Comparison Study Of Hybrid Energy Storage System With Two Different Converter Topologies For Electric Vehicle Applications

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Abstract: The main objective of doing this project is to design and develop a proper converter topology, which better support the energy management and power flow in both direction. In other words to formulate a hybrid energy storage system with battery and supercapacitor (SC), which is able to reduce the stress in the battery. The whole system is designed such that it is applicable in a permanent magnet direct current (PMDC) motor drive for electric vehicle (EV). A proper control strategy has to be developed in order to obtain the optimal solution. There are two topologies (Single unidirectional and bidirectional converter topology, Two bidirectional converter topology) selected to do this work and these two topologies are studied, verified in detail. Also a comparative study of these two topologies is carried out. The entire Simulation of system is done in MATLAB/Simulink.

Keywords: Supercapacitor, Battery, Hybrid energy storage system, Bidirectional converter, Electric vehicle, Hybrid electric vehicle (HEV). Plug-in hybrid electric vehicle (PHEV)

1. Introduction

Electric vehicle is one of the field which is gaining much popularity now a days . Many research and advancement is going on in this particular area. This is because of its very high efficiency and much smaller emission levels compared to (ICE) Internal Combustion Engine vehicles. Still it is difficult for (EVs) Electric Vehicles to completely replace the internal combustion engine vehicles, because of the problems in their energy system, driving range, charging time and life time . But these issues can be overcome to some extent. Other salient features of EV are noise free and it helps in saving fossil fuels.

Energy storage systems (ESSs) plays a major role in electric, hybrid electric and plug-in hybrid electric vehicles (EVs, HEVs and PHEVs) [1]-[3]. Batteries are one of the widely used energy storage device , because of its high energy density and low cost. However it has many disadvantages also. That batteries have low power density, in applications that demand instantaneous power input and output it is found that batteries suffer from frequent charging and discharging operations, which will adversely effect on battery life [3].

In order to solve the above mentioned problems hybrid energy storage systems (HESS) have been proposed [2]-[4]. HESS is one which consists of two or more energy storage devices. Battery-SC HESS is commonly used from the various kinds of HESSs available. The basic idea behind a battery-SC HESS is to combine the benefits of both SC and battery, in order to achieve a better overall performance. This

is because SC have high power density and low energy density compared to that of a battery. This battery-SC combination inherently have a better performance compared to any of them (battery, SC) using alone. There are several configurations for HESS design [4], of which we are using the multiple converter configuration shown in Fig. 1**.** A HESS with two different converter topologies is studied and verified in this paper. The two converter topologies selected are Single unidirectional and bidirectional converter topology and Two bidirectional converter topology.

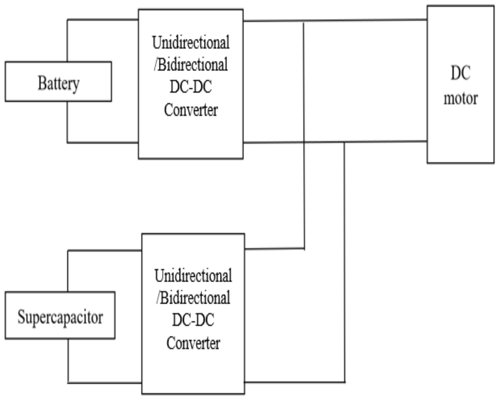


Fig. 1. Multiple converter configura

2.Hybrid Energy Storage System Topologies

A hybrid energy storage system (HESS) consists of two or more energy sources used together to improve system efficiency as well as to provide greater balance in energy supply [5]. Both batteries and SCs comes under the category electro chemical devices. However, there are lot of difference in the operating principles of these two devices [2]. Table I shows some of the features for different types of batteries and the same features for a SC is shown in Table II. From the Tables shown, it is clear that batteries have relatively higher energy density of 30-200 Wh/Kg. But the power density of battery is very low. On the other hand, SC have higher power density and slightly lower energy density. The most attracting feature of SC is that it has a life of over one million cycles. By using battery or SC alone it is not possible to achieve the desired characteristics (high energy density and high power density). In order to achieve an improved overall performance these two energy sources need to be combined. This combination inherently possess better performance.

Several researches have been done in HESS topologies over the past few years. There are several topologies available to implement a HESS [4]-[5]. A review of all the widely used HESS topologies is given in [4]. From these topologies multiple converter configuration as shown in Fig.1 is used in this work, because it better suits the objective of this work. This multiple converter configuration parallels the output of two converters.

