ANALYSIS AND DESIGN OF DOUBLY-SALIENT RELUCTANCE AND PERMANENT MAGNET MOTORS

By

SHETH NIMITKUMAR KIRITKUMAR
Department of Electrical Engineering

Submitted
In fulfillment of the requirements of the degree of
DOCTOR OF PHILOSOPHY

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI
June 2007

CERTIFICATE

This is to certify that the thesis entitled, **“Analysis and Design of Doubly Salient Reluctance and Permanent Magnet Motors,”** being submitted by **Mr. Sheth Nimitkumar Kiritkumar** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him in the Electrical Engineering Department of Indian Institute of Technology, Delhi.

Mr. Nimit Sheth worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard. The results obtained here in have not been submitted in part or in full to any other University or Institute for the award of any degree.

(Prof. K. R. Rajagopal)
Electrical Engineering Department
Indian Institute of Technology Delhi
Hauzkhas, New Delhi-110016, INDIA

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisor, Prof. K. R. Rajagopal, for his support, patience and encouragement through out my research and course work at IIT Delhi. It is not often one finds a supervisor, who always finds the time for listening to the little problems and roadblocks, which unavoidable crop up in the course of performing research. His technical, non-technical and editorial advice was essential for the completion of this dissertation. The advices provided by him has helped me a lot in my overall growth as a researcher and helped me to look forward to the future with enthusiasm and confidence in my ability.

My thanks are due to my research committee, particularly to Prof. B. P. Singh, Prof. R. Balasubramanian, and Dr. I. N. Kar for providing me many valuable suggestions that improved the content of this dissertation.

I wish to extend my warmest thanks to Mr. Meharban Singh, Mr. Srichand, Mr. Puran Singh and Mr. Gurucharan Singh for their support in the laboratory and for creating homely working atmosphere in the laboratory during my tenure.

I also would like to express my gratitude to my former lab members Mr. A. R. C. Shkharbabu, Dr. Parag Upadhyay, Mr. Vipul Patel, Mr. Kamal Pandey, Mr. Shashank Tandon for the cooperation, friendly behavior and invaluable help. The cooperation from all the present lab members Mr. Madhan Mohan, Mr. Sanjay Gairola, Mr. Satishbabu, Mr. Sathaiah and Mr. Illamparithi is also greatly appreciated.

I am thankful to the management of Institute of Technology, Nirma University of Science and Technology, Ahmedabad, for sponsoring me to carry out research at IIT Delhi. I am also thankful to Indian Institute of Technology Delhi, Indian National Science

Academy, Council for Scientific and Industrial Research, Department of Science and Technology and All India Council for Technical Education for providing me financial support to attend and present my research work at international conferences.

Additional energy and vitality for this research was provided externally through my involvement in several social activities. For that, I express my thanks to Prof. N. K Jain, Mrs. Veena Jain, Dr. Kiran Momaya, Mrs. Manisha Momaya, Mr. Bhavik, Mr. Sanjay, Mr. Rajesh, Mr. Rajen, Mr. Bhavesh, and their families.

My heartfelt thanks go to my parents and brother, for their love and understanding, the encouragement and the sacrifice they have made during the entire course of my life. Without their overwhelming positive influence on my life, I would not have been able to achieve my goals.

I acknowledge my sincere thanks to my wife and my soul mate Priyanka, whose faith and belief in my capability gave me immense inspiration. She always is being my pillar of strength, patience, inspiration and encouragement. She devoted her valuable youth time in just eagerly waiting for me in days and nights, months and years. I can never forget her dedication and support for my research work.

Lastly, I must thank God for giving me the strength, the patience and the ability to accomplish this work.

