ENERGY MONITORING SYSTEM FOR SUPERCAPACITOR

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A project report submitted in partial fulfillment of the requirements for the award of Master of Engineering (Electrical)

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR and other institutions.

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Name : ____________________________

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"ENERGY MONITORING SYSTEM FOR SUPERCAPACITOR"** was prepared by **HO CHEN WENG** has met the required standard for submission in partial fulfilment of the requirements for the award of Master of Engineering (Electrical) at Universiti Tunku Abdul Rahman.

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ENERGY MONITORING SYSTEM FOR SUPERCAPACITOR

ABSTRACT

The Hybrid energy storage system (HESS) is the main focus in this research project. Hybrid Energy Storage System (HESS) consists of several types of energy which is commonly used in electric vehicle. In this final year project, a simulation model is developed to investigate behaviour of supercapacitor, charging and discharging conditions when it is under different power demands. Lead acid batteries and supercapacitor are the most crucial components to be used as the combination for HESS. In electric vehicle, the performance is improved where supercapacitor is used due to battery's power density issue, quick discharging and charging conditions. With the help of supercapacitor, the battery is relieved from peak stress and the efficiency can be optimized. However, the challenge is the optimization of HESS in order to take the advantage of their strengths (battery and supercapacitor) respectively. Other than that, discharging characteristic is determined by investigating the combination of HESS. Thus, case studies of power demands are studied in order to understand the behaviour of supercapacitor when it is under different power demands. Hence, the behaviour of supercapacitor is investigated and validated with the simulation results of MATLAB Simulink. The experimental and simulation results are presented to verify the analysis of supercapacitor. The results

have shown under various power demands, proposed strategy to study discharging characteristic is effective.

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LIST OF SYMBOLS / ABBREVIATIONS

BC	Battery Capacity, Ah
C	Capacitance, F
f	Frequency, Hz
z	Impedance, Ω
I	Current, A
V	Voltage, Volts
mV	Milli-Volts
R_i	Internal Resistance, Ω
AC	Alternating Current, A
DC	Direct Current, A
HESS	Hybrid Energy Storage System
EV	Electric Vehicle
SOC	State of Charge
DOD	Depth of Discharge
PWM	Pulse Width Modulation
SLA	Sealed Lead Acid
VRLA	Valved-Regulated Lead Acid

CHAPTER 1

INTRODUCTION

1.1 Background

In this generation, environmental issues provide the motive force to develop efficient, clean and sustainable vehicles for transportation (Krakowska 2002). Electrification of the automotive powertrain is one of the main trends in the current vehicle development. Thus, electric vehicle has become eco-friendly technology in current world.

In hybrid vehicle, energy transferred from fuel cell and batteries are fully utilized to give power for propulsion. Electric vehicle has brought the advantages of reducing pollution levels, but it has its limitation which is shortage of power. In hybrid vehicle, batteries are one of the essential elements that required extra care as battery life cycle. It is much dependent on the charging and discharging cycles. In the event, lifespan of the car batteries can be reduced. In this case, the common solution that has been used is Hybrid Energy Storage System (HESS). HESS is characterized as coupling of two or more energy storages such as batteries with supercapacitor (Bocklisch 2015). By using these two energy sources, supercapacitors and batteries solve the limitation of power density problem, and supercapacitor has higher power density (Rajabzadeh et al. 2015). Hence, this solution leads to advantages such as increases the reliability of power sources, enhance performance of EV and prolong lifespan of battery.

Supercapacitor is commonly integrated into HESS. It helps to store energy so energy in batteries could be saved and enlarge the lifespan of batteries. However, the actual charge and discharge behaviors of supercapacitor are still unclear in HESS. Researchers and engineers are hard to investigate on how the processes of internal charging and discharging happened in HESS (Xiong et al. 2015). In the current status, there are several techniques to be applied for solving this problem. Before the execution, understanding and literature studies of fault are necessary to be studied properly.

In HESS, supercapacitor can store remaining energy from battery during low power demand, gives extra energy during high power demand (Pedram et al. 2010), regulates voltage during steady power demand and sudden demand. Other than that, during charging and discharging conditions, transient may be happened at the initial moment so it can give higher peak current to application and damage will be occurred. Based on transient response, response time can be determined (Zhang et al. 2014). In HESS technology, load sides must be considered to run in different configurations such as high load, low load, steady power demand and sudden demand. Other than that, highly transient implies that batteries used are subject to regular charge and discharge cycles (Kim et al. 2014). Thus, lifespan of batteries could be shortened. In order to prevent damage happened because of transient, some understanding and literature studies of fault are necessary to be studied properly.

In this project, Matlab software is proposed to implement to build a simulation model. The purpose of this project is to develop a GUI simulation model that monitors the conditions of charging and discharging. Besides, the simulation results will be compared with practical results for making comparison. Next, study the cases of power demands during different configurations. In order to find the difference during different demands, case study and research must be carried out to validate the capabilities of supercapacitor at different demands. The expected outcome result consists of simulated Simulink models where show the current, voltage and SOC graphs on the interface. In fact, practical results are compared with simulation results. Simulated model is compared existing data between practical and theoretical. Lastly, a case study on different load in distinct configurations (High power demand, low power demand, sudden demand and steady power demand) is carried out.

1.2 Problem Statement

Supercapacitor is commonly integrated into HESS. It helps to store energy so energy in batteries could be saved and enlarge the lifespan of batteries. However, the actual charge and discharge behaviors of supercapacitor are still unclear in HESS. Researchers are hard to investigate on how the processes of internal charging and discharging happened when supercapacitor connects with battery packs. Due to these specialized processes, the demand of GUI monitoring model technique is improving continuously because a proper system needs to be built for monitoring the behaviours of supercapacitor.

During charging and discharging conditions, transient may be happened at the initial moment so it gives higher peak current to application and damage will be occurred. According to this factor, further case study of supercapacitors' power demands need to be carried out in order to investigate the different conditions on high load, low load, steady power demand and sudden demand. Thus, a case study has been studied to consider the load sides of supercapacitor. Based on these two statements, identification has been made to solve the challenge faced by electric vehicle.

1.3 Aims and Objectives

In this research, the two major challenges are the case study of power demands and monitor behaviour of supercapacitor. Therefore, this Final Year Project is carried out to understand the both challenges and propose some methods to solve the problems. The objectives of this research project are:

1. To investigate and study the behaviour and characteristics of supercapacitors.
2. To monitor the status of charging and discharging conditions.
3. To develop an energy transfer protocol for supercapacitor.
4. To investigate a case study about the differences between different load sides such as heavy load, low load, steady power demand and sudden demand.

1.4 Research Methodology

Simulation and experiment research is used in this project. The simulations of the propose GUI model should be conducted before conducting the practical work. The results obtained in the practical work are compared to the simulation results. If the practical results are similar to the simulation results, the GUI model is trustable and reliable. Hence, this system will be implemented into the Electric Vehicle for future plan. Besides, the case study of supercapacitors' power demands need to be carried out in order to investigate the different conditions on high load, low load, steady power demand and sudden demand. In these experiments, discharging current is investigated in two conditions such as "with supercapacitor" or "without supercapacitor". To identify the difference, the same time interval is set at same timing while achieving the target. Thus, a case study has been studied to consider the load sides of supercapacitor.

1.5 Scope of the Project

This project is mainly focused on the operation of the Hybrid Energy Storage System. The charging and discharging of the HESS, GUI model for monitoring the supercapacitor's operation and the case study on different load sides are used to improve the HESS output. For series connection of supercapacitor in a module, the module achieves high performance of charging so it may charge up until maximum voltage. The voltage range is 0 V to 26.1 V DC, current range is set as 3.8 A during condition of charging supercapacitor. While for parallel module, voltage range is between 0 – 2.65 V and current is 3.8 A. Besides, discharging conditions can cause high power consumption because the connected load that can draw high current. With the appropriate heat sink, it maintains the interior temperature which minimizes the current usage.

1.6 Project Specification

1. Sealed lead acid battery

Table 1.1: Specification of sealed lead Acid battery

Parameter	Operating
Voltage	12 V
Capacity	1.2 AH/ 20 HR
Max initial current	Less than 0.36 A

2. Series connection of supercapacitor in a module

Table 1.2: Specification of series module

Supply Voltage	12 V – 26.1 V (Charging)
Output Current	Adjustable

3. Parallel connection of supercapacitor in a module

Table 1.3: Specification of parallel module

Supply Voltage	2.2 V – 2.65 V (Charging)
Maximum Continuous Current	17 A
Leakage Current	0.26 mA

Output Current	Adjustable

4. Shunt resistors with heatsink (1W22Ω, 5W 22Ω, 10 W 1Ω, 10W 22Ω, 25W 22Ω,)

Table 1.4: Specification of shunt resistors

Withstand Power (W)	Resistance (Ω)
1	22
5	22
10	1
10	22
25	22
80	7

5. 12 V – 24 V Power supply

CHAPTER 2

LITERATURE REVIEW

2.1 Case Study of HESS (Hardware)

In this section, there are some discussions on HESS. Supercapacitors and battery are the components which can be implemented in HESS. This combination is proposed to optimise the performance of battery. In order to avoid the short life time of battery, the peak power conditions must be focused on. Therefore, discharging and charging conditions are also the concern in this project. Hence, all the literature studies of supercapacitor's behaviours and battery are shown and discussed.

2.1.1 Batteries in Research

Lead-acid battery has been the most famous choice of batteries for electric vehicle during the origin (Development process). In this final year project, lead-acid battery is the choice amongst all types of batteries. It supplies power to electric vehicle; it can be defined as main component. When this type of battery deals with electric vehicle, it has higher mass with certain range of charging capacity. It has lower cost, lower energy density, higher reliability and safe. Besides, this battery gives less peak current demand and withstands regular discharging simultaneously (Durham 2013). Compared to all types of batteries, lead acid battery has medium range of voltage. The internal resistance is lower so it can provide higher power. This battery has one disadvantage about the overcharge tolerance. When the battery is being charged till a limit, the voltage drops immediately if the battery is kept charging.

For lead-acid battery, its chemical reaction is slightly studied. During discharging condition, two lead sulphate plates is formed and dissolved sulphuric acid into water. When fully charging, concentration of sulphuric acid is increased. On the contrary, concentration is reduced. For this type of battery, hydrogen and oxygen gases are generated from positive electrodes to form chemical reaction.

There are two types of batteries which are used in real life. The first type is starter lead-acid (SLA) battery. Its SLA battery is designed for starting an automotive engine. It has many thin plates which are designed for maximum surface area and current output. Starter batteries will have low internal resistance to deliver a maximum output power by the help of thin plates. However, repeated deep discharges will result in capacity loss and malfunction. For the current application, SLA battery is commonly used in applications which are smaller in size such as computer system and electric bicycle. The cell plates deliver output power, where it activates the starter battery and keep open circuit condition while operating. Thus, this action prolongs the quality of battery.

Valve-regulated lead acid battery (VRLA) battery is designed to deliver less maximum current and frequent discharging simultaneously. These battery are has thicker plates so the thicker plates can reduce the availability of the plate's surface area for chemical reactions to allow deep cycle discharging. Thus, higher tolerance is obtained from deep discharge as well. Therefore, deep cycle batteries are used to provide a constant output power for the Electric Vehicle to operate. Other than that, this type of battery has been used as interruptible power supply in electronics wheelchair. It is commonly used as a backup supply if the main supply goes off. Due to high ability of withstanding temperature and power density, submarine uses VRLA battery to reduce maintenance, save cost for future maintenance and increase the safety purpose while diving. At last, lead-acid battery is recommended to use in this project. The batteries characteristic are shown in Table 2.1:

Table 2.1: Batteries characteristics (Kularatna 2011)

Table 1—Secondary battery chemistry characteristics (© 2011 CRC Press, used with permission [1].)

Parameter	Units/ conditions	Sealed lead-acid	NiCd	NiMH	Li-Ion	Li-Polymer	$LiFePO_4$
Average cell voltage	Volts	2.0	1.2	1.2	3.6	1.8 -3.0	3.2-3.3
Internal resistance		Low	Very low	Moderate	High	High	High
Self discharge	%/month	2%-4%	15%-25%	20%- 25%	6%-10%	18% - 20%	
Cycle life (The # of charge-discharge cycles until 80% of the rated capacity remains.)	Cycles	500-2000	500-1000	500-800	1000- 1200		1500-2000
Overcharge tolerance		High	Med	Low	Very Low		
Energy by volume (Volumetric energy density)	Watt hr/liter	70-110	100-150	200-350	200-330	230- 410	200
Energy by weight (Gravimetric energy density)	Watt hr/kg	30- 45	40-60	60-80	120-160	120-210	100

2.1.2 Supercapacitor

Supercapacitor is commonly used in Hybrid Energy Storage System (HESS). Due to its characteristics, it is able to provide high power, short charging time, discharging time, long life cycle and high power density (Halper & Ellenbogen 2006). mentioned that it is useful especially provides high power, short charging and discharging time, long life cycle, high power density. Besides, supercapacitor has greater energy while maintaining the power during the discharging conditions. Compared to conventional capacitors, supercapacitor has its advantage so it is a trend in current market. In the research, supercapacitor reduces peak current. In HESS, this type of supercapacitor supplies and stores peak power during discharging and charging (Medora & Kusko 2012). Compared to conventional capacitor, supercapacitor is much better and reliable. In Table 2.2, the comparisons of capacitor and supercapacitor are shown.

Table 2.2: Comparisons of capacitor and supercapacitor

Capacitor	Supercapacitor
● Low breakdown voltage rating ● Slow charging and discharging ● Low energy density ● Long life cycle	● High breakdown voltage rating ● Fast charging and discharging ● High energy density ● Longer life cycle ● Higher superior efficiency

2.1.3 Charging and Discharging Conditions of Battery

In this final year project, battery's performance is concerned especially in charging and discharging conditions. During acceleration, the current is drawn by motor and maximum power is delivered. In charging condition, the voltage is increasing and remaining constant if it reaches steady state. In Figure 2.1, discharging curves of battery shows the result where under different cut off voltage. For discharging state, voltage is decreasing and remaining constant if it reaches steady state (Rahn, and Wang, 2013). Other than that, overcharge and undercharge situation are also the concerns. During overcharge, the battery is charged sufficiently for long period. This behaviour may cause damage to battery, and heat dissipation is higher as well. On the contrary, undercharge condition means the voltage is being charged below the cut-off voltage.

According to the literature survey, battery is able to withstand high current at low State of Charge (SOC) by using supercpacitor (Medora & Kusko 2012). With help of supercapacitor, peak battery current is reduced so the battery is able to withstand high current. Supercapacitor stores peak power during charging and discharging conditions, so the losses are decreased in the average battery power. In battery, State of Charge is defined as the voltage range of battery. Based on lower SOC, Supercapacitor gives higher power as capacility of battery reduces. In HESS, stress of peak power is decreased during discharge and charge. Thus, battery is protected if supercapacitor is applied (Ming et al. 2014). Furthermore, supercapacitor is used to meet the energy or power demands while power split ratio in HESS system.

