Simulation Study of FPGA based Energy Efficient BLDC Hub Motor Driven Fuzzy Controlled Foldable E-Bike

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Abstract— This paper presents the simulation study for designing a foldable electric bicycle using hub motor. In order to reduce the air pollution, traffic congestion and also to reduce drudgery of conventional bicycle users, the aim of this paper is to develop a cost efficient electric bicycle powered by Brushless DC hub motor which can be easily installed on the bicycle wheel. Nowadays Brushless DC motors find wide application in industries such as automation, traction, appliances, aerospace, instrumentation etc because of high efficiency, high torque, high speed and less maintenance. BLDC motors are non linear in nature and are greatly affected by non-linearities like load disturbances. A comparative study on the speed response of BLDC motor using PI and fuzzy controller is done to ascertain the suitability of speed controller. Regenerative method of braking of an electric bicycle helps in charging the battery using the power that is wasted during braking and thus helps in efficient utilization of battery power. Simulation is done using MATLAB/SIMULINK. Since FPGA has the ability to operate faster than the microprocessor chip, and the hardware is programmable according to the user applications, the whole system is planned to implement using FPGA to get better performance and efficiency.

Key words: BLDC, PI Controller, Fuzzy Controller, Hub Motor, Regenerative Braking, FPGA

I. INTRODUCTION

Every developing country has problems like limited access to energy, exploitation of resources, pollution etc. One of the main reason for air pollution is due to vehicular exhaust. In countries like India, where the vehicular density is very large, results in traffic congestion and traffic problems. Even though the fuel price is increasing, we rely on motor vehicles for traveling small distances which in turn increase the air pollution. By increasing the use of bicycles, these problems can be minimized to a great extent. Compared to European countries, India has a very less percentage of people using bicycles these days. Indian government has initiated programs to encourage the use of bicycles in order to minimize traffic problems and pollution. Many colleges and factories have PFZ (Pollution Free Zone), where use of motor vehicles is prohibited which demands the use of bicycles. But the conventional pedaling bicycles require lot of man power which may affect the productivity of people.

A global shift to a greener and low carbon economy became essential for preserving our nature and future. In order to solve energy crisis and global warming, battery powered electric vehicles are one of the best proposed solution. In order to reduce the drudgery of conventional bicycle users this paper presents the development of foldable electric bicycle. Besides being cost effective, their reduced size allows the users to move with agility and to park easily. This electric bicycle is powered using BLDC hub motor.

II. BRUSHLESS DC MOTOR

A. Conventional BLDC Motor

BLDC motor is a type of permanent magnet synchronous machine (PMSM). In BLDC motor back emf is trapezoidal in shape but in PMSM machine it is sinusoidal in shape. A conventional BLDC motor has permanent magnet as rotor and a wound stator. BLDCM is controlled using a three phase inverter. For starting purpose and proper commutation of power electronic devices in inverter, BLDC motor requires rotor position sensors. At every 60 degrees, commutation occurs according to the rotor position. Electronic commutation is used in BLDC motor drives and this eliminates problems like sparking and wearing out of the brushes. So compared to a DC motor BLDCM is rugged in its construction. Basic block diagram of a BLDC motor is given in Fig 1. It consists of a power converter, BLDCM, sensors and a controller.

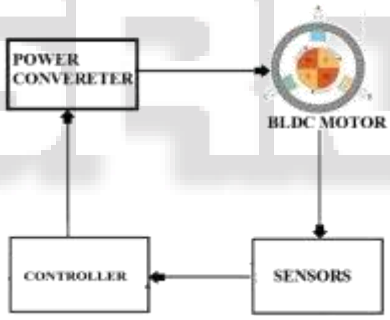

Fig. 1: Block Diagram of BLDC motor

B. BLDC Hub Motor

BLDC hub motor is a motor built into the wheel hub itself and the stator is fixed solidly to the axle. In hub motor, the electromagnets are rotating with the wheel ie, a wheel hub motor is an electric motor incorporated into the hub of a wheel and drive the wheel directly.

