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Cascaded Multiport Converter for SRM-Based Hybrid Electrical Vehicle Applications

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ABSTRACT:-This paper proposes a cascaded multiport switched reluctance motor (SRM) drive for hybrid electric vehicle (HEV) applications, which not only allows flexible energy conversion among the generator/ac grid, the battery bank, and the motor, but also achieves battery management (BM) function for state-of-charge (SOC) balance control. By integrating the battery packs into the AHB converter, the cascaded BM modules are designed to configure multilevel bus voltage and current capacity for SRM drive, which can accelerate the excitation and demagnetization processes during the commutation region, extend the speed range, reduce the voltage stress on the switches, and improve the torque capability and system efficiency. According to the different operation requirements, the multiple driving modes, regenerative braking modes, and charging modes are equipped in the proposed converter. Moreover, with the proposed BM strategy, each battery pack can be separately connected or disconnected from the power supply, which will greatly enhance the fault-tolerance ability and easily avoid the overcharge and overdischarge issues during the motor operation. The feasibility and effectiveness of the proposed cascaded multiport SRM drive are verified by the experiments on a three-phase 12/8 SRM.

KEYWORDS: Cascaded multiport converter, battery management (BM), state-of-charge (SOC), switched reluctance motor (SRM), hybrid electric vehicles (HEVs).

I. INTRODUCTION

With the growing concerns of fossil fuel crisis and environmental issue, the electric vehicles (EVs) and hybrid electric vehicles (HEVs) have drawn increasing attention due to their reduced fuel consumption and enhanced energy efficiency [1]-[4]. For the powertrain systems in the EV and HEV applications, permanent magnet synchronous motors (PMSMs) have always be dominated due to their superior torque and power densities [5]-[7]. However, with the rapid depletion and increased cost of rare-earth magnet source, the rare-earth-less and rare-earth-free motors are attracting more attention [8], [9]. As one rare-earth-free motor, switched reluctance motors (SRMs) are becoming a promising alternative due to their simple structure, low cost, exceptional robustness, high reliability, and strong applicability for harsh environments.

II. LITERATURE SURVEY

- **L. Dong-Hee and K. Tomczewski [IEEE 2014]-**
  Four-level and a quasi-three-level converter are respectively proposed in and to achieve fast current excitation and demagnetization processes.
- **M. Rajesh and B. Singh [IEEE 2017]-**
  Three-level power factor correction (PFC) rectifier is added to reduce the total harmonic distortion of supply current and the ripple of dc-link voltage.
- **F. Peng, J. Ye, and A. Emadi [IEEE 2009]-**
  Neutral point diode clamped three-level converter is developed to improve the system efficiency and reduce the current ripple and noise.
- **C. Hung-Chun and L. Chang-Ming [IEEE 2011]-**
  DC/DC boost converter integrated with PFC circuit is presented, which can not only provide a bootable well-regulated supply voltage under driving mode, but also achieve good energy feedback capability under demagnetization mode.

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- **C. Hung-Chun and L. Chang-Ming [IEEE 2015]-**
  Modified Miler converter is developed to improve the motor performance at high speed and achieve the battery charging function with good power quality.
- **K. W. Hu, P. H. Yi, and C. M. Liaw [IEEE 2017]-**
  Bidirectional dc/dc circuit-based converter is presented to achieve the interworking among the vehicle, the home appliance, and the utility grid.

