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Design of DC-DC Converter for Hybrid Energy Storage Systems

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ABSTRACT

In Electric Vehicle (EV), the energy storage system plays a vital role as it controls and regulates the flow of energy. The desirable features of energy storage systems include high energy density, power density and good life cycle. In this context hybrid energy storage system combining the features of Lithium-ion battery and ultracapacitor for electric two-wheeler is considered in this work. The battery ultracapacitor system results in efficient energy storage with reduced cost, increase in lifetime of the battery and vehicle range extension. This work deals with the design of the power electronic interface to regulate the power flow from the hybrid energy storage system to the motor load. The modelling and simulation of the electric vehicle drive and the energy management system is carried out in MATLAB/Simulink and the performance is evaluated. The results reveal the effectiveness of the proposed approach.

Keywords— Battery, ultracapacitor, BLDC motor, energy management, State of Charge

I. INTRODUCTION

Electric vehicles are gaining popularity around the world due to their improved performance and lack of carbon emissions. The effectiveness of electric vehicles depends on proper interfacing between energy storage systems and power electronics converters [1]. On the other hand, the power delivered by energy storage devices exhibits unstable and uncontrolled voltage drops. Hence, electric vehicle converters, controllers, and modulation techniques are required to ensure a secure and reliable power transmission from energy storage systems to the electric motor. Modern Electric Vehicles (EV) are powered by Li-ion batteries. The attractive traits of these batteries include higher energy-density, better cycle-life, lower self-discharge and absence of memory effect. However, the limited power-density is a major hindrance in achieving high-current discharge or charge demanded during rapid acceleration and deceleration respectively [2]. Ultracapacitors (UC) are also known as super capacitors. They supply large amounts of power and can be recharged in a short period of time. Batteries work on the principle of conversion of electrical energy from chemical energy but due to the Electric Double Layer (EDL)effect UC can directly accumulate the electrical energy. UC can be charged and discharged at a very high specific current value (A/kg), 100 times more 2 than that of battery, without damaging the unit. Hence hybrid energy storage systems consisting of battery and UC are utilised in modern electric vehicles [3]. The design presented in this project attempts to replace a battery-alone system with Li-ion battery and Ultracapacitor based hybrid energy storage system for a two-wheeled electric vehicle and design a converter for the same. Introduction of UCs increases the specific power of the system and enables improved response during acceleration and regeneration. The limited cycle-life of the Li-ion battery can be extended by utilizing the energy from UC during high current requirements and dynamic load changes. These complementary electrical characteristics make them an ideal pair to realize a hybrid energy storage system (HESS). By combining battery bank and capacitor tank, it is possible to use a smaller battery with less peak-output power capability. Therefore, the cost would decrease significantly and the efficiency of the energy sources would increase.

II. VEHICLE DYNAMICS OF ELECTRIC TWO-WHEELER

A. Two wheeler specifications

As the proposed approach is to re-engineer the conventional battery-operated two-wheeler into an electric vehicle with Li-ion battery and UC, the specifications of the Hero electric Photon HX have been considered for analysis. The specifications of the Photon HX is given in Table 1.

TABLE 1: TWO WHEELER SPECIFICATIONS

S.No	Specification	Value
1	Mass of the vehicle (Curb weight +payload weight)	240 kg (90+150 kg)
2	Maximum Speed	45 km/h
3	Tyre (wheel) diameter	10 inches
4	Rolling resistance coefficient, Crr	0.015
5	Drag coefficient, Cd	0.6
6	Frontal area, Ad	0.8
7	Dimensions	1970/745/1145 mm

