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Performance analysis of a hybrid storage system for electric vehicles

电动汽车混合存储系统之性能分析

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Abstract - **One of the major concerns in electric vehicles is the performance and maintenance of the battery as the storage system. The vehicle load requirements have a great impact on the life and cost of the batteries. High power pulses during acceleration and regenerative breaking requires large amounts of discharge and charge currents. A small capacity battery will result to a lower cycle life due to high current charging and discharging rates. An increase in the capacity of these batteries to meet the current requirements will result in expensive and bulky battery banks. Batteries have the capacity for very high energy storage but low power densities. To compensate for this, a high-power density device in the form of ultra-capacitor is used with the battery to form a hybrid energy storage system. However, it has the disadvantage of having a low energy density.**

This research implemented a hybrid energy storage system with a single bidirectional dc-dc converter between the battery and an ultracapacitor. This configuration lets the converter control the power derived from the battery more efficiently as it controls the discharge to let the battery operate at the optimum levels. The ultracapacitor is connected directly to the load and will deliver peak currents directly to the bank and can absorb the regenerative energy during braking conditions.

The system was modeled in Simulink to determine the energy distribution of the two storage sources. The results show that the ultracapacitor delivers the required power surges of the load with the battery delivering an average power that is at optimum levels. An actual drive cycle was tested and showed that the configuration chosen maximized the benefits of using the ultracapacitor

Keywords - **hybrid energy storage system, lithium ion, electric vehicles.**

I. Introduction

The study of the different configurations of energy storage systems have been done in different research activities. These have proven to be beneficial in electric vehicle systems in terms of performance and cost implications. One of the major concerns in electric vehicles is the performance and maintenance of the battery as the storage system. The load requirements of these vehicles have a great impact on the life and cost of the battery systems. High power pulses due to acceleration and regenerative breaking require large amounts of discharge and charge currents in the batteries. A small capacity battery results to a lower cycle life due to these high current charging and discharging rates. An increase in the capacity of these batteries to meet the current requirements results in very expensive and bulky battery banks. Batteries have the capacity for very high energy storage but low power densities. In order to compensate for this, a high power density device is used with the battery to form a hybrid energy storage system. A device with this characteristic is the ultracapacitor, but has the disadvantage of having a low energy density. The hybrid system lets the battery supply the energy required by the load and the capacitor delivers the high power pulses due to acceleration and absorbs the power from braking of the vehicle.

This project implements a hybrid energy storage system using the configuration in Fig. 1. This configuration allows the converter to control the power derived from the battery more efficiently as it controls the discharge to let the battery operate at the optimum levels. The ultracap will be connected directly to the load and delivers peak currents directly to the bank and is able to absorb the regenerative energy during braking conditions. The voltage variation is larger than the battery voltage variations but operates within the limits of the motor controller. In some configurations, another converter is connected between the capacitor and the load to stabilize the voltage but this adds to the losses in the system because of the added conversion stage.

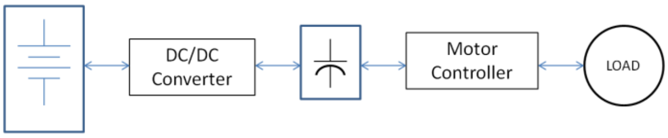


Fig.1, HESS System Configuration

II. Components of a Hybrid Energy Storage System

2.1. Battery

Energy storage systems for both electric vehicles and hybrid electric vehicles have been lenient on using batteries as the main storage component. Different types have been used but the lead-acid and lithium-ion are the most used kinds in this application.

Lead-acid has the advantage of low cost, low maintenance requirements, and ease of use. It’s mostly used for hybrid buses [4] [7] but is not very ideal for low speed vehicles such as electric tricycles because of its weight and low energy density. For low speed vehicles, lithium ion batteries are more commonly used. With higher energy density, the lighter lithium ion cells are more favorable for smaller electric vehicles. This paper presents the simulation results for an energy storage system using the lithium ion battery pack.

Applications such as motor drives for electric vehicles have a different power requirement due to different modes of operation. Acceleration and regenerative energy or braking require higher power from the battery which in turn increases the power rating needed as well as decrease battery life [7] [8]. These moments of high-current pulses cause higher cost due to decrease in battery life as well as the need to increase battery capacity [2]. These limit the capabilities of the lithium ion battery pack, hence the need for hybridization or an additional storage element.

2.2. Ultracapacitor

The electrolytic double layer capacitor, also called ultracapacitor, is known for its high capacitance, very high energy storage density, smaller capacity, and long cycling life. [8] With these characteristics, the ultracapacitor becomes a complementary storage component to batteries.

