

Solar PV-Powered SRM Drive for EVs with Flexible Energy Control Functions

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Abstract—Electric vehicles (EVs) provide a feasible solution to reducing greenhouse gas emissions and thus become a hot topic for research and development. Switched reluctance motors (SRMs) are one of promised motors for EV applications. In order to extend the EVs’ driving miles, the use of photovoltaic (PV) panels on the vehicle helps decrease the reliance on vehicle batteries. Based on phase winding characteristics of SRMs, a tri-port converter is proposed in this paper to control the energy flow between the PV panel, battery and SRM. Six operating modes are presented, four of which are developed for driving and two for standstill on-board charging. In the driving modes, the energy decoupling control for maximum power point tracking (MPPT) of the PV panel and speed control of the SRM are realized. In the standstill charging modes, a grid-connected charging topology is developed without a need for external hardware. When the PV panel directly charges the battery, a multi-section charging control strategy is used to optimize energy utilization. Simulation results based on Matlab/Simulink and experiments prove the effectiveness of the proposed tri-port converter, which has potential economic implications to improve the market acceptance of EVs.

Index Terms—Electric vehicles, photovoltaics (PV), power flow control, switched reluctance motors (SRMs), tri-port converter.

I. INTRODUCTION

Electric vehicles have taken a significant leap forward, by advances in motor drives, power converters, batteries and energy management systems [1]-[4]. However, due to the limitation of current battery technologies, the driving miles is relatively short that restricts the wide application of EVs [5]-[7]. In terms of motor drives, high-performance permanent-magnet (PM) machines are widely used while rare-earth materials are needed in large quantities, limiting the wide application of EVs [8][9].

In order to overcome these issues, a photovoltaic panel and a switched reluctance motor (SRM) are introduced to provide power supply and motor drive, respectively. Firstly, by adding the PV panel on top of the EV, a sustainable energy source is achieved. Nowadays, a typical passenger car has a surface enough to install a 250-W PV panel [10]. Second, a SRM needs no rare-earth PMs and is also robust so that it receives increasing attention in EV applications [11]-[16]. While PV panels have low power density for traction drives, they can be used to charge batteries most of time.

Generally, the PV-fed EV has a similar structure to the hybrid electrical vehicle, whose internal combustion engine (ICE) is replaced by the PV panel. The PV-fed EV system is illustrated in Fig. 1. Its key components include an off-board charging station, a PV, batteries and power converters [17]-[19]. In order to decrease the energy conversion processes, one approach is to redesign the motor to include some on-board

charging functions [20]-[22]. For instance, paper [22] designs a 20-kW split-phase PM motor for EV charging, but it suffers from high harmonic contents in the back electromotive force (EMF). Another solution is based on a traditional SRM. Paper [23] achieves on-board charging and power factor correction in a 2.3-kW SRM by employing machine windings as the input filter inductor. The concept of modular structure of driving topology is proposed in paper [24]. Based on intelligent power modules (IPM), a four-phase half bridge converter is employed to achieve driving and grid-charging. Although modularization supports mass production, the use of half/full bridge topology reduces the system reliability (e.g. shoot-through issues). Paper [25] develops a simple topology for plug-in hybrid electrical vehicle (HEV) that supports flexible energy flow. But for grid-charging, the grid should be connected to the generator rectifier that increases the energy conversion process and decreases the charging efficiency. Nonetheless, an effective topology and control strategy for PV-fed EVs is not yet developed. Because the PV has different characteristics to ICEs, the maximum power point tracking (MPPT) and solar energy utilization are the unique factors for the PV-fed EVs.

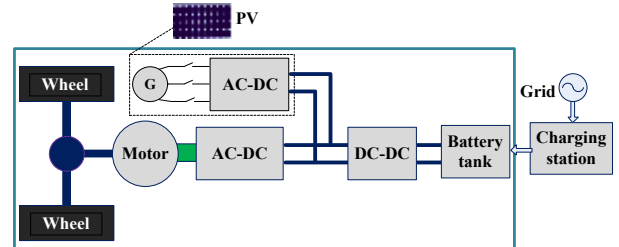


Fig. 1 PV-fed hybrid electrical vehicle.

In order to achieve low cost and flexible energy flow modes, a low cost tri-port converter is proposed in this paper to coordinate the PV panel, SRM and battery. Six operational modes are developed to support flexible control of energy flow.

II. TOPOLOGY AND OPERATIONAL MODES

A. Proposed topology and working modes

The proposed Tri-port topology has three energy terminals, PV, battery and SRM. They are linked by a power converter which consists of four switching devices ($S_0 \sim S_3$), four diodes ($D_0 \sim D_3$) and two relays, as shown in Fig. 2 [26].

By controlling relays J1 and J2, the six operation modes are supported, as shown in Fig. 3; the corresponding relay actions are illustrated in Table I. In mode 1, PV is the energy source to drive the SRM and to charge the battery. In mode 2, the PV and battery are both the energy sources to drive the SRM. In mode 3, the PV is the source and the battery is idle. In mode 4, the battery is the driving source and the PV is idle. In mode 5, the battery is charged by a single-phase grid while both the PV and

SRM are idle. In mode 6, the battery is charged by the PV and the SRM is idle.

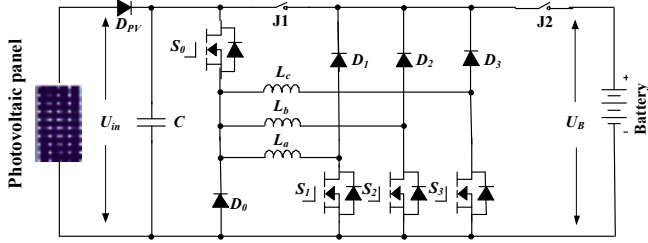


Fig. 2. The proposed Tri-port topology for PV-powered SRM drive.