III. PROPOSED METHODOLOGY AND DISCUSSION

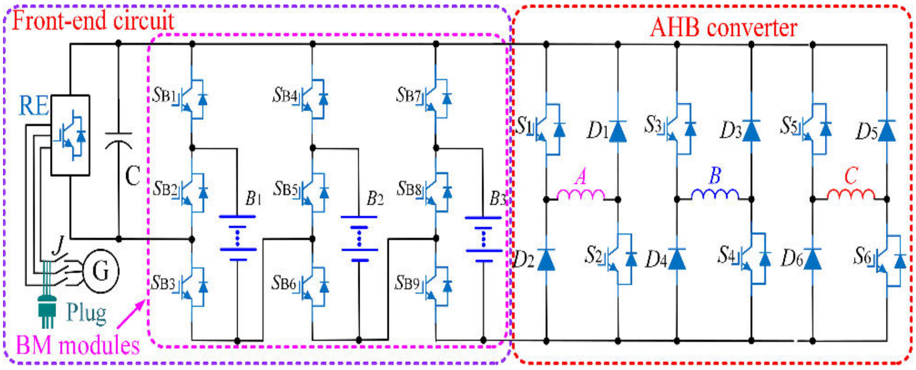

Fig. 1. Proposed cascaded multiport converter for a three-phase SRM

A. Proposed Converter Topology

To achieve the high-efficiency energy conversion among the generator/ac grid, the battery bank, and the SRM for HEV applications, a highly integrated multiport converter is proposed with BM function, as shown in Fig. 1, where a relay J is used to connect the generator and the rectifier; a plug is used to connect the ac grid, and three BM modules are presented for function description. It can be seen that the generator/ac plug, the ac/dc rectifier, the BM modules, the AHB converter are orderly connected in series. Hence, the proposed converter canbe considered as the combination of a front-end circuit and an AHB converter. The generator can not only act as a starter motor, but also be used to charge the battery bank and power the SRM. The battery bank can also be charged by the SRM and the ac grid. The SRM can be powered by the generator and battery bank respectively or simultaneously. To enhance the flexibility and reliability of the battery packs, more BM modules can be designed, which are separately managed and composed of a battery pack and three power switches with anti-parallel diode. By employing the proposed topology, multiple driving modes, regenerative braking modes, and charging modes are achieved to satisfy different operation condition.

B. Driving Modes

1)Operation Principle of Driving Modes for SRM

When the SRM is under driving modes, the relationship between phase current, phase inductance is presented in Fig. 2(a). A can be divided into five regions. In Region I, the phases C and A are simultaneously conducting. In Region II, the phase C is turned off and its current starts to decrease. In Region III, the phase C current reduces to zero and only phase A is conducting. In Region IV, the phases A and B are simultaneously conducting, and in Region V the phase A.

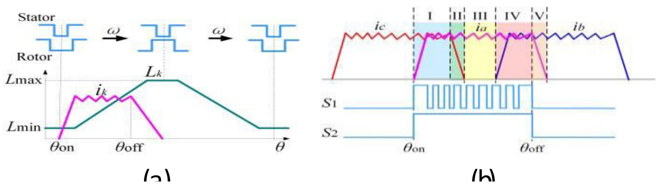

Fig.2. Driving Operation condition (a) phase current and phase inductance. (b) Phase currents and drive signals.

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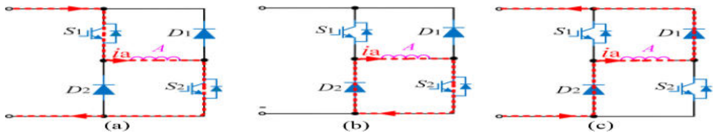


Fig. 3. Operation states of AHB converter (a) Excitation states (b) Freewheeling states (c) Demagnetization states.

There are two switching states in the first four regions for phase A, including excitation state and zero-voltage freewheeling state. The positive dc voltage is supplied to the phase winding, which is the excitation state, as shown in Fig. 3(a). With the upper switch S_1 off and the lower switch S_2 on, which is the zero-voltage freewheeling state, as shown in Fig. 3(b). In Region V, the phase A winding is in the demagnetization state, as shown in Fig. 3(c), where the switches are both turned off, and the energy stored in the phase winding is fed back to the power supply through diodes D_1 and D_2.