Table I. Typical Characteristics Of Battery Cells

Name	*Nominal Cell Voltage (Volt)*	*Power Density (kW/Kg)*	*Energy Density (Wh/Kg)*	*Cycle Life (Times)*
Lead Acid	2	0.18	30-40	Up to 800
Ni-Mh	1.2	0.4-1.2	55-80	Up to 1,000
Li-Ion	3.6	0.8-2	80-170	Up to 1,200
Li-Polymer	3.7	1-2.8	130-200	Up to 1,000
Li-Iron Phosphate	3.2-3.3	1.3-3.5	80-115	Up to 2,000

Table Ii. Typical Characteristics Of Supercapacitor Cells

Name	*Nominal Cell Voltage (Volt)*	*Power Density (kW/Kg)*	*Energy Density (Wh/Kg)*	*Cycle Life (Times)*
SC	2.5-2.7	4-10	2-30	Over 1,000,000

The major components used to implement the two HESS topology are battery, SC, bidirectional/unidirectional converters and PMDC motor. The two converter topologies used to implement HESS are single unidirectional and bidirectional converter configuration and two bidirectional converter configuration. In single unidirectional and bidirectional converter configuration battery is connected to load through a unidirectional boost converter and the SC is connected to the load through a bidirectional boost-buck converter. On the other hand in a two bidirectional converter configuration, battery and SC are connected to the load through two different bidirectional boost-buck converters. A bidirectional converter allows the current to flow in both direction. i.e. from source side to load side and vice versa. When current flow is from source side to load side, converter works in boost mode of operation and if current flow is from load to source converter works in buck mode of operation.

3.Modes Of Operation

There are four different modes of operation for the two converter topology considered. They are forward low current operation, forward high current operation and two reverse mode of operations for charging SC and battery. These Four operating modes will be discussed in detail next.

3.1.Mode I: Forward Low Current Operation

This particular mode is same for both of the converter topology selected. It occurs, when the current drawn by load is less than the set limit i.e. battery alone is sufficient to handle the power demanded by the load. In this mode current flow is from battery to load. The converter connecting battery to load, boost the source voltage and is fed to the PMDC motor. Block diagram of this mode is shown in Fig . 2.

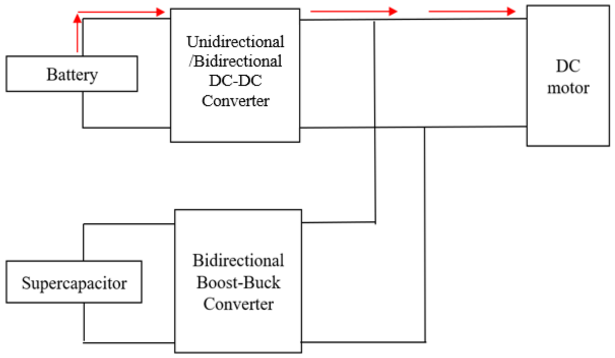


Fig. 2. Block diagram for mode-I operation

3.2.Mode II: Forward High Current Operation

This mode happens in both of the converter topology selected. It occurs, when the current drawn by the load is greater than the set limit i.e. during peak load of operation. Then supply is switched from battery to SC. During this mode of operation the bidirectional/unidirectional converter, which connects battery to load has no role (It is kept in off state). Then the SC comes in to action, in order to meet the load requirements. Here SC is connected to load through another bidirectional converter as shown in Fig. 3. This bidirectional converter (which connects SC to load) is operated in boost mode during this particular mode of operation.

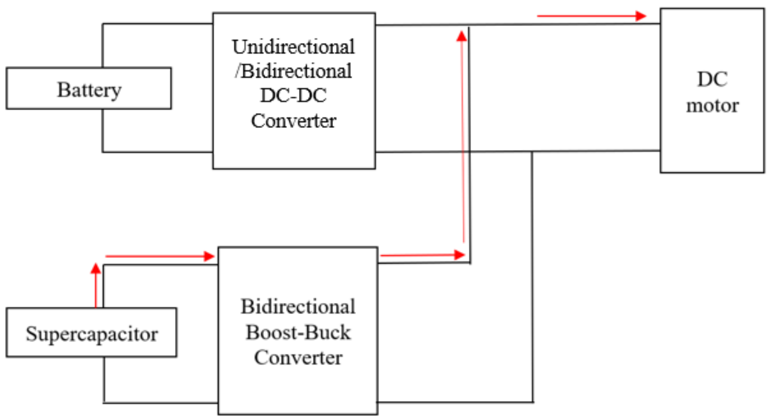


Fig. 3. Block diagram for mode-II operation

3.3.Mode III: Reverse Mode for Charging SC

This mode also occurs in both of the converter topology selected. Here energy captured during regenerative braking is stored in SC. Then the bidirectional converter, which connects SC to load need to be operated in reverse direction. So that current flows from motor to SC. For this to happen bidirectional converter (which connects SC to load) is operated in buck mode, which is shown in Fig .4.

