Journal of Engineering Sciences
Vol 13, Issue 02, FEB / 2022
ISSN NO:0377-9254

A MODIFIED MULTIPORT CONVERTER FOR SRM BASED HYBRID ELECTRICAL VEHICLE APPLICATIONS

[1]MOHD AMAIR, [2]Dr. MD. QUTUBUDDIN
[1]M.Tech Student, [2]Associate Professor
Department of Electrical & Electronics Engineering
TKR COLLEGE OF ENGINEERING AND TECHNOLOGY(AUTONOMOUS), Medbowli, Meerpet, Saroornagar, Hyderabad-500097

ABSTRACT

SRM-based Hybrid Electrical Vehicle Applications using a Cascaded Multiport Converter Buses (HEBs) have lately attracted a lot of attention as a feasible means of public transportation in urban settings. The proposed fuzzy and PI driven cascaded multiport switched reluctance motor (SRM) drive for hybrid electric vehicle (HEV) applications not only allows for flexible energy conversion between the generator/ac grid, battery bank, and motor, but it also achieves a battery management (BM) function for state-of-charge (SOC) balance control and bus voltage regulation, among other things. By incorporating the battery packs into the AHB converter, the cascaded BM modules are intended to configure multilayer bus voltage and current capacity for fuzzy driven SRM drive. This may increase the torque capability and system efficiency by speeding up the excitation and demagnetization processes during the commutation area, extending the speed range, reducing the voltage stress on the switches, and increasing the speed range. The suggested converter has a number of driving modes, regenerative braking modes, and charging modes, all of which are tuned to satisfy the demands of different operations. More crucially, the BM technique allows each battery pack to be separately coupled to and detached from the power supply, greatly enhancing fault tolerance and making it much simpler to avoid overcharging and over discharging difficulties while the motor is operating.

I.INTRODUCTION

1.1 Introduction

Because of their lower fuel consumption and increased energy efficiency, electric cars (EVs) and hybrid electric vehicles (HEVs) have gained increasing interest in the wake of the rising worries about the fossil fuel crisis and environmental issues. Permanent magnet synchronous motors (PMSMs) have historically dominated the powertrain systems in electric vehicle (EV) and hybrid vehicle (HV) applications because of their higher torque and power densities. However, as a result of the increasing depletion and rising expense of rare-earth magnet sources, rare-earth-less and rare-earth-free motors are becoming greater popularity. When it comes to motors that are devoid of rare earth elements, switching reluctance motors (SRMs) are emerging as a potential alternative owing to their simple construction, cheap cost, remarkable durability, high dependability, and wide range of applications in severe environments. A large number of voltage-boosting converters are being developed for the SRM system in order to increase motor performance across a larger speed range. In order to accomplish quick current excitation and demagnetization operations, a four-level converter and a quasi-three-level converter are proposed, respectively. To minimize the overall harmonic distortion of supply current and the ripple of dc-link voltage, a three-level power factor correction (PFC) rectifier is included. A three-level converter with a neutral point diode clamp is being developed in order to increase system efficiency while also reducing current ripple and noise.

In this work, an integrated DC/DC boost converter with a PFC circuit is given. This converter can not only offer a bootable and well-regulated supply voltage under driving mode, but it can also accomplish excellent energy feedback capability under demagnetization mode. In order to increase the motor performance at high speeds while still achieving the battery charging function with excellent power quality, a modified Miler converter has been designed and built. In order to accomplish interoperability between the vehicle, the home appliance, and the utility grid, a bidirectional direct current to direct current circuit-based converter is given. Due to the introduction of a central-tapped node in each phase winding, the suggested tri-port converter may accomplish both parallel and series winding connections to meet the needs of various operating requirements. This work describes the development of a front-end circuit that implements a five-level driving scheme that is capable of significantly speeding up the excitation and demagnetization processes when the conduction zone is less than 15° for the three-phase 12/8 SRM.

