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Development and Analysis of Switched Capacitor Four Quadrant DC-DC Converter for Hybrid Electric Vehicle

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Abstract

Background/Objectives: The main objective of this research is to develop a bi-directional four quadrant DC-DC converter for an energy efficient electric vehicle. **Methods/Analysis:** The model of electric vehicle is designed using MATLAB software. The results confirm that the proposed DC-DC converter structure is highly reliable, lighter in weight, smaller in volume, with good efficiency, less electromagnetic interference and lower current or voltage ripple. **Findings:** The issues on global warming and fossil fuels depletion have created opportunities to Electric Vehicle (EV). The main characteristics of Energy storage system in vehicles include energy density, power density, lifetime, cost and maintenance. Most of the electric and hybrid electric configurations use two energy storage devices, one with high energy storage capacity, called the "Main Energy System" (MES) and the other with high power capacity called the "Auxiliary Energy Storage System" (AESS). Other challenge in electric vehicle is to maintain the state of charge within the allowable limits and sharing of energy between the storage devices. For proper sharing of energy between the storage devices, DC-DC converter plays a crucial role. **Novelty /Improvement:** A novel Switched Capacitor DC-DC power converter and their controllers are investigated.

Keywords: Auxiliary Energy Storage System, Bidirectional Dc-Dc Converter, Hybrid Electric Vehicle, Main Energy System, Ultra capacitor

1. Introduction

An innovation on green technologies is demanded greatly in modern cities. The appreciable growth of today's cities leads to an increase in use of transportation, results in pollution and other problems in environment. Vehicle produced gases should be controlled and necessary preventive measures must be taken in order to minimize the use of internal combustion engines by incorporating them with electric motors[1]. In general vehicle can be classified into three groups based on their sources: Internal Combustion Engine (ICE), Hybrid Electric Vehicles (HEV) and All Electric Vehicles (AEV). Figure 1 shows currently available vehicle types. AEVs and HEVs are highly popular when compared to ICE vehicles as it saves energy that is getting lost during number of accelerations and decelerations of the ICE vehicles. In order to this, many kind of power source or energy storage systems must be employed. The reason for many power sources requirement are to offer vehicle with optimum rating and high efficiency (like ICE) and for the requirement of additional accelerations (like battery and UC). Customer demands for greater acceleration performance and vehicle range in AEVs and HEVs increase the appeal for combined on-board energy storage systems.

We propose a control technique for a multiple quadrant switched capacitor dc/dc converter that is applicable for HEV Energy Storage System applications. The dc-dc converter modelled is meant for bidirectional usage. The organization of our paper is as follows: Section

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2 will discuss in detail about the Energy sources which is associated with Electric Vehicle. Section 3 will describe the controller design part for a proposed converter operation. Section 4 will explain the multi quadrant operating characteristics of switched capacitor converter considered and the operating modes. Section 5 and 6, will realize the simulation results and detailed modeling and analysis of the converter.

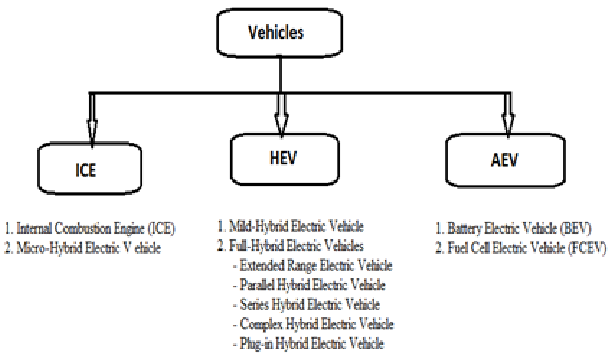

Figure 1. The classification of the vehicle.

2. Energy Sources in Electric Vehicle

In practice, most of the commonly used energy storages are batteries. Other energy storage devices include Ultracapacitor (UC), flywheel and hydrogen tank and so on.

2.1 Battery

The principle of battery is to convert chemical energy into electrical energy and vice-versa during the time of charging and discharging respectively. Independent cells are combined together to form a battery with desired voltage. Each single cell or a combination of it may have a capability to store or to deliver the required amount of energy[2]. The factor which leads the battery to use on roadmap of electric vehicle is higher energy densities and its affordability[3]. The present status of available charge in the battery can be represented by State of Charge (SOC) of the battery. The battery has to operate within a specified SOC range in order to increase the life span of it[4]. Figure 2 specifies the battery technologies with their characteristics.