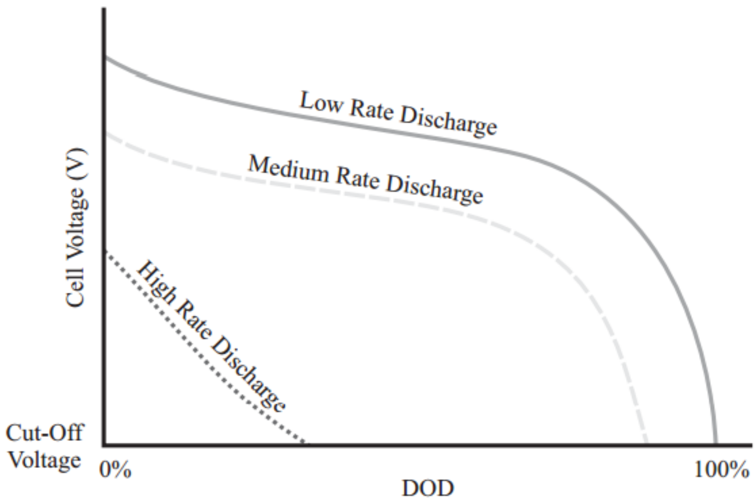

Figure 2.1: Voltages curves for different discharging rates (Rahn, and Wang, 2013)

2.1.4 Topology of HESS

In Hybrid Energy Storage System (HESS), battery and supercapacitor are the common combination to be applied in renewable energy applications. HESS is suitable for the energy system by using supercapacitor via battery and AC-DC power converter for supplying energy to grid via renewable energy system. HESS stores power from the power grid and the PV system when the electricity fee is higher, and it will perform peak shaving. HESS has its benefits such as large power capacity, huge energy capacity, faster response time and longer cycle life. Thus, the efficiency of power conversion is increased (Bocklisch 2015). Next, HESS can be applied into low power embedded system application. This combination is used in wireless sensor node system. In this application, supercapacitor acts as a buffer which filters the noise during conditions of charging and discharging. Energy harvesting from heat is significantly extend the lifespan of devices (Kim et al. 2014).

For the application of electric vehicle, four components are used to store and recharge energy. These four components include motor, controller supercapacitor and battery. In electric vehicle, supercapacitor gives power to the motor for reducing stress of peak power so that battery is not under peak demand. Next, the speed of discharging or charging can affect the quality of battery. In order to avoid this issue, converter is used to control the peak power demand. Otherwise, the transient may burn the battery after a moment. According to the literature survey, battery is being discharged and stored energy during low discharging rate. Supercapacitor helps to allow high peak power through HESS, where battery can deliver and absorb high peak power (Medora & Kusko 2012). At high discharge rate, the current is increased as capacitor of battery decreases; cycle life can be reduced as well. In HESS, this type of supercapacitor supplies and stores peak power during discharging and charging (Medora & Kusko 2012). Compared to conventional capacitor, supercapacitor is much better and reliable. Besides, it results in higher fault current but low impedance.

According the literature survey, (Yanzi & Wang 2014) has mentioned that the bi-directional DC-DC converter is designed to accept high power level. Three different power levels have its operating mode. For mode I, the overall loss can be reduced if current is flowing through the supercapacitor directly. In mode II, battery bank provides more power via the converter. In mode III, battery is connected to the DC-DC link with supercapacitor so the power level is decreased. By using the switches, energy is flowing between DC link and supercapacitor through switch 1 during mode I. Next, switches condition in mode II result in the energy flow. Energy flows through the switch from battery pack. The voltage of the supercapacitors synchronises with the state of charge of the battery. The supercapacitor needs to increase its voltage when the SOC of battery is high while it is still supplying power to DC bus (Yanzi & Wang 2014). In mode III, the supercapacitors act as the low-pass filter. Besides that, when the DC bus does not require any power, the energy will flow in between the supercapacitors and battery through the converter in order to bring the SOC of the battery and the supercapacitor back to the original level.

Based on the journal, (Hiray & Kushare 2013) has designed an energy storage system by using DC-DC chopper and inverter. Three are three modes of operation in the system. In mode I, no real power exchange between the supercapacitor and the grid as the main generator can deliver all of the required power. In mode II, supercapacitor delivers energy to the grid due to higher load demand (Heavy load). For mode III, charging behaviour of supercapacitor is started if there is excess energy available in the grid due to low load demand.

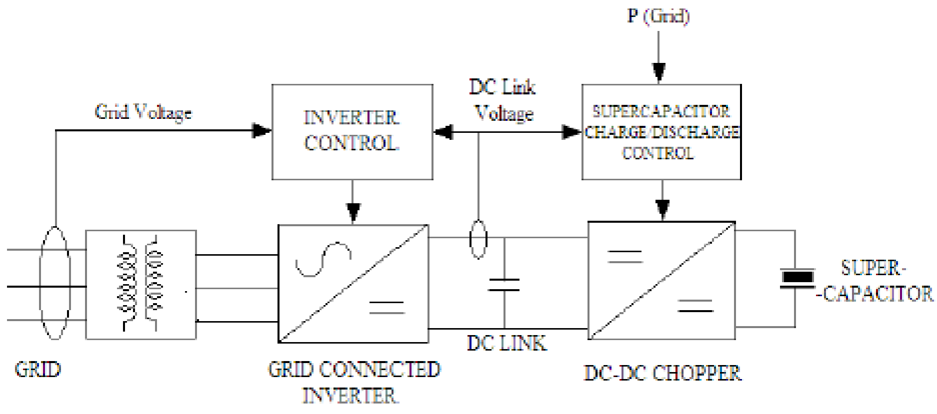

Figure 2.2: Energy storage and inverter control (Hiray & Kushare 2013)

Figure 2.2 shows the overall system. The supercapacitor is charged or discharged by adjusting the average voltage across the coil to be positive or negative values by means of the DC-DC chopper duty cycle. When the unit is on standby, the supercapacitor current is kept constant, resulting in the net voltage across the supercapacitor to be zero (Hiray & Kushare 2013). Next, buck-boost converter with grid as the main driving control signal obtained from calculating the three phase power in the grid. During charging mode, double loop control is performed with triangle-wave comparator to generate pulse width modulation waveform to control the switching device. In mode III, direct current control is used in the discharging control through double-loop control. The outer ring is the output voltage control, and the inner loop is the input current control. Compared the actual output voltage with the command voltage signal, then put the error goes through regulator to get the DC current signal. As a result, supercapacitor is charged without affecting the load power demand. The work is done when the supercapacitor feeds the energy demand in DC link.

2.1.5 Power Peak Demands

In the final project, supercapacitor is used to regulate the current demand in HESS. According to the literature review, (WU et al. 2012) said that battery is protected from the stress of peak power if supercapacitor is used. Thus, HESS may result in energy heat loss. Supercapacitor acts as low pass filter which it can filter and smoothen the voltage after the transient. Next, (Park et al. 2013) agreed that power loss is reduce successfully by HESS because supercapacitor absorbs high power and battery has its capability. (Medora & Kusko 2012) said that supercapacitor helps to increase efficiency, reduce peak current demands.

For the case study, supercapacitor and lead acid battery are used to implement in HESS system. In HESS, peak power demands can be avoided if the battery is protected with supercapacitor. Thus, supercapacitor's functions and behaviours are discussed in this section. In conclusion, literature review and case studies of HESS are done.

Firstly, case study of high load and low load demands are discussed. According to this literature study, (Gualous et al. 2011) have mentioned that ambient temperature affects the results of charging and discharging conditions at higher current rate. If high current is supplied to charge battery through supercapacitor at 34° and above, initial starting current (Transient) is occurred. Supercapacitor temperature can be increased until it reaches a steady state if the heat loss increases on the external part of supercapacitor. Hence, higher current leads to situation which having higher transient and instability of power at initial stage. Next, (Polenov et al. 2007) havestated that parallel module (Supercapacitor with battery) is the best module to buffer transient. The author has proved that parallel module can decrease the impedance in certain frequency range. The input impedance is decreased if current is increasing. Next, (Hiray & Kushare 2013) said that supercapacitor gives energy to compensate voltage due to heavy load demand during charging condition. While for discharging, supercapacitor is charged up if energy available due to low power demands (Hiray & Kushare 2014). At steady state, there is no power between supercapacitor and loads.

Next, battery can be drained quickly during sudden power demand. Due to losses of internal resistance, discharging batteries with higher current can bring lower energy efficiency. To deal with sudden demand condition, parallel module is likely to be used for energy management (Azib et al. 2009). According to the case study, parallel module can reduce battery stress with peak current (Transient) during charging and discharging stages. However, authors have told that the best way to utilise supercapacitor bank is to control energy protocol through converter. This activity may reduce transient at initial stage (Pay et al. 2003). During sudden demand, the sudden changes of current can result in low energy efficiency of batteries. Batteries and supercapacitors could be damaged as well. Besides, (Thounthong et al. 2005) said that supercapacitor provides energy to load for compensating lack energy by main sources (Batteries). In steady state, there is no much difference because it has already in the normal stage even though happen in discharging or charging modes.

2.2 Methods of Simulating and Modelling Supercapacitor

There are several types of methods for simulating and modelling supercapacitors. The methods have their own pros and cons due to the behaviour, charge and discharge conditions of supercapacitors. Various simulation methods have own algorithms to prove that methods could be implemented in order to perform simulation of supercapacitor. Various simulation tools have been studied and they are categorized as MATLAB withfuzzy logic, LabVIEW, MATLAB Simulink, PLECS (Piecewise Linear Electrical Circuit Simulation), PSCAD (Power

System Computer Aided Design) methods. In conclusion, these methods are categorized into each group for literature review commenting.

2.2.1 MATLAB with Fuzzy Logic

According to the literature study, (Yanzi & Wang 2014) have suggested that this new topology increases the efficiency and power rating of converter. In this paper, fuzzy logic helps to calculate the power distribution of supercapacitor. (Fărcaş et al. 2009) has stated that fuzzy logic is useful in non-linear system especially energy management, efficiency of overall condition is improved. This method has improved the operation while modelling supercapcitors and battery.

(Fărcaş et al. 2009) have recommended that fuzzy logic can be implemented in Simulink. In the Simulink model, relay is added to perform prevention of high voltage goes across the supercapacitor. A resistance is created to balance the overall system. Next, In this literature study, power comes in, this shows that once the current flow capacitor is fully charge and discharge over time which current is stopped. Current, voltage and SOC (state of charge) is directly proportional. Furthermore, Observation of supercapacitor is fully observed by checking the graph (Voltage versus time), simulation result is performed as well. By using Simulink with fuzzy logic method, result is accurate compared to only Simulink program (Fărcaş et al. 2009). Fuzzy logic increases the performance measurement, efficiency, and also stabilizes the framework.

Next, (Gao et al. 2016) agreed that fuzzy logic is helpful when dealing with supercapacitor and energy storage system for electric vehicle. In this simulation program, fuzzy logic controller is added for splitting the power because it has to prevent high power goes across the overall circuit and avoid damage. Supercapacitor has higher power density and discharge condition (Gao et al. 2016). In this literature study, membership function is performed in this program while executing the simulation to improve stability of simulation (Talla et al. 2015).

2.2.2 LabVIEW

In this literature review, (Cultura A.B. 2015) has created own mathematical equation to perform simulation of supercapacitor energy units, voltage and current responses. In this journal, series resistance and parallel resistance are being used in experiment for making the comparsion of supercapacitor. In the experimental result, it shows the series resistance gives less energy loss to supercapacitor but better performance is obtained (Cultura A.B. 2015). Furthermore, mathematical equation and models of supercapacitor are implemented in LabVIEW software program. By using this method, LabVIEW can create voltage controller and sizing a supercapacitor (Cultura A.B. 2015).

According to the literature study, (Yin et al. 2014) have said that LabVIEW helps to simulate results of supercapacitor. By using this method, faster reaction is performed in real time but having slight affect due to high voltage and energy loss. As a result, dynamic current and load current have to be measured. These may affect the performance of control (Yin et al. 2014). ALD-based is also implemented with the LabVIEW to increase the efficiency and accuracy of simulation results. (Nedialkov et al. 2014) have agreed that supercapacitor is helpful in renewable energy. Thus, battery is set as buffer and supercapacitor acts as converter. In the software program, these two assumptions can be suggested to create Simulink models.

In conclusion, LabVIEW has more advantages which are graphical programming interface increase flexibility on programming and understanding algorithm/code flow structure and VISA read/write to communicate instrument and perform data acquisition easily.

2.2.3 MATLAB Simulink

Based on this journal, (Karangia et al. 2013) have stated that MATLAB improves the efficiency while simulating the behaviour of supercapacitor. According to graphs (Voltage versus time), the voltage decreases slowly as supercapacitor discharges along time. Authors have discussed about the internal resistance as well. By making comparison with other journals, authors have found out the importance of internal resistance (Karangia et al. 2013). Furthermore, (Yanzi & Wang 2014) have agreed with the previous statement. MATLAB performs better result for the feasibility of simulation program.

(Logerais et al. 2015) have done simulation by using MATLAB Simulink. Data acquisition is used in conditions of charging and discharging. Authors have found out that resistance is better to be implemented in a circuit. To measure the correct voltage level of supercapacitor, resistor is necessary to be used (Logerais et al. 2015). Other than that, (Barua et al. 2015) agreed with the previous statement which is adding the internal resistance in parallel circuit. Anyhow, (Jinrui et al. 2006) said that supercapacitor can provide large power at short time, and the discharge rate will also be faster when no more voltage supplied. Besides, (Du 2009) has agreed the circuit design where resistor is added in the parallel circuit (Resistors add before the supercapacitors).

2.2.4 PLECS

In this journal, (Schönberger 2010) mentioned that long-term leakage effect is totally neglected because of the transient simulation. Author has used the PLECS software with MATLAB, linmod function (Linearizing model) has applied for extracting the model to search the current pulse at the beginning. Once it has reached steady state, then it becomes stable. Next,frequency response is required in order to find the pulses of supercapacitor. Frequency response has two components which are real and imaginary components. Based on these two components, signal capacitance will be increased as frequency increases (Schönberger 2010). (Gualous et al. 2011) are agreed with previous author as impedance of real and imaginary components may measure the supercapacitor value. As a result, the internal resistance losses can be helpful during simulating the supercapacitor energy unit.

2.2.5 PSCAD

According to the journal, (Zheng et al. 2015) have stated that this software improves the transient quality of overall system. When the system has transient, supercapacitor values will be unstable at the beginning. By using this method, it may help to reduce the instability while doing simulation. Next, errors between data and output model are obtained. Load data must be varied correctly in the program in order to prevent temperature effect of supercapacitor occurs. In another literature study, it has mentioned that temperature does affect the voltage and current levels of supercapacitor. Besides, load peak is decreased until steady state as state of change decreases. (Wu et al. 2013) is strongly recommended buffer mode is helpful to apply in simulation program.

2.3 Comparisons of Simulation Software

All the software programs have been studied. Table 2.3 shows the comparisons, pros and cons of various types of software programs.

