Energy Management and Control of Electric Bike Using Hybrid Power Source

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Degree of Master of Science in Industrial Automation

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DECLARATION OF THE CANDIDATE & SUPERVISOR

I declare that this investigation done by me is the dissertation which has not been incorporated with any other previous material submitted for a degree or diploma in any university or institute of higher learning and also it suits the best of my knowledge and belief. This does not include the content of any other sources made previously except the acknowledgement in the text.

Signature:……………….. Date:…………………

The above candidate has carried out research for the Masters Dissertation under our supervision.

Signature of the supervisor :…………………. Date : ……………………..

(Prof.J.P Karunadasa)

Signature of the supervisor :…………………. Date : ……………………..

(Dr. AGBP Jayasekara)

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Finally, thanks for the encouragement given by my parents and relatives until the completion of my work with success.

ABSTRACT

Fuel sources for modern transportation systems are getting pricey and negatively affect the environment which lead to increase the demand for electric vehicles. Energy storage systems in majority of electric and hybrid vehicles are based on battery storage devices. Nevertheless, battery based systems have several issues that caused by high peak power demand which could resolved by high power density batteries .However, high power density batteries are much more expensive which lead to increase the overall cost of the vehicle.

Proposed Hybrid system (HESS) which connected to exciting electric bike consist of super capacitor bank ,DC to DC converter, motor controller, Battery bank and BLDC motor.DC to DC converter positioned between supercapacitor bank and battery bank, which pumps required energy to the supercapacitor bank,in order to maintain a greater voltage value than the battery terminal voltage. In most riding occations in a control manner.

Only when battery voltage equal to the capacitor bank voltage at continous bulk energy demands, battery connected to the Brush less DC-Motor which Maintain a relatively fixed load profile. Further, regenerative energy generated by braking is also fed to the battery indirectly via capacitor array, thus, battery pack isolated from frequent power demands which caused to reduce number of charge discharge cycles hence, increase the lifetime of the battery.

Finally, Test results clearly indicate, this Hybrid energy storage system has enormous benefits compared to Electric bikes such as reduction of overall power consumption of the battery , enhance quick acceleration , increased travelling range per single charge and decrement of per kilometer cost. Further, HESS system more energy efficient, more cost efficient and smooth in running compared to current electrical bikes in the market which makes HESS bike good choice for future higher speed electric bike industry.

LIST OF FIGURES

Contents

Chapter 1: Introduction

1.1: Background

Presently , fuel sources which used by vehicles are getting pricey and negatively affect to the environment which lead to increase the demand for electric vehicles.Energy storage system in most of the electric and hybrid vehicles (Plug in hybrid, E_ bike) are based on battery storage devices.Nevertheless,battery based systems (ESS) has several drawbacks that caused by high peak power demand which could resolved by high power density batteries .However, high power density batteries are much expensive which lead to increase the overall cost of the vehicle.

1.2: Problem Statement

Due to high rate power demands capacity of the battery array decresases with the time which could caused to total failure of battery system.Especially, during high rate charging due to sudden deceleration and high rate discharging during sudden acceleration cause batteries to drain instantaneous high Energy that seviourlyaffect on the life of the battery.

1.3: Approach

This Hybrid electric bike is a modification of conventional Electrical bike which uses super capacitors and Buck, Boost converters between battery and the motor.This will enhance the acceleration performance and battery lifetimeby using fast and efficient charging, discharging capabilities of super capacitors and by decreasing the charging cycles of the battery.

The combination of battery and super-capacitor results in the best of bothworlds, creating an ultra-efficient power source for a hybrid Electrical bike with,Increase theservice life of batteries , Extend the driving range ,Increase the fast acceleration capabilities. In order to achieve above qualities for the system there must be a buffer or an additional energy storage system (ESS) have to be installed to handle surge power demands. This system must , absorb the braking energy with high efficiency and lower negative effects to the batteries , supply instantaneous and extreme energy output during acceleration , maximally increase the driving range of the E-bikes.

1.4: Thesis outline

- Literature Review

  Studied about relevant theories and other related projects about Hybrid energy storage systems

- Methodology

  Here , whole structure and procedure of the Hybrid energy storage system hasdeeply explained

- System Development

  Here illustrates the development of the hardware structure of the system, including selection of hardware components and modules for the system.

- Result and analysis

  Here, outcomes of the Hybrid energy storage system analyses with the alternative external and internal conditions.

- Conclusion

  Here, Discussed about the advantages achieved by introducing Super capacitors and convertors to a Hybrid energy storage system .

Chapter 2: Literature Review

2.1: Introduction to literature review

In this chapter, explaining the electric vehicles which consist with capacitors, converters in order to improve their performance. Further, theories related to components and modules used in proposed systems also explained.

2.2: Related Researches

Following researches related to electric vehicle driver system improvement are analyzed to identify their advantages and disadvantages that will used to improve the proposed system for this project.

2.2.1: Energy management and control of electric vehicles, using a hybrid power source in regenerative braking operation

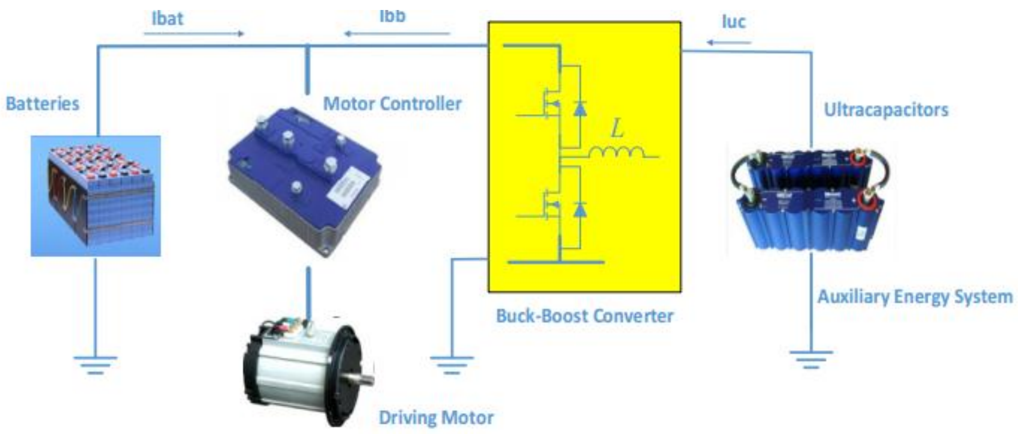

Figure 2.2.1.1

Energy management and control of electric vehicles, using a hybrid power source in regenerative braking operation overall structure[1]

The research paper is proposed to manage and control electrical energy in electrically driven vehicles, mainly in order to, increase the range with a single charge and energy absorb energy efficiently.Battery,Motor controller , buck-boost controller ,driving motor and ultra capacitor bank arranged as in Figure 2.2.1.1

In advancement of modern technology, electric vehicles play an important role because of it's valuable features such as high efficiency and environmental friendly. In last decade , more attention is focused on plugging electric vehicles , hybrid electric vehicles and fuel cell electric vehicles. Currently many electric vehicles still face many challenges, For examples , how to 'recover regenerative energy with minimum harm to the batteries'[1] ,and how to deliver maximum power at various road conditions, and how to increase mileage.

Many steps have been taken to find a win win solution for this challenge, with the use of Ultra capacitors.Ultra capacitors have many benefits compared to the other electric capacitor ,as it has high energy and high power density .Another two more features that lead to achieve this challenge are it's long endurance, high efficiency and number of cycling's.

To optimize the operation of this design both batteries and ultra capacitors have been used for power releasing. This design uses small DC to Dc converter to keep ultra capacitor at a high higher voltage than the ordinary battery, which specially boost running at city driving conditions. The battery directly feed power ,when ultra capacitor voltage drops lower than the battery voltage. The state of battery charge, capacitor voltage and current are maintained in safe limits, moreover ultra capacitor allocate , instant charging and discharging due to its capability.

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Figure 2.2.1.2
Energy management and control of electric vehicles, using a hybrid power source in regenerative braking operation hardware structure[1]

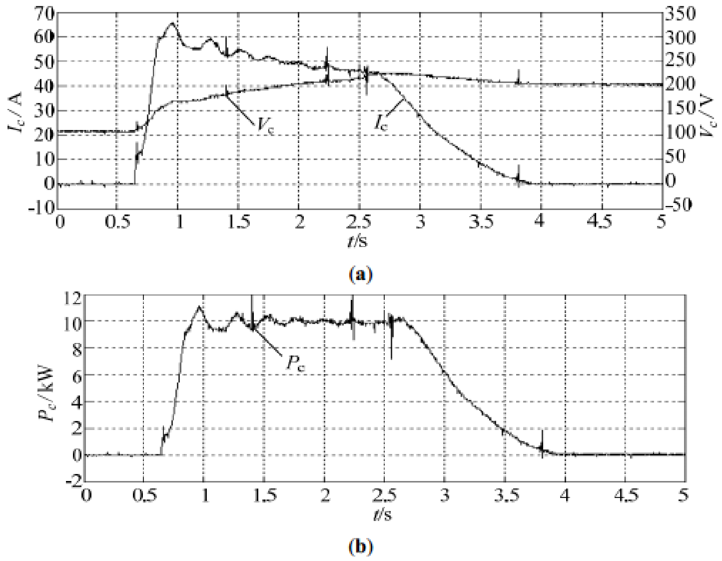

Figure 2.2.1.3
Super capacitor charging current during negative breaking braking.(a) Supercapacitor terminal voltage (Vc) and charging current Ic; (b)supercapacitor charging power (Pc).([1])

This system absorb the braking energy with high efficiency and lower negative effects to the batteries and also this system Supply instantaneous and extreme energy output during acceleration ,Thus Maximally increase the driving range of the E-bikes. On the other hand ultra_capacitorbank array bridged to the motor indirectly through a buck and boost converter,ultra capacitor bank unable to fully perform its quick charge, discharge capabilities due to, delays occurred in buck-boost converter.In regenerative state most of the sudden peak regenerative energy may drain by motor controller unit due to indirect coupling of capacitor bank to the motor.Because of the direct connection of the battery to the motor controller some of the unfiltered energy surges and instant power demand via motor controller may effect to the battery that will eventually reduce the lifetime of the battery.

2.2.2: Energy management system of Fuel-cell-Battery hybrid Tramway

This research paper describe the design ,layout ,and control of a fuel cell (FC)-hybrid metro tram in spain. Here ,polymer electrolyte membrane and nickel_metal hydride battery used as as primary and secondary energy source respectively which fulfill the energy demand during acceleration and absorb energy when braking .

The traction system of this vehicle is composed with four induction motor drives. In this design there are two boost converters, unidirectional DC-DC converter and Bi-Directional Converter, Unidirectional one for the Fuel Cells and Bi-directional one for the Battery. To regulate the power accurately, reference signals were taken from electric motor drives , fuel cells and power converters and also while regenerative breaking braking chopper dissipate energy accordingly. In this project, ‘all the test results evaluated for the real driving cycles and reveal that the system has the capability to meet appropriate driving cycles.’[2]

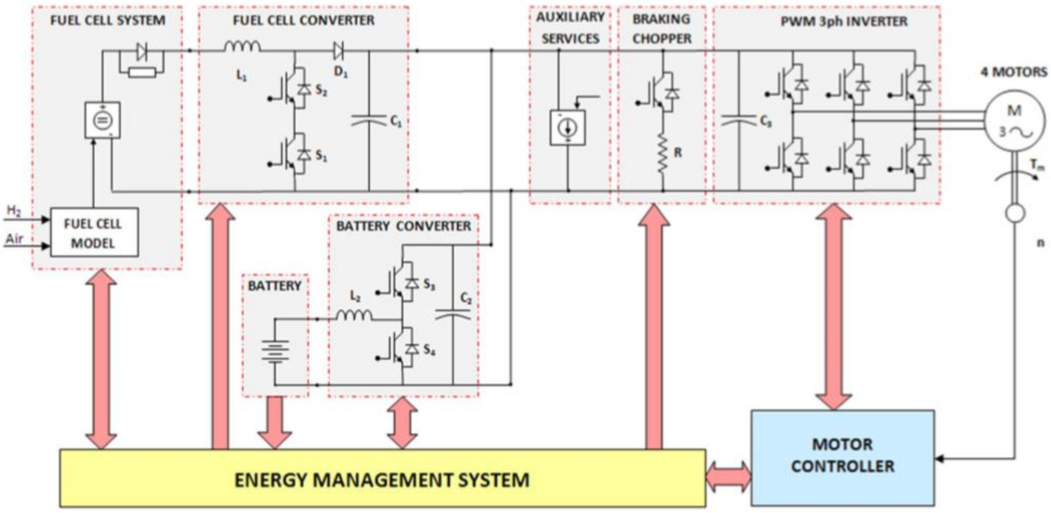

Figure 2.2.2.1
Fuel-cell-Battery hybrid Tramway operation structure of EMS
(Energy management systems)[2]

This system absorb the braking energy with high efficiency and lower negative effects to the batteries and Supply instantaneous and extreme energy output during acceleration , The other side of this design is most of the regenerative energy will wasted via breaking chopper and $R_{DS(ON)}$ of MOSFETS

2.2.3: The Ultra capacitor-Based Controlled Electric Drives With Braking and Ride-Through Capability: Overview and Analysis

In this research paper , it is highlighted that mainly two problems remains as a challenge in design advanced controlled electric drives, especially how to recover the braking energy. Ordinary devices are equipped with the energy storage elements and this phenomina help to boost in use of Ultra capacitors.Ultra capacitor power density is much higher than the excisting batteries.'Power density of the ultra capacitor is much higher than that of the Existing electro chemical batteries'[3]. In this paper discussed how to increase the ride-through capability via these regenerative electric drives. In this design three level DC-DC converter is used as the interface of the power converter.

This Ultra capacitor based , regenerative controllable electric device, consist with voltage DC-bus, Diode rectifier and output inverter and with a parallel connected energy storing unit , (Ultra capacitor and bidirectional DC-DC converter) , This two level or three level converter is controlled by a variable adjuster ,'which controls Duty cycle , switching frequency and phase shift'[3] .