Using solar panels as part of the proposed multiport architecture, it is possible to reduce the dependency on car batteries while simultaneously charging the battery bank. Despite the fact that a variety of multilevel and multiport converters have been previously proposed to support multiple driving and charging modes for improved motor performance, there are few schemes that take into account the battery management (BM) issue in SRM-based EV and HEV applications, according to the authors. Practical applications are prone to overcharge, over discharge, and potentially lethal damage to battery cells as a result of state-of-charge (SOC) imbalance caused by manufacturing variability and deterioration over time. This may result in the failure of a battery bank as a whole. To govern the energy conversion for electric vehicles and hybrid electric vehicles, an energy-efficient and highly reliable BM system is often needed. This is accomplished by dividing the whole battery bank into numerous battery packs that are linked in series, with each pack consisting of many battery cells that are connected in parallel. This allows the variable voltage level to be achieved while also providing a larger current capacity. The SOC balance is attained and the fault-tolerance ability is increased by regulating each cell with a single switch. It is proposed to use a cascaded multilayer inverter to perform the power distribution scheme, which may significantly increase the stability and reliability of the system by controlling each battery unit with a single inverter. Each battery cell is handled by a half-bridge converter, which produces a dc voltage that is a staircase. The development of a four-battery modulus-based BM converter is underway.

1.2 Literature Review

This work followed by **Qingguo Sun et al, IEEE 6th International Conference on Information and Automation for Sustainability, Beijing, 2012, pp. 258-261.**

This work represents that the chargers used in fast charging stations can handle high power ratings which greatly reduces the charging time and thus the ease of vehicular charging in less time. Therefore, larger amounts of currents are required in fast charging while feeding to the battery. When a large number of chargers are placed in a charging station, power degradation takes place which may affect the entire charging station along with the vehicles connected. The traditional charges use diode rectification at the secondary side of an isolated DC-DC converter. Due to diode rectifiers at the output side may cause some problems like high output harmonics, high absorption of reactive power from the grid and thus results in low input power factor. Due to this the life of the battery gets affected dissipating more heat around the battery. The transmission of reactive power from grid to vehicle causes step down voltage and reduces the power efficiency showing severe effect on voltage quality. To isolate electric vehicles during charging, a traditional converter has a grid frequency transformer which is bulky resulting in increasing the weight of the vehicle and costly. To overcome the above problems, DC charger can be designed with Phase Width Modulation (PWM) rectifier along with phase shift full bridge converter. The high frequency PWM charger makes the grid current sinusoidal in nature and thus reduces the total harmonic distortion and increases the power factor. In high power applications, DC charger is designed with PWM rectifier and with a phase shift full bridge converter. A prototype of a power rating 10kW charger is explained in this work.

The experimental analysis of this DC charger has better electrical characteristics and can be employed for fast charging applications in smart grids. Nowadays, EVs are more popular for energy conservation and environmentally friendly. The traditional charger design has diode rectifier topology cascaded with isolated DC-DC converter which causes reduction in power quality and efficiency. The proposed DC fast charger with PWM rectifier and phase shift converter is adapted in high power applications. This type of charger can reach unity power factor with low THD value i.e., 3%. The DC fast charger has good steady state and dynamic characteristics which is suitable in smart grids. In this, Direct current control technique is used and it is easy to implement.

1.3 Problem Identification

This is the slowest charging method and is suitable for people who travel less than 60 kilo meters per day and have all night to charge. At home or at a public station, a specialized Electric Vehicle Supply Equipment (EVSE) provides power at 220 V or 240 V and up to 30 A. DC rapid charging is another name for level 3 charging. DC fast charging stations provide up to 90 kW of charging power at 200/450 V, cutting charging time in half to 20-30 minutes. Due to the rapid power transfer needed when EVs are used for energy storage, DC fast charging is recommended for establishing a Vehicle to Grid architecture in a micro grid. The dc bus may also be utilized to include renewable energy into the system. The V2G idea has been used in the general electricity grid for services such as peak shaving, valley filling, regulation, and spinning reserves in the majority of prior studies.

The development of V2G technology in a micro-grid infrastructure to support power production from intermittent renewable is still in its early stages. In addition, most of the works mentioned use level 1 and level 2 ac charging for V2G technology. These ac charging solutions are restricted by the on-board charger's power rating. Another problem is that the distribution system was not built to handle bi-directional energy flow. In this case, research is needed to create technically feasible charging station architectures to enable V2G technology in micro- grids. In a micro-grid facility, this study presents DC fast charging station architecture with V2G capabilities. A solar photovoltaic (PV) array is integrated into the micro-grid using the same dc bus that connects EVs. Off-board chargers may provide high-power bi-directional charging for EVs under the proposed design. The suggested model's effectiveness is assessed using MATLAB/Simulink simulations in both V2G and G2V modes of operation.