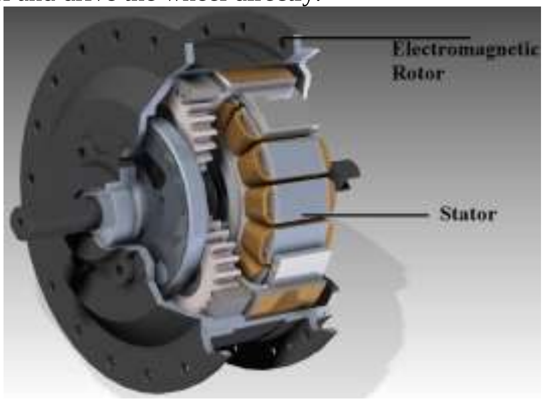

Fig. 2: BLDC Hub motor

Stationary windings of the motor supplies the required electromagnetic field and the outer part of the motor which is the electromagnet tries to follow the electromagnetic fields, which in turn turns the wheel to which the motor is attached. A BLDC hub motor requires no physical contact between stationary and moving parts for the energy transfer. Although brushless motor technology is more expensive, it is long lasting and more efficient compared to brushed motor system. Efficiency of this motor is high since it requires no additional transmission system.

III. Regenerative Braking

There are four possible modes of operation for a BLDC motor namely forward motoring, reverse motoring, forward braking and reverse braking as shown in fig 3. If the BLDC motor is operated in forward motoring and reverse motoring modes which is first and third quadrant, the supply voltage is greater than the back emf of the motor. Similarly if the motor is operated in forward braking and reverse braking modes, which is the second and fourth quadrant, the back emf should be greater than the supply voltage.

When brakes are applied all the kinetic energy stored in the motor is wasted. In regenerative method of braking, instead of wasting this useful energy, it is utilized and can be converted back into electrical energy and stored in a battery or any other energy storage system such as ultra-capacitors. During high energy demands like starting and accelerating this stored energy can be retrieved and can be used. Hence regenerative braking of BLDC motor helps in efficient utilization of battery power to increase the range of the vehicle

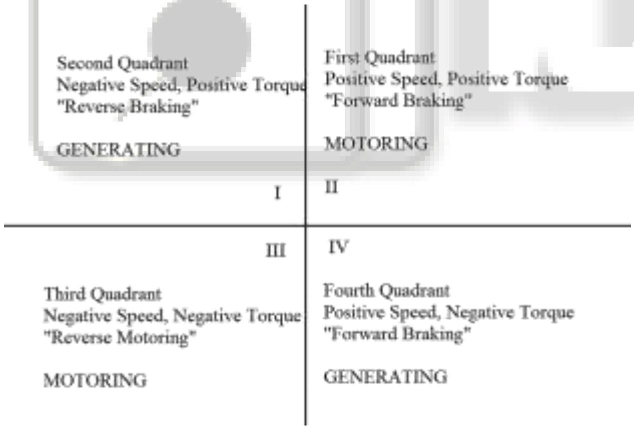

Fig. 3: Four quadrant operation of BLDC motor

IV. Selection of Speed Controller

For applications like aeronautics, electric vehicles, robotics, and food and chemical industries brushless dc motors are used. P, PI, and PID are the conventional controllers being used for control application. For designing these controllers the exact mathematical model of the system or response of the system should be known, but it is impossible in practical applications since systems are nonlinear and more complex; so they are approximated. The controllers designed for such systems will not give optimum responses; it can only give satisfactory transient and steady-state responses. It is assumed that during the operation system parameters never change but in real case due to coupling and decoupling, the mechanical parameters such as inertia and friction may change. The phase resistance may also change slightly. The conventional controllers will work efficiently when the parameters to which they are designed remain unchanged. But there is an uncertainty in the parameter values of the system while it is operating. So a PI controller based BLDCM and fuzzy controller based BLDCM is designed and is compared here for facilitating the selection of speed controller for electric bicycle application.