Table 2.3: Comparisons of simulation software

Software	Advantages	Disadvantages
MATLAB Simulink With Fuzzy Logic	-Accurate mathematical model while applying to non-linear system	-Hard to withstand high power if connects with hardware (In real time)
LabVIEW	-Good for development and debugging - Readily build graphical user interface (GUI) for data reading	-Graphical programming is totally different compared to text based programming
MATLAB Simulink	-Large user base -Easier implementation of control algorithms	-Only mathematical modelling
PLECS (Piecewise Linear Electrical Circuit Simulation)	-Access to MATLAB directly -Has modeling simulation	-Different functions as MATLAB to simulate results -Not user friendly
PSCAD (Power System Computer Aided Design)	-Good at editing schematic	-Information is not complete -Not suitable to create models

2.4 Summary

In this chapter, the research has conducted on methods, techniques and applications. According to the case studies, further investigation need to be carried out for identifying the differences between different load sides such as heavy load, high power demand, low power demand, sudden demand and steady state. As a result, components of HESS are used to enhance the performance, reduce lifespan of batteries and solve the peak power demand issues for electric vehicle. Based on the journals, the simulation methods, performance of parameters are studied as well. According to the methods, they have their own pros and cons while locating faults. As a result, MATLAB software will be chosen in this project because it is user friendly, large user base, create Simulink model perfectly and simulate program easily. Next, some literature studies on power demand have conducted in the previous section.

CHAPTER 3

METHODOLOGY

3.1 Overall View of Proposed HESS (Hardware)

This section is used to determine the operating profile and discharging profile when the battery is connected with/without supercapacitor. The purpose is to investigate the difference and behaviours of supercapacitor during discharge condition. In Figure 3.1, it shows the overall view of proposed HESS. Battery is directly connected to load and oscilloscope. During discharge process, the power will be discharged while connecting to shunt resistors. In Figure 3.2, same components are used as the proposed HESS but supercapacitors module acts as the power supply and load for discharging process. In Figure 3.3, MATLAB Simulink is used to construct the design of including circuit diagram and scope label.

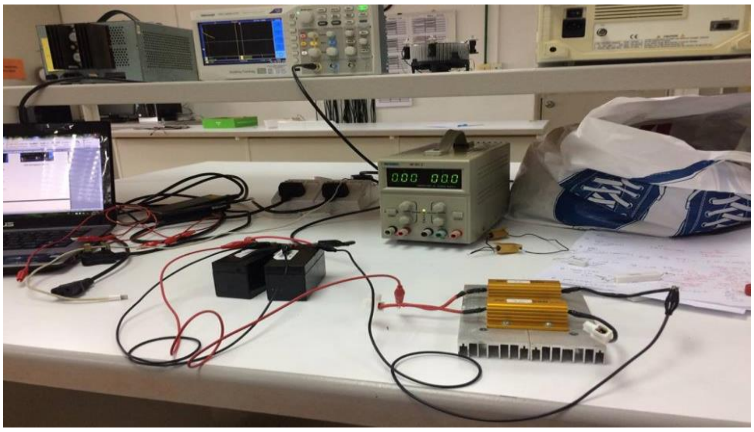

Figure 3.1: Overall view of proposed HESS (without supercapacitor)

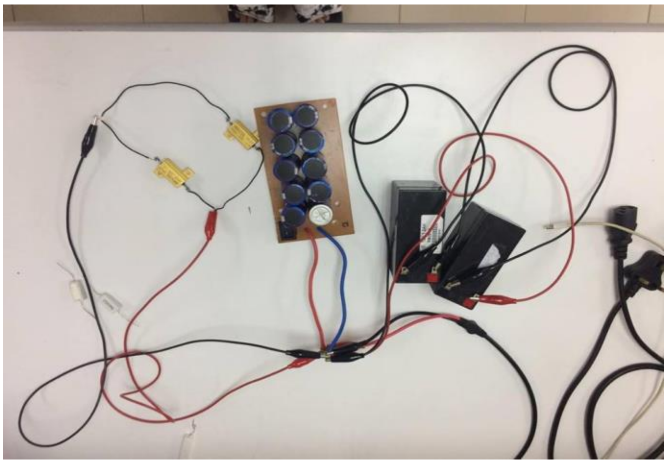

Figure 3.2: Overall view of proposed HESS (with supercapacitor)

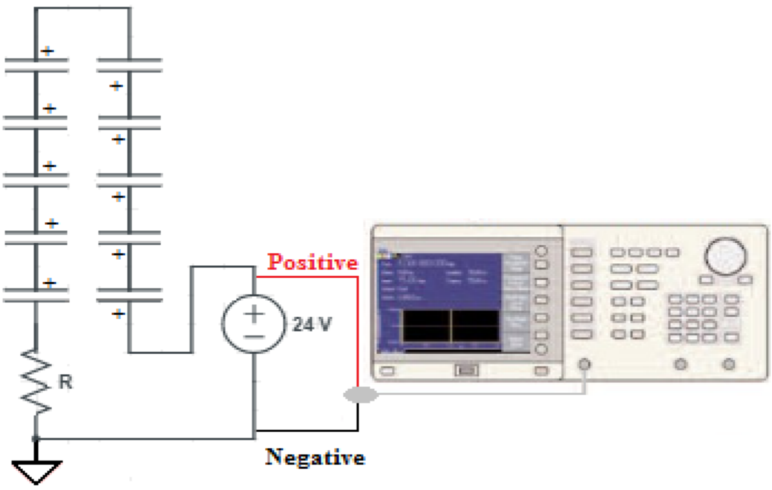

Figure 3.3: Overall design of proposed HESS

3.2 The Design of HESS (Hardware)

In this project, the main problem is about the short power limit of charging and discharging. Battery pack is a concern because it's the main component for electric vehicle. This kind of energy storage system is important for protecting the battery packs from overheating or its lifespan decayed during the peak demand power is required. In the experiment, the configurations will be categorised into low load, heavy load, steady state, heavy load via peak and sudden demand. Each case from all cases represents each category of testing behaviour of supercapacitor. Cases 1, 2, 3, 4 and 5 (series modules of supercapacitor) will be represented in the category respectively but tested in series module. Besides, cases 6, 7, 8, 9 and 10 (parallel modules of supercapacitor) will be represented in the categories respectively but tested in parallel module. Thus, results will be shown in chapter 4.

For the supercapacitors module in series connection, this consists of 10 units to achieve a required voltage level. For experiment of series module, the required voltage level is set as 12 V to 26.1 V. While for the experiment of parallel module, the voltage level is 2.2 V to 2.65 V. Next, the battery packs are connected to the supercapacitor module with load. At the load, the loads are categorised into four groups such as heavy load, light load, sudden demand and typical stage. At heavy load, the load has higher resistance and power rating. For light load, the power rating is high but low resistance value. For sudden demand, the load is added accordingly until it reaches a limit. Lastly, typical stage is the period where it shows the steady state after transient part. Furthermore, the discharging and charging conditions are connected to oscilloscope through probes in order to see the behaviours of supercapacitor. While for the parallel module, the procedures are the same as series module. The proposed HESS is shown in Figure 3.4.

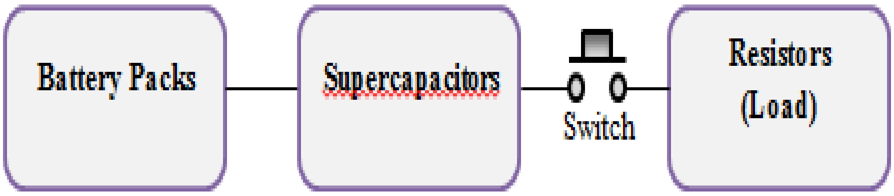

Figure 3.4: Block diagram of proposed HESS

3.2.1 Battery Packs

In electric vehicle, battery packs provides power to the electric motor. In this project, sealed lead-acid battery is the main source that will be used in the experiments. Therefore, 2 batteries with a rating of 12 Volts are used in experiments such as 12 V and 24 V configurations while the battery can supply energy to load continuously. In order to achieve higher voltage level, the batteries are connected in series so that the voltage is increased. When the voltage is higher, the experiment of supercapacitor can be investigated during a process while discharging to a load. In this experiment, the operating voltage is scaled down to minimum 24 V.

For series module, the operating voltage is around 24 V. It operates heavy and on light loads. Heavy load can be defined as load which can draw high current. On the other hand, fan can be the example of light load. The proposed battery packs model is shown as Figure 3.5.

Figure 3.5: Sealed lead acid battery

3.2.2 Supercapacitors

In the experiment, 10 units of supercapacitor units are used in both series module and parallel module. The specification of the supercapacitors will be chosen as the 100 F, 2.7 V. In this project, there is configuration that will be used in experiment purposes. 10 units are connected in series module. Each of them consists of 2.7 V so 10 set of the supercapacitors connected in series to achieve 27 V in one module. Next, 10 supercapacitors are connected in parallel module. 10 pieces of supercapacitors are connected in parallel, can be used to achieve 2.7 V but having higher current rating during charging and discharging.

Figure 3.6 shows a sample of supercapacitor with a voltage level of 2.7 V, and a capacity of 100 F that is used in hardware testing. Figure 3.7 and Figure 3.8 show the schematic diagram of the module with 10 units of supercapacitors connected in series and parallel respectively. Besides, supercapacitor has its own leakage current. It has higher charging and discharging characteristics as well. Thus, it is dangerous if the safety issue is not protected and concerned. Due to the safety issue, a manual switch is connected to the positive terminal of every supercapacitors and negative terminal respectively. Lastly, Figure 3.9 and 3.10 show the circuits of module with 10 units of supercapacitors connected in series and parallel respectively. Then the components are same but the solder connection is different.

Figure 3.6: Supercapacitor

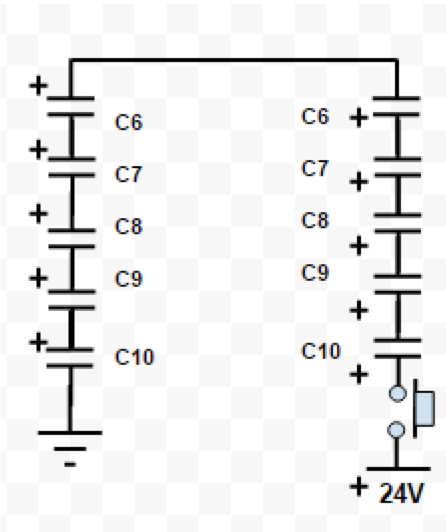

Figure 3.7: The connection of the supercapacitor in series module

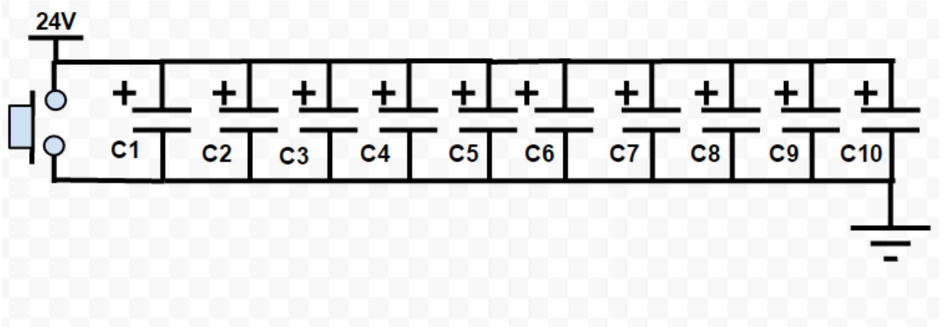

Figure 3.8: The connection of the supercapacitor in parallel module

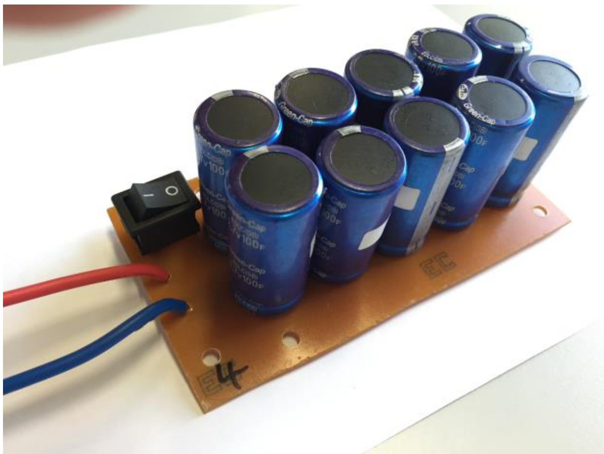

Figure 3.9: The supercapacitor in series module

Figure 3.10: The supercapacitor in parallel module

3.2.3 Shunt Resistors

In this research, shunt resistors are used to represent the experimental loads. During discharge condition, it can cause high power consumption because the connected loads draw high current. The power is increased if the resistors are connected in parallel module. With the appropriate heat sink, it maintains the interior temperature which minimises the current usage. Besides, a few cases of power demands are investigated and validated. For first condition (Heavy load), the loads draw high current so the power rating is increased accordingly. In order to see its behaviour of discharging, the connections of resistors must be correct. Next, light load can be defined as cooling fan because the operating voltage of the fan is 12 V. Next, sudden demand is discussed in this research. Sudden demand means how current has been drawn, which depends on the loads connected. It can be the case of increasing loads suddenly. The models of shunt resistors are shown in Figure 3.11.

Furthermore, the loads are tested under different configurations such as high power demand, low power demand, steady state and sudden demand. Hence, the resistors are categorized under different demands so that each resistor has its own power rating and resistance value. For low power demand, a single unit of 25 W, 22 Ω resistor is used in experiment. Next, experiment of high power demand is also carried out. 2 units of 25 W, 22 Ω are connected in series module so that resistance is reduced and current is increased. Other than that, 1 unit of 80 W, 7 Ω resistor is used as experimental elements under investigation of steady state demand. 10 W, 1 Ω represents the high demand as well. This test is to investigate the maximum stress of discharging rate while power is supplied to the overall circuit via resistor. Lastly, all resistors are used accordingly to carry out the test of sudden demand. The specifications of shunt resistors are show in Table 3.1.

Figure 3.11: Shunt resistors

Table 3.1: Specifications of shunt resistors

Withstand Power (W)	Resistance (Ω)
1	22
5	22
10	1
10	22
25	22
80	7

3.3 Design of MATLAB Simulink (Software)

In this research, practical and simulation results are compared to see their difference of discharging rate from the transient to steady state. In this section, the MATLAB Simulink model is designed and the flow chart is being introduced to explain the procedures. However, supercapacitors are required monitoring and protection. During discharging condition, this Simulink model tracks and monitors the behaviour of supercapacitor.

Simulink model is used to support the case study especially the measurement of supercapacitor. For hardware, the experiments are harder to achieve target due to lots of noises and high frequency. With the help of software, the results can be investigated and the factors can be found out. Hence, software is needed for monitoring the behaviour of supercpacitor during high demand, low demand, sudden demand and steady stage.

3.3.1 Project Overview (Software)

Figure 3.12 shows the project overview of running MATLAB Simulink software to obtain experimental results. Firstly, the pulse signals will be generated if the MATLAB Simulink starts to run the program. Next, switch is used to turn ON/OFF to operate the modes of discharging charging state. The modes are set as ON/OFF modes, charge and discharge. DC voltage source will be suppied to charge the supercapacitor modules in series or parallel. When the battery is fully charged, the battery is started to discharge where connects with supercapacitor and without supercapacitor. The graphs will be shown after the program is complete. Lastly, the simulation results are compared with practical results.