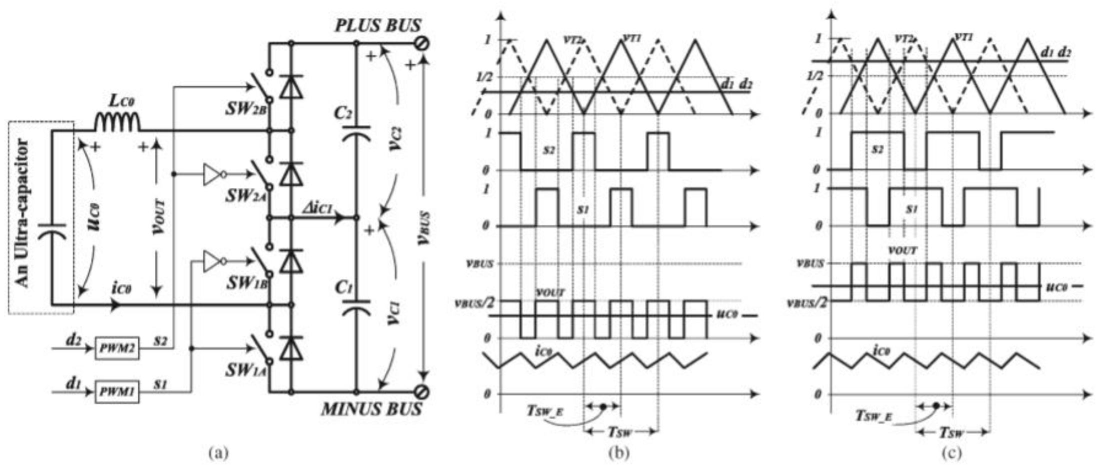

Figure 2.2.3.1

DC–DC CONVERTER USING A THREE-LEVEL TOPOLOGY[3]

(a). Circuit Diagram   (b).Wave foam d < 0.5   (c).Wave foam d > 0.5

Here, three Level bi-directional converter is used as the main power interface of the system and Figure 2.2.3.1 shows three levels of Bi-Directional converter's circuit diagram including four Bi-Directional Switches, a Inductor and two Capacitors. The switches are IGBT or MOSFET with free wheel Diodes. PWM 1 & PWM 2 are pulse width modulators. The Figure shows the wave foams of the Three Level DC-DC Converter. Output Voltage is between zero and Vbus / 2 if d =d1=2 and in a range 0 < d < 0.5   output voltage is between Vbus / 2 and Vbus 0.5 < d <1

This is most suitable for the controlled electric drives in equipments such as Lifts and cranes, "characterized by low balance between average and peak power"[4] This system capable of recovering regenerative energy dissipating via braking resistor (chopper circuit) much efficiently in most applications. On the other hand Power losses are higher than usual when this system handling sudden spikes and regenerations.

2.3: Summary of Literature Review

Literature review reveals about, theories explaining about the electric vehicles which consist ofcapacitors, converters in order to improve their performance. Further, theories related to components and modules used in proposed systems also explained. The literature review can be used to identify the advantages, drawbacks and technical detials of Hybrid electric vehicles with capacitors. Main advantages and disadvantages of these systems can be pointed as follows.

The main advantages of the system are Supply instantaneous and extreme energy output during acceleration and Maximally increase the driving range of the vehicle . These systems absorb the braking energy with high efficiency and lower negative effects to the batteries , it has the capable of recovering regenerative energy dissipating via braking resistor (chopper circuit) much efficiently in most applications.

On the other hand there are several negatives in the system ,Because of the ultra_capacitorbank array bridged to the motor indirectly through a buck and boost converter,ultra capacitor bank unable to fully perform its quick charge, discharge capabilities due to, delays occurred in buck-boost converter.In regenerative state most of the sudden peak regenerative energy may drain by motor controller unit due to indirect coupling of capacitor bank to the motor.Because of the direct connection of the battery to the motor controller some of the unfiltered energy surges and instant power demand via motor controller may effect to the battery that will eventually reduce the lifetime of the battery.Most of the regenerative energy will wasted via breaking chopper and $R_{DS(ON)}$ of MOSFETS

Chapter 3: Methodology

3.1: Fundamental Concept of the System

The main driving motor is connected to the capacitor bank via buck-boost converter to the battery pack, in order to reduce the amount of sudden current drain from the battery packwhich eventually prolong its lifespan. Further, use of Buck-Boost converter will also increase the operating voltage range of the batteries.

In addition to that, this arrangement of the system able to deliver more energy to the motor in a short period due to increased operating voltage range of the super capacitor array.

Moreover, during braking process system able to gather and deliver wasting energy as regenerative energy of the motor via a second loop of a buck - boost converter which further enhancethe system efficiency.

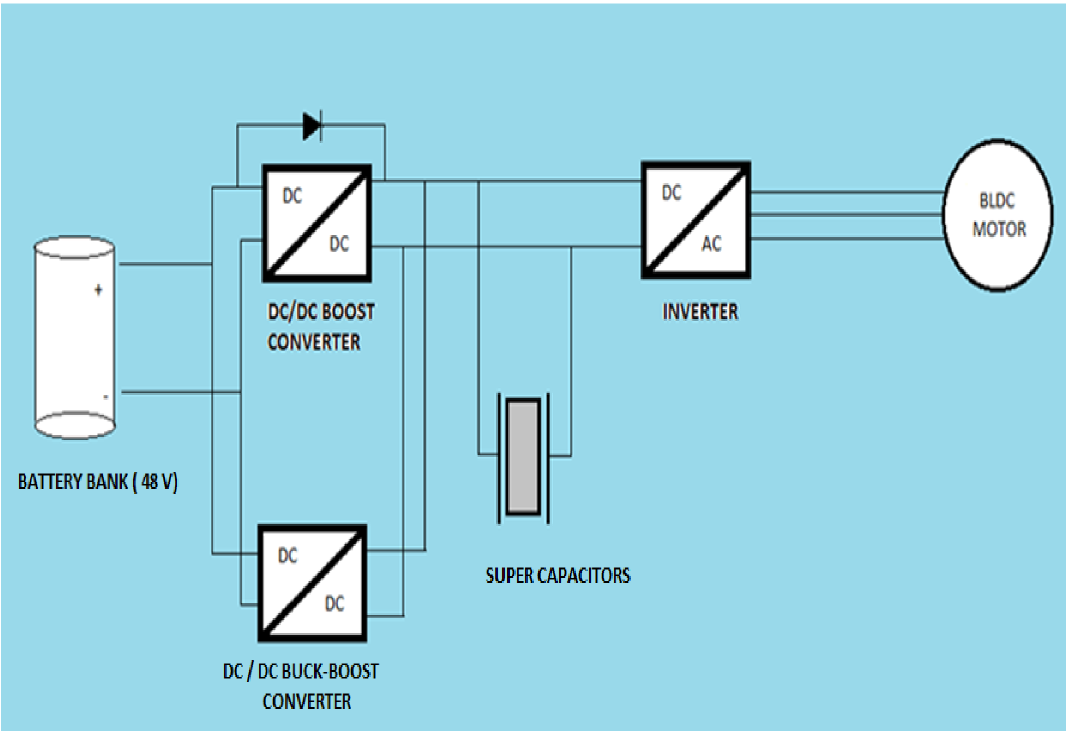

Figure 3.1.1
Overall conceptual design of the system

3.2 Energy management and control stratergy

Accelaration resistance power , aerodynamic power, slope resistance power and rolling power are the key components that calculation of hybrid systems power demand depends on .

$$P\ (veh) = P\ (roll) + P\ (aer) + P\ (slope) + P\ (acc\ )$$

The total current demand can be calculated as

$$\mathrm{I\ (\ load\ )} = \frac{P\ veh}{U\ bus}$$

Life time of the battery and overall system efficiency are increased by protecting battery pack from sudden current demand (without over charging or discharging ultra capacitor array) using power balancing stratergy that based on basic control logics.

3.3: Power flow chart

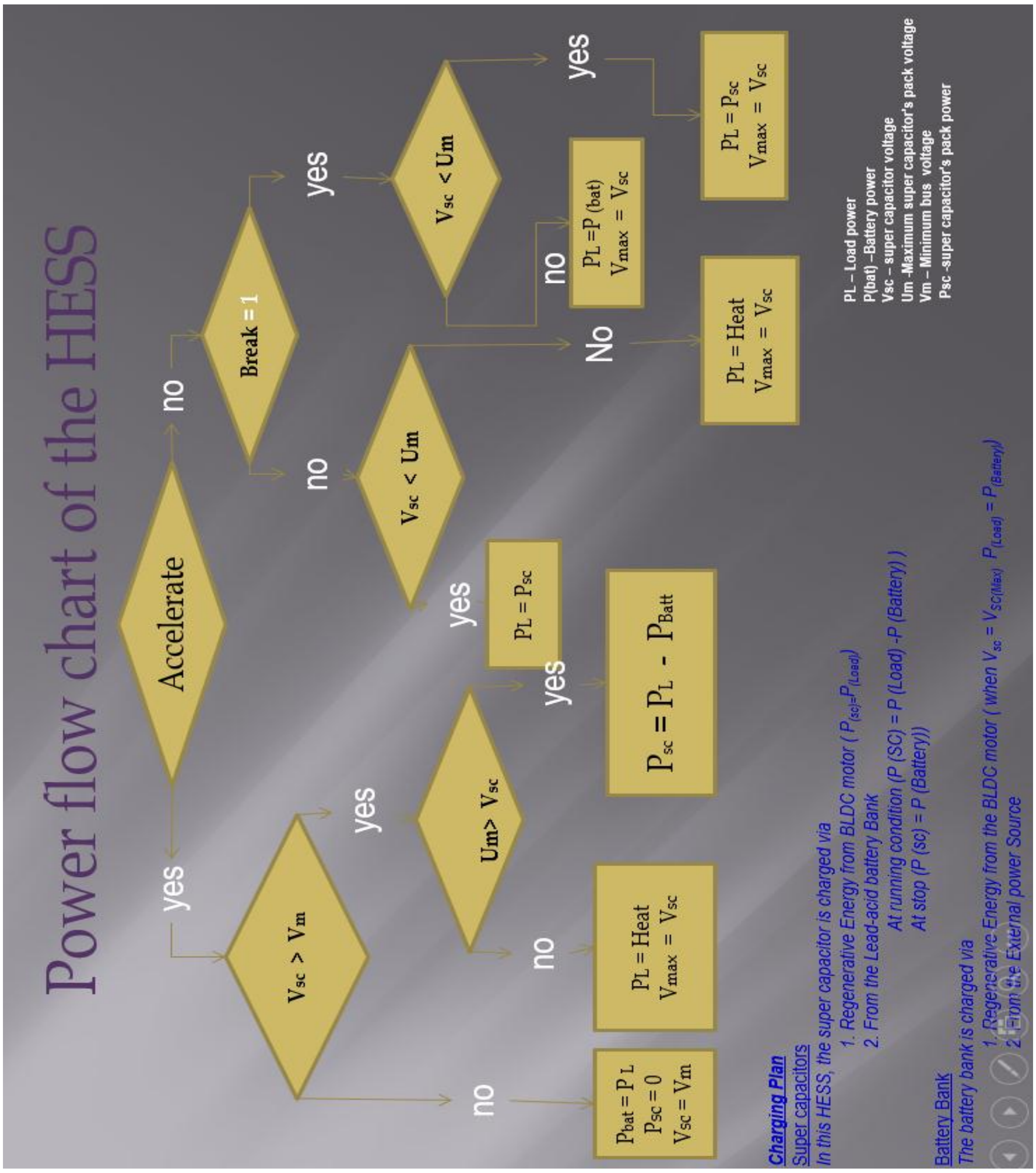

Figure 3.3.1
Power flow chart

Charging Plan

- Super capacitors

In this HESS, the super capacitor is charged via

1. Regenerative Energy from BLDC motor ($P_{(sc)=}P_{(Load)}$)

2. From the Lead-acid battery Bank

At running condition ($P\ (SC) = P\ (Load)\ -P\ (Battery)$)

At stop ($P\ (sc) = P\ (Battery)$)

- Battery Bank

The battery bank is charged via

1. Regenerative Energy from the BLDC motor
   (when$V_{sc} = V_{SC(Max)}$ $P_{(Load)} = P_{(Battery)}$)
2. From the External power Source

3.4:System operation (Constant speed operation)

There are two types of operation modes at constant speed as follows

- Low constant speed mode
  when$P_{load}$is equal to or smallerthan$P_{battery}$ ($P_{load} <= P_{battery}$)
- High constant speed mode
  When $P_{load}$is higher than $P_{battery}$ ($P_{load} > P_{battery}$)

Both above modes (Low constant speed mode and High constant speed) are ideal modes because in real world application power demand of the bike continuously varing.

3.4.1: Low constant speed

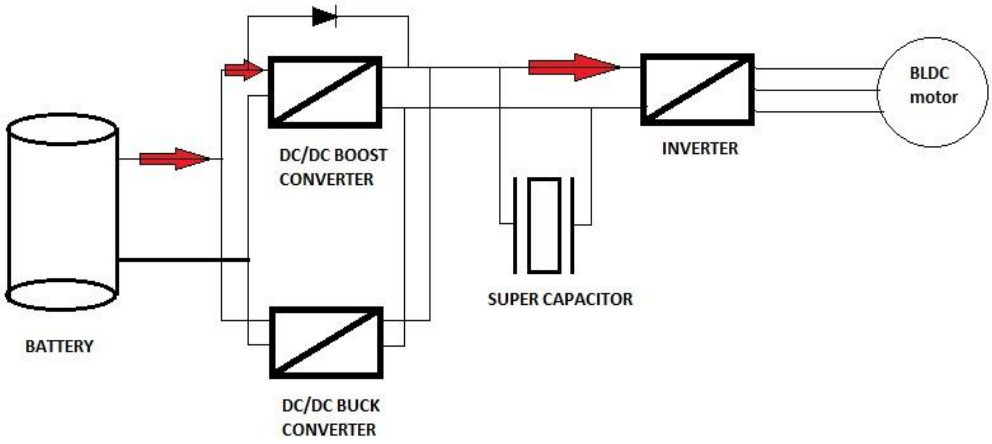

Figure 3.4.1.1
Low constant speed, energy flow diagram

Low contant speed energy flow demonstrates in**Figure 3.4.1.1**whichreveiled,at Low_speedmode,super capacitor voltageV_{SC} maintained at higher level than battery voltage V_{Batt}due to battery power is grater than load power($P_{battery}>P_{load}$). Likewise,DC bus voltage kept at greater value than battery voltage.Super-capacitor is not absorbing or delivering any power to the electric motor at constant speed mode.BLDC-Motor not receive any energy from the battery since ,main power diode at its reversed biased mode due to super-capacitor voltage is at greater value than the battery voltage.