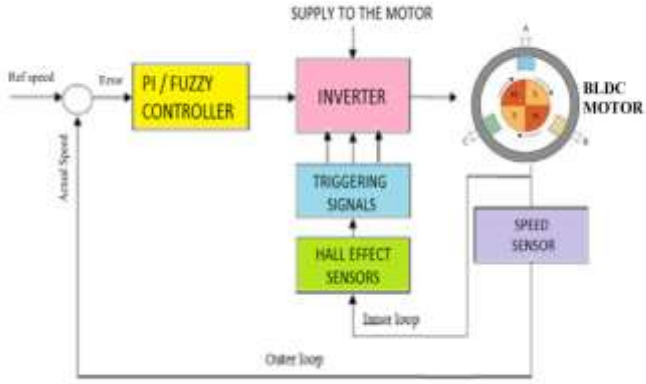

Fig. 4: Block diagram for speed control of BLDC motor

Fig 4 shows the block diagram for the speed control of BLDC motor. The actual speed of the drive is obtained from the shaft encoder. The actual speed is compared with reference speed and the error speed is obtained. This error speed is processed in the speed controller to minimize the error in speed and to make the actual speed equal to the reference speed. At a time only two phases out of three will be conducting for a BLDC motor. The conducting sequence is determined by the switching signals from the inverter switches. The switching signals are generated according to the rotor position information obtained from the Hall Effect sensors.

A. *PI Controller*

Due to their simple control structure and ease of implementation conventional PI controllers are widely used in the industry. PI controller calculations involve two modes proportional mode and integral mode.

Proportional mode**:** By multiplying the error by a constant- Kp, called the proportional gain, the proportional response can be adjusted. A high proportional gain results in a large change in output for a given change in error.

Integral mode**:** The contribution of the integral term is proportional to both magnitude and duration of error. The accumulated error that should have been corrected previously is eliminated by this controller. Integral gain (Ki) is multiplied to the accumulated error and added to the controller output. Integral term eliminates the steady state error.

The output of the PI controller is given by,

$$U(t) = K_p . e(t) + K_i \int e(t)\, dt \qquad (1)$$

Tuning of PI controller is done by Ziegler-Nichols rule. PI controllers pose difficulties where there are some control complexity such as non-linearity, parametric variations and load disturbances. Also precise linear mathematical model is required for a PI controller.

B. *Fuzzy Controller*

Fuzzy logic controller gives an improved dynamic behaviour of the system. Also it is immune to uncertainties like load torque variations and internal parameter variations like inertia, resistance etc. Fuzzy logic controllers are popular because of its logical resemblance to a human operator. Fuzzy control involves fuzzification, fuzzy inference and defuzzification. Fuzzification involves the conversion of the input data which is usually a crisp value to linguistic variables. Membership function is used for this conversion. The fuzzy inference consists of a rule base, database and reasoning mechanism. The process of mapping from a given input to an output using fuzzy logic is known as fuzzy inference. Rule base consists of a number of rules, similar to human thoughts. Defuzzification involves converting the internal output values of the controller to a crisp value. Fig 5 shows the components of fuzzy logic controller.