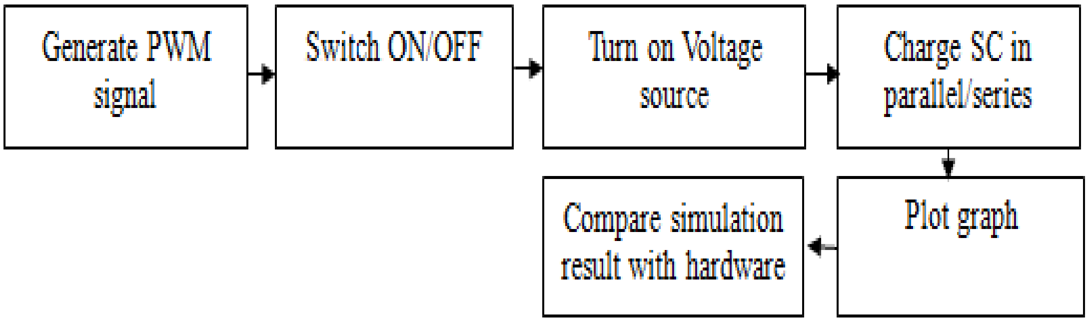

Figure 3.12: Project overview (software)

3.3.2 Flow Chart of Proposed HESS (Software)

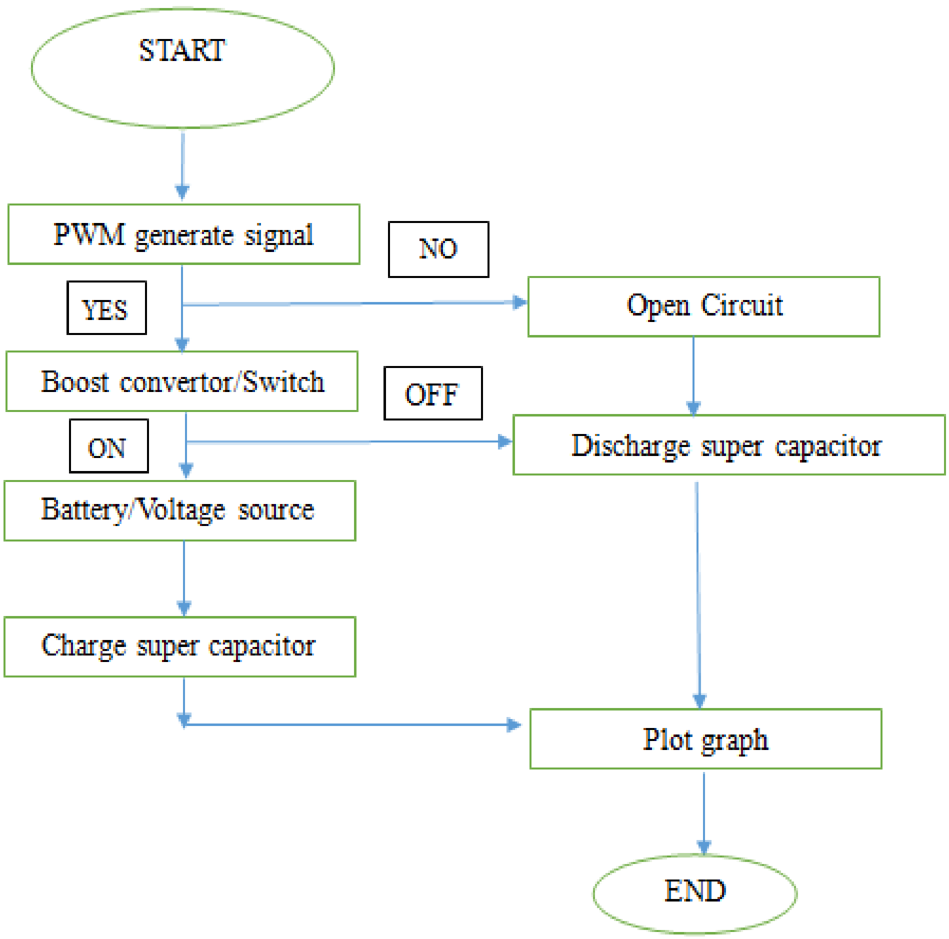

Figure 3.13: Flow chart of proposed HESS (Software)

According to Figure 3.13, this figure explains the flow of overall design. When the signal is received, battery is charged by power supply. Thus, battery may charge the supercapacitor until a certain limit. The limit depends on the battery capacity, maximum limit goes up to 100 % and the minimum value is at least 90 %. Besides, the current demand, voltage and State of Charge (SOC) will be measured and graphs are performed accordingly. At last, the simulation results obtained are used to compare with practical results.

3.3.3 Simulation of Supercapacitor

In MATLAB Simulink, supercapacitor is used to perform simulation of its performance during charge and discharge conditions. It can be used in series capacitance or parallel upon the desire design. The proposed simulation model is shown in Figure 3.14.

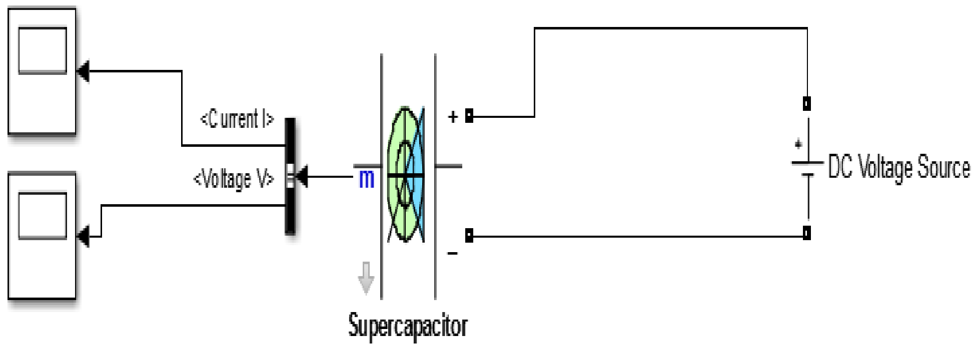

Figure 3.14: Simulation of supercapacitor

3.3.4 MATLAB Simulink (Without Battery)

In MATLAB Simulink, supercapacitors act as low pass filter. For smoothen purpose, it can filter the transient until steady state during the discharge condition. Besides, mosfet is used for the purpose of switching to simulate the charge and discharge control by PWM signal to ON or OFF the circuit. DC voltage supplies voltage to the capapacitor when it is at charging condition. When the pulse generates a “YES”, it generates “ON” where it allows flowing through mosfet. Thus, it is enabling current to flow through the charging state. Once the pulse generates "OFF", the system will trigger the switch to be turned off. The proposed design of Simulink model is shown as Figure 3.15.

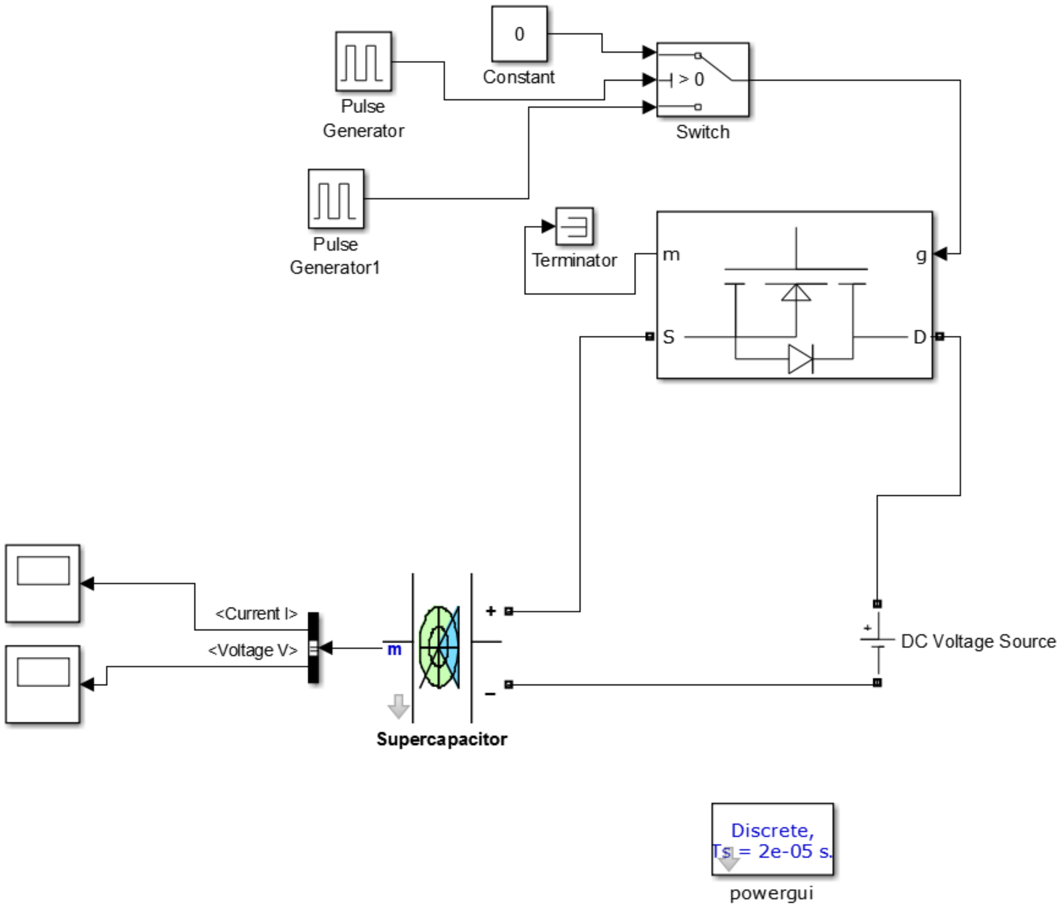

Figure 3.15: MATLAB simulink (without battery)

3.3.5 Design of Boost Converter

According to Figure 3.16, a switch is designed by using PID controller method. This boost converter is controlled by pulse width modulator, so the current flow can be turned on and off. If the circuit receives signal of "YES", MOSFET is turned on and it enables the current flows through from power source to supercapacitor in an open circuit. Hence, PID controller is used to control the wave signal to have a stable constant waveform of charge and discharge. Lastly, the proposed of boost converter/ switch is shown in Figure 3.16.

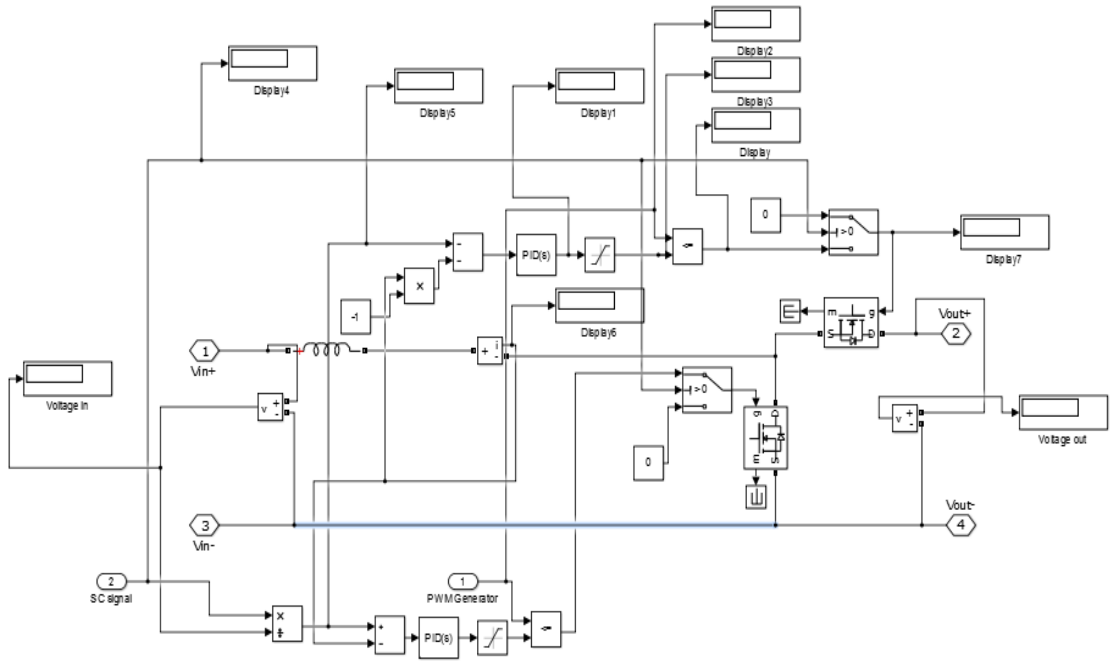

Figure 3.16: Design of boost converter

3.3.6 Overall Design of HESS

Based on the Figure 3.17, supercapacitor is connected to boost convertor/switch. Battery is also connected to boost convertor. Both circuits are connected to voltage power supply. Firstly, the power supply gives power to charge the battery. During the discharge conditions, the battery may discharge through a supercapacitor so the current demand will be smoothen. Furthermore, this simulation is compared between the charge and discharge conditions of supercapacitor, along with battery performance. The switch is triggered by pulse width modulation to switch on the both circuits. When boost convertor is “ON”, the supercapacitor is on charging state (Series and parallel are likely depending on the desire supercapacitor configurations). Voltage is set as 24 V and 12 V for this simulation.

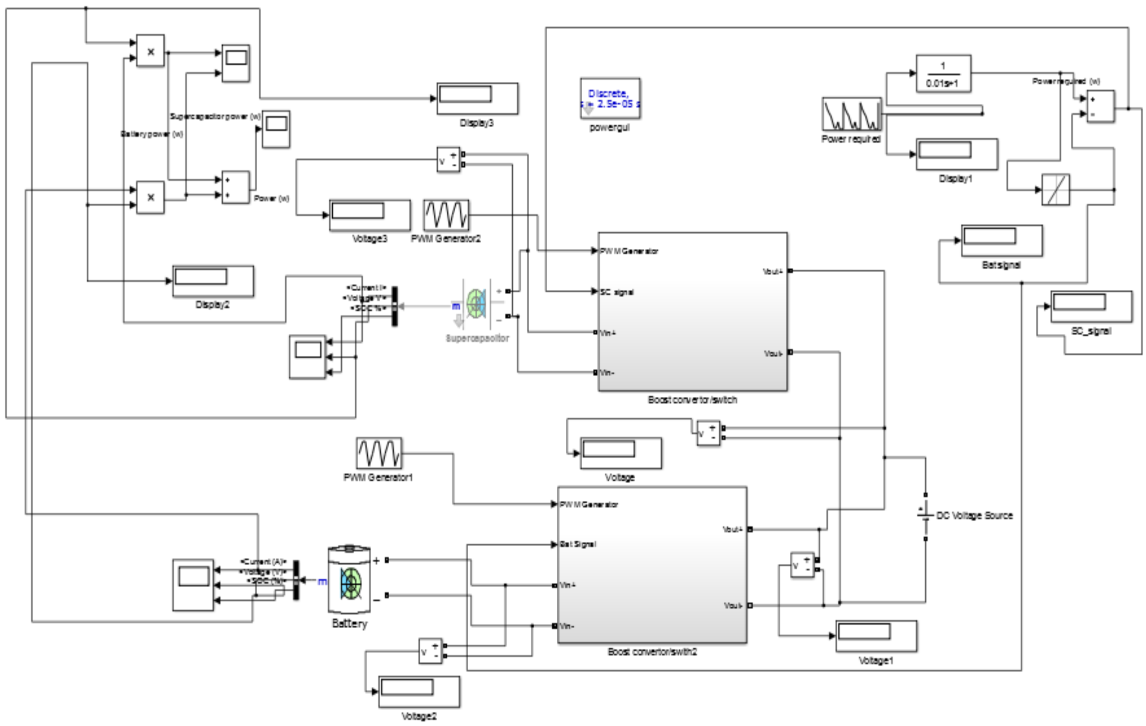

Figure 3.17: Overall design of HESS

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Behaviours of Supercapacitor

Supercapacitor is a common component which is used in electric vehicle. It has higher power density to store energy; it has higher power to discharge and charge. In this chapter, the behaviours of supercapacitor during discharging process are studied and investigated. The basic introduction of supercapacitor is briefly explained as well.