In EV applications, the ultracapacitor will be able to handle the peak power requirements of the motor as well as utilize the regenerative energy from breaking [2] [4] [5] [7] [9]. With the same application, the lower limit of the ultracapacitor voltage is chosen at 50% since the energy stored below that threshold is only 25% [1] [3].

2.3. Bidirectional DC-DC Converter

Different bidirectional dc-dc converter topologies have been used with the same goal of facilitating power transfer between the ultracapacitor and battery as well as to the power train of the EV. Buck-boost is one popular topology that can address the power requirements needed in a HESS [6].

The specifications of voltage and power levels for this converter are often dictated by the sizing of both the battery and the ultracapacitor.

For this paper, several assumptions regarding the operation of the DC-DC converter are enumerated. It should have a Constant Current (CC) – Constant Voltage (CV) charging characteristic that depends on the voltage level of the load side. Upon reaching the target voltage at the load side, the converter will automatically switch from CC mode to CV mode. Along with this, the converter should have a generation and regeneration mode to be able to fully utilize the functionality of the ultracapacitor.

III. Existing HESS Configurations

Several HESS configurations have already been proposed. This section discusses the basic configurations used.

3.1. Passive Parallel Connection To DC Link

To achieve the target operation of the HESS, the most basic connection of the ultracapacitor and battery is in parallel. The two components can be interchanged as shown in Fig. 2 and Fig. 3. This kind of configuration has no possibility of controlling the power flow between the ultracapacitor, battery and the DC link. The internal resistances and voltages of the components are the sole determinants of current distribution. Voltage across the two components and the DC link are always equal [3][4][9].

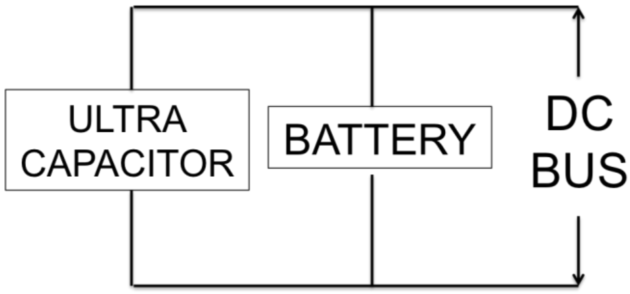


Fig.2, Ultracapacitor – Battery Direct Connection.

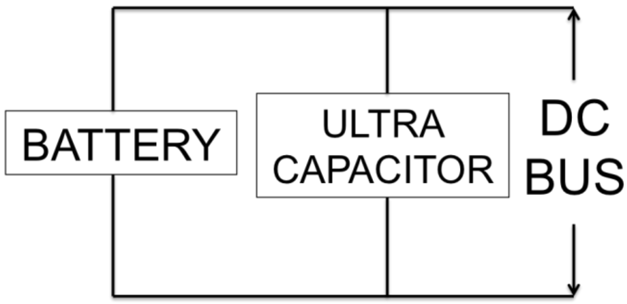


Fig.3, Battery – Ultracapacitor Direct Connection.

Shown in Fig. 4 and Fig. 5 are other passive configurations of HESS. These figures are considered passive because the power flows between the two storage components are still not controllable [9]. The battery and ultracapacitor are also interchangeable while maintaining similar operation. In these passive configurations, the ultracapacitor becomes a low pass filter.

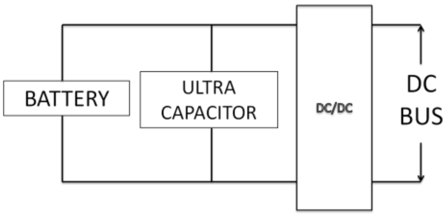


Fig.4, Battery – Ultracapacitor with DC-DC interface to DC Bus.

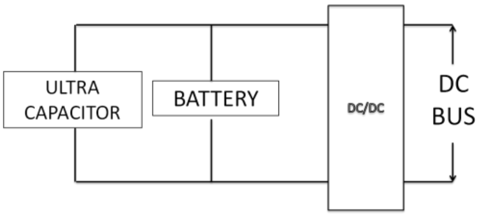


Fig.5, Ultracapacitor – Battery with DC-DC interface to DC Bus.

Ease of implementation and minimal power converter requirement are the advantages of these passive configurations. However, one major issue is pre-charging the ultracapacitor. Directly connecting them without pre-charging would cause extremely high currents within that loop [4]. Aside from this, the energy provided by the ultracapacitor is not utilized effectively [3]. Hence, the hybridization is considered inefficient.

3.2. Active Parallel Connection To DC Link

To address the lack of power flow control in the previous configurations, a more active hybrid energy storage system was developed [3]. The main difference from the previous section is the bidirectional dc-dc block that facilitates and controls the power exchange between the battery and the capacitor as shown in Fig. 6 and Fig. 7.