3.4.2: High constant speed

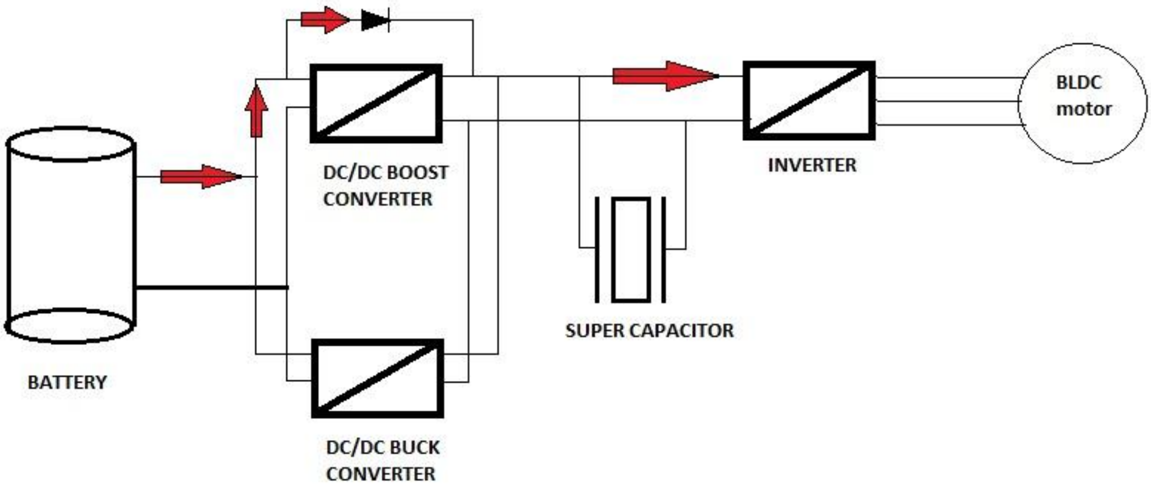

Figure 3.4.2.1
High constant speed energy flow diagram

High- contant speed energy flow demonstrates in Figure 3.4.2.1 whichreveiled, at High-speed mode,super capacitor voltage V_{SC}no longer maintained at higher level than battery voltage V_{Batt}due to battery power is lower than load power ($P_{battery}<P_{load}$) . Likewise,DC bus voltage no longer kept at greater value than battery voltage.BLDC-Motor directly receive energy from the battery since ,main power diode at its forward biased mode.

3.5: Acceleration

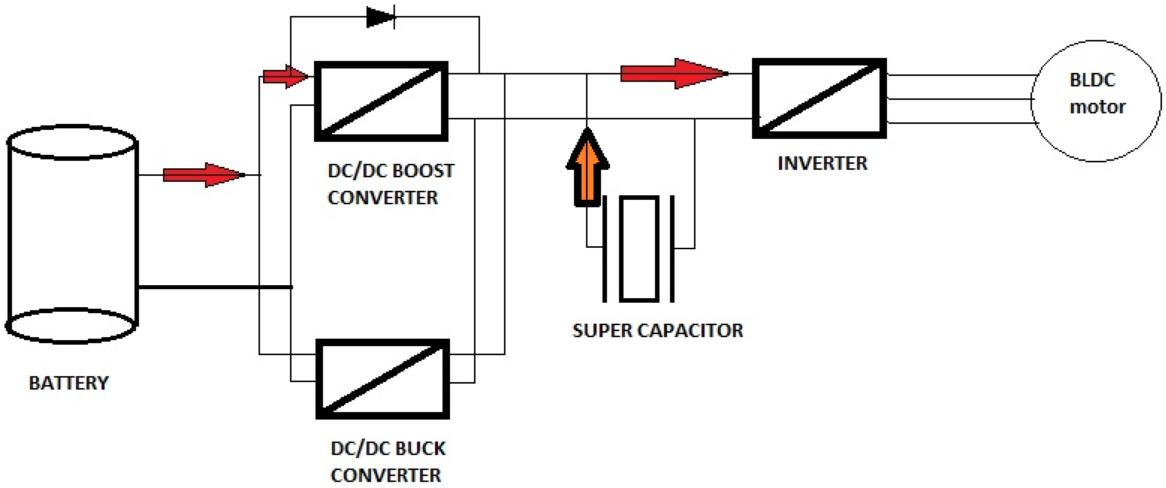

Figure 3.5.1
At acceleration energy flow diagram (phase I)

Figure 3.5.1 shows acceleration mode in (Phase-I) energy flow.Assume $V_{SC}>V_{Batt}$ At starting point of the acceleration mode . Since $P_{battery}<P_{laod}$, V_{SC} keep decreasing. Energies from the SC and the DC-DC converter are both supporting the E-bike acceleration process.

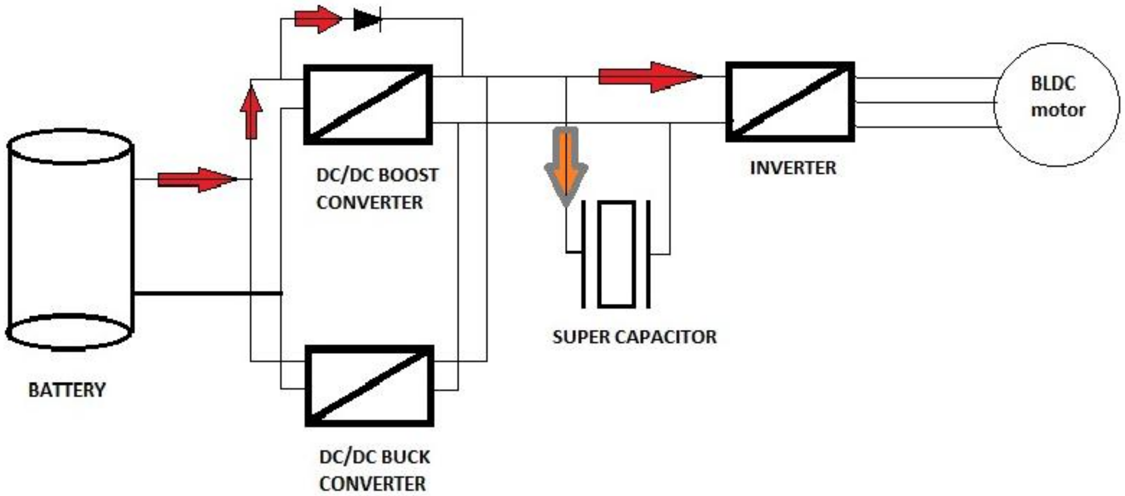

Figure 3.5.2
At acceleration energy flow diagram (phase II)

If acceleration continoues voltage of the supercapacitor reduced to the battery voltage (V_{Batt}).At this point , super_capacitor and the battery directly connected via forward biased power diode.

3.6: Deceleration (Braking)

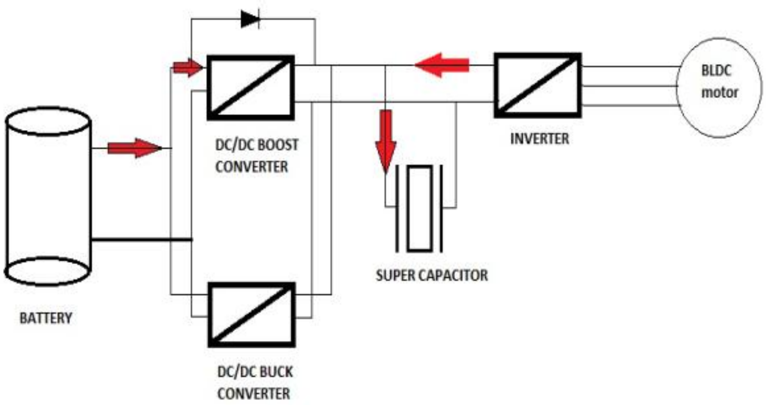

Figure 3.6.1
At deceleration (braking) energy flow diagram (phase I)-a

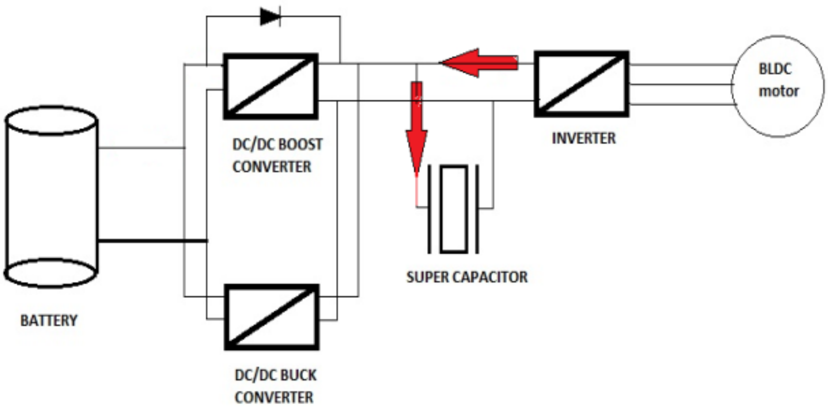

Figure 3.6.2
At deceleration (braking) energy flow diagram (phase I)-b

In deceleration mode can be divided into several phases as follows,

- Deceleration mode – Phase I-a(Figure 3.6.1)

  This occurs when accelerator of the bike released without braking. At this mode regenerative energy of the motor fed only into the supercapacitor bank.

- Deceleration mode – Phase I-b(Figure 3.6.2)

  This occurs when breaking . At this mode DC-DC converter set into boost operating mode when target super-capacitor voltage (V_{SCtgt}) greater than or equal to the supercapacitor voltage (V_{SC}). If supercapacitor voltage is lower than the target super-capacitor voltage ($V_{SC\ tgt}$),DC-DC converter set into the No operation mode.

- Deceleration mode - phase II (Figure 3.6.3)

  This occurs when regenerative braking power continuously fed into the super-capacitor(V_{SC}). array and eventually terminal voltage of the supercapacitor bank reached to its target voltage($V_{SC\ tgt}$).At this point , DC-DC converter operate in buck mode to feed excess energy towards the battery pack.

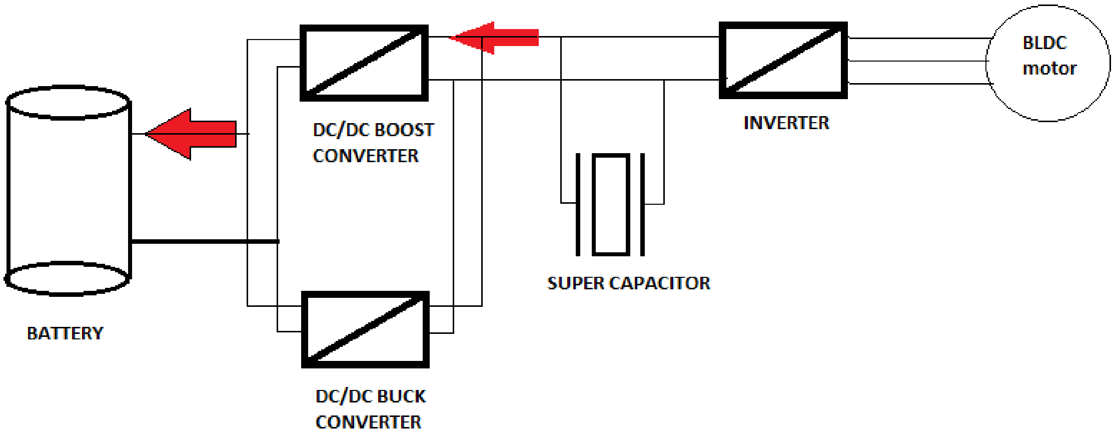

Figure 3.6.3
At deceleration (braking) energy flow diagram (phase II)

3.7: Sudden acceleration

At sudden acceleration immediate power demand to the motor is supplied by the super capacitor array.Because , super-capacitors are muchsustainable to withstand more charge and discharge cyclesthan batteriesand well suited for fast dynamic cycles (which cause of sudden acceleration).

Chapter 4: System Development

This chapter illustrates the development of the hardware structure of the system, including selection of hardware components and modules for the system.

Figure 4.1
HESS bike- completed structure

4.1: Hardware components selection and Modules

4.1.1: Battery Bank selection criteria and deciding cutoff voltage of the motor controller

Number of test reveals that average energy consumption per kilometer Conventional E-bike is vary between 20 Wh to 30 Wh, there for by considering cost factor and availability , as well as motor controller operating voltage(42V-66V) range four number of 20Ah lead acid batteries were taken to design the battery bank to drive 32km-48km

Determining state of charge (SOC) and depth of discharge (DOD) of the batteries

Assumptions

- There is no as self-discharge of the cells and leakage effects.