4.1.1 Charging Condition of Supercapacitor

For the charging process, 24 V lead acid battery, supercapacitor module and shunt resistors are connected and tested in experiments. During charging process, the current is higher so shunt resistors are used to limit the current flowing into the other components. Throughout the experiment of charging process, the current spikes and then battery will be charged slowly afterwards. When the switch of supercapacitor module is turned on, the transient happens and causes the high current level at the moment. Anyhow, the current will be slowly supplied to charge the battery until steady state. Next, higher current can increase the speed of fully charging the battery.

Due to steady state of supercapacitor, current is decreased after the initial moment where transient happens during charging condition. However, initial charging of supercapacitor is increasing slowly if low saturation of charges, it increases the voltage level during charging process.

4.1.2 Discharging Condition of Supercapacitor

For discharging process, supercapacitor is used as main power and shunt resistors act as load. In the next section, the results will be discussed and observed in different categories. In this project, the behaviour of supercapacitor and transient behaviours are discussed in the next section.

4.2 System Design in Series Module (Discharge Condition)

This section is used to determine the difference of with/without supercapacitor during discharging process. 24 V batteries, supercapacitor in series module and different loads are carried out in the experiments. For series module, the voltage capacity of supercapacitor can obtain around 26 V. Due to tolerance, the voltage source has affected around that charging capacity. Besides, the time scale and amplitude scale of oscilloscope are set as 25 ms and 5 V respectively. The loads are categorised into five cases which consider case 1 of low load demand, case 2 of heavy load demand, case 3 of steady state demand, case 4 of heavy load via peak and case 5 of sudden demand. In this part, process of discharge is fully investigated and studied. The works are done based on case studies and experiments. In Figure 4.1, it shows the circuit diagram to perform the experimental case studies of series module. Thus, the results of the system are shown as next section.

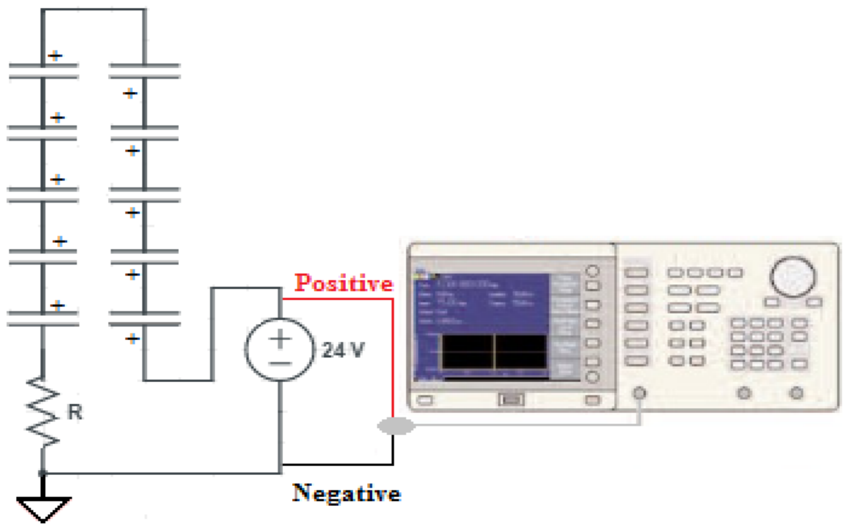

Figure 4.1: Experimental setup of series module

4.2.1 Case 1: Series Module using 25 W, 22 Ω

In this experiment, low load demand is being investigated during the discharging condition. The 25 W, 22 Ω resistor is used as load. In Figure 4.2, battery is charged until a certain operating voltage and starts to discharge while connection to the load. In Figure 4.3, battery is charged until a certain limit; while supercapacitor is being charged and starts discharging to the load.

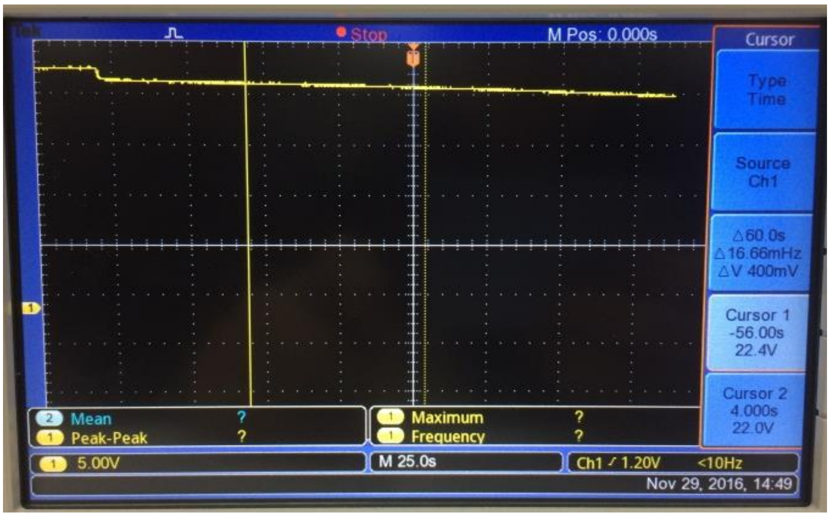

Figure 4.2: Discharging process of case 1 (without supercapacitor)

Figure 4.3: Discharging process of case 1 (with supercapacitor)

Based on the Figure 4.2 and Figure 4.3,

Average initial voltage = 22.0 V,

R_{eff} = 22 Ω,

Current = (22V/22Ω) = 1 A,

Heat loss on resistor, $P = I^2R = 1^2 (22) = 22$ W

In this experiment, 25 W, 22 Ω is used as load for discharging process. According to the calculations, the heat loss and current rating are lower than the specifications of required load so this load is categorised as light load. Besides, the discharging rate is slightly slower than other demands so this case is categorised into low power demand.

Based on the result in Figure 4.2, the transient state is appeared after the voltage source is being supplied. The sudden drop is happened after the discharging process is operated. When the switch is turned on, the current isn't appeared to discharge the load at a constant value at the initial state. At the beginning, the battery is discharged to a load in a "new state" than earlier. Hence, the operation needs to reach another new steady state then it can only start to discharge after the sudden drop. Besides, the battery discharges slowly without supercapacitor.

In Figure 4.3, the discharging rate is faster as voltage source decreases gradually. Discharging rate is faster as the higher power is supplied during discharging process. The current is decreasing while voltage decreases in supercapacitor. In this process, battery has the same energy density because the battery is not fully discharged. With help of supercapacitor, battery is able to supply more energy in specific timeframe. On the other hand, transient is appeared at higher state if the power required is higher. Thus, the initial state is not stable either. Based on results in Figures 4.2 and 4.3, the oscilloscope shows the result of discharging 13.4 V in 99 seconds. Due to this is a transient graph instead of linear graph, so the timing of average discharging time can't be calculated perfectly. Hence, the 6.8 V is not discharged at the complete value during discharging. As a result, voltage is decreasing gradually and the waveform becomes smoother if supercapacitor is connected.

4.2.2 Case 2: Series Module using Two Resistors of 25 W, 22 Ω

In this case, two resistors of 25 W, 22 Ω are used and connected in series module. These resistors values are used which represent the condition of high power demand. The current and power ratings have exceeded the limit of resistors' specifications. In Figure 4.4, battery is charged until a certain operating voltage and starts discharging. In Figure 4.5, battery is charged until a certain limit; while supercapacitor is being charged and starts discharging to the load.

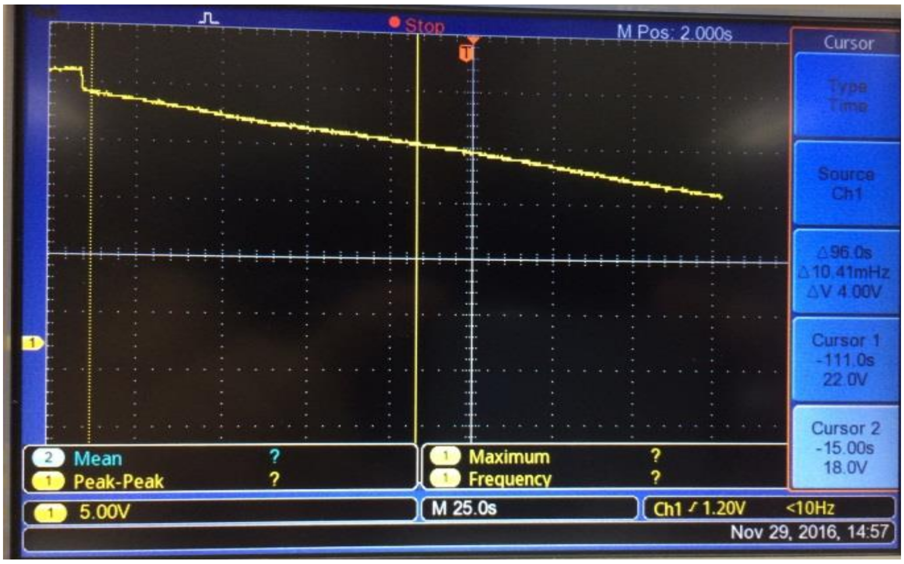

Figure 4.4: Discharging process of case 2 (without supercapacitor)

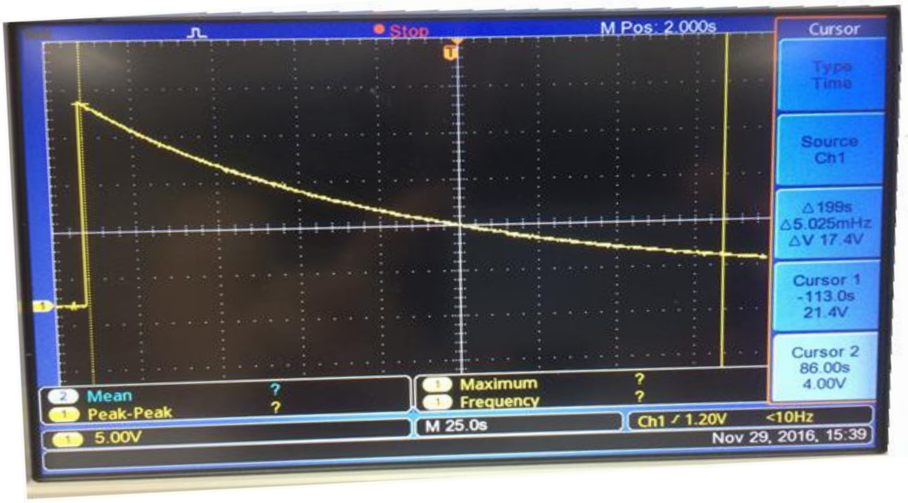

Figure 4.5: Discharging process of case 2 (with supercapacitor)

Based on the Figure 4.4 and Figure 4.5,

Average initial voltage = 22.0 V,

R_{eff} = 11 Ω,

Current = (22V/22Ω) = 2 A,

Heat loss on resistor, $P = I^2R = 2^2 (22) = 88$ W

Based on the result in Figure 4.4, the transient state is appeared after the voltage source is being supplied. The battery is reducing linearly as the higher power ratings and currents are being supplied. As a result, battery consumes more power to discharge if the load is considered as high power demand.

According to the Figure 4.5, the waveform is decreasing gradually with the help of supercapacitor. Supercapacitor smoothens the ripple voltage throughout the process of discharging. Battery is able to supply more energy in specific timeframe. On the other hand, transient is appeared at higher state if the power required is higher.

Thus, the initial state is not stable either. Based on results in Figures, the oscilloscope shows the time base of discharging where it is faster to discharge with the help of supercapacitor. It only needs 86 seconds to discharge until 4 V. In the energy discharge mode, supercapacitor fed more energy demand. Thus, discharging rate is getting faster. Besides, with the help of supercapacitor, the voltage drops more and the waveform becomes smoother.

As a result, the transient spikes to the peak and then starts discharging. The supercapacitors and resistors are getting hotter because of higher power and current ratings supplied into loads.

4.2.3 Case 3: Series Module with 80 W, 7 Ω

A resistor of 80 W, 7 Ω is used and represented in the steady state demand. The power rating and current demand are higher based on the calculation. Thus, the discharging rate is also faster. The experimental results are shown in Figure 4.6 and Figure 4.7.

Figure 4.6: Discharging process of case 3 (without supercapacitor)

Figure 4.7: Discharging process of case 3 (with supercapacitor)

Based on the Figure 4.6 and Figure 4.7,

Average initial voltage = 22.0 V,

R_{eff} = 7 Ω,

Current = (22V/22Ω) = 3.1428 A,

Heat loss on resistor, $P = I^2R = 3.1428^2 (7) = 69.14$ W

Based on the result in Figure 4.6, the transient state is appeared after the voltage source is being supplied. The battery is reducing linearly as the higher power ratings and currents are being supplied. Hence, it needs 90 seconds to discharge from 23 V to 6 V.

In Figure 4.7, the discharging rate is faster as voltage source decreases gradually. Discharging rate is faster as the higher power is supplied during discharging process. The current is decreasing while voltage decreases in supercapacitor. In this process, battery has the same energy density because the battery is not fully discharged. With help of supercapacitor, battery is able to supply more energy in specific timeframe. On the other hand, transient is appeared at higher state if the power required is higher. Thus, the initial state is not stable either. Based on the results, it needs only 94 seconds to discharge the battery until 1.8 V. As a result, lower resistance value increases the speed of discharging rate. The waveform becomes smoother while discharging with the supercapacitor.

4.2.4 Case 4: Series Module with 10 W, 1 Ω

In this case, the power rating and current demand are the highest amongst all loads. Resistor value is 10 W, 1 Ω and this case is represented as peak demand. The purpose is to investigate the limitation of loads and the discharging timing. In the experiment, the load is tested and stressed until the maximum limitation. The resistor can't withstand the power so the resistor is burnt. Hence, the discharging rate is extremely fast.

