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Design and Implementation of a Converter Model for Hybrid Electric Vehicle Energy Storage System

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ABSTRACT

The simulation of a hybrid electric vehicle motor-drive system used to investigate power flow at the conditions of both motoring and regeneration is presented in the paper. The proposed control strategy includes a bidirectional switched capacitor dc/dc converter, which is applicable for a hybrid electric vehicle energy storage system. Topographies of voltage step up / down and bidirectional power are incorporated into a single circuit, and are verified by Simulation using MATLAB / Simulink.

Keywords: Switched capacitor converter (SCC), Energy storage system (ESS), Electromagnetic interference (ESS), Plug-in hybrid electric vehicle (PHEV), Ultra capacitor (UC), Load power (LP).

I. INTRODUCTION

Electricity can be defined as an electric vehicle nowadays "an automotive-type vehicle used for highway, that includes passenger automobiles, buses, trucks, vans, low speed vehicles, etc., powered by an electric motor(s) which are feed by Energy Storage Devices. There are three types of EV: Hybrid Electric Vehicles (HEVs), Plug-in Hybrids (PHEVs) and Battery Electric Vehicles (BEVs). HEVs have two motors: an internal combustion engine and an electric motor [1]. Their storage batteries are usually low-capacity, which greatly limits their range and top speed in electric mode. In all three types of Electric Vehicles Energy storages system plays a vital role. The energy storage devices widely used for automotive applications are rechargeable storage battery, fuel cell, photovoltaic array, super capacitors. In order to increase the overall efficiency of the system the battery is used to supply a large amount of power at light loads, on the other side UC bank is used for satisfying acceleration and regenerative braking requirements and also helps in improving the on-board battery lifetime.

The capacitor are controlled by switches, which are charged and discharged through different paths, and transfer their stored energy to either the high voltage (HV) battery side, or the low voltage (LV) ultra capacitor (UC) side [2]. Various switched-capacitor (SC) converters are used to convert or invert dc voltages have been developed and are available in the market. Basically, an SCC is a combination of capacitors and semi conductor switches. The various set of capacitors and switches result in SCC topologies gives out a various output voltage that may be higher (boost mode) or lower (buck mode) than the input voltage. The switches are controlled such that capacitor *C* is charged and discharged through different paths [4].

SC bidirectional converters, with their large voltage conversion ratio, indeed, possess the potential to be one of the possible solutions for achieving high efficiency conversion. At the same time, they possess the ability to realize voltage step-up/step-down [5], [6]. Basically proposed converter consists of three set

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switches and one pair of capacitors. The Figure 1 represents typical system operation in all the four quadrants. Each switch consists of two MOSFETs for current flow in both directions. This paper provides a detailed insight into the operating modes of the developed SC converter, followed by detailed energy transfer efficiency modelling and analyses.

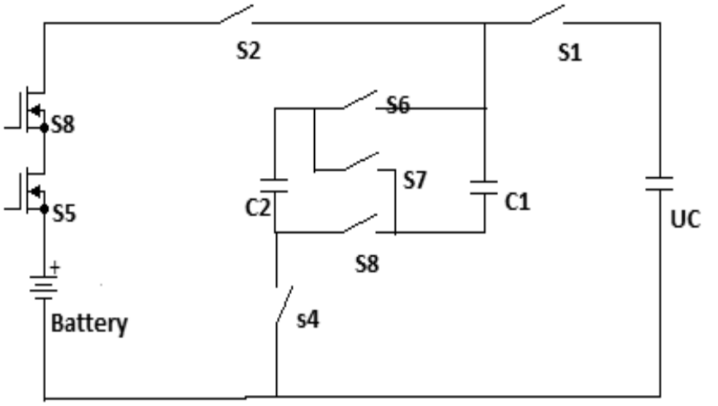

Figure 1: A typical system with hybrid energy sources and SC converter

II. SCC OPERATING FEATURES AND APPROACHES

(A) General Description

Figure 2 represents the complete system of proposed HEV hybrid energy storage system, the high voltage (HV) side typically consists of battery modules and the low voltage (LV) side could consist of UC modules