    - Total released capacity of the battery when it fully discharged from a certain level is difined as releasable-capacity (Creleasable). Percentage value of the releasable-capacity respective to the battery rated-capacity (Crated), defined as the state of charge (SOC). Battery rated capacity of this project-20Ah (According to datasheet of the manufacture)

$$\text{SOC} = \frac{C\ releasable}{C\ reted}\ 100\%$$

There are several techniques that can be used to calculate the SOC value. Here ,amphere - hour counting and current-Integration method has been used to determine by intergrating current ratings over usage-period to obtain the SOC as follows.

$$SOC = \text{SOC (to)} + \frac{1}{\text{Crated}} \int_{\text{to}}^{\text{to}+\pi} (\text{I}_\text{b} - \text{I}_{loss})\ dt$$

SOC(to) - The Initial SOC

C_{rated}- Rated Capacity

I_b – Battery Current

I loss –Current consumed by the loss reactions

When a battey is discharging ,the depth of discharge can be expressed as follows

$$\text{DOD} = \frac{C\ releasable}{C\ rated}\ 100\ \%$$

The measured charging and discharging current I (b) , the difference of the depth of discharge in an operating period can be calculated by

$$\Delta DOD = -\frac{\int_{\text{to}}^{\text{to}+\pi} \left(\text{ I (b)} \right) \text{dt}}{\text{C (rated)}} 100\ \%$$

here Ib is negative (-) for discharging and positive(+) for charging. As time elapsed DOD is accumulated

$$\text{DOD(t)} = \text{ DOD(to)} + \Delta \text{ DOD}$$

Lead acid battery characteristics

Percentage of State of charge of the 12V Lead acid battery and terminal voltage

State of Charge	12 Volt battery	Volts per Cell
100%	12.7	2.12
90%	12.5	2.08
80%	12.42	2.07
70%	12.32	2.05
60%	12.20	2.03
50%	12.06	2.01
40%	11.9	1.98
30%	11.75	1.96
20%	11.58	1.93
10%	11.31	1.89
0	10.5	1.75

Figure 4.1.1.1
State of charge and Lead acid battery terminal voltage[5]

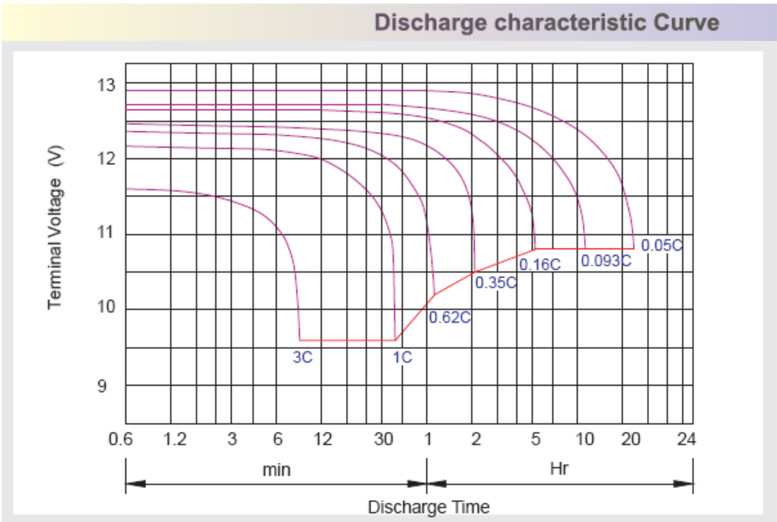

Figure 4.1.1.2
Lead acid battery discharge characteristic curve[6]

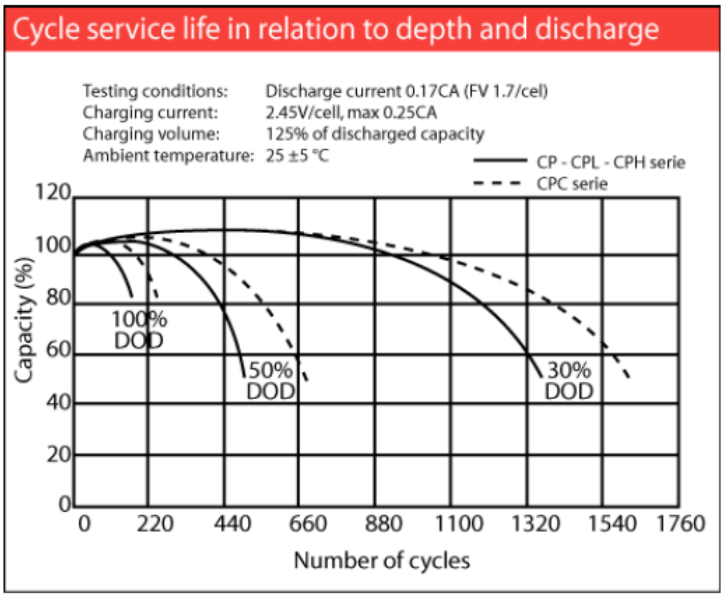

Figure 4.1.1.3
Lead acid battery cycle service life in relation to depth and discharge[7]

Discharge Current VS. Discharge Voltage

Final Discharge Voltage V /cell	1.75V	1.70V	1.60V
Discharge Current (A)	(A) ≤0.2C	0.2C< (A) <1.0C	(A) ≥1.0C

Figure 4.1.1.4
Lead acid battery discharge current vs discharge voltage[7]

Test result of 12 V (20 Ah) lead acid battery terminal voltage at open circuit and close circuit (1C (rated)discharge)

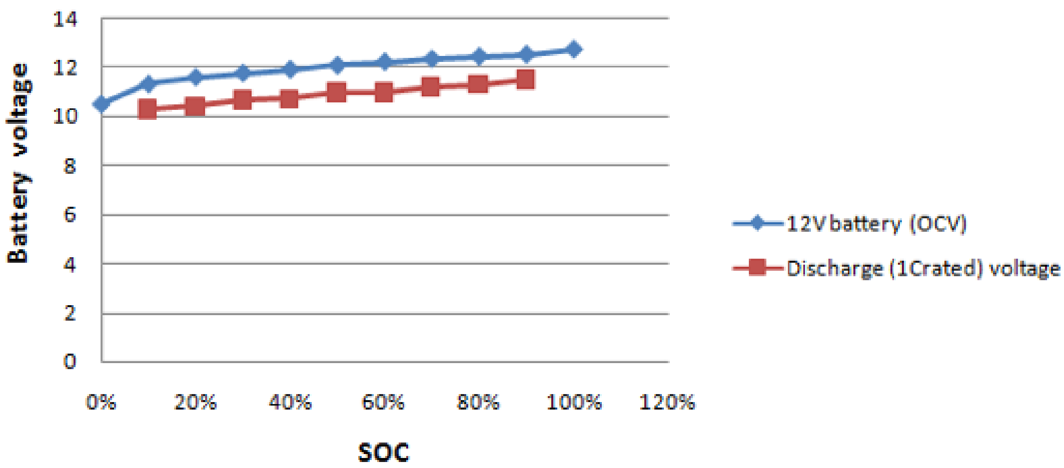

Figure 4.1.1.5
Lead acid battery open and close circuit voltage vs SOC

Calculation

Without considering the battery aging and operating efficiency

$$SOC\ (t) = 100\% - DOD(t)$$

Practical testing is done at the same flat foam before modification and after modification

Conventional E – bike testing

After the number of practical testing average battery current C_{rates} were 15 Ah, 12 Ah, 16.5 Ah 15.5 Ah,13Ah, 13.6Ah, 16 Ah,

No of tests	$C_{released}$
Test-1	15 Ah
Test-2	12 Ah
Test-3	16.5 Ah
Test-4	15.5 Ah
Test-5	13 Ah
Test-6	13.6 Ah
Test-7	16 Ah

Table 4.1

Conventional E- bike practicle testing results

Depth of discharge (***DOD***) = {(16.5 / 20)} × 100 = 82.5 %

(0.82 Crated))

SOC of the battery-Pack (100% - 82.5 %) = 17.5 %

According to characteristic (SOC-17.5 %) terminal voltage is= 46 V

According to the data sheet if discharge rate $0.82C_{rated}$ is continues final discharge voltage (per cell) is 1.70V =10.2 v

Final discharge voltage (1.70 × 6) =10.2 v

There for battery bank final discharge voltage(10.2 × 4) = 40.8 V

Modeled HESS testing

After the practical testing average battery current C_{rates} and supercapacitor C_{rates} are as below .

No of tests	$C_{released}$ – Super capacitor	$C_{released}$- Battery
Test-1	15 Ah	4 Ah
Test-2	12 Ah	3.7Ah
Test-3	16.5 Ah	5.3Ah
Test-4	15.5 Ah	4.8Ah
Test-5	13 Ah	3.9Ah
Test-6	13.6 Ah	3.9Ah
Test-7	16 Ah	5.3Ah

Table 4.2
practicle testing resultsof the HESS

HESS battery discharge current is ($C_{released}$) = 5.3 Ah

Battery discharge current is below $0.2C_{(rated)} < (A) < 1\ C_{(rated)} = 4 < (A) < 20$

Depth of discharge (*DOD)* = (5.3 / 20) × 100 % = 26 %

State of charge (***SOC***) of the battery (100% - 26%) = 74%

According to characteristic (SOC-74 %) terminal voltage is = 49.2 V

According to the data sheet if discharge rate $0.26C_{rated}$ is continues final discharge voltage (per cell) is 1.70V

Final discharge voltage (1.70 × 6) = 10.2 V

There for battery bank final discharge voltage(10.2 × 4) = 40.8 V

Test result shows that Conventional E-bike DOD is 82 .5 % and SOC 17.5%, and battery bank terminal voltage 46V .HESStest result shows Battery DOD is 26 % and SOC 74% battery bank terminal voltage 49.2 V.By decreasing the Battery-DOD of the battery 82.5 % to 26 % charging cycles of the battery can be increased more than double than the conventional E-bike system.According to the internal impedance and chemical reaction of the battery, terminal voltage drops when loaded, according to the test results in sudden acceleration terminal voltage drops 9 % - 10 % from the initial battery terminal voltage. There for Motor controller cut off voltage(at SOC 30 % initial battery bank terminal voltage is 47 V) is taken as 42 V as the safety factor of the battery

4.1.2: Super Capacitor Bank selection criteria

State ofcharge of the supercapacitor which can be used to determine the rated energy capacity percentage , calculated as follows.

$$SOC = \frac{Usc - Uc\ min}{Uc\ \mathrm{max} - Uc\ min}$$

U sc – super capacitor load voltage
Ucmax - maximum terminal voltage of the Super capacitor
Ucmin- maximum terminal voltage of the Super capacitor

Hybrid energy storage system capable of depending the Battery-Array from extreme vigorous current demands without over Charging / Discharging the Ultra-Capacitor bank. Energy management system used in HESS based on power balancing stratergydetermined by simple logical rules.

For this system (HESS) energy storage capability of capacitors depends on following factors,

- Regenerative energy generating volume
- Sudden acceleration
- Sudden acceleration rate

Energy storage capability of charging& discharging of super capacitors depends on,

- Rated voltage of the super capacitor
- Super capacitor rated capacitance

Maximum voltage to the super capacitor array always less than or same to the bus voltage

$\mathbf{V_{cap\,(max)} \leq V_{bus}}$

To get the Super-Capacitor maximum efficiency the Minimumvoltage should be limited to 40% ~ 50 % of maximum voltage. Here, bottom level of the limitation considered to 40% also by considering the safety limit of the battery.

Therefore, voltage range values selected as follows,

$V_{max} = 62$ V

$V_{min} = 42$ V

Considering Braking Energy (capacitor charging)

Energy storage capacity

$$\mathbf{E_{cap} = C_{cap}\{ V^2_{max} - V^2_{min}\} / 2}$$

V_{max} – Super capacitor maximum working voltage

V_{min} - Super capacitor initial working voltage

$$\mathbf{C_{cap} = 2\, E_{cap} / [V^2_{max} - V^2_{min}]}$$

By number of practical tests, it is observed that maximum regenerative energy can be stored in the super capacitor bank is within 3s, 55Vmaxis 800W

In most of the Conventional braking systems, regenerating energy is dissipated via internal $R_{DS\ (ON)}$(Total resistance between the drain and source of MOSFETs) and an external braking resistor. This will convert mechanical energy into electrical energy, and finally dissipated as heat.

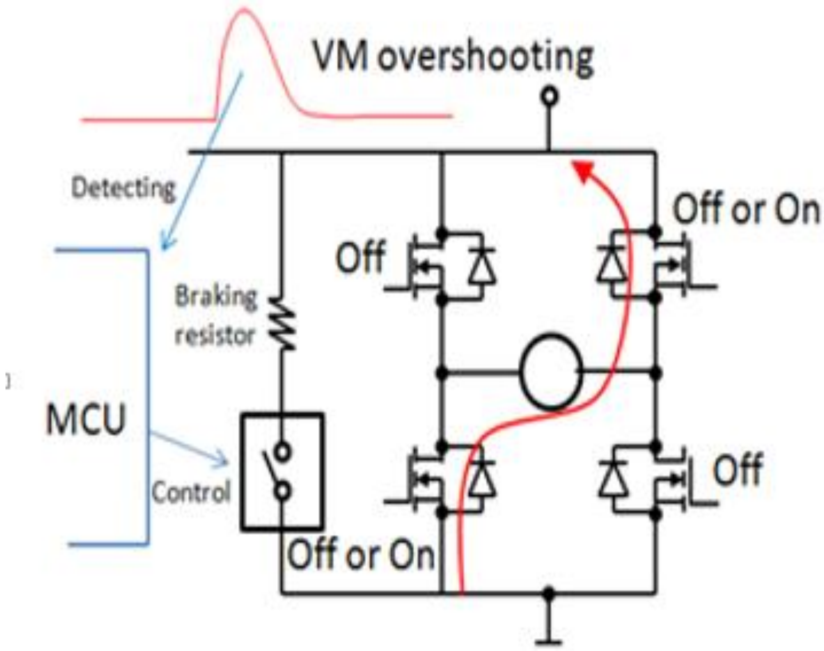

Figure 4.1.2.1
Dynamic braking with braking resistor and control loop[8]

In HESS, super capacitor acts as a “current storage tank” When the motor is stopped, the tank absorbs regenerating current and level up(smooth) the voltage overshooting and enhance the efficiency of the system hence, increase the mileage of the bike.