2. Driving Modes by the Generator

When the relay *J* is turned on and all switches are turned off in the front-end circuit, the motor is powered by the generator alone. When the generator provides the energy to the SRM, the working mode is shown in Fig. 4(a).When the energy stored in the phase winding is fed back to the three battery packs through the storage capacitor, the working mode is shown in Fig. 4(b).

As mentioned below, the whole conduction region of phase A can be divided into five regions.

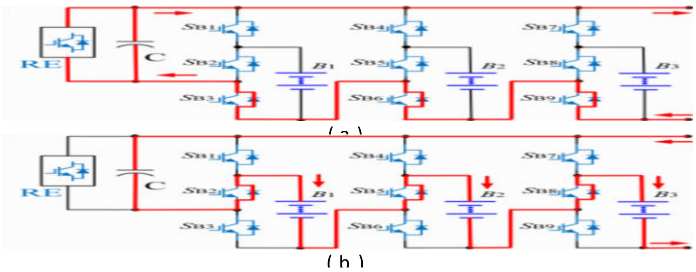
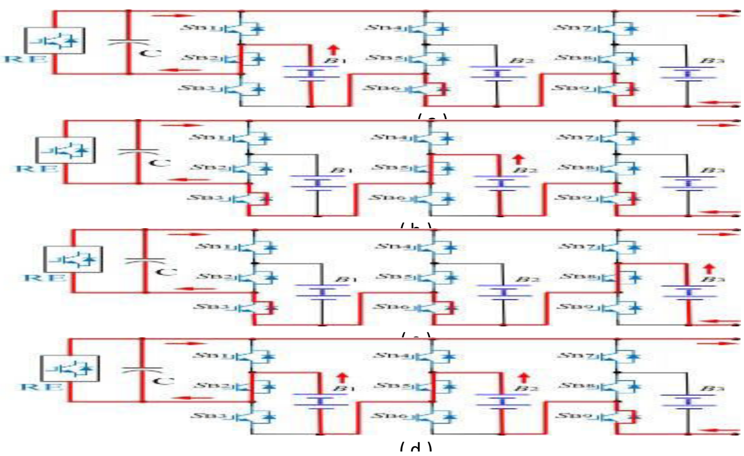


Fig. 4. Working conditions of the front-end circuit by the generator. (a) Driving mode. (b) Energy regeneration mode.

In Region I, phases A and B can both be in the excitation or freewheeling states.In Region II, phase C can only be in demagnetization state, and phase A can be in excitation or freewheeling states. phase C current is bigger than phase A current.

3. Driving Modes by the Generator and Battery Packs

When the motor needs to be powered by the generator and battery packs together, seven operation modes can be obtained by turning on the relay *J* and managing the switches in the front-end circuit, as shown in Fig. 5.



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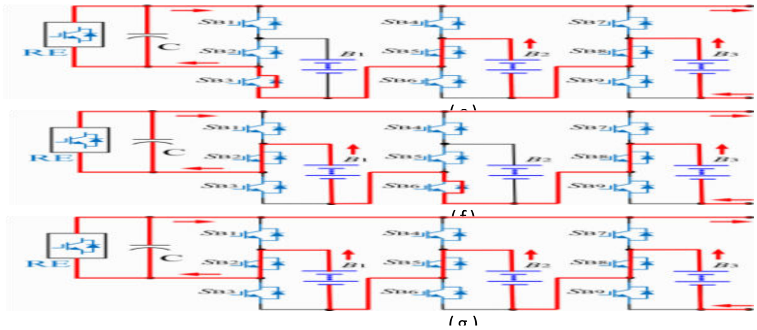


Fig. 5. Working Condition of the front end circuit by the Generator and battery packs. (a) mode1. (b) mode 2. (c) mode 3. (d) mode 4. (e) mode 5. (f) mode 6. (g) mode 7.

