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CASCADED MULTIPORT CONVERTER FOR SRM-BASED HYBRID ELECTRICAL VEHICLE APPLICATIONS

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Abstract

This thesis presents a novel cascaded multiport switching reluctance motor (SRM) drive designed for hybrid electric vehicles (HEVs) in this master thesis. The capacity of this technique to adeptly handle energy conversion between the generator/ac grid, battery reserves, and the motor is what makes it special. Aside from that, it provides a strong battery management (BM) system that successfully monitors SOC balance and orchestrates bus voltage regulation. A critical component of our design is the seamless integration of the battery packs and the AHB converter. This not only makes it easier to create cascaded BM modules, but it also prepares the stage for SRM drive-specific multilevel bus voltage and current capacity adjustments. This configuration improves the excitation and demagnetization phases of commutation, broadens the speed spectrum, reduces voltage stresses on switching components, and improves torque capability and overall efficiency. Here tailored the system to meet a variety of operational demands by including alternative driving patterns, regenerative braking systems, and charging techniques into the proposed converter. Our BM strategy's ability to manually link or unlink each battery pack from the power supply is an exciting feature. This one-of-a-kind feature considerably improves the system's fault-tolerance and easily avoids any overcharging or over draining problems during motor activity. Empirical experiments using a three-phase 12/8 SRM confirmed the feasibility and efficacy of our proposed cascaded multiport SRM drive.

Keywords: Cascaded Multiport Converter, Battery Management (BM), State-of-Charge (SOC) Balance, Switched Reluctance Motor (SRM), and Hybrid Electric Vehicles (HEVs) are some of the terms used in this paper.

I. INTRODUCTION

The rise in environmental concerns, as well as the imminent issue of dwindling fossil resources, has pushed electric cars (EVs) and hybrid electric vehicles (HEVs) to the forefront of automotive debate. They are praised for their reduced reliance on fossil fuels and outstanding energy efficiency [1–4]. Permanent magnet synchronous motors (PMSMs) have long been the foundation of EV and HEV

powertrains, owing to their high torque and power densities [5–7].
Nonetheless, the increasing scarcity and high cost of rare-earth magnets has shifted attention to motors that do not rely on these materials [8], [9]. Among these, switching reluctance motors (SRMs) are gaining popularity. Their attractiveness stems from their simple design, low cost, exceptional durability, and appropriateness for harsh settings [10]-[13]. Numerous voltage-boosting converters have been included into SRM systems to improve their performance across a wider speed range. To promote rapid current excitation and demagnetization operations, certain converters such as a four-level and a quasi-three-level have been introduced [14], [15]. Other techniques try to balance supply currents, reduce voltage ripples, or improve system efficiency [16–18]. Some sophisticated systems even emphasize enhancing motor performance at high speeds or including efficient battery charging processes [19].
While several converters have been devised to maximize motor performance and suit various driving and charging modes, tackling battery management (BM) in SRM-integrated EVs and HEVs remains a major challenge. In real-world circumstances, state-of-charge (SOC) discrepancies caused by manufacturing differences and wear over time can result in overcharging, overdraining, or catastrophic battery cell degradation. These concerns have the potential to jeopardize the entire battery bank [25-27]. As a result, a BM system that prioritizes energy efficiency and reliability is required for optimal energy conversion in EVs and HEVs [28]. More research is being conducted to create changeable voltage levels.

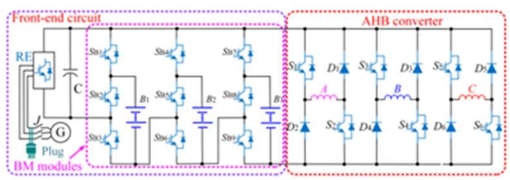


Fig. 1. Proposed cascaded multiport converter for a three-phase SRM.

Figure 1 depicts a proposed cascaded multiport converter expressly intended for a three-phase Switched Reluctance Motor (SRM). The converter system is divided into two major parts: the "Front-end circuit" and the "AHB converter."

II. PROPOSED CASCADED MULTIPORT SRM DRIVE FOR HEV APPLICATIONS

A. Proposed Converter Topology

One of the most difficult difficulties in the field of Hybrid Electric Vehicles (HEVs) is obtaining effective energy transfer. This difficulty is exacerbated by the many sources and destinations of this energy, most notably the generator/ac grid, the SRM, and the battery bank. In light of this, my master's thesis proposes a sophisticated multiport converter that has been specifically created to meet these requirements. Figure 1 shows a graphic illustration of this.
Relay J is at the heart of this system. This isn't just ordinary relay; it connects the generator and the rectifier, serving as a linchpin for the entire system. Furthermore, a specialized socket facilitates connectivity with the larger AC grid, assuring compatibility and simplicity of access.
The incorporation of three painstakingly developed Battery Management (BM) modules is a notable aspect of this system. These aren't just add-ons; they're essential for monitoring the functional descriptions and general health of the battery operations. When you look at the arrangement, you can see that the generator/ac plug, ac/dc rectifier, BM modules, and the AHB converter are all connected

in series. This layout allows the converter to be viewed as a hybrid of a front-end circuit and an AHB converter.

B. Driving Modes

The Switched Reluctance Motor (SRM) has several operating modes, each distinguished by the complex connection between phase current and phase inductance. This connection is seen in Fig. 2(a). In this diagram, denotes the rotor position angle, whereas on and off denote the turn-on and turn-off angles, respectively. Furthermore, ik and Lk represent the kth phase current and phase inductance, respectively.

When studying the SRM's properties, it becomes clear that the phase winding must be active during the area when positive torque is created. This relates to the stretch when phase inductance increases. Fig. 2(b) displays the three-phase currents, highlighting the signals from phase A during its driving modes to offer a clearer perspective. The switching signals, represented by S1 and S2, are critical to understanding this.

A deeper look into phase A's conduction range indicates that it may be divided into five separate regions:

Region I: Both phases C and A are operational
and running concurrently in this initial phase.

Transition begins in Region II, with phase C turning off. The result of this adjustment is a progressive decrease in its current.

Region III is distinguished by the full cessation of phase C current, with only phase A remaining in the active conduction state.

Region IV: A joint conduction is taking place here, combining both phases A and B.

