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Advanced Control of Switched Reluctance Motor Drives for Electric Vehicles

Ph.D. Dissertation

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1. Motivation

Electric vehicles (EVs) are the way forward for green transportation and for establishing a low-carbon economy. EVs offer many advantages of no emissions, low maintenance, cost-effective, safety drive, popularity, and reduced noise pollution. However, high reliability is essential for automotive applications since breakdowns on the road are not acceptable. Besides, the limited space and the allowed weight for a vehicle make it more challenging to package its propulsion system. Also, all the EV's parts and components have to be low-cost and suitable for mass-production. These unique requirements and trade-offs in automotive applications pose great challenges for the electrical propulsion system of EVs [1].

The propulsion system of the EV is comprised of a motor, power converter, and controller. For different types of new energy vehicles, the motor and its drive system are the core and common technology. The electrical propulsion system of modern EVs is required to deliver high starting torque, peak torque capability, wide constant power band above base speed, reliable operation, fault-tolerance, low-maintenance, high-efficiency operation in both regions of the low and high speeds, high power density and high torque density, high torque to inertia ratio, small size, low weight, low-cost, low electromagnetic interference, and Low acoustic noise [2].

For the electric motor of an EV, the most important characteristics are to provide flexible drive control, high-efficiency, high-reliability, fault-tolerance, and low acoustic noise. The motor drive must have the capability to handle voltage fluctuations of the source. It also has to produce low electromagnetic interference (EMI). The fault tolerance, reliability, and robustness affect directly the maintenance and related costs. When it comes to mass production, the low production cost is of the greatest importance [1]–[3].

DC machines, induction machines (IMs), permanent magnet synchronous machines (PMSMs), and switched reluctance machines (SRMs) are taken into consideration for EVs. The main drawback of DC machines is the existence of commutators and brushes. They decrease the reliability, require regular maintenance, and limit the maximum speed. Moreover, electromagnetic interference is generated due to the commutation process. In addition, the low power density, low efficiency, increased volume and weight did not qualify the DC machines for electric car propulsion [3]–[5].

Recently the progressive revolution in power electronics and semiconductors allowed the use of IMs in electric power drives. The lack of brushes and commutators made IMs more reliable and maintenance-free. Besides, IMs brought advantages like higher efficiency, higher power density, and, thus, lower volume and weight. However, IMs requires a more complicated control. Moreover, IMs are confronted with low efficiency at light loads, a limited range of operating speed, and extreme heating of the rotor. Furthermore, IMs have difficulty to provide high starting torque with economical sizes of the inverter. Also, they have a problem to achieve a wide constant power range [1].

The lack of rotor winding in PMSMs decreases the machine's losses; makes it more efficient and easier to cool. PMSMs have an increased power density, an increased torque, smaller size, and reduced weight. The permanent magnets (PMs) can be mounted on the surface of the rotor or can be buried in the rotor. By burying the PMs inside the rotor, an additional reluctance torque is inflicted by the saliency that increases the speed range at constant power operation, also the robustness is increased. PMSMs have been credited with the best overall performance Because of their inherently high power density and high efficiency. However, the drawbacks of PMSMs are related to their manufacturing costs since they have PMs with complex structures. Besides, PMs not only expensive but also have limitations on operating temperature (such as NdFeB) or have long-term corrosion problems (such as SmCo). The already high and still increasing price of PMs and the shortage of rare earths are forcing the researchers to come up with alternatives for the PMSM [1], [3].

The simple and robust structure, low cost, less maintenance, high reliability, fault-tolerant, high efficiency, high-speed capability, and large constant power-speed ratio make the SRM a strong candidate with real chances on the market for vehicle propulsion. SRMs do not suffer from the drawbacks noted in DC, IM, and PMSM drives. They offer great robustness of construction. It has none of the mechanical problems at high speeds that beset other drives. Besides, the lack of PMs or rotor winding not only reduces the cost, but also offers increased high-speed operation capability. In addition, The SRM drives have a highly reliable converter topology. The stator windings are connected in series with the switches preventing the shoot-through faults at which the AC rotating field machine's converters are exposed to [2]. Moreover, the low rotor inertia allows high torque per inertia ratio and fast response. Furthermore, the robust rotor construction raises the maximum operating speed and the permissible rotor temperature. Also, SRM has an inherent four-quadrant operation that meets the demands of EVs propulsion. However, the double salient structure causes high nonlinearity in magnetic characteristics that leads to complicated modeling and control. It also produces high torque ripple and acoustic noise which are the main drawbacks of SRMs. Weaknesses of noise and torque ripple can be attenuated by improving the machine design and control strategy [3], [5]–[7].

