University of Waterloo
Faculty of Engineering
Department of Mechanical and Mechatronics Engineering

Design of a Battery/Supercapacitor Hybrid Energy Storage System for Electric and Hybrid Electric Vehicles

Prepared By
Tahir Dawson
ID: 20550717
Email: t2dawson@edu.uwaterloo.ca
4A, Mechanical Engineering

August 10th 2018

Summary

This report details the research conducted on a Battery/Supercapacitor Hybrid Energy Storage System (ESS) for UWAFT's upcoming vehicle, the EcoCar 4. The report first discusses the required background such as the need for such an ESS and details the shortcomings of batteries. These shortcomings include the low power density (W/kg) provided by Lithium-Ion batteries, the limited cycle life of these batteries, their limited capability of receiving recovered energy during regenerative braking and the negative effects of pulsing current load on their cycle life.

In order to counteract these shortcomings, a type of supercapacitor known as the Electrolytic Double-Layer Capacitor is introduced and its method of operation through seperation of ions and physical adsorption on the terminal surface is discussed. It is further shown how these supercapacitors provide very high power density, virtually unlimited cycle life and robustness to high temperature and fluctuating current loads. The ability of these devices to receive greater amounts of energy during regenerative braking is also discussed.

Section 2 of the research report discusses two possible configurations that combine Lithium-Ion batteries and supercapacitors to form the Energy Storage System. The first design, the Fully Decoupled Hybrid Supply, involves the use of supercapacitors to assist during periods of high power requirements. The battery unit is connected to a unidirectional Boost converter while the supercacitor is connected to a bidirectional Boost-Buck converter, both of which ultimately connect to the same DC-Bus. This feature of the design allows energy recovered during braking to be received solely by the supercapacitor bank in order to maximize the amount of energy recovered. The second design presented in this section involves both supercapacitors and batteries to service different loads, with the batteries providing power to the main motor load while the smaller supercapacitor bank powers the auxillary load. This design contains a seperate DC-Bus for each load type since seperate sources are used to provide power. The supercapacitor is still the preferred choice for receiving recovered energy with excess energy going to the battery once the capacitor bank is fully charged.

The third section moves on to analyse the two design as well as present the simulation models developed for each design and the results obtained. This section notes the Fully Hybrid Supply's ability to increase efficency of the vehicle and improve battery life by decreasing current flucations in the battery. The results obtained show 16 percent increase in recovered energy and 80 percent decrease in

current fluctuation amplitude but also shows that this design greatly increases the cost of the design as well as the complexity of the required control circuitry. The second design shows less increase in efficiency and performace giving only about a 2 percent increase in recovered energy and little effect on current fluctuation but also incurs a much smaller increase in the cost of implemenation and the complexity of the required circuitry.

The conculsions and recommendations for future research is detailed in sections 4 and 5 that follow. It is concluded that either of the designs can make a suitable choice for EcoCar 4 but the decision must be made based on the team's current priorities in the design and budget allocations for the Energy Storage System. The next steps for the research are then presented and it is recommended that team look in to Metal-Air batteries which offer high energy density and their combination with supercapacitors to obtain higher efficiency and lower weight of the Energy Storage System. It is also recommended that Hybrid supercapacitor technology be researched which can provide higher energy density that Electrolytic Double-Layer Capacitors and therefore further assist in weight reduction. Lastly, the team is also urged to simulate more conditions for the designs and models developed in this research to get a better understanding of the advantages and drawbacks of each design, how the design fare in short running periods as opposed to long running periods and the total extra range that can be added due to the increase in efficiency.

Table of Contents

List of Figures

List of Tables

1.0 Introduction

As it currently stands, the majority of vehicles in production still utilize fossil fuels for operation. With growing concerns about the environment, rapid increase in fuel costs and the depletion of fossil fuel resources used to operate motor vehicles, manufacturers have no turned towards hybrid electric vehicles (HEVs) and electric vehicles (EVs) as an energy efficient and evironmentally friendly solution to address these issues.

Electric Vehicles and Hybrid Electric Vehicles utilize electric motors for propulsion of the vehicle. The vehicles both contain a power system, hereby known as the Electric Storage System (ESS), to draw electrical energy in order to power the motors as well as any auxillary loads in the vehicle such as the air conditioning systems, sound system and rear and front lights. This increases the efficiency of the vehicle as electric motors operate at a very high efficiency of over 90 percent, a stark increase over the traditional powering system of using a combustion engine and burning fuel, a process in which only about 30 percent of the energy produced can be utilized. In addition, this method of propelling the vehicle drastically decreases the emissions in HEVs as no fuel is burned during all-electric operation and the engine can be operated at maximum efficiency during a series hybrid operation, thereby offering more complete burning of the fuel. Lastly, the introduction of electric power to these vehicles greatly decrease the running cost of the vehicle due to the lower cost of electricity as compared to the rising costs of fossil fuel.

The braking system used by EVs and HEVs further help reduce the running costs and provide an increase in efficiency of the vehicle. Traditional braking involves the use of brake pads which come in to contact with the wheels and remove the kinetic energy of vehicle by dissipating it as heat. EVs and HEVs replace this energy wasting method of braking by utilizing the electric motors property of functioning as an alternator. The drivetrain of these vehicles, coupled with this alternator then allows the vehicle to recover the kinetic energy of the vehicle by converting it into electrical energy instead of removing energy as heat.

With rising demands of EVs and HEVs and the move towards more energy efficient and environmental friendly solutions, this research is aimed towards the design of an efficient Energy Storage System that can be used with EVs and HEVs in order to better service motors and auxillary loads.

