Development of the C-dump topology-based four-level converter for switched reluctance motor drives

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Abstract: Demand for brushless and commutator-less motor drives is increasing day by day for industrial applications. So improvement in switched reluctance motor (SRM) drives remains an important research area due to cheap and maintenance free motor construction. In literature, various converter topologies and their control strategies are described, however the C-dump-based converter topologies have gained interest owing to its ability to retrieve the stored magnetic energy. This can be further utilised to achieve desirable performance characteristics. The paper addresses the development of a drive system for a four phase, 8/6 switched reluctance motor. The drive system consists of a power circuit and its control scheme. The power components are designed for a 4-phase, 3 hp, 8/6 SRM which is used to obtain the experimental results. A simple PI-based speed control scheme is implemented which is suitable for low power applications such as cooling fan, blower, etc. A C-dump-based converter is proposed which allows reduction of switching losses, especially in the low speed range and it eliminates energy intake from the source during energy discharge process.

Keywords: switched reluctance motor; SRM; C-dump converter; FEA modelling; four-level converter.


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1 Introduction

The modern era of inexpensive power electronic switches and computer-aided electromagnetic design methods brought out the full-fledged design of switched reluctance motor (SRM) even though its concept can be traced back to 1830s (Miller, 1989). In spite of being relatively new, SRM is now being used for a wide range of applications including general-purpose industrial drives, compressors, domestic appliances, offices and business equipment attributed to its advantages in terms of efficiency, power per unit, weight and volume, robustness and operational flexibility. On the other hand, SRM has disadvantages such as high torque ripple and severe noise issues.

Several power converter topologies have been presented in the literature and still the demand for novel converter topologies prevail. Since the performance of SRM depends much upon the converter topologies, the requirements to be satisfied by the converter used can be summarised as follows (Ellabban and Abu-Rub, 2014):

1. independent operation of each phase should be ensured
2. each phase must be strictly demagnetised before it reaches generating region/motoring region as in case of motor/generator respectively.

Recovery of magnetic energy, augmented voltage supply at higher speeds, provision for phase overlap control, freewheeling option to reduce the switching frequency are
other favourable requirements. The selection of converter depends upon the application, performance, control flexibility, cost, number of phase elements, etc. For low performance applications, low cost converters such as shared switch converters can be used. 2N switch topology, namely asymmetric bridge, affirms enough justification for high power applications due to its control flexibility. Following are the major observations obtained from literature survey.

1. Power converter is the most expensive subsystem in a SRM drive system.
2. Asymmetric converter has the maximum power switch count per phase (two switch per phase) and has the maximum control flexibility compared to its counterparts (Krishnan, 2001).
3. Split dc converter has achieved significant control flexibility though it has single switch per phase. But it is limited to machines with even number of phases.
4. C-dump converter can provide higher power than standard converters with normal stiff dc source (Hava et al., 1992).
5. Variable dc-link (front-end buck/boost/buck-boost) converter use only one switch per phase, allows independent phase control but fails to provide zero voltage across the phase winding.
6. Switching losses are theoretically zero in resonant-based converters but device voltage ratings should be a multiple of the source voltage.
7. The use of converters which provide higher voltage results in better utilisation of SRM than that with standard converters for high speed application (Tomczewski and Wrobel, 2014).

In essence, this paper deals with the development of a converter with fast demagnetisation ability and the implementation of a basic speed control for 3 hp, 4-phase, 8/6 SRM. Section 2 describes modelling of SRM, mainly basic modelling and finite element analysis (FEA) based modelling. Proposed converter and its modelling is depicted in Section 3. The techniques used for the hardware implementation is also narrated.

2 Modelling of SRM

Development of a simple equivalent circuit for SRM is not possible due to its inherent nonlinear nature. The torque constant of the machine depends upon the slope of inductance vs. rotor position. But the inductance itself is a function of both rotor position and phase current, thus making it nonlinear. Comparatively, mutual inductance and dependence of torque on phase currents has less impact on the model performance and hence they are approximated in the basic modelling technique. Finite element-based modelling is a time consuming process and is deployed with finite element data analysis, which can be done with software packages like Ansys-Maxwell. In this section, basic modelling and FEA-based modelling is considered.

2.1 Basic modelling

Basic modelling of SRM can be done based on the following equations (1), (2), (9) and (4) (Ke Rdtauad and Ki Tiratsatcha, 2004).

\[ V_a = I_a \cdot R_a + \frac{d\psi_a(i_a, \theta_a)}{dt} \]
\[ \psi_a(i_a, \theta_a) = i_a \cdot L_a(i_a, \theta_a) \]
\[ T_a = \frac{1}{2} \cdot \frac{i_a^2}{L_a(i_a, \theta_a)} \]
\[ T_e - T_L = J \frac{d\omega}{dt} + B\omega \]

Here, \( V_a \) is the phase voltage, \( i_a \) is the phase current, \( R_a \) is the phase resistance, \( \psi_a(i_a, \theta_a) \) is the flux linked with the phase in terms of phase current and rotor position, \( L_a(i_a, \theta_a) \) is the phase inductance in terms of phase current and rotor position, \( \theta_a \) is the rotor position \( \omega \) is the rotor speed, \( J \) is the moment of inertia and \( B \) is the viscous coefficient of friction.