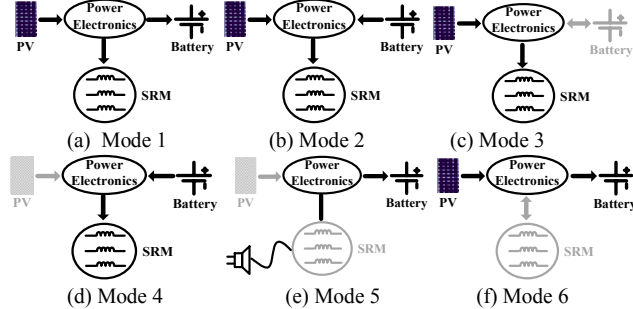


Fig. 3. Six operation modes of the proposed Tri-port topology.

TABLE I J1 and J2 Actions under Different Modes

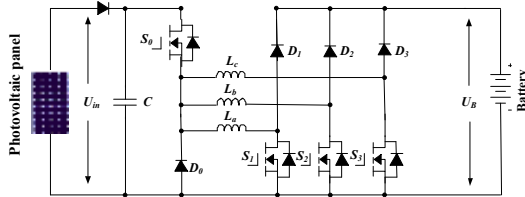
Mode	J1 and J2
1	J1 turn-off; J2 turn-on
2	J1 and J2 turn-on
3	J1 turn-on; J2 turn-off
4	J1 and J2 turn-on
5	J1 and J2 turn-on
6	J1 turn-off; J2 turn-on

B. Driving modes

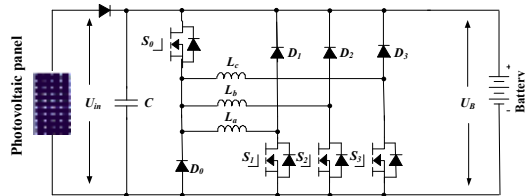
Operating modes 1~4 are the driving modes to provide traction drive to the vehicle.

(1) Mode 1

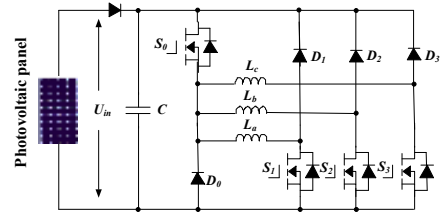
At light loads of operation, the energy generated from the PV is more than the SRM needed; the system operates in mode 1. The corresponding operation circuit is shown in Fig.4 (a), in which relay J1 turns off and relay J2 turns on. The PV panel energy feed the energy to SRM and charge the battery; so in this mode, the battery is charged in EV operation condition.



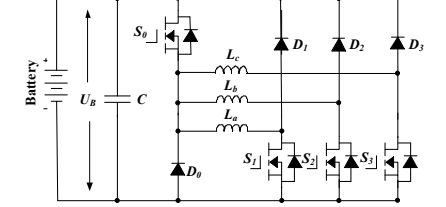
(a) Operation circuit under mode 1



(b) Operation circuit under mode 2



(c) Operation circuit under mode 3



(d) Operation circuit under mode 4

Fig. 4 The equivalent circuits under driving modes.

(2) Mode 2

When the SRM operates in heavy load such as uphill driving or acceleration, both the PV panel and battery supply power to the SRM. The corresponding operation circuit is shown in Fig. 4(b), in which relay J1 and J2 are turned on.

(3) Mode 3

When the battery is out of power, the PV panel is the only energy source to drive the vehicle. The corresponding circuit is shown in Fig. 4(c). J1 turns on and J2 turns off.

(4) Mode 4

When the PV cannot generate electricity due to low solar irradiation, the battery supplies power to the SRM. The corresponding topology is illustrated in Fig. 4(d). In this mode, relay J1 and J2 are both conducting.

C. Battery charging modes

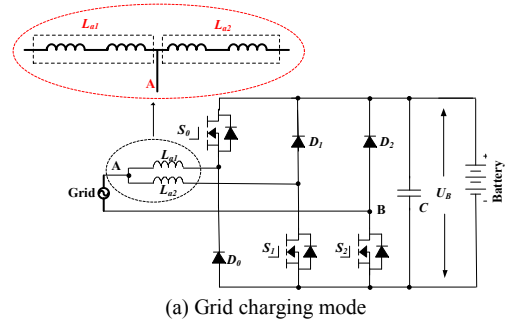
Operating modes 5 and 6 are the battery charging modes.

(5) Mode 5

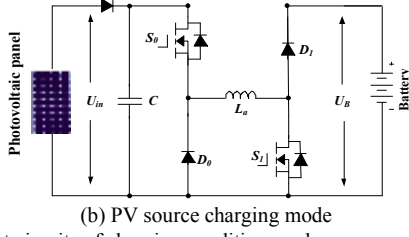
When PV cannot generate electricity, an external power source is needed to charge the battery, such as AC grid. The corresponding circuit is shown in Fig. 5(a). J1 and J2 turns on. Point A is central tapped of phase windings that can be easily achieved without changing the motor structure. One of the three phase windings is split and its midpoint is pulled out, as shown in Fig. 5(a). Phase windings L_{a1} and L_{a2} are employed as input filter inductors. These inductors are part of the drive circuit to form an AC-DC rectifier for grid charging.

(6) Mode 6

When the EV is parked under the sun, the PV can charge the battery. J1 turns off; J2 turns on. The corresponding charging circuit is shown in Fig. 5(b).



(a) Grid charging mode



(b) PV source charging mode

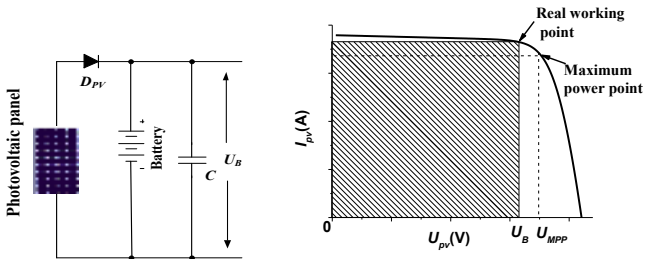
Fig. 5 Equivalent circuits of charging condition modes.