1.1 Motivation

Currently, Eletric Vehicles and Hybrid Electric Vehicles in production rely on batteries as the sole energy source to provide electric power in the system. These batteries generate electric power through an electrochemical reaction. Each battery cell is composed of a positive and negative electrode as well as an electrolyte solution. In the process of generating electrical energy, a redox reaction takes place in which anions are oxidized at the negative electrode and reduced at the positive electrode. The process allows electic current to flow from the positive electrode to the negative electrode when the circuit is closed.

With increased use of Lithium-Ion batteries in vehicles, the amount of energy that can be stored in these batteries as chemical energy is very high per weight of battery cell, that is, these batteries have high energy density (Wh/kg). However, becasue the process of gerenating electric power invloves a slow chemical reaction, the rate at which the rate at which the chemical energy stored in these batteries can be converted into electrical energy is slow, that is, they have low power density (W/kg). With increasing demands of power, Lithium-Ion batteries fail to provide the high power needed by the vehicle, thereby limiting some applications such as faster acceleration.

Lithium-Ion batteries using the same phenomena of redox reactions. Since these reactions are reversible, the process can operate in the opposite direction which takes in electrical energy through the electrodes and builds up chemical energy in the battery cell [8]. As stated before, these electrochemical reactions are slow and as such the rate at which the battery can charge is low. While this increases charging time of batteries at charging stations, one big drawback during regular vehicle operation is the drop in effeciency of energy recovery through regenerative braking. The low charge rate of batteries mean that much of the kinetic energy of the vehicle that is converted to electrical energy by the alternator is lost.

In addition to the low charge and discharge rates that result from the slow electrochemical reactions taking place, Lithium-Ion batteries have a very limited cycle time. Manufactures generally put this number at 500 charge and discharge cycles before the battery’s capacity decreases to 80 percent of its original value. This cycle life is further affected by high temperatures as well large current pulses which occur during both acceleration and regenerative braking.

Due to these shortcoming of battery units, further options must be considered to improve performance of the vehicle. This research discusses how a hybrid Energy Storage System using Supercapacitors alongside Lithium-Ion battery units can be used to eliminate the drawbacks of a standalone battery system.

1.2 Supercapacitor

Supercapacitors (also known as Ultracapacitors) are energy storage device that offer characteristics similar to a traditional capactior. However, unlike the traditional capacitors, these devices are capable of storing large amounts of energy per unit weight. The most popular type of supercapacitor that is produced today is the Electrolytic Double-Layer Capacitor (EDLC). These capacitors store energy through the seperation of charge in thin layers between a solid, conducting surface and a liquid electrolyte. The conducting surface, or electrode, used in these capacitors is commonly porous, activated carbon which increases the area of the electrodes and allows these devices to better use the phenomena of adsorption and store more energy without increasing the size of the capacitor as with traditional capacitors [5] . Figure 1 below shows the structure of a supercapactior and the formation of the electrostatic double-layer.

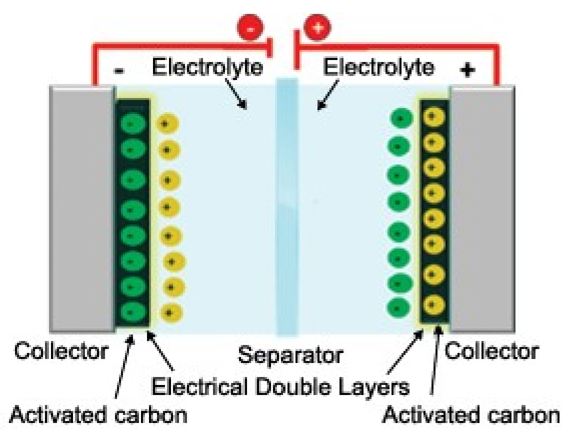

Figure 1.1: Structure of Supercapacitor and fomation of electrostatic double-layer

As mentioned above, superacapacitors operate using physical adsorption in which ions in the electrolyte adheres the surface of the collector. These physical reactions are very fast compared to the slow redox reactions used in battery cells and as such Supercapacitor units can deliver very high power density of up to 10 kW/hour [3]. This makes supercapactiors an ideal choice during periods of high power demands such as during acceleration of the vehicle.

Supercapactiors also offer very high charge rates as compared to battery cells since once again physical reactions take place instead of chemical ones. As a result, these capacitors can charge in a fraction of the time that is needed by batteries, making them ideal for use in energy recovery through regenerative braking[9].

Unlike battery units, Supercapacitors provide an extremely long cycle life of about 1 million charge and discharge cycles [9]. Since the operation of these devices are not dependant on maintaining a certain internal chemistry, they can also withstand large current pulses and higher temperatures without degrading their performance. This again makes Supercapacitors a good choice to use during acceleration and regenerative braking when the current on the DC-Bus has high fluctuations.

As Supercapacitors offer characteristics that counteract the drawbacks of a battery unit, these devices can be used in conjunction with battery cells to provide a more efficient Energy Storage System. Section 2 discusses some possible ways in which the battery and Supercapacitor units can be combined to better service the electrical loads in a vehicle.

1.3 UWAFT Integration

As a Hybrid Electric Vehicle design team, UWAFT aims to increase their vehicles' efficiency while maintaing or increasing its performace. With the new 4 year competition starting, the team is looking to develop the architecture for the new EcoCar 4, a mid-sized hybrid electric SUV. In order to target this research for the purpose of integration into EcoCar 4, the sizing and modelling of components were based on power requirements of similar vehicles in production. Since the exact details were not known for EcoCar 4 regarding electrical loads such as the motor sizes, averaged values were used based on All-Electric SUVs currently in the market such as the Tesla Model X. While the models and sizes developed in this research pertain to an Electric Vehicle, the design process is detailed such that the selected design can be easily scaled to fit the parameter of EcoCar 4 once more detail on the remaining architecture has been determined.