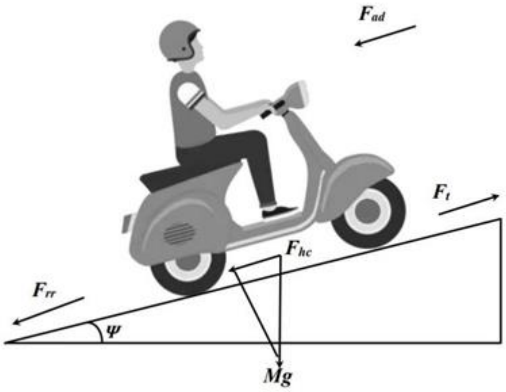

Fig.1. Modelling of vehicle load

The extended form of the above equation is given by

1
$Ft = Crrmgcos\Psi + 2\ \rho AdCdv$
$0.1Fla$

$+ mgsin\Psi + m\ dv +$
dt

where Crr is the rolling resistance coefficient, M is the mass of the vehicle (kg),
g is the gravitational constant (9.81 m/s2), C is the grade angle (degree),
ρ is the density of air (1.22 kg/m3), Ad is the frontal area (m2),
Cd is the drag coefficient and y is the speed of vehicle (m/s).
The gradient of road (***Ψ***) contributes a major role in the responses of the vehicle model. For simplicity, the maximum gradient of the road is assumed as ***Ψ***= 6 with a maximum speed of 15 km/h. The tractive power required at the wheels of the vehicle is calculated using the tractive force and velocity(v) of the vehicle, which is given by
$Tractive\ power, Pt = Ft\ x\ v$
By using the tractive power and transmission efficiency, the motor power is obtained as,

Pt
$Motor\ power, Pm =$
ηt

; $Pt \geq 0$

B. Vehicle dynamics

By using Newton's law of motion, the vehicle is modelled as a load by considering various longitudinal forces acting on it which is depicted in Figure 2.1. The tractive force (Ft) required to drive the wheels by overcoming resistive force is given by
$Ft = Frr + Fad + Fhc$
Where, Frr is the rolling resistance force, Fad is the aerodynamic drag,
Fhc is the hill climbing force.

$= Pt\ x\ \eta t;\qquad Pt < 0$

C. Power requirement for constant speed operation

Constant speed operations in drive cycle represent the continuous operation of the vehicle. The energy storage system with high energy density has the tendency to power the vehicle continuously during this mode. Hence, the maximum power demand during constant speed operation of the drive cycle must be provided by the main battery energy source. It is inferred from the IDC profile that the maximum constant speed occurs at the speed of 38km/h. For flat road(Ψ=0), the maximum cruising power required at wheels can be calculated from

$$P_{cruising} = [(C_{rr}\, mg\cos\Psi) + (0.5\, \rho\, A_d C_d\, v^2)]v_{max}$$

$$P_{cruising} = 1013W$$

where ρ is density of air (1.22kg/m3) and g is the gravitational constant (9.81 m/s2). The maximum cruising power the motor is obtained as 1.19 KW by considering the transmission efficiency(ηT=85%). Therefore, the maximum power required from the battery is calculated as 1.40KW by assuming motor and controller efficiency as 85%.

D. Power requirement for acceleration mode

The highest acceleration request occurs at the standstill condition of 0 km/h to 20 km/h in 6 sec of IDC. The maximum mechanical power required during acceleration request is obtained from

TABLE 3: SPECIFICATION OF LI-ION BATTERY CELL

S.No	Parameter	Value
1.	Voltage Range	2.5V to 3.7V
2.	Nominal Voltage	3.2V
3.	Weight and Cost	0.54kg and 20US $

$$P_{acceleration} = [(C_{rr}\, mg\cos\Psi) + (0.5\, \rho A_d C_d\, v_t^2) + (m \frac{dv_t}{dt})]\, v_t$$

$$P_{acceleration} = 1481\, W.$$

The electrical motor power required during this interval is 1.74 KW. Hence, the maximum power required from the HESS during acceleration is 2.05 KW. Since the battery can provide a maximum power of 1.401 KW, the remaining power required to be provided by UC. Therefore, the UC must provide the remaining power of 0.648 KW during acceleration by assuming converter efficiency as 0.85%.

TABLE 2: OPERATING MODES

S.No	Operating Mode	Motor power	Battery/UC power
1	Constant Speed	1191 W	1401W/0W
2	Acceleration	1742 W	1401 W/648 W

The required battery bank capacity is calculated as

$Energy\ required$

$Battery\ bank\ capacity = Nominal\ Voltage$
$1400\ Wh$
$= 200\ V$
$= 7Ah$
The number of series connected battery cells is obtained as,
$Nominal\ voltage\ of\ DC\ bus$

$Nbs = Nominal\ voltage\ of\ battery\ cell\ 200$
$= 3.2 = 62.5\ Nos$
$Nbs = 63\ Nos$
The number of parallel-connected battery cells corresponding to battery capacity is obtained as,

III. DESIGN OF POWER ELECTRONIC INTERFACE FOR THE ENERGY STORAGE SYSTEM

Nbp

$Battery\ bank\ capacity$
$=$
$Battery\ capacity$
Nbp

7
$= \quad = 0$
20

A. Proposed EV with hybrid energy storage system

In order to enhance the performance of the battery and to increase its lifetime, UC is interfaced along with the battery. The battery along with the UC constitutes the hybrid energy storage system. The block diagram of the proposed system is shown in Figure 2.