2.2 Ultracapacitor

Ultracapacitor (UC) or supercapacitor is structure wise similar with a normal capacitor, but UC have high capacitance around a factor of 20 times more than capacitor. The capacitor characteristics include long operating life span, maintenance free operation and highly insensitive to variation in environmental temperature. Around 1000-2000 kW/kg is the specific power density for UC[4].

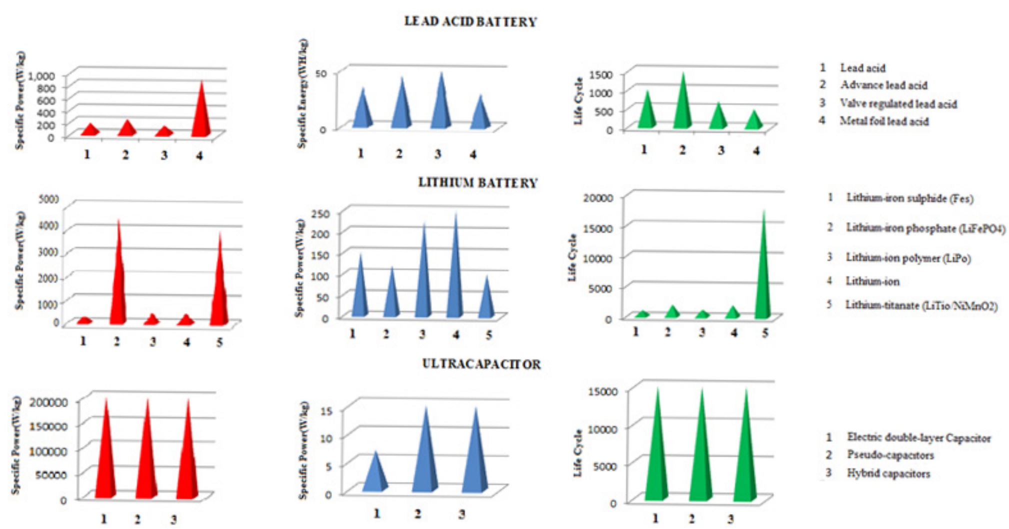

Figure 2. Battery technologies and their characteristic.

2.3 Flywheels

Flywheel type of energy storage device is the one to store or maintain the kinetic energy from a rotor rotation. Flywheel technology is considered to have two approaches, i.e. rotational energy as input and electric energy as output energy[5]. A research has been made over many decades to store as well as to deliver mechanical energy. But implementation of such system in vehicle application has been limited due to high weight and cost. Recent advancements in carbon-fiber composite materials, frictionless magnetic bearing, manufacturing technique and power electronic controllers have been paved a way for the development of flywheel energy storage system[6].

2.4 Hydrogen Energy

In hydrogen vehicle, onboard energy uses hydrogen to power the vehicle. Here, chemical energy is converted into mechanical energy by burning hydrogen in the case of ICE or hydrogen reacts with oxygen in the case of FC so as to provide electricity. In the case of Hydrogen, it is considered to have an enormous energy per unit weight but lesser energy per unit volume. That was the major drawback as far as transportation is taken into account[4].

2.5 Fuel Cells (FC)

Fuel cell is an energy conversion device. It converts chemical energy in to electricity. It is done by the process of electrolysis. In FC, the byproducts are heat and water. It was proved that FC technology greatly reduces the dependency of oil resource and harmful CO_2 emission[7,8]. The major types of FC are Direct Methanol Fuel Cells (DMFC), Alkaline electrolyte Fuel Cells (AFC), Phosphoric Acid Fuel Cells (PAFC), Proton Exchange Membrane Fuel Cells (PEMFC), Solid Oxide Fuel Cells (SOFC) and Molten Carbonate Fuel Cell (MCFC)[9].

2.6 Photovoltaic Cells (PV)

Solar energy or Photovoltaic (PV) is used as energy sources in many vehicles since around 20 years[10]. At initial stages solar panel was not an attractive idea to use it in ICE[11]. However, in recent scenario, more attention is drawn towards the PV in many automakers in order to improve the passenger's comfort. Vehicles such as the Audi A8, 2010 Prius, Mazda 929 and Aptera 2 have solar sunroof options. There exists a greater challenge in solar powered vehicle. The challenge is limitation in space for the accommodation of PV and the generated power is also not so high[12]. Thus many researchers initiate the installation of solar panel onto the vehicle and positively, in the upcoming year, the power can be fully generated from PV. Maximization of the surface of the vehicle can be recommended for the PV panel accommodation[13].

