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A Novel SRM Converter Topology with Double Demagnetization Voltage and Minimum Components

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Abstract

Currently, switched reluctance machines (SRMs) have attracted the attention of the research community for electric vehicle (EV) applications due to their good performance at high speeds. This paper presents a new converter that doubles the negative demagnetization voltage for EV applications, so that, the provided converter is capable of reducing demagnetization time considerably with a new strategy. This method reduces the current commutation time and improves the average torque of the motor. Compared to the previous converters with the ability to increase the demagnetization voltage, the mentioned method significantly improves the efficiency of the motor at all speeds. This is due to the use of minimal electronic devices in the proposed topology. The mentioned method significantly increases the average torque and efficiency in the motor at all speeds, compared to the conventional asymmetric converter, due to the lack of additional electronic devices. This topology is very suitable for EV applications with multi-module battery structures. All operating modes of the proposed converter and simulation results will be described. As can be seen from the simulation results, the proposed converter improved efficiency and output torque significantly.

Keywords: Demagnetization voltage, output torque, switched reluctance motor, converter, electric vehicle.

Introduction

Recently, because of their simple structure, high power density, and low manufacturing cost, SRMs are a strong candidate for EVs [1]. Reducing the commutation period becomes more critical at high speeds as this keeps the phase current at its nominal value for most of the phase energization period to produce the required load torque[2]. Therefore, the overall performance of the SRM drive system is highly affected by the power converter topologies. Asymmetrical half-bridge topology (AHB) is one of the earliest-used converters [3]. AHB has a simple structure, but it cannot increase the demagnetization voltage to more than the DC link voltage. Therefore, the commutation time of the current between the phases increases and leads to an increase in the torque ripple and a decrease in the average output torque. In EV applications, increasing the demagnetization time shows its adverse effect more at high speeds [4]. Hereupon so far, several topologies have been presented to increase the demagnetization voltage, and all works have their own advantages and disadvantages.

For example, in [1]-[2], a multi-level converter for EV applications has been introduced, which has a significant number of devices. This has increased the volume and complexity of control in the SRM drive. A new three-phase SRM drive with minimal electronic devices for EV is presented in [3],[4]. However, fast demagnetization is not possible and due to the non-isolated phases in the converter circuit, it does not have the ability to withstand the fault. In hybrid vehicle applications, multi-module battery structures are used to manage battery energy. In [5], a front-end circuit developed as a cascade converter with the ability to increase the excitation voltage and demagnetization is presented. In this structure, three battery modules are used with the approach of separating the charging and discharging of batteries, which is mostly used for hybrid vehicles. However, a lot of electronics devices are used, which increases the size and cost of the drive. In [8], the Flexible C-dump converter is introduced for high-speed applications with minimal electronic devices. But the Flexible C-dump converter is a three-level converter and produces only a double demagnetization voltage, which causes drastic $\frac{dv}{dt}$ changes in the SRM wiring. In [9], a converter with the ability to increase the demagnetization voltage has been introduced. But its disadvantage is applying excitation voltage $\frac{V_{dc}}{2}$ to SRM phases. To compensate for this defect, an external converter is used, which will reduce the efficiency of the SR drive.

In the articles presented so far, the most important thing to consider is the use of additional electronic devices in the SRM converter in order to increase the demagnetization voltage, which leads to an increase in volume, cost and power loss in the drive. For this purpose, in this paper, a new converter for SRM drive is proposed for use in EVs. The proposed topology is a 4-level converter that has a simple structure, no additional electronics (equal to AHB), and no complexity in converter control. Another feature of the proposed converter is the use of battery modularization system, which can be useful in multi-module structures to manage battery energy. Another advantage of the proposed converter is its performance as an AHB converter. This can only be achieved by changing the switching method.