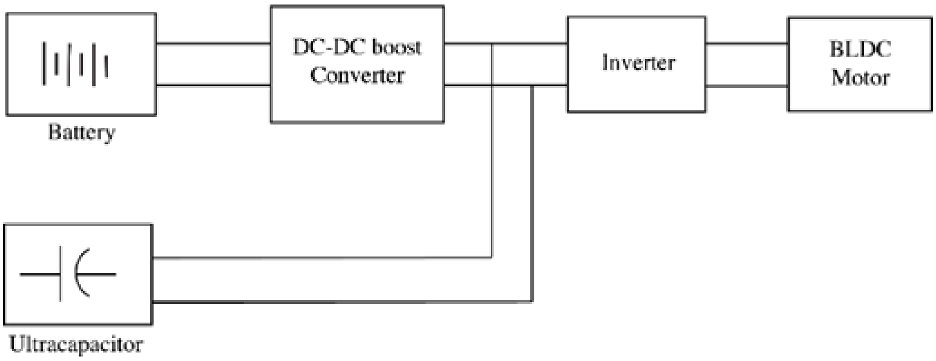

Fig.2 Block Diagram of the proposed system

B. Sizing of Hybrid Energy Storage System

The energy stored in one stack of battery =200V x 7Ah

=1400Wh

The maximum continuous current of battery

=1200W/200V=6A

Hence for a 1400W of energy storage,63 units of Li-ion battery cells (stacks with 63 cells in series and 0 in parallel) are needed.

C. UC specifications

The maximum and minimum voltage of the UC cell is 2.7 V and 1.5 V. Therefore,74 numbers of 2.7V UC cells are connected in series to achieve a maximum voltage of 200 V on the LV side. The nominal voltage of the UC bank is 27 V. The minimum capacitance requirement of UC cell for the maximum velocity of electric vehicle can be calculated from

1

$u \quad 2\ UC$

$[V2$

$UCmax$

$- V2UCmax]$

$1\ C$

$[V2$

$- V2$

$] * No\ of\ series\ cells =$

This section presents a design methodology adopted for sizing the Li-ion battery and UC energy sources for a two-

wheeled EV using IDC. This methodology determines the

$2\ \ UC$

$UCmax$

$UCmax$

1 $mv2$

2

max

number of battery and UC cells needed in series or parallel stacking to achieve the demanded energy of the vehicle.

A. Battery Specifications

LiFePO4 prismatic battery cell with a nominal voltage of 3.2V, 20Ah is considered in this study. The battery pack with the terminal voltage of 200V is directly connected to the motor drive.

CUC = 100F

Where, CUC- Capacitance of UC;

VUCmax - maximum UC voltage of a cell= 2.7V. VUCmin - minimum UC voltage of a cell = 1.5V

Hence, a UC with 100F capacitance should be chosen. The commercially available UC is 100F.The specification of the chosen UC is given in Table 4.

TABLE 4: SPECIFICATION OF UC CELL

S.no	Parameter	Value
1	Internal resistance	15mΩ
2	Stored energy	0.101Wh
3	Continuous and maximum current	11A and 36A
4	Weight	0.021kg
5	No. of cells in series (NUS)	200/2.7≅74 No.
6	Allowable voltage range	1.5V to 2.7V

The current supplied to the output RC circuit is discontinuous. Thus, a larger filter capacitor is required to limit the output voltage ripple. The minimum value of filter capacitor that provides the DC current to the load when the diode D is off is given by

$Cmin$

DVo

$= V\ RF$

TABLE 5: COMPONENT VALUES OF DC-DC BOOST CONVERTER

Description	Rating
Inductor	120 μH
Capacitor	330 μF
Switching frequency	20 kHz

The UC bank must provide 648 W power during the initial acceleration request in a time period of 6 sec. Hence, the average current of UC is calculated as

648 + 648

IV. SELECTION OF MOTOR

$iUC(acc) =$

200 110
2

$= 4.56A$

The electric motor and its power rating are chosen based
By assuming number of parallel UC (NUP=1), the total capacitance of the UC bank can be obtained as on the requirements of the propulsion system and the driving road conditions. The electric motor employed in EV should

