A PARTICULAR TRI-PORT HIGH-CONTROL CONVERTER FOR SRM BASED PLUG-IN HYBRID ELECTRIC TRUCKS

***DURGAM KUMARASWAMY*[1] *M. PAVAN KUMAR*[2] *Dr. K .VINAY KUMAR*[3]**
[1]*Associate professor, HOD Department of EEE, SVS Institute of Technology, Bheemaram, Warangal, TS, India*
[2]*Assistant professor, Department of EEE, SVS Institute of Technology, Bheemaram, Warangal, TS, India*
[3]*Assistant professor, Department of EEE, SVS Institute of Technology, Bheemaram, Warangal, TS, India*

ABSTRACT

Switched reluctance motors (SRMs) are one of the well-known decisions for PHETs applications because of attributes of rear earth free, high starting torque, wide-speed range and good fault tolerance to internal failure. Typically, in excess of two converters are expected to accomplish adaptable vitality change among various electrical energy parts on board, i.e., generator, battery bank, and engine. High-control converters ought to be utilized to drive the trucks that possess the constrained on-board space. Besides, an additional converter is likewise expected to accomplish AC network associating charging. Every one of these converters make the on-board power electronics converter confounded. In this paper, a particular tri-port high-control converter for SRM based PHETs is proposed to join the various electrical energy segments into one converter. The measured tri-port high-control converter can bolster adaptable energy stream, as well as help parallel and arrangement twisting associations as indicated by various conditions. Moreover, AC grid associating nodes are additionally created in the drive, which enables the proposed converter to fill in as a framework interfacing charger without additional facilities. The simulation and examinations are utilized to check the practicality of the proposed converter and relating control procedures.

Key words: *SRM, Tri-port, plug-in hybrid electric trucks , converter, winding connection*

1. INTRODUCTION

PHETs combine the merits of the electrical vehicles and hybrid electrical vehicles, which have a longer running time, flexible grid connection interface and acceptable cost [6]-[9]. Compared to permanent magnet synchronous motors (PMSMs), switched reluctance motors (SRMs) have simple structure with no rotor windings and permanent magnets made from rare-earth materials, and only silicon steel and stator windings are needed. Therefore, these motors have the capability of working for a long time under harsh environment due to their rugged structure [10]-[12].

SRMs also have other advantages such as high efficiency, low cost, good fault tolerance operation, and high starting torque for initial acceleration. Hence, they are considered as a potential candidate for drive trains of PHETs [13]-[21]. Although PHET is a promising green transport solution, there are two challenges on electrical energy conversion of PHETs. The first one is on-board high power electrical energy conversion. For series type hybrid electrical vehicles, there are three main electrical energy components including generator, battery bank and driving motor, respectively.

In order to optimize operation efficiency, flexible energy flows among those energy components are needed. For PHETs, an AC-DC converter is also needed to achieve the charging function [22]. To equip with these energy conversion functions, at least two power electronics converters are needed to link the generator, battery bank and SRM. For example, a DC-DC converter is needed to connect the battery bank with the generator and motor [23]. However, the on-board space is limited, and the bus voltage control and coordination control of converters also increase the control complexity and decrease the reliability of the on-board energy conversion equipment. Therefore, it is important to integrate all the converters together to give a more compact solution for on-board energy conversion [24]. The other challenge is AC grid-connected charging [25]. The massive construction of charging stations not only occupies limited city land, but also needs large funding investment. The locations must be carefully chosen, which impedes the wide application of PHETs.

To deal with those two challenges, several solutions have been proposed. In the switched reluctance motor operates under AC mains or a low voltage battery supply by using the proposed circuit. The motor can also be utilized as a voltage-changing transformer without increasing the system cost. For the electric vehicle (EV) application background, by integrating a bidirectional AC-DC charger with a DC-DC converter, the on-board energy conversion can be simplified.

In this case, the charging system can control energy flow between the high voltage bus and the battery bank. However, its circuitry is complicated and the available power flow modes are limited. An integrated driving/charging SRM drive for EVs is presented. A Miller converter and a fronted DC-DC boost converter are constructed by using two intelligent power modules (IPMs), which improve the driving performance by adopting the proper control strategies. In order to reduce the cost and weight effectively for hybrid vehicles, a new concept is proposed to integrate the DC-DC converter functionality into the traction drive system, in which the inverter and the machine can be utilized to implement a primary bridge leg of an isolated full-bridge DC-DC converter. In a converter is presented to combine motoring and charging functions. However, an auxiliary winding is connected to one SRM phase winding, which increases the complexity and inconvenience of the system.