By turning on switch S_{B2}, the generator and the battery pack B_1 are connected in series to provide the energy, as presented in Fig. 5(a). Similarly, Fig. 5(b) and (c) show the operation modes when the battery packs B_2 and B_3 operate, respectively. The generator and the two packs B_1 and B_2 are connected in series to drive the motor, shown in Fig. 5(d). The two similar operation modes are presented in Fig. 5(e) and (f) respectively when two battery packs work. When switches S_{B2}, S_{B5} and S_{B8} are all turned on, Fig. 5(g). Under the hybrid source driving mode, the conduction modes of AHB converter are still same to those under generator powered driving modes, and the energy feedback flow of the front-end circuit is still same to that in Fig. 4(b).

C. Regenerative Braking Modes

When the SRM operates under the regenerative braking condition, the motor can be used to charge the battery packs. Fig. 6(a) phase current and phase inductance waveforms under regenerative braking mode.Fig. 6(b) phase currents and drive signals. The energy regeneration process of the front end circuit is same the fig. 4(b).

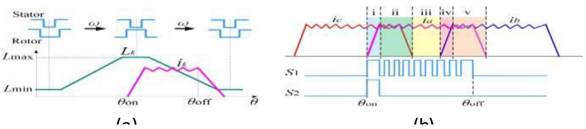
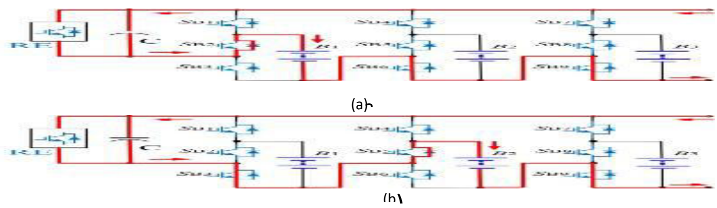


Fig. 6. Regenerative braking condition. (a) Relationship between phase current and phase Inductance. (b) Phase currents and drive signals.

D. Charging Modes

There are total seven available states for battery charging. With switches S_{B6} and S_{B9} on, the battery pack B_1 is charged, shown in Fig. 7(a). With $S_{B3}$and S_{B9} on, the B_2 is charged, shown in Fig. 7(b). With $S_{B3}$and S_{B6}on, the B_3 is charged, shown in Fig. 7(c). When switch S_{B9} is turned on, the $B_1$and $B_2$are charged, shown in Fig. 7(d). With S_{B3} on, the $B_2$and $B_3$are charged, shown in Fig. 7(e). With S_{B6} on, the $B_1$and $B_3$are charged, shown in Fig. 7(f). When no switches are turned on, shown in Fig. 7(g).



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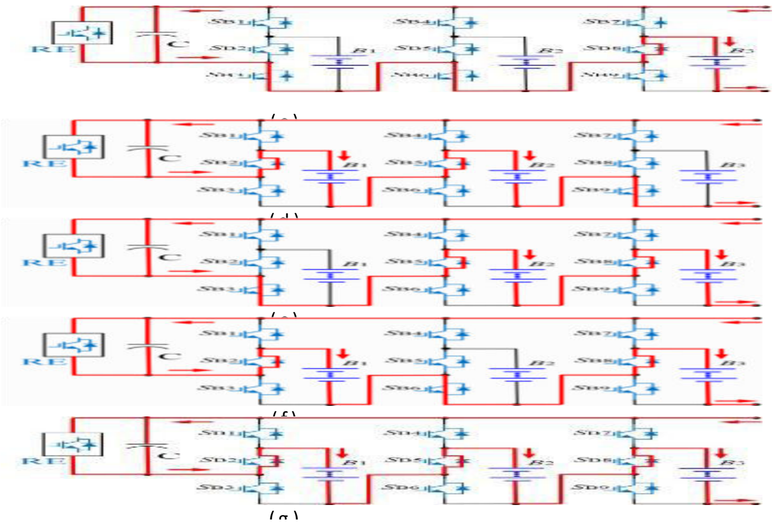

Fig. 7. Charging conditions of the front-end circuit under standstill charging condition. (a) Mode 1. (b) Mode 2. (c) Mode 3. (d) Mode 4. (e) Mode 5. (f) Mode 6. (g) Mode 7.

