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Design Parameter and Simulation Analysis of Electric Bike Using Bi-Directional Power Converter

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Abstract **- Energy and environment are the supreme priority of the 21st century. Proliferating use of Electric vehicles introducing zero pollution transport system. Electric bikes are widely attractive due to the affordability and compact size. Paper provides basic design analysis of electric bikes. The research analyzed and compute the power requirement, battery capacity, maximum angular velocity, converter parameters and filter values for the required electric bike. Simulation and calculation analysis are performed for both driving and regenerative mode using a bidirectional converter. The research concludes the power consumption, regenerative energy, charging current behavior while driving and the impact of regenerative braking on mileage. Results also provide a comparison of electric bikes with ICE bikes.**

Index Terms –Electric Bikes, bidirectional DC-DC converter, filter values, regenerative energy, quadrant operation, power electronic converter, Energy and environment.

I. INTRODUCTION

Electrical vehicles (EV) are tending transport of the 21st century due to global environmental and energy dilemmas. Modern countries are focusing on zero pollution transport system. Lahore, Pakistan marked topped in the ranking of cities with the disaster air quality index [1]. In generic two types of electric bikes (E-bike or EB) are available. One is entirely electric which can work on motor power and pedaling independently. Others are electric assist bikes which provide the hybrid function of electric and human pedaling.

Due to the rapid increase in Electric vehicles, the worldwide chronological development in the research trends towards Electric Bike is also increased. Research on electric bike converted into a practical model back in 1890's by Ogden Bolton when he designed a battery fed DC motor for EB. In the end of 1990's the weight of EB was much reduced and the storage capacity of batteries was much increased which improved the performance. Moreover, torque sensors and power control were also introduced. E-Bikes are attaining worldwide acceptance, generally in Europe, Chine, US and Japan. China is the largest developer of electric Bikes due to its population and pollution problem. Chines E-bicycles design for slow a speed of 20Km/h weighing nearly 40kg. Pedelec power E-bikes are more popular in Japan. In future electric vehicles are the main transport for urban roads. Power electronic research is also important to improve the steady state, transient and dynamic load variation of these vehicles. They also improve the efficiency and performance of the vehicle [2-3]. Study shows that electric bicycles save an average of 8.5L of gasoline for every 100km and are an alternative means of transport to the car. Electric bikes are much popular today due to the increasing cost of gasoline. Analysis advocate that the price of E-bikes is decreasing rapidly because EB offers an economical traveling cost [4].

This Environment Friendly Electric Bike, which of course has an electric motor attached to it comes with a battery as a source of energy. Traditionally electric bikes use customized DC hub machines fitted in the rear wheel [5]. China, being an excessively populated country, has benefited the most from this invention. As proof of the above statement, 31 million e-bikes were sold in 2012. EB has both economic and environmental benefits as its main advantages. The economic advantage is that the total cost per km travelled by an electric bicycle is less than 0.7 cents as compared to the gasoline scooter's $0.031/Km [6] or $0.62 by a car and that too with the energy, purchasing and maintenance. Typically, EB needs 6-8 hours to recharge and has a range of 35 to 70Km. It has been designed according to the needs and studies show a person travels average 15 km daily.

A regenerative power control circuit has also been included in the EB to charge the battery from the rotation of the wheel. An electric motor is fixed in the wheel of EB. As far as the construction of the motor is concerned there is a permanent magnet in the rotor and the stator has a coil winding. Now a

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day's electric bikes use regenerative braking to convert their kinetic energy into electrical energy which is stored in the battery to increase the travel time of the bike. In order to achieve higher voltage even at lower RPM an electronic circuit is designed in which the voltage output of the motor is increased by increasing the duty cycle of the MOSFET.

II. METHODOLOGY

Electric bikes use an electric machine to power wheels. Normally motors are known as hub-motor in EB. The system block description is briefly defined in figure [fig:1]. Throttle input provides electrical energy from battery to DC machine by mean of the bi-directional power converter. The amount of energy is depending on the throttle setting, increasing throttle regulator tends to raise the angular velocity of the DC machine. The battery pack is charged from external charger or from the regenerative energy. For this purpose, bidirectional converter is used, it provides a path to charge the battery from the motor back EMF [7-8]. Normally 48volt small form factor converter is used [9].