The proposed converter is designed based on a 4-phase SRM while the demagnetization voltage rises up to twice the dc-link voltage. Moreover, the reduction of electronic elements in order to increase demagnetization voltage

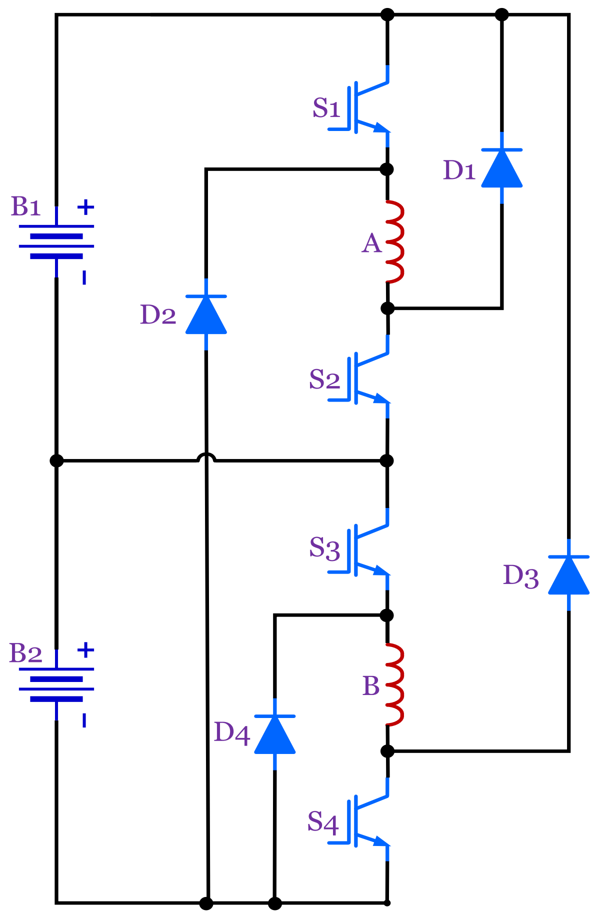

Figure 1. Proposed converter

results in efficiency increasing at all speeds of the proposed converter in comparison to the previous converters.

In this paper, first all of the mode operations of the proposed converter are presented and analyzed. Demagnetization times, efficiency, and output torque between the proposed converter and AHB converter are compared. The simulation results, verify the higher performance of the proposed converter than AHB converter.

Proposed Drive System

"Figure 1" shows the proposed converter for EV application. According to figure 1, in the proposed converter, the DC link voltage is composed of two battery modules separately, each of which is responsible for supplying the power of two phases of the motor. With this approach, the demagnetization voltage can be increased up to twice the DC link voltage without using additional electronic devices.

Principle of Operation of the Proposed Converter

The proposed converter is based on two main states:

- Performance of the proposed converter to increase the demagnetization voltage.
- The proposed converter operation is the same as the AHB converter.

Each stage is consist of different modes of operation. In order to better understand the proposed converter operation, the operating modes are classified into 8 modes each of these modes is described.

Performance of the proposed converter to increase the demagnetization voltage

In this stage, the operation of the proposed converter in six modes is described. So that the demagnetization voltage is increased up to twice the DC link voltage, and as a result, it will reduce the commutation time of current between phases in SRM. Improving current commutation will increases the average torque in SRM. "Figure 2" shows the operation modes of the proposed converter in this state.

Mode 1: Phase-A Magnetizations

When S1 and S2 are turned on, battery-link voltage Vb1 is applied to phase-A winding, and due to applying the rated voltage, the phase current will quickly increase to the current reference value. "Figure 2(a)" shows the excitation mode of phase-A.

Mode 2: Phase-A Freewheeling

"Figure 2(b)" presents the freewheeling mode at the proposed converter. The freewheeling mode is implemented by applying zero voltage on phase-A. When switch S1 is turned on and switch S2 is turned off, can regulate the phase current with soft chopping. The main advantage of soft chopping is to reduce switching frequency and switching losses. In this mode, the phase freewheeling current flows in the switch S1 and diode D1.

Mode 3: Phase-A Fast Demagnetization

When S1 and S2 are turned off, high demagnetization voltage is applied to phase-A winding. The fast demagnetization mode of the converter operation is presented in "Figure 2(c)". The energy discharge circuit consists of phase-A winding, diodes D1 and D2, and Voltage of batteries ($V_{B1} + V_{B2}$). By doing this, the -2Vb voltage is applied to the wiring of phase-A and it will cause a rapid decrease in current.