At Constant current discharge (discharging)

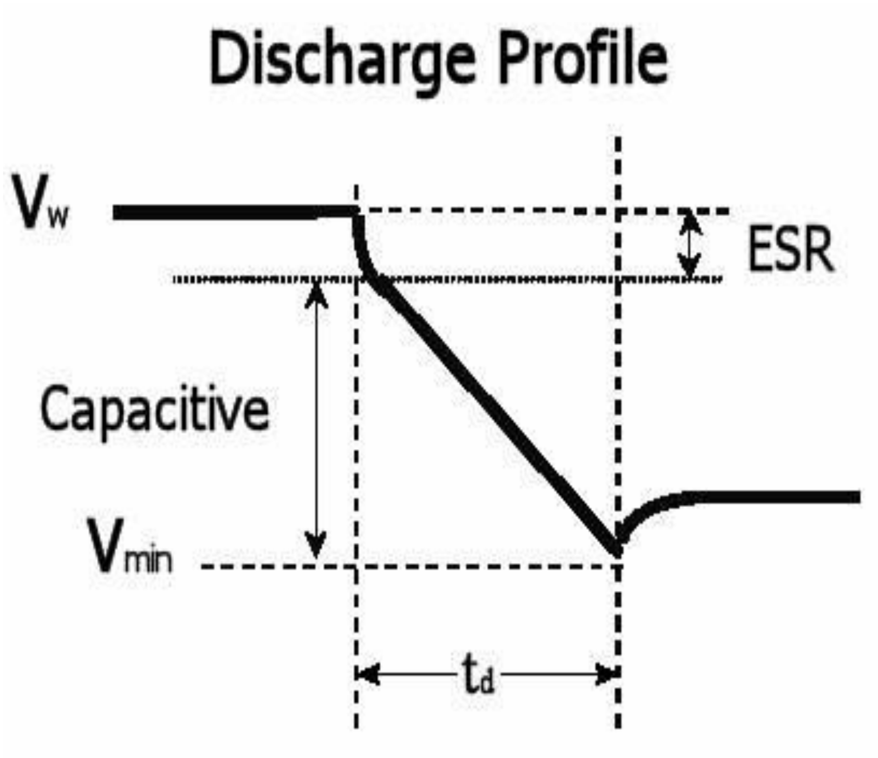

Figure 4.1.2.2
Discharge profile[9]

Capacitance = $I_d \times t_d$ / (V_w -V_{min})

I_d - discharge current

TD – Time to discharge from the initial voltage to minimum voltage

V_d=V_w-V_{min} (Initial voltage – Minimum voltage under load)

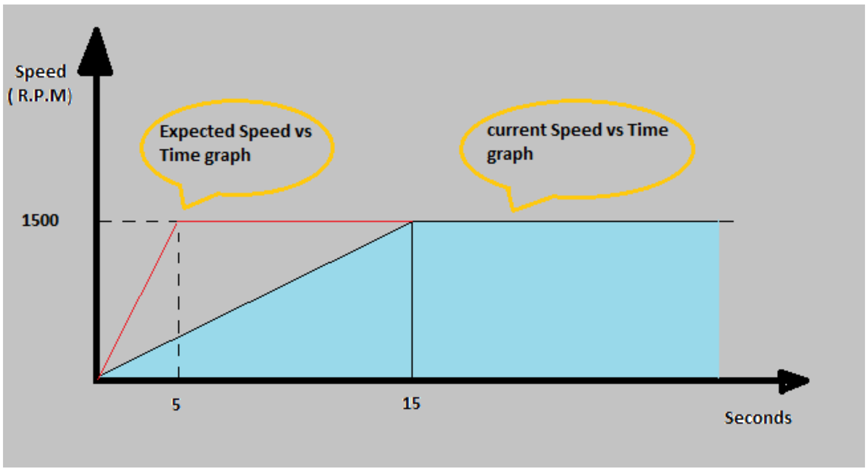

Figure 4.1.2.3
HDSS bike speed vs. time plot

Without modification (in conventional systems)

Practically, time takes to reach to its maximum speed = 33 s

Maximum speed = 1500 r.p.m

Maximum current I_{max} = (1000 w / 42 v) *1.052

= 24.21 A

The main target of HESS system is to reach its maximum speed within 5 seconds

$V_d = V_w - V_{min} = 62-42$

T_d = 5 s

I_d = 24.21 A

Capacitance = ($I_d \times t_d$) / ($V_w - V_{min}$)

= 24.21 × 5 / (62-42) = 6.05 F

At a heavy traffic congestion ,3 to 6 number of sudden accelarationscan beexpected in a short period of time, specially in developing countries.

In order to achieve a single maximum acceleration required energy of the super capacitor,

$E = C_{c1} \{ V^2{}_{W} - V^2{}_{min}\}/2$

$=\{6.05(62^2 - 42^2)\} / 2$

$=6.2$ KJ

Therefore, 3 times acceleration requires total energy of 18.6kJ (6.2×3) can be given if the capacitance value,

$3C_{c1} = 6.2 * 3 \approx 20$ F

By considering regeneration energy storagecapacity requirement and sudden acceleration (3 times) required overall capacitance of the capacitor array should be 20 F

4.1.3: Modules

Buck-Boost converter

Figure 4.1.3.1
Buck-Boost converter[10]

Input voltage : 8-60V
Input Current : 20A
Output voltage : 12-80V continuously adjustable

Constant Range : 0.5-20A

Output Current : 20A MAX Over 15A, enhance heat dissipation (input, the greater the pressure the smaller the output current output pressure related,)

Operating frequency : 150 KHz
Conversion efficiency : Uup to 95% (efficiency and input and output voltage, current, pressure related)

Super Capacitor Bank

Figure 4.1.3.2
Super capacitor bank[11]

Each cell voltage: 2.7 V
Each cell capacitance: 500 F

Battery

Figure 4.1.3.3
Sealed lead acid battery

Sealed lead acid battery
12V 20AH
Constant charge current 2.4 A - 3 A
Constant voltage charge 14.7A- 14.9A

Energy meter (kW meter)

Figure 4.1.3.4
kW meter

Type : PAEM-051

Working voltage : 6.5-100V DC

Test voltage : 6.5-100V DC

Color: as picture shows

Shunts Current : 50A

Shunts Voltage: 75mV

Rated power : 100A/10000W

Measurement accuracy: 1.0 grade

Shunts Size : approx. 120*25.5*1.75mm(L*W*H)

LCD screen size: approx. 51*30mm(L*W)

Size: approx. 89.6*49.6*24.4mm(L*W*H)

Shunts Material : steel + plastic

Note : when use of 50A or 100A shunt you need to set the Meter range of 50A or 100A

Brushless DC (BLDC) motor

Figure 4.1.3.5
BLDC motor

BLDC motor	1000 W (no load)
Service life	>10000h
Rotation speed	1500 Rpm. (no load)

Figure 4.1.3.6
Motor speed controller (48V 1000W) & Electric BLDC bike throttle Twist Grip

4.2: Final Hardware System Arrangement

Different modules (LCDdisplay,relays, motor controller, BLDC motor, super capacitor bank, Lead-acid battery bank, and Buck & Boost Converters) are arranged as **Figure 4.2.1** below

