An SRM Cascade Converter For Hybrid Electric Vehicles

Hamid Malekpoor[1], Amir Rashidi, Sayed Morteza Saghaian Nejad

Department of Electrical and Computer Engineering Isfahan University of Technology[1]

Abstract: In hybrid vehicles, the electric motor and the combustion engine work as complements. In choosing the electric motor, the simplicity, cheap price, robustness and stability of the motor are considered, so the reluctance switch machine (SRM) is one of the best options. the beating heart of hybrid and electric vehicles is their drive, which is responsible for transferring energy from the battery to the electric motor, charging the batteries, and meeting different performance modes. In order to meet different performance modes, more battery modules are needed, and cascade topologies can improve the performance of the vehicle by taking advantage of this feature. In this article, a cascade topology is proposed, which in addition to having the advantage of creating different voltage levels, makes it possible to provide simultaneous charging and discharging for different modules, and this leads to the optimal use of electric energy in the hybrid vehicle, as well as by reducing diodes In the power path it tries to reduce losses and also it has the possibility of connecting to different drives of the reluctance switch machine.

Keywords: reluctance switched machine, hybrid vehicle, power electronics, cascade converter

Introduction

Today, greenhouse gases have increased due to various factors, including the excessive use of fossil fuels, because of researchers are looking for alternatives to fossil fuels in order to reduce the risk of increasing greenhouse gases, Using hybrid and electric vehicles is one of the best alternatives [1,2]. In electric vehicles only the electric motor is used, and in hybrid cars, the combustion engine and electric motor are used in a complementary manner. It can be said that hybrid vehicles are a more suitable option than electric vehicles due to the possibility of charging by the combustion engine Therefore, there is no need for charging stations and it is more practical for less developed areas. One of the suitable options for to choose electric motor is a permanent magnet synchronous motor due to it's high power density and high efficiency [3]. But due to the presence of permanent magnet in this motor, the costs increase in mass production and also the resources to provide it are limited, therefore the researchers are looking for a suitable alternative for this motor, which is one of the suitable options the reluctance switch motor. The advantage of this machine compared to the synchronous motor and other electric motors is the lower cost due to the lack of permanent magnet and the absence of coils in the rotor increases the mechanical resistance of the motor, as well as the stability of this motor and its ability to be used in unsuitable environments [5,4]. the reluctance switch motor needs a converter to meet the excitation and demagnetization modes, which is one of the most famous among the asymmetric bridge converter [6]. in the application of the reluctance switch motor For electric and hybrid vehicles, there is a need to manage the battery module to supply the necessary energy for the motor phases, which creates the need for a front-end converter. Also, one of the issues that is being considered today is the need to charge the battery by another energy source such as gride. The gride can be used to charge the batteries when the engine is at rest therefore, it increases the use of electric and hybrid vehicles. For this reason, the attention of researchers has been drawn to hybrid vehicles connected to the grid Topologies are examples that have worked on this issue [7,8]. Also, in order to reduce the weight and cost of converters in the mentioned topologies, integrated converters are used. Researchers are interested in optimal use of the motor and the operation of the motor at the maximum power density, as well as eliminating the torque ripple and sound noise of the reluctance switch motor in different applications of this motor therefore different voltage levels can be used to supply energy. In this way, to provide different voltage levels, researchers have been drawn to cascade converters. Also, the use of cascaded converters helps to meet different motion demands [9] [10]. An important point in these converters is the presence of multiple diodes in the power path, which increases conduction losses. In the proposed topology, in addition to using the cascade converter to increase different voltage levels and create more performance modes to improve the performance of the motor in different road conditions, it was tried to reduce conduction losses by reducing the diodes in the power path. Also, in all the mentioned converters, when the vehicle is in motion and charge of the battery decrease