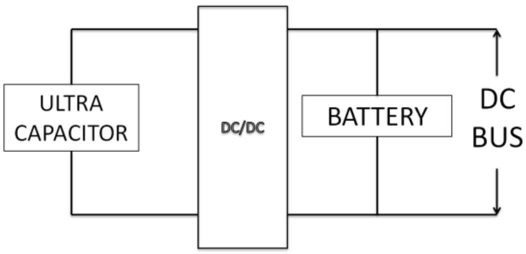


Fig.6, Active Ultracapacitor – Battery Configuration.

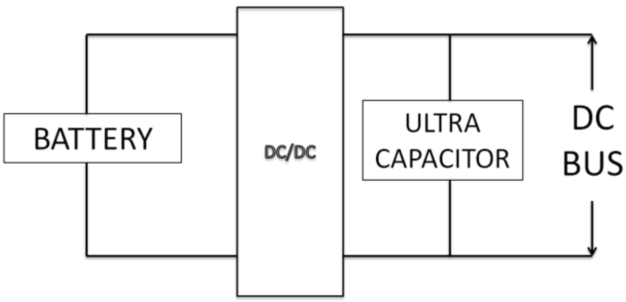


Fig.7, Active Battery – Ultracapacitor Configuration.

The configuration in Fig. 6 has a more stable voltage in the DC bus because of the direct connection to the battery [9]. Another advantage is that the voltage level of the ultracapacitor is not limited by the requirements of the motor controller. However this configuration is demanding on the specifications and ratings of the DC-DC converter, since the peak power provided by the ultracapacitor has to be interfaced with that block [3].

The swapped version of the active topology shown in Fig. 7 addresses the disadvantages presented in the original configuration. Since the ultracapacitor is directly connected to the DC link, the DC-DC converter is only required to interface the average power provided by the battery bank. The battery voltage level can also be varied and not tied down to the requirements of the motor controller. To ensure stability in the DC link, this topology allows the bus voltage level to swing depending on the operation of the ultracapacitor [3].

In this paper both active parallel configurations are going to be investigated and simulated to confirm the advantages and disadvantages presented in this section.

IV. Drive Cycle Profile

Drive cycle profile is an important tool to evaluate the configuration of the hybrid energy storage system. This will determine the operation and performance of the simulation. It is important to choose a suitable profile that will demonstrate the modes of operation where using only the battery, as the storage system, is disadvantageous: start-up, acceleration, and breaking.

4.1. Most Common Profiles Used for EVs and HEVs

The New European Driving Cycle (NEDC) was originally used for fuel-based vehicles. However, due to lack of standard test drive cycle, this profile has been applicable to EVs and HEVs in the recent times [10]. This cycle is more concerned with testing the overall efficiency of the vehicle versus simulating real life driving conditions. It also does not satisfy the portrayal of high current pulse generating operations discussed in the previous section.

Due to the lack of a standard driving cycle for electric vehicles, a number of papers opted to develop their own drive cycles using actual EV on-road test recorded by means of data acquisition [5] [6]. By doing so, the simulations are closer to real life driving situations. It also increases the accuracy by using an actual drive cycle by electric vehicles or hybrid electric vehicles. Several tools can be used to migrate these data to actual simulations such as the Aerovironment ACB-150 Power processing system and the Advanced Vehicle Simulator (ADVISOR) [5] [6] [7].

4.2. Actual Drive Cycle Profile

The drive cycle shown in Fig 8 was acquired from on-road testing of an electric vehicle under Philippine conditions. It simulates the actual start-and-stop driving characteristics of an electric vehicle. The regenerative capability of an EV is also incorporated in the drive cycle to further observe the dynamics of the electric storage systems under test. The profile statistics are shown in Table 1.

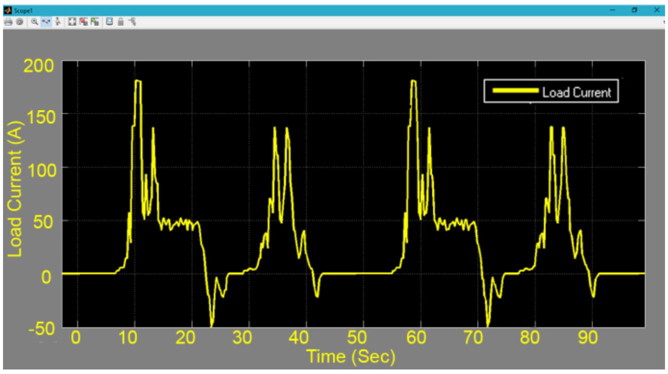


Fig.8, Drive Cycle Snippet.