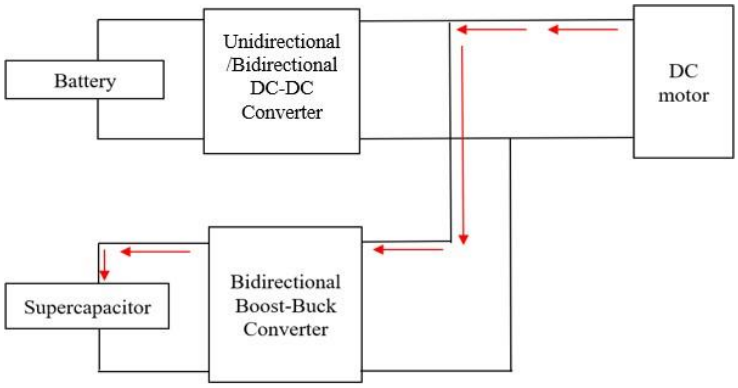


Fig. 4. Block diagram for mode-III operation

3.4.Mode IV: Reverse Mode for Charging Battery

This particular mode occurs only in two bidirectional converter combination. Once SC gets fully charged during reverse mode of operation, then battery is charged next. For this to happen the bidirectional converter that connects battery to load need to be operated in buck mode. Then current flows from load side(PMDC motor) to battery. Battery is charged only after the SC is charged fully. Block diagram for this mode is shown in Fig. 5.

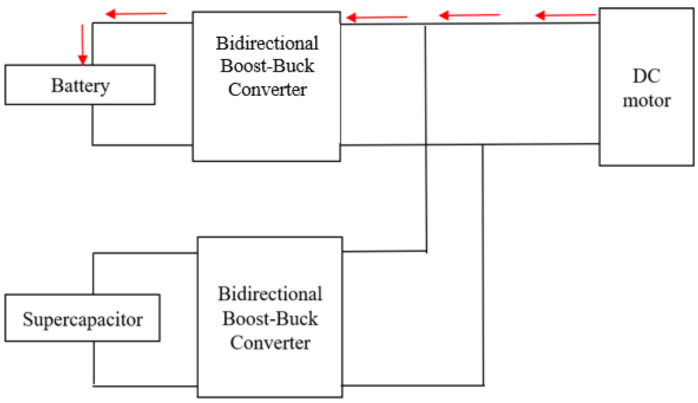


Fig. 5. Block diagram for mode-IV operation

4.Control Strategy

Control strategy opted for switching between different modes of operation for the two converter configurations are discussed in detail in this section.

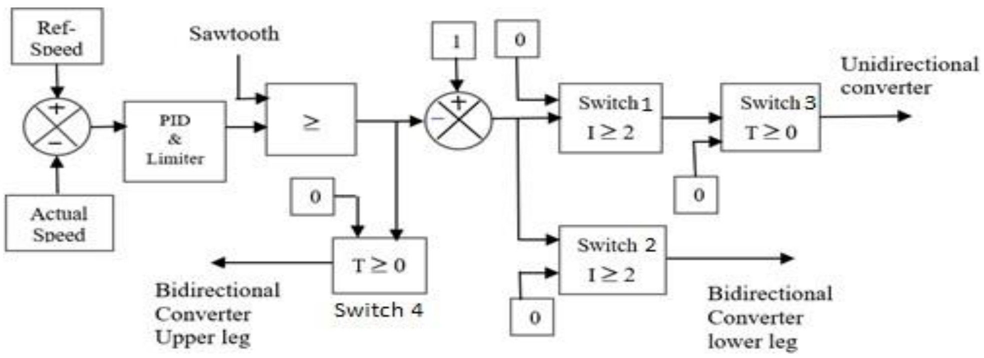


Fig. 6. Control strategy for single unidirectional and bidirectional converter configuration

4.1.Control Strategy for Single Unidirectional and Bidirectional Converter Configuration

Here we will be discussing how each converter is turned on or off up on the changes in the operating conditions. Fig.