Mode 4: Phase-B Magnetization

When S3 and S4 are turned on, battery-link voltage Vb2 is applied to phase-B winding, and the current will be increased to reach its reference value. "Figure 2(d)" shows the excitation mode of phase-B.

It should be noted that the phase excitation mode and the demagnetization mode for the other phase can be performed simultaneously and there will be no limitation in the phase current overlapping.

Mode 5: Phase-B Freewheeling

According to "Figure 2(e)", when S3 is turned off and S4 is on, the Freewheeling current in phase-B will flow through S4 and D4. In this mode, the voltage of phase-B wiring is zero.

Mode 6: Phase-B Fast Demagnetization

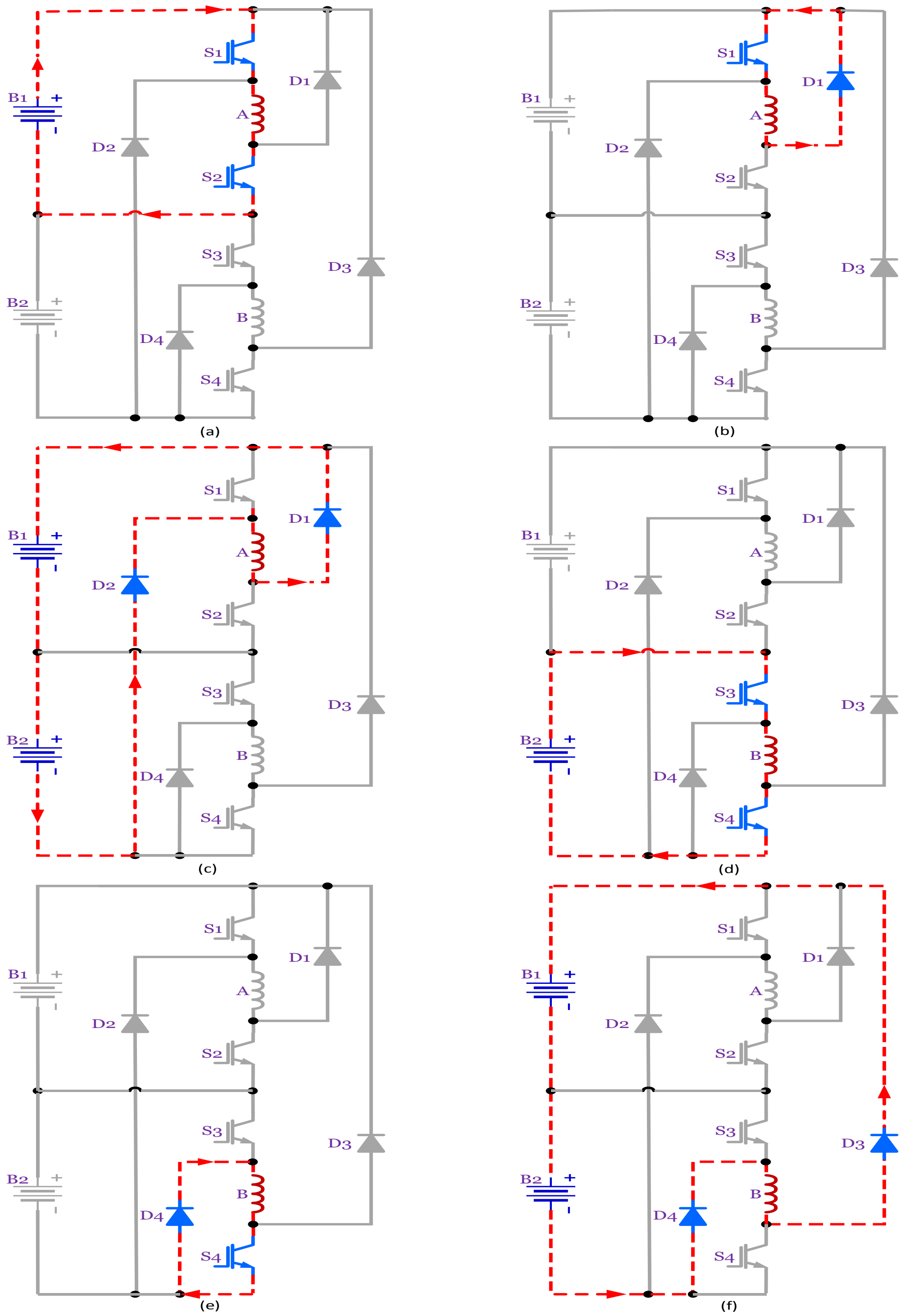

Figure 2. Operating modes of the proposed converter to increase the demagnetization voltage. (a) Phase-A Magnetization. (b) Phase-A Freewheeling. (c) Phase-A Fast Demagnetization. (d) Phase-B Magnetization. (e) Phase-B Freewheeling. (f) Phase-B Fast Demagnetization.