TABLE 1, DRIVE CYCLE PROFILE CHARACTERISTICS

Parameter	Value	Unit
Peak forward current	200	A
Peak forward power	60	kW
Average forward current	31.34	A
Average forward power	9.4	kW
Minimum forward power	0	kW
Peak regenerative current	50	A
Peak regenerative power	15	kW
Average regenerative current	1.96	A
Average regenerative power	586.96	kW
Maximum current slew rate	364	A/sec
Simulation time	2.7	h
Peak forward power time	5	sec

V. METHODOLOGY

5.1. SYSTEM COMPUTATIONS

For this paper, the sizing of the ultracapacitor and the battery are based on the assumption that the HEV or EV system is using a high voltage to high voltage energy storage system. Table 2 shows the specifications of each component of the HESS.

TABLE 2, SIMULATION SYSTEM SPECIFICATIONS

Parameter	Value
Battery Rating	$360V_{NOM}$, 100Ah, Lithium-ion bank
Ultracapacitor Rating	$340V_{MAX}$, 65 Farads
Bidirectional DC/DC Rating	20kW

The simulation time ($T_{simulation}$) at 2.7 hours and the average forward current ($I_{average}$) at 31.34 A are considered in computing for the minimum battery capacity ($Batt_{capacity}$) needed for both configurations shown in Eq. (1).

$$Batt_{capacity} = I_{average} \times T_{simulation} \quad (1)$$

$$Batt_{capacity} = 31.34A \times 2.7 \text{ hours}$$

$$Batt_{capacity} = 84.618 \text{ Ah}$$

The minimum battery capacity needed for both configurations is 84.618 Ah. For a more standard capacity rating, a 100 Ah lithium ion battery specification was used.

For the ultracapacitor sizing, the voltage swing is assumed to be 50% at max. The voltage rail is assumed to be at 340V max. Therefore the minimum capacitance requirements can be computed.

$$E_{initial} = \frac{1}{2} CV_{initial}^2 \quad (2)$$

$E_{initial}$ = initial capacitor energy

C = capacitance

$V_{initial}$ = initial voltage of capacitor

$$E_{final} = \frac{1}{2} CV_{final}^2 \quad (3)$$

E_{final} = final available energy of capacitor

V_{final} = final voltage of capacitor

$$E_{initial} - E_{final} = ((P_{peak} - P_{ave}) \times T_{peak}) \quad (4)$$

P_{peak} = peak power

P_{ave} = average power

T_{peak} = time during peak power

Using Eq. (2), Eq. (3) and Eq. (4) and plugging in the parameters from the drive cycle profile to get the minimum capacitance needed:

$$\frac{1}{2} CV_{initial}^2 - \frac{1}{2} CV_{final}^2 = (60kW - 9.4kW) \times 5 \text{ sec}$$

$$\frac{1}{2} C(340V)^2 - \frac{1}{2} C(170V)^2 = (60kW - 9.4kW) \times 5 \text{ sec}$$

$$C_{min} = 5.83 \text{ F}$$

The minimum capacitance needed is 5.83F. However, this is not a standard value and is difficult to find commercially. Therefore, a more standard value was used to carry-on with the simulation as shown in Table 2. A total of 65F with a maximum voltage of 340 V is used.

Lastly, the rating of the DC-DC converter was dictated by the peak regenerative power, which is at 15kW. A surplus of 5 kW was added for margin.

VI. MODELLING AND SIMULATION

The following figures show the two configurations used in the simulations of the system. Figure 9a shows a bidirectional converter connected between the battery and ultracapacitor with the ultracapacitor connected to the load side. The other configuration switches the locations of the two sources and puts the battery at the load side. In both cases, the ultracapacitor is intended to handle the peak currents that the load presents to the source.

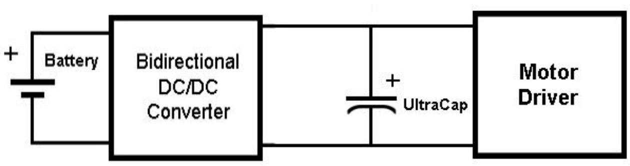
The flowchart for the configuration in Fig. 9a is shown in Fig. 10a. The ultracapacitor is always connected across the load of the system. The load voltage is allowed to swing within the operating range of the motor driver. This requires the ultracapacitor to be rated beyond the maximum allowable voltage for the motor driver. With a motor driver connected as the load of the energy storage system, there are different characteristics of the load that the ultracapacitor addresses like high peak load currents and regenerative power.