2.7 Automotive Thermoelectric Generators (ATEG)

Thermoelectric generator can convert heat energy into electricity. Currently, it is very popular in obtaining optimal fuel economy and high efficiency in both ICE vehicle as well as electric vehicle, since loss of energy due to heat is high in vehicles. ATEG is a storage device which can convert waste heat into electrical energy. The researcher from[14] had built a prototype of ATEG module and successfully achieved in having 40% to 70% of efficiency. An ATEG can have life time of about 10 to 20 years with less maintenance and cost. The economy of fuel test is also done and proved to improve fuel economy by 1% to 4 % based on the vehicle type.

2.8 Regenerative Braking

Whenever the electric vehicle is in coasting mode or braking mode, the running vehicles kinetic energy will generate electricity and that generated electricity is fed back to the supply. This principle is said to be regenerative braking. Presently there are four ways to store the generated energy from regenerative braking. It can be directly stored into an energy storage system or by using hydraulic motor that can store the energy in a small canister through compressed air. Also energy can be stored in spring as gravitational energy or in FES in the form of rotating energy[15].

3. Controller Design for the Proposed Converter

The multi quadrant switched capacitor converter has 7 bidirectional switches with 2 capacitors namely C1 and C2. Each switch is considered to have two MOSFETs for the purpose of current flow in either direction. For an HEV application, the High Voltage (HV) side typically consists of battery modules and the Low Voltage (LV) side could consist of Ultra-Capacitor (UC) modules as shown in Figure 3. Such a type of converter will be operated in all four quadrants (forward as well as reverse mode). Table 1 depicts the details of switching sequence of the converters.

Whenever the converter is assumed to operate in motoring mode i.e., Pm<0.95, couple of condition arises: either the load gets the supply from the battery module or power from the UC module. If the battery module is fully discharged and requires energy, it can share part of the energy from a UC module. On the other hand if UC is fully discharged and requires energy, Battery can share its energy to UC. Now, under regenerative mode of operation, the generated power in motor can be used to feed either battery or UC.

In the first quadrant i.e., forward motoring operation,

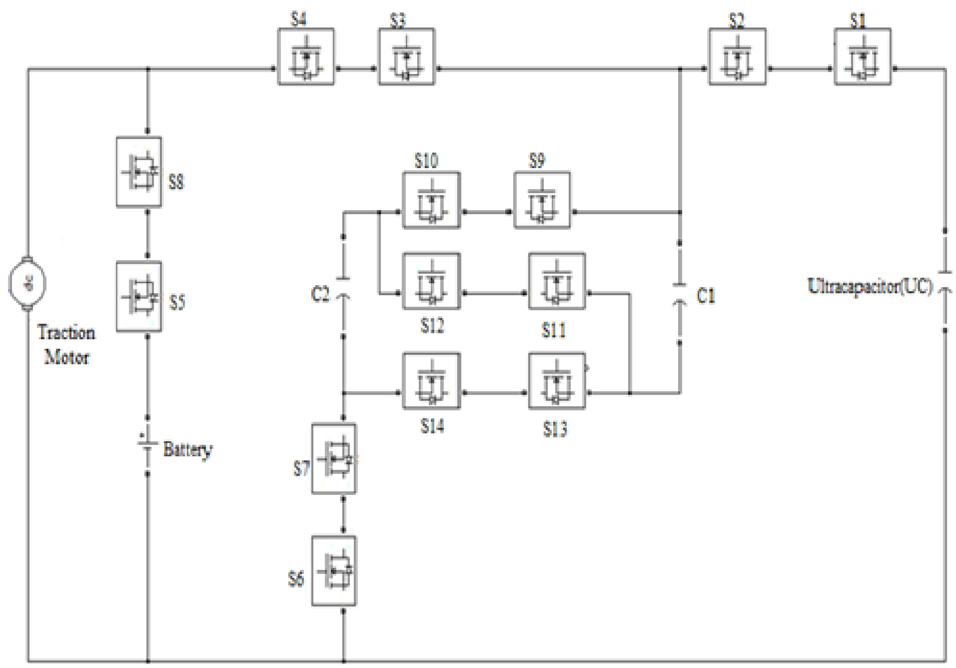

Figure 3. Typical system schematic with hybrid energy sources, traction motor and SC converter.