III. CONTROL STRATEGY UNDER DIFFERENT MODES

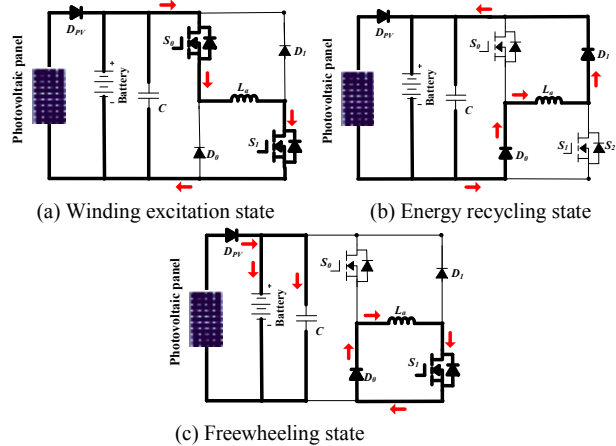
In order to make the best use of solar energy for driving the EV, a control strategy under different modes is designed.

A. Single source driving mode

According to the difference in the power sources, there are PV-driving; battery-driving and PV and battery parallel fed source. In a heavy load condition, the PV power cannot support the EV, mode 2 can be adopted to support enough energy and make full use of solar energy. Fig. 6(a) shows the equivalent power source; the corresponding PV panel working points is illustrated in Fig. 6(b). Because the PV is paralleled with the battery, the PV panel voltage is clamped to the battery voltage U_B . In mode 2, there are three working states: winding excitation, energy recycling and freewheeling states, as shown in Fig. 7. Modes 3 and 4 have similar working states to mode 2. The difference is that the PV is the only source in mode 3 while the battery is the only source in mode 4.



(a) Compound power source
Fig. 6 Power supply at mode 2.



(c) Freewheeling state
Fig. 7 Working states at mode 2.

Neglecting the voltage drop across the power switches and diodes, the phase voltage is given by

$$\begin{aligned} U_{in} &= R_k i_k + \frac{d\psi(i_k, \theta_r)}{dt} \\ &= R_k i_k + L_k \frac{di_k}{dt} + i_k \omega_r \frac{dL_k}{d\theta_r}, \quad k = a, b, c \end{aligned} \quad (1)$$

where U_{in} is the DC-link voltage, k is phase a , b , or c , R_k is the phase resistance, i_k is the phase current, L_k is the phase

inductance, θ_r is the rotor position, $\psi(i_k, \theta_r)$ is the phase flux linkage depending on the phase current and rotor position, and ω_r is the angular speed.

The third term in Eq. 1 is the back electromotive force (EMF) voltage given by

$$e_k = i_k \omega_r \frac{dL_k}{d\theta_r} \quad (2)$$

Hence, the phase voltage is found by

$$U_k = R_k i_k + L_k \frac{di_k}{dt} + e_k \quad (3)$$

In the excitation region, turning on S_0 and S_1 will induce a current in phase a winding, as show in Fig. 7(a). Phase a winding is subjected to the positive DC bus voltage.

$$+U_{in} = R_k i_k + L_k \frac{di_k}{dt} + e_k \quad (4)$$

When S_0 is off and S_1 is on, the phase current is in a freewheeling state in a zero voltage loop, as shown in Fig. 7(c), the phase voltage is zero.

$$0 = R_k i_k + L_k \frac{di_k}{dt} + e_k \quad (5)$$

In the demagnetization region, S_0 and S_1 are both turned off, and the phase current will flow back to the power supply, as show in Fig. 7(b). In this state, the phase winding is subjected to the negative DC bus voltage, and the phase voltage is

$$-U_{in} = R_k i_k + L_k \frac{di_k}{dt} + e_k \quad (6)$$

In single source driving mode, the voltage-PWM control is employed as the basic scheme, as illustrated in Fig. 8. According to the given speed ω^* , the voltage-PWM control is activated at speed control.

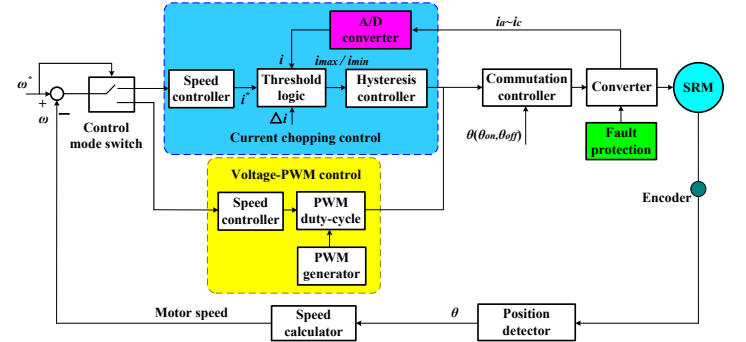


Fig. 8. SRM control strategy under single source driving mode.

B. Driving-charging hybrid control strategy

In the driving-charging hybrid control, the PV is the driving source and the battery is charged by the freewheeling current, as illustrated in drive mode 1. There are two control objectives: maximum power point tracking (MPPT) of the PV panel and speed control of the SRM.

The dual-source condition is switched from a PV-driving mode. Firstly, the motor speed is controlled at a given speed in mode 3. Then, J2 is tuned on and J1 is off to switch to mode 1. By controlling the turn-off angle, the maximum power of PV panel can be tracked.

There are three steady working states for the dual-source mode (mode 1), as shown in Fig. 9. In Fig. 9(a), S_0 and S_1 conduct, the PV panel charges the SRM winding to drive the motor; In Fig. 9(b), S_0 and S_1 turn off; and the battery is charged with freewheeling current of the phase winding. Fig. 9(c) shows

a freewheeling state.