When S3 and S4 are turned off, demagnetization voltage which is the sum of Vb1 and Vb2, is applied to phase-B winding. In this mode, fast demagnetization current flows in the diodes D3 and D4. "Figure 2(f)" shows the fast demagnetization mode of phase-B.

The Proposed Converter Operation as an AHB Converter

One of the advantages of proposed converter is that can work as an AHB converter. This work can be implemented only by changing the switching mode of the converter. Also, the performance as an AHB converter has been done with minimal electronic devices, which will make the efficiency of the proposed converter not different compared to AHB.

"Figure 3" shows the operation modes of the proposed converter as an AHB converter. To better understand the performance of the proposed converter, they are classified into two operating modes, each of which is described.

Mode 7: Phase-A Demagnetization

When S1 is turned off and S2 is turned on, the

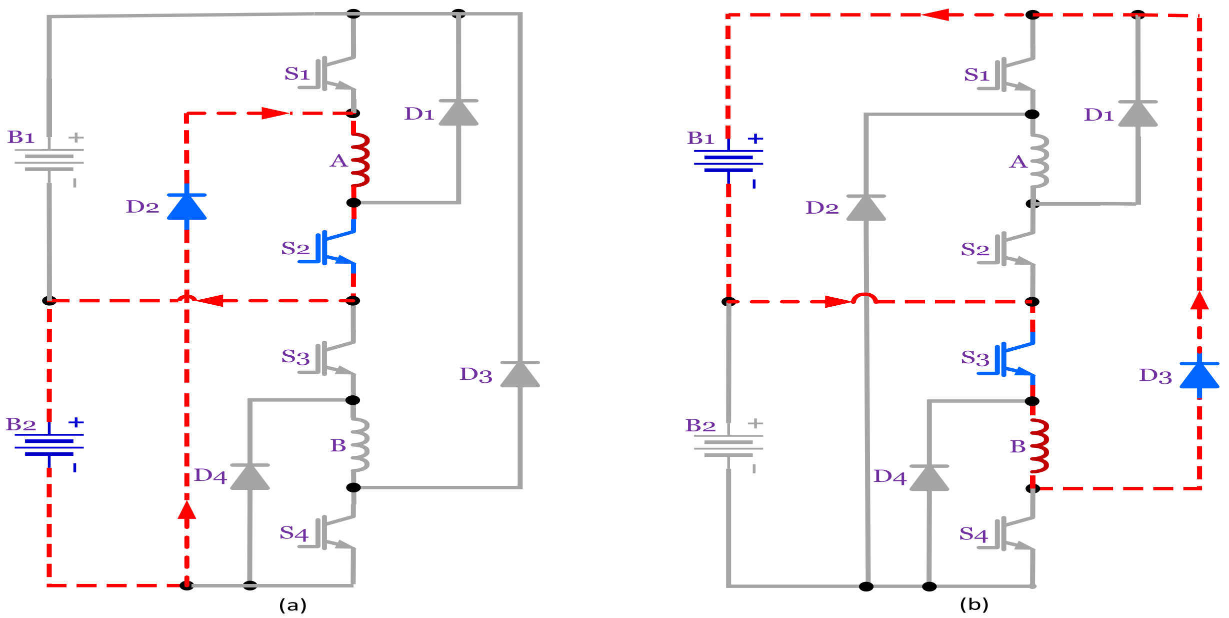

Figure 3. Operating modes of the Proposed Converter as a AHB Converter. (a) Phase-A Demagnetization. (b) Phase-B Demagnetization.