Date: 4-6-2007 (Nimit K Sheth)
IIT Delhi, New Delhi 2002REE012

ABSTRACT

Switched reluctance motor (SRM) is a doubly-salient motor usually having concentrated windings on the stator poles. The rotor is made out of soft magnetic material and doesn't have any winding or permanent magnets on it. It has the advantages of rugged construction, high efficiency and tailored torque-speed characteristics. Compared to an induction motor, SRM has higher power density and higher staring torque. The absence of cogging and crawling torques gives the advantage of fast dynamic response for the SRM with respect to the permanent magnet brushless dc (PM BLDC) motor and induction motor. Unipolar drive requirement in the SRM in comparison to the bipolar drive in the PM BLDC motor makes the converter immune to shoot through fault. The drawbacks of this motor are the necessity of a rotor position sensor and presence of large torque ripple. Research is going on worldwide to get rid of these drawbacks by having a sensorless operation and reduced torque ripple either by appropriately designing the tooth geometry or by suitable control methods. Research aimed at improving the performance indices like torque-to-volume, torque-to-power and torque-to-mass ratios is also ON. SRM is considered a good alternative to conventional and PM BLDC motors in the domestic applications like washing machine, vacuum cleaner, electric vehicle, robotics, and also in aerospace and industrial drives. Doubly-salient permanent magnet motor (DSPM) is the latest addition in the category of brushless motors. In a DSPM motor, the magnets are located on the stator, eliminating the problems of demagnetization and also the assembly related issues for high-speed applications. Still, it has the inherent advantages of PM BLDC motors such as high efficiency and power density. Rotor of the DSPM motor is similar to that of an SRM, providing the advantages of simple construction and robustness. A comprehensive literature survey on these motors leads to the opportunities for

developing better design concepts for these motors for achieving compact and efficient designs.

Calculating the outer dimensions based on available standards for the induction motors, accurate estimation of the flux-linkage and inductance characteristics for various rotor positions and excitations, loss calculation based on the actual excitation, and computing the actual torque profile of the motor based on the actual phase excitations are some of the requirements towards better designs of SRM. For the calculation of the average torque of the motor a new concept of best step angle is presented in this thesis. Invariably, in all the literature related to the design of multi-phase SRM, the unaligned and aligned flux-linkage characteristics only are considered in calculating the torque, and thereby assuming that all the torque developed over this half-cycle period of the static torque profile is available as the output torque from the phase. This is not true as the phase excitation generally exists only for a step angle, which happens to be only one-third of one cycle of the static torque profile in case of the 6/4 SRM (which is 30°), and one-fourth of one cycle of the static torque profile in case of the 8/6 SRM (which is 15°). The commutation aspects needing excitation for a little more time to raise or commutate the current need not be misunderstood as the phase excitation for a longer period as these will keep on changing based on the varying speed and torque requirements. To arrive at a situation that the sequential excitations of the phases of the SRM really results in the highest possible average torque having low ripple content for the same phase currents, the phase excitation should ideally start from the rotor position when approaching rotor pole just starts overlapping with the stator pole that is going to be excited.

From the experience obtained after conducting several finite element (FE) analyses of the multi-phase SRM, it is observed that for the calculation of actual flux-linkage characteristics, the rotor position for the half rotor pole pitch – from the fully aligned to fully unaligned - can be divided in to three possible regions viz. (i) fully unaligned to starting of the pole over lap, (ii) partial pole over lap to full pole overlap and (iii) from full pole overlap to fully aligned condition. These three regions are identified in such a way that each one of these can be accurately modeled using a predetermined number of flux tubes, which is decided after analyzing the flux plots of the motor obtained from the FE analysis for all rotor positions and various excitations. Core loss calculated based on the actual waveform of flux in various parts of the motor and the copper loss based on the actual current waveform considering the finite rise and fall time gives more accurate results than the core loss calculated based on the assumption of triangular flux in stator pole and hence gives more accurate estimation of efficiency of the motor.

Putting all these information together, a computer aided design (CAD) program for the design of multi-phase SRM is developed in this work. A GA based optimization technique has been explored for the design optimization of the SRM and a compact motor for the same torque has been obtained. For the constant stator and rotor pole arcs, increase in the number of variables increases the torque/volume of the motor. The designs obtained from the CAD program as well as the GA based optimized ones are verified using the two-dimensional (2-D) FE analyses.

It is observed that the SRM having maximum aligned to unaligned inductance ratio is not always giving the highest developed torque due to the fact that the actual inductance variations in between the fully aligned and unaligned positions also do play a major role in deciding the average and ripple torques. Considering the importance of effect of stator and rotor pole geometry on the torque production of the SRM, an extensive 2-D FE analysis is carried out on a typical 8/6 SRM with various tooth shapes of the stator and rotor. The study shows that for the dovetail kind of the stator or rotor pole, the optimum values of the rotor outer pole arc and the stator inner pole arc in cases of the analyzed motor are 30° and 25° respectively. For this motor, the optimum values of the rotor and stator outer pole arc are 28° and 20.2°, when the pole geometry in both the cases is parallel-sided. Harmonic analysis of static torque for optimum pole arcs shows that the optimum values of the pole arcs will give more average and fundamental torque with reduced ripple and harmonic torques in both the cases. With the increase in the stator or rotor pole arc, the value of the unaligned and aligned inductance increases. Novel pole shapes like the slanted stator pole having flattened pole face and the noncircular stator pole face with varying airgap under a pole for the SRM are also investigated. FE analysis of the motor with such pole geometry shows that the torque developed by both of these poles is higher for the unidirectional operation. For a typical 8/6 SRM considered in this work, for a slant of 5° on the stator pole face, the average torque goes up to 11.84 Nm and for an airgap having a 30% lift on one side, the average torque goes up to 9.88 Nm from the nominal value of 9.41 Nm. But in both the cases, the ripple content in the developed torque goes up.