Multiphase induction machine and its driving topology are employed to achieve charging without charging station, while the stator structure have to be changed and switching devices number is triple compared with a traditional induction machine. Split-phase technology has been used in permanent-magnet (PM) machines. A 20 kW PM motor drive is specially designed and its traction/charging modes are controlled by a switch based relay, but the motor suffers from high harmonic contents in the back electromotive force (EMF). For SRM based EVs, charging without charging station technology has been explored. A 2.3kW SRM with an asymmetrical half-bridge converter can provide on-board charging and power factor correction functions for EV applications. However, a boost-type front-end DC-DC converter is externally equipped, making this topology less practical and flexible for the target application. In summary, the current technologies cannot give satisfactory solutions to the proposed challenges, because there are mainly two drawbacks in existing technologies for the PHET applications. (1) The state-of-the-art on-board converters only achieve converter integration for EV applications; while for the PHET applications, more energy components are on board; no integration converter has been reported yet, which combine generator, battery bank and motor in one converter and also support flexible energy flows. Especially for high power level background, no solutions have been put forward yet. (2) Charging technology without charging station has been explored in induction machines, PMSMs and SRMs. However, either complicated motor structure or power electronics topology is used to achieve the grid-connection function.

2. PROPOSED SYSTEM

2.1Proposed Tri-port Topology

The proposed tri-port topology for three-phase 12 slots 8 poles SRM based PHET is presented in Fig.1. A1, A2, A3 and A4 are the phase A windings. Na1 and Na2 are the AC grid connecting points, and *S1~S8* are the Insulated Gate Bipolar Transistors (IGBTs). Phase B and phase C have the same topology with phase A. The proposed topology has a modular structure that is convenient for massive production. Two single-phase inverters are employed for each phase. Compared with the traditional asymmetrical half-bridge driving topology for SRM, the proposed converter is easier to manufacture.

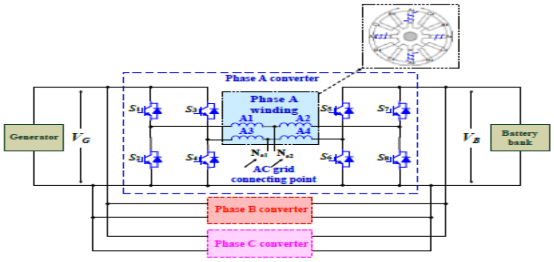
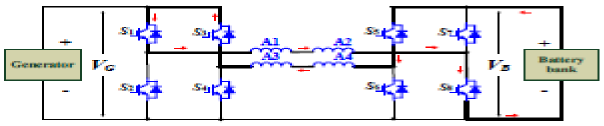


Fig. 1. Proposed tri-port high power SRM driving topology.

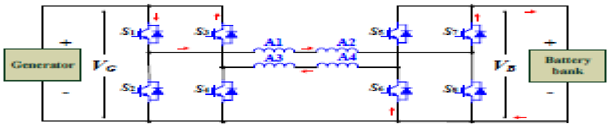
2.2 One Source Driving Mode with Series Winding Connection

Phase winding connected in series is a traditional driving mode for SRM operation. For example, in phase A, the windings A1, A2, A3 and A4 are connected in series, as shown in Fig.2. When turning on *S1*, *S3*, *S5* and *S8*, the battery bank supplies energy to the windings, as illustrated in Fig.2 (a). When turning on *S1*, *S3*, *S6* and *S7*, windings energy is recycled to battery bank, as shown in Fig.2 (b). By conducting *S1*, *S3*, *S5*, and *S7*, the motor is in the freewheeling state, as shown in Fig.2(c). Apart from the situation that the battery bank supplies energy to the motor, the generator can also supply energy to the motor; when turning on *S1*, *S4*, *S5* and *S7*, the generator supplies energy to the windings, as illustrated in Fig.2 (d). When turning on *S2*, *S3*, *S5*, and *S7*, the energy in the windings is recycled to the generator, as illustrated in Fig.2 (e). The motor can also work in the freewheeling state, as presented in Fig.2 (c).

