PSIM Modelling and Hall Sensors Based Adaptive Control of Switched Reluctance Motor Drive for EV Applications

Muhammad Barkat Saifee, Muhammad Umar Javed, Muhammad Sohaib , Nauman A. Zaffar
Department of Electrical Engineering, Lahore University of Management Sciences (LUMS), Pakistan
Email: {17100217, 17100136, 17100092, nauman.zaffar}@lums.edu.pk

Abstract—SRM is widely used in Electric vehicle applications due to its high starting torque, wide range of variable speed operation and independent phase control. For the work in this paper, we have extended the models in Powersim (PSIM) to include 12/8 Switched Reluctance Motor (SRM) and its drive and have implemented the control parameters with focus on energy efficiency, drive complexity and control characteristics. For enhanced-energy efficiency, regenerative braking is used to recover energy during de-energizing and braking. The hardware implementation has been carried out on a SRM with sensing permanent magnets over the rotor poles for enhanced position accuracy and the drive control has been established on mini6410 using kernel level programming with input from three Hall sensors for complementary positioning and control of phase currents, as shown in block diagram in figure 1. The controller output is used to drive an asymmetric converter to actuate the propulsion operation. Further, the speed tracking and control is done using discrete time PI controller. Our results indicate an efficiency of 88.03% with rise time of 7 sec for 3000 rpm (3200 rpm rated) with steady state error of 0.22%. The drive has been incorporated for EV application in a purpose built structure for the Shell Eco-Marathon Asia Challenge, 2017 to validate the performance of our drive design.

Keywords—SRM, Electric Vehicle, Asymmetric Converter

I. INTRODUCTION

In recent years, the electric vehicles (EV) and hybrid electric vehicles (HEV) have seen a lot of interest due to increased environmental concerns and deliberate shying away from fossil fuels. The move has been supported by advances in electric motors, high power and high performance power electronic converters for efficient control and advances in batteries and energy management [1, 5]. A SRM is a singly-excited motor with salient poles on both the stator and the rotor with windings only on the stator. In a typical SRM, the rotor is constructed from stacked steel laminations and does not have windings or magnets. The torque is produced by the tendency of its rotor to move to a position where the inductance of the excited winding is maximized. During motor operation, each phase is excited when the inductance is increasing (motor profile), and unexcited when the inductance is decreasing (generator profile) as indicated by SRM torque equation (1):

\[ \tau = \frac{1}{2} i^2 \frac{dL}{d\theta} \]  (1)

Where \( L, \theta, i \) indicate inductance, angular position and phase current respectively. The air gap is minimum at the aligned position (the position where a pair of rotor poles is exactly aligned with a stator pole) and the magnetic reluctance of the path of flux is at its lowest; it will be highest at the unaligned position. Thus, when for a given phase the rotor is not aligned with the stator, the rotor will start to move to align with the excited stator pole [2]. Due to this structure, SRM has a high torque ripple and different methods are there in literature to reduce the torque ripple [11-14]. One way to overcome torque ripple is by sequentially switching the current from one phase to the next phase and to synchronize each phase’s excitation as a function of the rotor position [3]. The speed is controlled by a Pulse Width Modulator which tracks the speed for SRM by adjusting the duty cycle according to controller output for speed set point [4]. Another aspect to consider for safe operation is the over-current protection. This is best done by incorporating this requirement within the drive control and can be done by introducing tolerance to hysteresis control logic for duty cycle chopping [4].

<table>
<thead>
<tr>
<th>Propulsion System</th>
<th>DC</th>
<th>IM</th>
<th>Pm</th>
<th>SRM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Density</td>
<td>2.5</td>
<td>3.5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Efficiency</td>
<td>2.5</td>
<td>3.5</td>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td>Controllability</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td>Reliability</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Technology Maturity</td>
<td>5</td>
<td>4.5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Cost</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>22</td>
<td>24</td>
<td>24</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 1: Comparison of different motors
For the mechanical design of the EV, frame was first simulated in Solid Edge ST8 and subsequently constructed with carbon fiber shell and Aluminum frame for the support structure, as shown in figure 2.