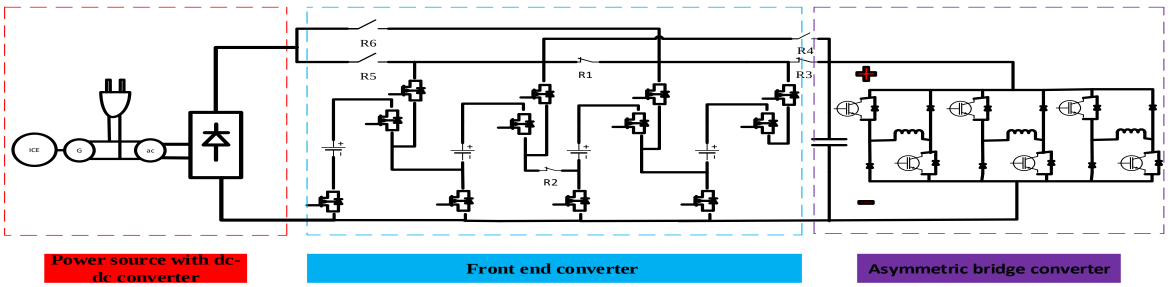

Figure1: diagram of proposed SRM converter topology

the combustion engine must provide both the necessary energy to charge the battery and the necessary force to move the wheels, which increases the volume of the combustion engine and Increases fossil fuel consumption, so the proposed topology makes it possible to charge and discharge different battery modules simultaneously by creating separate paths to save fossil fuel consumption and the volume of the combustion engine.

I. Proposed topology diagram

Figure 1 shows the details of the provided converter diagram. In the power sources section, which includes the combustion engine, generator and grid, the energy required to charge the batteries is provided, and these sources are supplied to the topology by the R_5 & R_6 relays when needed. there is a front converter and a DC-DC converter In the part marked with a blue line The front converter modularly provides as much battery as is needed to supply the excitation voltage of the SR motor and there are three switches in each module which can apply different operating modes and different voltages on the SRM also these switches have been used for DC-DC converter to save both costs and space. The topology is used relays in order to make the battery modules two by two independent from each other. when all the batteries are in a suitable state in terms of SOC and do not need to be charged relays 4 & 5 are open and Remaining relays are close. 5, 4, and 6 are placed in the unconnected state so that the excitation function is done by the four modules, as shown in Figure 1. The last part marked with a purple dashed line shows the asymmetric half-bridge, which has task providing magnetizing, demagnetizing, and freewheeling modes and by two switches installed for each phase the current is proportional to the on angles (ON) applies to the machine phase and returns the current in the OFF angles to dc link and it is prevented from entering the negative torque region. Also, when the phase current of the motor reaches its maximum value, the converter can do soft and hard switching. In soft switching, only one of the switches is turn off, and the current path continues through the other switch and one of the diodes, so that by applying zero voltage on the phase, the current decreases and does not exceed its maximum. In hard switching, both switches are turn off and the current path continues through the diodes and by applying a voltage with opposite polarity the current phase is reduced. In hard switching compared to soft switching losses are higher because the switches are turn off under voltage.

II. Generating mode

When the battery charge decreases Mechanical energy is converted into electrical energy by the combustion engine and then it is rectified and applied to the battery for charging. When the vehicle is resting or in the parking of the house the batteries can be connected to the grid for charging which increases the application of topology. In the proposed topology it is possible to charge and discharge batteries simultaneously by using relays. Therefore the energy of other modules can be used during charging mode to excite the SRM, thus reducing the use of combustion engine and reducing the consumption of fossil fuels. By using the switches in the front-end converter it is possible to charge flexibly in other words the batteries can be charged In pairs and singles as a result overcharging of the batteries is prevented which increase life of batteries.

III. SR machine in motoring mode & generating mode

The motor phase is excited in the positive slope of the inductance and the phase current increases and in the negative slope of the inductance it is demagnetized and the phase current decreases. The advantage of asymmetric bridge converter is maintaning independent of the phases well, which improves the performance of the machine. when the phase current exceed its maximum, soft switching is used For this purpose when the current reaches the maximum value one of the switches is turn off and the current is continued by the other switch and one of the two diodes In this mode zero voltage is placed on the phase and the current decreases with a soft slope compared to demagnetization until it reaches the lower limit of the current This mode makes the current stay between its upper and lower limits This mode is known as freewheeling mode. Excitation, freewheeling and demagnetization modes are shown in Figure 2. For the approach in generating mode the mechine is excited in negative torque generation and is demagnetaizated before entering in possitive torque generation.