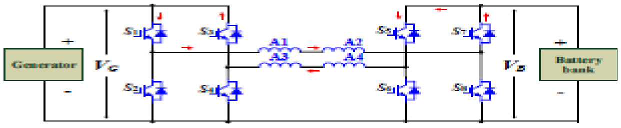
For one source driving mode with series winding connection, the PHETs can work at low speed running.



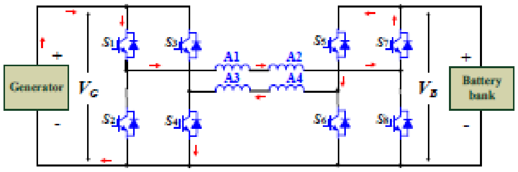
(a) Battery bank supply energy state 1



(b) Battery bank supply energy state 2



(c) Freewheeling state



(d) Generator bank supply energy state 1

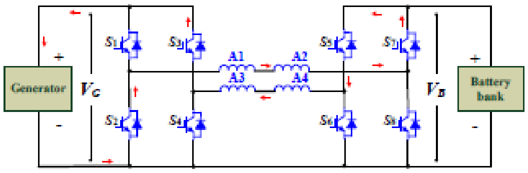
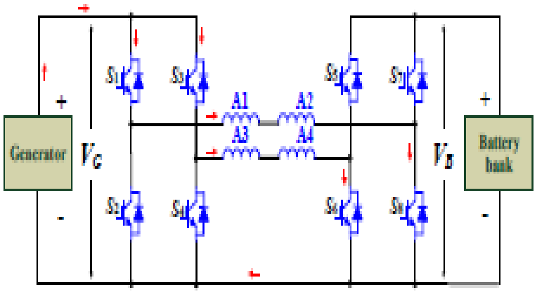


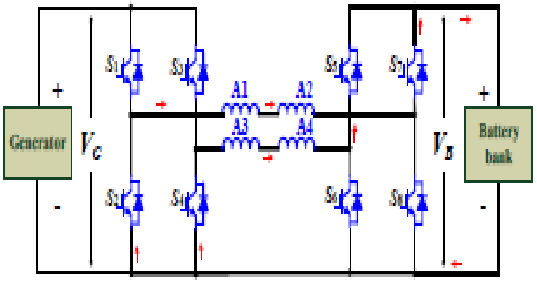
Fig. 2. Series winding connection driving mode.

2.3 One Source Driving Mode with Parallel Winding Connection

The proposed topology can also support SRM working in parallel winding connection mode. In phase A, the winding A1 and A2 are connected in series; A3 and A4 are connected in series; windings A1 and A2 are parallel with windings A3 and A4. When turning on *S1*, *S3*, *S6* and *S8*, the generator supplies energy to the windings, as illustrated in Fig.3 (a). When turning on *S2*, *S4*, *S5* and *S7*, windings energy is recycled to the battery bank, as shown in Fig.3 (b). By conducting *S2*, *S4*, *S6* and *S8*, the motor is in the freewheeling state, as shown in Fig.3 (c). In the parallel driving mode, the energy supply source and energy recycling source are different, which can be employed for tri-port energy conversion. As shown in Fig.3, the energy from the generator is delivered to the SRM and battery bank simultaneously. Furthermore, since the phase windings are connected in parallel, the equivalent phase inductance is lower than that in series connection and the corresponding phase current increases faster. For one source driving mode with parallel winding connection, the PHETs can work at high speed running.



(a) Excitation state under parallel driving mode



(b) Energy recycling under parallel driving mode

Fig. 3. Parallel winding connection driving mode.

2.4. Dual Source Driving Mode

By controlling switching devices, both the generator and battery bank can supply energy to the motor. Turning on *S2* and *S7*, the battery bank supplies energy to windings A1 and A2; by turning on *S3*, *S6*, the generator supplies energy to windings A3 and A4. When *VG* equals *VB*, the whole circuit is equivalent to the case that the generator and the battery bank are connected in series to supply energy to series windings A1~ A4. When *S1* and *S8* are turned on, the energy in windings A1 and A2 is recycled to the generator; by turning on *S4* and *S5*, the energy in windings A3 and A4 is recycled to the battery bank. When *S2*, *S4*, *S5* and *S7* are on, the windings are in the freewheeling state, as illustrated. For dual source driving mode, the PHET can output maximum power that supports PHET starting and accelerating scenarios. In this working mode, the phase current.