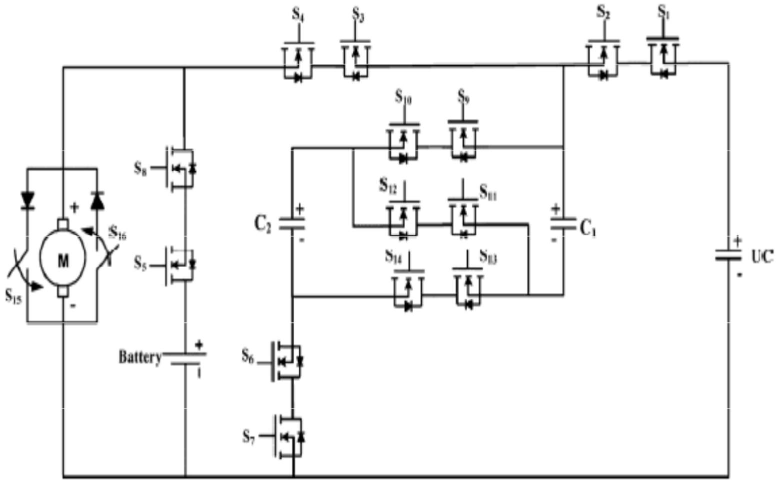

Figure 2: Circuit schematic of Switched Capacitor

In the generating mode (P <0), the capacitor is less than the battery voltage and the battery pack is charged by load, and after that, it charges capacitor *C*. It must be noted that if the battery voltage is less than the capacitor voltage, only the battery is charged by the load [7]. If the capacitor voltage is less than the battery voltage, and the battery modules do not need energy and are fully charged, then they can deliver energy to capacitor *C*. In turn, when capacitor *C* is charged, it transfers its stored energy to the UC modules [8].

When the circuit works in the motoring mode, if capacitor voltage is greater than the UC voltage, it directly transfers its stored energy to the load. If the battery modules are not fully charged, and if the capacitor voltage is less than the UC voltage, then during the first step, UC modules charge capacitor *C*, followed by capacitor *C* transferring its stored energy to the battery modules [10]–[11].

(B) SCC Modes of Operation

In forward motoring mode, if POUT<PL, The high voltage side supply to motor side or battery or UC modules deliver their energy between each other. The switches S2, S10, S14 and S7 are on and C1 and C2 are charged by the Low Voltage side. Now, the voltage across the two capacitors increases.

Once C1 and C2 are charged, S6, S11 and S4 are on and the capacitors are disconnected. Figure 3 the operation and the voltage across the two capacitor gets decreases.

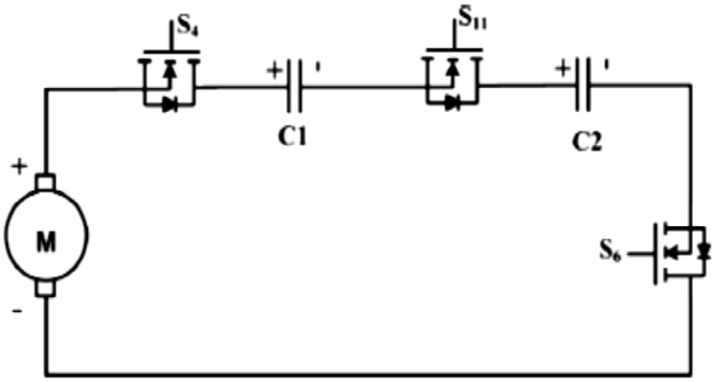

Figure 3: Forward motoring; Capacitors connected to Motor side

As a next step, suppose if the battery modules deliver their energy to motor side, switch S5 is closed. This mode is depicted in Figure 4.

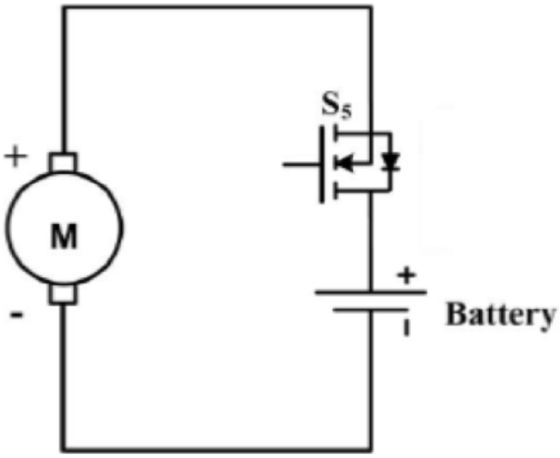

Figure 4: Forward motoring; Battery connected to Motor side

Now, if POUT ≥ PL, and battery modules are fully discharged, LV side or UC modules transfer their energy to HV side. For that capacitors are initially charged and after this operating stage S6, S11, S4 and S8 are on. Figure 5 shows the transfer their stored energy from the capacitors C1 and C2 to the HV side to LV side.