Region V: At this point, phase A is shut off, signaling the end of its conduction range.

These locations emphasize the SRM's operating intricacies in various driving modes, demonstrating its versatility and diverse functionalities.

I. Region:

This initial area contains both phases A and B, which can be in either the excitation or freewheeling states. This adaptability in both phases' operating states results in four unique conduction modes for the AHB converter.

2nd Region:

Phase C is entirely restricted to the demagnetization state in this location. Meanwhile, phase A maintains its adaptability, alternating between excitation and freewheeling states. When phase A is stimulated while phase C is demagnetizing, an intriguing interaction occurs: if the current in phase C exceeds that of phase A, the energy from phase C not only drives phase A but is also diverted to the battery packs.

3. Zone III:

This area is distinguished by single conduction of phase A, which can be either excitation or freewheeling. No other phase is involved in any operations in this region.

Regions IV and V:

These two areas' behaviours parallel those of areas I and II. Region IV, in particular, duplicates the modalities found in Region I, whereas Region V mirrors the operational subtleties seen in Region II.

3) Driving Modes by the Battery Packs

When relay J is turned off, the Switched Reluctance Motor (SRM) operates in pure-battery mode. Controlling the switches in the Battery Modules (BM) determines the various voltage levels detected in the front-end circuit. Figure 5 depicts these arrangements.

1. No Switch Is in Use (Fig. 5(a)):

None of the switches in the front-end circuit are active in this setup. As a result, the three battery packs are effectively linked in parallel. To guarantee unidirectional current flow, each of these packs is accompanied with a diode. A battery pack's State Of Charge (SOC) is directly proportional to its voltage. As a result, the battery pack with the greatest SOC (and consequently voltage) will automatically conduct and power the motor. The diodes in their respective circuits prevent the remaining packs from conducting.

2. Switch SB5 activation (Fig. 5(b)):

Switch SB5 enables the serial connection of battery packs B1 and B2, therefore activating the motor.

3. Switch SB8 activation (Fig. 5(c)):

When switch SB8 is activated, battery pack B3 connects in series with whichever of the remaining packs has the higher SOC. The motor is then powered by this combined energy source.

4. Switches SB5 and SB8 are both turned on (Fig. 5(d)):

When both SB5 and SB8 are engaged, all three battery modules form a series connection, directing their energy to drive the motor collectively.

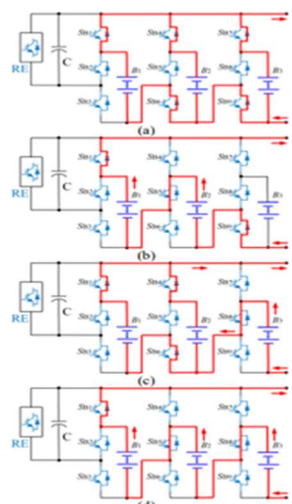


Fig. 5. Working conditions of the front-end circuit by the battery packs. (a) Mode 1. (b) Mode 2. (c) Mode 3. (d) Mode 4.

Figure 5 depicts the various operational states of the front-end circuit as dictated by the battery packs. This breakdown demonstrates the system's versatility and adaptability, since it is capable of handling a variety of operational modes.

(a) Mode 1:

The first mode is depicted in the schematic in subfigure (a). The circuit diagram shows energy mostly coming from the source labeled "RE," being routed through the capacitor "C" and a series of switches from Sb1k to Sb4k. The arrows indicate the direction of current flow, and specialized switches are activated in this mode to assist this particular pattern of energy distribution.

(c) Mode 2:

The second mode is depicted in subfigure (b). While the underlying structure stays similar, the switch locations show distinct variances, affecting the energy route. This one-of-a-kind setup exhibits a distinct energy distribution pattern customized to specific operating needs.

(c) Mode 3:

Another different energy flow pattern is visible in the third mode, represented in subfigure (c). The changes in switch locations from the previous modes result in this alternate pathway, showing the system's adaptability to changing energy demands.

(d) Mode 4:

Mode 4 is seen in subfigure (d). This energy flow concept is unique due to switch placement and engagement. Like its predecessors, this mode adapts to operational situations, showing the system's versatility.

Energy flow is buffered by capacitor "C" in all modes. These sets show how the system effortlessly switches modes to optimize energy allocation.

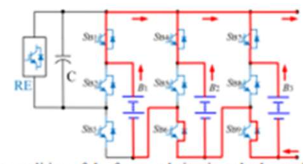


Fig. 6. Working condition of the front-end circuit under heavy load or uphill condition.

Figure 6 shows how the vehicle handles hills and high loads. The picture emphasises switches to demonstrate the system's proactive response to challenges.

System adaptability is essential for large power increases. In such cases, battery pack parallel connection is essential. Through parallel construction, battery packs can improve currents.

Switches SB1, SB4, and SB7 demonstrate this. The three battery packs synchronize when these switches are activated. Combining resources boosts battery current.

Torque is greatly increased by this setup. Vehicle torque makes heavy chores and steep climbs easy. Strategic resource allocation and alignment help the vehicle exceed demanding operational conditions.

. Fig. 6 shows the vehicle's system layout, particularly the front-end circuit, under heavy loads or mountainous terrain. It shows the system's flexibility by reconfiguring to meet certain needs.

When the car needs a lot of electricity, the system must react. This adaptability depends on battery pack layout. Under heavy demand, the battery packs can be coupled in parallel to maximize production, as illustrated in the diagram.

The switch activation pattern shows this. SB1, SB4, and SB7 swaps matter. These switches connect the three battery packs, making them work together. This synchronization allows battery packs to share resources, boosting current.

This parallel arrangement boosts torque significantly. This increased torque ensures the car can handle demanding tasks or climb hills without stalling. Due to its planned arrangement, the vehicle is sturdy and ready for any challenge.Understanding a vehicle's driving modes is essential for energy management. We find surprising parallelism between generator-powered and pure-battery driving modes, particularly in the AHB converter's conduction modes.

AHB converter behavior is consistent across modes. Pure-battery driving mode conduction patterns are comparable to generator-powered driving. This consistency enables for smooth mode changes, providing optimal vehicle performance.