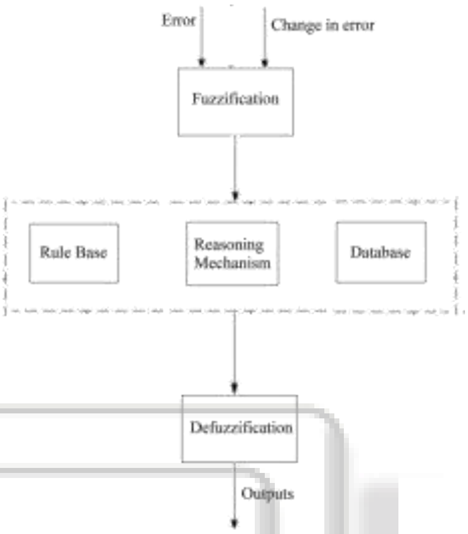

Fig. 5: Components of Fuzzy Logic Controller

There are two inputs to the fuzzy controller; they are speed error and change in speed error. There is only one output. Fuzzy controller uses 49 if then rules for mapping from input to output. The linguistic variables used are negative big, negative medium, negative small, positive big, positive medium and positive small. The membership functions for error input, change in error input and output is shown in fig 6, fig 7 and fig 8 respectively. The fuzzy rules are shown below in table I.

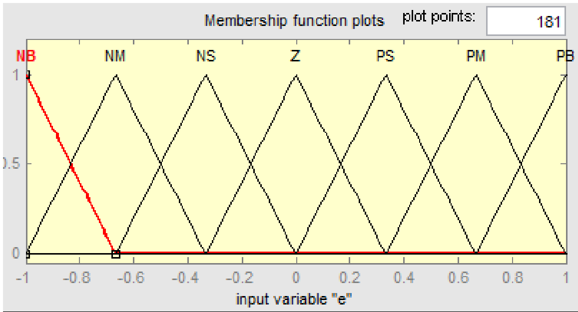

Fig. 6: Membership functions for error input

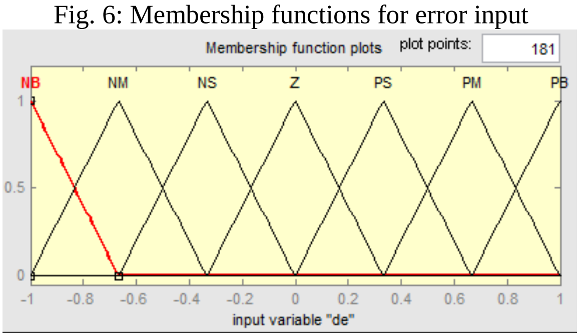

Fig. 7: Membership functions for change in error input

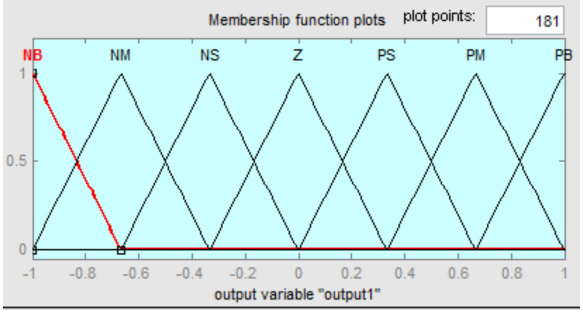

Fig. 8: Membership functions for output

e/de	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

Table 1: Fuzzy Rule Base

V. SIMULATION

A. PI Controller

The simulation diagram for speed control of BLDC motor using PI controller is shown in fig 9.

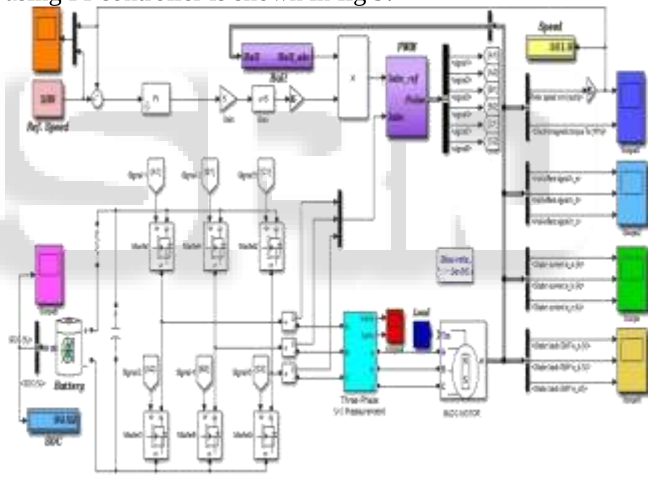

Fig. 9: Simulation block diagram using PI controller

1) No load condition

The speed response of BLDC motor using PI controller under no load condition for step increase in speed with reference speed of 500 rpm, 700 rpm and 900 rpm is given in fig 10. The back emf waveform and electromagnetic torque waveform of BLDC motor is shown in fig 11 and fig 12 respectively.