In order to model phase inductance effect of both rotor position (\( \theta \)) and current (\( i \)) should be considered. Basic modelling considers phase inductance as a function of rotor position alone. Phase inductance for every two degree of rotor position over 60 degree span is plotted in Figure 2 as obtained from experiment (Zhang et al., 2010). The inductance profile period (\( \alpha_r \)) of the machine is found to be 60 degree \( (\alpha_r = \frac{2\pi}{\text{no. of rotor poles}}) \) for an 8/6 configuration and hence inductance profile is repeated for every 60 degrees. Figure 1 shows the basic block diagram for the realisation of one phase of SRM.
Electrical torque of the machine per phase can be easily modelled using the following assumptions

\[ T_e = F_1(\theta) \cdot i_2^2 \]

where function \( F_1(\theta) \) depends upon the inductance profile and can be written as (Soares and Branco, 2001):

1. if \( \theta \) lies on \(+ve\) \( \frac{dL}{d\theta} \) region; \( F_1(\theta) = S \)

2. if \( \theta \) lies on \(-ve\) \( \frac{dL}{d\theta} \) region; \( F_1(\theta) = -S \)

3. if \( \theta \) lies on \( 0 \) \( \frac{dL}{d\theta} \) region; \( F_1(\theta) = 0 \).

where ‘\( S \)’ is a constant which is given by equation

\[ S = \frac{1}{2} \times \frac{L_u - L_m}{\theta_2 - \theta_1} \]  

\[ (5) \]

2.2 Finite element-based modelling

FEA is a numerical method, which solves boundary value problems especially partial differential equations. In electrical engineering, FEA can be useful for evaluating flux, inductance, capacitance, magnetic field intensity and losses in electrical machines. The following assumptions are necessary for further steps:

- the vector field outside the object is negligible
- the triangle shaped finite elements are used to form the meshes
- field distributions inside the object is invariant along with the axial directions
- magnetic vector potential \( A \) and current density \( J \) are defined only in the \( Z \) direction.

A custom SRM as per Table 1 is analysed using magneto-static tool in ANSYS-MAXWELL-14. Geometry of the machine is defined with its material properties. Major steps in FEA includes assigning excitations to the coils, torque, inductance, etc. (Ohyama et al., 2006). After obtaining various results, data is exported to MATLAB environment for drive simulation purpose.

Table 1: Details of the SRM

<table>
<thead>
<tr>
<th>Switched reluctance motor specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
</tr>
<tr>
<td>No. of phase</td>
</tr>
<tr>
<td>Configuration</td>
</tr>
<tr>
<td>Speed</td>
</tr>
<tr>
<td>Unaligned inductance</td>
</tr>
<tr>
<td>Aligned inductance</td>
</tr>
<tr>
<td>Maximum current</td>
</tr>
<tr>
<td>Stator resistance</td>
</tr>
<tr>
<td>Friction</td>
</tr>
<tr>
<td>Inertia</td>
</tr>
</tbody>
</table>

Figure 3: Two dimensional SRM FEA model with mesh formation (see online version for colours)

Figure 4: Flux linkage-rotor angle-phase current (FEA result) (see online version for colours)

Figure 5: Torque-rotor angle-phase current (FEA result) (see online version for colours)
3 Proposed c-dump-based converter

The proposed power converter is a modification of the paper ‘Improved C-dump converter for SRM drives’, by Tomczewski and Wrobel (2014). The consecutive phases are arranged as two different groups so that reduction in the number switches is achieved. The same technique can be extended to any number phases to reduce the number of switches without performance deterioration. The proposed configuration has $N + 2$ switches, $N + 2$ diodes and an energy recovery capacitor. It works almost similar to the asymmetric bridge converter except that it has an additional capacitor for energy recovery purpose. The capacitor allows retrieval of magnetic energy stored in the phase windings and thus enables faster demagnetisation of the windings as in C-dump converter. But the control flexibility is not much curtailed as in the case of C-dump converters and even more, has an additional capability of extended voltage supply. The analysis of the converter is as shown below.

3.1 Modes of operation

Figure 6 shows the basic converter diagram. $A_1$, $A_2$, $B_1$ and $B_2$ are the phase windings of the machine. The capacitor is connected in series with the voltage supply $V_{dc}$, $N + 2$ number of semiconductor switches and $N + 2$ number of diodes are also part of the configuration. The voltage stored in the capacitor must be low as it is directly connected in series with voltage source and may adversely affect insulation of the machine.