6. shows how gating pulses for various switches in single unidirectional and bidirectional converter configuration is generated. First the reference speed signal is compared with the actual speed of the motor and the error is passed through a PID controller and limiter in order to generate the control signal. This control signal is then compared with a sawtooth wave form of required frequency to generate the Pulse width modulated signal. In order to get the complement of this signal it is then subtracted from one (constant). From the two signals generated one (non- complemented PWM-

signal) is fed to bidirectional converter upper switch and the other one(complemented PWM-signal) is given to either unidirectional converter switch or to bidirectional converter lower switch. When signal is given to bidirectional converter upper switch, SC will be in charging and the bidirectional converter will be in buck mode of operation. This happens only when load torque is less than zero, otherwise this switch is kept in off state. In order to implement this condition PWM signal is given to a selector switch-4, which will pass this signal to bidirectional converter upper switch up on load toque reduces below zero. Every other conditions this selector switch-4 will pass zero to next stage. Thus SC get charged when load torque is negative. If signal is given to unidirectional converter switch, then current flow is from battery to load . This situation occurs only when load current is less than the set limit (2A). For this switching to happen PWM signal is given to a selector switch-1, which will pass the signal only when load current is less than 2A. All other conditions it will pass zero to next stage. If the condition satisfies i.e load current I< 2A; this condition is also true when load current is negative (when current flows from load to source). We don’t need unidirectional converter switch to operate during this situation. So we add another selector switch-3 right after the first selector switch-1 (switch which checks the condition I³ 2A). The condition for that selector switch-3 is whether load torque T³ 0 . Thus signal is passed to unidirectional converter switch only when load current I< 2A and Load torque ³ 0. All other conditions unidirectional converter switch is off.

At a time only one source is active either battery or SC. In other words either unidirectional converter switch is on or bidirectional converter lower switch is on. If PWM signal is given to bidirectional converter lower switch current flows from SC to load (boost mode of operation) . this situation occurs only when Load current I³ 2A. PWM signal is given to bidirectional converter lower switch if this condition is satisfied (I³ 2A) also unidirectional converter switch is kept in off state during this period. The selecting condition (I³2A, in selector switch) is same for choosing either unidirectional converter switch or bidirectional converter lower switch to turn on. Let call selector switch for choosing unidirectional converter to turn on as switch 1 and the other one as switch 2. Switch 1 one will pass zero and switch 2 will pass PWM signal to next stage if selecting condition is satisfied (I³2A). If selecting condition is false switch 1 will pass PWM signal and switch 2 will pass zero to next stage. Thereby ensuring that only one source is active at a time. Circuit diagram for single unidirectional and bidirectional converter onfiguration is shown in Fig. 8.

4.2.Control Strategy for Two Bidirectional Converter Configuration

Comparing with the previous control strategy, it is same till the generation of PWM pulse and its complement. After that, selection of switch which is to be turned on is entirely different from the previous one. Once we get the PWM signal and its complement, the non-complemented PWM signal is passed either to top bidirectional converter (which

connects battery to load) upper switch or to lower bidirectional converter (which connects SC to load) upper switch. If pulse is given to top bidirectional converter upper switch then battery is in charging from the current that flows from load to battery, when load torque is negative. On the other hand if pulse is given to lower bidirectional converter upper switch then SC is getting charged. Before giving signal to switch 2 or switch 3, switch 1 will check the condition whether Load torque T ³ 0. Switch-1 will pass zero to next stage if condition is satisfied. If this condition is not satisfied (T<0) then only switch 2 & switch 3 will get signal else it passes zero to next stage (it implies that condition during regeneration either battery or SC is charged based on circuit condition). After Switch 1, signal is given either to switch 2 or to switch 3. Switch 2 and switch 3 will check for a condition that whether SOC of SC ³ 100. If SOC of SC is greater or equal to 100 then switch 2 will pass PWM signal to top bidirectional converter upper switch and switch 3 will pass zero to lower bidirectional converter upper switch. This implies battery is charged only after SC is charged fully. If the condition SOC of SC ³ 100 fails, then switch 2 will pass zero to next stage and switch 3 will pass PWM signal to lower bidirectional converter upper switch. This indicates during regeneration if SOC of SC is less than 100 then, SC is charged until it is fully charged