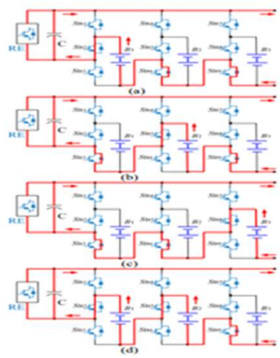
Long-term vehicle systems require energy conservation and feedback. The mechanism recycles phase winding energy to the front-end circuit. This energy feedback mechanism matches Fig. 4(b). This recycles energy back into the system, improving vehicle efficiency and sustainability.

4) Driving Modes by the Generator and Battery Packs

In vehicles, the motor may need generator and battery power. This combined power source allows more robust and motor-specific energy flow. Fig. 7 shows how to combine seven operating modes to achieve this setup. Turning on relay J and tweaking front-end circuit switches activates these settings.

This system's versatility is remarkable. The generator can be used with one, two, or all battery packs, depending on system power needs and availability. This strategy optimizes power generation and resources.

Allowing a combination of power sources ensures the Switched Reluctance Motor (SRM) receives a continuous and efficient power supply. This adaptability ensures that the SRM functions best in various circumstances, enhancing vehicle performance and dependability.



Mode (a): The generator and one battery pack (B1) supply electricity. The active switches control energy flow, suggesting power management flexibility.

Mode (b): The generator and two battery packs (B1 and B2) power the system. This may be useful for higher energy output.

Mode (c): This generator-only arrangement is unique. This may be the case when the batteries are low.

Mode (d): The generator and two battery packs (B1 and B3) power the system. Another type that adapts power delivery to battery condition or demand.

These modes show that the front-end circuit adapts power management and distribution to changing conditions and requirements, optimising energy use and possibly boosting system efficiency and lifetime.

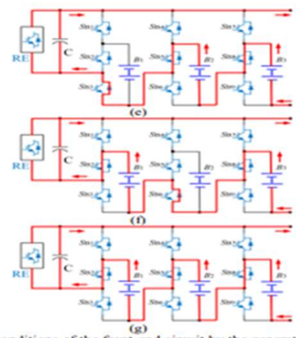


Fig. 7 Working conditions of the front-end circuit by the generator and battery packs. (a) Mode 1. (b) Mode 2. (c) Mode 3. (d) Mode 4. (e) Mode 5. (f) Mode 6. (g) Mode 7.

Figure 7 displays the various working situations of the front-end circuit when the system is powered by both the generator and the battery packs. From Mode 1 to Mode 7, each configuration displays a distinct combination of active switches, reflecting several ways the system can work to maximize energy flow from the generator and battery packs to the motor

1. Only the generator:

J Conducted Switch

Voltage Levels: Ua

This simply implies that when the generator is the sole thing running, the switch "J" is switched on and the system outputs voltage "Ua."

2. Only Battery Packs:

When only one battery pack is in use:

S8s, S5s, or S2s are the available switches.

Voltage values are as follows: Ua/U3, Ua/U2, and Ua/U1.

For all operational battery packs:

S8s, S5s, and S2s are the switches.

Voltage values are as follows: (U1 + U2 + U3)/3

For the use of two battery packs:

J and S2s or J and S5s as switches

Voltage values are as follows: Ua/U1 or Ua/U2.

This implies that each switch corresponds to separate battery packs, and combinations result in a total of their voltage levels or an average when all of them are active.

3. Combined Generator and Battery Packs:

For one battery pack and one generator:

J and S8s, or J and S5s, or J and S2s

Voltage values are as follows: Ua + U3, Ua + U2, and Ua + U1.

The following are the specifications for the generator and two battery packs:

J, S2s, and S5s, or J, S5s, and S8s, or J, S2s, and S8s.

Voltage values are as follows: Ua + U1 + U2 or Ua + U2 + U3 or Ua + U1 + U3.

For all battery packs and the generator:

J, S2s, S5s, and S8s are the switches.

Ua + U1 + U2 + U3 Voltage Values

This section describes the switch combinations that must be activated when running the generator with one, two, or all three battery packs.

this table clearly maps the various power supply setups, the accompanying conducted switches, and the resulting voltage values. This facilitates understanding of the various configurations and their results, assisting in system operation and diagnostics.

The voltages of the generator, UB1, UB2, and UB3 are represented by UG, UB1, UB2, and UB3, respectively.

Relay J: This is crucial in deciding whether or not the generator is included into the circuit. If relay J is turned on, the generator is included in the setup.

Switches for selecting a battery pack:

SB2: This refers to battery pack B1.

SB5: This refers to battery pack B2.

SB8: This refers to battery pack B3.

When any of these switches is activated, it indicates that the relevant battery pack has been selected to be active in the circuit.

Switches for Parallel Configuration:

SB1, SB4, and SB7: These are utilized when the three battery packs must be connected in parallel, which is commonly done to provide a larger torque capability.

Other Switches: The other switches in the system are not manipulated manually. They can only conduct passively via their anti-parallel diodes. This implies that these switches provide a protective or regulated role, ensuring that power flows in the intended direction while preventing potential backflow or undesirable circuit behavior.

Understanding these characteristics clarifies how the power supply configuration may be changed using the system's switches and relays. The table provides a fast reference for how to configure the switches for desired settings, and the accompanying explanation provides context for each component's role.

B. Regenerative Braking Modes

Instead of losing energy as heat, a vehicle or system's braking energy is converted into electrical energy and stored in the battery. This method boosts system efficiency.

Figure 8(a): Phase Inductance/Current In regenerative braking mode, this figure shows phase current and phase inductance waveforms. The decreasing phase inductance zone generates braking-aiding negative torque.

Drive Signals (Figure 8(b)): Phase currents and driving signals are shown in this diagram. Initial phase:

The excitation state generates the initial current in Region i. Figures 4(a), 5, 6, and 7 show how to choose a driving mode. Current starts flowing in the motor coil at this point.

The technology uses freewheeling and demagnetization after stimulation. Phases create negative torque for braking. This energy is returned to the battery packs, converting kinetic energy into electrical energy.

Energy Regeneration: As indicated in Fig. 4(b), braking energy is converted and delivered back to the front-end battery packs.

In essence, the SRM not only drives the system but also plays an important part in energy regeneration during braking, resulting in more effective energy use.