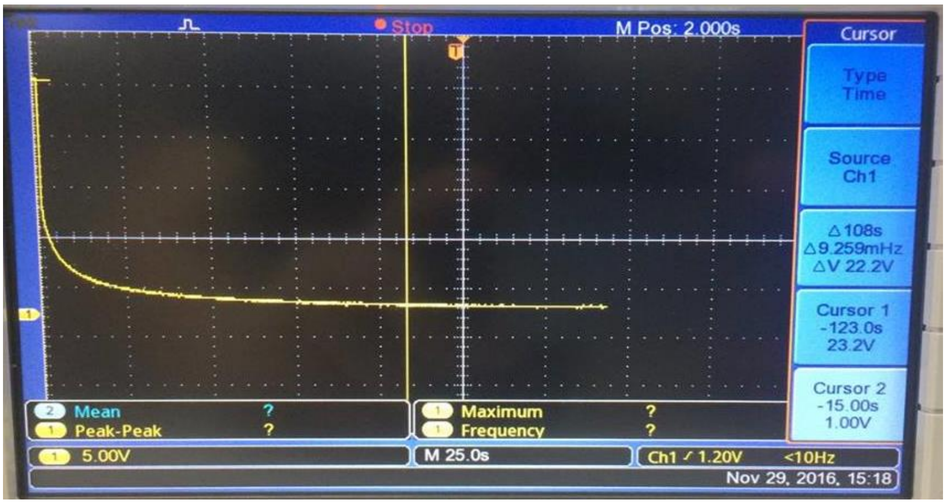

Figure 4.8: Discharging process of case 4 (without supercapacitor)

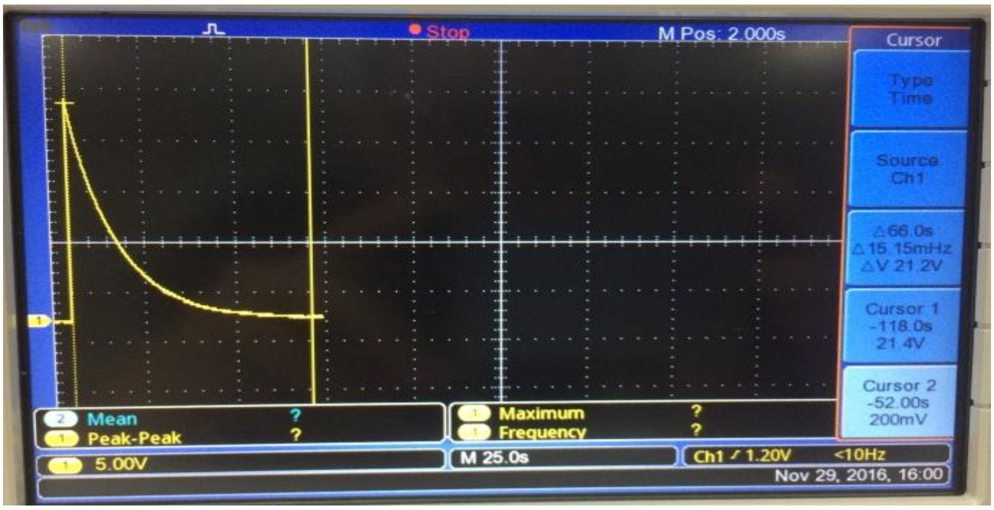

Figure 4.9: Discharging process of case 4 (with supercapacitor)

Based on the Figure 4.8 and Figure 4.9,

Average initial voltage = 22.0 V,

R_{eff} = 1 Ω,

Current = (22V/1Ω) = 22 A,

Heat loss on resistor, $P = I^2R = 22^2 (1) = 484$ W.

In Figure 4.8, battery is discharged without supercapacitor when connected to a load of 10 W, 1 Ω. In this result, it can conclude that higher power and current ratings increase the speed of discharging rate. In Figure 4.9, the discharging rate is much faster than others. The current is decreasing while voltage decreases in supercapacitor. In this process, battery has the same energy density because the battery is not fully discharged. With help of supercapacitor, battery is able to supply more energy in specific timeframe. On the other hand, transient is appeared at higher state if the power required is higher. Energy may be radiated away if battery is discharged to 0 V. As a conclusion, higher power causes the battery to discharge quickly. During discharging process, the internal resistance allows supercapacitor itself to provide high current to discharge. Therefore, the drawbacks to supercapacitor are much higher than battery so the energy stored of supercapacitor will be decreased.

4.2.5 Case 5: Sudden Demand Experiment in Series Module

In case 5, the loads are added after every 10 seconds. 25 W, 22 Ω is the first choice to discharge for the initial state. Next, 80 W, 7 Ω is added and the waveform performs faster discharging condition. Next, 10 W, 1 Ω is added and 5 W, 22 Ω is the last load to be discharged. Therefore, the results and discussion are discussed.

Figure 4.10: Discharging process of case 5 (without supercapacitor)

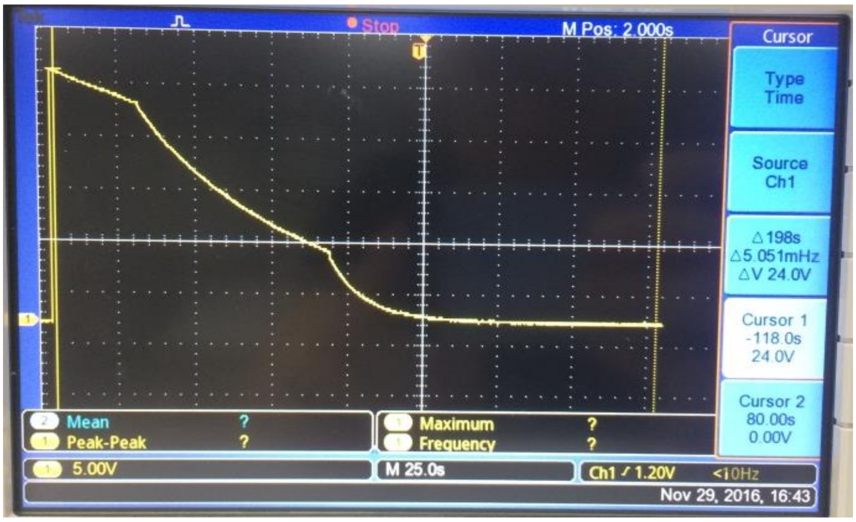

Figure 4.11: Discharging process of Case 5 (with supercapacitor)

According to Figure 4.10 and Figure 4.11, sudden changes in demand can be discharged as fast as possible but high power performs high probability in discharging efficiency. Discharging the battery with higher current can perform lower energy efficiency.

In Figure 4.10, the discharging rate is faster as voltage source decreases. Voltage is decreasing as lower resistance value is added during the experiment. The current is decreasing while voltage decreases in supercapacitor. In this process (Without supercapacitor), battery has the same energy density because the battery is not fully discharged. The sudden drop is happened after the discharging process is operated. When the switch is turned on, the current isn't appeared to discharge the load at a constant value at the initial state. At the steady state, it is much faster to reach the steady state at the end. On the contrary, battery has different power density as the battery is fully discharged in Figure 4.11. With help of supercapacitor, battery is able to supply more energy in specific timeframe.

Besides, transient is appeared at higher state if the power required is higher. Thus, the initial state is not stable either. With the help of supercapacitor; it needs only 80 seconds to discharge the battery until 0 V. As a result, lower resistance value increases the speed of discharging rate.

As a conclusion, sudden change in demand can discharge quickly during the process. Higher current results in low energy efficiency. The loss of internal resistance may affect the discharge rate as well. However, form of sudden changes will affect the waveform in order to rise or reduce.

4.3 System Design in Parallel Module (Discharge Condition)

This section is used to determine the difference of with/without supercapacitor during discharging process. 24 V batteries, supercapacitor in parallel module and different loads are carried out in the experiments. For parallel module, the voltage source can only reach maximum voltage of 2.7 V. The time scale and amplitude scale of oscilloscope are set as 25 ms and 5 V respectively. The loads are categorised into five cases which consider as case 6 of low load demand, case 7 of heavy load demand, case 8 of steady state demand, case 9 of heavy load via peak moment and case 10 of sudden demand. In this part, discharge process is fully investigated and studied. In Figure 4.12, it shows the experimental setup of parallel module. The overall circuit diagram is constructed. The works are done based on case studies. Thus, the results of the system are shown as next section.

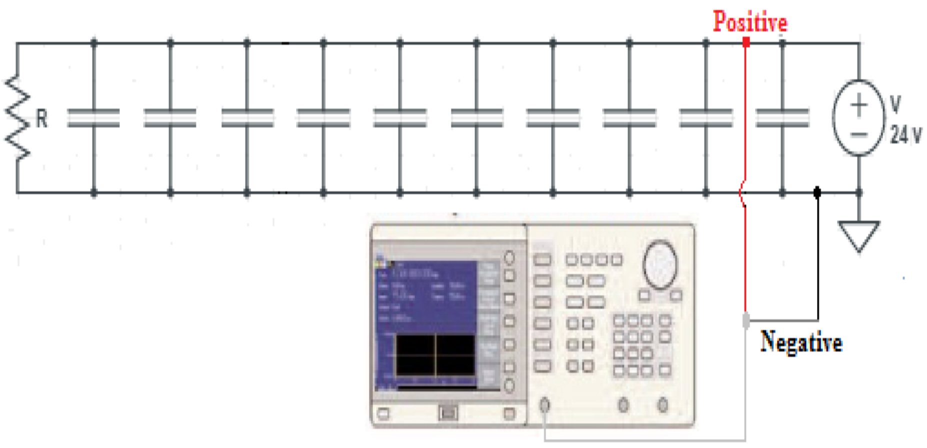

Figure 4.12: Experimental setup of parallel module

4.3.1 Case 6: Parallel Module with 25 W, 22 Ω

In case 6, the parallel module of supercapacitor is tested in the experiment. 25 W, 22 Ω resistor is used as low load. Some investigations are measured and validated. The discussion is shown in Figure 4.13 and Figure 4.14.

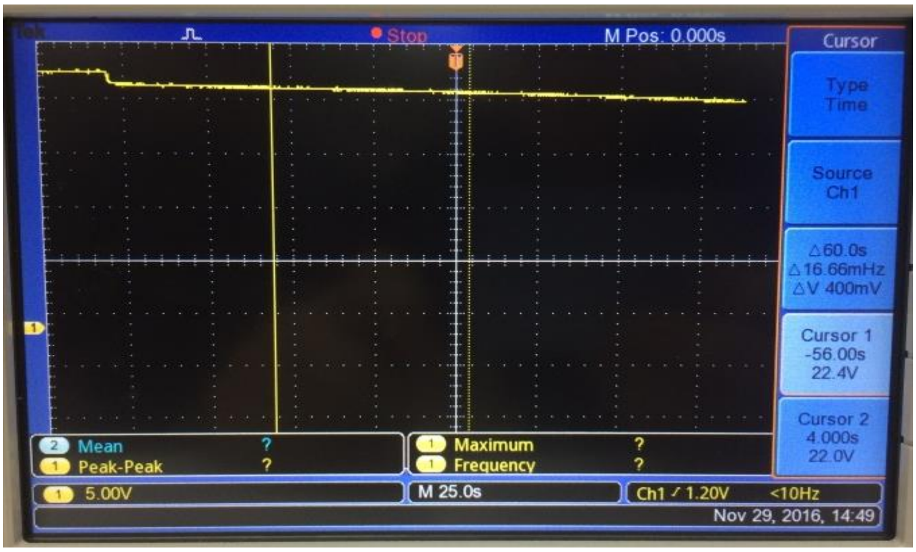

Figure 4.13: Discharging process of case 6 (without supercapacitor)

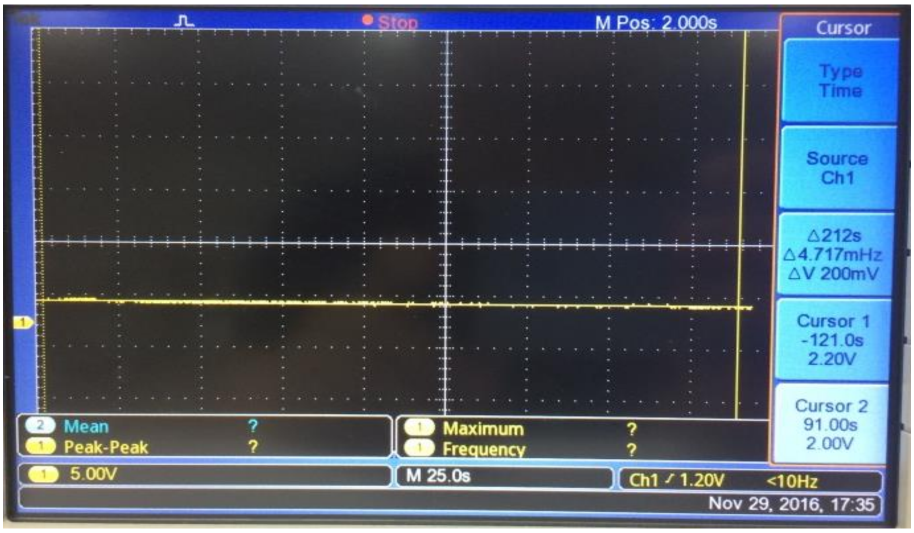

Figure 4.14: Discharging process of case 6 (with supercapacitor)

In Figure 4.13, the discharging process is much faster. The transient is appeared after the voltage source is supplied. The transient behaviour is appeared during the moment of ON/OFF. As a result, battery consumes more power to discharge if the load is considered as high power demand. In Figure 4.14, parallel module of supercapacitor discharges slowly even though it is connected with load. Parallel module maintains the SOC (State of Charge) to its performance. Hence, the discharging rate is extremely slow although the resistance value is low. As a result, longer discharging time is required during the discharging condition. The difference is not obvious but the voltage is decreasing slowly as oscilloscope results show. It has contributed to the behaviour as well. Thus, longer time taken to discharge a load as resistance value is lower.

4.3.2 Case 7: Parallel Module using Two Resistors of 25 W, 22 Ω

In case 7, two resistors of 25 W, 22 Ω are used and connected in parallel module. These resistors values are used which represent the condition of high power demand. The current and power ratings have exceeded the limit of resistors' specifications.