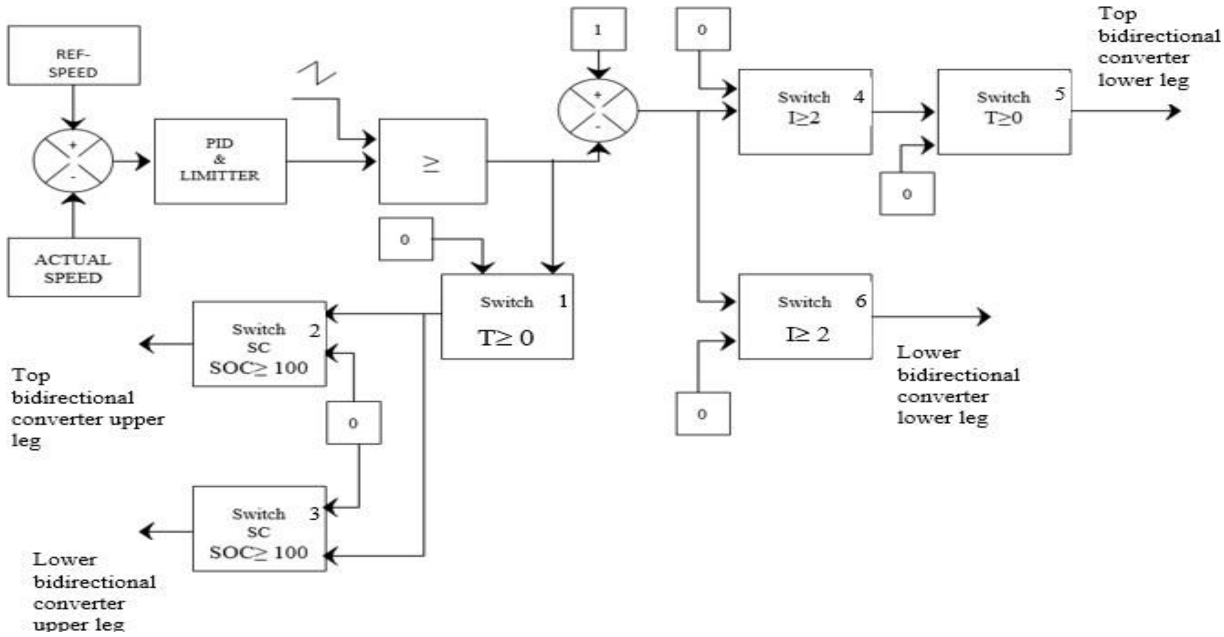


Fig. 7. Control strategy for two bidirectional converter configuration.

The complement of PWM signal is produced by subtracting the non complemented PWM signal from one(constant). This signal is given either to top bidirectional converter lower switch (to discharge battery) or to lower bidirectional converter lower switch (to discharge SC). Battery will discharge (current flow from battery to load) only when load current is less than the set limit (2A). If load current I ³ 2A then SC will discharge (current flow from SC to load). Switch 4 and switch 6 checks for the condition that whether load current I ³ 2A, if the condition is true then switch 4 will pass zero to next stage and switch 6 will pass pulses to lower bidirectional converter lower switch (implies

the condition that SC discharging to load). On the other hand if the condition if false then switch 4 will pass pulses to next stage and switch 6 will pass zero to lower bidirectional converter lower switch. Before giving the output of switch 4 to Top bidirectional converter lower switch one more switch is added in between (switch 5), this switch-5 will check for a condition either load torque T ³ 0. Once this condition (T ³ 0) is satisfied then only the PWM signal output form switch 4 is given to Top bidirectional converter lower. This is to prevent battery from discharging when load current is negative. Circuit diagram for two bidirectional converter configuration is shown in Fig. 11.

Table III. System Specifications

Components	***Ratings***
Battery	15V,24AH
Super Capacitor	15V,11F
Inductor	150mH
Capacitor	566mF
Frequency	10kHz
Duty ratio	40%
Load torque	1Nm
Motor	PMDC
Armature resistance	1.5W
Armature inductance	25mH
Torque constant	1.5Nm/A
Inertia	0.05117kg.m2
Viscous friction	0.003014Nms

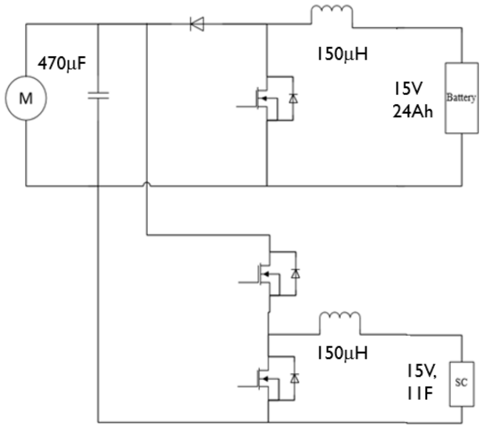


Fig. 8. Ciircuit diagram of single unidirectional and bidirectiona l converter configuration..