1.4 Objective of Thesis

In this project, a cascaded multiport converter is proposed to achieve the flexible energy conversion in the SRM-based HEV system. In the proposed scheme, the multiple driving modes, regenerative braking modes, and charging modes are achieved. By integrating the cascaded BM modules with the asymmetrical half-bridge (AHB) converter, the multilevel bus voltages and current capacity can be configured to satisfy different operation requirements, which will 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. To achieve the SOC balance management and improve the fault-tolerance ability, each battery pack can be independently regulated in the proposed converter. The effectiveness of the proposed scheme is verified by experiments based on a three-phase 12/8 SRM.

1.5 Proposed Model

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, and the AHB converter are orderly connected in series. Hence, the proposed converter can be 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 conditions.

B. Driving Modes

1) Operation Principle of Driving Modes for SRM When the SRM is under driving modes, the relationship between phase current and phase inductance is presented in Fig. 2(a), where θ is the rotor position angle; θ ON and θ OFF are the turn-on and turn-off angles, respectively, and ik and Lk are the kth phase current and phase inductance, respectively. According to the SRM characteristic, the phase winding should be conducted during the positive torque region, where the phase inductance is increasing. Three phase currents and the phase A signals under driving modes, where S1 and S2 are the corresponding switching signals.

II.PROPOSED SRM MOTOR

The original idea of switched reluctance motors (SRMs) dates back to 1814; however, these motors were reinvented and came into practical use in recent decades in line with the development of power electronic devices. Switched reluctance motors have salient poles in both the rotor and the stator and act as a single-excited configuration with inactive (coil-free) rotors. The stator has a centralized winding system with multiple phases. The coils are fed regularly and sequentially from a DC power supply, and thus, they generate electromagnetic torque. Because of their simplicity and structural strength, SRMs have been of great interest in the past two decades, and they are expected to find broader applications in terms of price and quality compared to other motors. In addition, many studies have been carried out to enhance the performance of these motors as potential alternative to AC (asynchronous and synchronous) motors. At present, switched reluctance motors are in their infancy in commercial terms, but it is expected that they will be used more widely in the near future.

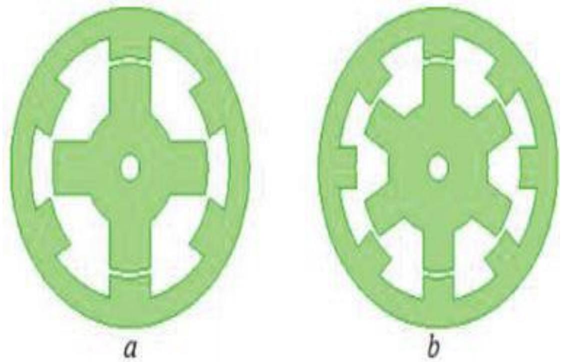

Figure 1 (a) A three-phase and (b) a four-phase SRM configuration.

III. DEVOLPMENT OF MULTIPORT CONVERTER

The primary task of power electronics is to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited for user loads. Modern power electronic converters are involved in a very broad spectrum of applications like switched-mode power supplies, active power filters, electrical-machine-motion-control, renewable energy conversion systems distributed power generation, flexible AC transmission systems, and vehicular technology, etc.

The main dc-dc converter changes dc power from an on-board 200-800V high voltage battery into lower dc voltages (48V or 12V) to power headlights, interior lights, wiper and window motors, fans, pumps and many other systems within electric vehicles (EV) and hybrid electric vehicles (HEV). This high voltage to low voltage (HV-LV) dc-dc converter is often referred to as an auxiliary dc-dc, or Auxiliary Power Module (APM). Isolation is critical for separating the control systems from high-voltage domains.

To improve the motor performance over wider speed range, many voltage-boosting converters are developed in the SRM system. A four-level and a quasi-three-level converter are respectively proposed in and to achieve fast current excitation and demagnetization processes. In a 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. In a neutral point diode clamped three-level converter is developed to improve the system efficiency and reduce the current ripple and noise. In a 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. In a modified Miler converter is developed to improve the motor performance at high speed and achieve the battery charging function with good power quality.