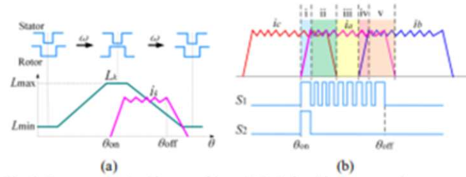


Fig. 8. Regenerative braking condition. (a) Relationship between phase current and phase inductance. (b) Phase currents and drive signals.

Stator and Rotor: The upper section of the figure depicts two rotor locations (numbered 1 and 2) in relation to the stator.

The pink waveform labeled "Lx" reflects the SRM's phase inductance as a function of rotor position. As the rotor revolves, the inductance fluctuates, moving between a maximum (Lmax) when the stator and rotor poles are aligned and a minimum (Lmin) when they are misaligned.

on and off: The angles at which the current is switched on and off are shown by these two markers. This is the time when the phase is actively aroused and deactivated.

Figure 8(b) - Drive signals and phase currents:

ic Curve: The multicolored waveform labeled "ic" depicts the SRM's phase current with time. It contains several peaks, each of which corresponds to a distinct phase of the motor. The distinct intervals of the present waveform are highlighted by the regions (i to v). As previously mentioned in the book, these zones correspond to distinct operating stages of the SRM during regenerative braking.

S1 and S2 Curves: These two waveforms reflect the phase drive signals. The driving signals govern when current can flow in each phase. When S1 or S2 is high (or active), the associated phase is activated; when they are low (or inactive), the phase is deactivated. In these waveforms, the points labeled on and off correspond to when the driving signal activates and deactivates the current, respectively.

Fig. 8 depicts the SRM's operational characteristics under regenerative braking situations. During this mode of operation, it stresses the interaction between phase inductance, phase current, and the driving signals. The SRM creates negative torque during regenerative braking by using regions of decreasing phase inductance, and the accompanying energy is stored in the battery packs.

The explanation digs into the varied conduction modes of the AHB converter in five locations during the regenerative braking mode of an SRM (Switched Reluctance Motor). Let's go over these conduction modes in detail for each region:

D. Charging Modes

Mechanisms of Charging:

When relay J is turned on, the generator becomes the principal source of electricity.

AC Grid: Power is drawn from the AC grid if relay J is disengaged and an AC plug is attached to it.

The Charging Procedure:

The procedure is divided into two major steps:

Step 1 - Phase Windings Activation:

The AHB converter's switches are all turned on.

All switches in the front-end circuit are turned off.

This enables the three-phase windings to be powered by the rectifier's direct current voltage.

AHB Converter Conduction Mode: See Fig. 9(a).

Figure 4(a) shows the working condition of the front-end circuit.
Step 2 - Battery Pack Charging:
The AHB converter's switches are all turned off.
The stored energy in the three-phase windings is used to charge the battery packs.
AHB Converter Conduction Mode: See Fig. 9(b).
Check Fig. 10 for the charging states of the front-end circuit.
when the motor is at rest, it can permit charging of the battery packs in two independent periods. The three-phase windings are first activated, and the energy stored in these windings is then used to charge the battery packs. The diagrams provided might help you see the conduction modes and states of the circuits involved.

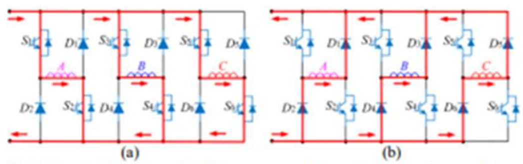


Fig. 9. Conduction states of AHB converter under standstill charging condition. (a) Conduction state 1. (b) Conduction state 2.

Conduction State 1 (Fig. 9a): In this state, the switches 1, 2,SL1,SL2, and 3SL3 are turned on, allowing current to flow through them. At the same time, the diodes,DA,DB, and DC are in their conducting state, as indicated by the direction of the current arrows. This indicates that energy is being channeled into the phase windings.
Conduction State 2 (Fig. 9b): Here, 1,2,SL1,SL2, and 3SL3 are turned off, blocking the flow of current through these switches. The diodes ,DA,DB, and DC remain in their conducting state. This represents the scenario where energy stored in the phase windings is directed towards charging the battery packs.
The transitions between these two conduction states dictate the charging process. In State 1, the phase windings are charged up, and in State 2, the accumulated energy is utilized to charge the battery packs. The clear distinction between these states provides a mechanism to manage the flow of energy efficiently, ensuring optimal charging of the battery packs while the motor is at a standstill.
The described battery charging configuration offers a robust and flexible framework for managing the energy needs of three separate battery packs: B1, B2, and B3. Specific switches, namely, SB3, SB6, and SB9, are activated to determine which battery or combination of batteries are charged. For instance, activating switches SB6 and SB9 charges the B1 battery, while turning on SB3 and SB9 charges the B2 battery. The system even accommodates simultaneous charging scenarios, such as having all three battery modules charged when no specific switches are activated. Furthermore, the charging source can be chosen based on the status of relay J; when engaged, power is drawn from the generator, but when disengaged and connected to the AC grid, the grid supplies the energy. Notably, switches,SB1,SB4, and SB7 are consistently deactivated, ensuring they don't unintentionally interfere with the charging process. Lastly, the system is safeguarded by allowing certain switches to conduct only when their corresponding anti-parallel diodes are triggered, enhancing the circuit's safety and functionality.

III.CONTROL STRATEGIES OF THE PROPOSED CONVERTER

Control Strategy under Driving Modes

There are two basic control schemes in the Switched Reluctance Motor (SRM) drive system: current chopping control (CCC) and voltage-PWM control (VPC). These techniques are critical for controlling how the motor performs under various settings.

The SRM control system block diagram, shown in Fig. 11, provides an organized perspective of this system. The position encoder, which is critical for determining the rotor's location, is an important component. This information is critical for both commutation control, which guarantees that the phases of the motor are triggered in the correct order, and determining the motor's speed.

A Proportional-Integral (PI) controller is used to govern speed in a feedback loop. This controller regulates the motor's activity to maintain a desired speed, correcting for any differences between the goal and real speeds.

This system also has a control mode switch. Its job is to choose between the two control tactics indicated above based on the speed reference. The selected control method, in particular, impacts how the motor is driven.