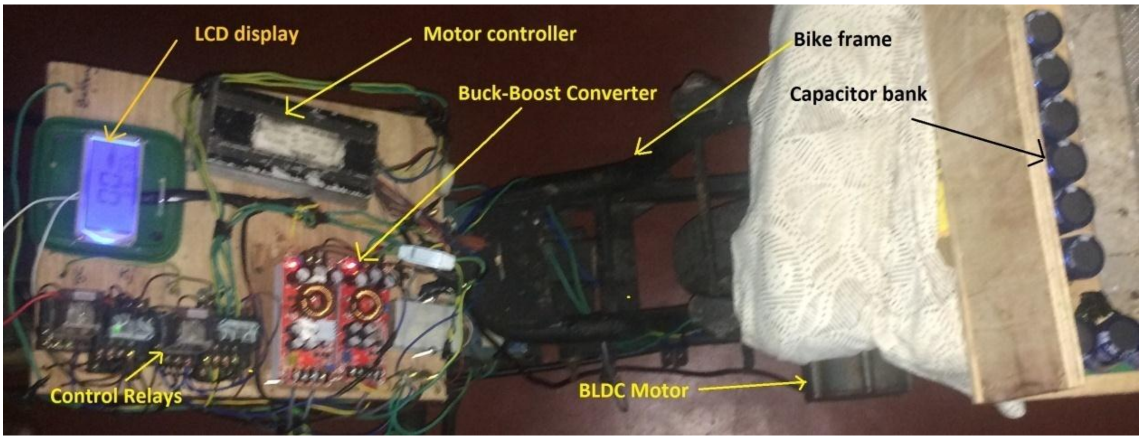

Figure 4.2.1
Over view of the complete system

Figure 4.2.2
Side view of the complete system

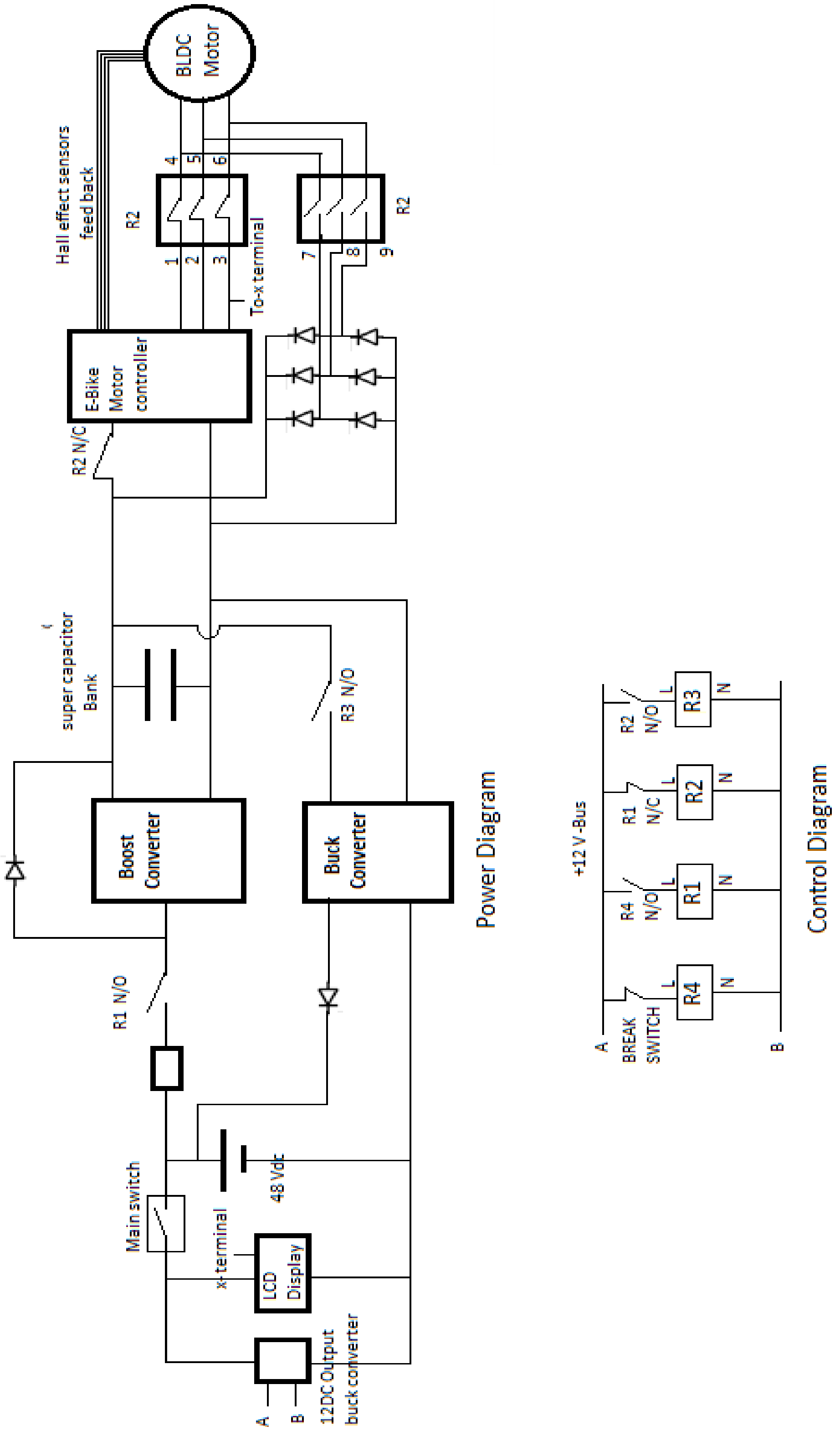

Figure 4.2.3
Hardware operational structure of the HESS

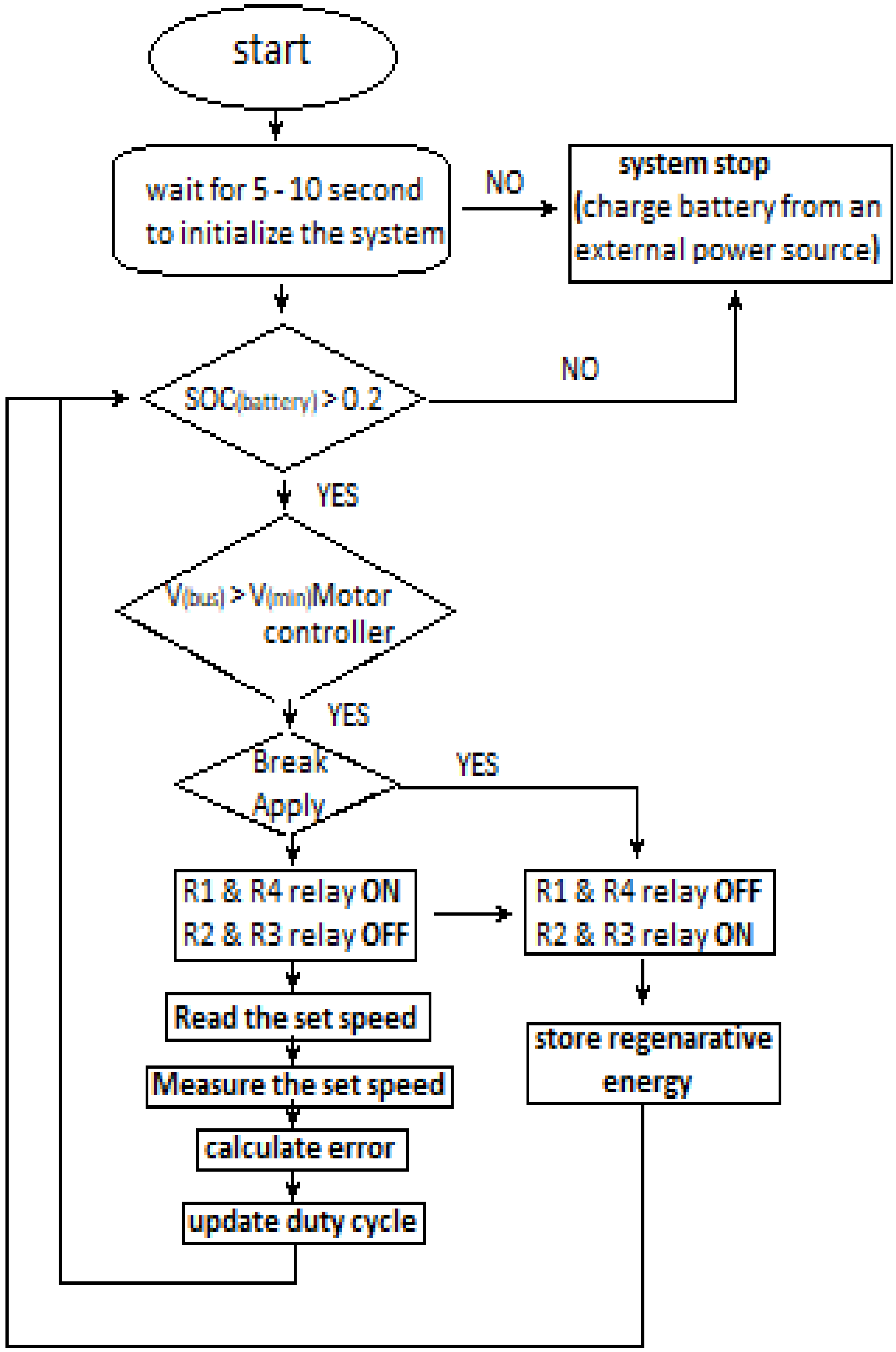

Figure 4.2.4
Operational flow chart-HESS

Typical Operation of the system

When main switch of the system turnON, batteries supply necessary power to capacitor bank if capacitors are at its minimum voltage level (But usually capacitors are at its maximum voltage level because it fed with regenerative energy when parking). Capacthe main switchrovidesthe initial power demand of the motor through motor controller module. Motor controller module feed power to the motor according to the adjustment of the accelerator (accelerator can adjust by throttle twist grip).When accelerating the bike, capacitor bank pumps necessary power to the motor controller, at the same time capacitors are fed continuously through boost converter. At Low constant speeds capacitors saturated to its maximum voltage leveland motor controller supplied directly by batteries through Buck converter. At high constant speed capacitors drop to its minimum voltage level because of the high demand of energy which cannotfulfilled through the boost converter, then necessary energy supplied through the bypass diode. At a sudden acceleration, supercapacitor pump necessary high power demand of the motor controller. Further, when brake applied, then regenerative energy absorb from the motor and feed in to the super capacitor unless capacitors are at its saturated level, hence, excess regenerative energy feedback to the batteries via buck converter.

Chapter 5: Result and analysis

5.1: No-load Test Analysis

Here, modeled system test under no-load condition (motorruns freely without a load).This test has been conducted by using two clips on ampere meter, voltmeter and LCD display as shown in **Figure 5.1.1.**There are two types of test has been conducted on this condition as follows,

- Sudden acceleration test
- Typical running test

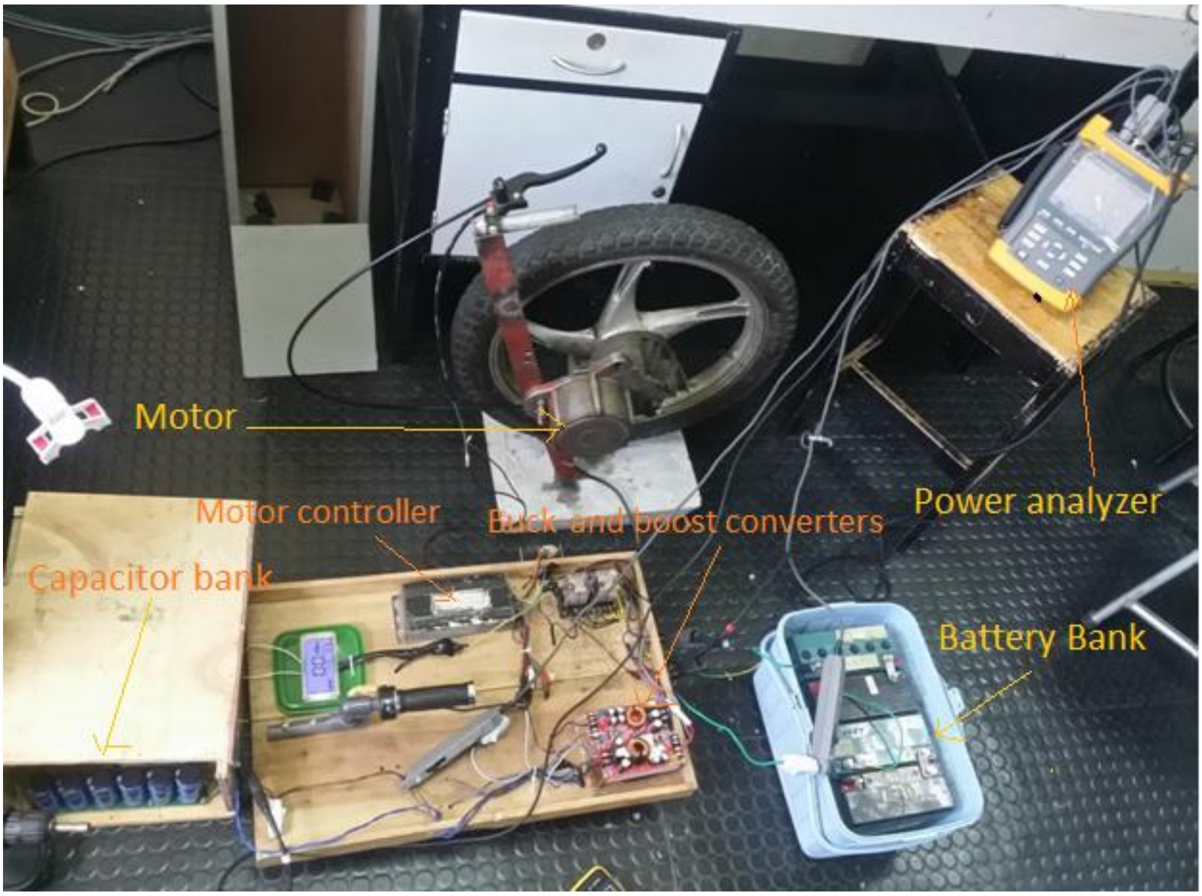

Figure 5.1.1
No-load test arrangement

5.1.1: Sudden acceleration test (NO-Load)

Two types of sudden acceleration test has been conducted as follows

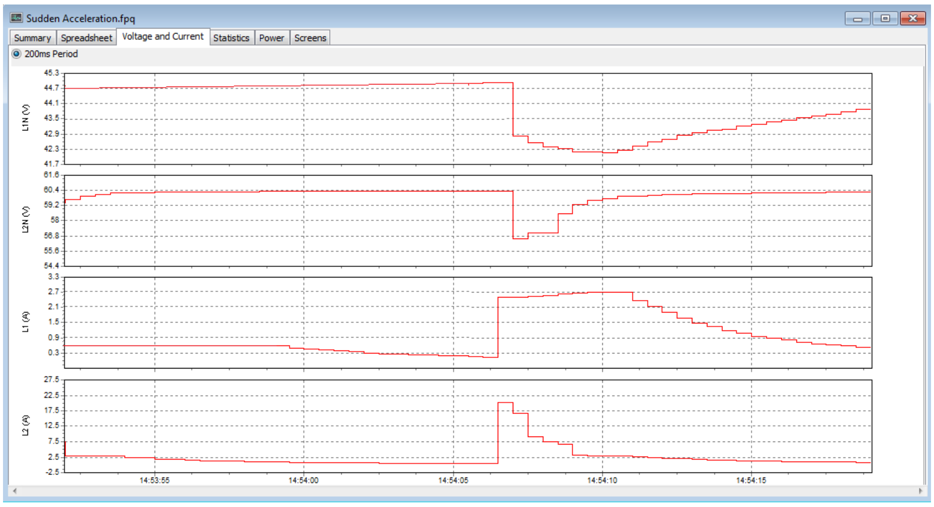

Figure 5.1.1.1
Sudden acceleration test result (no-load)-with super capacitor array

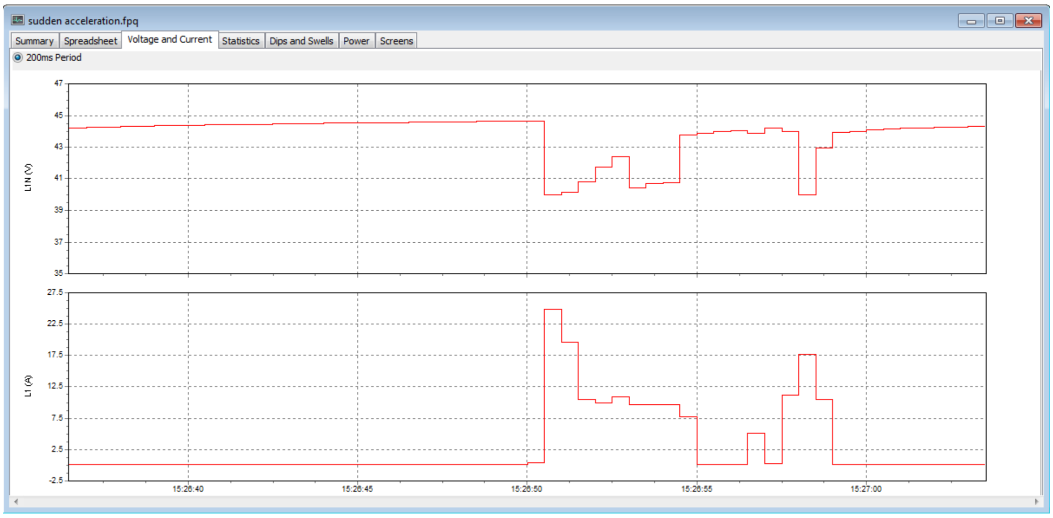

Figure 5.1.1.2
Sudden acceleration test result (no-load)- without capacitor array

Test results reveal that,

Without a super capacitor - Sudden acceleration instantaneous battery current is 25 A (in 200ms period)

With super capacitor (in HESS)- Sudden acceleration Battery current is 2.5A .With super capacitor arrangement ,test result reveal that DOD(Depth of Discharge) of the battery can be minimized and able to increasethe life cycle of the battery

5.1.2: Typical running test (No-Load)

Two types of typical running test have been conducted as follows

- Typical running test with capacitor array
- Typical running test without capacitor array

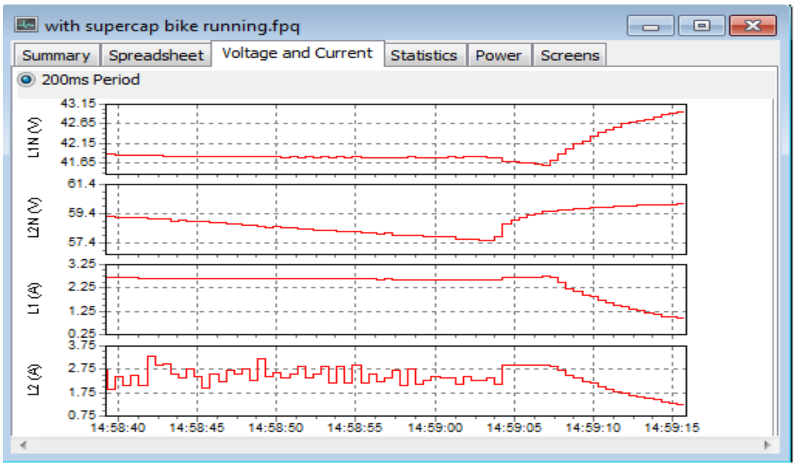

Figure 5.1.2.1

Typical running test result (no-load)-with super capacitor

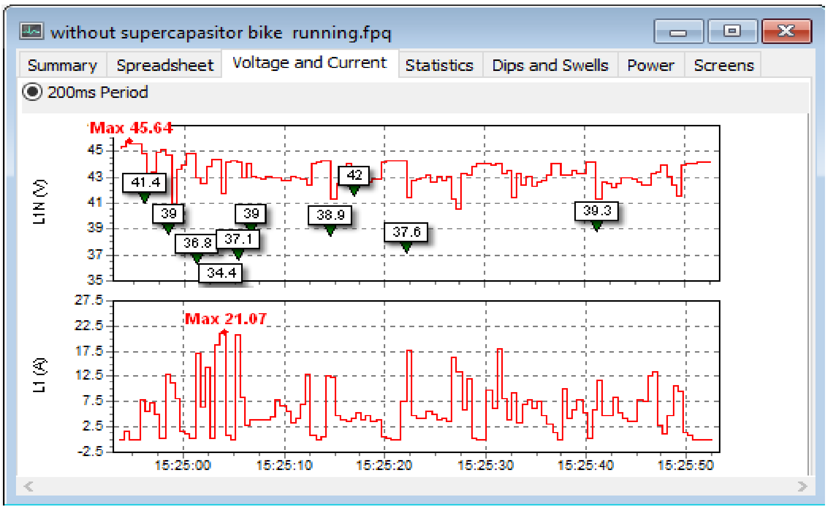

Figure 5.1.2.2

Typical running test result (no-load)-without super capacitor

At No-Load testing (various speeds), the results shows a constant current profile for the battery , which lead to enhance the battery life time.