3.1 Multiport Converter

Fig. 3.1 depicts the general architecture of EV power train with charging systems. In Electric vehicle power trains, batteries or Super Capacitors (SCs) are connected to a high voltage DC bus to drive the three phase Induction Motor. For BEVs and PHEVs, some problems arise inoperation like voltage drop and unregulated power while charging. In FC based automobiles, the dynamic response is low during the operation and voltage drop take place in a short period of time. Compared to batteries and SCs, FC based vehicles have many disadvantages like limited supply infrastructure and less availability of refuelling stations. Therefore, there is more scope for using BHVs and PHEVs in the automobile industry. Moreover, SCs have more advantages like capturing high electric energy during regenerative braking and more power density while delivering power to the motor. Also, the battery is suitable for providing long term energy with high density, reliability and compact size.

In order to integrate into the high voltage DC link of the powertrain, an energy source requires a DC-DC converter. For storing energy during regenerative braking, a bidirectional converter is more suitable. Bidirectional converter gives energy from battery to motor and during regenerative braking the energy is stored into the battery which maximizes the overall efficiency of the system. In fast charging techniques, a fast-dynamic controlled converter is required for theprotection of Battery from overheating.

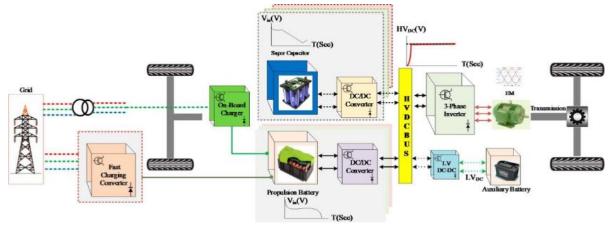

Fig. 3.1 Block diagram of Electric Vehicle power train

3.2 Proposed DC-DC Converter

An example of a DC-to-DC converter is the buck–boost converter, which produces an output voltage magnitude that is either higher or less than the input voltage magnitude. Instead of a transformer, it is analogous to a fly back converter that uses a single inductor as its output. Buck–boost converters are a term that refers to two distinct topologies. Both of them are capable of producing a wide variety of output voltages, ranging from considerably greater (in absolute magnitude) than the voltage level to nearly zero.

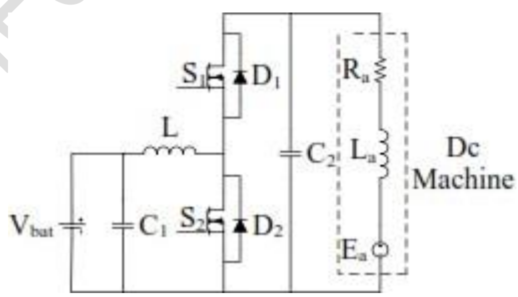

Fig 3.3 Proposed DC-DC converter

IV.DESIGN OF CONTROL TECHNIQUES

4.1 Design of Proposed PI Controller and Converter Topology

A PI controller-based DC-DC converter mechanism is established for EVs employing multiple energy sources, including BSSs, SCs and FCs. Advanced vehicle simulator software (ADVISOR) is proposed in this study considering the state of charge of the battery and super capacitor, speed of the vehicle and power demand. Though FCs are taken as the main energy source, they exhibit poor efficiency during light loads, and thus rely on a battery to

Journal of Engineering Sciences
Vol 13, Issue 02, FEB / 2022
ISSN NO:0377-9254

supply the power in this situation. The complementary switching is used in the battery converter to avoid discontinuous transition which further reduces the current peaks and saves the active and passive components from dangerous stresses. The overall lifespan of the battery and the temperature adaptability of the hybrid system are improved significantly.

The battery maximum energy was calculated as:

$$\text{Energy max} = \frac{Ah_{max} * V_{nom} * 3600\ s/h}{1000 J/kJ}$$

where Vnom is the nominal voltage, Rint is the internal resistance and Ahmax denotes the maximum ampere-hour of the battery. However, optimal size and cost are not considered in this study.