As the motor drive is started, corresponding to an electric vehicle accelerating, there is a high peak current that the load draws from the source. This peak current is naturally supplied by the ultracapacitor because it is connected across the load. The battery delivers only an average power as limited by the constant current mode of the bidirectional converter. During the accelerating condition, the load current is the sum of the battery current and ultracapacitor current. After acceleration, the vehicle is expected to be coasting or in braking mode. In the first mode, the vehicle is drawing a more or less constant current from the battery. The bidirectional converter is operating at a current limit level such that it can be higher than the average current that the motor driver is drawing. The excess current is used to charge the capacitor to replenish the expended energy during the peak current discharge of acceleration. When the vehicle brakes, there is regenerative energy that flows back to the source. Since the ultracapacitor is already across the load, it automatically absorbs this energy and prevents the battery from having very large charging currents. The state of charge of the ultracapacitor is always monitored determine whether it needs to be charged by the battery or if it is operating beyond a threshold where the energy should be transferred back to the battery.

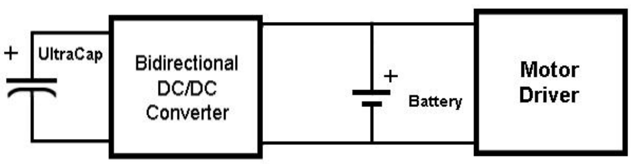
The ultracapacitor is expected to have a threshold of 90% of the state of charge. Whenever the load is not requiring high peak currents, the ultracapacitor is charged from the battery using the bidirectional converter. The state of charge is limited to 90% so that the ultracapacitor still has capacity to absorb a fair amount of braking power when the vehicle suddenly brakes and delivers regenerative power to the source.

The configuration in Fig. 9b has a control scheme that is shown in the flowchart of Fig. 10b. This configuration has a battery system connected directly across the load. The ultracapacitor is still intended to deliver and absorb high peak currents but is dependent on the operation of the bidirectional converter. During accelerating conditions, the high peak currents drawn by the load have to be sensed right away by the system in order to signal the bidirectional converter to operate and source the peak power from the ultracapacitor. This is also the same requirement during braking conditions where the load current has to trigger the converter to operate in the opposite direction and discharge the high regenerative energy into the ultracapacitor. There are also limits to the operating state of charge of the ultracapacitor in order to ensure availability of storage capacity during the peak current charging and discharging conditions. The ultracapacitor excess energy is discharged to the battery system when the state of charge is greater than 90%. When the state of charge is less than 90%, the battery charges the capacitor to replenish the extinguished energy during the accelerating condition of the vehicle. The lower limit of the ultracapacitor state of charge is 25% because the operating voltage is already at 50% during this level of state of charge. This is the recommended minimum voltage for operating an ultracapacitor. When this condition is met, the battery is the only source delivering energy to the load and bidirectional converter will be disabled.

These two control schemes may operate using an integrated logic controller in the bidirectional converter or it may be triggered and controlled by an external circuit. Current sensors are used to monitor load current levels and voltage sensors are used for state of charge estimation.