demagnetization voltage applied to phase-A winding is battery voltage –Vb2. Therefore, the demagnetization voltage is equal to the battery-link voltage. In this mode, demagnetization current flows in switch S2 and diode D2. "Figure 3(a)" shows the demagnetization mode of phase-A.

Mode 8: Phase-B Demagnetization

"Figure 3(b)" presents the demagnetization mode phase-B at the proposed converter. When S4 is turned off and S3 is turned on, the demagnetization voltage applied to phase-B winding is battery voltage –Vb1. In this mode, demagnetization current flows in switch S3 and diode D3.

Simulation Results

In this section, the detailed simulation test results in the proposed converter and AHB converter are presented. To verify the proposed converter SRM drive system, a computer simulation is performed. The SRM model is developed based on analysis for a 4kW SRM and four-phase 8/6 SRM prototype. The drive system simulation included a Non-ideal model of the converter and a nonlinear model of the SRM with current and torque Lookup Tables, and MATLAB/SIMULINK software is used for modeling the whole system.

This is a simulated SRM, the battery-link voltage is set to 270V. "Figure 4" shows the compared simulation results for the proposed converter and the AHB converter at the same on and off angles, a reference speed of 1000 rpm, and a load torque of 11 N.m.

According to Figure 4, increasing the demagnetization voltage in the proposed converter compared to the AHB converter can reduce the commutation time of current between phases. Therefore, reducing the commutation

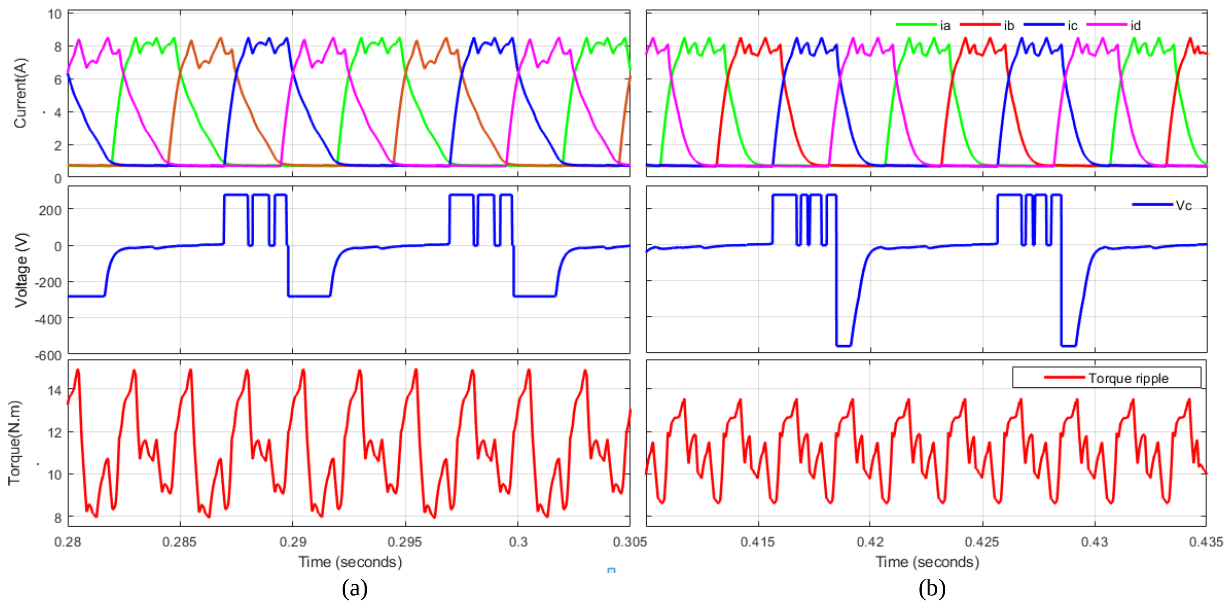

Figure 4. Compared simulation results. (a) AHB converter. (b) Proposed converter.

time of current between phases leads to a decrease in the torque ripple and an increase in the average output torque.