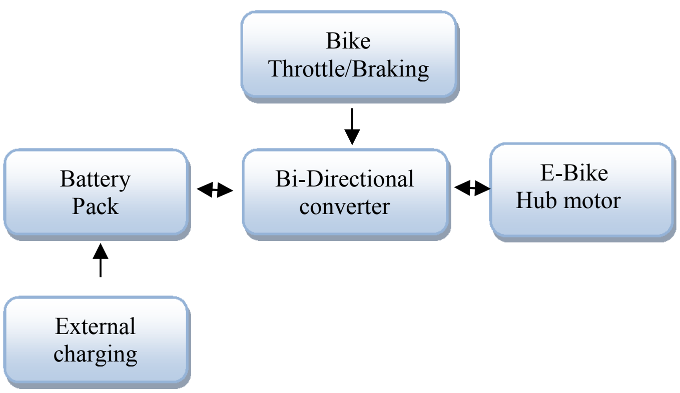

Fig.1: System Block Diagram

A. First Quadrant

If we observe the motor operation, the first quadrant represents forward motoring because in this quadrant, battery voltage is greater than the motor's EMF and the direction of current is from battery to motor.

B. Second Quadrant

On the contrary, in second quadrant regenerative braking phenomena occurs in which the voltage magnitude is positive but the current direction is from the motor towards the battery. In order to charge the battery, motor's back EMF must be greater than the battery voltage which in turn increases the electric bike mileage.

C. Four Quadrant

Full controlled or four quadrant operation provides 4 modes i.e. forward motoring, revere motoring, forward braking and reverse braking.

D. System working

Normally the back EMF of the machine is less than the battery terminal voltages then it has to be boosted with the help of the electronic circuitry to make it higher than battery voltage to move the current from motor towards battery. Traditionally permanent magnet direct current (PMDC) and brushless direct current (BLDC) are used for Electric bikes depending upon the power, torque and control scheme. Here, the general term of DC machine is used for analysis. Research provides the basic design calculation analysis and the buck & boost mode operation of bidirectional converter. The battery pack provides power to DC motor by means of throttle which controls the duty cycle of MOSFET and converter is working in driving or buck mode. Paper uses a higher potential battery pack then the nominal voltage of DC machine. When the throttle is release or brakes are applied converter will be shifted to regenerative mode. As the back EMF is less than the battery voltages, boost mode increase the machine EMF to higher potential then battery potential.

III. SYSTEM DESIGN CONSIDERATION

The first step is to estimate the power requirement of the selected DC machine. Suppose motorbike speed should be 50Km/h with an acceleration of $1.16ms^{-2}$. Total weight including driver is nearly 130Kg and tire of the radius (R) 0.28m. The twist movement in a tire can be thought of as a torque that can be measure from the product of force and movement arm for maximum value. Force is equal to mass into acceleration given in equation (1). Bike Linear speed is the tangential component of rotational velocity, which is the product of angular velocity and radius (2). Power required to develop that much torque with required linear speed is found by the relation (3). Required torque and power is computed as,

$$T_{req} = Rma \tag{1}$$

$$= 0.28 \times 130 \times 1.16 = 42.2\text{Nm}$$

$$V = \omega R \tag{2}$$

$$\omega = \frac{13.8}{0.28} = 49.6 \text{ rad/sec}$$

$$P_{req} = \omega T_{req} \tag{3}$$

$$= 49.6 \times 42.2 = 2093 \text{ watt}$$

Approximately 2KW hub motor should be placed within a bike tire. The Machine rated voltage should be less than the battery terminal voltages. To move the machine with nearly 50 rad/sec by providing 70 voltage, the required speed constant becomes 1.4 V/rad. As the customized machine is assumed, it has negligible armature inductance of 0.1mH. The required parameter of the machine is shown in table 1. The basic bi-directional power flow converter for E-bike is shown in figure [fig: 2]. Two MOSFET S1 and S2 control the speed and direction of power. Diode D1 is used as freewheeling and D2 helps to move power from machine to battery. C1, C2 and L are used as filter components.