The PI control methods for DC-DC converters to enhance the stability of an integrated charging system in a hybrid EV (HEV). The feed-forward compensation method is employed to regulate the DC-link voltage and load current in the transient state, which improves the overall system stability. The advantage of this system is that it does not require additional capacitance, leading to a reduction in the system volume and cost. Figure 6 depicts the block diagram of the PI control-based DC-DC converter where the controller operation is executed in constant current (CC) and constant voltage (CV) modes. During CC mode, the operation of the DC-DC current controller depends on the reference current i ∗ Bt, whereas during CV mode, the operation of the controller relies on the reference voltage v ∗ Bt.

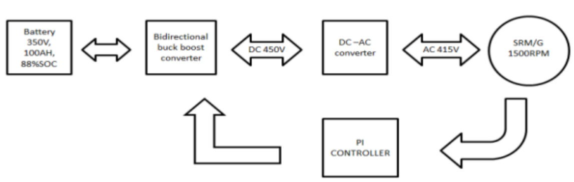

Figure 4.1 Block diagram of cascaded multiport converter using PI controller.

4.2 Design of Proposed Fuzzy Logic Controller and Converter Topology

In power converters, efficiency is a main concern. Power circuits consist of capacitors, magnetic elements and transistors in switched mode. Resistors and power switches in linear mode are not used in most power circuits due to significant losses generated by current through these components which decrease the efficiency and cause thermal problems. It is desirable that the conversion be made with low losses in the converter. To obtain low losses, resistors are avoided in the power electronics converter circuits. Capacitors and inductors are used instead since ideally they have no losses. The electrical components can be combined and connected to each other in different ways, called different converter (DC-DC, AC-DC) topologies, each one having different properties.

A modern power electronic system is a power processing system based on Pulse Width Modulation (PWM) technique. In a control system, a desired PWM signal is synthesized and transferred to power switches through gate drives to generate the same waveform at different voltage or current level. Thus, the power switches chop high voltages and/or currents when they are turned on and off. By using pulse-width modulation (PWM) control, regulation of output voltage is achieved by varying the duty cycle of the switch. The proposed converter circuit uses Insulated Gate Bipolar Transistor (IGBT) as the switching device. Use of IGBTs allows building cheaper and better converters.

IGBTs have three attractive advantages: higher switching frequency, easy and simple gate control and no need for snubber circuits. IGBTs are continuously controllable during turn on and turn off. This makes overcurrent limitation much easier and allows dV/dt control to reduce the and dV/dt stresses. MATLAB-SIMULINK is used to design and simulate the proposed controller circuit for various power electronics converters . Fig 2 shows simulink model of DC-DC (buck) converter using Fuzzy Logic Controller (FLC).

Journal of Engineering Sciences
Vol 13, Issue 02, FEB / 2022
ISSN NO:0377-9254

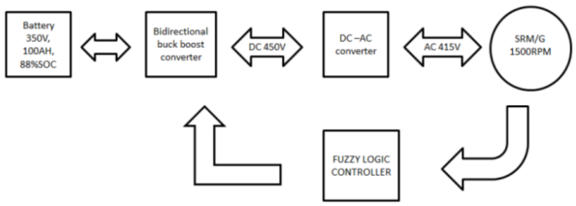

Figure 4.2 Block diagram of cascaded multiport converter using Fuzzy logic controller.

IV.RESULTS AND DICUSSION

5.1 Simulation Results for Fuzzy Logic Controller

A **simulation** is the imitation of the operation of a real-world process or system over time. Simulations require the use of models; the model represents the key characteristics or behaviors of the selected system or process, whereas the simulation represents the evolution of the model over time. Often, computers are used to execute the simulation.

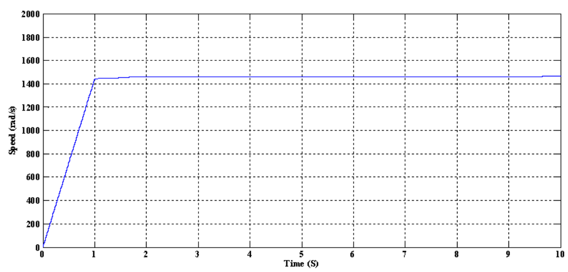

Figure 5.1 Output speed (rad/s) Vs Time (S)

Fig. 5.1 shows the plot of Speed (rad/s) vs Time (S) i.e, the output of the motor we can observe that the speed increases linearly up to 1400 (rad/s) in 1 second and then it remains almost constant for the remaining time and it is the useful characteristics of the EV which is important in the point of view of consumer.

