Design and comparative evaluation of converter topologies for six-phase switched reluctance motor drives

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Abstract: This paper presents a novel converter topology for six-phase switched reluctance motor (SRM) drives, which reduces the number of switches and diodes by half, compared with the conventional asymmetric half-bridge (AHB) converter, and needs no additional energy storage component. A dynamic model of a six-phase SRM is developed in the MATLAB/SIMULINK environment and conventional control technique is applied to the proposed converter, demonstrating successful operation with modified conventional current control technique, lower converter losses, and higher system efficiency compared with the AHB converter. Furthermore, a direct torque control (DTC) method has been proposed for the novel converter to further reduce the torque ripple. Experimental tests comparing the proposed converter with the AHB are described and verify the predictions of the simulations.

1 Introduction

Switched reluctance machines (SRMs) and their drive systems have the advantages of simple structure, low manufacturing cost, high system reliability, high efficiency, and a wide speed range, and are contenders for electric vehicle traction drives [1–3]. In recent years, they have also been developed for the aviation industry [4, 5].

However, torque development in SRMs is fundamentally prone to high ripple giving rise to vibration and acoustic noise, and this characteristic is a significant drawback [6]. The reduction of torque ripple is an active research topic and improvement strategies include machine design optimisation [7–9] and advanced control techniques [10–12].

In the wake of power electronics development, increasing the phase number is a simple and generally accepted way to reduce torque ripple. In the last two decades, machines with higher phase numbers have been considered due to their potential for lower torque ripple, less phase current for a given power rating, and better fault-tolerant ability compared with traditional machines [13, 14].

Although the continued development of power electronic devices offers some support for higher phase numbers, the cost and volume of the converter, and the number of connections to the SRM, all increase with phase number. Therefore, despite the benefit to torque production, the development of SRM converters has tended towards fewer switches, fewer energy storage devices, fewer connections between the SRM and converter, and increased efficiency.

Many potential converters exist for SRMs [15], including the asymmetric half-bridge (AHB) converter, the H-bridge converter, the capacitive type converter, the magnetic type converter, and the dissipative converter among others. The AHB converter is most commonly employed, exhibiting excellent phase independence at the expense of a large number of power electronic devices, requiring two switches and two diodes per phase [16]. Of the alternatives, the H-bridge, bifilar, and dissipative converters each reduce the number of switches by half, but each has consequent drawbacks and limitations. The H-bridge converter is only suitable for four or multiples of four-phase machines [17]; the bifilar converter employs an extra inductance for each phase, which increases the converter cost and volume [18]; the dissipative converter employs extra resistance to absorb the energy stored in the phase winding, giving rise to reduced efficiency and limited scope of application [19].

A method for driving a six-phase SRM from a three-phase inverter has recently been proposed [20]; an unconventional winding scheme was investigated in this context, and the resulting drive demonstrated low torque ripple and high torque density, in addition to a number of substantial benefits arising from the use of a standard converter. In particular, it was shown how additional steering diodes rectified the sinusoidal, three-phase supply to a six-phase unipolar group suitable for a six-phase SRM. However, current control is somewhat decoupled from the machine in this configuration and conventional SRM control cannot be directly implemented.

This paper develops the advantages of the six-phase SRM, proposing a ring converter topology which facilitates the application of conventional control techniques with some adjustments. A dynamic control model for this proposed drive has been simulated in MATLAB/SIMULINK, and the results are presented here. On this basis, a direct torque control (DTC) method has been proposed for the ring converter to further reduce the torque ripple. Experimental investigation and validation of the proposed drives is presented through a range of tests on a dedicated 4.0 kW prototype SRM.

2 Six-phase SRM and its converters

2.1 Conventional converter

It is well understood that increasing the number of phases reduces torque ripple. Thus, a six-phase 12/10 SRM is proposed in Fig. 1. Table 1 gives the design parameters for this machine.

The AHB converters are the most popular choice for SRM drives because they give independent control of each phase. Fig. 2 shows a six-phase AHB power inverter. Note that this requires 12 controlled switches and 12 diodes – double that of a standard six pulse, three-phase AC drive – adding complexity and cost.

2.2 Proposed converter

In order to develop the advantages of the six-phase SRM, the ideal converter has the following features:

i. Minimal number of switches;
ii. Minimal number of diodes;
iii. Minimal connections between the motor and converter;
iv. No additional energy storage element;
v. Conventional control techniques are applicable.
None of the above candidates are fully compliant and so a new converter configuration is proposed here. Fig. 3 shows a novel converter for a six-phase SRM. This converter combines many of the advantages of the candidates described in Section 2, requiring only one diode, switch, and power connection per phase having no additional energy storage element, and facilitating some form of conventional SRM current control. Compared to the full-bridge converter in [20], diodes placed in series with each phase are no longer required. Since the six-phase windings are connected in a ring, this arrangement is subsequently named a 'ring converter'.

### 3 Control method

#### 3.1 Modified conventional control method

Since each phase are controlled by two switches, the positive, zero, or negative voltage can be applied to any group of phases, there are some restrictions with regard to the voltages applied to two adjacent phases. If, for example, positive voltage is applied to phase A, then Phase B must also have positive or zero volts applied: the converter topology does not permit application of positive voltage to one phase and negative voltage to the adjacent phase. The above restrictions give rise to phase interactions and so the application of conventional control strategies requires some adaptation.