Table 1: Machine parameters

Parameter	Value
Rated Voltage	72 V
Power	2000 Watt
Armature inductance	0.1mH
Resistance	0.2 Ω
Speed constant	1.37 V/Rad

A. Battery Pack and Bike millage

Two packs of 48 Volt 30Ah (90 ~ 96V, 30Ah) batter is used to drive 2000-watt machine. Latest Panasonic or Tesla Li-ion cells pack can be used as a battery to power E-bike. Here 13p, 10s combination is used for a battery pack with a cell capacity of 3.7V, 3000mAh as shown in figure [fig:3]. The battery backup can be calculated with known total capacity, no of pack, efficiency and load in watts [10]. 2880Wh battery bank ideally able to drive E-bike for 1 hour 26 minutes at speed of 50Km/h. On single charge bike will cover nearly 75Km and approximately 45~50Km at acceptable SOC.

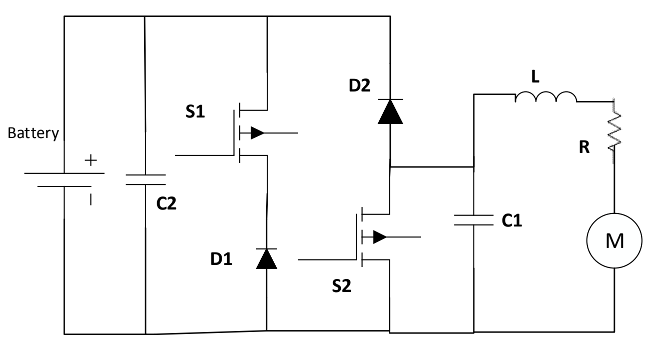

Fig 2: Bi-directional converter for E-Bike

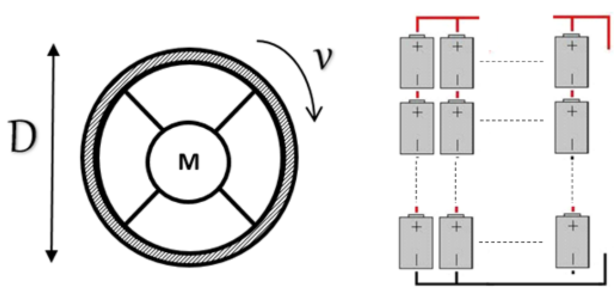

Fig 3: E-Bike wheel and battery assembly

B. DC machine parameter

The required DC Machine constant K_e is 1.37V/rad and operating potential of 72V. Its internal resistance and inductance are 0.2Ω and 0.1mH respectively [table:1]. EMF of bike is related with angular velocity in following terms.

$$E_a = \omega K_e \tag{4}$$

C. DC-DC power converter

In driving mode converter is performing buck operation, the desire duty cycle D_1 will find as,

$$V_m = D_1 V_B \tag{5}$$

$$D_1 = \frac{72}{90} = 0.8$$

For regenerative mode, converter will operate in 2nd quadrant assuming transient back emf of 70V and to boost it to level 100V for charging mode, duty cycly D_2 should be,

$$V_{B2} = \frac{E_a}{1-D_2} \tag{6}$$

$$D_2 = 1 - \frac{70}{100} = 0.30$$

D. Required filter values

Filter components are required for smooth operation for driving and battery charging mode. Assuming switching frequency of 10Khz, ΔI ≈ 0.3A and ΔV ≈ 3.6V. L_1 and L_2 are calculated as,

$$L_1 = \frac{V_m(1-D_1)}{\Delta i\, f_s} \tag{7}$$

$$L_1 = \frac{72(1-0.8)}{0.3 \times 10 \times 10^3} \approx 4.8 \text{ mH}$$

$$L_2 = \frac{V_m D_2}{\Delta I\, f_s} \tag{8}$$

$$L_2 = \frac{72(0.3)}{0.3 \times 10 \times 10^3} \approx 7 \text{ mH}$$

The inductor L , valve of 10mH is used for both modes. Machine internal reistance is 0.2Ω, For analysis capacitor value of 5000uF is used.

$$C = \frac{D_2}{R\,(^{\Delta V}/_{V})\, f_s} \tag{9}$$

$$C = \frac{(0.3)}{0.2 \times \left(\frac{3.6}{96}\right) \times 10 \times 10^3} \approx 4000\text{uF}$$

IV. Simulation Analysis

The E-bike driving and regenerative analysis using two quadrant power converter are perform on the simulation model (PSPICE/MultiSIM/PSIM). According to the design calculation the final circuit is shown in figure [fig:4]. Switches are controlled by connector P1 and P2 which represents the duty cycle of each mode. Both duty cycle can be controlled using a variable DC level. By feedback control system desire and optimum duty ratio can be achieved.