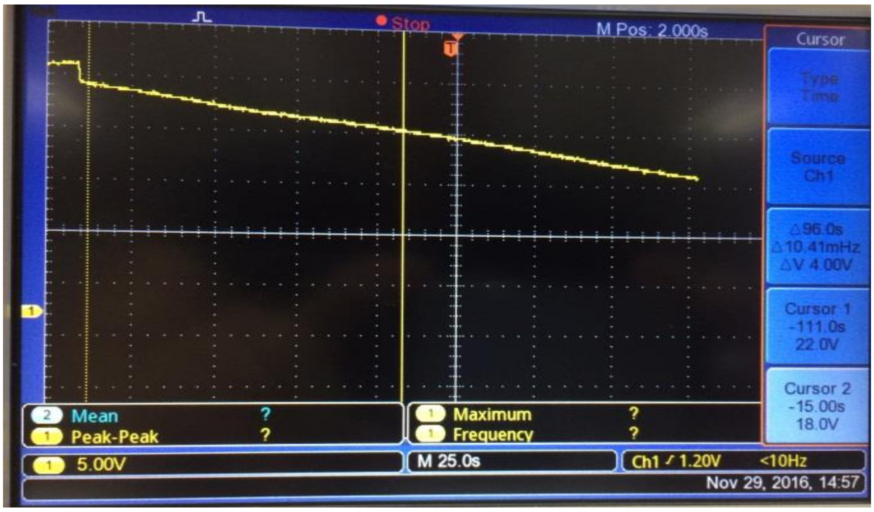

Figure 4.15: Discharging process of case 7 (without supercapacitor)

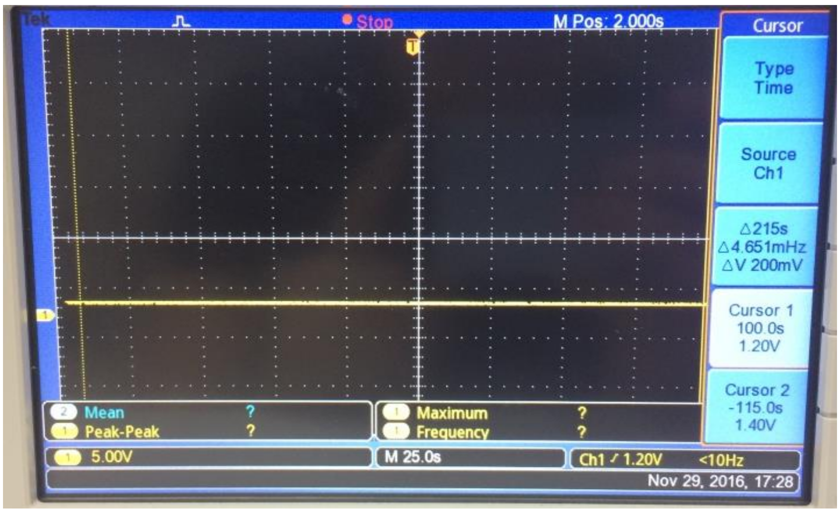

Figure 4.16: Discharging process of case 7 (with supercapacitor)

In Figure 4.15, the discharging process is faster. The transient is appeared after the voltage source is supplied. As a result, battery consumes more power to discharge if the load is considered as high power demand. However, parallel module of supercapacitor discharges slowly even though it is connected with load. Parallel module maintains the SOC (State of Charge) to its performance. Hence, the discharging rate is extremely slow although the resistance value is low. In this experiment, the power rating and current rating have already exceeded the limitation of resistors. Due to the help of supercapacitor in Figure 4.16, the discharging rate is slower and battery is not damaged. Next, the parallel module of supercapacitor is being charged and discharged all the time so the supercapacitor is hardly to be fully charged. The voltage is only started at 1.4 V. However, the discharging rate is slow as well. The peak power capability may be increased in the system. As a result, longer discharging time is required during the discharging condition. The difference is not obvious but the voltage is decreasing slowly as oscilloscope results show. It has contributed to the behaviour as well. Thus, longer time taken to discharge a load as resistance value is lower.

4.3.3 Case 8: Parallel Module with 80 W, 7 Ω

In this experiment, 1 resistor of 80W, 7 Ω is used and represented in the steady state demand. The experimental results are shown in Figure 4.17 and Figure 4.18.

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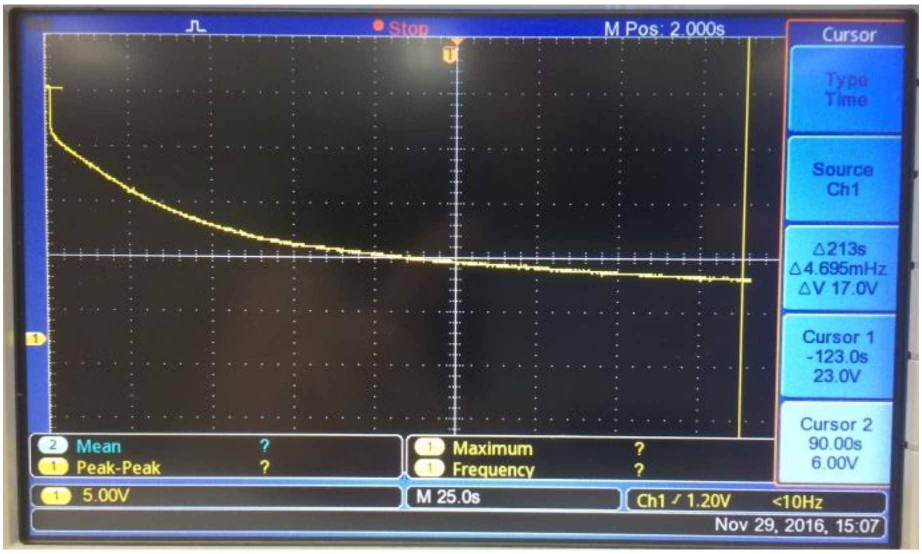

Figure 4.17: Discharging process of case 8 (without supercapacitor)

Figure 4.18: Discharging process of case 8 (with supercapacitor)

In Figure 4.17, the discharging process is faster. The battery consumes more power to discharge if the load's resistance value is lower. However, parallel module of supercapacitor discharges slowly even though it is connected with load. Hence, the discharging rate is extremely slow although the resistance value is low. In this experiment, the power rating and current rating have already exceeded the limitation of resistors. Due to the help of parallel module, the discharging rate is slower and battery is not damaged. Next, the parallel module of supercapacitor is being charged and discharged all the time so the supercapacitor is hardly to be fully charged. As a result, discharging rate is slow if the parallel module of supercapacitor is connected in a DC-DC converter circuit. The advantage of parallel module is the stability of power net voltage is higher during discharging process. As a result, longer discharging time is required during the discharging condition. The difference is not obvious but the voltage is decreasing slowly as oscilloscope results show. It has contributed to the behaviour as well. Thus, longer time taken to discharge a load as resistance value is lower.

4.3.4 Case 9: Experiment of Parallel Module with 10 W, 1 Ω

In this case, the power rating and current demand are the highest amongst all loads. Resistor value is 10 W, 1 Ω and this case is represented as peak demand. The purpose is to investigate the limitation of loads and the discharging timing. In the experiment, the load is tested and stressed until the maximum limitation. The results and discussions are discussed and shown in Figures 4.19 and 4.20.

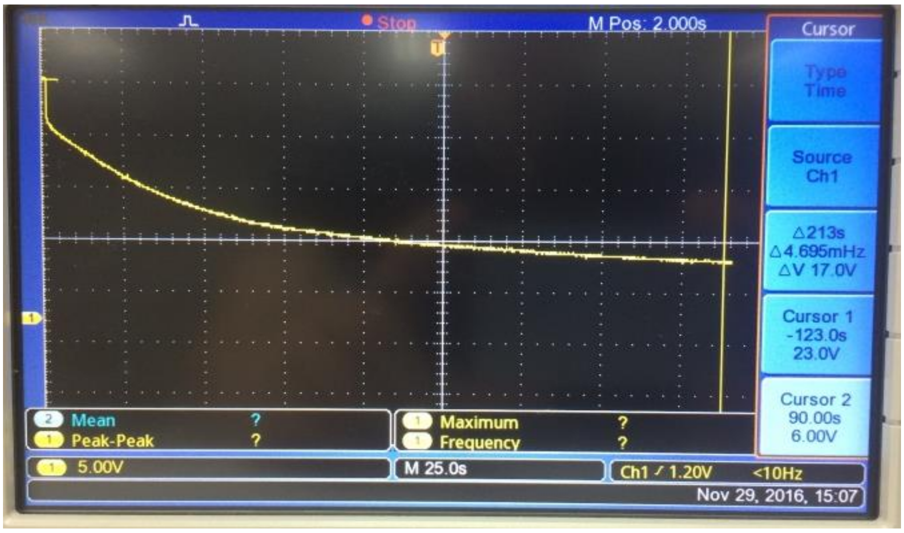

Figure 4.19: Discharging process of case 9 (without supercapacitor)

Figure 4.20: Discharging process of case 9 (with supercapacitor)

Without help of supercapacitor, the discharging process is faster. The battery consumes more power to discharge if the load's resistance value is lower. With the help of supercapacitor, it is discharging slowly when connected with supercapacitor and load. Compared to other cases, this case has higher discharging rate. Due to lower resistance value, the supercapacitor is discharged slightly faster. In this experiment, the power rating and current rating have already exceeded the limitation of resistors. As a result, parallel module helps to smooth out the output current. The longer time taken to discharge a load if the resistance value obtained is lower.

4.3.5 Case 10: Sudden Demand Experiment in Parallel Module

In final case, the loads are added after every 10 seconds. 25 W, 22 Ω is the first choice to discharge for the initial state. Next, 80 W, 7 Ω is added and the waveform performs faster discharging condition. Next, 10 W, 1 Ω is added and 5 W, 22 Ω is the last load to be discharged. Therefore, the results and discussion are discussed.

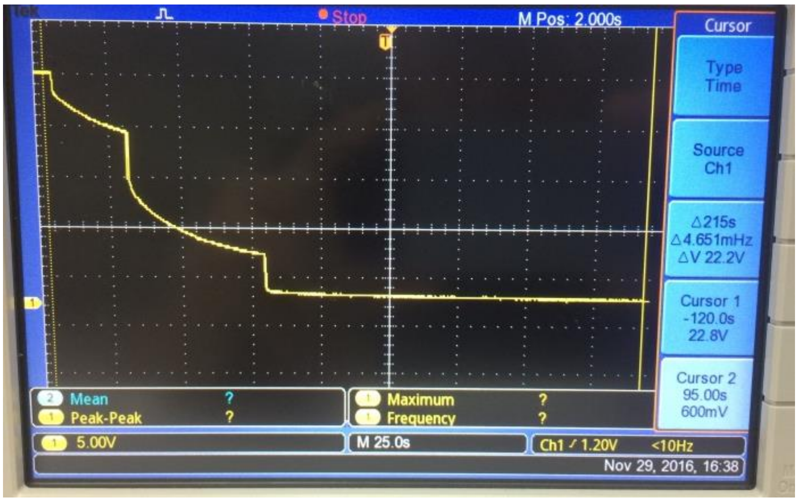

Figure 4.21: Discharging process of case 10 (without supercapacitor)

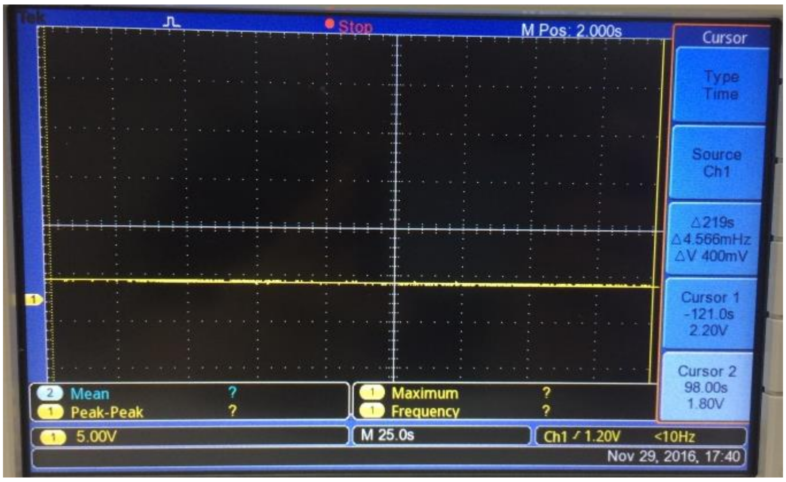

Figure 4.22: Discharging process of case 10 (with supercapacitor)

In Figure 4.21, it discharges even faster when the load is added up. The different resistance value changes the speed of discharging rate. Next, Figure 4.22 shows the stable result of discharging condition. At the end, the discharging rate is still slower. The benefit of parallel module can be stabilising the overall voltage output. . Thus, parallel module helps to smoothen the output current. As a result, longer discharging time is required during the discharging condition. The difference is not obvious but the voltage is decreasing slowly as oscilloscope results show. It has contributed to the behaviour as well. Thus, longer time taken to discharge a load as resistance value is lower.

4.4 Overall View of Proposed HESS (Software)

This part is used to determine the operating profile and discharging profile when the battery is connected with/without supercapacitor. The condition of battery is also measured and investigated. Besides, series and parallel modules of discharge condition are discussed in the next section.

4.4.1 Series Module of Supercapacitor (Discharge Condition)

In software part, PWM signal configuration in MATLAB Simulink is “0 0 1 1 -1 0” in order to see the changes of supercapacitor in each point. The operating voltage source is 24 V. In the Figure 4.23, this Simulink model is under investigation of series module. The setting has set as the series configuration. It also shows the scope locations where supercapacitor and battery are located. Scope 4 and scope 5 show the results of supercapacitor’s behaviour and battery’s behaviour respectively. In the simulation model, current, voltage and power are investigated and studied before compare the result with practical results. Hence, the discussion and results are shown in Figure 4.24 and Figure 4.25.

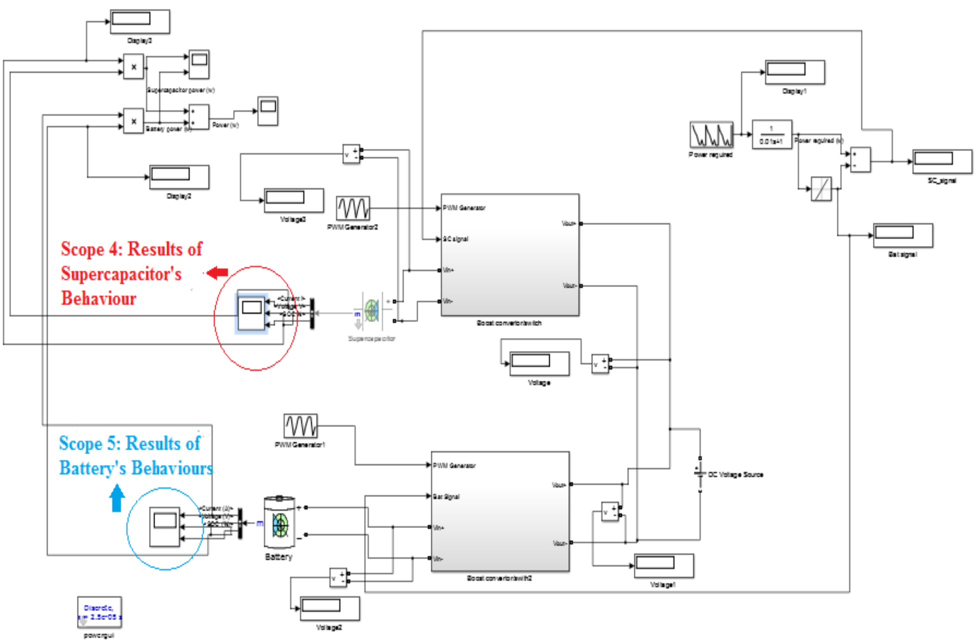

Figure 4.23: Scopes locations of supercapacitor and battery

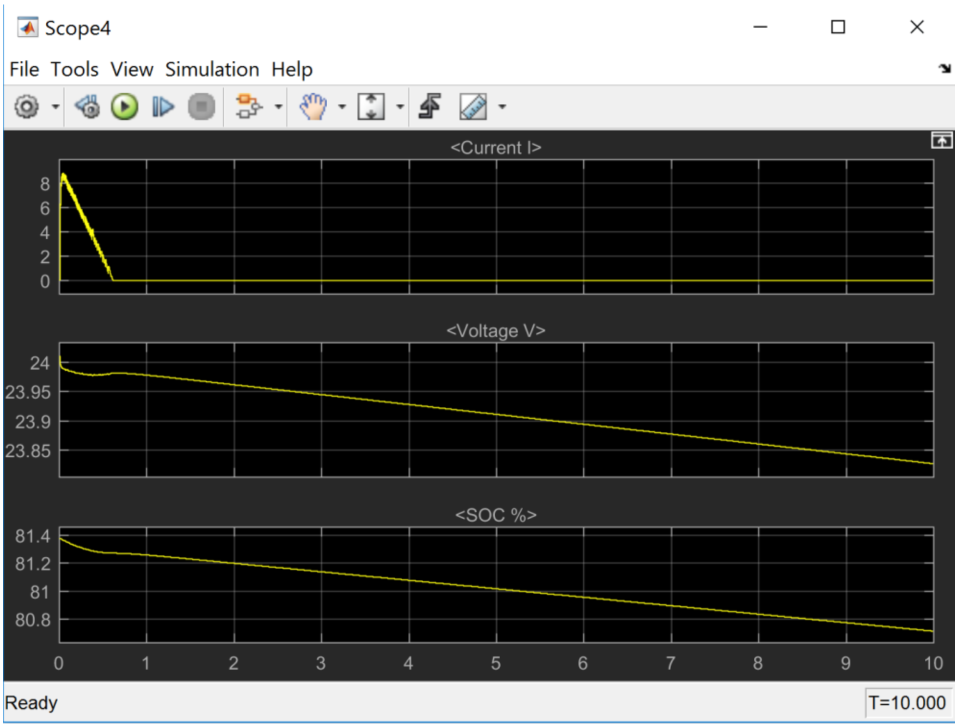

Figure 4.24: Discharging process with supercapacitor (series module)

Result shows DC voltage apply is 24 V connected to supercapacitor. The result is same while its SOC is 81.4% and start discharging while there is current supply turn off. Based on the current graphs, the result is decreasing faster because signal is OFF, so decrease till the end. Thus, discharge situation can be observed easily. Besides, there is no affect or simulation impact to this MATLAB Simulink. The graph is showing ideal result so no noise is included even though the result is being simulated for discharging process.