Table 1. Switching Table

SW/MODE	1 UC-Motor	2 Battery-Motor	3 UC-C1,C2	4 C1,C2-Battery	5 Battery-C1,C2	6 C1,C2-UC	7 Motor-UC	8 Motor Battery
S1						ON	ON	
S2	ON		ON					
S3					ON		ON	
S4	ON			ON				
S5		ON			ON			
S6				ON		ON		
S7			ON		ON			
S8				ON				ON
S9						ON		
S10			ON					
S11				ON				
S12					ON			
S13						ON		
S14			ON					

both current and voltage are positive. The load demanded by the vehicle is average then energy is offered by the battery with great attention on the battery SOC. Under such case, S5 switch is operated as shown in Figure 4(a). And in contrast when vehicle demands for peak energy, UC offers its energy with great attention on SOC of UC. Here, S2 and S4 are on as shown in Figure 4(b). In order to understand the operation of the converter each process in named with mode number. 4(a) and 4(b) is named as mode 1 and 2 respectively.

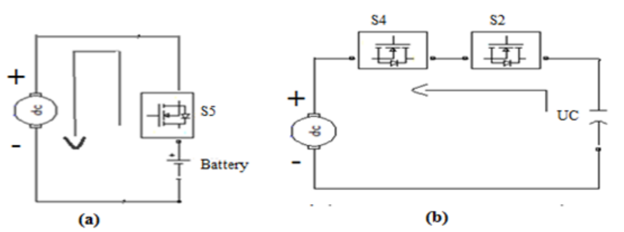

Figure 4. Quadrant I (a) Battery supplies power to load. (b) UC supplies power to load.

Now, if the battery is fully discharged and UC SOC is high, UC modules transfer energy to the battery. Since the discharge made by UC is instantaneous that leads to the degradation of battery as it supports only the average charging and discharging. So initially the capacitors C1 and C2 are charged by UC by turning on the switches S2, S7, S10 and S14. Later, the average charging of battery is done from C1 and C2. Under this condition, the switches S4, S6, S8 and S11 are turned on as per the Figure 5(a) and 5(b) respectively.

The voltage lift technique was implemented in boost mode. Here, during ON-state, the capacitors are made to be charged. The voltage given as input was appeared across the capacitors. During OFF-state, the capacitors are discharged. Therefore the voltage output is boosted by capacitors. Now, if the UC is fully discharged and Battery SOC is high, Battery modules transfer energy to the UC. Since the discharge made by Battery is average which leads to the decrease in life time of the UC as it supports

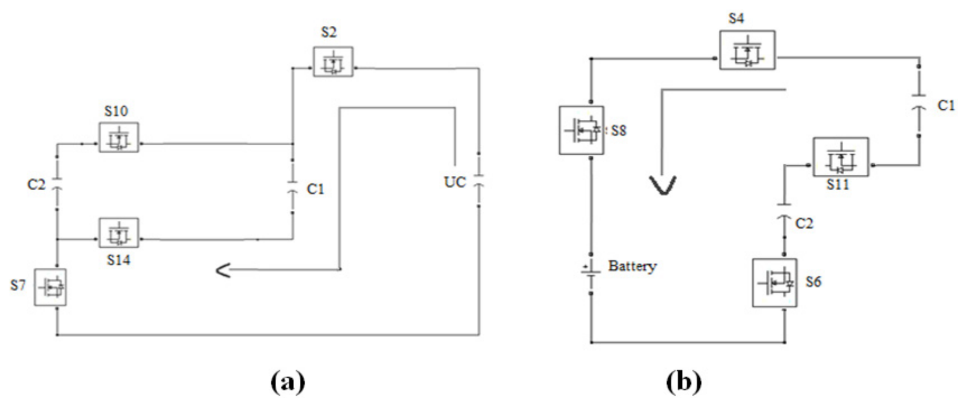

Figure 5. (a) UC charges the capacitor C1 and C2 and (b) C1 and C2 charges the Battery.