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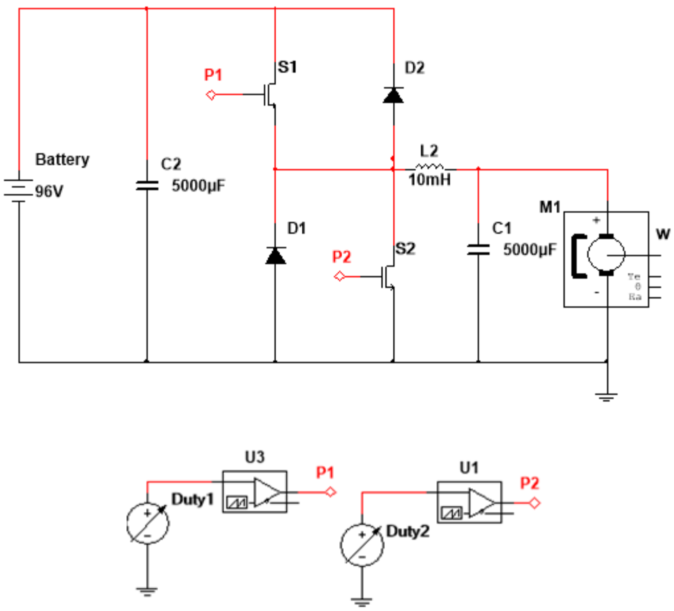
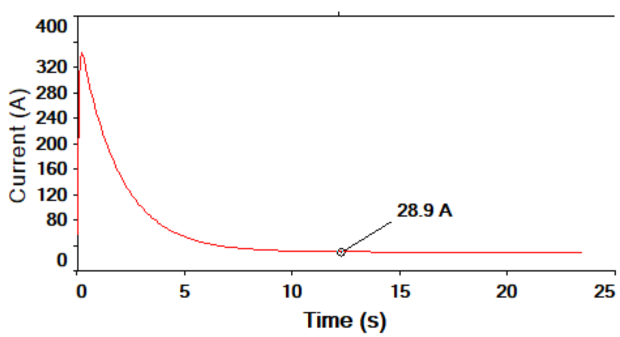
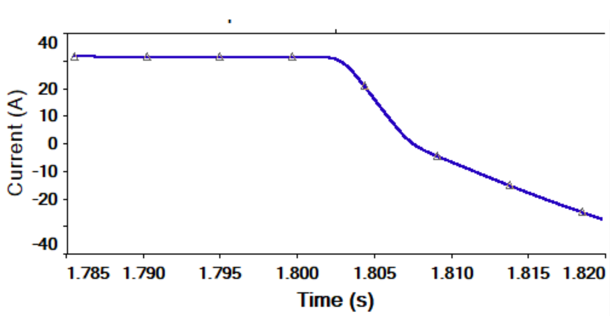


Fig 4: Simulation Circuit

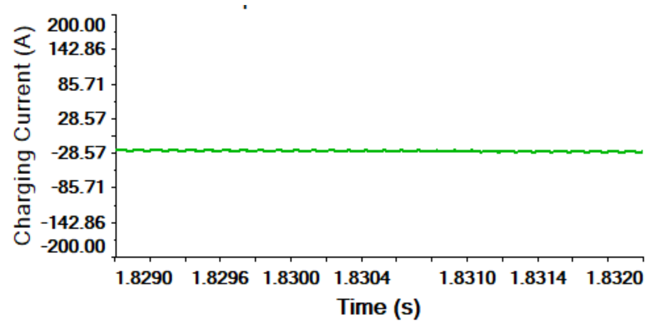
Driving motor current consumption response is shown in figure [fig: 5]. At steady state 29 ampere current (i_m) is consumed by a bike hub motor. Suppose at time 1.8s regenerative mode is applied, now converter is working in 2nd quadrant and the machine is start providing -28.3A regenerative current to charge the battery with time interval of 15ms [fig:5b]. The figure demonstrates nearly ripple free instantaneous charging current.