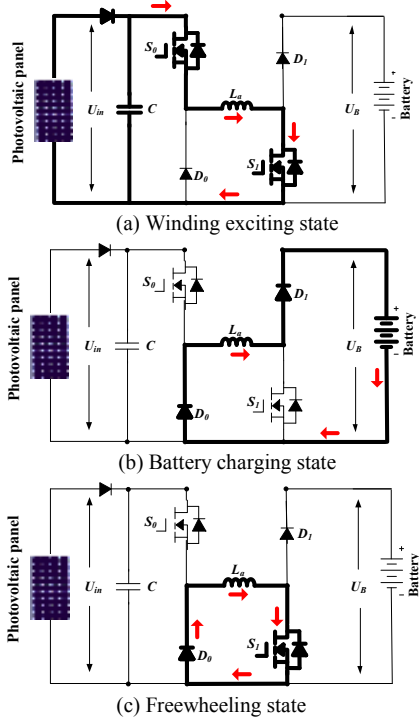


Fig. 9 Mode 1 working states.

Fig.10 is the control strategy under driving-charging mode. In Fig.10, θ_{on} is the turn on angle of SRM; θ_{off} is the turn-off angle of SRM. By adjusting turn-on angle, the speed of SRM can be controlled; the maximum power point tracking of PV panel can be achieved by adjusting turn-off angle, which can control the charging current to the battery.

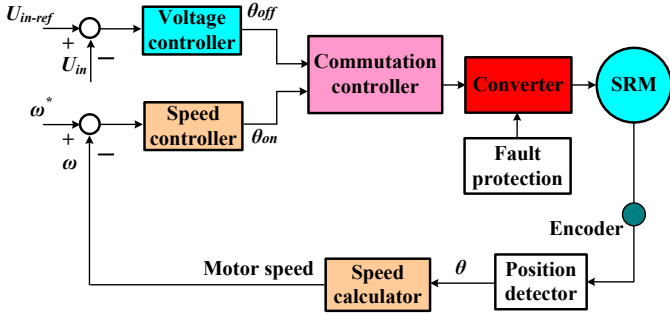


Fig. 10. Control strategy under driving-charging mode (mode 1)

C. Grid-charging control strategy

The proposed topology also supports the single-phase grid-charging. There are four basic charging states and S_0 is always turned off. When the grid instantaneous voltage is over zero, the two working states are presented in Fig. 11(a) and (b). In Fig. 11(a), S_1 and S_2 conduct, the grid voltage charges the phase winding L_{a2} , the corresponding equation can be expressed as Eq. 7; In Fig. 11(b), S_1 turns off and S_2 conducts, the grid is connected in series with phase winding to charges the battery, the corresponding equation can be expressed as Eq. 8.

$$U_{grid} = L_{a2} \cdot \frac{di_{grid}}{dt} \quad (7)$$

$$U_B - U_{grid} = L_{a2} \cdot \frac{di_{grid}}{dt} \quad (8)$$

When the grid instantaneous voltage is below zero, the two

working states are presented in Fig. 11(c) and (d). In Fig. 11(c), S_1 and S_2 conduct, the grid voltage charges the phase winding L_{a1} and L_{a2} , the corresponding equation can be expressed as Eq. (9); In Fig. 11(d), S_1 keeps conducting and S_2 turns off, the grid is connected in series with phase winding L_{a1} and L_{a2} to charges the battery, the corresponding equation can be expressed as Eq. 10.

$$U_{grid} = \frac{L_{a1} + L_{a2}}{L_{a1} \cdot L_{a2}} \cdot \frac{di_{grid}}{dt} \quad (9)$$

$$-U_B - U_{grid} = \frac{L_{a1} + L_{a2}}{L_{a1} \cdot L_{a2}} \cdot \frac{di_{grid}}{dt} \quad (10)$$

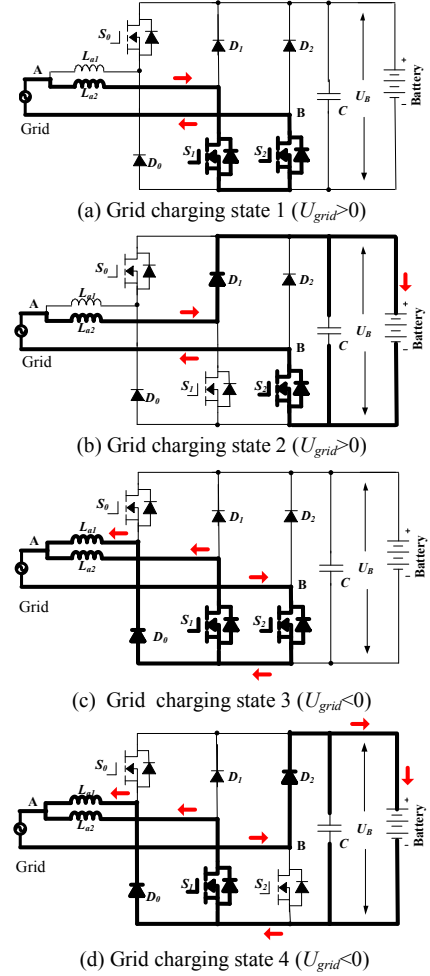


Fig.11 Mode 5 charging states

In Fig. 12, U_{grid} is the grid voltage; by the phase lock loop (PLL), the phase information can be got; I_{ref_grid} is the given amplitude of the grid current. Combining $\sin\theta$ and I_{ref_grid} , the instantaneous grid current reference i_{ref_grid} can be calculated. In this mode, when $U_{grid} > 0$, the inductance is L_{a2} ; when $U_{grid} < 0$, the inductance is paralleled L_{a1} and L_{a2} ; in order to adopt the change in the inductance, hysteresis control is employed to realize grid current regulation. Furthermore, hysteresis control has excellent loop performance, global stability and small phase lag that makes grid connected control stable.