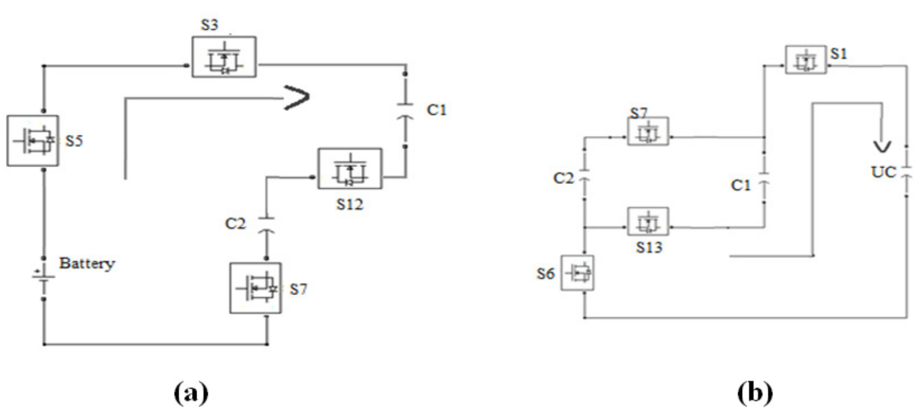

Figure 6. (a) Battery charges the capacitor C1 and C2 and (b) C1 and C2 charges the UC.

only the instantaneous charging and discharging. The capacitors C1 and C2 are charged by Battery by turning on the switches S3, S5, S7 and S12. Then the instantaneous charging of UC is done from C1 and C2. The switches S1, S6, S9 and S13 are turned on during this condition. This is shown in Figure 6(a) and 6(b) respectively.

Current amplification technique was used in the buck mode since during ON state, the capacitors must be charged. Capacitors carry the input current. And during OFF state, those capacitors must be discharged. Hence amplification of the output current is done by this capacitors[16-18].

Under quadrant II or forward regenerative braking mode, current is negative whereas voltage is positive. In such a case, initially the Battery current gradient is taken into account. In the case of half or fully drained battery, the motor fed back the power to the battery shown in Figure 7a and 7b. Once the Battery is fully charged, then the UC current gradient must be considered. If the UC is half or fully discharged, then the motor supplies its energy to UC. This operating mode is shown in Figure 7.

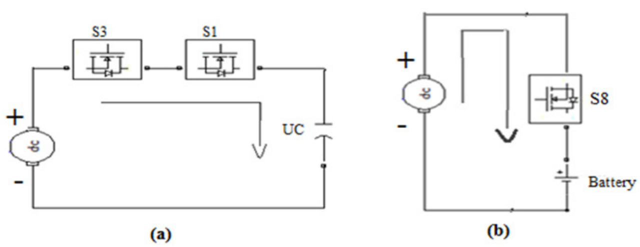

Figure 7. Quadrant II (a) Motor charges UC. (b) Motor charges Battery.

In the reverse motoring or quadrant III operation, both current and voltage are negative. This mode is same as forward motoring mode. Either the Battery module or the UC module will supply their energy to motor. This is shown in Figure 8a and 8b.

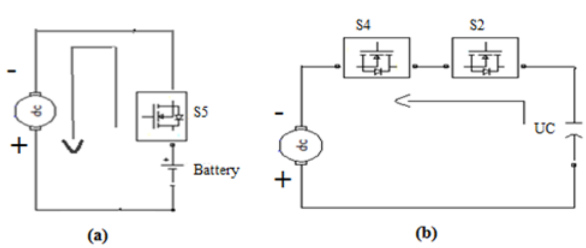

Figure 8. Quadrant III (a) Battery supplies power to load. (b) UC supplies power to load.

In reverse regenerative braking or quadrant IV mode, current is positive but voltage is negative. This mode is similar to forward regenerative braking. Initially the Battery current gradient is considered and then UC. Based on the discharging status of both, the motor supplies its energy either to battery or to UC as shown in Figure 9a and 9b respectively.

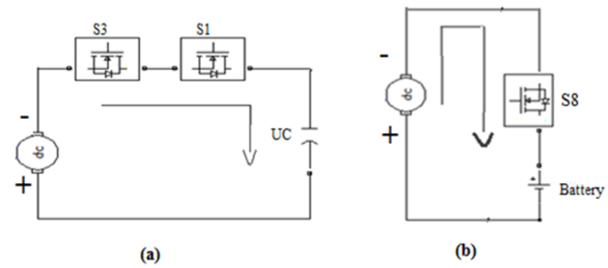

Figure 9. Quadrant IV (a) Motor charges UC. (b) Motor charges Battery.