(a)



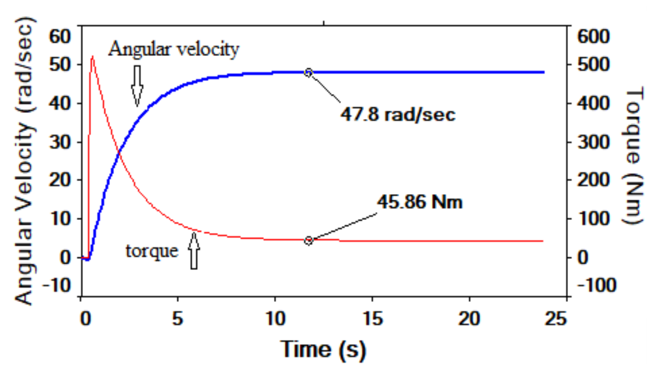
(b)



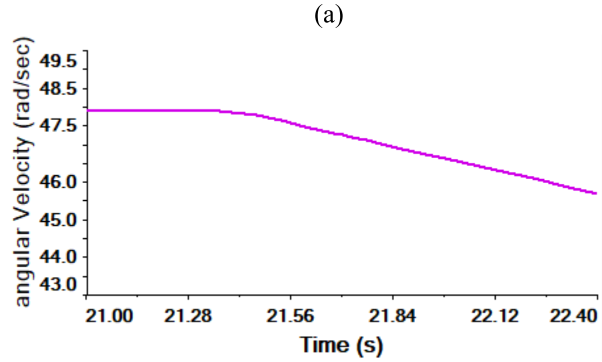
(c)

Fig 5: Current (i_m) response of DC machine (a) throttle driving mode (b) driving to regenerative mode (c) regenerative charging

The reverse current value may affect with the uphill and downhill direction of E-Bike. It also depends on the linear angular speed, torque and total weight. The angular velocity of the machine at different modes and intervals of time is shown in figure [fig: 6]. Waveforms are closed to the calculated values. When regenerative mode is applied, bike angular velocity reduced to 45.8 rad/sec within the interval of 0.84s [fig: 6b].



(a)



(b)

Fig 6: Angular velocity of DC machine (a) driving mode (b) regenerative mode (deceleration)

A fully controlled four quadrant operation of DC machine is also shown in figure [fig:7]. Connector P1, P2, P3 and P4 are used for throttle, energy regenerative and braking of the E-bike.

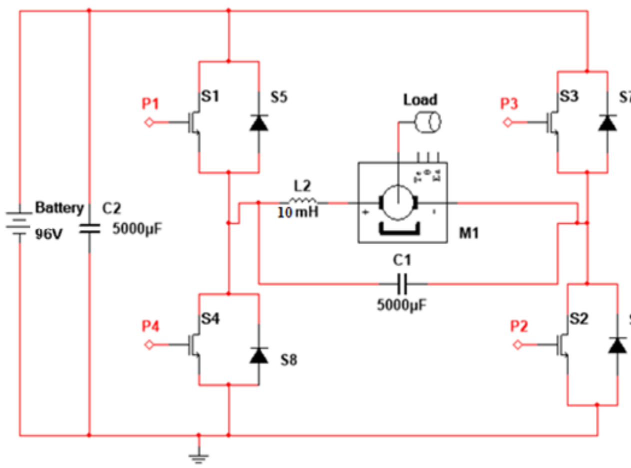


Fig 7: Four quadrant mode of operation (a) circuit diagram (b) angular velocity response

Fig 8. Shows the power consumption of the machine in different mode. Steady state power is 2122W that is nearly the same as calculated in (3). During constant speed when the throttle is release and regenerative operation is start it regenerate negative 1970W power within nearly 20ms and peak power of 3286W. Negligible distortion shows the shifting of the machine in regenerative mode [fig:8b].