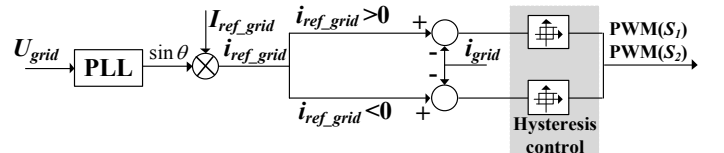


Fig. 12 Grid-connected charging control (Mode 5).

D. PV-fed charging control strategy

In this mode, the PV panel charges the battery directly by the driving topology. The phase windings are employed as inductor; and the driving topology can be functioned as interleaved Buck-boost charging topology. For one phase, there are two states, as shown in Fig. 13(a) and (b). When S_0 and S_I turn on, the PV panel charges phase inductance; when S_0 and S_I turns off, the phase inductance discharges energy to battery. According to the state-of-charging (SoC), there are three stages to make full use of solar energy and maintain battery healthy condition, as illustrated in Fig.13 (c). During stage 1, the corresponding battery SoC is in 0~SoC1, the battery is in extremely lack energy condition, the MPPT control strategy is employed to make full use of solar energy. During stage 2, the corresponding battery SoC is in SoC1~SoC2, the constant voltage control is adapted to charging the battery. During stage 3, the corresponding battery SoC is in SoC2~1, the micro current charging is adapted. In order to simplify the control strategy, constant voltage is employed in PV panel MPPT control.

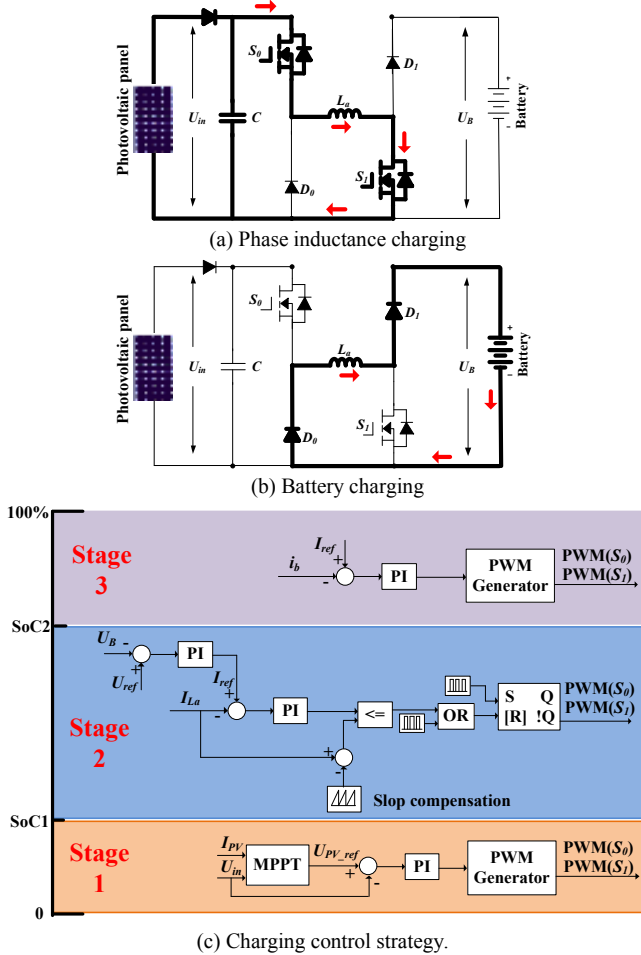


Fig. 13 Mode 6 charging states and control strategy.

IV. SIMULATION

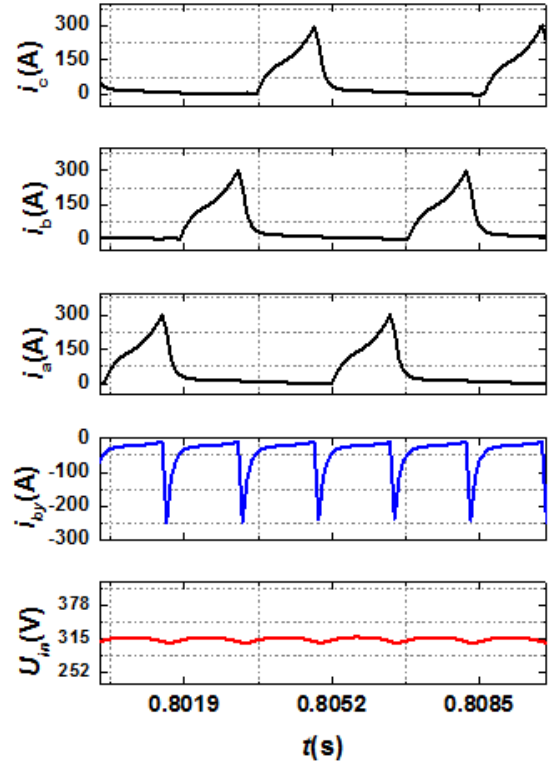
A 12/8 SRM is first modeled in Matlab/Simulink using parameters in Table II. Fig. 14(a) presents the simulation results at mode 1. The load torque is set as 35 Nm, the PV panel voltage is controlled at the MPP. The freewheeling current is used to charge the battery. Fig. 14(b) shows the simulation results of the single-source driving modes (modes 2-4).

