Super-Capacitor Assisted Battery System in EV using Quadratic Gain Bidirectional DC-DC Converter

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***Abstract*—Energy storage systems are gaining importance in the current scenario. To improve efficiency, Hybrid Energy Storage Systems (HESS) are the most researched topic nowadays. HESS make use of one or more energy storage devices utilizing the advantage of each device. Battery supercapacitor combination is used in this system. Batteries and supercapacitors require bidirectional converters to charge and discharge according to necessary conditions. The main drawback associated with bidirectional converters are that they require more switching devices to operate thereby increasing the control complexity of the circuit. Here a quadratic gain bidirectional converter is used which has a simpler topology so that only one switch is to be controlled i.e. only one switch is responsible for power flow in Buck and Boost modes.**

Keywords—Hybrid Energy storage Systems, Bidirectional Converter, Quadratic gain, Buck mode, Boost mode.

I. INTRODUCTION

The usage of fossil fuels results in environmental pollution, the clean energies become very important in the world. In recent years, the renewable energy systems, including photo-voltaic systems, fuel-cell systems, wind-power generating systems, are developed rapidly. Because the renewable systems cannot provide a stable power for user, the renewable energy systems and battery can be utilized for the hybrid power systems. When the renewable energy systems cannot supply enough power for the load, the battery must replenish insufficient power. Whereas the whole power of the renewable energy systems cannot be used completely by the load, the surplus energy can be used to charge the battery.

Due to floating nature of renewable energy system, they are not suitable for stand-alone applications causing stability issues in power network. Energy storage devices came into picture to overcome the stability issues. The other problem was that the output of renewable energy sources is very low. So they require DC-DC converters with high gain [4]. Conventional ESDs cannot satisfy the load requirements. Afterwards hybrid energy storage devices have emerged to provide overcapacity and to ensure voltage and frequency stability. ESDs are based on supercapacitor or high performance batteries such as Ni-Cd, Ni-Metal Hydride and Lithium Ion batteries. Batteries are characterized by high energy density [13], [14], [17]. Ultracapacitors are undergoing manufacturing improvements so that they can compete with batteries in all respects. They are manufactured using Lithium ion technology. Supercapacitors can deliver power for a long interval of time and also have the capability to handle high currents [18]. Bidirectional DC-DC converters can transfer the power between two DC sources in either direction [7]. Non isolated topology is preferred over isolated one because in the former the need for transformer is eliminated. This reduces the cost and bulkiness of the circuit [5]-[12], [15]. There are different topologies available for isolated bidirectional converters based on voltage transfer ratio [19], [20]. Multi input and multi-level DC-DC converter topologies are also available [16]. Quadratic gain bidirectional DC-DC converters have emerged which are widely used for renewable energy hybrid power systems, hybrid electric vehicle energy systems etc. [2], [3]. As the converter has high gain during Buck and Boost modes, a small ultracapacitor is only required eliminating the need of ultracapacitor banks. This helps to achieve a hybrid system in electric vehicle where supercapacitor system can be used as a supplement to the vehicle battery [1].

Supercapacitor assisted battery system is used in this system. As more than one energy storage systems are connected in parallel the entire system is unaffected by any fault occurring on individual system i.e. the system will work without any interruptions. Current mode control is used to generate gating signals for the power switch in each mode of the bidirectional converter.

II. BATTERY SUPERCAPACITOR HYBRID SYSTEM

Fig. 1. shows the block schematic of battery supercapacitor system for an electric vehicle. There are two input sources, two bidirectional converters (conventional and modified bidirectional converters), DC bus and load. Hybrid Energy Systems offer many advantages such as increased efficiency, improved system performance and extending the battery life. Batteries have high energy density whereas supercapacitors have high power density.

Supercapacitor is a high capacity capacitor that has the capability to store 10 to 100 times more energy than conventional capacitors. They can tolerate more number of charge and discharge cycles than batteries. A supercapacitor is made up of two metallic or carbon plates having opposite polarity. They are separated by a very thin dielectric material.

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The large value of capacitance of supercapacitor is due to the porosity of plates of the capacitor holding the charge.