5.2 On-Load Test Analysis

Here, modeled system test under Load condition (motor run under a load).This test has been conducted by using two clips on ampere meter, voltmeter and LCD display as shown in **Figure 5.2.1** There are two types of test has been conducted on this condition as follows,

- Sudden acceleration test
- Typical running test

Figure 5.2.1
On-load test arrangement

5.2.1: Sudden acceleration test (On-Load)

Two types of sudden acceleration test have been conducted as follows

- Sudden acceleration test with capacitor array
- Sudden acceleration test without capacitor array

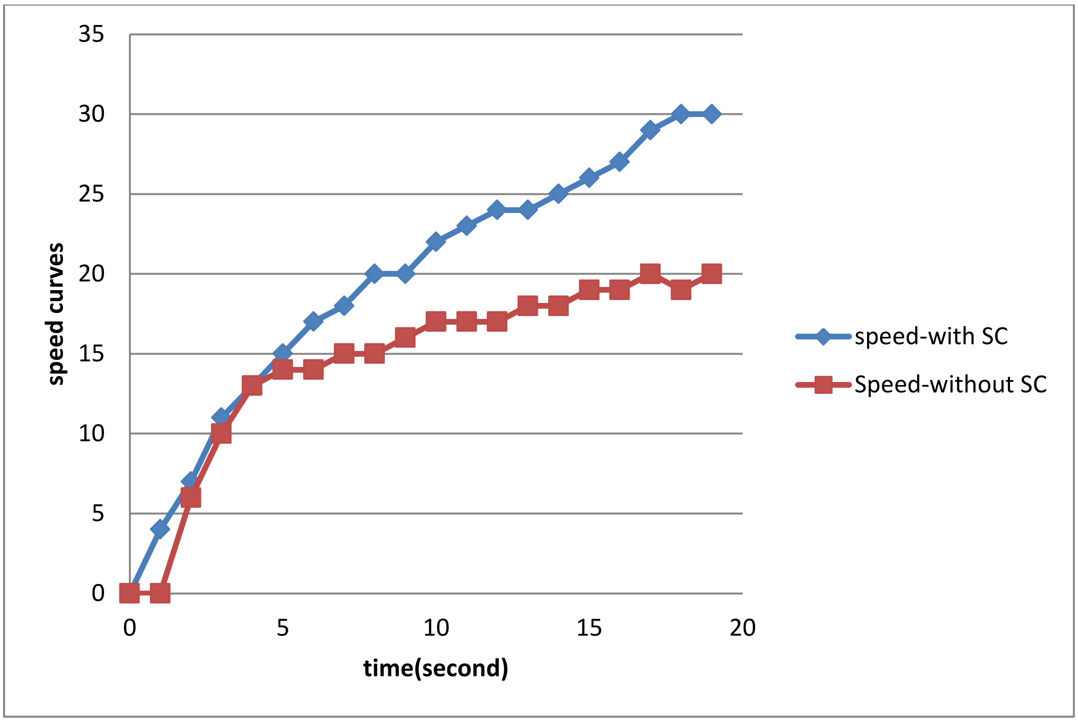

Figure 5.2.1.1
Speed curves of HESS and conventional E-bike

Test results reveals that, HESS reached to its maximum speed instantaneously (quick acceleration) compared to its conventional counter-parts due to very fast dynamic cycles of the super-capacitor. For optimize the operation of this design both batteries and ultra capacitors are being used for power release. DC to Dc converter keeps ultra capacitor at higher voltage than the battery to boost sudden acceleration especially when driving at city conditions

5.2.2: Typical running Test (On-Load)

Two types of typical running test have been conducted as follows,

- Typical running test with capacitor array
- Typical running test without capacitor array

Graph shown in Figure 5.2.2.1 is used as basic speed curve to test the system with above conditions with capacitor array , without capacitor array.Here , speed curve maintained , as following curve (Figure 5.2.2.1) then monitor battery and capacitor power variation according to the speed fluctuations.

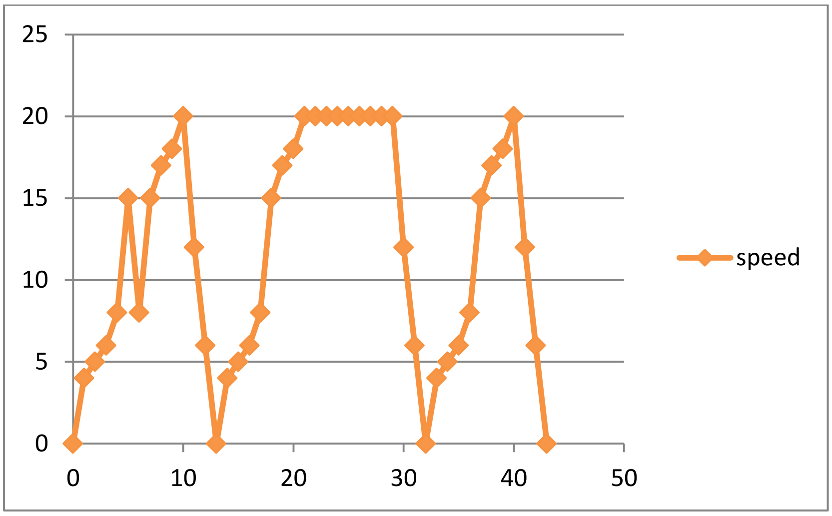

Figure 5.2.2.1
Typical running test (on-load)-speed(km/h)vs time(second) curve

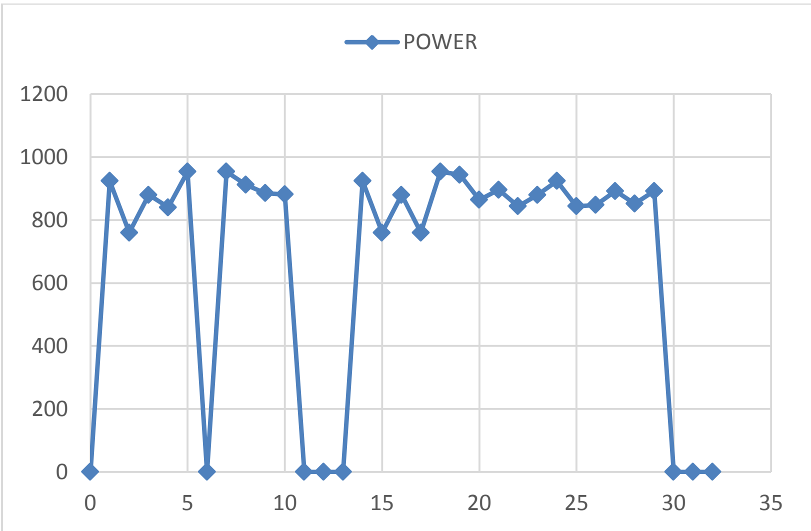

Figure 5.2.2.2
Typical running test (on-load)-power vs time(second)curve

According to the above test results, conventional E-bike runs 1km of distance using 0.056kWh Test result indicates, that vigorous energy is delivered directly via battery bank, and it leads rapid current drains in the system. In addition, the battery array unable to harvested sudden spikes and regenerative energy while braking. There for it shows that conventional E-bike unable to ,increase the prolong life of the battery array.

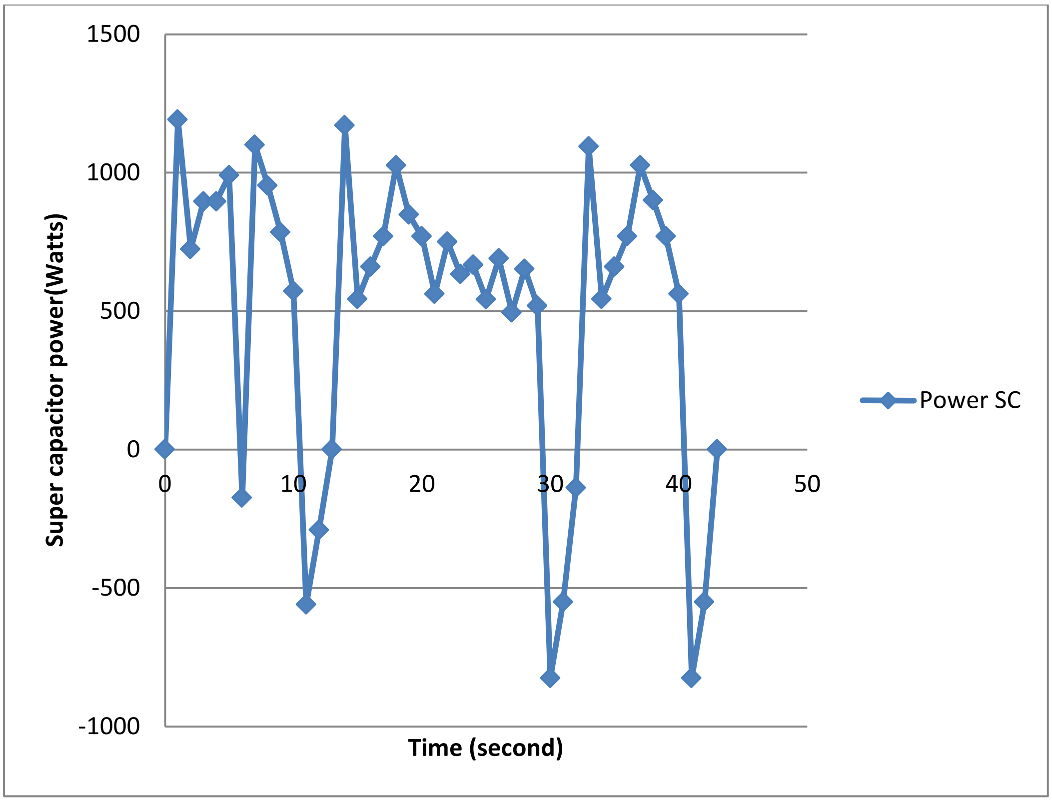

Figure 5.2.2.3
HESS-super capacitor power (on-load)-power curve

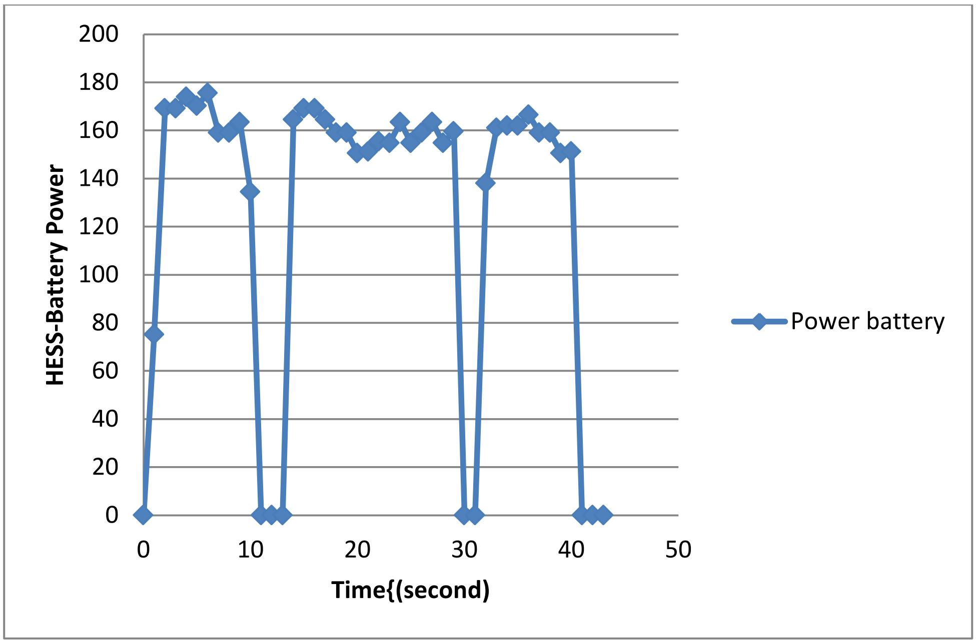

Figure 5.2.2.4
HESS-Battery power (on-load)-power curve

Test result indicates, a relative constant load profile is generate for the Battery-Array. Not only that, the battery not directly fed with harvested regenerative energy while braking. Instead, super capacitor first absorb regenerative energy and feed that energy to the motor for its frequent smaller demands unless regenerative energy is too large for the capacitor array which then feed back to the battery. This mechanism reducestha amount of charging-dischargingcycles of the battery and hence ,increase the prolong life of the battery array. HESS system run efficiently with lower energy per kilometer (0.049 kWh per 1km)

5.3 Overall Test Results Analysis

The designed system work as expected according to the test results. In complete drive cycle the super-capacitor combine with Buck-Boost converter able to satisfy system power demands.

The peak power demand for the super capacitor bank ranges from −0.8 kW to 1 kW. While, the peak power to the battery pack is limited to 0.170 W.

In HESS, the current demand via the DC/DC converter minimized because of the capacitor array fulfill high rated demands and reduce the impact on DC/Dc converter hence, low rated DC/DC converter can be used.

In a situation which motor continuously demands power from the system and come to a certain point which voltage of the capacitor array and battery terminal voltage equal

(V_{SC}<=. V_{batt}) This will activate the bypass diode and hence, bypass the DC/DC converter and deliver current via diode loop that reduce the additional burden to the converter.

Here test result shows HESS takes 10 -20s to reach it's maximum speed , as well as HESS system reduces frequent charging cycles and depth of discharge of the battery and increases the service life of the battery.

Test result shows that, in conventional systems Lead –acid batteries demand nearly 20A of current as its initial current to achieve its initial torque ,HESS demands only 3.6 A initial current thus, reduce DOD of the Lead acid batteries will caused to increase charging cycles up to1000 or more.

5.3 Overall Cost Result Analysis

Existing bike

E-Bike	Rs. 100000.00

Expenses for the modification of existing bike

Super Capacitor	Rs. 25000.00
Buck / Boost converters	Rs. 6500.00
Other expenses	Rs. 10000.00
Total Expenses	Rs.41500.00
HESS Total Cost	Rs. 141500.00

E-bike prior to modification

Total cost for 4 numbers of lead-acid battery	= Rs 30000.00
Number of average charging cycles	= 500
For 500 charging cycles cost for units (500 × (18.5 * 6))	= Rs 55500.00
Average distance that the battery can drive at an single charge	= 40 KM
For 500 charging cycles total distance battery can drive	= 40 KM × 500
	= 20000 KM
Total cost the battery set & charging units	= Rs. (30000 + 55500)
Unit cost	= 4.20 RS/KM

HESS bike after modification

Total cost for to design the New HESS system for E-bike	= Rs.41500
Increased mileage for a single charge	= 13 %
	= 40 KM × 13 %
	≈ 6 KM
Total distance that can drive for a single charge	=46 KM
After increasing the efficiency by changing DOD of the battery	
Number of average charging cycles	= 1000
For 1000 charging cycles total distance battery can drive	= 46 KM × 1000
	= 46000 KM
Of 1000 charging cycle cost of units	= 1000 × 18.5 * 6
	= Rs 111000.00
Total cost, the battery set & charging units	= Rs 141000 / 46000
Unit cost	= 3.06 RS/ Km

Chapter 6: Conclusion

By introducing Buck-Boost converter and super capacitor bank to the conventional Electrical bike following advantages has been achieved.

- **Reduction of Overall power consumption per kilometer,**

  0.056 kWh/km of power consumption in conventional E-bike reduced to 0.049 kWh /Km by harvesting the regenerative energy without dissipating it as heat in HESS which indicates a increment of 13 % efficienc ,by reducing power consumption

- **Increased the service lifetime of the battery**

  By overtaking additional stress of batteries(lowest rate of discharge) by the super capacitor bankduringpeakand frequent power demands and during sudden acceleration byincreasing the efficiency by changing DOD of the battery .