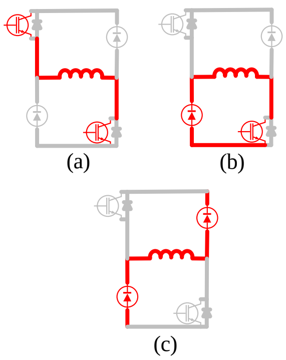

Figure 2: Functional modes of asymmetric bridge. a. Stimulation mode b. Stray fashion c. Demagnetization mode

The phase A voltage equations are as follows.

Phase A voltage in excitation mode

$$0 = Ri_a + \frac{d}{dt}\lambda(i,\theta) = Ri_a + L(i,\theta)\frac{di}{dt} + i\omega\frac{dL(i,\theta)}{d\theta} \quad 1$$

$$V_a = Ri_a + \frac{d}{dt}\lambda(i,\theta) = Ri_a + L(i,\theta)\frac{di}{dt} + i\omega\frac{dL(i,\theta)}{d\theta} \quad 2$$

Phase A voltage in freewheeling mode

$$0 = Ri_a + \frac{d}{dt}\lambda(i,\theta) = Ri_a + L(i,\theta)\frac{di}{dt} + i\omega\frac{dL(i,\theta)}{d\theta} \quad 3$$

Phase A voltage in demagnetaization mode

$$-V_a = Ri_a + \frac{d}{dt}\lambda(i,\theta) = Ri_a + L(i,\theta)\frac{di}{dt} + i\omega\frac{dL(i,\theta)}{d\theta} \quad 4$$

IV. Driving modes

These modes include the following parts according to the conditions shown in Figure 3. There are different functional modes that require different voltage levels. Based on Figure 3, the driving states and battery packs that should be placed on the machine phase to improve performance are as follows.

1. **Start**: two battery packs are used to make the motor speed faster and the torque is sufficient to overcome the inertia. In this mode, the vehicle's speed is lower than the base speed.
2. **Low speed:** in this mode, when the vehicle moves at a constant speed and at a speed lower than the base speed in the urban area, a battery pack is used to supply energy.
3. **Acceleration:** in this mode, when the vehicle is above the base speed and it is necessary to increase the speed, and therefore the vehicle needs acceleration and also in order for the produced torque to be able to overcome the friction well and provide the appropriate acceleration to reach the desired speed machine can use two, three or four battery packs according to its needs and batteries soc.
4. **High speed:** this mode shows the high base speed on the smooth road, the speed remains almost constant and in this mode since there is no need to provide acceleration a lower torque than acceleration mode is needed so the necessary energy is provided with two battery packs.
5. **Deceleration:** in braking mode, the SR machine acts as a generator and converts the mechanical energy in the wheels into electrical energy and stores it in the battery. In this mode to reduce the speed quickly the maximum available voltage can be used at speeds above the base speed and at speeds lower than the base speed two battery packs can be used to produce the reverse torque, or according to SOC considerations any number of packs can be used.

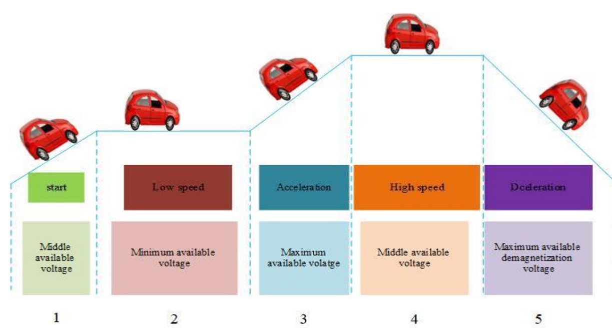

Figure 3: Different driving states

1. **Functional mode in driving 1 state**

According to battery management and based on soc, two consecutive battery packs are connected to the motor terminal to excited the motor, and for this purpose S_{n2} switches are turned on in two consecutive packs as shown in figure 4. (n is the module number)

1. **Functional mode in driving 2 state**

In this mode where the speed is low and constant, the voltage of a battery pack is placed on the phase and the appropriate battery pack is selected according to the soc. To transfer energy from the battery to the motor, the S_{n2} switch corresponding to each phase is turned on and during demagnetization, the S_{n1} and S_{n3} switches are turned on as shown in figure 5 & 6. (n is the module number)