Supercapacitor is able to handle peak power in short intervals. Battery is capable of supplying load at constant rate for long intervals. By using a hybrid system a small battery with less peak power output is only required. So cost concerns and bulkiness issues are resolved.

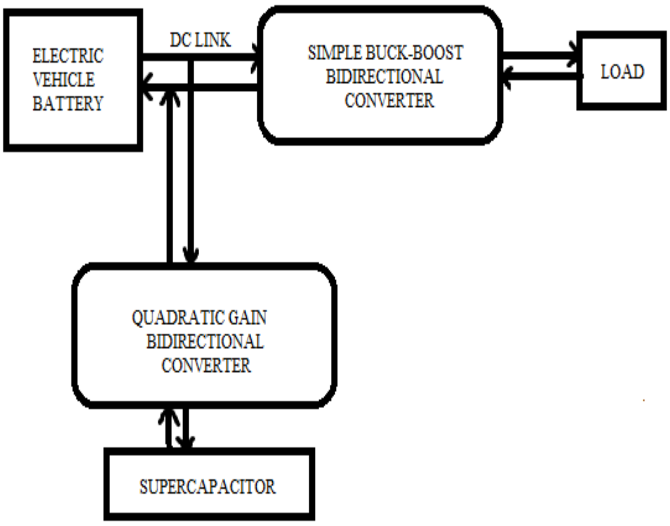

Fig. 1. Block diagram of battery- supercapacitor hybrid system

III. INTERFACING CONVERTERS

Battery supercapacitor system is interfaced to the load via two bidirectional converters, i.e. a simple Buck-Boost bidirectional converter and a quadratic gain DC-DC bidirectional converter. The input battery (vehicle battery) is rated at 24 V. A 5 V supercapacitor is also used at the input side which is interfaced to DC link via quadratic gain bidirectional converter. A simple Buck-Boost type bidirectional converter is used for supplying the load (forward motoring) in Buck mode and regenerative braking (reverse direction) in Boost mode (if the load is an electric motor).

A. QUADRATIC GAIN BIDIRECTIONAL CONVERTER

The quadratic gain bidirectional converter has two inductors, two diodes, four switches and a capacitor. Fig. 2. shows the circuit diagram of quadratic gain converter. The input to the converter is supplied by a supercapacitor. The output of the converter is given to a DC link at the input side of the system. Converter has two modes of operation-Buck and Boost modes. In each mode only one switch is responsible for the power flow so control complexity of the circuit is less. This converter is characterized by high gain in both step up and step down modes.

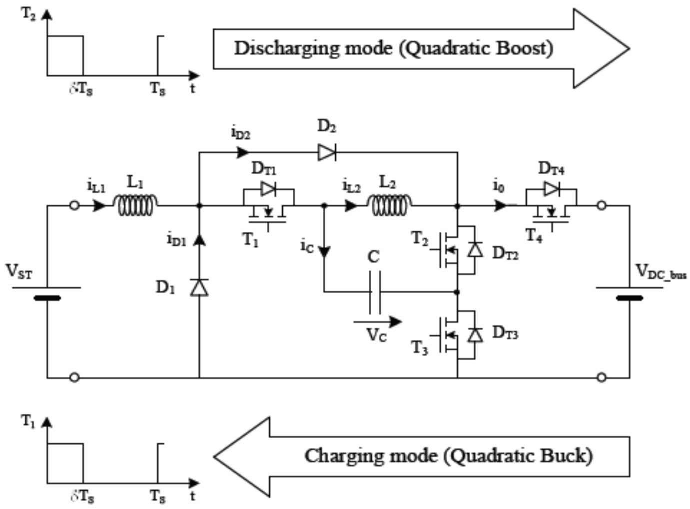

Fig. 2. Circuit diagram of quadratic gain converter

The converter is assumed to be operating in steady state continuous conduction mode. The capacitor value is taken large enough so that voltage across it is taken constant along one switching cycle.