TABLE II Simulation parameters

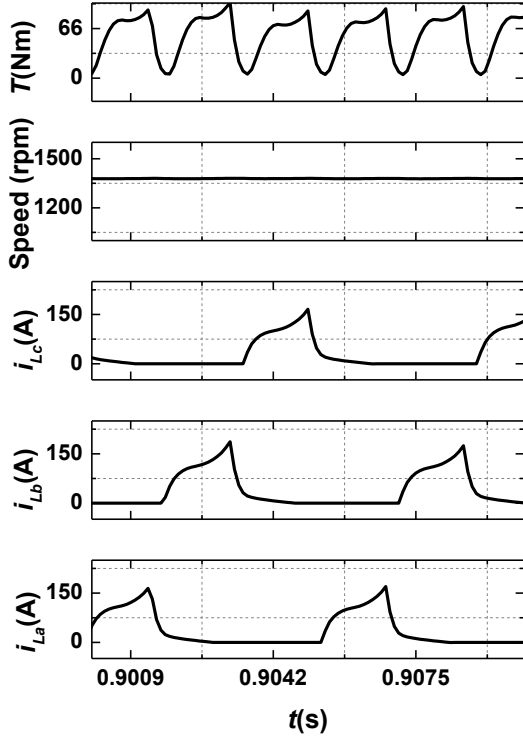
Parameter	Value
SRM	12/8
PV panel	310 V
Maximum power point voltage reference voltage	350 V
Battery voltage	350 V
Constant voltage control reference voltage	355 V
Constant current control reference current	1 A
Mode 1, charging current	60 A
Mode 4, driving speed	1250 rpm
Mode 6, constant voltage charging reference	355 V
Mode 6, constant current charging reference	1 A

Fig. 15 shows the simulation results of charging where Fig. 15(a) is for grid-charging. The positive half current quality is better than the negative half that is caused by the change in the grid-connected inductance.

Fig. 15(b) and (c) are for PV-charging. Fig. 15(b) presents the step change from stage 1 to 2. In stage 1, the battery is low in SoC. In order to achieve MPPT of the PV, the constant-voltage control is employed and the PV output voltage is controlled at MPP (310 V), as shown in Fig. 15(b). In stage 2, a constant voltage is adopted; the reference voltage is set to 355 V. As shown in Fig. 15(b), the charging converter output voltage is controlled at reference voltage in the step change from stage 1 to stage 2. In stage 3, 1 A trickle charging is also achieved, as shown in Fig. 15(c).

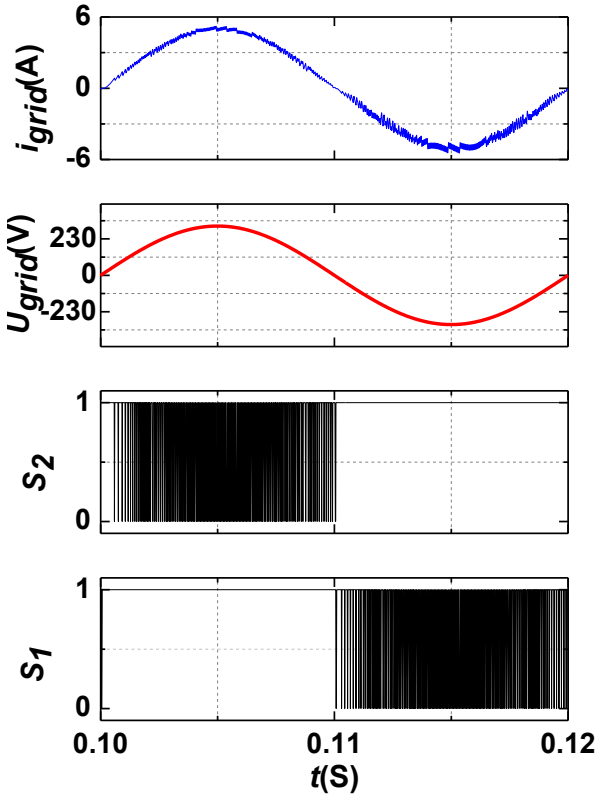


(a) Simulation results of driving-charging mode (mode 1)

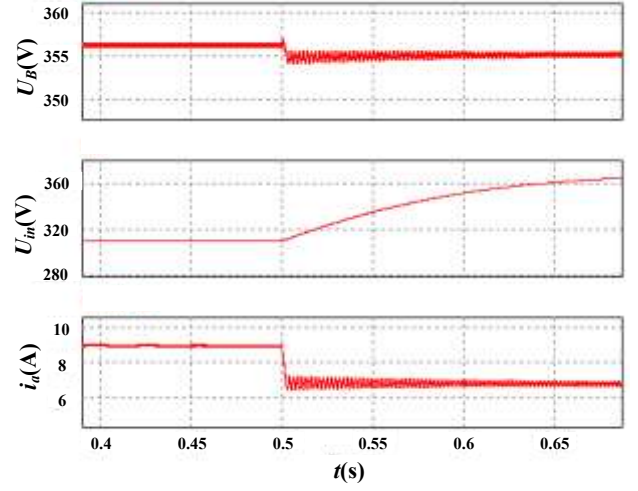


(b) Simulation results of single source driving mode (modes 3 and 4)

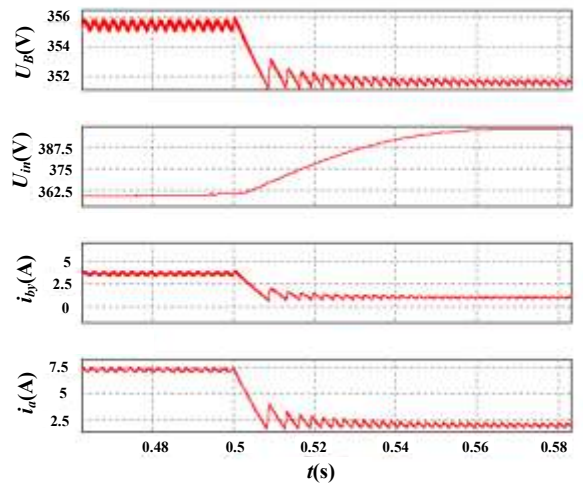
Fig. 14 Simulation results for driving conditions at modes 1, 3 and 4.