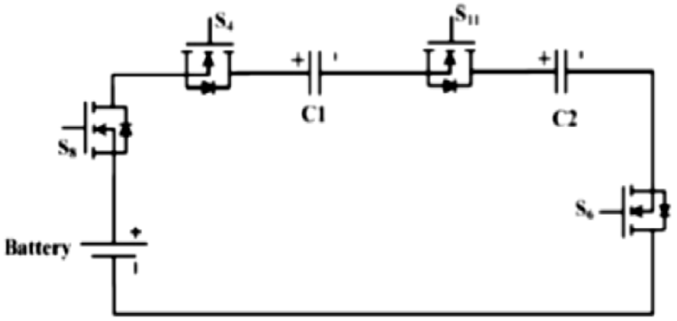

Figure 5: Capacitors are discharged and are disconnected from LV side

Now, if POUT ≥ PL and UC modules are fully discharged, battery modules transfer their energy to the LV side. As a first step, switches S5, S3, S12 and S7 are on. Now, capacitors C1 and C2 are charged by HV side. At this time, the voltage across the two capacitors increases. This mode is shown in Figure 6.

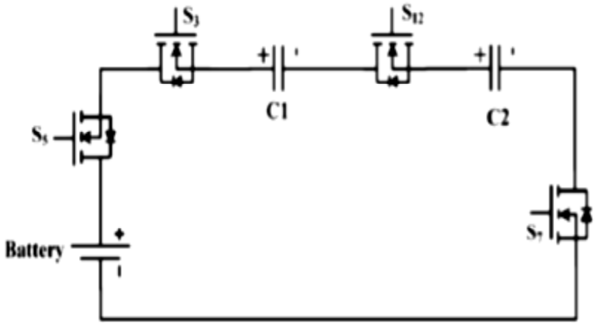

Figure 6: Capacitors are charged by HV side

The buck mode uses the current-amplification technique, because the capacitors are charged in series during on-state. The input current flows through capacitors. These capacitors are discharged in parallel during off-state. Therefore, the output current is amplified by these capacitors. This operation mode is depicted in Figure 7.

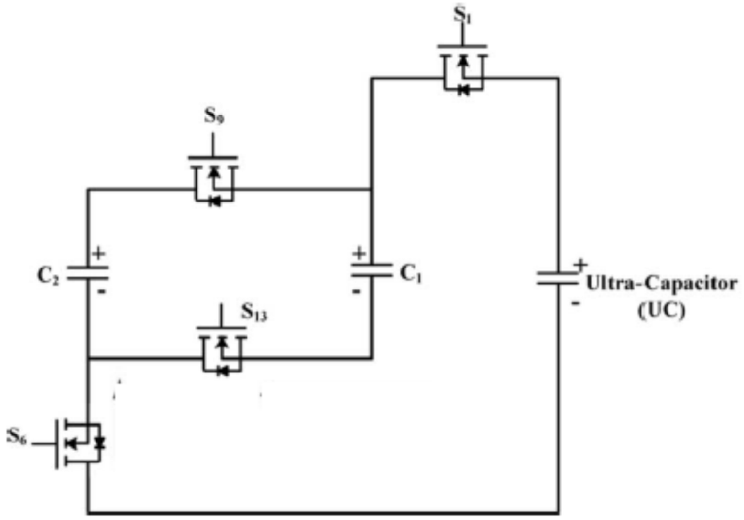

Figure 7: Capacitors are discharged and are disconnected from HV side

III. APPLICATION OF SCC IN HYBRID ELECTRIC VEHICLE

For a hybrid electric vehicle to run, both internal combustion engine and battery is used. There are two mostly common types of hybridization, series and parallel hybrids. In series hybrid only electrical energy is used for driving the vehicle [12]. In case of parallel hybrid both internal combustion engine and electrical motor is used for driving the vehicle. The figure 8 shows parallel hybrid electric vehicle where the Switched capacitor based converter is used.