OPERATION IN BOOST MODE

In this given mode of operation switches T_1 and T_4 are turned OFF while T_3 is turned ON. T_2 is the single semiconductor responsible for power flow. In the first stage T_2 is turned ON. Fig. 3. shows the current flow in mode 1. Here energy from storage device is transferred to inductor L_1. During this mode capacitor C discharges and transfers energy into inductor L_2. As a result currents in inductors L_1 and L_2 will linearly increase. Following equations can be formed in this mode of operation.

$$V_{L1} = V_{ST}$$
$$V_{L2} = V_{ST} - V_C$$

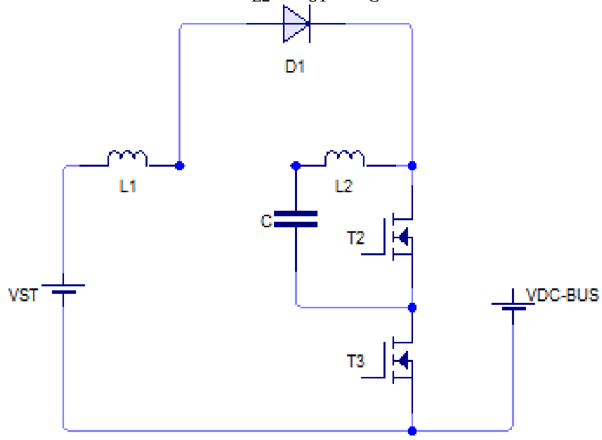

Fig. 3. Current flow in mode 1 in Boost mode

In the second stage T_2 is turned OFF. Currents in inductor L_1 and L_2 will linearly decrease transferring the energy from L_1 and L_2 to capacitor C and DC bus respectively. Fig. 4. shows the current flow in mode 2. Following equations can be formed in this mode of operation.

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$$V_{L1} = V_C$$
$$V_{L2} = V_C - V_{DC\ BUS}$$

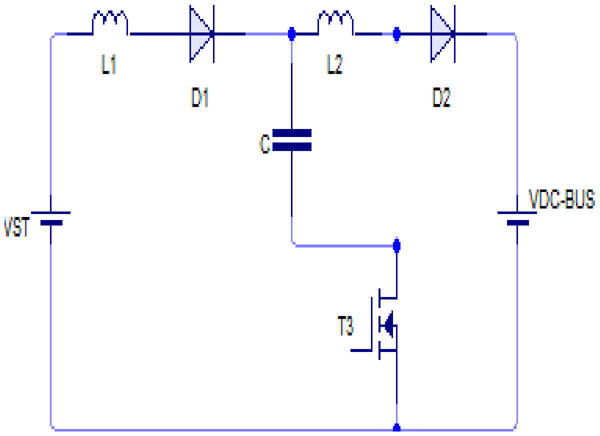

Fig. 4. Current Flow during Mode 2 in Boost mode

OPERATION IN BUCK MODE

In this given mode of operation Switches T_2 and T_3 are turned OFF while T_4 is turned ON. T_1 is the single semiconductor responsible for power flow. In the first stage T_1 is turned ON. Fig 5 shows the current flow in mode 1. Here energy from DC bus and capacitor is transferred to inductor L_1 and L_2 respectively. During this mode capacitor C discharges and transfers energy to inductor L_2. As a result currents in inductors L_1 and L_2 will linearly increase. Following equations can be formed in this mode of operation.

$$V_{L1} = V_{ST} - V_C$$
$$V_{L2} = V_{ST}$$

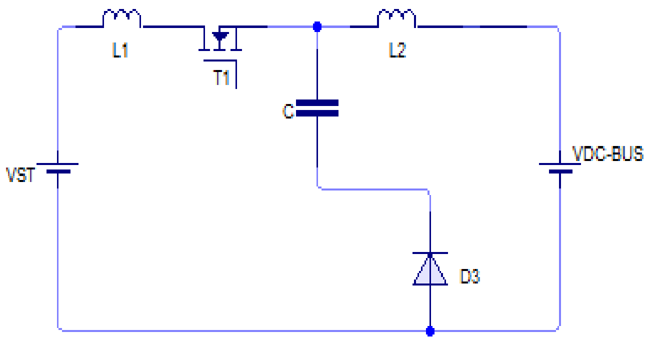

Fig. 5. Current flow in mode 1 in Buck mode

In the second stage T_1 is turned OFF. Currents in inductor L_1 and L_2 will linearly decrease transferring the energy from L_1 and L_2 to capacitor C and storage device respectively. Fig. 6. shows the current flow in mode 2. Following equations can be formed in this mode of operation.