(a) Grid charging (mode 5)



(b) PV charging mode 6 (stage 1 to stage 2)



(c) PV charging mode 6 (stage 2 to stage 3)

Fig. 15 simulation results for charging modes.

V. EXPERIMENTAL RESULTS

The proposed scheme is validated by a 750-W three-phase 12/8-pole prototype SRM, and the experimental setup is shown in Fig. 16. The motor parameters are presented in Table. III. A PV array simulator (Agilent Technology E4360A) is adopted as input source. A dSPACE-1006 board is employed as the main controller and the PI algorithm is used for closed-loop control. A 24-V lead-acid battery is used for charging and discharging tests. The rotor position and motor speed are calculated from an incremental encoder. An asymmetric-half bridge converter is used to drive the motor.

TABLE III Motor Parameters

Parameter	Value
Phase number	3
Stator poles	12
Rotor poles	8
Rated speed (r/min)	1500
Rated power (W)	750
Minimum phase inductance (mH)	27.2
Maximum phase inductance (mH)	256.7
Rotor outer diameter (mm)	55
Rotor inner diameter (mm)	30
Stator outer diameter (mm)	102.5
Stator inner diameter (mm)	55.5
Core length (mm)	80
Stator arc angle (deg)	14
Rotor arc angle (deg)	16

The motoring and braking modes for the SRM when the relay J1 is on is shown in Fig. 17, where i_a , i_b , and i_c are the phase currents for phase A, B and C. The motor is powered by the battery in this condition. The turn-on and turn-off angles are set to 0° and 20° , respectively, when motoring. In Fig. 17(c), the speed follows the given value well when it changes from 300 to 800 rpm, and stabilizes within 1.5 s. The Inertial braking condition is presented in Fig. 17(d), however, the braking time is 2.5 s, and the energy cannot flow to the power supply. In Fig. 17(e), the turn-on and turn-off angles are set to 22° and 43° , respectively, when the motor runs in the regenerative braking mode, and the braking time is also decreased to 300 ms.

Fig. 18 shows the motoring and braking modes for the drive when the relay J1 is off, where i_{by} is the current flowing out from the battery. Clearly, the battery is charged by the demagnetization current in motoring condition, as shown in Fig. 18(a) and (b). The energy is recycled to the battery when employing the regenerative braking mode in Fig. 18(c), compared to Fig. 18(d). Fig. 19 is the standstill charging, in this mode, PV charges the battery by driving topology and SRM phase winding; the three phases are in parallel working mode. Fig. 19 illustrates the battery charging waveforms in stand still condition. In Fig. 19(a), the battery is charged by PV panel; P_z

is the rotor position sensor signal that keeps at zero proof the proposed standstill charging doesn't influence the electrical vehicle. In Fig. 19(b), the battery is charged by AC source; by the proposed hysteresis control, the grid current (THD) is 4.716%; and the corresponding THD analysis waveform is presented in Fig.19 (c), which meets the requirement of the international standards IEC61727 and IEEE1547.

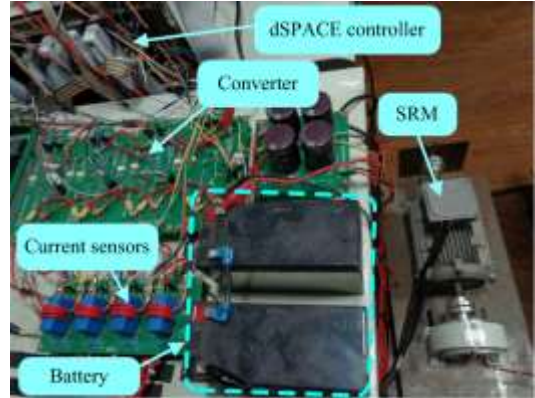


Fig. 16. Experimental setup of the proposed SRM drive system.