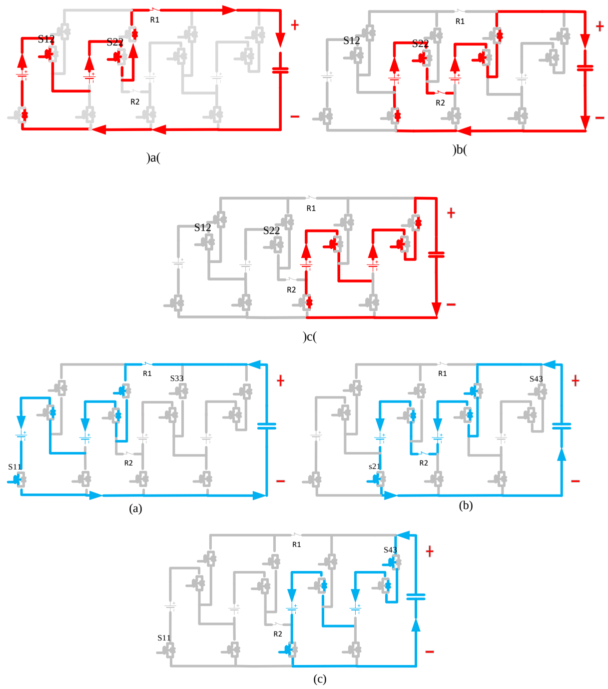

Figure 4: red paths shows functional condition in excitation mode by two battery packs. blue paths shows functional condition in demagnetization mode by two battery packs

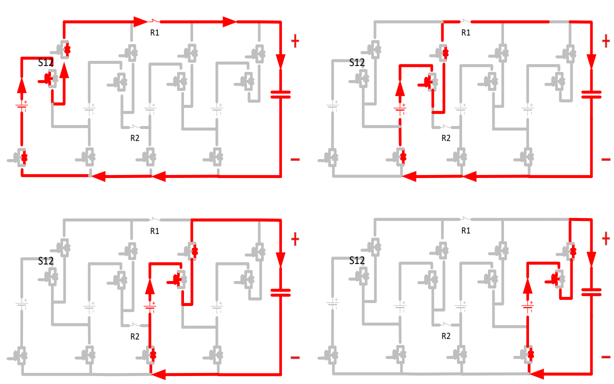

Figure 5: Constant low speed driving in excitation modes mode by a battery pack

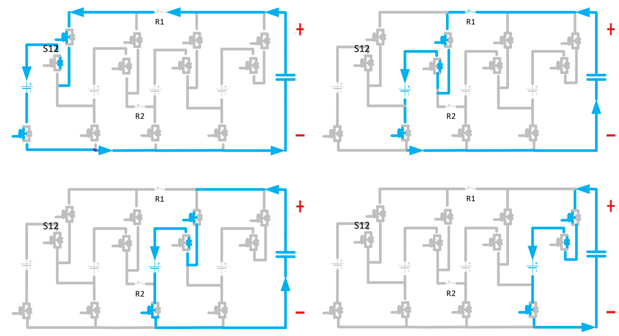

Figure 6: driving at constant low speed in demagnetization modes by a battery pack

2. **Functional mode in driving 3 mode**

In this mode, the vehicle is at high base speeds and the acceleration must be increased, therefore a high excitation voltage is needed which can be used two, three and or four consecutive packs according to the conditions and based on the soc. For this purpose S_{2n} switches are turned on in two, three or four consecutive packs as shown in figure 7. (n is the number of modules)

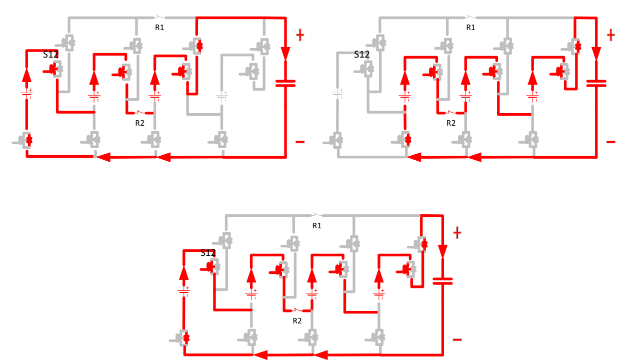

Figure 7: steady driving at above base speeds using by three or four battery packs

When there is a need for demagnetization in motion mode 3, the same battery packs that provided the necessary energy to the motor can receive the demagnetization energy. For this purpose as shown in Figure 8, in condition a switches S_{11} and S_{33} are turned on, in condition b switches S_{21} and S_{43} are turned on and in condition c switches S_{11} and S_{43} are turned on.