2. Thesis Objectives

The main objective of the thesis is to develop an efficient, simple, and robust switched reluctance motor drive for electric vehicle applications. To fulfill the main objective, smaller secondary objectives, but all serving the same final goal, can be defined as:

2.1 Accurate Modeling of SRM

A highly trusted model of SRM has to be created. This model should be able to eliminate all the unwanted approximations while obtaining the highly nonlinear characteristics of the machine. It should be capable of providing a realistic and accurate behavior of the machine during transient or steady-state load conditions to implement and compare different control techniques.

A complete drive system has to be designed, built, and integrated on a test bench for testing SRMs for vehicle propulsion. The simulation results can be compared to the measured results and this will allow the validation of the described principles.

2.2 Optimal Control Parameters and MTPA of SRM

For improved system operation, the determination of optimal control parameters such as the optimal turn-on angle, turn-off angle, and reference current have to be created. The optimum control parameters should be determined by simplified mathematical formulations that fit the highly nonlinear characteristics of the machine or using artificial intelligence techniques based on optimization problems.

To assure high torque and power densities with faster torque response, the maximum torque per ampere (MTPA) operation for SRM drives have to be achieved over the entire range of operating speeds.

2.3 Advanced Torque Control Techniques of SRM

Different torque control techniques including instantaneous torque control (ITC) and average torque control (ATC) have to be implemented and compared. For each operating point, the most suited control technique has to be chosen. A cost function can be determined using efficiency, torque ripple, and losses at optimal state searching. Investigation of the drive speed control can be executed after this. Algorithms ensuring fast adaptation and having simultaneously a fairly few calculation requirements can be applied effectively for torque ripple reduction and efficient current and speed control.

2.4 Universal Control of SRM

A universal control technique of SRM drives for EV propulsion should be achieved. It could include one or more torque control techniques. It is supposed to obtain all the benefits of the gathered techniques and achieve all the vehicle requirements. A smooth transition between the chosen combinations of torque control techniques should be achieved simply without any complications for the overall control algorithm.

3. Thesis Outline

Chapter 2 gives the fundamental principles of SRM drives. It obtains the machine configurations, the operational and control principles, the converters topologies, the equivalent circuit modeling of SRM, and the EV model.

Chapter 3 presents an accurate magnetic characterization and model development of SRM drives. First, it gives the finite element method (FEM) based electromagnetic analysis of SRM. Second, it measures experimentally the magnetic characteristics of the tested 8/6 SRM in order to obtain the imperfections introduced by manufacturing processes. The measurement errors are analyzed and post-processed to reduce/cancel them. The accuracy of measurement is verified by FEM, inductance-capacitance-resistance (LCR) meter, and by comparison with the results of an installed search coil on stator poles. Finally, a dynamic model for the tested machine is developed. An analytical model of torque is developed to express the details of torque behavior. A very good agreement is found between the simulated and experimental measured current and torque waveforms which demonstrates measurement accuracy and verifies model dependability.

Chapter 4 introduces a new analytical technique for optimum excitation of SRM drives. The proposed control technique considers accurately the effect of back-emf voltage for high and even low-speed operation. It determines the most efficient turn-on angle and turn-off angles. The proposed technique simplifies SRM control to cut down complexity and cost. It offers easy implementation and can be used for sensor and sensor-less operation. In order to show the feasibility of the proposed control technique, a closed-loop turn-on angle controller is built and a series of results are compared under different operating conditions. Moreover, experimental results are obtained to prove the promising performance and simplicity of the proposed control.

In addition, a multi-objective optimization of SRM control parameters is achieved. It optimizes the motor performance based on its dynamic torque-speed characteristics instead of the common analysis of static torque curves. The aim of the optimization process is to obtain the maximum average torque with the minimum copper losses. Because of the highly nonlinear magnetic characteristics of SRM, the objective function is calculated using the built Simulink model. A searching algorithm is developed for the optimization. It also calculates the base values of the objective function as they vary for each operating point. The optimum control parameters are defined for each operating point. Then, the obtained data are used to train a feed-forward artificial neural network (ANN) in order to implement the control algorithm.

Chapter 5 describes the instantaneous torque control (ITC) for torque ripple reduction of SRM drives. A proposed method is developed to achieve the maximum torque per ampere (MTPA) production based on indirect instantaneous torque control (IITC) using the torque sharing function (TSF) strategy. The TSF is used to distribute the total commanded torque among the motor phases. The reference torque signal is converted into a reference current signal with two proposed methods. The obtained reference current is directly used for optimum control parameters that fulfill MTPA production.