II. LITERATURE REVIEW
A typical EV drive train system is made up of three basic components: Electric motor, control elements and power electronic converters [4]. Electric Motor: EV applications can incorporate from a choice of motors. The choice of SRM as a propulsion motor has shown promising results in EV applications over Permanent Magnet Synchronous Motor, Brushless DC Motor and Induction Motor [2, 20, 19], as shown in Table 1.

Controller: Simplified drive controllers lead to torque ripples as in [6] and structural modifications make the problem complex in terms of motor parametric estimation as previously was done in asymmetric rotor SRM drive [7] and high speed drive design [2]. Further, the use of Kalman, extended-Kalman filters and Neural Networks has increased the reaction time of the controller [8-10]. Our proposed drive design utilizes component wise research based on existing literature [1, 10-15] to come up with a controller design to optimize the overall controller’s complexity to performance profile. The resultant proposed SRM controller is adaptive to multiple speed set points with low reaction time as it is based on reduced PWM chopping without using any state space filters [8, 9]. For speed control, we have looked into digital Dead-beat PWM controller [16] and controller with torque sharing function (TSF) [17] to eventually propose a soft switching based discretized PI controller for speed tracking with minimized rise time and negligible steady state error. Moreover, instead of implementing predictive torque control [11], we have selected position based control because of the explicit torque control freedom in terms of current and rotor position [13].

Converter: We compared three converter topologies (R-dump, C-dump and Asymmetric converter) based on phase independence, number of devices, control, fault tolerance and efficiency parameters [2] and selected the Asymmetric converter because of its complete phase independence, simple control and high fault tolerance and efficiency. The circuit design of Asymmetric converter provides maximum phase independence and power handling [1, 15, 18]. In order to further improve the performance of our drive design, we have implemented regenerative braking [10, 14] which recovers energy for charging the battery while braking.

III. DESIGN METHODOLOGY
Simulation for the SRM drive was done on PSIM—subsystems represent the respective Phase Converters, external hall sensors are used with sixteen poles as shown in Figure 3.

A. Switched Reluctance Motor
In PSIM, we have modeled a 12/8 SRM with stator resistance of 1.6958 ohms, inductance range of 428.31 uH to 2.7138 mH and dwell angle of 22.5 to 37.5 degrees. The power and speed rating of SRM is 1.2kW, 60V/20A and 3000 rpm respectively. Unlike SRM block in MATLAB, PSIM does not provide in built Hall Sensors. So, bipolar Hall sensors were externally connected to the SRM for the purpose of simulation

B. Asymmetric Converter
Asymmetric converter consists of two power switches and two diodes per phase. It has two modes of operation, defined as magnetization (phase excitation) and demagnetization (phase de-excitation) [2]. Asymmetric converter has an advantage over other converters that all phases can be controlled independently. If one switch is damaged, the drive can still work with the reduced power level as it uses six independent half-bridge legs with each pair controlling each phase, so it provides maximum fault tolerance capability. In order to select between the most suitable topology, we have simulated asymmetric converter using both three half bridges (single IPM, for low cost applications), and using six half bridges (two IPM devices, more independent

<table>
<thead>
<tr>
<th>Converter Type</th>
<th>Drive Efficiency</th>
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<tbody>
<tr>
<td>Asymmetric Converter (using two IPMS)</td>
<td>88.03 %</td>
</tr>
<tr>
<td>Asymmetric Converter (using single IPM)</td>
<td>81.57%</td>
</tr>
</tbody>
</table>

Table 2: Converter Efficiencies
power handling as shown in Figure 4. However, implementing drive using three half bridges led to current interference in the independent phase operation of an SRM. Owing to which the overall drive efficiency has decreased as shown in Table 2. So, our proposed device topology is implemented by six half bridges (two IPMs).

C. Regenerative Braking

Our system can recapture much of the winding’s energy and can convert it into electricity to charge the battery. We can recharge the battery when the speed of the motor is decreasing or while we apply the brake of the motor using the energy stored inside the motor to increase efficiency [10]. If we excite the particular phase of the motor when the inductance profile of that phase is negative, torque will be negative and the motor will in turn charge the battery [14].

D. Speed Control

Speed control is required to change the speed of EV. For speed control, PI controller (P=5, I=1) is used to minimize the error between the wave. Initially the speed is zero, and hence the duty cycle is closer to one. As soon as the speed of the motor increases, the duty cycle decreases [4]. PI controller is used to stabilize the speed to a referenced speed by changing the duty cycle, as shown in Figure 5.