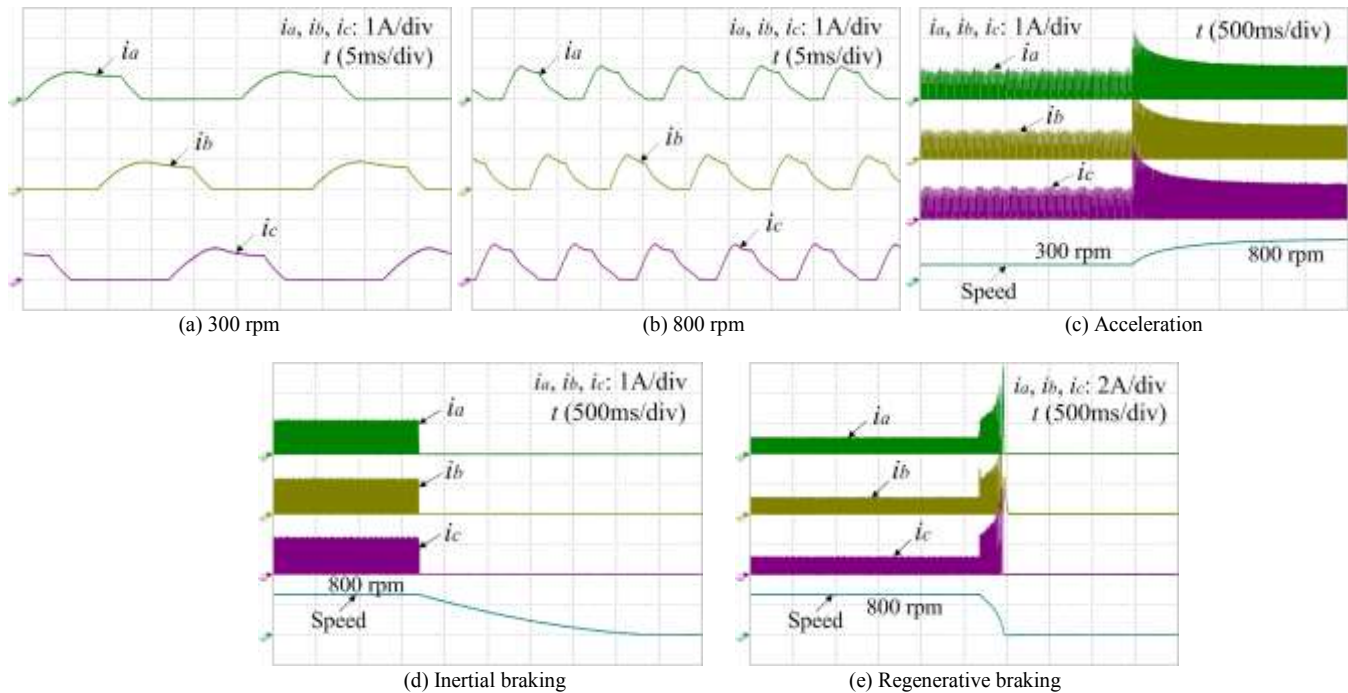
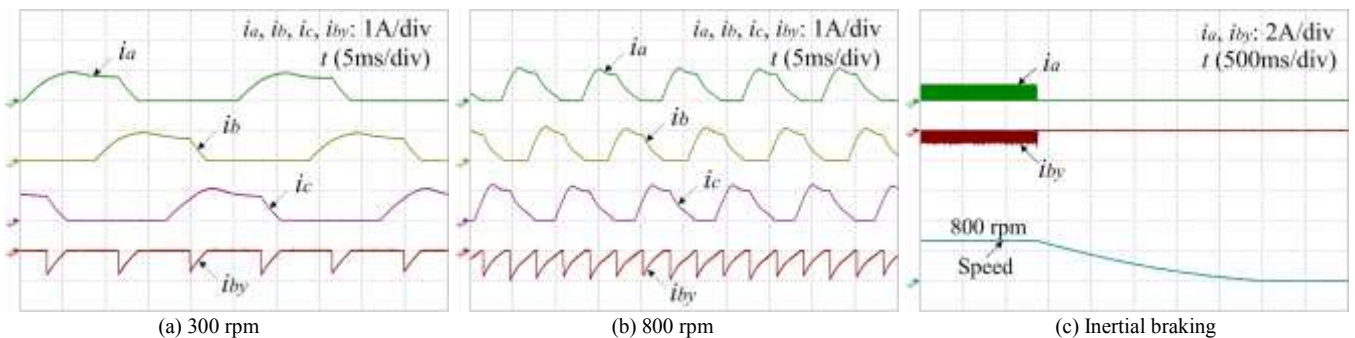
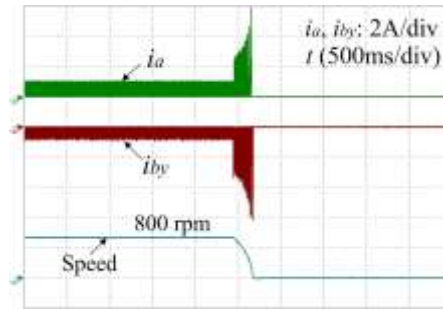


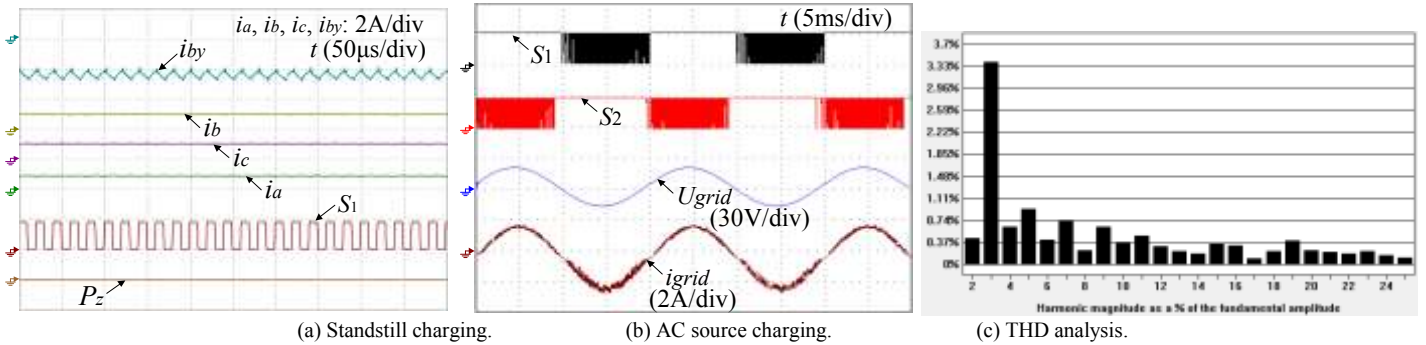
Fig. 17. Motoring and braking modes when J1 is on (modes 2, 3 and 4).





(d) Regenerative braking

Fig. 18. Motoring and braking modes when J1 is off (mode 1).



(a) Standstill charging.

(b) AC source charging.

(c) THD analysis.

Fig. 19 Charging experiment waveform in stand still condition (mode 5).

VI. CONCLUSION

In order to tackle the range anxiety of using EVs and decrease the system cost, a combination of the PV panel and SRM is proposed as the EV driving system.

The main contributions of this paper are:

- (i) A tri-port converter is used to coordinate the PV panel, battery and SRM.
- (ii) Six working modes are developed to achieve flexible energy flow for driving control, driving/charging hybrid control and charging control.
- (iii) A novel grid-charging topology is formed without a need for external power electronics devices.
- (iv) A PV-fed battery charging control scheme is developed to improve the solar energy utilization.

Since PV-fed EVs are a greener and more sustainable technology than conventional ICE vehicles, this work will provide a feasible solution to reducing the total costs and CO₂ emissions of electrified vehicles. Furthermore, the proposed technology may also be applied to similar applications such as fuel cell powered EVs. Fuel cells have a much higher power density and are thus better suited for EV applications.

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