This research report include multiple design option for the Energy Storage System in order to provide the team with multiple options based on different possible priorities in the upcoming competition. Since cost constraints for different components are not known at this time, this report details designs that can be used with either a small or large allocation of the budget to the power system of the new vehicle.

The designs presented in this report can greatly assist UWAFT in increasing energy efficiency and performance of EcoCar 4 and hence run longer distances per charge. The report also includes some recommendations for the team to further the research conducted in order to further benefit from more efficient energy solutions.

1.4 Objectives

This research project on more efficient Energy Storage Systems has the following objectives:

- Design of multiple energy storage solutions using battery and supercapacitor technology.
- Qualatative analysis performed for each of the designs considered and a comparison to a standalone battery system for energy storage.
- Development of a simulation model for each design as well as battery standalone system, including DC-DC converters and control algorithm for power management.
- Quantative results obtained through simulation of each design for various test parameters.
- Quantative comparison of each of the designs as well as the battery standalone system and the suggested solution based on the different priorities of UWAFT.
- Recommendations for the next steps that should be taken by the team to further this research and develop an optimal Energy Storage System as per requirements for EcoCar 4.

2.0 Electric Storage System Operation and Design

In this unit the different components of an Electric Vehicle’s powertrain are discussed and flow and control of power from the Energy Storage System to the electric motors is discussed . This unit presents the different topologies considered for combining battery units and supercapactiors as the electric power sources for EVs along with power management modules that need to be installed for the desired operation.

In order to appropriately discuss and compare the designs considered in this unit, the battery standalone powertrain must first be looked at to form a benchmark. Figure 2.1 below shows the configuration of a a typical EV powertrain that uses an AC motor for vehicle propulsion. The battery is connected to the

DC-Bus and is controlled via a power management module which modifies the amount of current drawn from the battery. The DC-Bus then provides power to the DC-AC converter so that the AC motor can be operated.

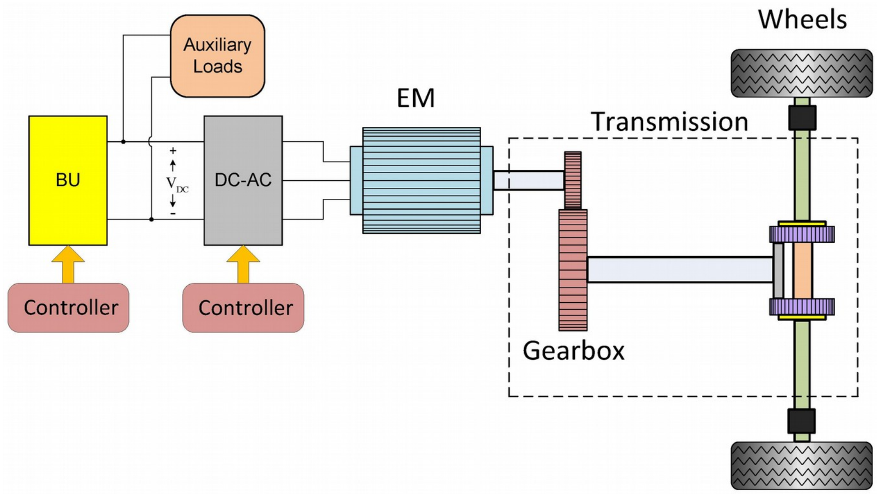

Figure 2.1: Typical Powertrain configuration of an Electric Vehicle [1]

To provide higher performance and more energy efficient solutions, the Energy Storage Systems considered in this unit consist of both a battery and a Supercapacitor unit. Figure 2.2 below shows a schematic of such a power system.

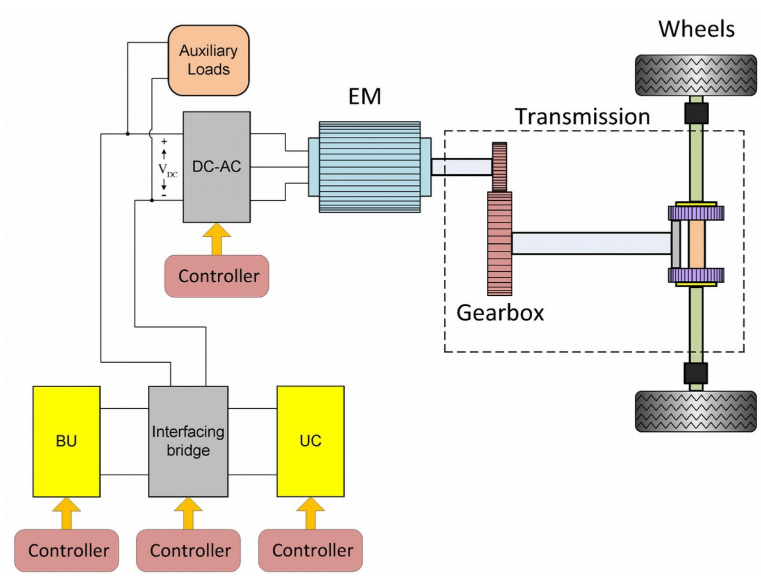

Figure 2.2: Schematic of an Electric Powertrain with multiple energy sources [1]

In this design, each power unit has a seperate controller that manages the power drawn from their respective sources. In addition, an iterfacing bridge is added which determines how the two sources are combined to provide the power required by the vehicle. This interface bridge performs the task of determining which power source is used to service either of the two types of loads, that is the AC motor and the auxillary loads as well as directing power to the appropriate source during regenerative braking.