High voltage Battery is used and its output is given to Full Bridge DC/DC converter and DC/AC inverter. The battery requirements were recommended based on two sets of electric range and time-frame [13]-[15]. If the vehicle is based on AC motor, inverter can be used else inverter part is eliminated. For charging low voltage battery full bridge DC/DC converter is used and low voltage battery is used to start the vehicle. Many techniques have been implemented when switching over from internal combustion engine to electric motor.

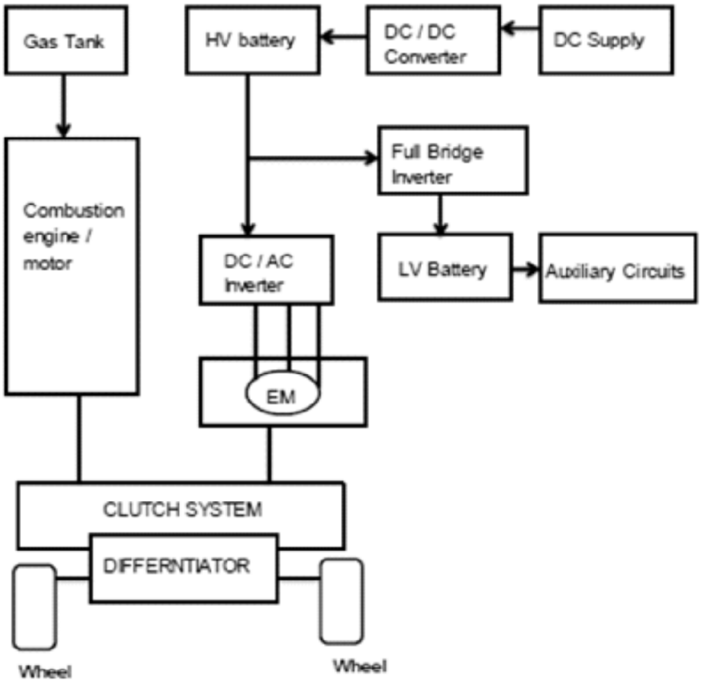

Figure 8: Hybrid Electric Vehicle Systems

IV. ENERGY TRANSFER EFFICIENCY

The Switched Capacitor converter has two main modes of operation, the buck mode and boost mode. The current-amplification technique is used in buck mode of operation. Therefore, the output current is amplified by these capacitors. It must be noted that capacitors and are of equal sizes, so that the voltage across each of them is equal. Therefore, the voltage across capacitor can be expressed as,

$$Vc(t) = Vc(0) + \frac{1}{C}\int_0^t Ic(t)dt = Vc(0) + \frac{1}{C}IBatt \;\; 0 \le t \le kT$$

$$Vc(t) = Vc(kT) + \frac{1}{C}\int_{kT}^t Ic(t)dt = Vc(kT) - \frac{t-kT}{2C}Iuc \; kT \le t \le T$$

The current flowing through capacitor can be written as

$$Ic(t) = \frac{Vbatt - 4Vt - 2Vc(0)}{Ran}\left(1 - e^{-\frac{t}{C+Ran}}\right) 0 \le t \le kT$$

$$Ic(t) = -\frac{-Vuc + Vc(kT) - 3Vd}{Raf}\left(1 - e^{-\frac{t}{C+Raf}}\right) kT \le t \le T$$

The overall transfer efficiency is given as,

$$\eta = \frac{Po}{Pi} = \frac{Vuc * (1-k)(-Vuc + Vc - 3Vd) * Ran}{Vbat * k * (Vbat - 4Vd - 2Vc) * Raf}$$

Next, the boost mode implements the *voltage-lift technique*. The capacitors and are charged in parallel during on-state and input voltage is applied across them. The capacitors are discharged in series during off-state. Therefore, the output voltage is lifted by the capacitors. Thus, the voltage across capacitor can be expressed as

$$Vc(t) = Vc(0) + \frac{1}{C}\int_0^t Ic(t)dt = Vc(0) + \frac{1}{C}Iuc \;\; 0 \le t \le kT$$

$$Vc(t) = Vc(kT) + \frac{1}{C}\int_{kT}^t Ic(t)dt = Vc(kT) - \frac{t-kT}{2C}Ibat \; kT \le t \le T$$