Recently Field Programmable Gate Array (FPGA) is used effectively for various PWM techniques in power electronic converters[19]. The energy sharing between the solar PV and other storages devices with the help of two bridge technology can increase the efficiency by highly reduce the EMI issues[20]. Similarly more than a single converter topology which uses switched capacitor can also be utilized in order to produce different voltages with less ripple content[21]. The proper planning of charging and discharging of storage systems in electric vehicle plays a major role in today's scenario. A proper peak hour demand planning must be recommended in order to use the DG capacity optimally from microgrid and to reduce the receiving power from the overhead systems[22].

4. Results and Discussion

In the applications of electric vehicles, varieties of electric load were used. The application of those concepts for various loads was verified using MATLAB Simulink in order to provide the true predictions. In this section, the analytic details of the proposed converter are explained. As discussed, the switched capacitor converter has two main modes of operation: 1. The buck mode and 2. The boost mode.

The Figure 10 shown represents the schematic diagram of the model considered. In this model, the forwarding motoring mode alone is considered as one case and in the other case the rest of the modes are considered. The comparator will compare the reference speed with the motor speed to produce the error signal. If the error signal is positive, then the mode 1 is operated, that is the motor starts rotating (forward motoring). Otherwise the random modes are selected. This is done by the selector switch. The saturation block is used to limit the operation within the modes considered.

Whenever load torque is greater than 0, then the converter should operate under motoring mode otherwise, it must be operated in generating mode. When the electrical load torque is above 0, then the mode1 is selected and according the motor picks up its speed and will reach its rated speed around 2500 rpm. This is depicted in Figure 10. The statuses of charging and discharging of the energy sources is shown in Figure 11, in relation with the operating modes. The simulation result shown in Figure 12 indicates the mode of operation for each period of the simulation time. That is the charging and discharging status of energy sources with mode 1 and other modes of operation.

The Battery State Of Charging (SOC) and the battery voltage results are as shown in Figure. 13(a) and (b). Initially the starting torque is more hence the SOC of the battery decreases rapidly as shown. Later it varies gradually since the electrical torque reaches a constant value. Similarly the battery voltage decreases rapidly at first then attains a constant value. By implementing soft switching technique in the proposed DC-DC converter, the total switching loss can be practically made zero, thus giving higher efficiency for the forward and reverse power flow control schemes. The power device reliability can be improved because of minimum switching stress during soft switching. EMI emission can also be significantly reduced and the switching frequency can be further increased. Furthermore, High power density can be achieved, because of low heat sinking requirement, reduced converter size and weight.