Moreover, an efficient technique is proposed to compensate for SRM torque ripples. The total electromagnetic torque is calculated based on machine modeling and compared to its reference torque signal to estimate torque error. The torque error is compensated through the TSF controller. The TSF compensates for the torque error with the incoming motor phase due to its lower changing rate of flux linkage. In addition, the incoming phase is switched-on at minimum inductance zone leading to a higher capability of current control. The torque error compensation provides a total electromagnetic torque with reduced ripple over an extended-speed range.

Furthermore, a direct instantaneous torque control (DITC) of SRM is developed. It provides both MTPA production and torque ripple compensation. A multi-objective optimization problem is set to obtain the lowest torque ripple, lowest copper losses, and the highest efficiency.

Chapter 6 presents a proposed simple average torque control (SATC) of SRM drives. An optimization problem is developed in order to obtain the lowest torque ripple, lowest copper losses, and the highest efficiency. The optimum control parameters are defined for each operating point.

Chapter 7 presents a universal controller of SRM drives for EV applications. It uses a DITC for low-speed operation and employs a SATC for high-speeds. A smooth transition between DITC and SATC is guaranteed within switching angles optimization while obtaining MTPA.

Chapter 8 involves the conclusions and future works.

4. The Novelty of the Dissertation

The most important new scientific results of the present dissertation can be summarized in six theses as follows:

4.1 Thesis 1

Due to the double saliency and deep magnetic saturation of SRMs, the modeling of SRM becomes a very complicated task,

- I designed, and experimentally implemented a complete SRM drive system that includes the SRM, IGBT power converter, gate drive circuit, current and voltage measuring units, encoder, loading unit, and a digital signal processor (DSP). The drive system is not only used for verification and demonstration purposes but it is also very important for future researches and educational purposes.
- I built an accurate and highly trusted model for the tested 8/6 SRM. The model can include accurately all the machine nonlinearities. Besides, it is capable of obtaining the imperfections introduced by manufacturing processes. The magnetic characteristics have been measured experimentally. The measurement errors have been analyzed and post-processed to reduce them. The measurement accuracy is verified by three different methods (FEA, inductance-capacitance-resistance (LCR) meter, and comparison with results obtained based on an installed search coil on stator poles).

- Moreover, I developed a simple analytical formulation of motor torque in order to be used in a real-time implementation. The measured torque data is analytically fitted using a proposed third-order polynomial. The fitting coefficients are calculated as functions of the rotor position, and then the coefficients are fitted using seven-order polynomials.

  ***This thesis was published in* [J6, B10, and C14].**

4.2 Thesis 2

The operation of SRM depends mainly on the synchronization of phases' excitation along with the inductance pattern. The excitation parameters are of great value for the optimum operation of SRM drives.

- I developed a new analytical technique for optimum excitation of SRM drives. The proposed technique considers accurately the effect of back-emf voltage for high and even low-speed operation. It determines the most efficient turn-on angle as a function of motor speed and current magnitude. Moreover, the optimum turn-off angle is defined to enhance motor output torque/power without negative torque production. The proposed technique simplifies the SRM control in order to cut down the complexity and cost, it offers easy implementation and can be used for sensor and sensor-less operation of SRM drives. It also provides an eligible candidate for industrial applications as the optimization strategy uses an analytical solution. Experimental results are obtained to prove the promising performance and simplicity of the proposed controller. ***This thesis was published in* [J7, C15].**
- In addition, an optimization-based method for SRM control parameters to improve torque production has been developed. The proposed control calculates the most efficient θ_{on} according to torque production and copper losses. Instead of the conventional analysis of static torque curves, a trust dynamic machine model is used to ensure the absolute calculation of optimum θ_{on} over the entire range of operating speeds. The proposed controller improves torque production capability by ***5.3%*** for speeds lower than the rated motor speed. ***This thesis was published in* [J5].**

4.3 Thesis 3

The indirect instantaneous torque control (IITC) has the capability of reducing torque ripples for SRM drives, but it lacks the best torque to current ratio. It is also meant for low-speed operation.