5.Simulation Results

In a closed loop speed control of PMDC- motor the reference speed is compared with actual speed of motor and error is given to PID-controller. The value of proportional,

integral and derivative constants are tuned as K_p=2, K_i = 0.1 and K_d = 0.004 respectively.

5.1.Results for Single Unidirectional and Bidirectional Converter Configuration

Circuit diagram of single unidirectional and bidirectional converter configuration is show in Fig.8. Load torque is given as a step change from 1Nm to -1Nm

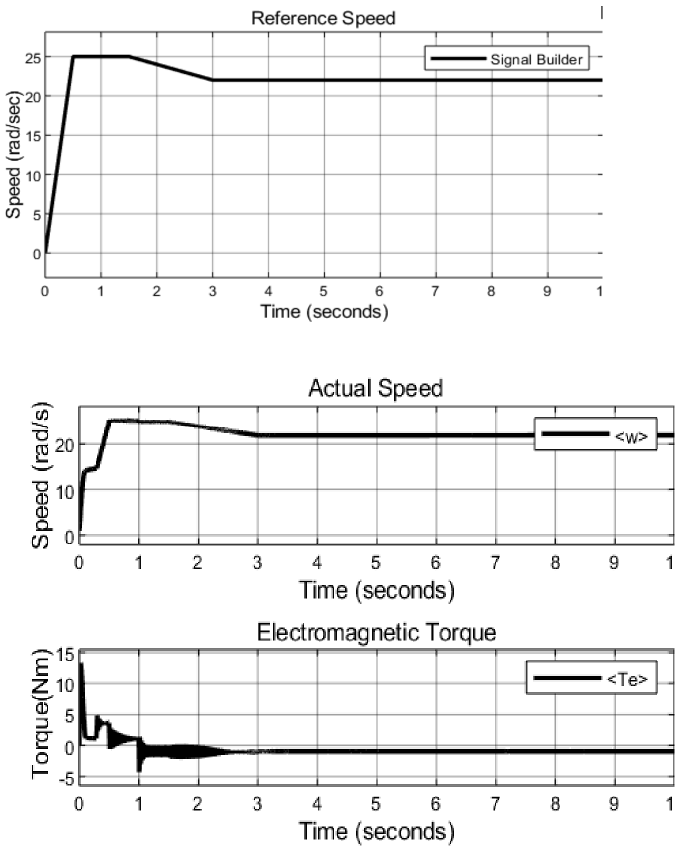


Fig. 9. Reference speed, Actual speed and Electromagnetic torque.

The reference speed signal which is given to the motor is shown in Fig 9. This signal is created using a signal builder. The signal is such that it contains a sudden rise from 0 to 25 rad/sec within 0.5sec. From 0.5sec to 1.5 sec speed remains same (25 rad/sec), then speed is decreasing and finally settles at 22 rad/sec in 3sec. It is observed that actual speed is following the reference speed from Fig. 9.

Limit for load current is set as 2A and load torque is given as a step change from 1N.m to -1N.m at 1sec. From Fig. 10. it is clear that, at starting armature current is greater than 2A and load torque T= 1N.m. During this period battery SOC remains at 100% and SC SOC starts decreasing, which means system is in mode II operation(SC is delivering to load). As armature current reduces below 2A and load torque being 1N.m, now battery SOC starts decreasing and SC SOC remains constant (previous value). This indicates that system is now working in mode I, were the current flow is from battery to load. Again armature current becomes greater than 2A and load torque T remains 1N.m, thus system enters to mode II. As a result SC SOC decreases (from previous value) and battery SOC remains constant.

Once again armature current reduces below 2A (load torque being 1Nm) , then system is now working in mode I. From 1 second onwards load torque is negative (1Nm). As this situation occurs system moves in to mode III operation (SC getting charged and armature current becomes negative), where battery is not in action thus battery current becomes zero and battery SOC remains constant. Thus all the three modes of operation for single unidirectional and bidirectional configuration are verified.