NUP
$Ctotal = Ccell *$
US

1
$= 100 * = 1.35\ F$
74

fulfill the following requirements:

- Wide speed range
- Frequent start/stop operations

Then, the total resistance of the UC bank is given by

- More torque and less speed for acceleration mode

$Rtotal$

$= Rcell$

NUP
$*$
NUS

$= 15 \ast 10–3 \ast 1$
74

$= 0.2027 m\Omega$

- Less torque and high speed for constant speed mode
- Acceleration/deceleration in high rate

Therefore, the weight of the UC bank is 1.554kg.

V. DESIGN OF DC-DC BOOST CONVERTER

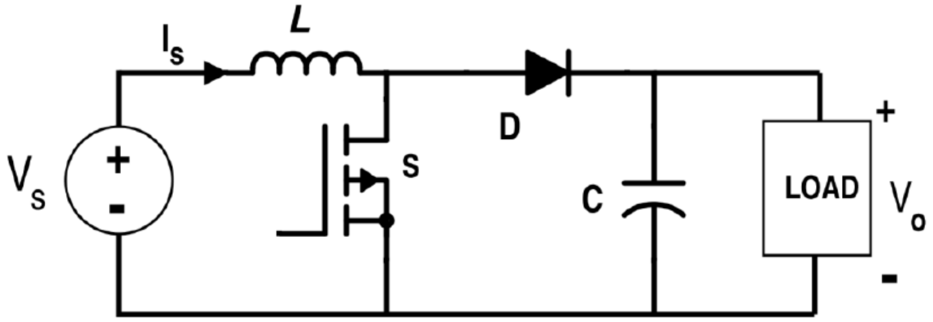

Fig.3. DC-DC Boost Converter

A DC-DC converter consists of a DC input voltage source VS, boost inductor L, controlled switch S, diode D, filter capacitor C and load resistance R. If the switch operates with a duty ratio D, the DC voltage gain of the boost converter is given by

By considering the propulsion system requirements, efficiency, fast response, easy maintenance, simple structure and expenses, a Brushless Direct Current (BLDC) motor is preferred.

A. BLDC motor

A BLDC motor with the trapezoidal back-EMF produces larger torque compared to a PMSM with the sinusoidal back-EMF.BLDC motors are a novel type of the conventional DC motors where commutation is done electronically, not by brushes. Therefore, a BLDC motor needs less maintenance, has lower noise susceptibility and lesser power dissipation in the air gap compared to a brushed DC motor due to absence of the brushes.

$Vo \qquad 1$
$Mv = V = 1 - d$

where Vs is input voltage, Vo is output voltage, and d is the duty cycle of the pulse width modulation (PWM) signal used to control the IGBT ON and OFF states.
The boost converter operates in the continuous conduction mode for the value of inductance L > Lb where,
$(1–D2)DR$

$Lb\ =$

,
$2f$

where Lb is the minimum value of inductance for continuous conduction.

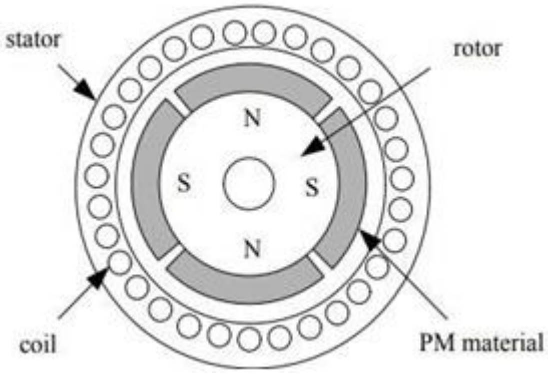

Fig .4.BLDC Configuration

B. BLDC drive system
The drive system of the motor is one of the most important components of electric vehicle that has influence over the performance of the system. Several topologies of DC/AC converters are available such as H-bridge, diode-clamped, cascaded, multi-level, matrix and flying capacitor. H-bridge converter is found to be the simple and cost-effective converter for AC drive applications. The BLDC motor drive system is shown in Figure 5.