IV. CONTROL STRATEGIES OF THE PROPOSED CONVERTER

A. Control Strategy under Driving Modes

Generally, two classic control strategies are adopted in the SRM drive system, including current chopping control (CCC) and voltage-PWM control (VPC). A proportional integral (PI) controller is employed for speed closed-loop control. Under driving mode, the CCC and VPC control strategies are chosen according to the motor speed. By employing the appropriate driving modes to drive the motor, the voltage stress on the switches and the switching loss can be reduced.

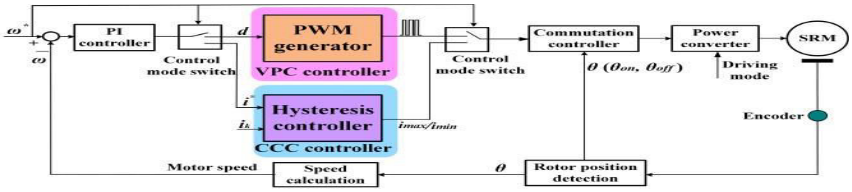

Fig. 8. Control strategy under driving modes.

B. Control Strategy under Regenerative Braking Modes

When the motor is under the regenerative braking mode, the SRM control system is illustrated in Fig. 9. To avoid the overcurrent damage and implement the pulsed charging procces, the CCC is employed to regulate the phase current. Meanwhile, the energy stored in the phase windings can be used to charge the battery packs.

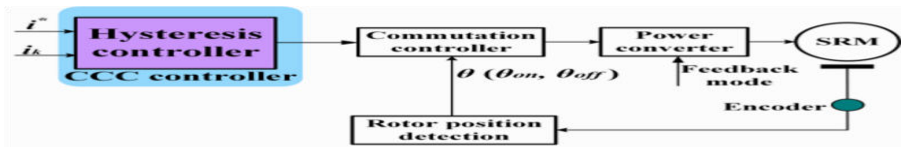

Fig. 9. Control strategy under regenerative braking modes.

C. Control Strategy under Charging Modes

When the motor is under the standstill condition and the SOC of battery packs are inadequate. The charging process can be divided into three stages according to the SOC, as shown in Fig. 10. In Stage 1, the SOC of the battery pack is between zero and SOC1, which means that the battery pack is under extreme energy loss condition. In Stage 2, the SOC of battery pack is between SOC1 and SOC2. In Stage 3, SOC of battery pack is between SOC2 and 100%, guarantee the battery pack fully charged.

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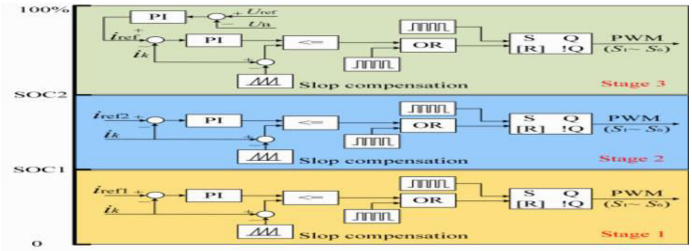

Fig. 10. Control strategy under charging modes.

D. **SOC Balance Control**

For the proposed converter topology, according to the operation conditions, the optimal voltage level will be configured to power the motor. In addition, to protect the battery packs from the overcharge issue, the SOC balance control is also necessary under regenerative braking and standstill charging modes.