$$V_{L1} = V_C - V_{DC\ BUS}$$
$$V_{L2} = V_C$$

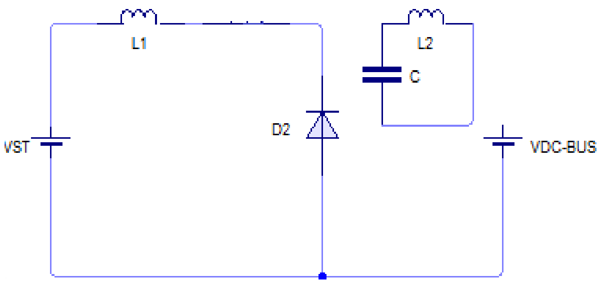

Fig. 6. Current flow in mode 2 in Buck mode

B. *SIMPLE BUCK-BOOST BIDIRECTIONAL CONVERTER*

Simple Buck-Boost type bidirectional converter has an inductor, two switches and input and output capacitors. The diodes in a conventional Buck Boost converter are replaced by controllable switches. Fig. 7. shows the circuit diagram of simple Buck-Boost bidirectional converter.

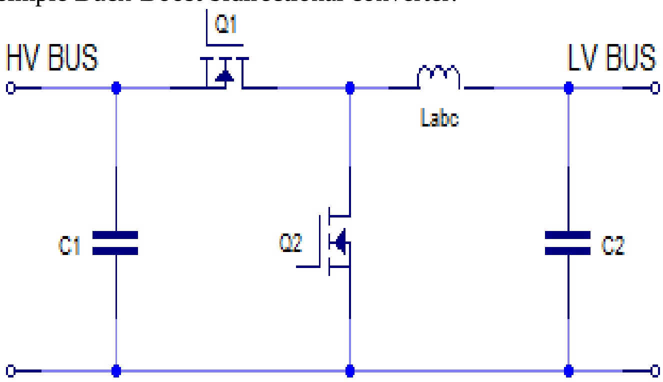

Fig. 7. Circuit diagram of simple Buck-Boost type bidirectional converter

OPERATION IN BUCK MODE

In this mode of operation Q_2 is turned OFF and Q_1 is responsible for the power flow. When the switch Q_1 is turned ON, the energy from HV bus is transferred to the LV side via inductor L_{abc}. When Q_1 is turned OFF, inductor L_{abc} discharges via the diode in parallel to Q_2.

OPERATION IN BOOST MODE

In this mode of operation Q_1 is turned OFF and Q_2 is responsible for the power flow. When the switch Q_2 is turned ON, the energy from LV bus is transferred to inductor L_{abc}. When Q_2 is turned OFF, inductor L_{abc} discharges via the diode in parallel to Q_1 to the HV side.

IV. SIMULATION OF BATTERY SUPERCAPACITOR HYBRID SYSTEM

Simulation of battery-supercapacitor hybrid system is done in MATLAB/SIMULINK 2016 version. In order to maintain a DC link voltage of 24 V, a 24 V battery is used. A 5 V supercapacitor is interfaced to DC link via quadratic gain bidirectional DC-DC converter. On the load side a 12 V battery is used. A 2.7 V ultra-capacitor is given as the input to the quadratic gain bidirectional converter. The output of this converter is given to the DC link. Fig. 8. shows the simulation parameters of battery supercapacitor hybrid system. Fig. 9. shows the simulation diagram of the battery supercapacitor hybrid system.