- **Enhanced quick acceleration**

  By fast operating capabilities of super capacitors which feed sudden power demands during acceleration.

  In HESS takes 15-20 s to reach its maximum speed while conventional e-bike takes more than 35 seconds

- **Increased traveling range per single charge.**

  Because of the increased energy efficiency of HESS(with harvest the regenerative energy) compare to conventional electric bike, the average traveling range per single charge of the batteries increased to 46+ km compared to 40km range in the conventional system (this result observed by driving both the conventional and HESS bike in similar driving platform)

- **Increased driving smoothness**

  Due to, quick energy releasing and absorbing capabilities of the super capacitors, they could supply a precise amount of energy demand of the motor in real-time (without delays) will lead to improve the smoothness of running of the bike.

- **Decrement of per kilometer cost**

  Because of the increased travelling range per single charge and increased lifetime of the battery that reduce the per kilometer unit cost from 4.20 Rs. /km to 3.06 Rs. /km

By considering aboveimprovements of HESS compared to conventional electric bike that conclude HESS system more energy efficient, more cost efficient and smooth in running compared to current electrical in the market which makes HESS bike good choice for future higher speed electric bike industry.

LIST OF ABBRIVATION

BLDC	Brush less DC motor
SC	super capacitor
V(sc-	Super capacitor voltage
V(Battery)	Battery Voltage
SOC	State of the charge
DOD	Depth of discharge
ESSs	Energy storage systems
HESS	Hybrid energy storage system

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Appendix:

DATASHEET 16V MODULES

FEATURES AND BENEFITS*

- Up to 1,000,000 duty cycles or 10 year DC life
- 16V DC working voltage
- Resistive or active cell balancing available
- Temperature output
- Overvoltage outputs available
- High power density
- Compact, rugged, fully enclosed splash-proof design

TYPICAL APPLICATIONS

- Wind turbine pitch control
- Transportation
- Heavy industrial equipment
- UPS systems

PRODUCT SPECIFICATIONS

ELECTRICAL	BMOD0500 P016 B01	BMOD0500 P016 B02
Rated Capacitance[1]	500 F	500 F
Minimum Capacitance, initial[1]	500 F	500F
Maximum Capacitance, initial[1]	600 F	600 F
Maximum ESR $_{DC}$, initial[1]	2.1 mΩ	2.1 mΩ
Test Current for Capacitance and ESR$_{DC}$[1]	100 A	100 A
Rated Voltage	16 V	16 V
Absolute Maximum Voltage[2]	17 V	17 V
Absolute Maximum Current	1,900 A	1,900 A
Leakage Current at 25°C, maximum (B01 Suffix - VMS 2.0)[3]	5.2 mA	N/A
Leakage Current at 25°C, maximum (B02 Suffix - Passive Balancing)[3]	N/A	170 mA
Maximum Series Voltage	750 V	750 V
Capacitance of Individual Cells[11]	3,000 F	3,000 F
Maximum Stored Energy, Individual Cell[11]	3.0 Wh	3.0 Wh
Number of Cells	6	6
TEMPERATURE		
Operating Temperature (Cell Case Temperature)		
Minimum	-40°C	-40°C
Maximum	65°C	65°C
Storage Temperature (Stored Uncharged)		
Minimum	-40°C	-40°C
Maximum	70°C	70°C

*Results may vary. Additional terms and conditions, including the limited warranty, apply at the time of purchase. See the warranty details for applicable operating and use requirements.

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PRODUCT SPECIFICATIONS (Cont'd)

PHYSICAL	BMOD0500 P016 B01	BMOD0500 P016 B02
Mass, typical	5.5 kg	5.5 kg
Power Terminals	M8/M10	M8/M10
Recommended Torque - Terminal	20/30 Nm	20/30 Nm
Vibration Specification	SAE J2380	SAE J2380
Shock Specification	SAE J2464	SAE J2464
Environmental Protection	IP65	IP65
Cooling	Natural Convection	Natural Convection
MONITORING / CELL VOLTAGE MANAGEMENT		
Internal Temperature Sensor	NTC Thermistor	NTC Thermistor
Temperature Interface	Analog	Analog
Cell Voltage Monitoring	Overvoltage Alarm	N/A
Connector	Deutsch DTM	Deutsch DTM
Cell Voltage Management	VMS 2.0	Passive
POWER & ENERGY		
Usable Specific Power, P_d [4]	2,700 W/kg	2,700 W/kg
Impedance Match Specific Power, P_{max} [5]	5,500 W/kg	5,500 W/kg
Specific Energy, E_{max} [6]	3.2 Wh/kg	3.2 Wh/kg
Stored Energy, E_{stored} [7]	18 Wh	18 Wh
SAFETY		
Short Circuit Current, typical (Current possible with short circuit from rated voltage. Do not use as an operating current.)	7,600 A	7,600 A
Certifications	RoHS, UL810a (150 V)	RoHS, UL810a (150 V)
High-Pot Capability[12]	2,500 VDC	2,500 VDC

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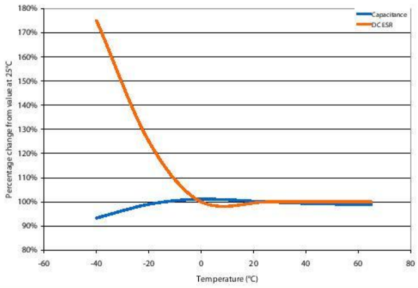
TYPICAL CHARACTERISTICS

THERMAL CHARACTERISTICS	BMOD0500 P016 B01	BMOD0500 P016 B02
Thermal Resistance (R_{ca}, All Cell Cases to Ambient), typical[8]	0.70°C/W	0.70°C/W
Thermal Capacitance (C_{th}), typical	4,300 J/°C	4,300 J/°C
Maximum Continuous Current (ΔT = 15°C)[8]	100 A_{RMS}	100 A_{RMS}
Maximum Continuous Current (ΔT = 40°C)[8]	160 A_{RMS}	160 A_{RMS}
LIFE		
DC Life at High Temperature[1] (held continuously at Rated Voltage & Maximum Operating Temperature)	1,500 hours	1,500 hours
Capacitance Change (% decrease from minimum initial value)	20%	20%
ESR Change (% increase from maximum initial value)	100%	100%
Projected DC Life at 25°C[1] (held continuously at Rated Voltage)	10 years	10 years
Capacitance Change (% decrease from minimum initial value)	20%	20%
ESR Change (% increase from maximum initial value)	100%	100%
Projected Cycle Life at 25°C[1,9,10]	1,000,000 cycles	1,000,000 cycles
Capacitance Change (% decrease from minimum initial value)	20%	20%
ESR Change (% increase from maximum initial value)	100%	100%
Test Current	100 A	100 A
Shelf Life (Stored uncharged at 25°C)	4 years	4 years

ESR AND CAPACITANCE VS TEMPERATURE



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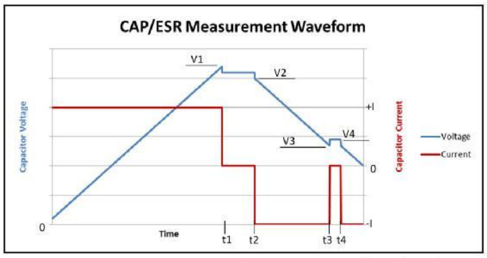
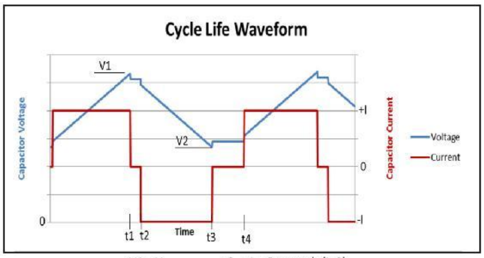
NOTES

1. Capacitance and ESR_{DC} measured at 25°C using specified test current per waveform below.
2. Absolute maximum voltage, non-repeated. Not to exceed 1 second.
3. After 72 hours at rated voltage. Initial leakage current can be higher.
4. Per IEC 62391-2, $P_d = \frac{0.12V^2}{ESR_{DC} \times mass}$
5. $P_{max} = \frac{V^2}{4 \times ESR_{DC} \times mass}$
6. $E_{max} = \frac{½ CV^2}{3,600 \times mass}$
7. $E_{stored} = \frac{½ CV^2}{3,600}$
8. $\Delta T = I_{RMS}^2 \times ESR \times R_{ca}$
9. Cycle using specified test current per waveform below.
10. Cycle life varies depending upon application-specific characteristics. Actual results will vary.
11. Per United Nations material classification UN3499, all Maxwell ultracapacitors have less than 10 Wh capacity to meet the requirements of Special Provisions 361. Both individual ultracapacitors and modules composed of those ultracapacitors shipped by Maxwell can be transported without being treated as dangerous goods (hazardous materials) under transportation regulations.
12. Duration = 60 seconds. Not intended as an operating parameter.



$V1 = V_{rated}$ $t2 - t1 = 15$ seconds Capacitance = I x (t3-t2)/(V2-V3)
$V3 = 0.5 \times V_{rated}$ $t4 - t3 = 5$ seconds ESR = (V4 - V3)/I



$V1 = V_{rated}$ $t2 - t1 = 5$ seconds (I=0)
$V2 = 0.5 \times V_{rated}$ $t4 - t3 = 15$ seconds (I=0)

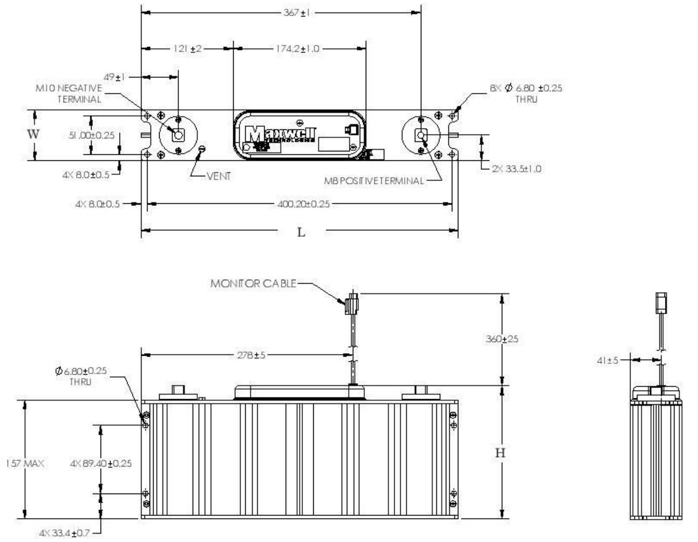
MOUNTING RECOMMENDATIONS

Please refer to the user manual for installation recommendations.

MARKINGS

Products are marked with the following information: Rated capacitance, rated voltage, product number, name of manufacturer, positive and negative terminal, warning marking, serial number.

BMOD0500 P016 B0X



Part Description	Dimensions (mm) L (max)	W (max)	H (max)	Package Quantity
BMOD0500 P016 B01/B02	418	68	179	3

Product dimensions are for reference only unless otherwise identified. Product dimensions and specifications may change without notice.
Please contact Maxwell Technologies directly for any technical specifications critical to application. All products featured on this datasheet are covered by the following U.S. patents and their respective foreign counterparts: 6643119, 7295423, 7342770, 7352558, 7384433, 7440258, 7492571, 7508651, 7580243, 7791860, 7791861, 7816891, 7859826, 7883553, 7935155, 8072734, 8098481, 8279580, and patents pending.

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Maxwell TECHNOLOGIES Enabling Energy's Future™

Efficient, Economical and Environmentally Friendly

Traditional lead-acid batteries rely on aging technology and toxic chemicals for energy storage. While adequate for some uses, chemical energy can create insurmountable limitations for emerging applications that require safe, dependable, quick-burst power, over long periods of time.

Seeking an alternative, many industries have embraced Maxwell Technologies' ultracapacitors – one of today's most efficient, economical and environmentally friendly energy storage alternatives.

Regenerative Braking and Peak Power

Ultracapacitors' unique performance characteristics make them ideal for capturing and storing braking energy generated in trains, trams, trucks and automobiles – and then releasing it on demand. They can deliver peak power for drive systems and actuators in a variety of vehicles.

Ideal for UPS Backup and Pulse Power

In UPS applications, ultracapacitors ensure that critical information and functions are available when supply voltage dips, sags, drops out or surges, or during a battery changeover. Working in tandem with a complementary power source, ultracapacitors reliably supply energy in peak power demand conditions, reducing strain on the primary source and extending its usable life.

Modular Storage Solutions

By linking multiple cells in a single module, Maxwell Technologies' ultracapacitors can meet or exceed the storage and power needs of today's most demanding applications. Based on either our K2 or BC series, modules provide a dependable, cost-effective solution for UPS, telecom, automotive, transportation, and other applications, reliably performing through hundreds of thousands of recharge cycles.

Specialty Modules

Maxwell also offers several dependable specialty modules that are tailored to the critical requirements of specific industries and applications. Our Heavy-duty Transportation Modules (HTM), for example, deliver the performance, reliability, and serviceability that satisfies transportation industry demands.

Our Engine Start Modules (ESM) for the trucking industry work in tandem with batteries, extending their life by providing reliable burst power at ignition. When the key turns, the engine cranks – even after a night of hotel loading in harsh conditions – in temperatures to forty below. The ESM also reduces or eliminates jump starts, improves driver safety and on-time deliveries; lowers total cost of ownership; and greater compliance with anti-idling laws. The ESM features a Group 31 form factor that can replace a battery in Class 3 to 8 trucks.

Numerous Benefits

- Environmentally safe
- No toxic chemicals
- Virtually maintenance free
- Long life***
- Operating temperature range -40ºC to +65ºC
- Higher energy vs. electrolytic capacitors
- Higher power vs. batteries
- Resists shock and vibration
- Multiple mounting options

Countless Applications

- Automated Meter Reading (AMR)
- Automotive
- Consumer electronics
- Industrial
- Telecommunications
- Transportation
- Renewable Energies
- Uninterruptible Power Supplies (UPS)
- Solid State Disk Drives
- Grid Storage
- Heavy Equipment

***Additional terms and conditions, including the limited warranty, apply at the time of purchase. See the datasheet and warranty details for applicable operating and use requirements.

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