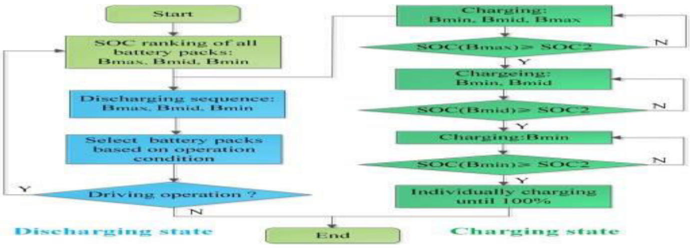

Fig. 11. SOC balance control strategy.

Fig. 11 presents the SOC balance control strategy under discharging and charging states. Firstly, the three battery packs are simultaneously charged until the highest SOC reach SOC2. Secondly, the rest two packs continue being charged until the medium SOC reach SOC2. Thirdly, the last module is charged until the SOC reach SOC2.

V. SIMULATION AND RESULT

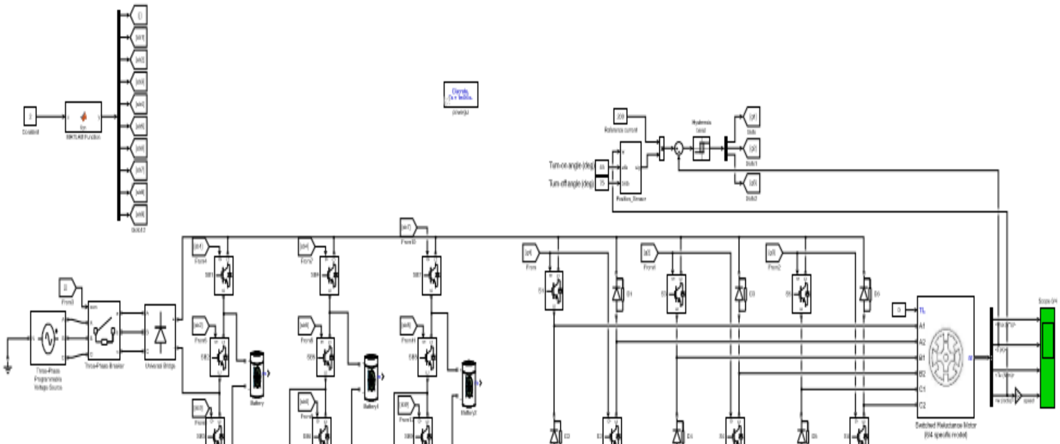

Fig. 12. Simulation Block Diagram of Cascaded Multiport Converter for SRM Based Hybrid Electrical Vehicle Application

In this paper, a cascaded multiport converter is proposed to achieve the flexible energy conversion in the SRM-based HEV system. The multiple driving modes, regenerative braking modes, and charging modes are achieved. To verify the Feasibility of the Proposed Multiport Converter and Control Strategy are carried out for proof of concept on a 3 phase 12/8 (6/4) SRM Motor. The Motor is accurately fixed in the test fed by a 3 Degree of freedom bracket. The power supply provide Generator is Simulated by an adjustable DC power source with 80V, A 72V Lithium- ion battery bank is divided into 3 battery packs. The proposed Converter is composed of a Front-End Circuit and AHB Converter. The high precision Torque and Position Sensors are adopted to detect the position respectively.

AS above fig. no.12 shows the 3 phase programmable voltage source 415V, 0 degree, 50 Hz is generator as I/P is connected to 3 phase Breaker. A,B,C phases is used for cut the position means is depends on Implementation. Battery nominal voltage 100V , Rated capacity 5.4 Ah, 100 % Initial State-Of-Charge and Battery Response time is 3 phase as it is for Battery.In that Discuss difference between Normal Converter and AHB Converter. In normal converter in that Bridge used Means Diode are used. Which is convert Converter and Inverter both and there are phase Legs. Occur. Come to SRM Motor. In that Switch Reluctance Motor 6/4 Specific model are used. Stator Resistance of Motor 0.05 ohm, Inertia 0.05 Kg.m.m and Fraction 0.02 N.M.S. this are the Normal common ratio are used. Motor Input one Inverter I/P and one Rectifier I/P. Switching is Closed Loop Switching see figure Number. 13 Position Sensor. Then motors O/P are used as I/P of Inverter get pulse. This position sensing is come to motor closed loop. Position sensing refer figure number 13 Simulation Block diagram of AHB Converter.