Also, current flowing through capacitor can be written as

$$Ic(t) = \frac{Vuc - Vc - 3Vd}{Rbn} = \frac{Iuc}{2}\ 0 \leq t \leq kT$$

$$Ic(t) = -\frac{-Vbat + 2Vc - 4Vd}{Rbf} = -Ibat\ kT \leq t \leq T$$

The overall transfer efficiency is given as,

$$\eta = \frac{Po}{Pi} = \frac{Vbat * (\frac{(1-k)(-Vbat+2Vc-4Vd)}{Rbf})}{Vuc * k * \frac{(Vuc-Vc-3Vd)}{Rbn}}$$

V. SIMULATION RESULTS

The control algorithm for Switched Capacitor Converter is modelled in MATLAB. In this simulation HV side is set at 250V and LV side is set at 180V. In this work, the UC and Li-ion battery is used, whereby the UC is modelled by an internal resistance (*R*eq) and an equivalent capacitance (*C*eq) and the total UC voltage is 180 V. The battery model includes a voltage source and an internal resistance (*R*bat), which accurately characterizes the system. The *R*bat in discharge mode depends on the battery current, state of charge (SOC), and the temperature (Δ*T*).

Hence, Li-ion battery modules, with SOC = 100% at 25 °C, are used, and the total battery bank voltage is 250 V. Values for the parameters of the equivalent circuit are given as follows—battery modules: nominal voltage = 250 V, internal resistance = 1.0417 Ω, rated capacity = 6 Ah, and initial SOC = 100%; UC modules: initial capacitor voltage = 150 V and resistance = 0.2 mΩ; and SC: capacitance = 44 mF, and series resistance = 10 mΩ.

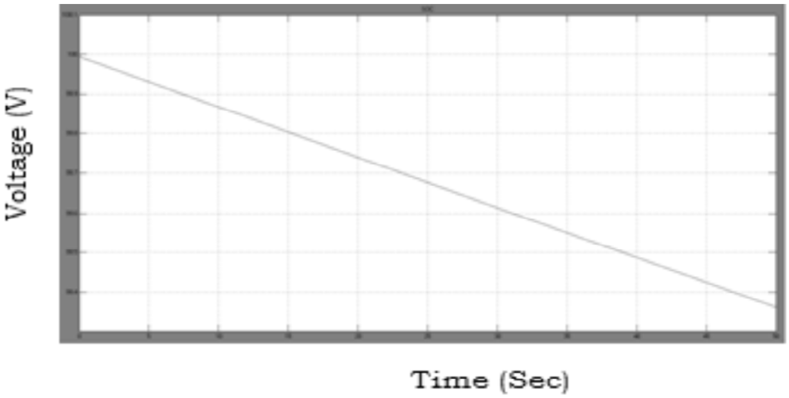

Figure 9: Forward Motoring; Battery State of Charge

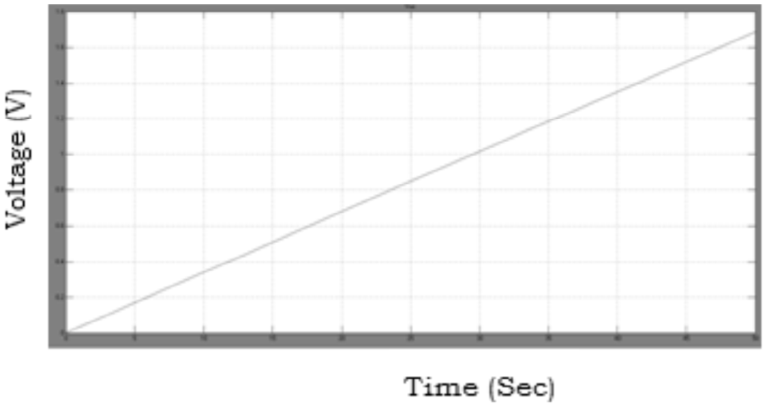

Figure 10: Forward Motoring; Capacitor voltage

The first simulation is carried out, in which the battery is supplying load. Hence there will be no reduction in Ultra capacitor voltage and the two capacitors are not charged. The time taken for running the simulation is 50seconds. The capacitor is not initially charged and has the voltage level varying from 0 to 1.7V.