Figure 7 shows different modes of operation. In mode 1, phase winding is energised by voltage source through the diode and the corresponding phase switch. At low speed operation, ‘turning on’ and ‘turning off’ in phase switch takes place in accordance with signal from current regulating strategies such as hysteresis or PWM. In mode 2, two power switches are ‘turned on’ so as to obtain the extended voltage supply from the capacitor-voltage source series connection. This mode enables the smooth operation under high speed as extended voltage makes fast development of the phase current. In mode 3, magnetic energy in the phase windings are transferred into the capacitor through the free-wheeling diode. The fast demagnetisation is achieved during this mode. In mode 4, zero voltage across the phase winding is achieved by short circuiting the phase winding by an upper phase switch and free-wheeling diode. Extended voltage supply capability, fast demagnetisation time, ability of energy recovery and zero voltage operating point are the main advantages of this converter.

Figure 6 Proposed C-dump-based converter

Figure 7 Modes of operation, (a) mode 1 (b) mode 2 (c) mode 3 (d) mode 4
### 3.2 Control strategy

Even though the proposed converter can provide extended voltage supply, the machine performance depends much upon the proper selection of ‘turn on’ and ‘turn off’ angle (Lee and Ahh, 2007). Energisation of stator coil results in a pull in the rotor and it starts rotating. When the rotor crosses the stator pole arc, torque is generated in the rotor in a direction opposite to the earlier case. This results in vibration and acoustic noise in the machine. Thus, commutation of the phase current before the negative $\frac{dL}{d\theta}$ is necessary. The upper two switch are operated to facilitate the simultaneous demagnetisation and augmented voltage operation. So, demagnetisation before $\frac{dL}{d\theta}$ region is negative and the extended voltage supply at the starting of each phase is ensured. The implementation of soft switching is much complex and is not required for low power applications (Lin et al., 2012). High performance system requires adaptive speed and current control strategies (Bayoumi et al., 2009).

### 4 Simulation results

A custom SRM is modelled in the MATLAB/Simulink environment based on the data obtained from FEA analysis. Details of SRM is shown in Table 1. The electromagnetic torque characteristics (Figure 9) and capacitor voltage waveform (Figure 8) are plotted for a basic speed control loop. The main advantages of the series connection of C-dump capacitor with voltage sources include reduction in the phase demagnetisation time and fast development of phase currents at high speed operation, which have already been proved in literature (Tomczewski and Wrobel, 2014). The reduction in no. of switches and its effect on the capacitor charging and discharging is studied here. Figures 8 and 9 undoubtedly proves operational feasibility of reduction in no. of converter switches without sacrifice in operational flexibility. Continuous capacitor charging and discharging cycles, constant steady state voltage and its low ripple content at steady state even with incorporation of techniques such as advance angle and phase overlap indicates the operation flexibility of the proposed converter.

![Figure 8](image-url) **Figure 8** Charging and discharging of the capacitor (see online version for colours)

![Figure 9](image-url) **Figure 9** Electromagnetic torque characteristics (see online version for colours)

Note: With advanced firing angle and phase overlapping.
5 Hardware implementation

This section describes hardware implementation of this project along with its control strategies. The proposed converter is designed for the custom SRM of rating: 3 hp, 4 phase, 8/6. The proposed converter has two upper switches and four lower switches. IGBTs are selected due to its high power handling capability at low frequency. FR3 (flame retardant) PCB class is used for the converter circuit and gate driver circuit. Number 14 SWG copper wire is used as an additional connection material in the power converter circuit. ENC58/IEP58-S10-programmable type incremental encoder and hall sensor-based absolute position sensor provision is used with the SRM. Fixed position-based speed calculators technique is more suitable rather than fixed time-based speed calculators for low speed applications (Texas Instruments, 2000). Feedback from the absolute position sensor can be used to calculate the speed during low speed operation. It is proven that incremental encoders are better for high speed calculations. Position sensor, Incremental encoder and ADCs are supplied from the Altium Nano board 3000. Level shifter is used which converts 5 V output of FPGA to 15 V supply. But it does not provide isolation between power level and signal level. Thus an additional power provision is required. An additional fly back converter circuit is used for that purpose. An uncontrolled diode rectifier is used as a front end converter. In order suppress the harmonic introduction at supply side, active rectifiers can be utilised (Hamed et al., 2015).

![Figure 10](image)

Front side view of proposed converter-prototype (see online version for colours)

6 Conclusions

SRM modelling requires much attention than other electrical machines due to its inherent nonlinear characteristics. The basic modelling method does not account on the effect of phase current on flux linkage. A two dimensional FEA-based model of the custom SRM is deployed for the magneto static analysis to obtain torque-rotor angle-phase current and flux linkage-rotor angle-phase current characteristics. Prototype of the converter is developed and it is found to be economical due to reduced number of Power switches and diodes. A simple closed speed control loop is implemented using FPGA (Spartan – XC3S1400AN-4FGG676C). The proposed converter can be developed for low power – high speed applications such as cooling fan, blowers etc.

References