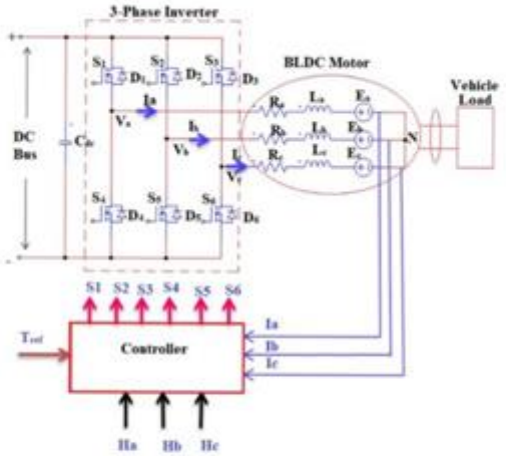

Fig 5: BLDC Motor drive system

VI. ENERGY MANAGEMENT OF THE HYBRID ENERGY STORAGE SYSTEM

In this chapter, an energy management strategy is proposed for the battery-supercapacitor hybrid energy storage system. A battery and supercapacitor have different characteristics in their operation. A battery has a relatively high energy density, but a low power density compared to an SC. In contrast, an SC has a relatively high-power density but a low energy density compared to battery. To overcome the shortcomings of the battery and supercapacitor, an energy management strategy is implemented with the help of DC-DC converter. The flowchart of the energy management strategy is presented in Figure 6.

First, the power demand of the motor and the SOC of the battery and ultracapacitor is obtained as input. The maximum power demand from the battery is 1400 W. When the power demand exceeds the maximum power of the battery (>1400 W), the demand is supplied by both the battery and the ultracapacitor. The voltage from the battery is increased accordingly to meet the power demand by the DC-DC boost converter. When the power demand is lesser than the maximum power of the battery (<1400 W), the State of Charge of the battery is checked. When the SOC of the battery is greater than the minimum SOC of the battery, the power demand is supplied by the boosted output from the battery alone. When the SOC of the battery is lesser than the minimum SOC, then the SOC of the UC is checked. If the SOC of the UC is greater than the minimum SOC, the power demand is supplied by both battery and ultracapacitor.

VII. SIMULATION RESULTS

The proposed energy management strategy is simulated in MATLAB and the following results are obtained. Figure 7 shows the motor power requirement. The system has been simulated for a period of 2 seconds. For the first 0.8 seconds, the motor power requirement is more than 1400W. For the next 0.4 seconds, the demand is less than 1400W and the demand decreases further for the next 0.4 seconds.

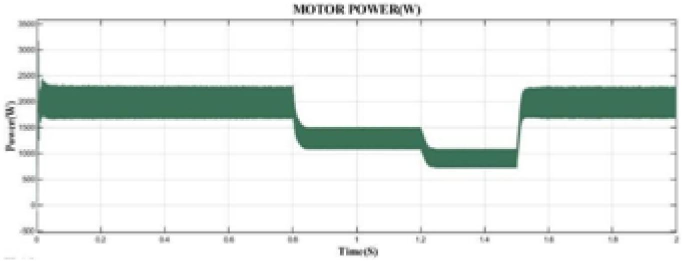

Fig 7: Motor power

The state of charge of the battery is shown in figure 8. From the graph the state of charge of the battery decreases steadily as the battery supplies the power demand continuously.