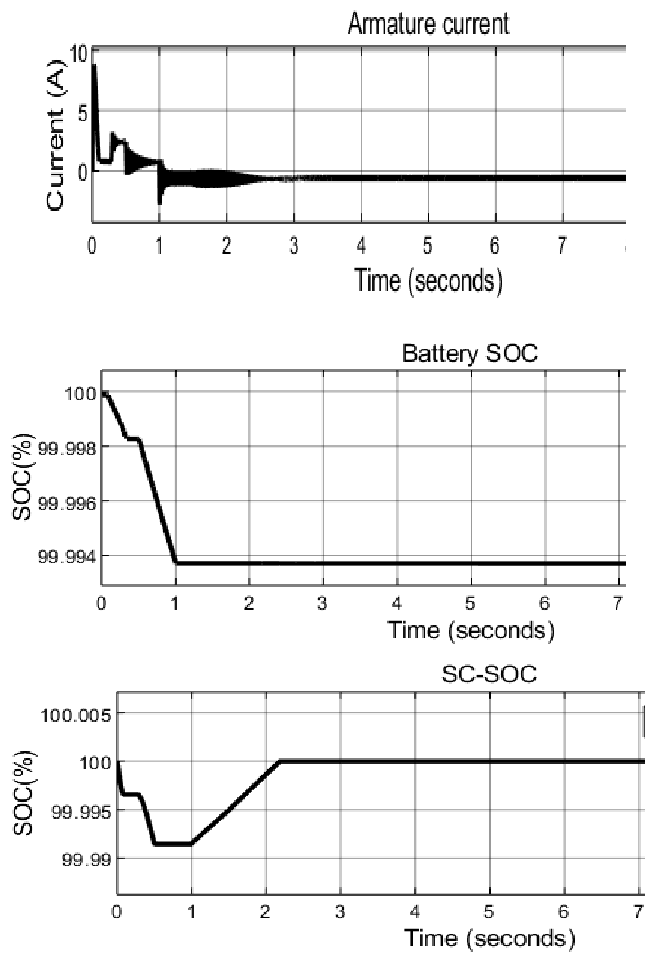


Fig. 10. Armature current, Battery-SOC and SC-SOC .

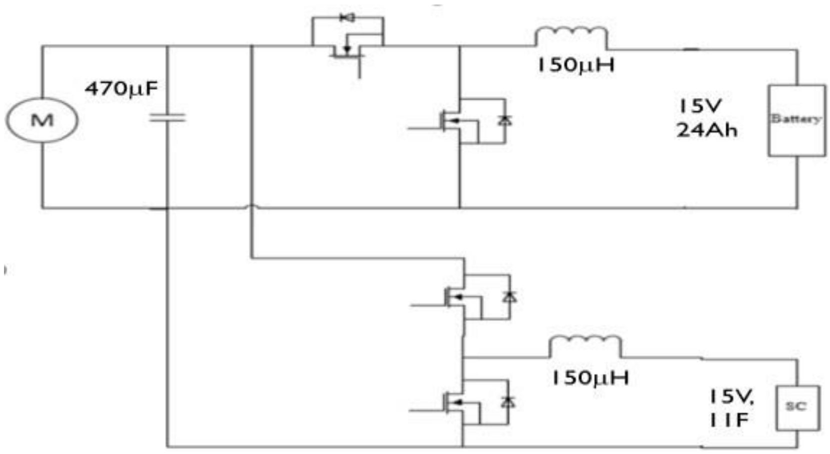


Fig. 11. Circuit diagram of two bidirectional converter configuration.

5.2.Results for two Bidirectional Converter Configuration

The test condition for this configuration is same as that in previous configuration. Circuit diagram for two bidirectional converter configuration is shown in Fig. 11.