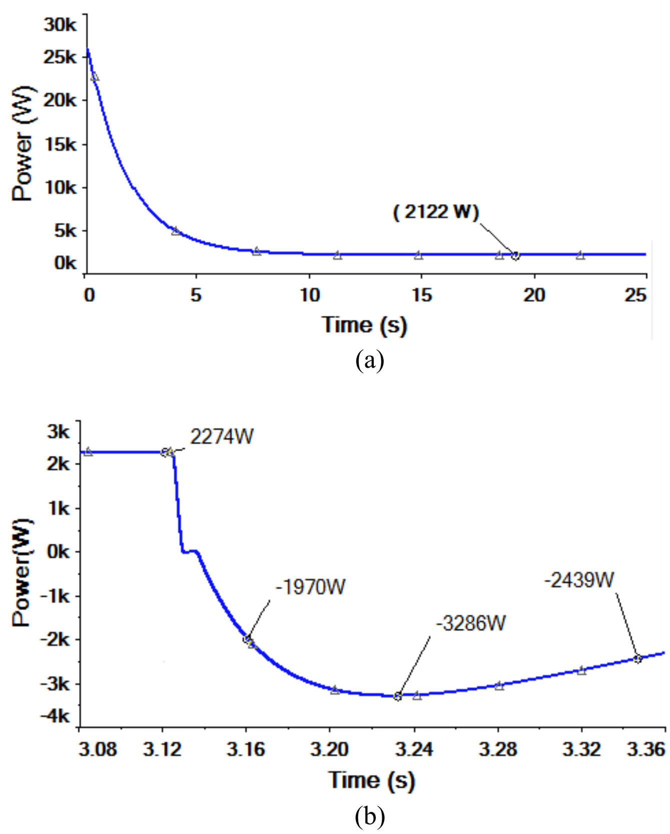


Fig 8: Power consumption of DC machine (a) driving mode (b) regenerative mode

V. System Result and Calculations

Electric bike design and simulation results shows the performance of system. Steady state point is achieved within a few seconds under ideal conditions. At rated angular speed power consumed by machine is,

$$P_m = E_a \, i_m \tag{10}$$

$$= 72 \times 28.9$$
$$= 2080 \text{ watt}$$

At stable position bike angular velocity is approximately 48 rad/sec as shown in figure [fig:6a]. Linear velocity can be found as,

$$V = \omega R \tag{11}$$

$$V = 48 \text{ rad / s} \times \; 0.288 \text{ m}$$

$$= 13.824 \text{ m / s} = 49.77 \text{ Km / h}$$

Dynamic response of machine current is defined as,

$$V_m = L_a \frac{di_m}{dt} + Ri_m + E_a \tag{12}$$

further solving for change of current at steady state with negligible machine resistance is nearly zero.

$$\frac{di_m}{dt} = \frac{V_m - E_a + Ri_m}{L} \approx \frac{V_m - E_a}{L} \approx 0$$

Regerative power transfer to battery for 15ms decceleration can be observe from figure [fig:5, fig:8b] .

$$P_{regenrative} = -i_m E_a \tag{13}$$

$$P_{reg} \approx -28.57 \times 68 = -1942 \text{ watt}$$

After 15ms of regenrative bike angular velocity reduce to 47 rad/sec [fig:6b] its linear velocity become,

$$V = \omega R = 47 \, {}^{rad}/_{s} \times \; 0.28 \text{ m} = 47.4 \, {}^{Km}/_{h}$$

If only 15% regenrative braking is applied on single charge trip, it will add approximately 11Km to total milage. The table 2 shows the comparison of EB with internal combustion engine bike (ICE).

The paper helps to develop an understading of parameters while designing electric bikes. Filter components reduce transient and increase the efficiency of the converter. Power and charging current response provides the charging possibilities for the battery.

Table 2: Comparison

Particulars	**E-Bike**	**70 CC (ICE)**
Weight	50-60kg	82Kg
Power/cc	2kW	72cc
Range (Km)/ unit	75Km/charge	55 Km/liter
Cost/100 Km	57 PKR	212 PKR
Regenerative	Yes	No
Energy saving with regenerative braking	11km per charge with 15% braking	No
Emissions	Nil	1.82 g CO^2/km

VI. CONCLUSION

Research provides the basic design approach of analyzing the electrical parameters of E-bikes. The study shows how to estimate the power requirement for specific desirable linear speed. Impact of tire diameter and machine angular velocity on E-bike linear velocity, the different trade-offs can be implemented to achieve specific results. The converter design parameter will help to reduce fluctuation in driving and regenerative mode also produce reliable results for estimating bike SOC.

Regardless of control scheme simulation analysis provides bike power consumption and regenerative energy extraction from DC machine. The required motor parameters can be computed and help to manufacture machines for E-bikes. Basic equations are help full to develop the effective electric bike and bidirectional power converter. Transient and dynamic responses of the machine during different modes provide a better understanding of EB behavior. The comparison shows that the Electric motorbikes are more suitable, economical and environmentally friendly than the fuel-based bikes.

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