Fig. 4 illustrates the control diagram of the six-phase ring converter using a modified current control method. In the diagram, the first two steps are similar to that of a conventional converter.

**Step 1:** compare the phase current with the current reference value to get the current hysteresis control result.

**Step 2:** combine the current hysteresis control result with the firing angles to achieve the single-phase switching signals.

**Step 3:** is further designed in order to obtain the final switching signals $G_{AB}$ to $G_{FA}$. In order to guarantee enough magnetisation energy, the switching signals $G_{AB}$ to $G_{FA}$ for the six switches in the ring converter are the logical OR operation results of every adjacent two single-phase switching signals.

where $G_A$ to $G_F$ are single-phase switching signals for phases A to F. Hence, if there is a positive demand for either phase A or phase B, then $G_{AB}$ is high and switch $S_{AB}$ is on.

#### 3.2 Direct torque control method

Fig. 5 shows the control diagram of the DTC method for six-phase SRMs, in which control parameters are instantaneous torque and stator flux linkage.

The main distinction between the six-phase AHB converter and the proposed converter is phase independence; therefore, the voltage vectors and switching table of the DTC method for the AHB converter [21] cannot be directly applied to the ring converter. For the proposed converter, every switch is shared by two phases. It is obvious that there are always two phases in...
freewheeling loops; therefore, it is impossible to define an equivalent voltage vector with three adjacent phases on and other phases off. Consequently, there are six reasonable voltage vectors that can be employed with the proposed converter. Table 2 demonstrates the six voltage vectors for the proposed converter.

\[
\begin{align*}
\psi_\alpha &= (\psi_1 + \psi_2 - \psi_4 - \psi_5)\cos 30^\circ \\
\psi_\beta &= (-\psi_1 + \psi_2 + \psi_4 - \psi_5)\sin 30^\circ + \psi_3 - \psi_6 \\
\psi_s &= \sqrt{\psi_\alpha^2 + \psi_\beta^2} \\
\delta &= \arctan \left(\frac{\psi_\beta}{\psi_\alpha}\right)
\end{align*}
\]

Table 2 voltage vectors for the ring converter

<table>
<thead>
<tr>
<th>Vector</th>
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<tbody>
<tr>
<td>V1(+1, +1, +1, −1, −1, +1)</td>
</tr>
<tr>
<td>V2(−1, +1, +1, +1, −1, −1)</td>
</tr>
<tr>
<td>V3(−1, −1, +1, +1, +1, −1)</td>
</tr>
<tr>
<td>V4(−1, −1, −1, +1, +1, +1)</td>
</tr>
<tr>
<td>V5(+1, −1, −1, −1, +1, +1)</td>
</tr>
<tr>
<td>V6(+1, +1, −1, −1, −1, +1)</td>
</tr>
</tbody>
</table>

In order to locate the stator flux, the vector space is segmented into six zones as shown in Fig. 6, every zone occupies 60°. The stator flux definition is similar to the AHB converter. The amplitude and position of the stator flux vector are calculated by (1)–(4). Stator flux vector and voltage vectors also fulfill the relationships in [21].

Considering demands of the stator flux and torque simultaneously, Table 3 shows the switching rule for the proposed converter. If torque and flux are to rise, the voltage vector can be selected in one zone ahead. To increase stator flux while instantaneous torque is to fall, the voltage vector can be chosen in one zone behind. To increase torque and decrease flux, the voltage should be chosen in two zones ahead. If torque and flux are to fall, the voltage vector should be selected in two zones behind.

### 4 Simulations

Dynamic simulation models of a six-phase SRM prototype are developed in MATLAB/SIMULINK environment to conduct simulations with the proposed circle converter and the traditional AHB converter. The models use the parameters of a 12/10 conventional SRM prototype, whose electromagnetic properties are shown in Fig. 7.

To analyse the performance of the converters under conventional control technique, the AHB converter and the proposed ring converter are controlled by the current chopping control (CCC) method at 200 rpm. Phase reference current is 15 A, hysteresis band width is ±0.5 A, conduction width is 160° and DC-link voltage is 200 V. Simulation results are shown in Figs. 8 and 9. Due to less phase independence, phase current has some distortions, but it does not affect the torque ripple reduction performance.

### 5 Experimental validation

In order to test the proposed converters and compare them with a conventional AHB converter, a test rig is constructed. Twelve fast switching IGBT modules are employed and mounted on the top of an air cooling heat sink as shown in Fig. 11. Through different
connections it can be constructed to the six-phase AHB converter or the ring converter.

Figs. 12–15 show six-phase current waveforms of the AHB converter and the ring converter under CCC and DTC method. All the waveforms are comparable to the simulation results.

When the SRM runs at high speed, the converter is simply controlled by the angle position control (APC). Table 4 compares torque ripple and system efficiency of two different converters at 1500 r/min. The ring converter has lower torque ripple and higher efficiency under current control due to less switch and diode losses.

By using the DTC method, two converters have very similar torque ripple, while the ring has higher efficiency.

6 Conclusions

This paper compares a novel converter topology with a conventional AHB converter for a six-phase SRM drive. The novel converter does not need additional energy storage elements, requires only six switches and six power connections, and facilitates a modified version of standard SRM control.

Conventional methods and the DTC method are successfully modified and applied to the novel converter. The ring converter has
lower converter loss, fewer devices, and higher system efficiency under conventional method and the DTC method, and is, therefore, an attractive proposition for this application.

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8 References