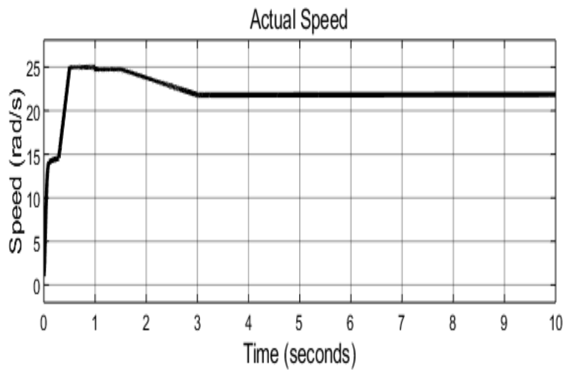
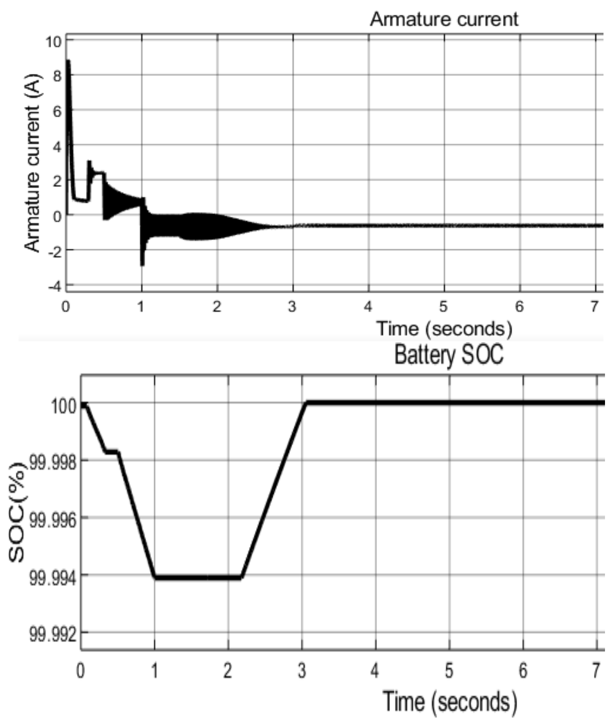


Fig. 12. Actual speed of PMDC motor



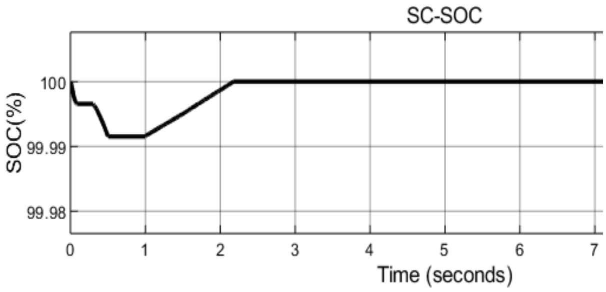


Fig. 13. Armature current, Battery-SOC and SC-SOC .

Actual speed of motor for this configuration is also following the reference speed given (as shown in Fig. 12). Mode I, mode II and mode III for two bidirectional converter combination is same as that of Mode I,II and III in single unidirectional and bidirectional converter combination. Compared to single unidirectional and bidirectional converter combination, two bidirectional converter combination has one extra mode (mode IV). From Fig. 13. it observed that as the load current goes above 2A and load torque T being 1Nm, SC starts delivering to load . Thus SOC of SC starts decreasing , but battery SOC remains constant (as it is isolated from load). This corresponds to the mode II operation (current flows from SC to load). When load current decreases below 2A and T= 1N.m, battery starts delivering to load followed by reduction in its (battery) SOC. Here SC SOC will remain constant at its previous value(as it is not active during this time). This corresponds to the mode I operation (current flows from battery to load). Now load torque is changed to (negative value) -1N.m form 1sec onwards, As this situation occurs system moves in to mode III operation SC SOC starts increasing (as it is getting charged, here battery SOC remains as the previous value). Once SC is fully charged and T remains as (-1) negative, system moves in to mode IV operation where battery SOC starts increasing (as it is getting charged) and SC SOC remains constant (100, as it is fully charged).

All the four modes of operations are thus tested and verified for the two bidirectional converter configuration and speed control of motor is also achieved. The advantage of two bidirectional converter configuration over single unidirectional and bidirectional configuration is that battery can be charged during regeneration as it (battery) is connected through a bidirectional converter (which allows the current to flow in both direction).

6.Conclusion

Speed control of PMDC motor can be easily achieved by using these two configuration (single unidirectional and bidirectional converter configuration , two bidirectional converter configuration). These two configuration produces the same results for speed control, as the actual speed of motor is following the reference speed for both the configuration. Compared to single unidirectional and bidirectional converter configuration, two bidirectional converter configuration provides a provision to charge battery during regeneration. There by not over charging SC during regeneration (i.e. once SC is fully charged then battery starts to charge during regeneration) . Thus we can say that energy management can be efficiently carried out by using two bidirectional converter configuration. At the end of the cycle Battery SOC if found to be approximately equals to 99.994% in single unidirectional and bidirectional converter configuration, but in two bidirectional converter configuration at the end battery SOC is found as 100%. From this it is clear that two bidirectional converter configuration is better and advanced version as the energy management between battery and SC can be efficiently carried out.

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