The control techniques are chosen based on the actual speed of the motor in what is known as the "driving mode." When the motor is running at low speeds, the CCC method is favoured. The VPC method, on the other hand, is better suited for greater speeds. This is not a random selection; the various methods have intrinsic traits that make them more appropriate for their respective speed ranges.

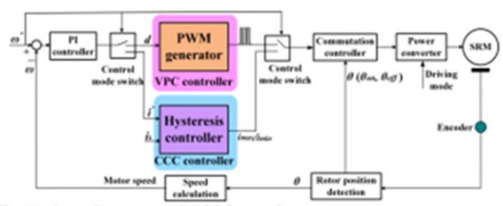


Fig. 11. Control strategy under driving modes.

The diagram presented in Fig. 11 illustrates the control strategy for driving modes in a Switched Reluctance Motor (SRM) system.

At the core of the control strategy is the choice between two primary controllers, based on driving conditions: the VPC (Voltage-PWM Control) controller and the CCC (Current Chopping Control) controller.

- PI Controller: The Proportional-Integral (PI) controller works by adjusting the motor's operation to maintain a set speed, considering any deviations from the target speed.
- Control Mode Switch: This switch determines which of the main control strategies (VPC or CCC) is employed. The decision is influenced by the speed reference and the motor's actual speed.
- VPC Controller and PWM Generator: When the VPC mode is selected, it utilizes Pulse Width Modulation (PWM) to control the voltage applied to the motor. This strategy is typically used for higher-speed operations.
- CCC Controller and Hysteresis Controller: In contrast, the CCC strategy is active during lower speeds. The hysteresis controller, a part of the CCC strategy, adjusts the current by turning the power switches on and off to ensure it doesn't exceed a specific threshold.
- Motor Speed Calculation and Rotor Position Detection: The encoder plays a crucial role in determining the rotor's position, essential for commutation control. Additionally, it aids in computing the motor's current speed.

- Commutation Controller: Once the rotor position is detected, the commutation controller takes over to ensure that the motor's phases are activated in the correct sequence.
- Power Converter and SRM: The power converter manages the energy flow to the SRM based on the chosen control strategy and the instructions from the commutation controller. The SRM then operates according to these inputs.

B.Control Strategy under Regenerative Braking Modes

The regenerative braking mode in the SRM control system, as described, focuses on utilizing the motor's kinetic energy during braking and converting it into electrical energy to be stored or used elsewhere. Let's break down the process and its features:

- Purpose of Regenerative Braking Mode: Unlike conventional braking systems that waste energy in the form of heat, the regenerative braking mode recovers a portion of the energy that would have otherwise been lost. This energy recovery method is beneficial for improving overall efficiency and extending battery life, especially in electric vehicles.
- Independence from Driving Mode: The regenerative braking system operates separately from the standard driving mode. When the braking mode is activated, the system shifts its focus from propelling the vehicle to recapturing energy.
- Employing CCC for Current Regulation: To prevent potential damage from overcurrent's and to facilitate a pulsed charging process, the Current Chopping Control (CCC) is utilized. The CCC works by intermittently interrupting or "chopping" the current flow to ensure it remains within safe limits.
- Braking Operation Variations: Depending on the desired braking intensity or the situation, different braking currents can be set. This means there can be varying levels or modes of regenerative braking:

1. Inertial Braking: This might involve a gentle brake application, allowing the vehicle to slow down gradually.
2. Slow Braking: A more deliberate braking action, but still not the most aggressive form.
3. Quick Braking: A rapid or sudden brake application for faster deceleration.

- Battery Charging with Stored Energy: The electrical energy generated from the regenerative process isn't wasted. Instead, it's redirected to charge the vehicle's battery packs. This energy redirection not only conserves energy but also enhances the vehicle's range, especially beneficial for electric vehicles.
- Hysteresis Controller & CCC Controller: At the heart of this system are two key controllers: The Hysteresis controller and the CCC (Current Chopping Control) controller. Both are essential for managing the current during the regenerative braking process. As mentioned earlier, the CCC ensures the phase current remains within safe limits by "chopping" or intermittently interrupting the current flow.
- Commutation Controller: This controller is crucial for the SRM's operation. It dictates the timing of the power supply to the motor's phases based on the rotor's position, ensuring optimal motor performance. The rotor position information (θ_{on}, θ_{off}) guides this controller on when to turn phases on or off.
- Power Converter: This component is responsible for converting the recovered electrical

energy into a format suitable for storage or other uses. During regenerative braking, it channels the generated energy to the appropriate storage units or systems.

- SRM & Feedback Mode: The Switched Reluctance Motor (SRM) is the primary actor in this setup. As the vehicle brakes, the SRM operates in reverse, acting as a generator to produce electrical energy. The "Feedback mode" might imply the manner in which the SRM feeds the generated energy back into the system.
- Encoder: This component detects the rotor's position and speed. It provides essential data to the commutation controller, ensuring the SRM operates efficiently.
- Rotor Position Detection: A separate system for determining the rotor's position, providing another layer of data to optimize the motor's function.

Fig. 12 delineates the strategy for managing the SRM during regenerative braking. By harnessing the kinetic energy usually lost during braking and converting it into electrical energy, the system showcases an innovative approach to energy conservation and vehicle efficiency.

C. Control Strategy under Charging Modes

the charging process of the motor when under standstill conditions is well-explained in three stages based on the state of charge (SOC) of the battery packs:

Stage 1 - Pre-charge Phase (Low SOC):

- SOC Range: 0 to SOC1.
- Description: At this stage, the battery is deeply discharged or has an extremely low energy level. Charging a deeply discharged battery at high current levels can potentially harm it, reducing its life cycle or even causing catastrophic failures.
- Charging Mode: Lower Constant-Current Charging.
- Charging Current: iref1.

Stage 2 - Bulk Charging Phase (Medium SOC):

- SOC Range: SOC1 to SOC2.
- Description: The battery pack is not deeply discharged anymore but still has a significant capacity left to fill. Charging at this stage can be done at higher current levels without damaging the battery, allowing for faster charging times.
- Charging Mode: Standard Constant-Current Charging.
- Charging Current: iref2.