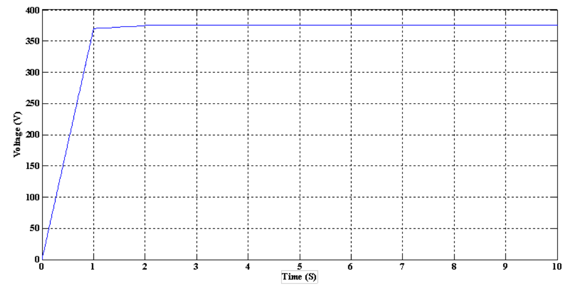

Figure 5.2 Input voltage (V) Vs Time (S)

Figure 5.2 shows the plot of input voltage i.e, battery voltage which is input to the converter and this input voltage increases to 375v approximately which is given to the motor and this remains constant.

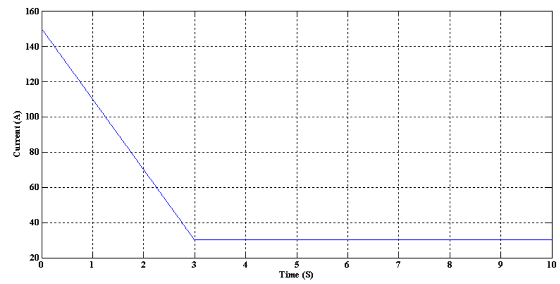

Figure 5.3 Input current (A) Vs Time (S)

Figure 5.3 shows the plot of input current i.e, battery current which is input to the converter and this input current reduces to 25A approximately which is raised due to transient condition to 150A and which is input to the motor and this remains constant after 3 seconds.

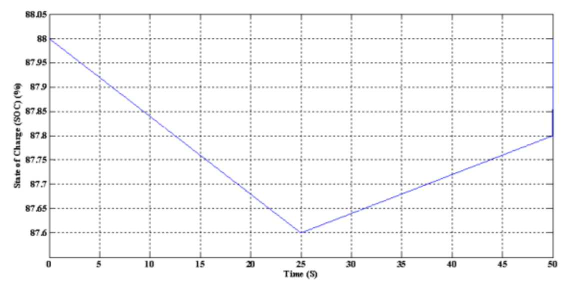

Figure 5.4 SOC of batter

Figure 5.4 shows the plot of SOC of battery which indicates discharging and charging of the battery condition, it can be observed from the plot that the SOC falls from 88% to 87.6% in first 3.4 seconds which is due to increased load on the motor i.e, the motor is assumed to run on the gradient after 25 seconds the SOC of the motor increases due to regeneration of the motor i.e, motor acting as generator for remaining 25 seconds and SOC raises to87.8%.

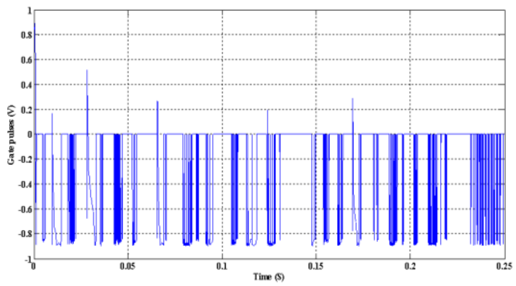

Figure 5.5 Gate pulse (V) Vs Time (S)

Figure 5.5 shows the plot of Gate pulses i.e, battery current which is input to the converter and this input current reduces to 25A approximately which is raised due to transient condition to 150A and which is input to the motor and this remains constant after 3 seconds.

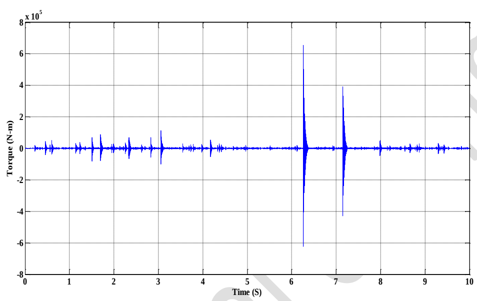

Figure 5.6 Torque (N-m) Vs Time (S)

Figure 5.6 shows the plot of Torque produced by SRM there is change in torque at various point in the plot changes this is due to change in load on the motor this is an essential characteristics of the motor for given load.