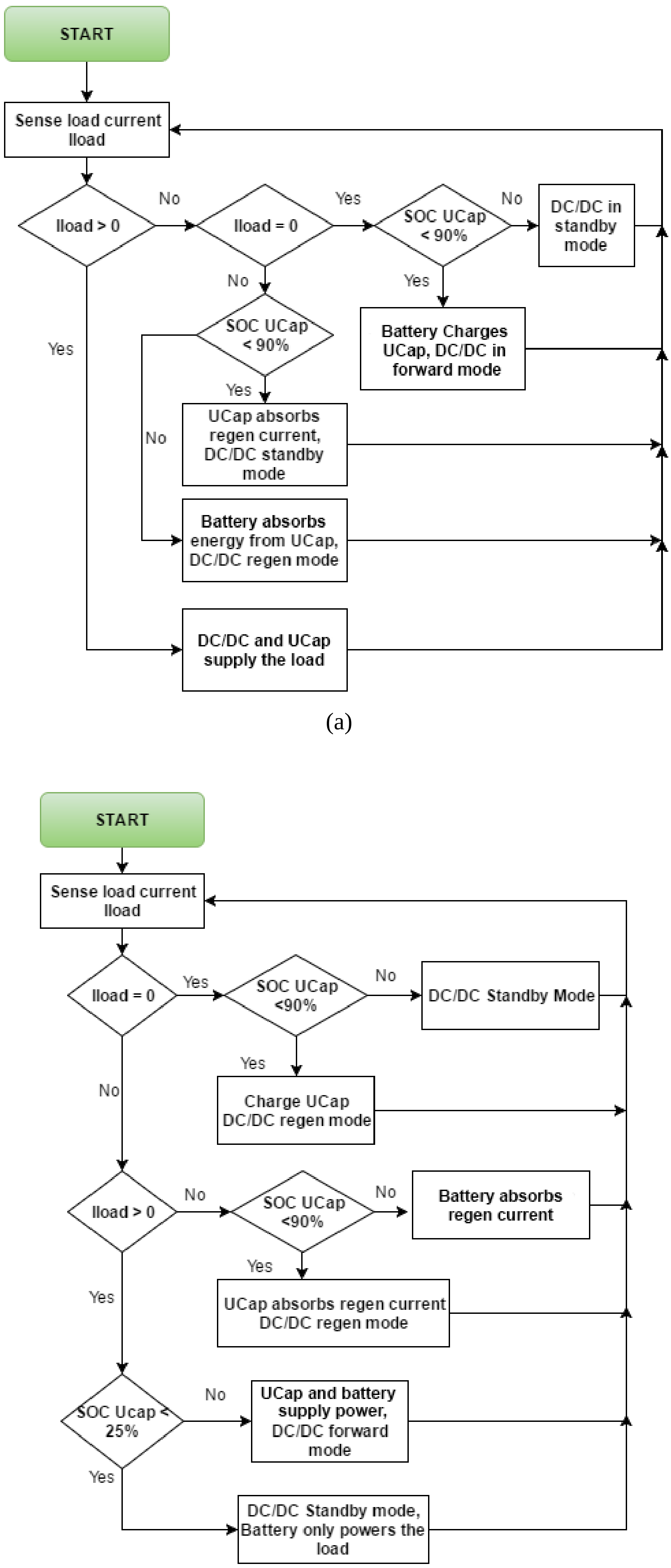


(a)



(b)

Fig.9, (a) Battery-UC Configuration, (b) UC-Battery Configuration.



(a)

(b)

Fig.10, (a) Battery-UC Configuration Flowchart, (b) UC-Battery Configuration Flowchart.

where

Iload = load current
SOC = state of charge
UCap = ultracapacitor

VII. Results And Discussions

The graphs in the following figures show the performance of the two different configurations when subjected to the given drive cycle in Fig. 8. The curves in Fig. 11 and Fig. 12 show the three currents from the battery, ultracapacitor and the load. The peak current drawn by the load is around 190A. A standalone battery system is required to deliver this peak current. If the required battery system cannot deliver this kind of current level, the battery ampacity is increased to the appropriate level. With the configuration in Fig. 9a, this load current is divided between the two sources. The peak current from the ultracapacitor is around 125A and the battery current peaks at around 65A. This shows that the ultracapacitor is able to deliver the required peak current of the load and prevents the battery from operating at very high peak current discharges.

The next part of the waveform in Fig. 11 shows that the current of the load drops to around 50A. This is divided between the battery and the ultracapacitor with the battery delivering 40A and around 10A coming from the ultracapacitor. This is then followed by a braking condition as seen from the negative current at the load. This is again distributed between the sources with the bidirectional converter operating in the opposite direction to charge the battery with the regenerative power. The bidirectional converter is still current limited in order for the battery to have a limited amount of peak charging energy. The excess energy that is delivered back to the source is absorbed by the ultracapacitor.

This is again followed by another accelerating condition that is shown with the peaking of the load current. The distribution of the currents shows that the battery is still delivering a lower level of current than the ultracapacitor. This again shows that the battery is limited to a safe current level that will not damage nor decrease the life of the battery. A brief braking condition ends one period of the drive cycle. The drive cycle is a periodic waveform that can show the different conditions in an electric vehicle road load. The important thing to consider in the selection of the system is that the battery system is selected properly in order to provide enough energy to cover the target driving range of the vehicle.

The second configuration shows waveforms in Fig. 13 and Fig. 14 that are very similar to the first set of waveforms in terms of current sharing. The capacitor is also able to supply a portion of the load current effectively reducing the load on the battery. The intention of both configurations has been achieved but have some differences that greatly affect the design of the system.

One difference in the performance of the two configurations is the wave shape of the ultracapacitor current. The ultracapacitor current from Fig. 11 shows that this is very similar in shape as the load current. This is the effect of having the ultracapacitor connected across the load. The current sourced from the ultracapacitor is automatically delivered. This lets the ultracapacitor to have a very fast response time in delivering the required current.

The ultracapacitor current waveform from Fig. 13 shows that it has a rectangular shape that is very different from the load current waveform. The ultracapacitor cannot respond right away to the fast transient that the load requires. This is because of the dependency of the delivery of the current to the response time of the bidirectional converter. The system has to sense the load current first and determine whether the ultracapacitor has to deliver current or not. Once this has been determined, the system enables the bidirectional converter to transfer energy from the ultracapacitor to the load. This has a finite time delay that is not present in the first configuration.

The two minimum features of the bidirectional converter of the second configuration are high slew rate and low time delay. The high slew rate will enable the ultracapacitor to deliver peak currents that can handle the rise times that the load current presents. This has to be fast enough so that the battery current does not have to support these transient conditions. The waveforms show that the battery current for the second configuration has a wave shape that follows the load current. This shows that the transient condition is supported by the battery and not by the ultracapacitor. A very fast converter may rectify this in order to account for these rise time requirements at the expense of a more expensive converter.