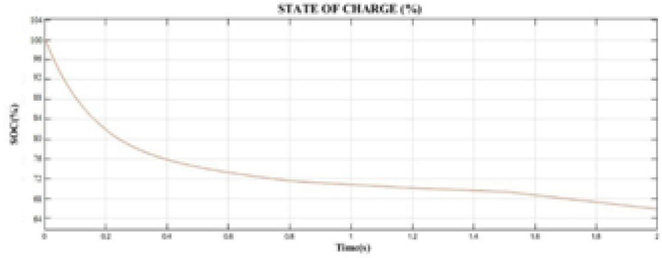

Fig 8: SOC of battery

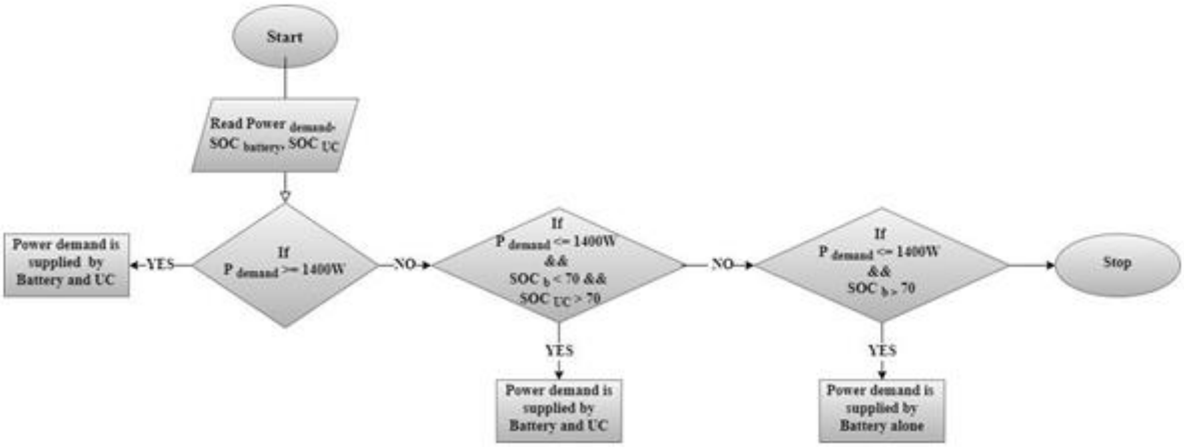

Fig 6: Flowchart of the energy management strategy

Figure 9 shows the electromagnetic torque of the motor. The initial torque of the motor is 5 Nm and it decreases to 2 Nm after 0.8 seconds. The torque then increases to 5 Nm after 1.5 seconds.

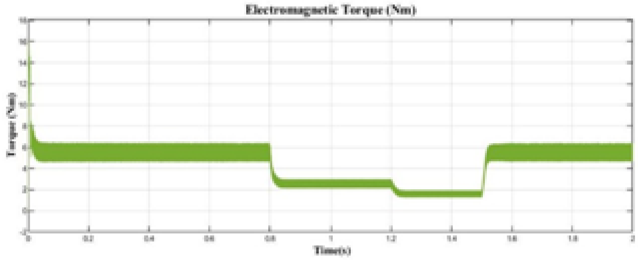

Fig 9: Motor torque

Figure 10 shows the current supplied by the battery. The battery current varies according to the torque of the motor. From figure 4.5 and 4.6, it can be inferred that when the motor torque decreases the current supplied by the battery also decreases.

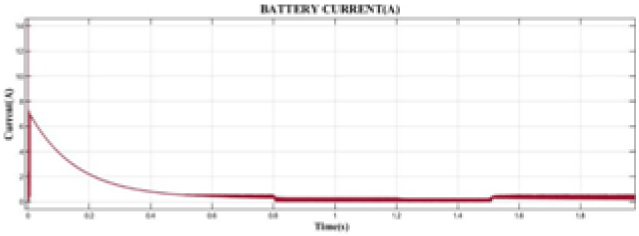

Fig 10: Battery current

Figure 11 shows the current supplied by the ultracapacitor. From the graph it is seen that the ultracapacitor supplies the demand for the initial 0.8 seconds when the power demand is greater than 1400 W and also from 0.8 to 1.2 seconds when the power demand is less than 1400 W and the SOC of the battery is less than the minimum SOC.

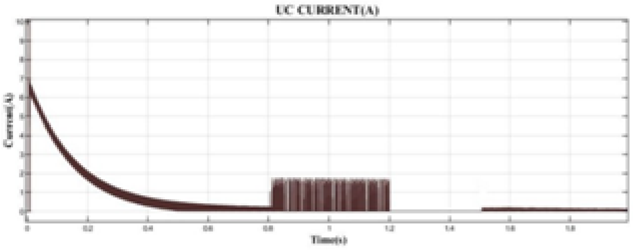

Fig 11: Ultracapacitor current

VIII. CONCLUSION

This project presents a battery/ultra-capacitor based hybrid energy storage system for electric two-wheeler. The design aspects and the power requirement of the components involved in EV has been presented by considering Hero Photon HX two-wheeler. The design of the power electronic interface is detailed in this work. The simulation studies are carried out in MATLAB/Simulink environment. The power electronic interface ensures that the battery and ultracapacitor provides the required power during acceleration. This aids in enhancing the performance of the battery. The energy management strategy is implemented and the control strategy ensures the UC supplies the power demand during transient peak power demand. This reduces the strain on the battery and enhances the battery life. The simulation is performed to supply the power demand based on the torque requirement and the SOC of the battery. The simulation results provide clear insights into the characteristics of EV with hybrid energy storage.

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