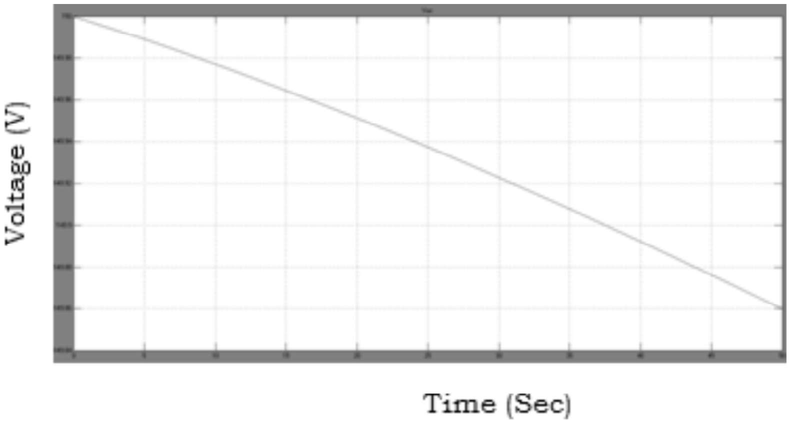

Figure 11: Forward Motoring; Ultra capacitor Voltage

The voltage of Ultra capacitor which is initially charged here has shown as varying between 150V and 149.86V.This shows the Battery State of Charge is reducing and it has the percentage value from 100 to 99.4 in 50sec.

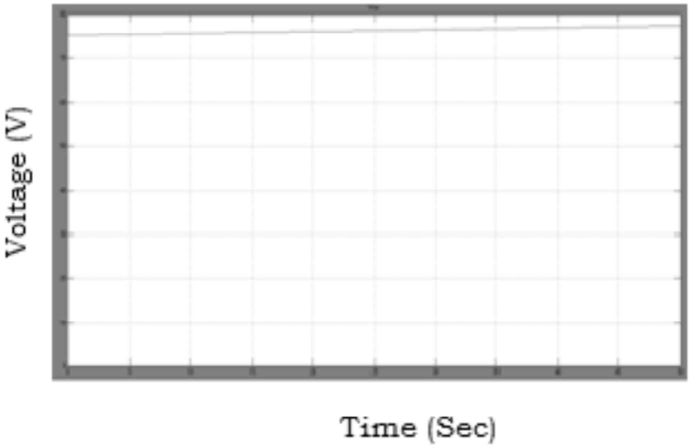

Figure 12: Boost Mode; Capacitor voltage

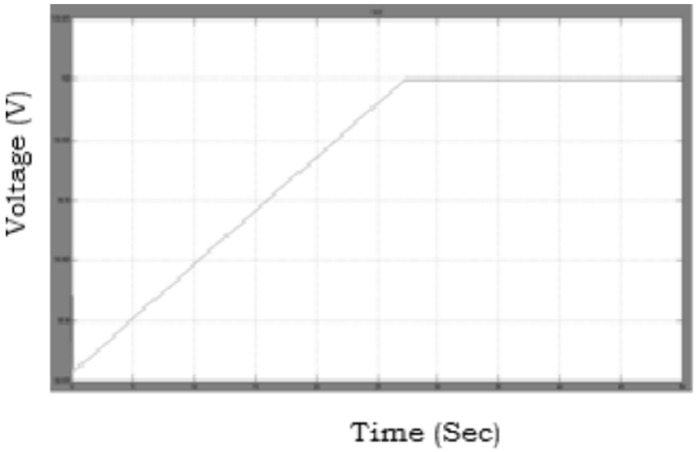

Figure 13: Forward Regeneration; State of charge

This mode represents generating. Now the capacitor is charged by the battery which is about 300V. Here the battery SOC is 100% and it represents full charge on the battery.