The time delay or response time of the converter has to be negligible so the battery does not have to deliver short burst of high peak currents when the output of the converter is not yet enabled because of the response time.

Another drawback of the second configuration is the power rating of the bidirectional converter. It is shown in the first configuration that the converter operates at a current limit level that is near the operating current of the battery. There are no peak currents expected since these current are supplied and absorbed by the ultracapacitor. In the second configuration however, the high peak current delivered by the ultracapacitor goes thru the bidirectional converter and in to the system. This means that the current rating of the converter has to be greater than the normal level that is being supplied by the battery. This peak current is repetitive but effectively has a low duty cycle. Even with a high peak current rating, the total power delivered by the converter is not as high as the power rating of the converter.

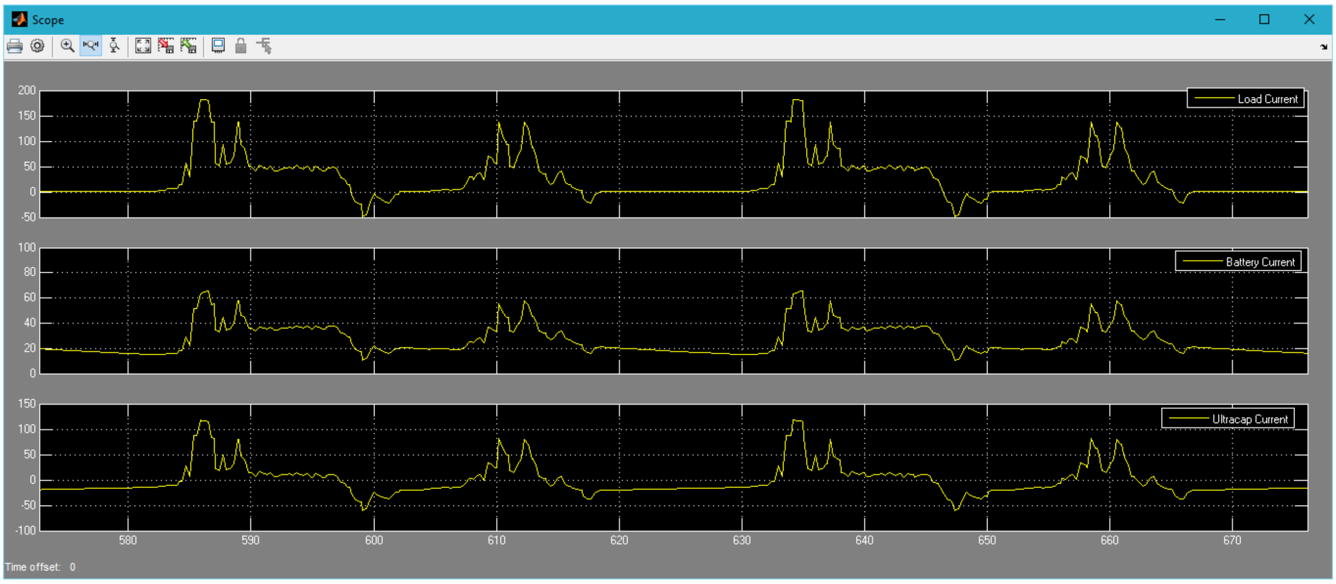


Fig.11, Simulation Results for the Battery – UC Configuration

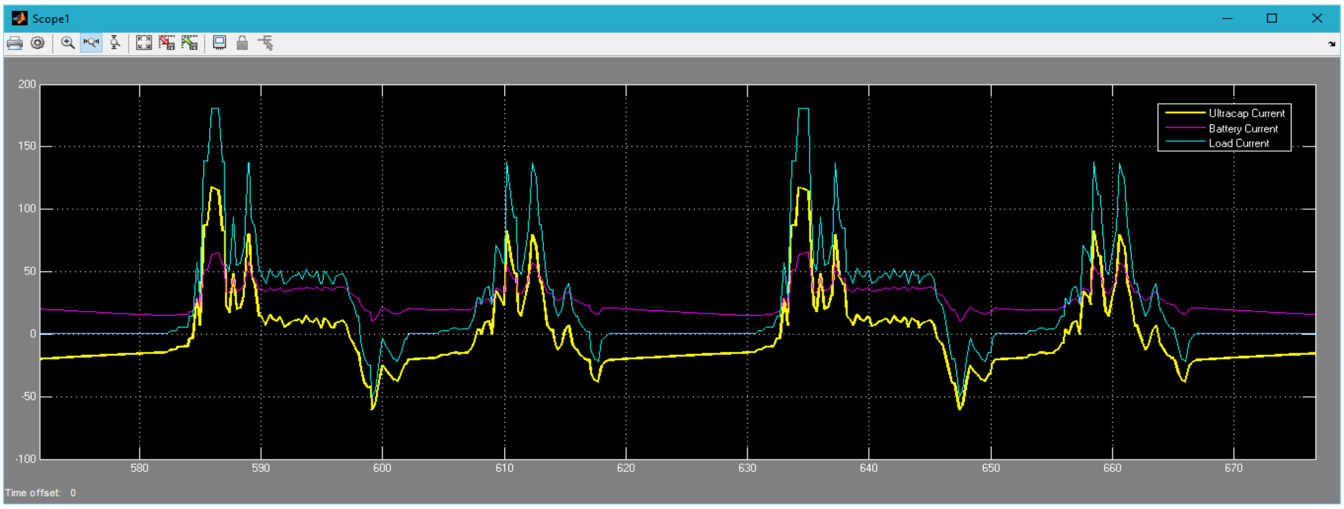


Fig.12, Battery – UC Overlaid Simulation

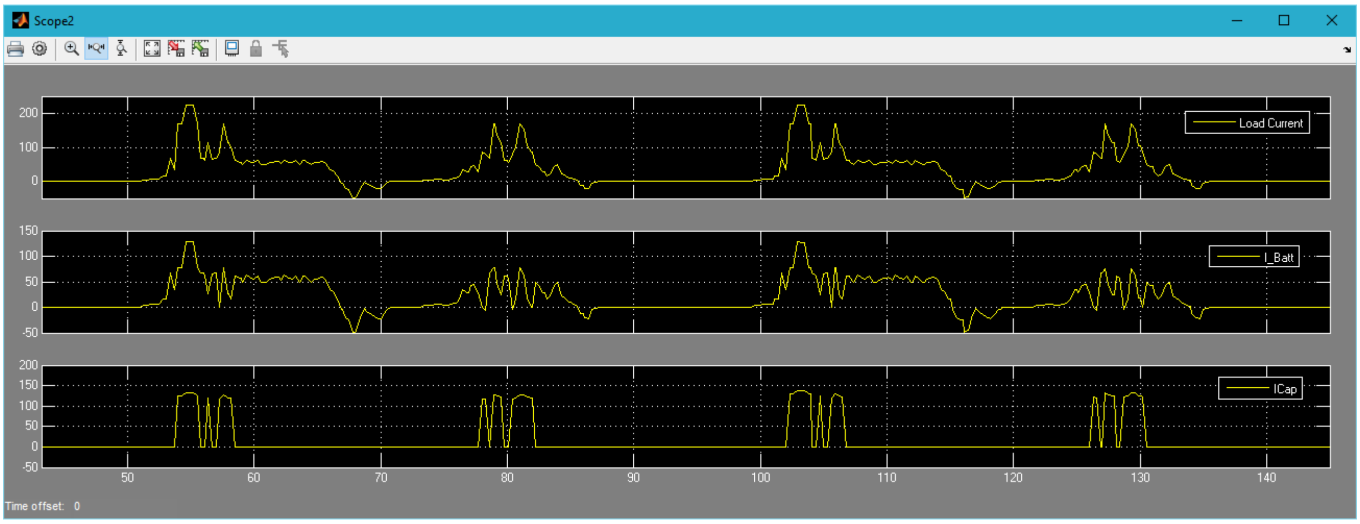


Fig.13, Simulation Results for the UC – Battery Configuration

Fig.14, UC - Battery Overlaid Simulation

VIII. Conclusion

This paper presented a performance comparison of two different configurations of a hybrid energy storage system for electric vehicles. The basic elements of the hybrid energy storage system have been discussed. The functionality of two different configurations has been compared. The two configurations were used in a simulation setup using an actual drive cycle of an electric vehicle to verify the performance of the two systems.

The two systems have both performed as intended. The ultracapacitor in both systems has contributed to the sharing of the load current and reduced the current delivered by the battery system. The HESS with an ultracapacitor connected across the load has shown advantages in overall system specifications and design. Although the intention for both systems has been achieved, there is a clear advantage in choosing one over the other.

In the second configuration, the power rating of the bidirectional converter is largely dependent on the expected peak current that the ultracapacitor is going deliver into the system. If the battery system is limited to a maximum of 1C discharge rate of the battery and the load requires 3C, the converter is rated at a current level of 2C but will only deliver this power level during the accelerating condition.

In the first system, the bidirectional converter is operating at a current limit that will be at an almost constant level and significantly lower than the peak current of the load. This allows the converter to be specified at a lower current and power rating and can be operated continuously at the target power rating. This let the converter operate at the optimum level without being over rated.

The preferred configuration is the first system where the ultracapacitor is connected directly across the load. This maximizes the benefits of having an ultracapacitor in a hybrid energy storage system not only in its electrical performance, but in the impact of the system design as well.

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