system has been developed using fundamental flux-linkage equations. The model equations are simple and give realistic results. The modeling system is general in nature and is capable of simulating the performance of drive with different types of variation in the system configuration used. The model is capable of comparing the effectiveness of different types of controllers. The dynamic response during transients such as starting, reversal, load torque disturbance, parameter variation has been studied. A simple closed loop scheme has been developed for implementation of the drive system. Behavior of SRM drive operating under various categories of fault conditions is analyzed. Simple modeling approach is used to predict the drive operation under fault conditions which compares well with the experimental results. The use of an integrated converter-inverter system as a source of excitation has been found to be useful in eliminating the non-sinusoidal currents and provides unity power factor operation at the input port of the controller. A switching strategy is developed to simulate the switched reluctance machine operating as generator feeding power to the ac mains.

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