- I developed a maximum torque per ampere (MTPA) scheme based on indirect instantaneous torque control (IITC) for SRM drives. The switching angles are optimized analytically for maximum torque production. The required reference current signal is obtained from torque data by two proposed methods. ***This thesis was published in*** **[C11].**
- Moreover, I developed an IITC with extended-speed and reduced torque ripple capability. An improved TSF that compensates torque ripples of SRM is introduced. Based on the absolute changing-rate of flux linkage, the improved TSF adds torque error to the reference torque signal of the incoming phase. In addition, the proposed controller has a simple construction and easy to implement. ***This thesis was published in*** **[C13, C16].**
- Furthermore, a combined system is developed that provides MTPA and torque ripple compensation. The proposed controller provides high efficiency and high dynamics. The torque ripple is kept minor over the whole speed range. The proposed system always provides MTPA.
- I developed an improved direct instantaneous torque control (DITC) for SRM drives. It provides MTPA production. Moreover, an optimization-based problem is set for the turn-off angle in order to obtain the lowest torque ripple, the lowest copper losses, and the highest efficiency. The proposed system provides simple structure, easy implementation, high dynamics, extended constant power range, and reduced torque ripples. ***This thesis is to be published in*** **[J3].**

4.4 Thesis 4

I constructed a simple structure average torque control (ATC) technique for SRM drives. It has an effective and promising performance for electric vehicles. It has a simple structure that offers easy implementation and lower cost. It has high dynamic performance over a wide range of operating speeds. The torque ripples are kept minor over the entire speed range. The torque ripples are low at low speeds which mean lower vehicle oscillations and noise. The torque ripples are reduced based on the optimization of excitation angles. The optimization is achieved with a multi-objective optimization function that aims to achieve the lowest torque ripple, the lowest copper losses, and the highest efficiency. ***This thesis was published in*** **[J4, C12].**

4.5 Thesis 5

I developed a universal control technique of SRM drives for EVs. It utilizes a DITC for low-speed operation and employs a simple average torque control (SATC) for high speeds. A very smart and smooth transition between DITC and SATC is guaranteed within switching angles optimization while obtaining MTPA. During the optimization process, greater importance is directed to efficiency improvement. ***This thesis is to be published in*** **[J1].**

5. Directions of Further Research

There are several research points around the topic of SRM control that need more investigations. Emerging research problems that come from this research include the following:

5.1 Multi-dimensional Design of SRM

The performance of SRM drives depends not only on control techniques but also in the first step on motor design. For the best overall performance, a Multi-dimensional design of SRM considering the real control parameters and limitations has to be considered.

5.2 PWM Current Control

The hysteresis current control is widely employed for SRM current controllers as it provides a simple implementation. It also fits for the entire speed ranges. But, it has a great disadvantage as it has a variable switching frequency. Hence, it is very important to develop a fixed-frequency PWM current control. It could help in torque ripple reduction and the limitation of switching frequency.

5.3 Analytical Modeling

The main problem that appears in each part of the SRM control algorithm is the highly nonlinear characteristics and their modeling in real-time processors. The accurate model is not only important for the machine analysis bur also for real-time control. Therefore, it is very essential to develop a simple analytical model for SRM to achieve high-performance real-time control.

5.4 Model Predictive Control

Model predictive control (MPC) has been adopted widely for AC motor drives. It is also a good choice for SRM drives as it can predict the best control state. The prediction depends on the machine model which is a complicated task for real-time processors. More effort has to be directed to machine modeling in order to fully use the benefits of MPC.

5.5 Sensor-less-Operation

Sensor-less-operation of SRM is very beneficial for industrial applications as the encoders are very fragile which means lower reliability. Besides, the resolvers are very expensive.

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7. List of Publications by the Author

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[J1] ***Mahmoud Hamouda***, Amir Abdel Menaem, László Számel, “Universal Control of Switched Reluctance Motors for Electric Vehicles", IEEE Access. ***To be Submitted***

[J2] Fahad Al-Amyal, ***Mahmoud Hamouda***, László Számel, “Torque Quality Improvement of Switched Reluctance Motor based Ant Colony Optimization Algorithm", Acta Polytechnica Hungarica. ***To be Submitted***

[J3] ***Mahmoud Hamouda***, Amir Abdel Menaem, László Számel, “An Improved Direct Instantanous Torque Control technique of Switched Reluctance Motors for Electric Vehicles ", Acta Polytechnica Hungarica. ***To be Submitted***

[J4] ***Mahmoud Hamouda***, Amir Abdel Menaem, László Számel, “A Simplified-Structure Reduced-Ripple Average Torque Control of Switched Reluctance Motor for Electric Vehicles", International Transactions on Electrical Energy Systems (ITEES). ***Submitted***

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