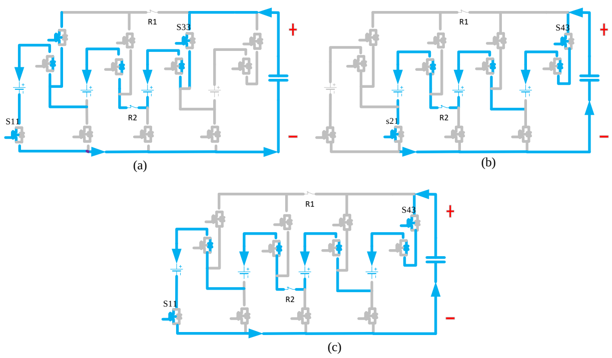

Figure 8: driving mode 3, steady driving at above base speeds in demagnetization mode

3. **Functional mode in driving 4 mode**

In this mode the speed is constant and also the speed is above of the base speed two battery packs are considered to supply the energy of the motor phases, the performance modes are as shown in Figure 4.

4. **Functional mode in driving 5 mode**

In this mode, when the vehicle brakes and the purpose is to reduce the speed, torque should be applied against the direction of movement thus the vehicle goes to the generator mode to reduce the speed faster and batteries modules are choosed according to the soc conditions and also based on the machine speed relative to the base speed. It is possible to connect two, three or four battery packs in series so that the voltage increases and the reverse torque produced increases and the speed of the machine decreases faster. If considered the speeds below the base speed, two battery packs are placed on the motor phase, and the excitation and demagnetization mode is the same as in Figures 4. If the machine is above the base speed, three to four battery packs are connected according to soc, and the excitation and demagnetization modes are the same as in Figures 7 and 8.

V. battery Charging by generator

When the battery charge is less than the specified value. The batteries are charged by the combustion engine and generator, for this purpose the batteries are separated from the excitation part in pairs using relays and are prepared for charging.

When the motor is excited by pack 3 and 4 respectively from the left side and packs 1 and 2 are connected to the generator for charging, in this mode the ac power source is connected to two modules 1 and 2 by relay R5 thus the path is provided for the charging operation and relays 1, 2, 4 and 6 are opened, and relay 3 remains closed to send energy to the motor. When switches S_{23} and S_{11} are turned on as shown in Figure 9-a, two battery packs 1 and 2 are charged and battery packs 3 and 4 are provided for excited. If battery pack 2 is charged earlier than battery pack 1, in order to prevent battery pack 2 from being overcharged, which causes damage to it, switch S_{23} is turned off and switch S_{13} is turned on as shown in Figure 9-b Battery 1 is charged and battery packs 3 and 4 are provided demagnetization mode. If battery packs 3 and 4 need to be charged based on soc then battery packs 1 and 2 perpare of excitation and demagnetization modes. In this mode, relays 1, 2, 3, and 5 are opened and relays 4 and 6 are closed as shown in Figure 10-a packs 3 and 4 are charging and packs 1 and 2 are provided for excitation mode. If during charging battery pack 4 is charged earlier than battery pack 3 then switch S_{43} will turn off and switch S_{33} will be turned on and only battery pack 3 will be charged to prevent battery pack 4 from being overcharged. In Figure 10-b pack 3 is charged and packs 1 and 2 are provided for demagnetization mode. If there is a situation where all the battery packs need to be charged based on the soc then the combustion engine is also provided for charging the battery packs and also is considered for providing the power necessary for the vehicle to move.

I. Charge battery by grid

In this case, by closing the relays R5, R1 and R2 and opening the relays R3 and R4, the flow path is provided for charging the batteries and the number of modules required for charging can be determined by the switches of each module. and as soon as the soc of a module reaches its maximum value it can be easily removed from the charging path. If switches S_{43} and S_{11} are turned on, all battery packs will be charged. If switches S_{33} and S_{11} or switches S_{43} and S_{21} are turned on battery packs 3, 2 and 1 and battery packs 2, 3 and 4 will be charged respectively. If switches S_{23} and S_{11} are turned on, or switches S_{33} and S_{21} are turned on and or switches S_{43} and S_{31} are turned on, packs 1 and 2, packs 2 and 3 and packs 3 and 4 will be charged respectively. To charge each pack independently can turned on the S_{n1} and S_{n3} switches of each module. (n is the module number). Functional modes when charging by the grid are shown in figures 11, 12 and 13.