2.1 Design Options for Electric Storage System

Two designs are considered in this research for providing a higher performance, more energy efficient Energy Storage System. As mentioned before, the topology of each design is based on an electric vehicle powertrain. Each of the designs can be integrated as the electric power system in a Plug-in Hybrid Electric Vehicle as required by UWAFT for EcoCar 4. The following subsections discuss the topologies in more detail.

2.1.1 Design #1: Fully De-coupled Hybrid Supply Configuration

The first design considered provides a fully hybridized power system in which both the battery and supercapacitor unit provide power to the entire load of vehicle, that is, both the main motor load as well as the auxillary loads. As the supercapacitor bank and battery system work in parallel, both power sources must be decoupled from the DC-Bus to avoid fluctuations in the voltage on the bus. Therefore, each source must be connected to a DC-DC converter which then services the DC-Bus. The first option considered for this design was to use a multi-input, bidirectional DC-DC converted which will connect to both power sources in parallel. This topology is shown in Figure 2.3 below.

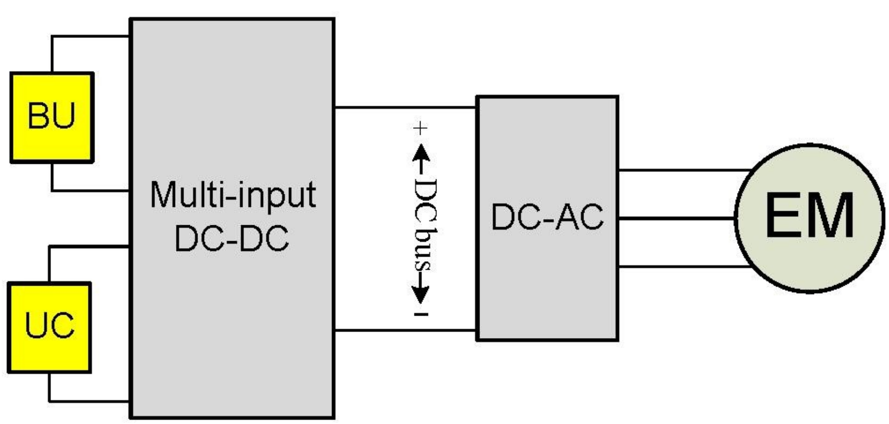

Figure 2.3: Fully De-coupled Hybrid System with Multi-input Converter [1]

While this topology provides good performance in theory, one problem with using this option is that the multi-input converter needs to be selected such that it fulfills the power requirements from both the battery unit and the supercapacitor. Since the supercapacitor unit will be used in periods of high power requirement, this will greatly increase the cost of DC-DC conversion. Moreover, since the energy recovery through regenrative braking is more efficiently done using supercapacitors, the use of a bidirectional converter for the battery unit presents an unneccessary cost as the conversion only needs to be in one direction.

In order to solve the issues in the first option, a second and final option was considered and is shown in Figure 2.4. This option involves two seperate DC-DC converters connected in parallel as opposed to a single multi-input converter. In this way, each converter can be selected based on the maximum power requirement from each source and will reduce the cost of the converters. In addition, since both converters are connected to their own respective power sources, there is no need to include a bidirectional converter in each case. As such, while a boost-buck converter can be connected to the supercapacitor bank, the battery unit only needs to be connected to a unidirectional boost converter. This further helps simplify the design and reduce costs.

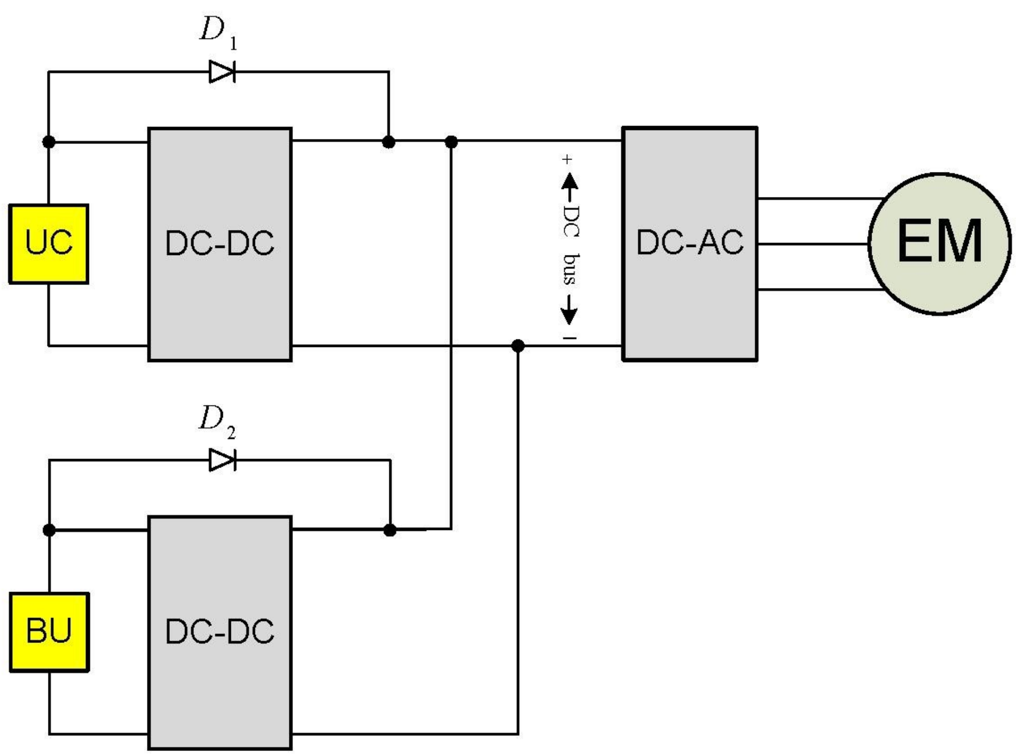

Figure 2.4: Fully De-couple Hybrid System with Parallel Converters [1]