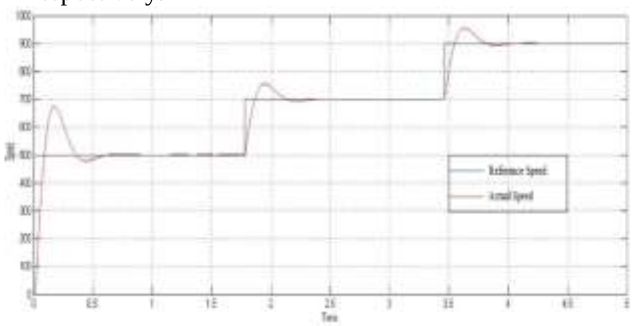

Fig. 10: Speed response using PI controller under no load condition

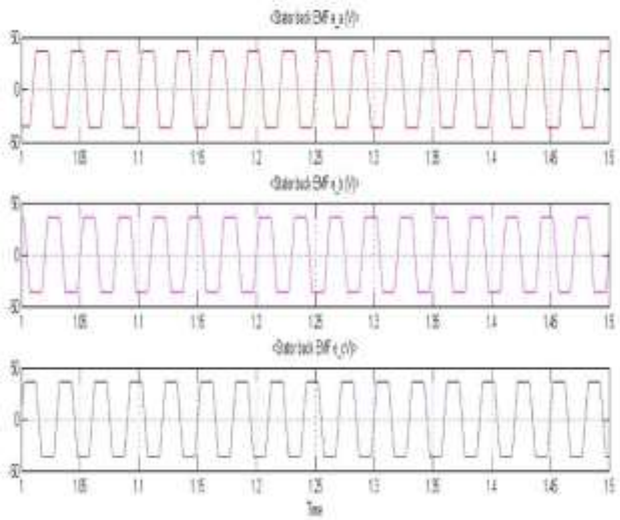

Fig. 11: Three phase back emf waveforms

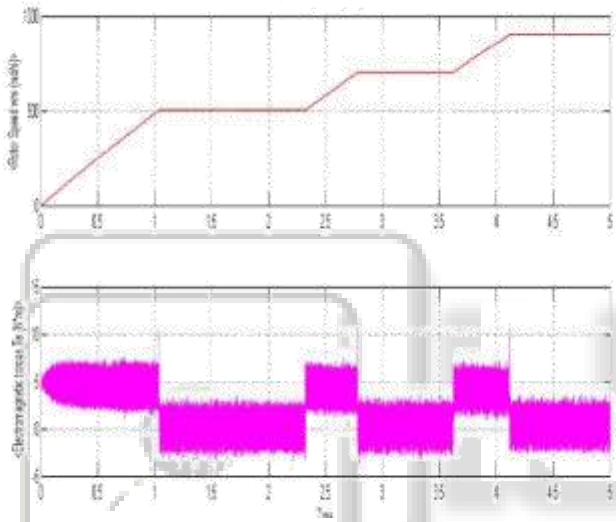

Fig. 12: Electromagnetic Torque waveform

2) Loaded Condition

The speed response of BLDC motor using PI controller when the machine is loaded at 2.5 seconds for step increase in speed with reference speed of 500 rpm, 700 rpm and 900 rpm is given in fig 13.