The analysis conducted to study the effects of airgap nonuniformity on the performance of the multi-phase SRM has revealed that with the increase in concentricity error in the positive direction, the average torque and torque ripple increase. For the positive concentricity error, the motor with the elliptical rotor produces more average torque compared to the motor having error in one half of the rotor, but with higher ripple. The airgap nonuniformity caused by the relative eccentricity between the stator and rotor axes will result in higher fundamental torque and higher average torque in SRM but with higher ripple. The rate of increase in average torque is more for relative eccentricity more

than 25%, but with drastic increase in the ripple content. The airgap nonuniformity changes the static torque characteristics of the different phases of the motor, so an accurate measurement of the static torque characteristics of the motor for all the phases separately must be measured and used in arriving at appropriate logic for the reliable and accurate performance of the motor. Airgap nonuniformity will lead to more noise and vibration.

Being a very promising motor for future robotic and industrial applications where special torque versus rotor position characteristics is required, the DSPM motor also needs careful investigations. In this work, a CAD program for the design of multi-phase DSPM motor has been developed. A new factor for incorporating the effects of the stator poles having different proximity with the permanent magnets is suggested and added in the power equation considered in the CAD program. Two 1 hp, 6/4 DSPM motors - one with a normal rotor and the other with a skewed rotor - are designed using the developed CAD program and the design output data are validated for both the motors using 2-D and 3-D FE analyses.

An extensive FE analysis has been carried out to study the effects of fault in phase winding on the performance of both the doubly salient motors. The analysis revealed that the inter-turn fault reduces the average torque and phase inductance with an increase in the ripple content in both the doubly salient motors. The DSPM motor has an inherent advantage of partial withstand to inter-turn faults. The study on the effect of phase to phase fault indicates that it reduces the average torque and increases the torque ripple in both the motors, but the phase independence makes SRM more immune to such faults. When one of the phases of the 8/6 SRM is open-circuited, then the reduction in the average torque is 25%, while in case of 6/4 DSPM motor it is 66%. The phase independence of SRM makes it more immune to open phase fault.

Some investigations are also carried out on various methods such as skewing of the rotor, appropriate excitation profiles, and tapered rotor poles for the improvement of performance of the multi-phase DSPM motors using 2-D and 3-D FE analyses. The analysis shows that in case of the typical 8/6 DSPM motor, skewing the rotor by 12° to 15° will lead to minimum detent torque and reduced torque ripple without much reduction in the torque capability of the motor and a combination of sinusoidal excitation and rotor skew angle of 12° to 15° will lead to further reduction in the torque ripple and improvement in the torque profile. The results of a 3-D FE analysis carried out on the same motor shows that at all rotor skew angles, the sinusoidal stator excitation with two-phase excitation mode is giving more average torque in comparison to the rectangular current excitation; this is also true for lesser torque ripple if the skew angles less than 24°. This analysis also indicates that rotor skewing reduces the phase flux-linkage and for the skew angle more than half of rotor pole pitch the amount of flux-linkage is very small with negligible variation. Skewing the rotor also reduces the difference between the phase inductance when phase excitation is aiding or opposing the permanent magnet excitation. The 2-D analysis carried out to study the effect of rotor pole tapering shows that the tapered rotor pole gives higher average torque than the parallel sided rotor poles for 8/6 DSPM motor. The maximum average torque in both the cases, occur when the stator inner and the rotor outer pole arcs are same, with the reduced torque ripple for tapered rotor pole. For the analyzed 8/6 DSPM motor, for rotor outer pole arcs of less than the optimum 22°, the tapered case is better; at 15° pole arc, the average torque developed by the motor is 14.8% higher than the corresponding value of parallel-sided case. The analysis also reveals that DSPM motor is immune to the type of restrictions like requirement of larger rotor pole arc compared to the stator pole arc prevalent in SRM for having non-zero torque zones.

CONTENTS