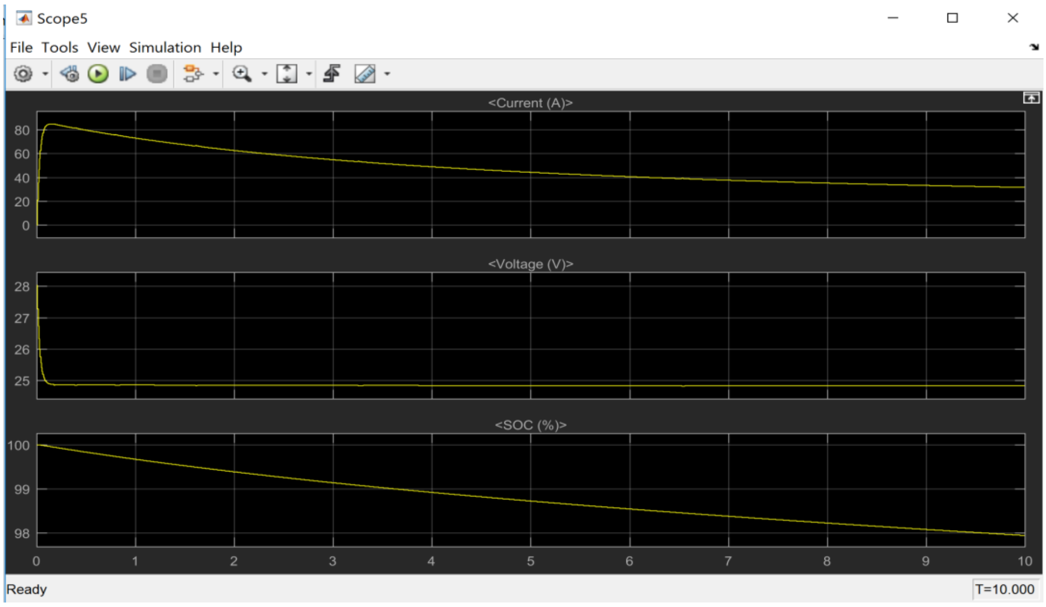

Figure 4.25: Discharging process without supercapacitor (series module)

According to Figure 4.25, the result obtained is smoother, decrease in voltage and SOC (state of charges). Once the current is decrease the voltage decrease to constant value and maintained. While for the SOC (state of charges) is discharge over time from 100% to 98%. The graphs obtained are linear and ideal, so the simulation results are different with practical results.

4.4.2 Parallel Module of Supercapacitor (Discharge Condition)

In Figure 4.26, this Simulink model is under investigation of parallel module. The setting has set as the series configuration. Scope locations are where supercapacitor and battery are located. Scope 4 and scope 5 show the results of supercapacitor's behaviour and battery's behaviour respectively. In the simulation model, current, voltage and power are investigated and studied before compare the result with practical results. Hence, the discussion and results are shown in Figure 4.27 and Figure 4.28.

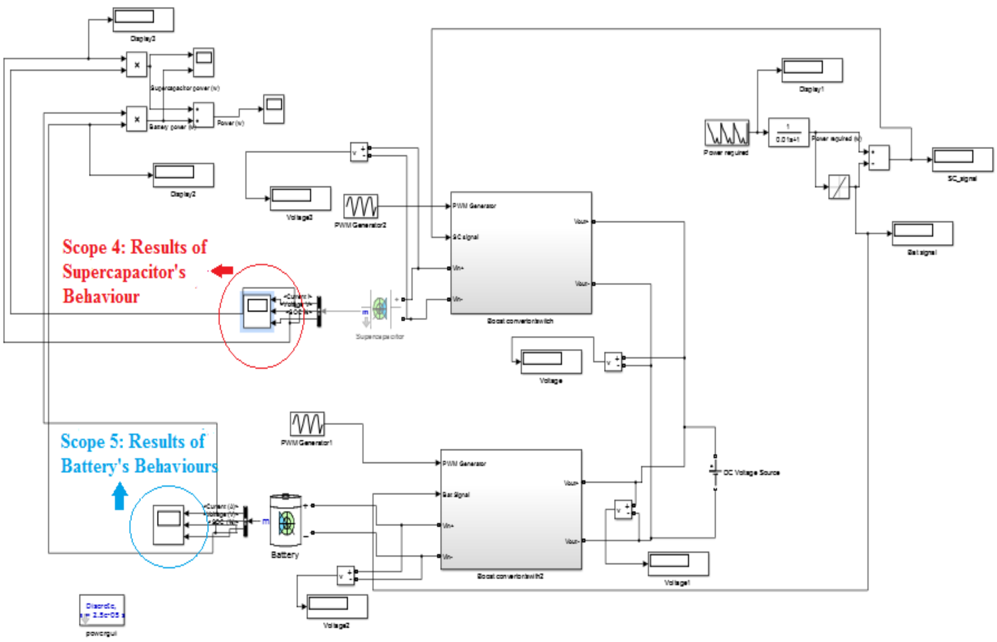

Figure 4.26: Scopes locations of supercapacitor and battery

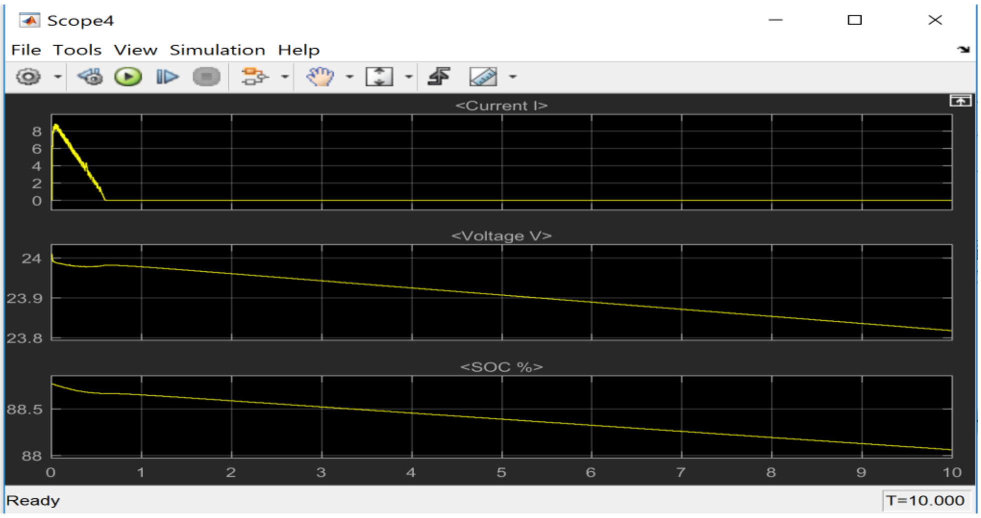

Figure 4.27: Discharging process with supercapacitor (parallel module)

Refer to Figure 4.27, result has shown that when there is current charge up the capacitor which charging until 89 % and slight decrease once there is no more current supply for charging situation. The supercapacitor starts to discharge over time until it reach zero. Voltage is directly proportional to state of charge at 24 V. As a result, longer discharging time is required during the discharging condition. The difference is not obvious but the voltage is decreasing slowly as oscilloscope results show. It has contributed to the behaviour as well. Thus, longer time taken to discharge a load as resistance value is lower.

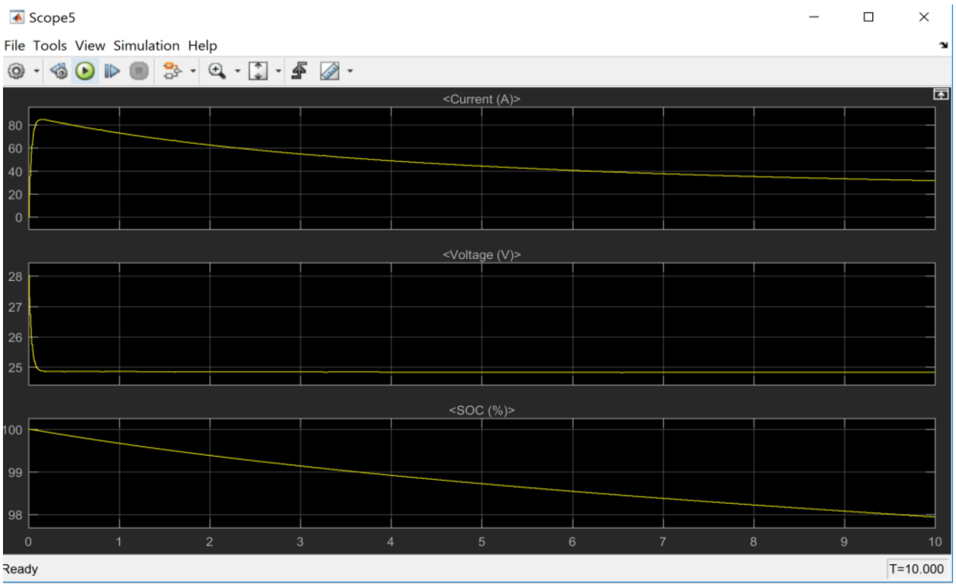

Figure 4.28: Discharging process without supercapacitor (parallel module)

In Figure 4.28, the current is indirectly proportional to voltage. When initial SOC (State of Charge) and current increase, the voltage starts to decrease. This has shown that current is drain to supercapacitor for charging up which cause the voltage drop. Voltage drop will drastically decrease the charge of battery. Based on this result, voltage and current are inversely proportional to each other. In simulation results, overall discharging time taken is around 20 minutes. The result is able to show a perfect discharging since the beginning.

4.5 Overall Comparisons between Hardware Configuration and Simulation Results

For hardware configuration, the results show the discharging condition since the initial state. Lower resistance value increases the speed of discharging rate. The waveform becomes smoother while discharging with the supercapacitor. Besides, the discharge behaviour of supercapacitor is easier to observe the difference and discharge rate at every single point. The result is not ideal case so observation and measurement of discharge rate is more obvious. Other than that, battery is discharged continually during the experiment. The battery is damaged and it could be discharged quickly and automatically if the battery isn't in charging condition. Thus, battery is drained extremely fast by itself. However, it has limitation of time frame issue. It is impossible to see a perfect discharging condition from the beginning till the end.

For software simulation, Lower resistance value increases the speed of discharging rate. The waveform becomes smoother while discharging with the supercapacitor. By using simulation, time frame issue is not a problem because discharging time can bet set in order to see a perfect discharging condition. The only concern is that the simulation performs waveform in ideal condition. The waveform has performed without noise at all. Besides, the controller parameters, set point and PID can be software programmed and adjusted from MATLAB Simulink. It is much easier to perform simulation but bug is needed to locate if having issue.

Discharging rate is faster as the higher power is supplied during discharging process. The current is decreasing while voltage decreases in supercapacitor. In this process, battery has the same energy density because the battery is not fully discharged. With help of supercapacitor, battery is able to supply more energy in specific timeframe. On the other hand, transient is appeared at higher state if the power required is higher. Thus, the initial state is not stable either.

As an overall comment, the differences of both configurations are the issues of ideal case and time frame. Hardware configuration can perform a better and obvious results, results are even easier to be observed and measured by any researches. The time frame issue is that the oscilloscope is unable to show overall discharging condition from the initial till the end. However, software simulation can show overall discharging condition for the whole discharging timing but the results are performed ideally. The difference is difficult to be notified because of low pass filter is added.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In the nutshell, the case study of power demands and behaviours of supercapacitor have been investigated. Based on the experimental results, the discharge rate of supercapacitor in series module is quicker than parallel module. The current and power ratings affect the discharge rate of supercapacitor during the process of discharging. The current is decreasing while voltage decreases in supercapacitor. In this process, battery has the same energy density because the battery is not fully discharged. With help of supercapacitor, battery is able to supply more energy in specific timeframe. Thus, the supercapacitor is reacted according to the various configurations such as high power demand, low power demand, sudden demand and steady state. For the simulation results, MATLAB Simulink performs the ideal results for the discharging rate of current, voltage and SOC which occurred in the discharge process. Simulink models are used to simulate behaviours of supercapacitor especially charge and discharge states. In software, simulations without and with supercapacitor show the difference of discharging states for temporary compact energy storage for long term and short term periods. For the case of without supercapacitor, the voltage drops linearly as the current is drained to supercapacitor for charging up which result in voltage drop. According to the case that consists of experiment with supercapacitor, simulation model shows that the voltage is decreased gradually as supercapacitor is fed more energy. The simulation and practical results are similar, but the Simulink model results are needed to improve especially locating each particular point to perform better and accurate simulation.

5.2 Recommendation

For the future development, supercapacitor module can be recommended to be bigger in size. It is easier to solve the discharge condition while testing with different power demands. Besides, charging circuit can be implemented so it could observe the difference between conditions of fully charged and being charged.

Last but not least, a perfect GUI model can be built to integrate with practical results obtained from hardware experiment. This could improve loss of time to measure, and also decrease the difficulty of detecting and measuring data. An energy transfer protocol can be created to monitor the behaviour of supercapacitor in real time. Thus, it can directly collect the data and perform results of showing different power demands.

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