2.1.2 Design #2: Battery/Supercapacitor Individual Load Operation

The second design considered in this research uses the two seperate power sources to service seperate loads in the vehicle. The battery unit operates in a similar manner to a standalone battery system with two exceptions that help improve performane and efficiency. Firstly, the battery unit only supplies power to the main motor load and does not service any of the auxillary loads. This helps reduce the power required from the battery unit a little. Secondly, the supercapacitor bank is used as the preffered choice of storage during regenerative braking due to its fast charging capabilities. The battery unit provides a backup for storage of recovered energy in the situation the supercapacitor becomes fully charged and cannot store any more energy. With the battery servicing the motor load, the supercapacitor bank provides power to only the auxillary loads in the system. This process is similar to the energy recovery mechanism used by Mazda 6 which utilizes supercapacitors to store recovered energy during regenerative braking and use the recovered energy to service the vehicle's auxillary power requirements.

Figure 2.5 below shows the configuration of this parallel power system design. In contrast to the previous design considered, the auxillary loads and motor loads are not connected to the same DC-Bus. Since the auxillary loads are not serviced by the battery and the supercapactior does not provide power to the high voltage DC-Bus that is connected to the DC-AC converter, a seperate DC-Bus with a lower voltage can be used for the auxillary loads.

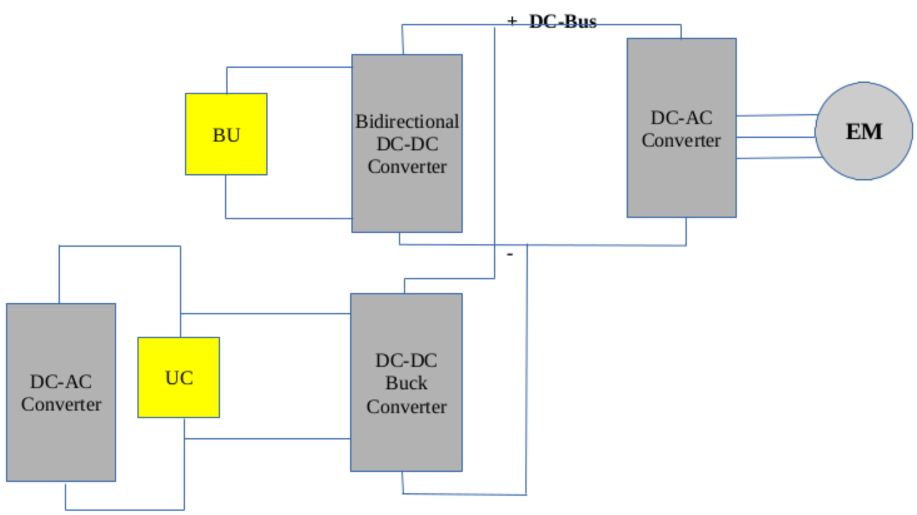

Figure 2.5: Schematic of Dual DC-Bus Parallel Operation

Since the battery is needed as a backup for energy storage of recovered energy it must be connected to a bidrectional converter. In the case of the supercapacitor bank, a unidirectional buck converter connected the higher voltage DC-Bus to the supercapacitors which is used to step down the voltage while charging the capacitors during regenerative braking. On the other side, the lower voltage DC-Bus which is also connected to the supercapacitor bank need not have a DC-DC converter connected as the smaller supercapacitor bank operates at a voltage closer to that needed by the auxillary loads. Furthermore, the auxillary loads systems contains additional regulators in their individual systems which further eliminates the need for a DC-DC converter to de-couple the low voltage DC-Bus from the supercapacitor.

3.0 Analysis of Electric Storage System Configurations

This section analyzes the desings considered in the previous section both by using quantative measures such as simulations as well as qualatative measures based on the ease and effectiveness of implementation. The designs are judged using four metric as follows:

- Cost of the Energy Storage System
- The total weight of the energy sources in the ESS
- The maximum fluctuations in the current during acceleration or regenerative braking
- The total amount of energy recovered during regnerative braking

The qualatative analysis is presented first and judges the designs based on the ease of imlementation as well as the complexity of the required control circuitry. In addition, the analysis also focuses on the how the design helps improve battery cycle life and overall performance of the system

Following the qualative analysis, the simulation model for the designs are presented which are developed in Simulink. Based on the concept that high demands of power of large recovery of energy during braking only occurs for a short period of time, this 20 second run of the simulation involves 5 seconds of increasing acceleration followed by 15 seconds of constant velocity and lastly, constant deceleration for the remaining 5 seconds. The required speed and torque are mapped to electrical power requirements and the respective power is then drawn from each of the two sources and fed to the DC-Bus(es).

The simulations use an averaged out power source sizing of 90 kWh for comparision using the sizes currently available in production of electric SUVs such as the Tesla Model X[10]. The motor power requirements are determined similarly to be a total of 386 kW[10]. The auxillary loads are divided into 2 sections, namely Prolonged Loads of 260 W on average and Intermittend Loads of a maximum of 1.7 kW[7].