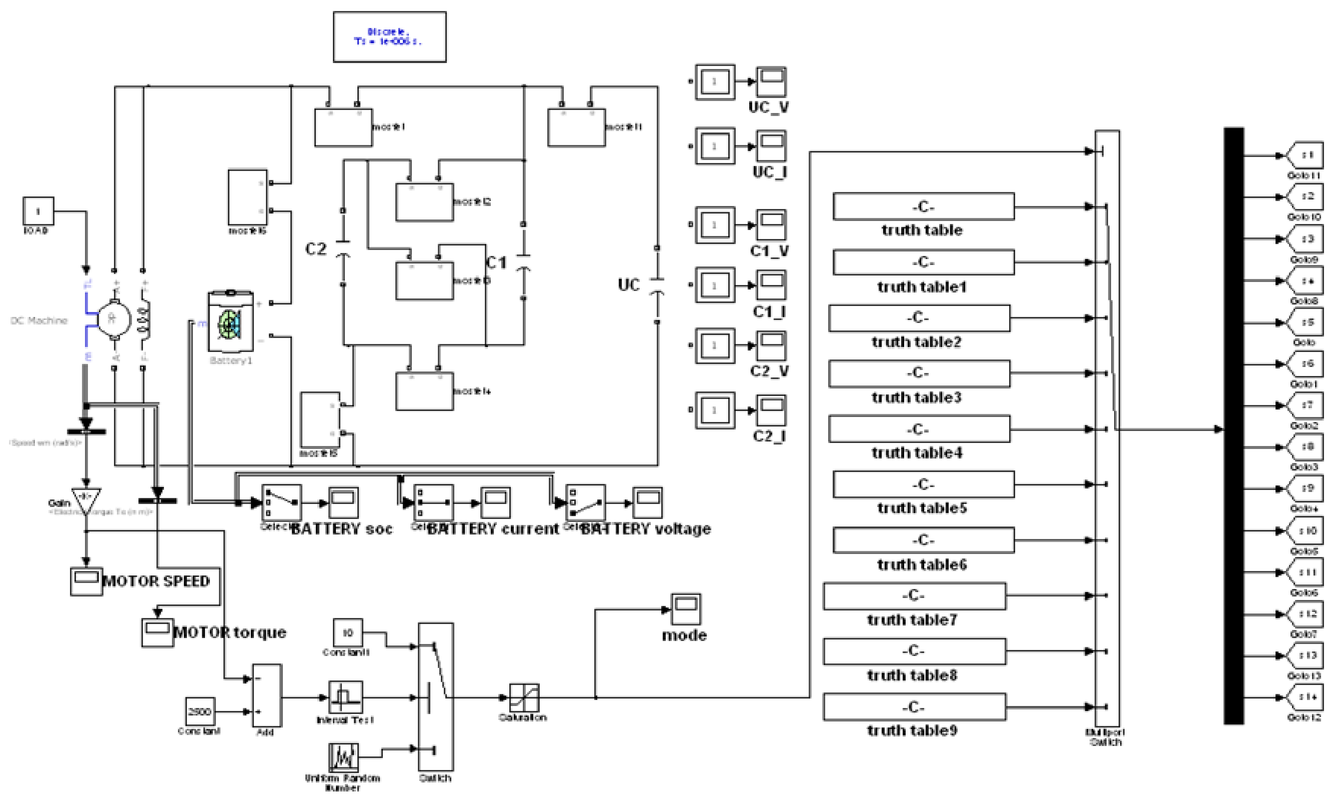

Figure 10. Schematic diagram of simulation.

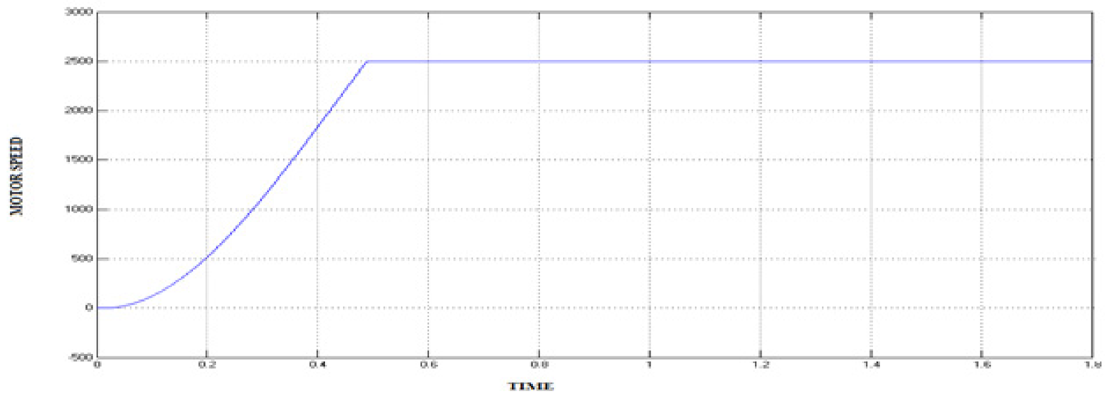

Figure 11 a. Speed.

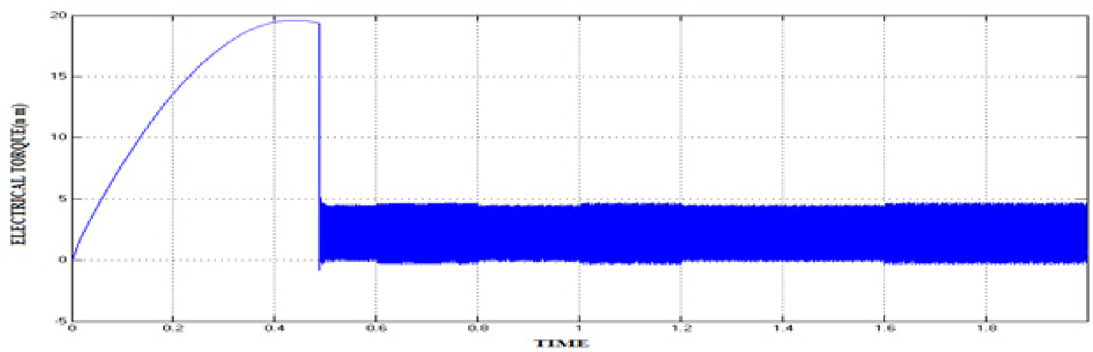

Figure 11 b. SElectrical torque of a tested motor.