2.5. Tri-port Driving Mode

When the output power of the generator is higher than the required value, the tri-port driving mode can be employed to achieve energy balance.

Both series winding connection working mode and parallel winding connection working mode can support tri-port driving mode.

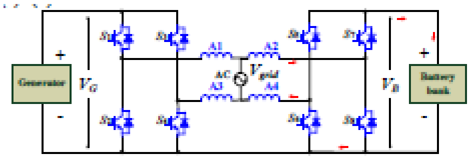
When the proposed converter is in series working mode, the generator can supply energy to the SRM and battery bank at the same time. During this state, the generator supplies energy to generate torque. The energy recycling state is the same as the situation. During the recycling state, the battery bank is charged by the energy from the phase winding storage. Therefore, the motor driving and battery charging can be simultaneously achieved. When the proposed converter is in parallel working mode, the generator can also supply energy to the SRM and battery bank at the same time. In this driving mode, the excitation state in which the generator supplies energy to phase windings. Then, the energy recycling state is which the windings energy is recycled to the battery bank.

2.6. Energy Charging/Discharging between the Generator and Battery

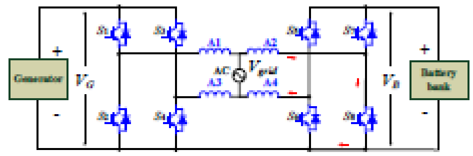
When PHET is in standstill mode, the battery bank needs to be charged. In this scenario, the proposed converter can work as a DC-DC converter. The converter working states are the same as the winding parallel connecting driving mode. When the internal combustion engine (ICE) needs to start in PHET, the battery bank can supply energy to the generator/starter with the proposed converter, which is similar to the case that the generator supplies energy to the battery bank.

2.7. AC Grid Charging

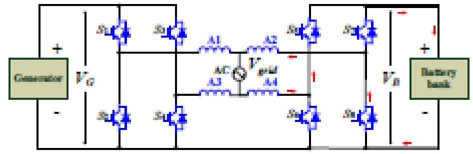
The proposed converter can connect with power grid directly to charge the battery bank. The central tapped nodes Na1 and Na2 can be employed to connect with the power grid. The corresponding four working states are presented in Fig. 4 (a)~(d).



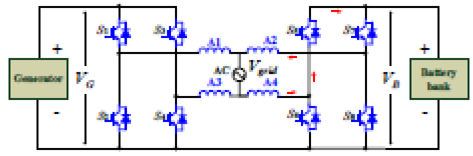
(a) Grid connecting charging state 1



(b) Grid connecting charging state 2



(c) Grid connecting charging state 3



(d) Grid connecting charging state 4

Fig. 4. Grid connecting charging

For high power charging, three phase AC grid connecting can also be realized by connecting Na1 and Na2 together to formthe charging point Na12. Similar grid connecting charging points Nb12 and Nc12 can be formed, as shown in Fig. 5.

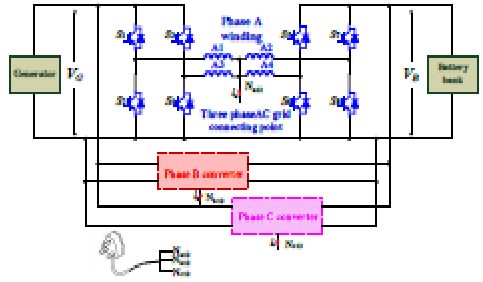


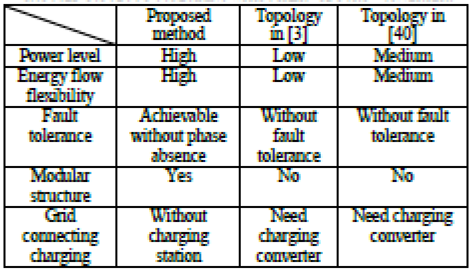
Fig. 5. Three phase AC grid charging connecting

2.8 Comparison with the State-of-the-Art Tri-port Topologies

In the proposed topology, although the total solid state device number is increased compared with the traditional asymmetrical half bridge topology, the voltage stress of solid state devices is decreased by the decentralized topology, which will benefit the cooling design. Also, the standard full bridge module structure makes the proposed converter easy and low cost to massive produce.