Following the simulation run, the sizes of the supercapactior bank and battery unit is recorded for each design and the combined weight and cost is compared with battery standalone system. The maximum current fluctuation is also recored for each design as well as the total amount total amount of energy recovered during the deceleration phase of the simulation. The following subsystems present the analysis and simulation of each design in more detail.

3.1 Analysis of Fully De-coupled Hybrid Supply Configuration

The Fully De-couple Hybrid Supply system utilizing parallel DC-DC converters provide a high performance, high efficiency configuration of the Energy Storage System. The supercapacitor bank provides power during high power requirements and receives the recovered energy during regenerative braking. As the supercapacitor is able to charge at a high rate, the amount of energy recovered during regeneration is greater than that with a battery standalone system.

The design limits the amount of power that can be drawn from the battery by limiting the rate at which the current drawn can be increased. This means that the excess power during acceleration is provided by the supercapacitor bank and the current drawn from the battery is kept stable. A similar scenario occurs during regeneration where only the supercapacitor receives recovered energy and the current load fluctuations in the battery are kept to a minimum. This feature of the design attempts to prevent the reduction in cycle life of battery caused by fluctuating current loads.

While this design provides high performace and energy efficiency, these improvements come at higher costs of the overall Energy Storage System. Supercapacitors are more expensive per unit energy of storage and as this design includes a larger supercapacitor bank, the overall cost of the ESS increases. In addition, this design includes an additional DC-DC converter. Comparing with the battery standalone system, while a bidirectional Boost-Buck converter is included in both systems, this design uses an additional Boost converter which is connected to the battery. This further adds to the cost of the design. Lastly, since the two sources used operate under different conditions of required power, more complex and expensive control circuitry needs to installed as part of the power management module.

3.1.1 Simulation and Results

The simulation model for the Fully De-couple Hybrid System is shown in Figure 3.1. The overall model consists of battery and supercapacitor models taken from the Simscape Power Systems library and DC-DC converters taken from an example model by Pierre Clement Blaud and L. Dessaint [6]. The model was iteratively redesigned for better performance and the final design was chosen such that the power outputted by the ESS tracks the required power very closely. This resulted in the sizing of the supercapacitor bank such that it can provide two-thirds of the power during maximum requirement conditions [2].

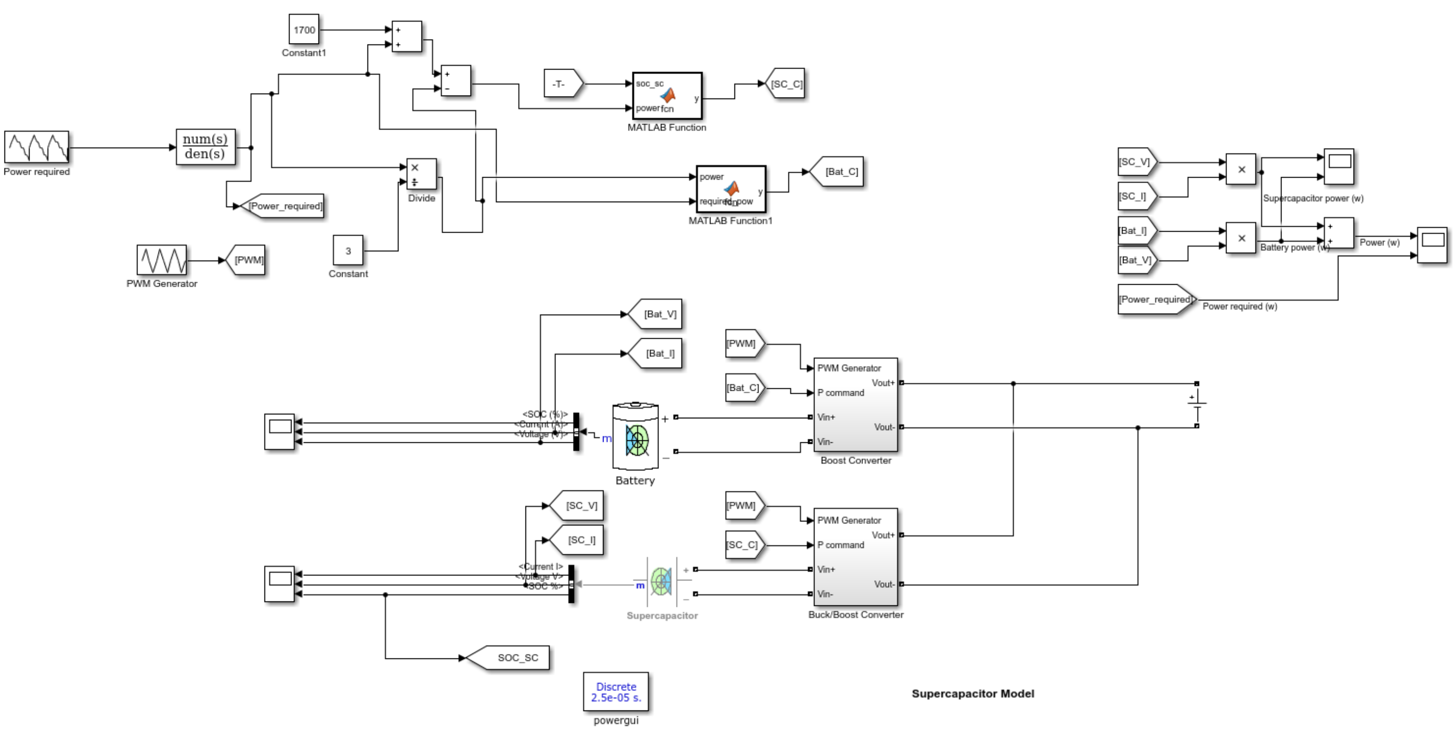

Figure 3.1 : Simulink Model of Fully De-coupled Hybrid Power System

The model includes two Matlab functions that decide how much power needs to be drawn from each of the two sources. The functions direct all power during regenerative braking to the supercapacitor bank while maintaining a fixed rate of increase for the current drawn from the battery during acceleration, allowing the supercapacitor bank to provide the remaining needed power.