Input battery voltage	24 V
supercapacitor voltage	2.7 V
L_1	2.4 µH
L_2	8.8 µH
C	2200 µF
Load side battery voltage	12 V
Switching frequency	15 KHz

Fig. 8. Simulation Parameters of battery supercapacitor hybrid system

A conventional bidirectional Buck-Boost converter is used to interface the battery supercapacitor hybrid system to the load side. In the forward direction Buck action takes

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place and 24 V DC link voltage is stepped down to 12 V at the load battery side.

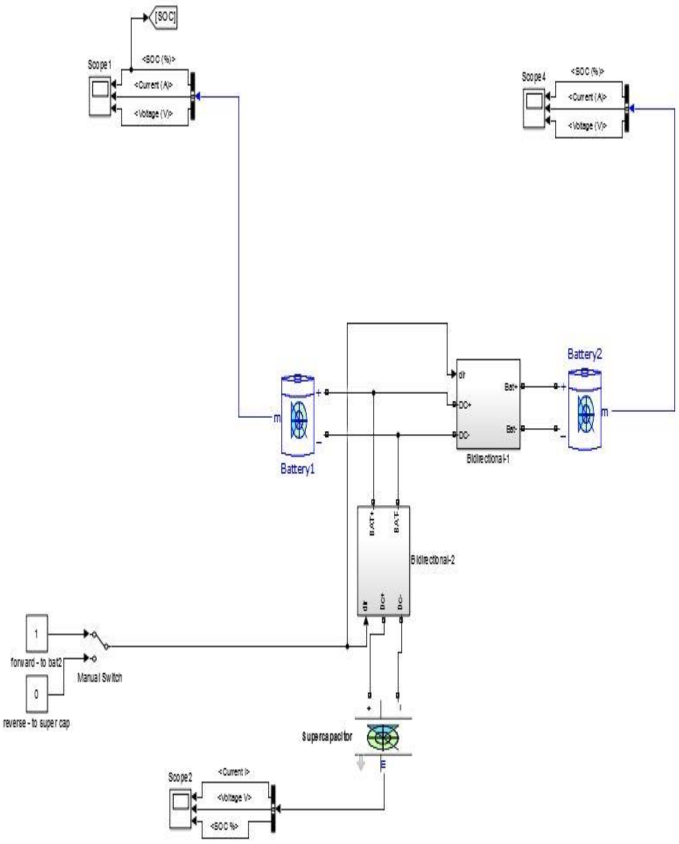

Fig. 9. Simulation diagram of the battery supercapacitor hybrid system

Fig. 10. shows the quadratic gain bidirectional converter subsystem. The input to the subsystem is the supercapacitor and output is connected to the DC link.

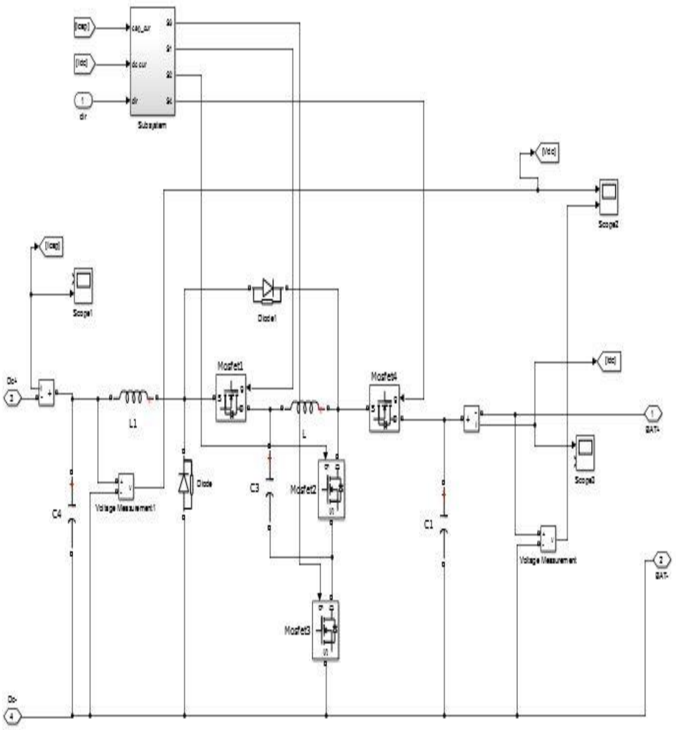

Fig. 10. Quadratic gain bidirectional converter subsystem

Fig. 11. shows the conventional Buck-Boost bidirectional converter subsystem. The input to the subsystem is the 24 V DC link voltage and output of the subsystem is the 12 V battery load.