In paper [39], a high power level DC-DC converter is employed to connect the battery bank to the DC bus in a hybrid power train, which needs a lot of solid state devices and passive components, while in the proposed tri-port topology, the battery bank, generator, and motor are combined in one converter. Therefore, the total number of solid state devices is not increased obviously.

TABLE I
PROPOSED TOPOLOGY COMPARING WITH OTHER TRI-PORT CONVERTERS



	Proposed method	Topology in [3]	Topology in [40]
Power level	High	Low	Medium
Energy flow flexibility	High	Low	Medium
Fault tolerance	Achievable without phase absence	Without fault tolerance	Without fault tolerance
Modular structure	Yes	No	No
Grid connecting charging	Without charging station	Need charging converter	Need charging converter

Table I shows the comparison of proposed converter and other tri-port converters for SRMs, which illustrates the advantages of the proposed converter over the-state-of-art converters. Paper is the solution for small power level hybrid electrical vehicle; paper gives a medium power level solution; while the proposed converter gives a solution for high power level electrical power train. Due to the high power level application background, the corresponding fault tolerance, modular structure and flexible energy flow characteristics are needed in the proposed converter. Furthermore, charging without charging station technology is explored in the proposed converter.

3. PROPOSED CONTROL STRATAGY

3.1Modeling of SRM with Different Winding Connecting Modes

Considering the complicated electromagnetic characteristic caused by the double salient structure of SRMs, the linear mathematical model of SRMs is adopted for convenient analysis. Under the hypothesis of the linear model, the profiles of the phase inductance and phase current in different rotor positions are illustrated in Fig6, where i is the phase current; L is the phase inductance; θon and θoff are the turn-on and turn-off angles, respectively. The phase inductance increases linearly from the unaligned position θ2 to the aligned position θ3, and the phase current decreases to zero at the rotor position θ=θ4.

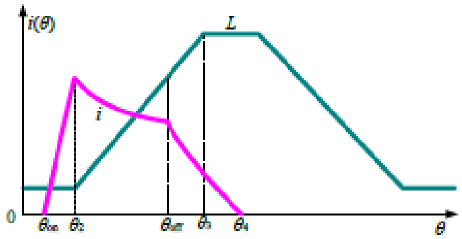


Fig. 6. Profiles of phase inductance and phase current

The phase current in different conduction regions can be expressed as

$$i_k(\theta)=\begin{cases}\dfrac{U_{in}}{\omega_r}\dfrac{\theta-\theta_{on}}{L_{\min}}, & \theta_{on}\le\theta<\theta_2\\[2ex] \dfrac{U_{in}}{\omega_r}\dfrac{\theta-\theta_{on}}{L_{\min}+K(\theta-\theta_2)}, & \theta_2\le\theta<\theta_{off}\\[2ex] \dfrac{U_{in}}{\omega_r}\dfrac{2\theta_{off}-\theta_{on}-\theta}{L_{\min}+K(\theta-\theta_2)}, & \theta_{off}\le\theta<\theta_3\\[2ex] \dfrac{U_{in}}{\omega_r}\dfrac{2\theta_{off}-\theta_{on}-\theta}{L_{\max}}, & \theta_3\le\theta<\theta_4\\[2ex] 0, & others\end{cases} \tag{1}$$

where *L*min and *L*max are the minimum and maximum of the phase inductance, and *K* is the slope factor of the phase inductance. The phase current reaches its peak value at the position *θ*=*θ*2, which is expressed as

$$i_{max}=\frac{U_{in}}{\omega_r}\frac{\theta_2-\theta_{on}}{L_{\min}} \tag{2}$$

For the proposed tri-port topology, the branch inductance is half of its original value under the winding parallel and dual source driving modes, which causes the slope factor to be reduced by half. According to (1) and (2), the current peak value of each parallel branch is twice as the one under the winding series driving mode due to the inductance decrease. For the conventional single pulse-APC and voltage-PWM control strategies, the increment of current peak value brings a series of unexpected consequences, such as low efficiency and high torque ripple. In order to diminish the negative influence caused by the winding parallel connection, the proper hysteresis of the turn-on angle is necessary, as shown in Fig. 7.