The simulation test runs for this model shows that a total of 0.35 MJ of energy is recoverd during the 5 second deceleratation phase of the simulation and the maximum current fluctuation seen during acceleration and regeneration is 80 A. The optimal size of the supercapacitor bank is determined to be a 48 V, 500 F bank while the battery unit can be decreased from 90 kWh to 80 kWh. Using these figures, the combined weight of the ESS is determined to be 1177 kg while the combined cost of the battery unit and supercapacitor bank, not including the DC-DC converters and control circuitry, is $20,250.

3.2 Analysis of Battery/Supercapacitor Individual Load Operation

The Battery/Supercapacitor Individual Load Operation design seperates the loads serviced by the battery unit and supercapacitor banks. In this design, the battery unit provides power to the main motor load while the supercapacitor bank receives braking energy and provides power to auxillary loads in the vehicle. This design offers higher efficiency in energy recovery as compared to the battery standalone power system as it uses the faster charging supercapacitor bank to recover energy.

Since the supercapacitor bank only services the auxillary load it can be sized smaller than in the previous design which keeps the increase in cost of the Energy Storage System small. The aim of the design is to reduce some of the required power from the battery, thereby decreasing the current drawn as well to receive most of the energy during regenerative braking and hence reducing current fluctuations in the battery during the deceleration phase.

The increase in performace and energy efficiency provided by this design is significantly lower than the first design considered. Since most of the power required in the system is still provided by the battery unit, the battery current load is still large. In addition, due to the smaller size of the supercapacitor bank the energy it can store is less and therefore the remaining energy during regenerative braking is directed to the battery unit. This makes the increase in the total recovered energy significantly less than the previous design.

The main goal of this design is to serve as middle point betweent the battery standalone power system and the Fully De-coupled Hybrid Supply configuration, both in terms of the increase in performace and efficiency, and the increase in cost of the Energy Storage System. The increase in cost is kept low due to the smaller size of the supercapacitor bank and the lower specifications of the additional Buck Converter added. In addition, because the loads of the two sources are completely seperated, the control circuitry required for this design is also less complex and less expensive.

3.2.1 Simulation and Results

The Simulink model developed for the Battery/Supercapacitor Individual Load Operation configuration is shown in Figure 3.2. The overall model shows the the supercapacitor and battery models taken from the Simscape library as in the previous model. This model, however, contains two DC-Buses, one connected to each of the two power sources. The battery unit is connected to the 300V DC-Bus while the supercapacitor connects to a 28V DC-Bus in order to provide appropriate voltage to all auxillary loads. The supercapactor bank in this system is sized based on the maximum auxillary power requirement of the vehicle while the battery size is reduced from the battery standalone system on the basis of the reduced power requirements from the battery as well as the additional energy recovered in the system during regenerative braking. This results in a supercapactior bank size of 16 V, 500 F while the battery unit is decreased to 85 kWh from 90 kWh.

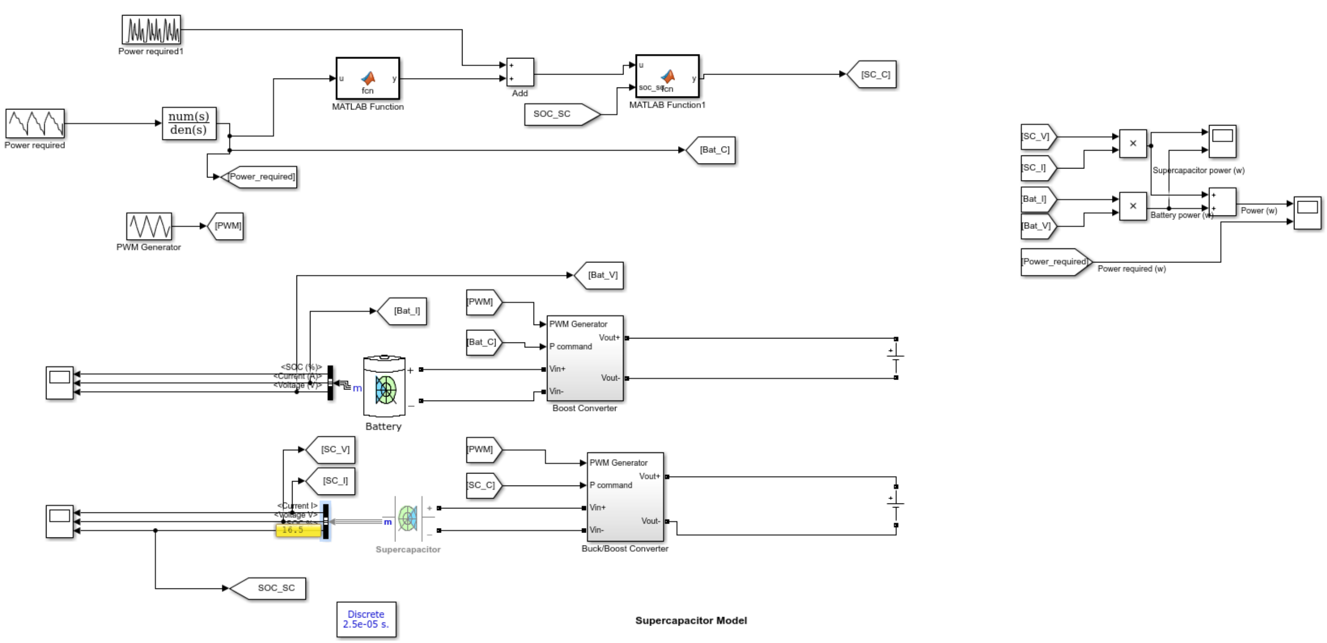

Figure 3.2: Simulink Model of Battery/Supercapacitor Individual Load Operation Configuration