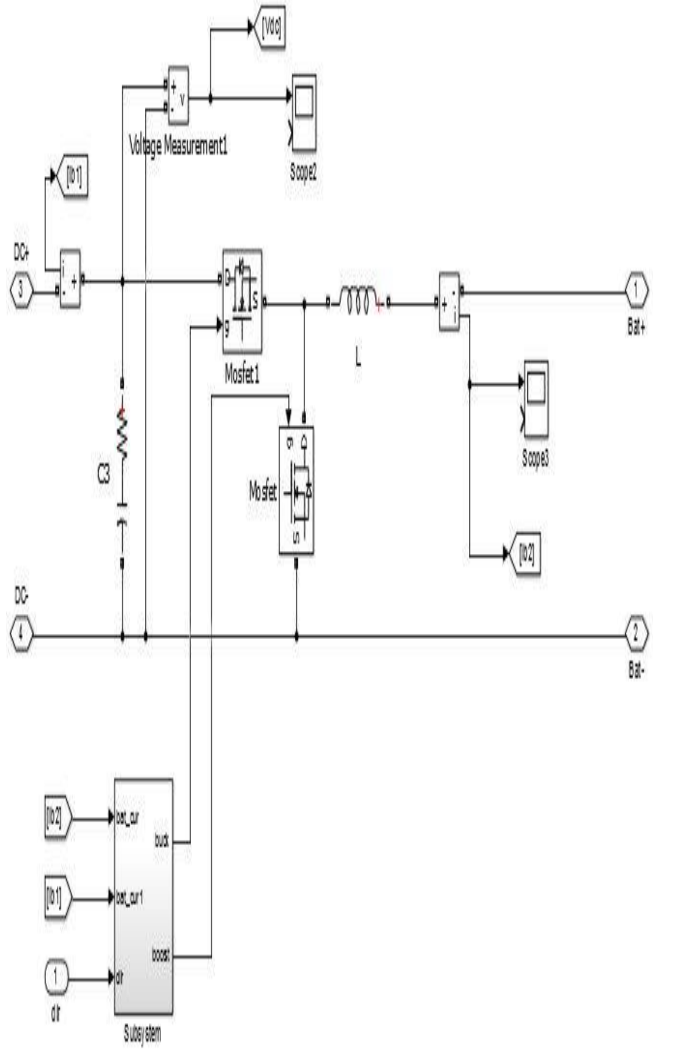

Fig. 11. Conventional Buck-Boost bidirectional converter subsystem

Current mode control is the control strategy used in the simulation. Fig. 12. shows the gating signal generation for quadratic gain bidirectional converter. The feedback loop consists of a constant block that acts as the reference signal. It is the signal with which the output current is compared. These signals are compared using an add block. The signal that we obtain is fed to the PID controller whose output is an error signal which is compared with the repeating sequence (triangular sequence) using a relational operator block, the output thus obtained will be square pulses. The saturation block is provided to limit the output from the PID controller.