Stage 3 - Top-off Charging Phase (High SOC):

- SOC Range: SOC2 to 100%.
- Description: The battery pack is near its full capacity. Charging in a constant-current mode would not be efficient or safe anymore, as it can cause overcharging. So, the charging mode is switched to a constant voltage where the voltage is kept constant, and the current gradually drops as the battery fills up.
- Charging Mode: Constant-Voltage Charging.

this is a typical charging strategy used for lithium-ion batteries to ensure they are charged safely and efficiently. The transition between constant current to constant voltage modes ensures the battery gets charged quickly during the bulk phase and then safely as it approaches full capacity.

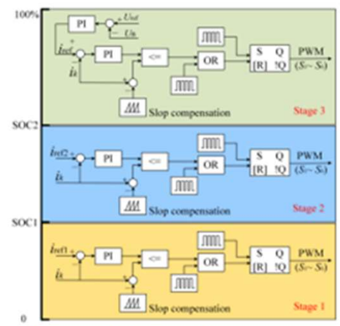


Fig. 13. Control strategy under charging modes.

D.SOC Balance Control

State of Charge (SOC) balance among the three battery packs used in the proposed converter topology. In electric systems that deploy multiple battery packs or cells, maintaining an even SOC across all units is crucial for the following reasons:

- Prolonged Battery Life: Continuously operating one battery at a higher SOC than others can lead to a reduced lifespan. Balancing ensures all batteries degrade at a similar rate, prolonging the overall system's life.
- Safety: Overcharging or over-discharging batteries can result in thermal issues, including potential fire hazards. SOC balance ensures that no individual battery is pushed beyond its safe limits.
- Performance: When the SOC of the batteries is balanced, the performance of the entire system remains consistent. Imbalances can lead to decreased efficiency or underutilization of available energy.
- Efficiency: Unbalanced batteries can cause some to work harder than others, leading to energy losses. A balanced system ensures all batteries share the load, optimizing the overall efficiency.

The statement also distinguishes between different operational modes and their relevance to SOC balance:

- Driving Modes: When the motor is powered, the optimal voltage level will be chosen from one of the three battery packs, potentially causing an SOC difference among them. Balancing ensures that one battery isn't consistently favored over the others, preventing over-discharge.
- Regenerative Braking Mode: During this mode, the energy recaptured from braking is fed back into the battery packs. If not properly managed, this can lead to an overcharge in some packs while others remain undercharged. SOC balancing ensures even distribution of this recaptured energy.
- Standstill Charging Modes: During periods when the motor is not in operation but charging is occurring, it's equally important to balance the SOC to prevent overcharging any single battery pack.

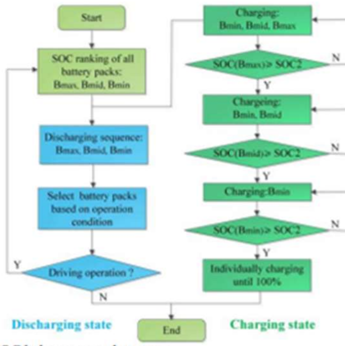


Fig. 14. SOC balance control strategy.

• Start:

1. The process begins by determining the SOC ranking of all battery packs, naming them as Bmax, Bmid, and Bmin based on their current SOC. Bmax has the highest SOC, Bmid has the middle SOC, and Bmin has the lowest SOC.

• Discharging Sequence:

1. When power is required (e.g., for driving), the system first uses the battery pack with the highest SOC (Bmax), followed by Bmid and then Bmin. This sequence ensures that the battery with the most energy is utilized first, likely to maintain a balance between packs over time.

• Driving Operation Decision:

1. If the system is in a driving operation (requiring power), it enters the discharging state and follows the aforementioned sequence.
2. If not in a driving operation, it proceeds to the charging strategy.

• Charging Strategy:

1. Initially, the system checks if the battery pack with the highest SOC (Bmax) is above a certain threshold (SOC2). If not, the system proceeds to charge the packs with the lowest and middle SOCs first (Bmin and Bmid).
2. Next, it checks the SOC of Bmid. If Bmid's SOC is not above the threshold (SOC2), the system proceeds to charge only Bmin.
3. If Bmin's SOC is still not above the threshold (SOC2), it gets charged individually until it reaches 100%.

• End:

1. Once the necessary charging or discharging operations are completed, the process ends.In essence, the control strategy aims to:

• For Discharging: Use the battery with the highest SOC first, thus ensuring that if one battery gets depleted, others can still provide power.

• For Charging: Prioritize charging the battery with the lowest SOC, ensuring that all batteries are reasonably balanced and ready for use. If any battery's SOC drops too low, it gets special attention to be charged back up to full to ensure its longevity and health.

1. SOC Ranking:

• At regular intervals, the SOC

• (State of Charge) of all battery packs is assessed and ranked. This helps the system decide which battery pack to utilize or charge based on their current SOC status.

2. Discharging State:

• During power usage (like driving the motor), the battery pack with the highest SOC is used first, followed by the pack with the next highest SOC and so on. This strategy ensures that the pack with the most energy is utilized first, helping to maintain a balanced use of all packs. As a result, the SOC of the battery packs can achieve dynamic balance during discharge operations.

3. Charging State:

• The charging strategy is designed to avoid overcharging and to reduce overall charging time. It follows these steps:

• a. Simultaneous Charging: All three battery packs are charged concurrently until the battery pack with the highest SOC reaches the threshold of SOC2.

• b. Medium and Lowest Packs Charging: Once the highest SOC battery reaches SOC2, it stops charging, while the other two packs (medium and lowest SOC) continue to charge. This continues until the pack with the medium SOC also reaches SOC2.

• c. Charging the Last Pack: After the first two packs have reached SOC2, only the battery pack with the lowest SOC continues to charge until it too reaches the threshold of SOC2.

• d. Final Charging: After all packs have reached SOC2, they are individually charged under a constant-voltage charging mode to ensure they are fully charged.

This comprehensive strategy ensures that:

• All battery packs are used efficiently and fairly during discharge operations.

• Overcharging is avoided, promoting the longevity and health of the battery packs.

• Charging is optimized to reduce the time it takes to get all battery packs fully charged.

The approach strikes a balance between ensuring battery health and optimizing system performance.