As before, this model also included two Matlab functions which are used to determine where the power needs to be directed during regenerative braking. The power is supplied to the supercapacitor bank while the supercapacitors are not fully charged. When the State of Charge of the supercapacitor bank is 100 percent, the regenerative power is supplied to the battery unit instead to avoid wastage of recovered energy.

The simulation test runs of this model shows that a total of 0.305 MJ of energy can be recovered with this configuration and ESS sizing. Using the figures calculated for the supercapacitor bank and battery unit size, the combined weight of the two sources is determined to be 1230 kg. The combined price of the two sources, decreases from the previous design to $19,130. However, since the battery supplies much greater power in this design, the maximum variation in current is seen to be 395 A, a big increase from the previous design.

4.0 Conclusions

In addition to the two models discussed above, the battery standalone model was also tested under the same power requirements. Table 4.1 below summarizes the results of all simulations based on the 4 metrics set for the Energy Storage System design.

	Cost ($)	Weight (kg)	Max Current Pulse (A)	Total Energy Recoverd (MJ)
Battery Standalone Model	18,810	1260	400	0.3
Fully Decoupled Hybrid Model	20,250	1177	80	0.35
Individual Load Operation Model	19,130	1230	395	0.305

Table 4.1: Summary of simulation results for all designs considered

These results show that the Fully Decoupled Hybrid Supply provides the greatest benefits with an 80 percent decrease in current pulse amplitude and a 16 percent increase in the amount of energy recovered. However, this design also incurrs the greatest cost increase of roughly 8 percent over the battery standalone model for just the power sources alone. The design will further include expensive and complex control circuitry which add to its cost. The Individual Load Operation design offers less benefits over the battery standalone model but also incurrs a smaller increase in cost. Either of these models can be integrated into EcoCar 4 to provide higher performace and efficiency of the vehicle. The final choice of design must be based on the team’s priorities as well as the budget allocations for the competition.

5.0 Recommendations and Next Steps

While the two designs presented in this research offer great methods of increasing efficiency and performance of the vehicle, further research can be done to obtain greater benefit from high efficiency hybrid power systems. The following list present some important technologies and methodologies UWAFT can further investigate to obtain a high performing , high efficiency Enery Storage System:

- Metal-Air batteries can be investigated to replace the Lithium-Ion batteries commonly used. These batteries use a negative electrode made of a pure metal and ambient air as the positive electrode in the electrochemical reaction. Metal-Air batteries offer very high energy density and as such they can be used to reduce the weight of Energy Storage System.
- A combination of Metal-Air batteries and Supercapacitors can be investigated to take advantage of both the high energy density provided by the batteries as well as the high power density provided by supercapacitors. This combination can help service higher power loads for longer periods of time, thereby increasing both acceleration of the vehicle and the distance travelled per charge.
- While this research focuses on Electrolytic Double-Layer Capacitors, the research can be extended to other types of supercapacitors such as Pseudocapacitors and Hybrid supercapacitors. Hybrid supercapacitors in particular can offer further weight reductions in the system as they have higher energy density than EDLCs.
- Lastly, in order to get a better understanding of how the combination of supercapacitors and batteries can provide improvements in performance and efficiency, more tests sets can be simulated to account for different driving conditions. An long time period test run can also be performed to (i) determine how the performace of the vehicle would vary in long time periods as opposed to short time periods and (ii) to determine the increase in total distance and the MPGe that can obtained with the battery and supercapacitor combination.

6.0 References

[1] Amir Ostadi, Battery/Ultracapacitor-Based Energy Storage Systems in Electric Vehicles, pp 14-24.

[2] Andrew Burke, Ultracapacitor Technologies and Application in Hybrid and Electric Vehicle, July 2009, pp 8, 18.

[3] A. Jarushi and N. Schofield, Modelling and Analysis of Energy Source Combinations for Electric Vehicle, May 2009, pp 5.

[4] Andrew Burke and Hengbing Zhao, Applications of Supercapactiors in Electric and Hybrid Vehicles, April 2015.

[5] Dorin Petreus, Daniel Moga, Ramona and Radu Munteanu, Modelling and Sizing of Supercapacitors, Volume 8, Number 2, 2008.

[6] Pieree Clement Blauda and L. Dessaint, Supercapacitor Model, Mathworks, https://www.mathworks.com/help/physmod/sps/examples/supercapacitor-model.html.

[7] Vehicle Electrical Loads (Automobile), What-When-How, Section 14.4, http://what-when-how.com/automobile/vehicle-electrical-loads-automobile/.

[8] Lithium-ion Batteries, Chris Woodford, ExplainThatStuff, August 2018, https://www.explainthatstuff.com/how-lithium-ion-batteries-work.html.

[9] Supercapacitor, Wikipedia, https://en.wikipedia.org/wiki/Supercapacitor.

[10] Tesla Model X, Wikipedia, https://en.wikipedia.org/wiki/Tesla_Model_X.