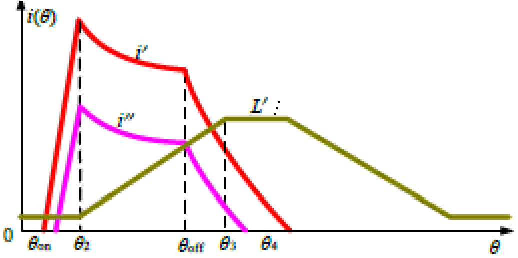


Fig. 7. Turn-on angle under APC and PWM schemes

3.2Control Strategy for Driving Mode

When the proposed tri-port converter is in SRM driving mode, the topology of the system is the same as the traditional asymmetrical half bridge topology; the voltage-PWM control and current chopping control (CCC) are adopted as two basic control schemes. According to the given speed ω*, the controller works in CCC strategy under low-speed condition, and the controller works in voltage-PWM control strategy under high-speed condition. The whole control block diagram is presented in Fig.8. The classical proportional integral (PI) algorithm is used in speed controller to regulate the SRM speed. An encoder gives the SRM rotor position information and the corresponding motor speed can be calculated by a micro-controller. The turn-on and turn-off angles of SRM are determined by a commutation controller. In the CCC strategy, the phase current is the control variable. The real-time phase current is measured by a current sensor, and the phase current reference i* is derived from the speed controller. The hysteresis controller is employed to generate the driving signal for switching devices. In the voltage-PWM control system, the phase voltage is the control variable. According to the speed error, the effective phase voltage is controlled by the duty ratio of the switching signal.

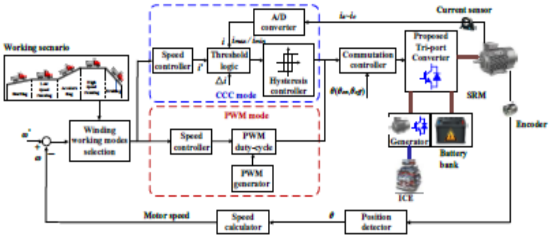


Fig.8. SRM control strategy under driving mode.

4.SIMULATION RESULTS

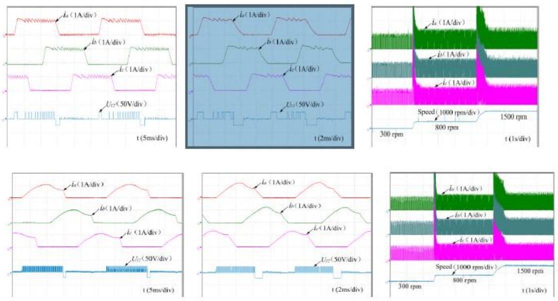
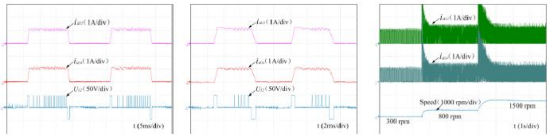
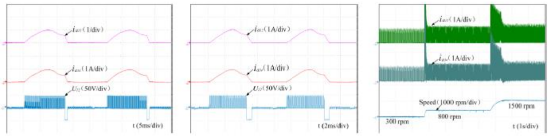


Fig 9.Simulation results under windings series driving mode

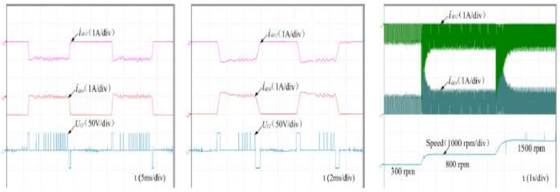


(a) 300 rpm under CCC scheme (b) 800 rpm under CCC scheme (c) Acceleration operation under CCC scheme

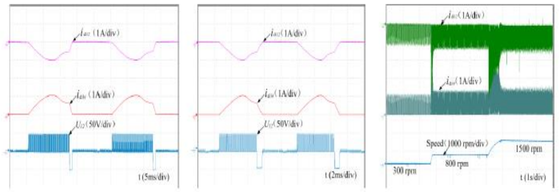


(d) 300 rpm under PWM scheme (e) 800 rpm under PWM scheme (f) Acceleration operation under PWM scheme

Fig. 10. Simulation results under windings parallel driving mode.