IV.EXPERIMENTAL VERIFICATION

• Motor Prototype:

1. A three-phase 12/8 SRM prototype is used for the experiments. The specific parameters of this motor are given in Table III (which hasn't been provided).

• Experimental Rig:

1. The SRM is set up in a test bed, secured accurately with a bracket that allows for three degrees of freedom. This ensures stability and accuracy during testing.

2. Fig. 15 (which hasn't been provided) illustrates the experimental setup.

• Load:

1. The load required for the motor during testing is provided by a Parker AC servomotor.

• Power Supply:

1. The power mimicking a generator is simulated using an adjustable DC power source that provides 80 V.

• Battery Configuration:

1. The battery system is a 72 V lithium-ion battery bank, segmented into three separate packs.

• Converter:

1. The proposed multiport converter consists of two primary components: a. A front-end circuit. b. An AHB (Asymmetrical Half Bridge) converter.

• Control System:

1. A dSPACE-DS1006 platform is deployed to enact the proposed control strategy. This is a

robust real-time control hardware suitable for complex control tasks.

- Sensors:

1. Three Hall-effect current sensors: These are utilized to measure the current in each of the three phases of the motor individually.
2. Torque and Position Sensors: High-precision sensors are implemented to detect and measure instantaneous torque and rotor position with accuracy.

The use of high-quality and precise equipment, like the dSPACE platform and Hall-effect sensors, suggests that the researchers have aimed for accuracy and reliability in their experimental validation. This setup will help in determining the effectiveness and feasibility of the proposed converter and control strategy in real-world applications.

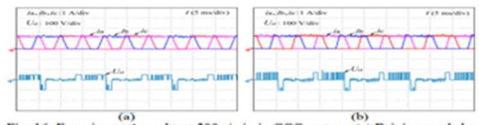


Fig. 16. Experimental results at 500 r/min in CCC system. (a) Driving mode by two battery packs. (b) Driving mode by three battery packs.

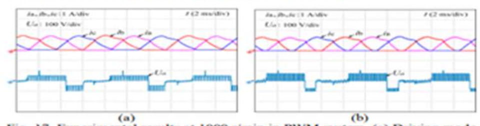


Fig. 17. Experimental results at 1000 r/min in PWM system. (a) Driving mode by two battery packs. (b) Driving mode by three battery packs.

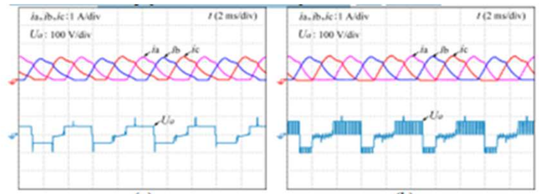
Figure 17 depicts the experimental waveforms of the PWM system when running at 1000 revolutions per minute (r/min) with a load of 1 Newton-meter (Nm). The motor works at a 5 kHz PWM frequency. The system's turn-on and turn-off angles are kept at 0° and 21°, respectively.

Fig. 17(a): This section of the picture depicts the motor in operation, powered by two battery packs.

Fig. 17(b): This section depicts the motor's driving mode when powered by all three battery packs.

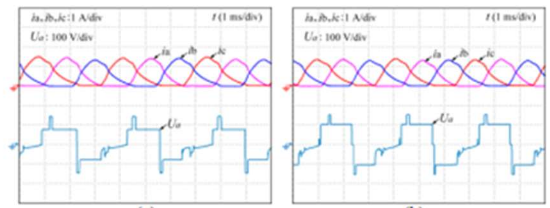
The role of the storing capacitor was a crucial insight made during the commutation region. The capacitor serves as a voltage booster, allowing for faster excitation and demagnetization operations. Even while the PWM method maintains a constant switching frequency, an increase in voltage (particularly when operating the motor with a larger number of battery packs) would aggravate the switching loss. As a result, careful voltage level adjustment during driving operations can result in lower switching loss, less voltage stress on the switches, and an overall boost in system efficiency.

Figure 18: PWM System Experimental Waveforms @ 1500 r/min The experimental waveforms of the PWM system when operating at 1500 r/min are shown in Fig. 18. Figure 18(a): This section depicts the motor's driving mode, which is powered by two battery packs. Figure 18(b): The motor's driving mode is fueled by three battery packs. An enhanced demagnetization voltage in the commutation zone causes a significant acceleration in the excitation and demagnetization processes. However, a possible disadvantage is an increase in switching loss, which is especially noticeable when all three battery packs are used to power the motor. In general, these findings emphasize the significance of carefully regulating the quantity of battery packs and their voltage levels in motor-driven systems in order to maximize efficiency and reduce losses.



(a) (b)

Fig. 18. Experimental results at 1500 r/min in PWM system. (a) Driving mode by two battery packs. (b) Driving mode by three battery packs.



(a) (b)

Fig. 19. Experimental results at high speed. (a) Driving mode by the generator. (b) Driving mode by the generator and one battery pack.

Figure 19 shows a graphic representation of the motor's performance at high speeds.

Fig. 19(a): The experimental waveforms of the motor running at 2200 revolutions per minute (r/min) are shown in this area of the figure. The generator is the sole source of electricity for the motor in this experiment

Figure 19(b): This section shows the motor's performance at a higher speed of 2400 r/min. The power source in this case is a mix of the generator and a single battery pack.

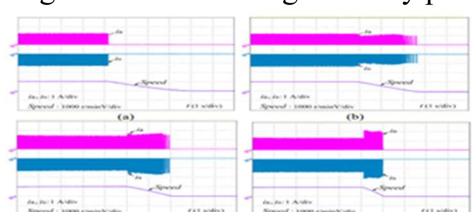


Fig. 20. Experimental results under regenerative braking condition. (a) Inertial braking condition. (b) Slow braking condition. (c) Medium braking condition. (d) Quick braking condition.

Fig. 20(a) - Inertial braking condition: The ia current remains constant throughout the duration, while the speed exhibits a gentle downward slope, indicating a gradual decrease in speed, consistent with the inertia of the system.

Fig. 20(b) - Slow braking condition: The ia current remains consistent for most of the duration but shows a sudden drop toward the end. The speed waveform displays a moderate decline, suggesting a gradual reduction in speed but at a slightly faster rate than the inertial braking condition.