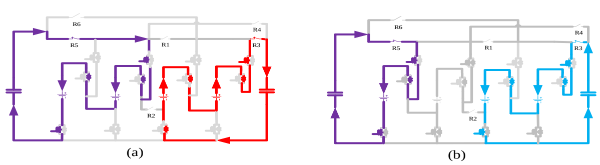

Figure 9: a. Battery packs 1 and 2 are charging, battery packs 3 and 4 are being excited b. Battery pack 1 is charging, battery packs 3 and 4 are being demagnetized

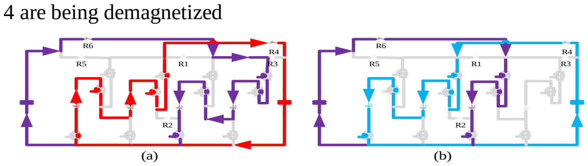

Figure 10: a. Battery packs 3 and 4 are charging Battery packs 1 and 2 are excited b. Battery pack 3 is charging, battery packs 1 and 2 are being demagnetized

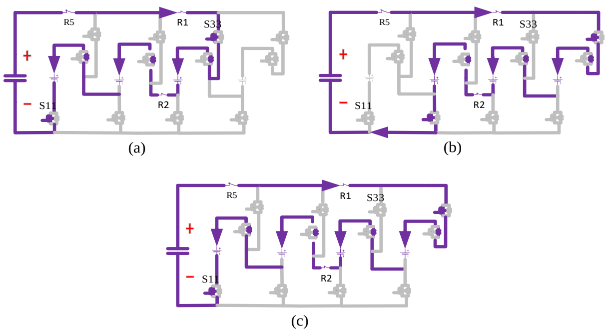

Figure 11: charging of three or four battery modules

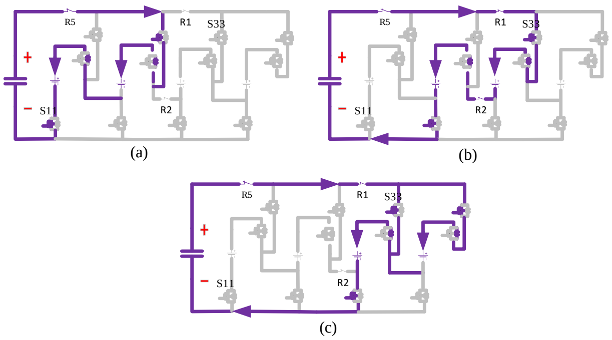

Figure 12: charging of two battery module

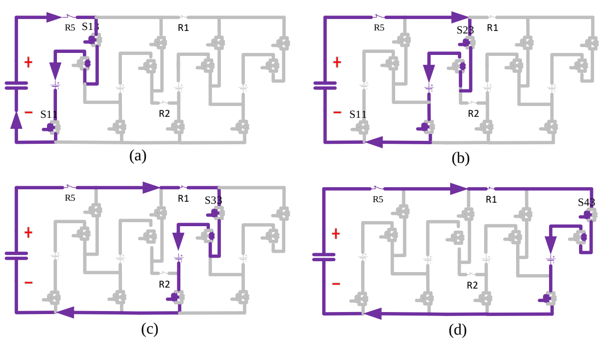

Figure 13: charging of a battery module

I. Control of preposed topology

In Figure 14, the schematic of the simulation of the proposed topology is shown. In the block of control of on & off angles the on and off angles are determined based on the driving and braking modes which determines the performance of the sr machine in the generator and motor modes. Based on the difference between the actual speed and the reference speed, the reference current is obtained which should be applied to the motor phases according to its on and off angles, and thus forms the switching pattern of the asymmetric bridge converter. The different levels of voltage supplying the phases of the sr machine are determined based on the soc of the batteries and different driving and braking modes. The front-end converter has the task to meet the need for the appropriate voltage level based on the priorities that are done by considering the soc of batteries and performance modes by performing appropriate switching, which the control block of front-end converter performs this task. in charge mode when the batteries want to be charged the control of the front converter has the task of preventing the overcharging of the battery packs in order to increase their useful life, and this is done by closing the flow path to the desired battery pack by turning off the corresponding switches, It can be done completely flexibly. The control of relay is done based on the soc status of the batteries in order to properly provide the flow path for charging and discharging the batteries.