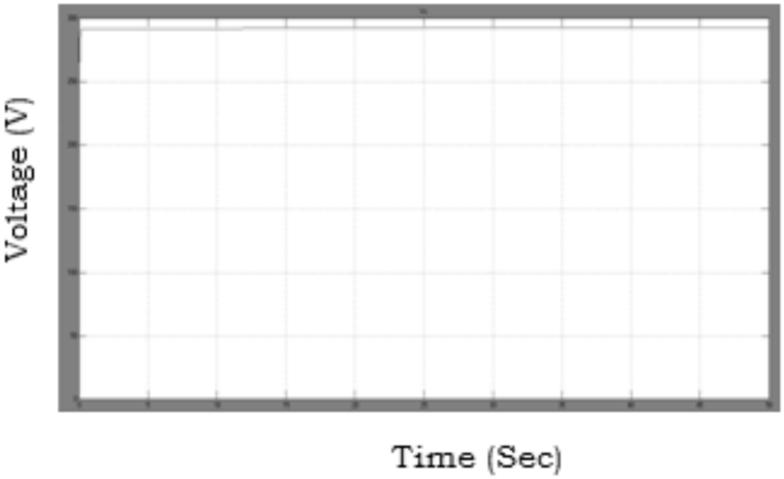

Figure 14: Forward Regeneration; Capacitor Voltage

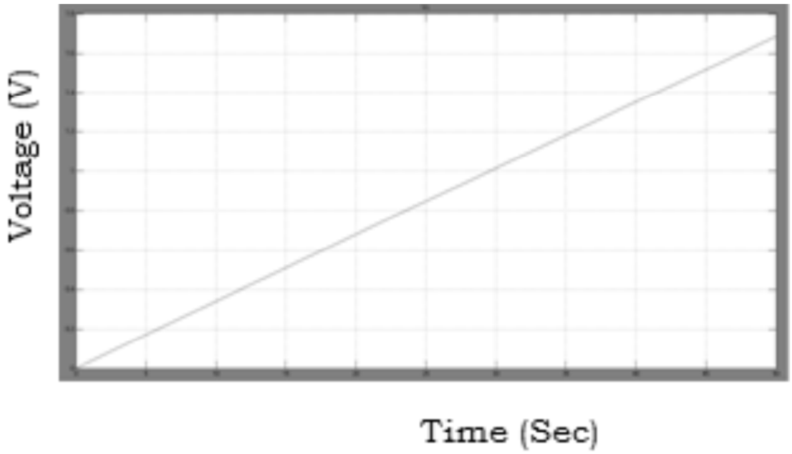

Figure 15: Buck Mode; Capacitor voltage

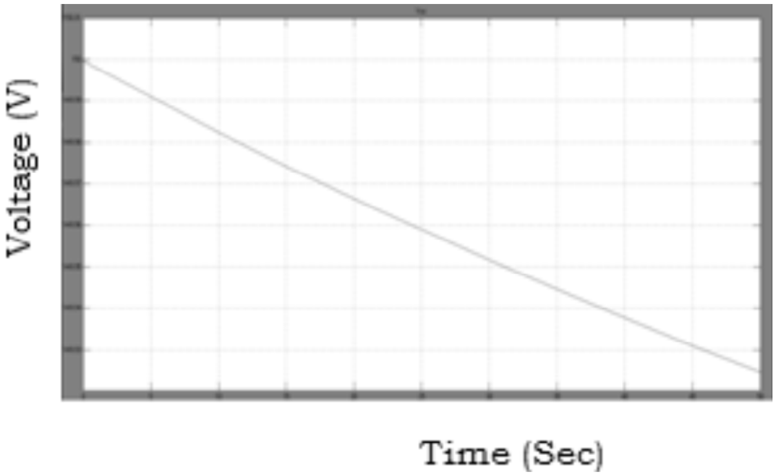

Figure 16: Buck Mode; Ultra capacitor voltage

Here the charge from the capacitor which is stored by battery is discharged in the ultra capacitor. The capacitor voltage is now 1.8V and the ultra capacitor voltage is now set at 150V.

VI. CONCLUSION

Energy storage systems [ESSs, e.g., batteries or ultra capacitors (UCs)] are usually employed in electric vehicles (EV) and hybrid EVs (HEVs) to reduce the overall cost, size, and weight of the vehicle and improve performance. This technology uses high voltage battery for charging and a hybrid car battery is used for this purpose. A hybrid car battery is like any other battery except that it is rechargeable and has enough juice to move a large heavy vehicle down the road for a few feet or a few miles. Switched Capacitor bidirectional DC/DC Converter applicable for HEV is used to charge this battery and ultra capacitor together called as Energy Storage System. The advantages in using Switched Capacitor Converter is voltage step – down, voltage step up and bidirectional power flow, associated with two or more HEV energy storage devices. It provides additional advantages like lower source current ripple, simpler dynamics and control simplicity and ease of control. The novel control strategy enables simpler dynamics compared to a standard buck converter with an input filter, good regulation capability; low electromagnetic interference and continuous input current waveform in both modes of operation (buck and boost modes).

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