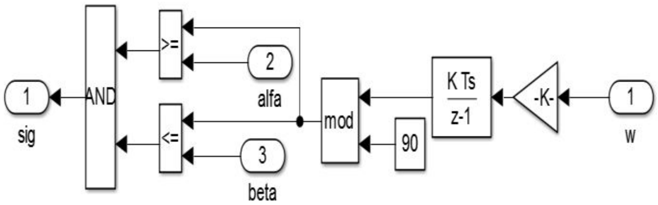

Fig. 13. Simulation Block Diagram of Position Sensor.

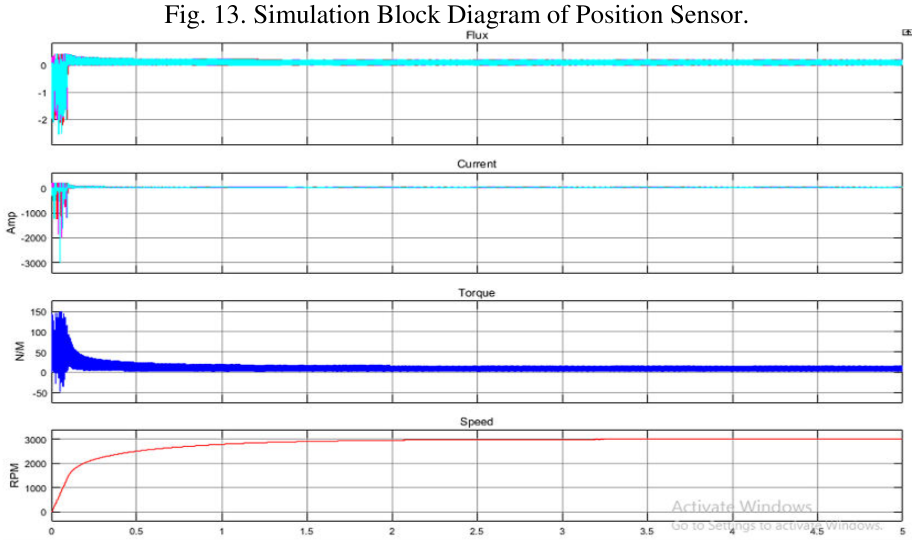

Fig. 14. Main Output Waveform.

In that Position- Flux, Current, Torque and Scope means Starting Position is Change, Torque is also change that position Speed is vary and that position Speed is Constant and that Position Motor is also constant. Fix position of Motor constant Time is 1.5 sec. Settling time is 1.5 sec.

VI. CONCLUSION

In this paper, a cascaded multiport converter is proposed for the SRM-based HEV applications. By integrating the battery packs into the AHB converter, the flexible energy conversion is achieved among the generator/ac grid, the battery packs, and the motor. Multiple driving modes, regenerative braking modes, and charging modes can be flexibly selected in the proposed integrated converter topology. By adopting the cascaded BM modules in the proposed converter, the multilevel bus voltage and current capacity are realized, which can accelerate the excitation and demagnetization processes during the commutation region, extend the speed range, reduce the voltage stress on the switches, and improve the torque capability and system efficiency. The battery packs can be flexible charged by the

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demagnetization current under running condition and by the generator/ac grid under standstill condition. Moreover, due to the proposed SOC balance control strategy under the charging and discharging states, the overcharging and overdischarging issues can be avoided. In addition, flexible fault-tolerance ability is also equipped by adopting the cascaded BM modules. Hence, the proposed cascaded multiport converter is promising for HEV application and can be extended to other applications, such as more-electric aircraft, traction drives, and electrical ships.