II. Simulation results

1. Motoring and braking functional mode

First the reference speed reaches from zero to 1000 rpm thus in order to meet the required torque two battery modules (nominal voltage of each battery is 130 volts) are placed on the motor phase then when the speed reaches 0.05 of the reference speed only a module is prepared to excite the motor. the motor continues to move steadily at this speed for a while then starts to accelerate up to the reference speed of 2000 rpm which to meet the required torque according to soc the four modules is used and when the speed reaches 0.05 reference, two modules are placed to provide the necessary torque to drive at constant speeds above the base later the braking mode takes place until the machine reaches a speed of 1500 rpm and in this mode the srm enters the generator mode and the mechanical energy is converted into electrical energy. in this mode to create the reverse maximum torque at speeds above of the base The four battery pack is considered and can be used then the srm enters the motor mode for constant driving at this speed and finally the speed decreases until it reaches zero. Figure 15 shows the current & speed, the maximum current is set to 5 amps. In general in the acceleration situation at low speeds two battery packs are considered and at high speeds four, three and two battery packs are considered according to soc. figure 16 shows the waveform of the current in the acceleration mode and in the constant speed driving mode.

1. study the voltage of the capacitor on the machine phases

As it is clear in Figure 17, first the voltage increases to the size of two battery modules, i.e. 300 volts, and then when it reaches the reference speed of 1000 rpm, it

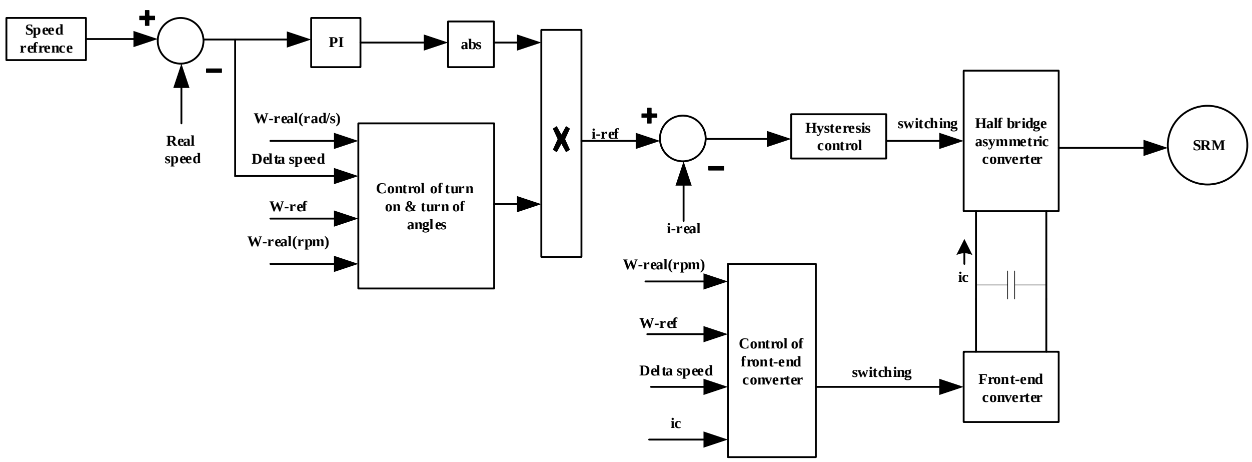

Figure14: control of proposed topology

decreases and reaches 150 volts. the maximum voltage is placed on the capacitor during acceleration above the base speed which causes the vehicle to operate quickly to reach the reference speed. In the braking mode if the speed is lower than the base speed the voltage of the capacitor is the size of two modules and if the speed is higher than base speed the maximum voltage is placed on the capacitor which makes the vehicle perform the braking mode with better performance.