E. Hysteresis Control Logic

Excess current control is important for motors to protect the motor from in-rush currents. In PSIM Simulation, we have used three current sensors to limit the input current by controlling the duty cycle which in turn controls the PWM as shown in Figure 6.

F. Motor and Control Logic

Based on the different combinations of the hall sensors, respective phases are excited as shown in figure 7. The output currents of respective phases are measured using the current sensor in PSIM, as shown in figure 7. After completing the simulation of an Asymmetric converter with two different topologies, we calculated the total drive efficiency including device non-idealities (internal resistance, capacitance) within our design, as shown in the table below and decided to implement the drive on hardware using two IPMs.

### Table 3: Phase Sequence

<table>
<thead>
<tr>
<th>Sequence</th>
<th>011</th>
<th>010</th>
<th>110</th>
<th>100</th>
<th>101</th>
<th>001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starting Sequence</td>
<td>A</td>
<td>A,B</td>
<td>B</td>
<td>B,C</td>
<td>C</td>
<td>C,A</td>
</tr>
<tr>
<td>Running Sequence</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>C</td>
<td>C</td>
<td>A</td>
</tr>
</tbody>
</table>

IV. HARDWARE IMPLEMENTATION

For the purpose of hardware, the exact positioning of the rotor is determined by permanent magnets mounted on the top of an SRM and 3 unipolar Hall sensors, 120 degrees out of phase as shown in figure 9. If there are Nr rotor poles, there must be Nr pairs of permanent magnets. So, in 12/8 SRM, which consists of 12 stator poles and 8 rotor poles, there must be 8 pairs of permanent magnets – with 8 North Poles and 8 South Poles facing the hall sensors, alternatively. Rotor can be rotated clockwise or anti-clockwise by exciting the respective phases based on six different combinations from three hall sensor outputs, i.e., (011,010,110,100,101,001), one being represented as North Pole and zero being represented as a South Pole. These six different combinations will repeat after every $360° / 8 = 45°$ as shown in figure 10. Therefore, if we know which particular phase is to be excited, for 6 different pair of combination as shown in table 3, to rotate the rotor in any direction, we can excite the same phases every time the sequence repeats itself.
For robust hardware implementation of six half bridges of Asymmetric Converter, we have used Intelligent Power Modules (IPMs) because of higher efficiency, low power losses and good performance. The drive was implemented by implementing the position based current chopping strategy and PI speed controller in mini 6410 at switching frequency of 20 kHz. The mini 6410 then generates a PWM based on the reference speed which in our case of experiment was selected to be 3000 rpm/s. The PWM input then controls the gates of an asymmetric converter in a complementary way to minimize the torque ripple. The overall implemented drive setup is shown in figure 11. The reference speed to be tracked was 3000 rpm. The time between the maximum PWM to approximately zero came out to be 7 sec, which is the tracking time of the controller (reaching the speed set point). Phase windings are excited using different combinations of three hall sensors placed on the top of the motor for the rotor positioning as shown in the figure 12. Figure 13 indicates output current of one phase, measured using a current probe, and is the same current used to excite the respective phase of the motor. Since it is an R-L circuit, the current can grow when the voltage is applied. In order to protect the windings, the current peak is managed through the duty cycle. Each phase current is independent of the other and is electrically 120 degrees out of phase. Furthermore, the energy of the excited winding is being recovered in each cycle by reversing the power flow which is indicated in Figure 14, where voltage becomes negative so as to charge the battery. The SRM is then placed in a cage at the rear side with a gear train (1:7) to the rear wheel. The steering and brakes control the front two wheels. The complete prototype vehicle is shown in figure 15.

V. CONCLUSION

The overall SRM drive efficiency is evaluated to be 88.03 % (with Regenerative Braking) when implemented with mini 6410 by soft switching of reduced PWM chopping at input of Asymmetric Converter. Further, the speed tracking is accomplished by using discrete time PI controller with rise time of 7 sec for 3000 rpm (3200 rated) with steady state error of 0.22%. The design is simple and compact and we have presented the analysis, simulation and hardware implementation results of the basic design. The experimental validation confirms that the results correspond well with the simulation and analysis.

REFERENCES