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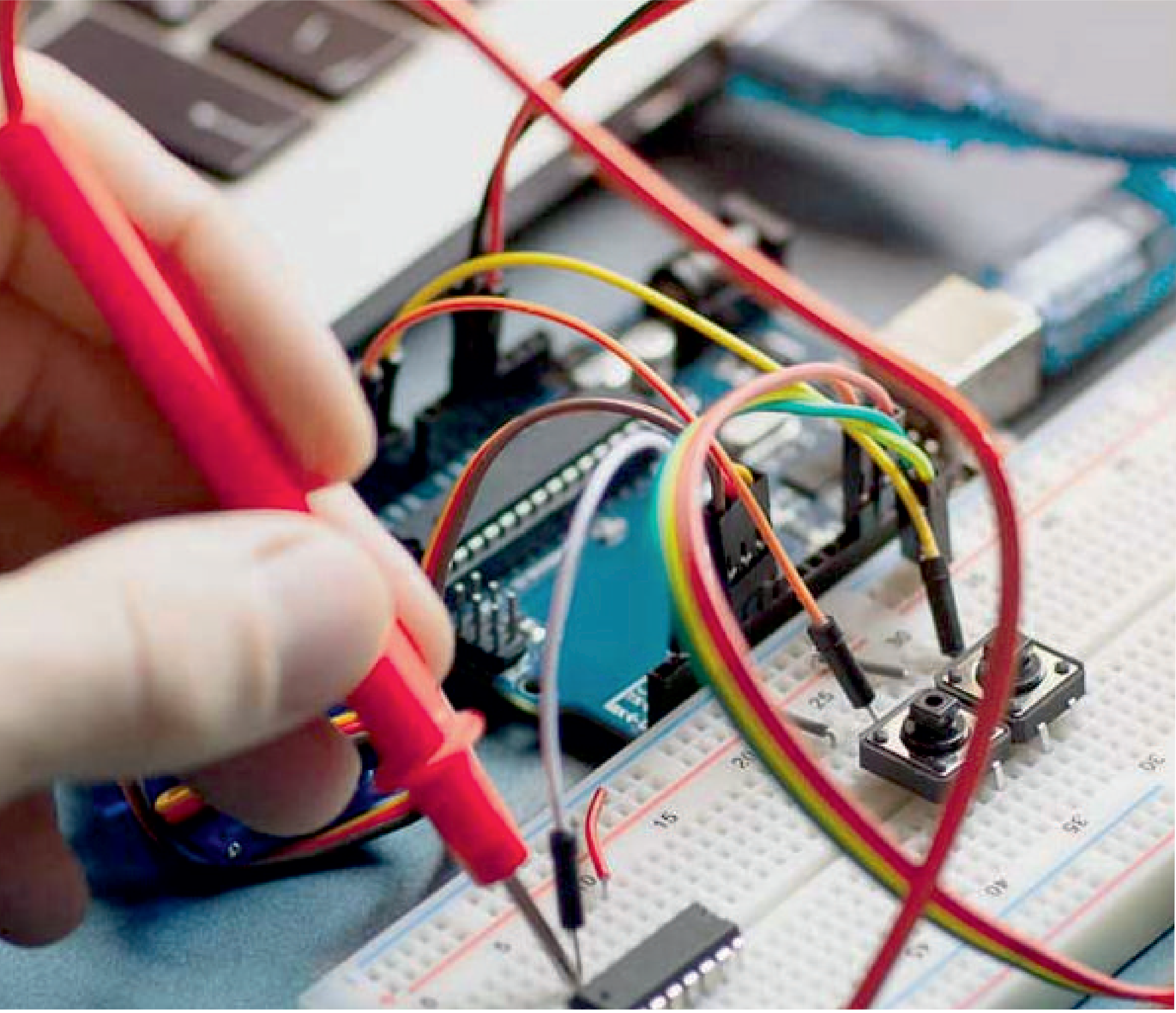

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