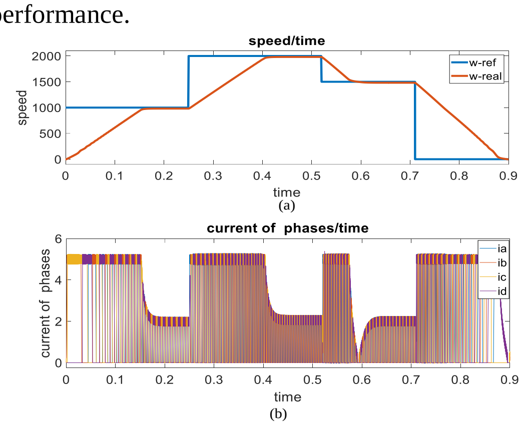

Figure 15: a. real speed & refrence speed b. four phase currents

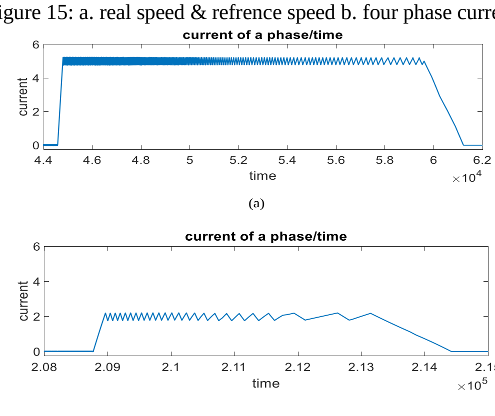

Figure 16: a. current in acceleration state b. current in steady state

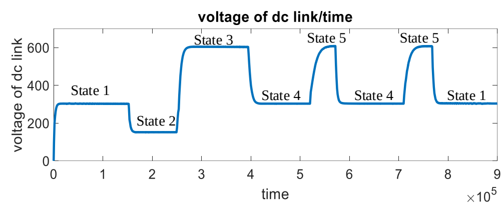

Figure 17: waveform of dc link capacitance voltage on the asymetric half bridge

I. Conclusion

The proposed topology improves the performance of the sr machine by creating different voltage levels, and by managing the charge and discharge of the batteries, it provides the possibility of operating in different motion. The complete independence of the front-end converter from the rest of the topology makes it possible for the front-end converter to be connected to all types of sr machine converters and dc-dc converters, thus increasing topology flexibility.

Refrences

[1] M. Ehsani, Y. Gao, and A. Emadi, Modern Electric, Hybrid Electric and Fuel Cell Vehicles Fundamentals, Theory, and Design, CRC Press, New York, 2010

[2] A. Khaligh and Z. H. Li, "Battery, Ultracapacitor, Fuel Cell, and Hybrid Energy Storage Systems for Electric, Hybrid Electric, Fuel Cell, and Plug-In Hybrid Electric Vehicles: State of the Art," *IEEE Trans. Veh. Technol.*, vol. 59, no. 6, pp. 2806-2814, Jul. 2010.

[3] 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.

[4] 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.
[5] M. Takeno, A. Chiba, N. Hoshi, S. Ogasawara, M, Takemoto and M. A. Rahman, "Test Results and Torque Improvement of the 50-kW Switched Reluctance Motor Designed for Hybrid Electric Vehicles," *IEEE Trans. Ind. Appl.*, vol. 48, no. 4, pp. 1327-1334, Jul./Aug. 2012.
[6] Bilgin, B, Jiang, J.W., Emadi, A, switched reluctance motor drives fundamentals to applications, Taylor & Francis, Boca Raton Londen New York, 2018.
[7] Ivan Subotic, Student Member, IEEE, Emil Levi, " A Review of Single-Phase On-Board Integrated Battery Charging Topologies for Electric Vehicles" IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD), 2015.
79
[8] Serkan Dusmez, Student Member, IEEE, and Alireza Khaligh, Senior Member, IEEE, " A Compact and Integrated Multifunctional Power Electronic Interface for Plug-in Electric Vehicles" IEEE Transactions on Power Electronics, 12 December 2012.
[9] Parneet Kaur Chowdhary1, Mohan P. Thakre2, "MMC-Based SRM Drives for Hybrid-EV with Decentralized BESS in Battery Driving Mode" International Conference on Power, Energy, Control and Transmission Systems (ICPECTS), 2020
[10] Qingguo Sun, Jianhua Wu, Chun Gan, Jikai Si, Jifeng Guo, and Yihua Hu, Senior Member, IEEE " Cascaded Multiport Converter for SRM-Based Hybrid Electrical Vehicle Applications" IEEE Transactions on Power Electronics, 03 April 2019.