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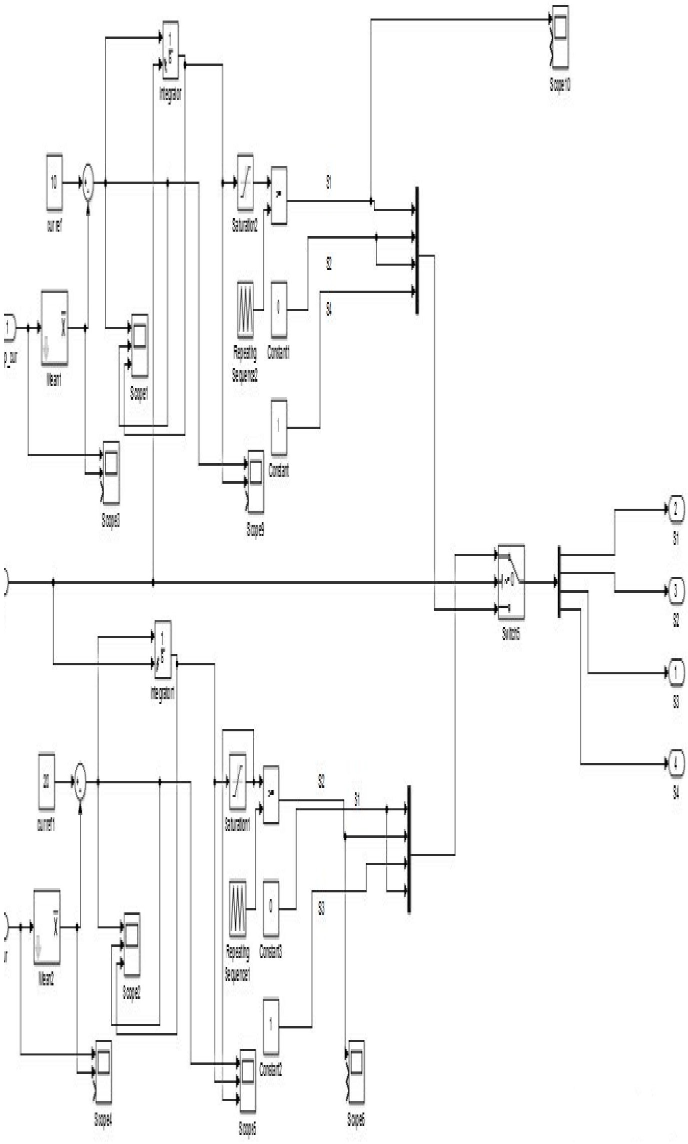

Fig. 12. Gating signal generation for quadratic gain bidirectional converter

A manual switch is used to select the mode of operation of quadratic gain bidirectional DC-DC converter. In the first position of the manual switch the ultracapacitor supplies energy (discharging mode) to the DC link. In the second position ultracapacitor charges. The charging and discharging rate of supercapacitor and battery are illustrated by SOC (State of Charge). Fig. 13. shows the gating signal generation for conventional bidirectional Buck-Boost converter. Buck mode and Boost mode of this converter are selected by using a direction switch.

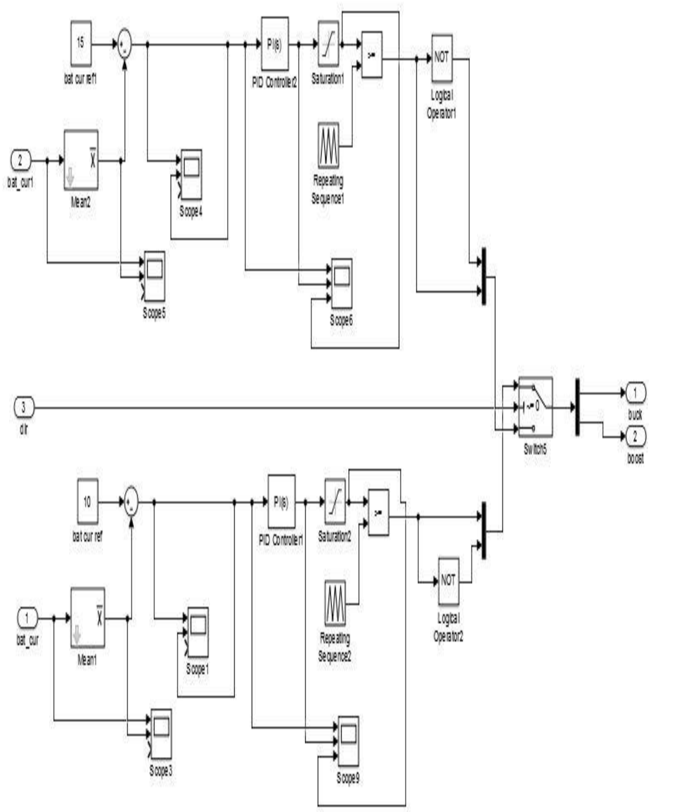

Fig. 13. Gating signal generation for conventional bidirectional converter

Fig. 14. shows the supercapacitor current, voltage and SOC . It can be seen that both SOC and voltage decrease slowly. The current is positive indicating discharging mode.