(a) 300 rpm under CCC scheme (b) 800 rpm under CCC scheme (c) Acceleration operation under CCC scheme



(d) 300 rpm under PWM scheme (e) 800 rpm under PWM scheme (f) Acceleration operation under PWM scheme

Fig. 11 Simulationresults under dual source driving mode

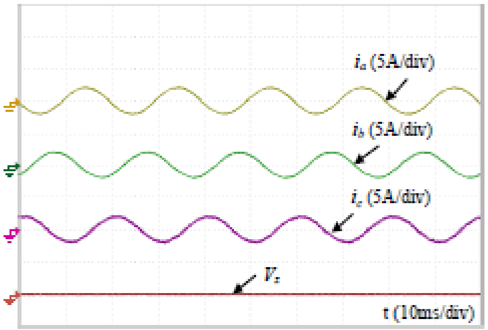


Fig. 12. Waveform of grid connected three phase AC charging.

CONCLUSION

SRM has been employed as the motor for the PHET application in this paper. In order to achieve flexible energy flow control of PHET, this paper has proposed a tri-port converter with modular and concise structure to combine a generator, a battery bank and an SRM into one converter; and the corresponding working modes and control strategies are investigated in details. The main contributions of this paper are:

(i) The proposed tri-port converter combines three on-board energy components together. The proposed converter is with the characteristics of high power level and modular structure that supports massive production.

(ii) A novel tri-port high power converter for PHET is proposed that supports flexible energy flow control. Under driving condition, the proposed topology supports five energy flow modes including generator to SRM, battery bank to SRM, generator and battery bank to SRM, generator to SRM and battery bank, and battery bank to SRM and generator; under standstill condition, the proposed topology supports two energy flow modes including generator to battery bank and battery bank to generator.

(iii) In order to cooperate with the six working modes, the corresponding control strategies are developed to achieve flexible energy flow control.

REFERENCES

[1]K. J. Dyke, N. Schofield, and M. Barnes，"The impact of transport electrification on electrical networks," *IEEE Trans. Ind. Electron.*, vol. 57, no. 12, pp. 3917- 3926，Dec. 2010.

[2] B. K. Bose, "Global energy scenario and impact of power electronics in 21st century," *IEEE Trans. Ind. Electron.*, vol. 60, no. 7, pp. 2638-2651, Jul. 2013.

[3] Y. Hu, X. Song, W. Cao, and B. Ji, "New SR drive with integrated charging capacity for plug-in hybrid electric vehicles (PHEVs)," *IEEE Trans. Ind. Electron.*, vol. 61, no. 10, pp. 5722-5731, Oct. 2014.

[4]B. Ji, X. Song, W. Cao, V. Pickert, Y. Hu, J. W. Mackersie, and G. Pierce, "In situ diagnostics and prognostics of solder fatigue in IGBT modules for electric vehicle drives," *IEEE Trans. Power Electron.*, vol. 30, no. 3, pp. 1535-1543, Mar. 2015.

[5] S. Morimoto, O. Shohei, Y. Inoue, and M. Sanada, "Experimental evaluation of a rare-earth-free PMASynRM with ferrite magnets for automotive applications," *IEEE Trans. Ind. Electron.*, vol. 61, no. 10, pp. 5749-5756, Oct. 2014.

[6]S. S. Williamson; A. K. Rathore; F. Musavi, "Industrial electronics for electric transportation: current state-of-the-art and future challenges," *IEEE Trans. Ind. Electron.*, vol. 62, no. 5, pp. 3021 - 3032, May. 2015.

[7] C. C. Chan, Alain Bouscayrol, and Keyu Chen, "Electric, hybrid, and fuel-cell vehicles: architectures and modeling, " *IEEE Trans. Veh. Technol.*, vol. 59, no. 2, pp 589-598, Feb. 2010.

[8]O. C. Onar, J. Kobayashi, and A. Khaligh, "A fully directional universal power electronic interface for EV, HEV, and PHEV Applications," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5489-5498, Dec. 2013.