Fig. 20(c) - Medium braking condition: The ia current appears stable for the first half, followed by a sudden drop. This is mirrored in the speed waveform, which also indicates a sharp decrease in speed after a certain point. The rate of speed reduction is more abrupt than the slow braking condition.

Fig. 20(d) - Quick braking condition: Both the ia current and speed waveforms display a swift drop at the beginning, indicating a rapid decrease in speed and braking current. This suggests a very abrupt braking action, consistent with the term "quick braking."

Fig. 20 visually represents the dynamic performance of the proposed system when it operates in the regenerative braking mode.

- iB: This denotes the regenerative current.
- The motor starts at an initial speed of 1000 r/min with turn-on and turn-off angles set at 20°

and 30° respectively.

- The three battery packs are connected in series throughout the operation.
- Fig. 20(a): Displays the inertial braking mode. Here, the braking capability appears to be suboptimal, taking around 2.5 seconds to bring the motor to a stop.
- Fig. 20(b), (c), and (d): These sections display slow, medium, and quick braking modes respectively. The key takeaway is that with an increase in braking current, the braking time decreases, implying faster stopping times with larger currents. Additionally, the battery packs are shown to charge from the demagnetization current during driving modes and from the regenerative current during braking modes through the proposed converter.

Fig. 21: Experimental Waveforms under Charging Mode

Fig. 21 depicts the waveforms during the charging mode of the system.

- iB1, iB2, and iB3: These represent the current of battery packs B1, B2, and B3 respectively.
- The described operation involves activating all switches in the AHB converter while deactivating all switches in the front-end circuit. This configuration allows the three-phase windings to charge using DC voltage sourced either from a generator or the AC grid. Deactivating all switches in the AHB converter enables the battery packs to charge from the energy retained in the phase winding. The PWM signals, with a frequency of 5 kHz, control the corresponding switches to adjust the charging current.
- Due to the intrinsic characteristics of the SRM, the motor remains stationary during the battery charging process.
- Fig. 21(a) and (b): These sections show the charging waveform when a single battery pack undergoes charging. In these scenarios, the duty cycles are calibrated to 0.5 and 0.6 respectively.
- Fig. 21(c) and (d): Display the charging waveforms when two battery packs are selected for charging. The duty cycles for these operations are also set at 0.5 and 0.6 respectively.

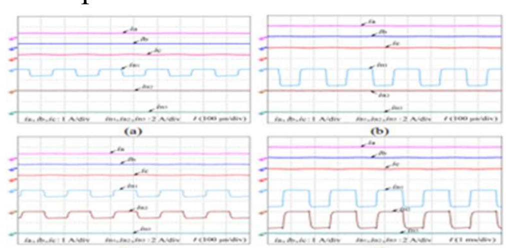


Fig. 21. Experimental results under charging mode. (a) One-pack charging mode under duty-cycle 0.5. (b) One-pack charging mode under duty-cycle 0.6. (c) Two-pack charging mode under duty-cycle 0.5. (d) Two-pack charging mode under duty-cycle 0.6.

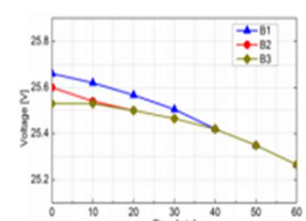


Fig. 22. Discharge waveform under two-pack charging mode.

Figure 22 depicts the dynamic balancing process across battery packs with varying State of Charge (SOC). The SRM drive is kept running at 1000 r/min with a 1 N•m load in the two-pack charging mode for this experiment. It has been shown that a battery pack's SOC is directly proportional to its voltage. As a result, by measuring the voltage of each individual battery pack, one may determine its state of charge. As the image indicates, the SOC of the three battery packs differs significantly at first. However, when the suggested SOC balance technique is implemented, the two battery packs with the greater SOC are first employed to power the motor. This mechanism guarantees that the SOC across the battery packs dynamically equalizes over time, establishing equilibrium.

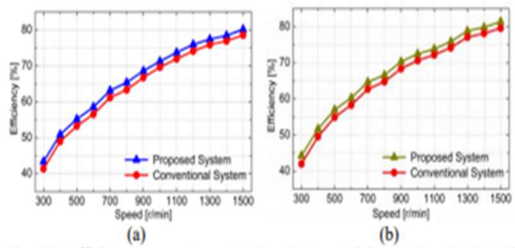


Fig. 23. Efficiency comparison. (a) Pure-battery driving mode. (b) Hybrid source driving mode.

Figure 23(a) shows the pure-battery driving mode:
This graph depicts the efficiency of the systems as a function of speed, ranging from 300 to 1500 revolutions per minute. A blue line with diamond marks represents the proposed system, while a red line with square markers represents the traditional system. Both curves are trending upward. Across all speeds, the suggested method consistently outperforms the current approach in terms of efficiency. The efficiency difference between the two systems appears to grow as the speed increases.

V.CONCLUSION

In this paper, here present a cascaded multiport converter designed for Switched Reluctance Motor (SRM)-oriented Hybrid Electric Vehicle (HEV) applications. The suggested design integrates battery packs into the Asymmetric Half-Bridge (AHB) converter, allowing for flexible energy conversion paths between the generator/ac grid, battery packs, and motor. This innovative converter architecture is compatible with a wide range of driving, regenerative braking, and charging modes. The development of multilayer bus voltage and increased current capacity are two key advantages of our cascaded architecture using Battery Management (BM) modules. These characteristics improve the excitation and demagnetization stages of commutation, resulting in increased speed ranges, reduced switch voltage stress, and increased torque capabilities. As a result, the entire system efficiency improves. Another notable feature is the battery packs' ability to be charged both while in use (by demagnetization current) and while stationary (via generator or alternating current grid).
The study also discusses the state-of-charge (SOC) balancing control approach that we devised. This technique handles battery charging and discharging efficiently, thereby avoiding potential overcharging and over discharging circumstances. Furthermore, because of the use of cascaded BM modules, our system has a flexible fault-tolerance mechanism that makes it resistant to anomalies. The suggested cascaded multiport converter has enormous potential for HEV applications due to its numerous benefits and versatility. Its design ideas can also be used to more-electric airplanes, traction motors, and electric naval vessels.

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