The torque-speed characteristic of the proposed converter and the AHB converter are presented in "Figure 5". As expected, the output torque is higher in the proposed converter. According to Figure 5, the maximum output torques of the two converters are the same at low speeds. But in high-speed operation, the output torque is mainly improved by the reduction in torque ripple under high demagnetization voltage for the proposed converter. Therefore, the proposed converter has better performance at high speeds. Due to the increased demagnetization voltage, the output torque of the proposed converter is improved by more than 20% higher than the AHB converter.

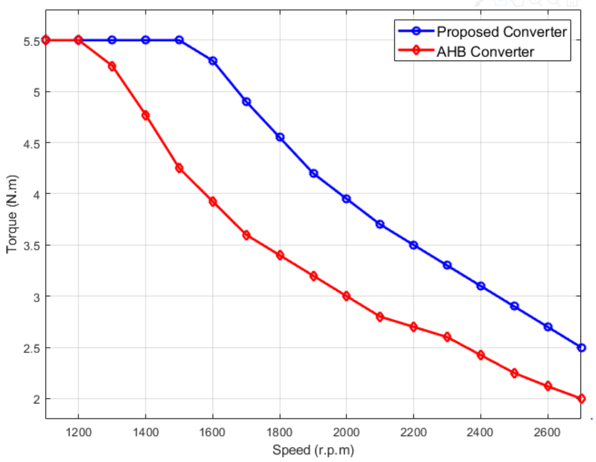

Figure 5. Torque–speed characteristic.

"Figure 6" shows the efficiency comparison between the proposed converter and the AHB converter. At low speeds, the efficiency of the proposed converter is slightly higher than the AHB converter. The efficiency is better in high-speed operation due to the negative torque reduction. However, the simulation results show an improvement of SRM efficiency for the proposed converter.

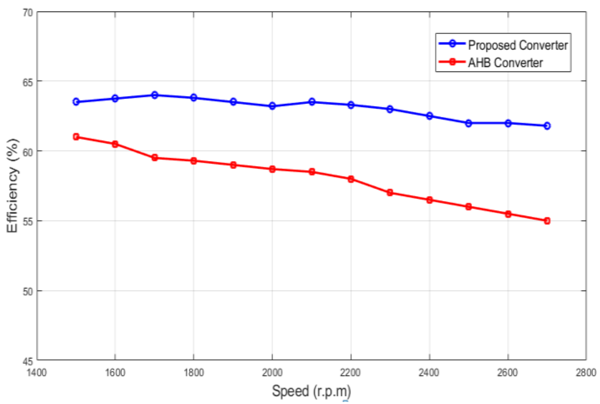

Figure 6. Efficiency–speed characteristic.

It can also be concluded that the efficiency of the proposed converter has been improved compared to the previously proposed converters with the approach of increasing the demagnetization voltage. This is due to the reduction of electronic devices in the proposed converter.

Conclusions

In this paper, a novel 4-level converter is designed for EV application based a 4-phase SRM while the demagnetization voltage rises to twice the dc-link voltage.

The proposed converter and its performance were analyzed and the whole system was simulated. As can be seen from the results, with the increase of the demagnetization voltage, the SRM output torque ripple is reduced and as a result, the average output torque increases by more than 20%. The efficiency of the proposed converter has increased compared to the AHB converter and previous converters with the approach of increasing the demagnetization voltage, due to the use of the least electronic devices. The proposed converter, due to its simple structure, has a smaller volume, no complexity in control, and lower cost compared to previous converters. The whole system was simulated with Matlab/Simulink software.

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