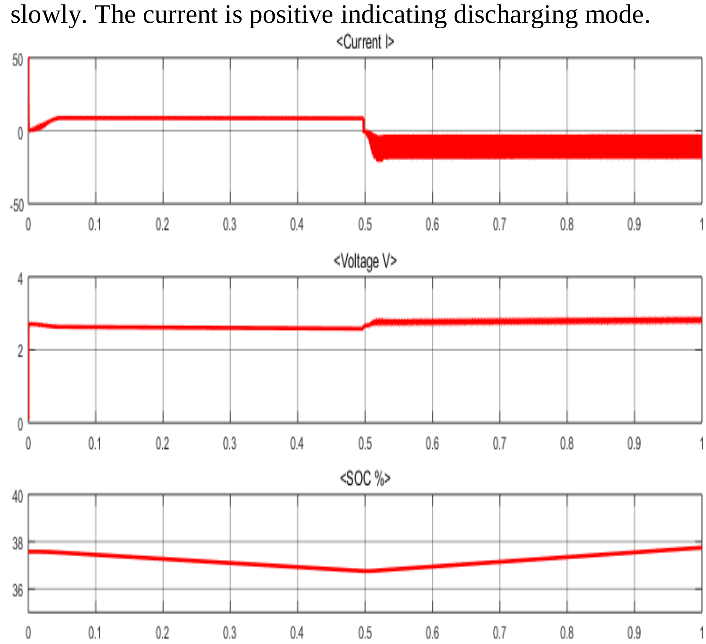

Fig. 14. Supercapacitor current, voltage and SOC

Simulation is done for both charging and discharging of battery and supercapacitor. Half of the simulation time shows charging mode and other half shows the discharging mode. Fig. 15. shows Battery current, voltage and SOC

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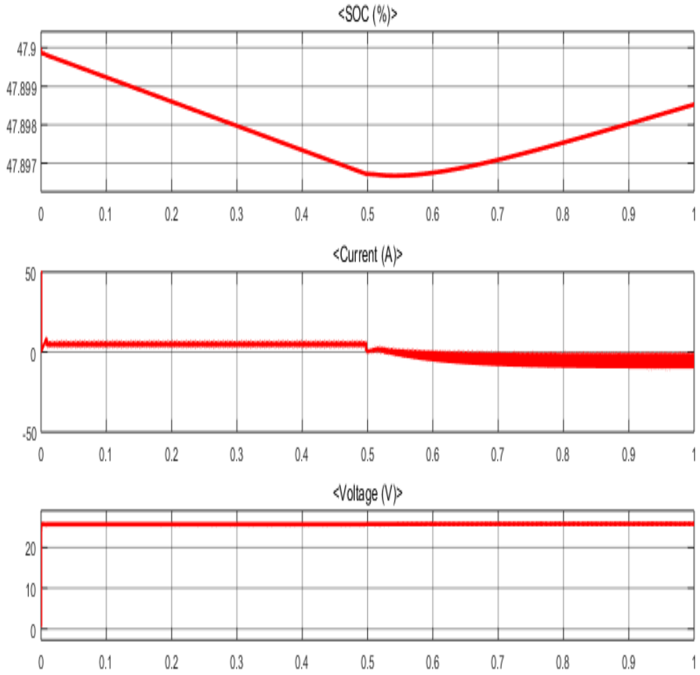

Fig. 15. Battery current, voltage and SOC

V. CONCLUSION

Supercapacitor assisted battery system is introduced which has many advantages. As two energy systems are connected in parallel, failure of one energy source doesn't affect the working of the whole system. The other advantage is that the requirements of high rated batteries are avoided. Batteries with less peak output power can be used which results in reduction of cost and bulkiness of batteries used. The quadratic gain bidirectional converter offers high gain so that small rated supercapacitors can be used other than capacitor banks.

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