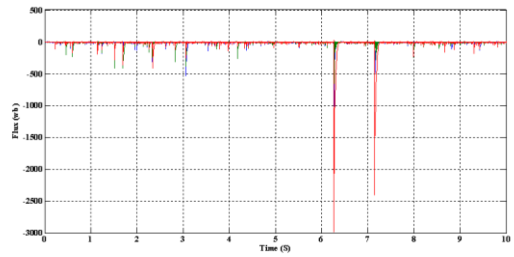

Figure 5.7 Flux (wb) Vs Time (S)

Figure 5.7 shows the plot of stator flux produced by SRM there is change in flux at various point in the plot changes this is due to change in load on the motor as the load changes the current drawn by the motor changes due to this the flux produced by the motor also changes.

CONCLUSION AND FUTURE SCOPE

In this thesis, a cascaded multiport converter is proposed for the SRM-based HEV applications. By integrating the battery packs into the AHB converter, with Fuzzy logic control and PI controller 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 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 over discharging 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 with Fuzzy logic control and PI controller is promising for HEV application and can be extended to other applications, such as more-electric aircraft, traction drives, and electrical ships.

REFERENCES

[1] S. Kimura, Y. Itoh, W. Martinez, M. Yamamoto, and J. Imaoka, "Downsizing effects of integrated magnetic components in high power density DC/DC converters for EV and HEV applications," *IEEE Trans. Ind. Appl.*, vol. 52, no.4, pp. 3294-3305, 2016.

[2] D. Moon, J. Park, and S. Choi, "New interleaved current-fed resonant converter with significantly reduced high current side output filter for EV and HEV applications," *IEEE Trans. Power Electron.*, vol. 30, no. 8, pp. 4264-4271, Aug. 2015.

[3] A. Kulvanitchaiyanunt, V. C. P. Chen, J. Rosenberger, P. Sarikprueck, and W.J. Lee, "A linear program for system-level control of regional PHEV charging Stations," *IEEE Trans. Ind. Appl.*, vol. 52, no. 3, pp. 2046-2052, May./Jun. 2016.

[4] L. Herrera, E. Inoa, F. Guo, J. Wang, and H. N. Tang, "Small-signal modeling and networked control of a PHEV charging facility," *IEEE Trans. Ind. Appl.*, vol. 50, no. 2, pp. 1121-1130, Mar./Apr. 2014.

[5] D. Li, R. Qu, J. Li, L. Xiao, L. Wu, and W. Xu, "Analysis of torque capability and quality in vernier permanent-magnet machines," *IEEE Trans. Ind. Appl.*, vol. 52, pp. 125-135, Jan./Feb. 16

[6] J. J. Justo, F. Mwasilu, E. K. Kim, J. Kim, H. H. Choi, and J. W. Jung, "Fuzzy model predictive direct torque control of IPMSMs for electric vehicle applications," *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 4, pp. 1542-1553, 2017.

[7] T. A. Huynh and M. F. Hsieh, "Comparative study of PM-assisted SynRM and IPMSM on constant power speed range for EV applications," *IEEE Trans. Magn.*, vol. 53, no. 11, Nov. 2017.

[8] I. Boldea, L. N. Tutelea, L. Parsa, and D. Dorrell, "Automotive electric propulsion systems with reduced or no permanent magnets: an overview," *IEEE Trans. Ind. Electron.*, vol. 61, no. 10, pp. 5696–5711, Oct. 2014.

[9] Z. Yang, F. Shang, I. P. Brown, and M. Krishnamurthy, "Comparative study of interior permanent magnet, induction, and switched reluctance motor drives for EV and HEV applications," *IEEE Transactions on Transportation Electrification*, vol. 1, no. 3, pp. 245-254, Oct. 2015.

[10] A. Chiba, K. Kiyota, N. Hoshi, M. Takemoto, and S. Ogasawara, "Development of a rare-earth-free sr motor with high torque density for hybrid vehicles," *IEEE Trans. Energy Convers.*, vol. 30, no. 1, pp. 175-182, Mar. 2015.

[11] Kiyota, and A. Chiba, "Design of switched reluctance motor competitive to 60-kW IPMSM in third-generation hybrid electric vehicle," *IEEE Trans. Ind. Appl.*, vol. 48, no. 6, pp. 2303-2309, Nov./Dec. 2012.