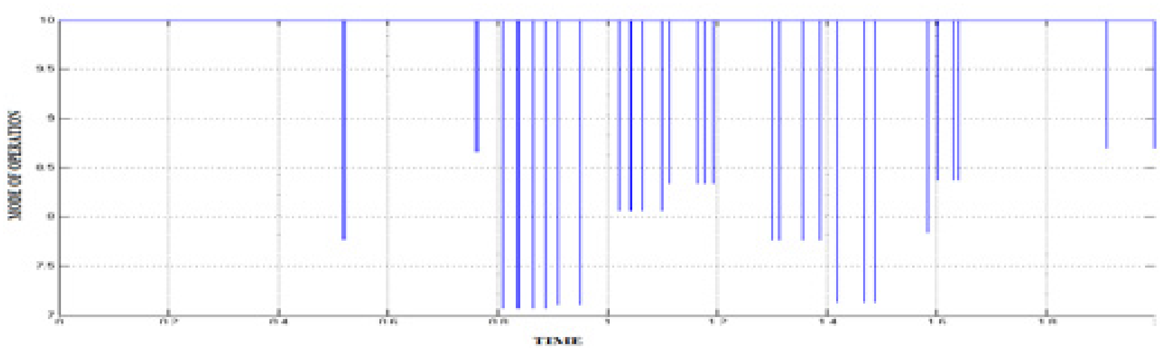

Figure 12. Charge and discharge status of energy sources.

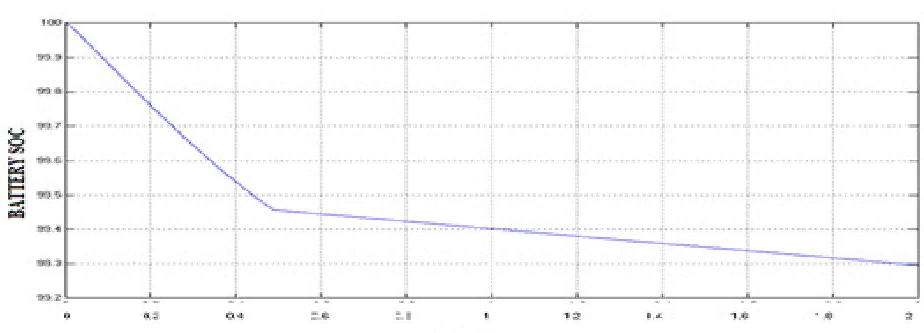

Figure 13 a. Battery SOC.

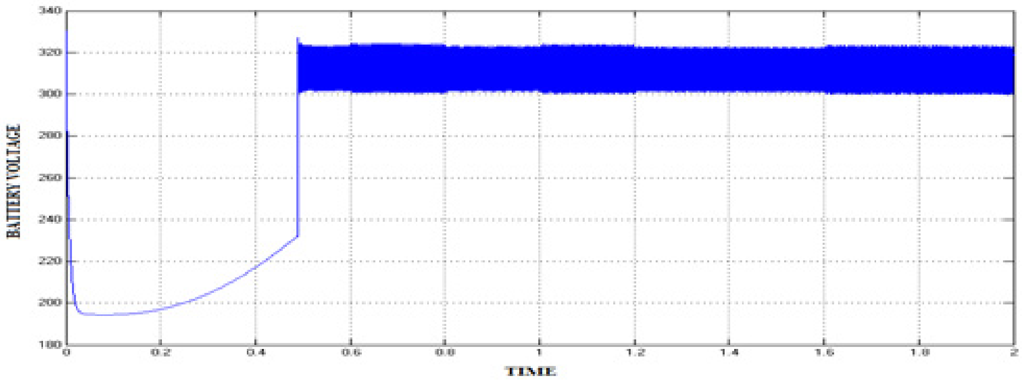

Figure 13 b. Battery voltage.

5. Conclusion

This paper represents a technique for hybrid Switched Capacitor bidirectional DC/DC converter which is applicable to Hybrid Electric Vehicle or Plug in Hybrid Electric Vehicle Energy Storage Systems. SCCs provide essential features of voltage step-down (buck), voltage step-up (boost), and bidirectional power flow, which is associated with two energy storage devices, one with high energy storage capability, called the "Main Energy System" (MES) and the other with high power capability and reversibility, called the "Rechargeable Energy Storage System" (RESS). Further, the detailed analyses have been conducted for the specific four-quadrant topology is also presented in this paper, using the designed SCC control strategy.

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