[9] S. Dusmez, and A. Khaligh, "A compact and integrated multifunctional power electronic interface for plug-in electric vehicles," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5690-5701, Dec. 2013.

[10] Miller T. J. E. "Switched reluctance motors and their control," London: Magna Physics Publishing and Oxford Science, 3-25, 1993.

[11] J. Ye, B. Bilgin, and A. Emadi, "An extended-speed low-ripple torque control of switched reluctance motor drives," *IEEE Trans. Power Electron.*, vol. 30, no. 3, pp. 1457-1470, Mar. 2015.

[12] W. Cai, and F. Yi, "An Integrated Multiport Power Converter With Small Capacitance Requirement for Switched Reluctance Motor Drive," *IEEE Trans. Power Electron.*, vol. 31, no. 4, pp. 3016-3026, Apr. 2016.

[13] K. Kiyota, T. Kakishima, and A. Chiba, "Comparison of test result and design stage prediction of switched reluctance motor competitive with 60-kW rare-earth PM motor," *IEEE Trans. Ind. Electron.*, vol. 61, no. 10, pp. 5712-5721, Oct. 2014.

[14] Y. Hu, X. Song, W. Cao, and B. Ji, "New SR drive with integrated charging capacity for plug-in hybrid electric vehicles (PHEVs)," *IEEE Trans. Ind. Electron.*, vol. 61, no. 10, pp. 5722-5731, Oct. 2014.

[15] K. M. Rahman, B. Fahimi, G. Suresh, A. V. Rajarathnam, and M. Ehsani, "Advantages of switched reluctance motor applications to EV and HEV: design and control issues," *IEEE Trans. Ind. Appl.*, vol. 36, no. 1, pp. 111-121, Jan./Feb. 2000.

[16] X.D.Xue, K.W.E Cheng, T.W. Ng, N.C. Cheung, "Multi-objective optimization design of in-wheel switched reluctance motors in electric vehicles," *IEEE Trans. Ind. Electron.*, vol.57, no.9, pp.2980-2987, Sept. 2010.

[17] S. Wang, Q. Zhan, Z. Ma, and L. Zhou, "Implementation of a 50-kW four-phase switched reluctance motor drive system for hybrid electric vehicle," *IEEE Trans. Magn.*, vol. 41, no. 1, pp. 501-504, Jan. 2005.

[18] K. W. Hu, P. H. Yi, and C. M. Liaw, "An EV SRM drive powered by battery/supercapacitor with G2V and V2H/V2G capabilities," *IEEE Trans. Ind. Electron.*, vol. 62, no. 8, pp. 4714-4727, Aug. 2015.

[19] Z. Q. Zhu, and D. Howe, "Electrical machines and drives for electric, hybrid, and fuel cell vehicles," *Proceedings of the IEEE*, vol. 95, no. 4, pp. 746-765, Apr. 2007.

[20] B. Bilgin, A. Emadi, and M. Krishnamurthy, "Comprehensive evaluation of the dynamic

performance of a 6/10 SRM for traction application in
PHEVs," *IEEE Trans. Ind. Electron.*, vol. 60, no. 7, pp. 2564-2575, Jul. 2013.

[21] M. Krishnamurthy, C. S. Edrington, A. Emadi, P. Asadi, M. Ehsani, and B. Fahimi, "Making the case for applications of switched reluctance motor technology in automotive products," *IEEE Trans. Power Electron.*, vol. 21, no. 3, pp. 659-675, May 2006.

[22] A. Emadi, Y. J. Lee, and K. Rajashekara, "Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2237–2245, Jun. 2008.

[23] A. J. Forsyth and G. Calderon-Lopez. "Sampled-data analysis of the dual-interleaved boost converter with interphase transformer". *IEEE Trans. Power Electron.*, vol. 27, no. 3, pp.1338–1346 Mar. 2012.

[24] S. Haghbin, S. Lundmark, M. Alakula, and O. Carlson, "Grid-connected integrated battery chargers in vehicle applications: Review and new solution," *IEEE Trans. Ind. Electron.*, vol. 60, no. 2, pp. 459–473, Feb. 2013.

[25] J. D. Santiago et al., "Electrical motor drivelines in commercial allelectric vehicles: A review," *IEEE Trans. Veh. Technol.*, vol. 61, no. 2, pp. 475–484, Feb. 2012.