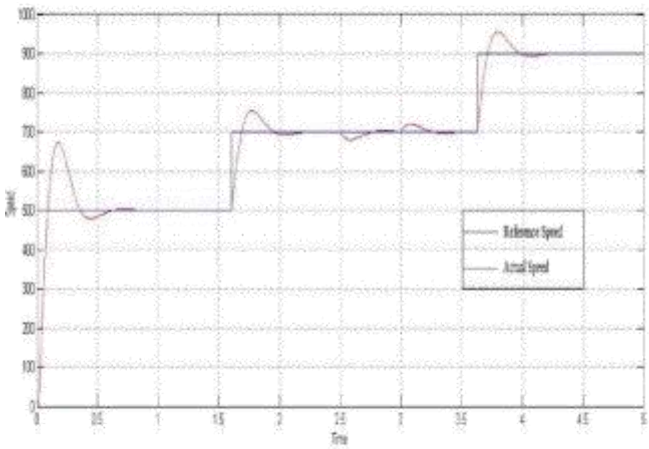

Fig. 13: Speed response using PI controller when the machine is loaded

B. Fuzzy Controller

The simulation diagram for speed control of BLDC motor using fuzzy controller is shown in fig 14.

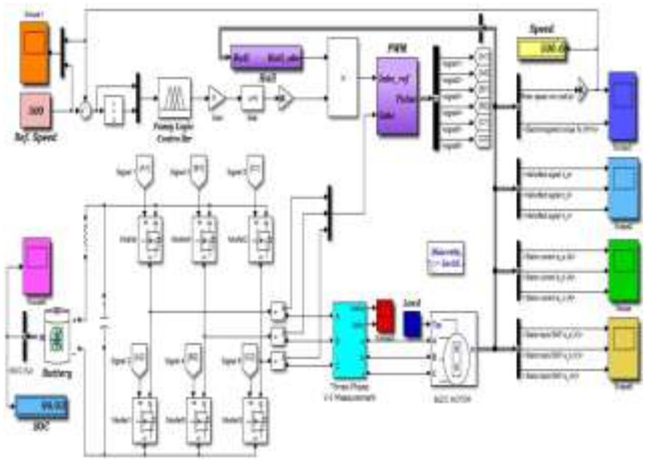

Fig. 14: Simulation block diagram using fuzzy controller

1) No Load Condition

The speed response of BLDC motor using fuzzy controller under no load condition for step increase in speed with reference speed of 500 rpm, 700 rpm and 900 rpm is given in fig 15.

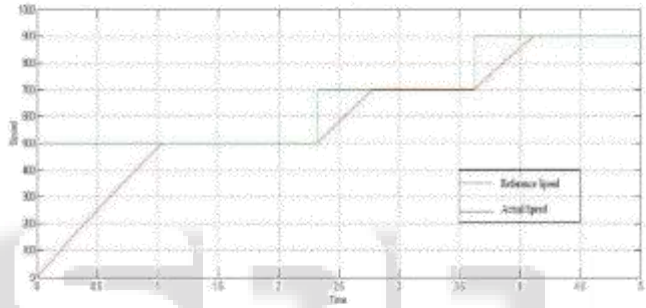

Fig. 15: Speed response using fuzzy controller under no load condition

2) Loaded Condition

The speed response of BLDC motor using fuzzy controller when the machine is loaded at 2.5 seconds when the speed is constant is given in fig 16 and when the speed is varying is given in fig 17.

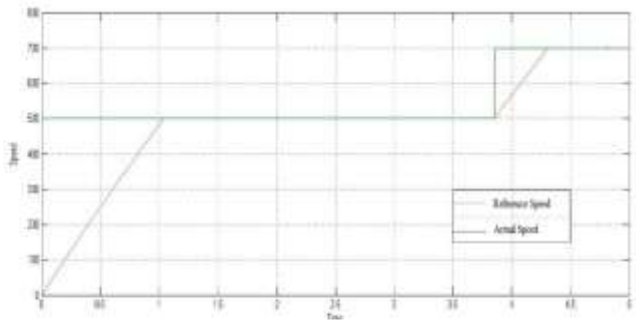

Fig. 15: Speed response using fuzzy controller when the motor is loaded and speed is constant

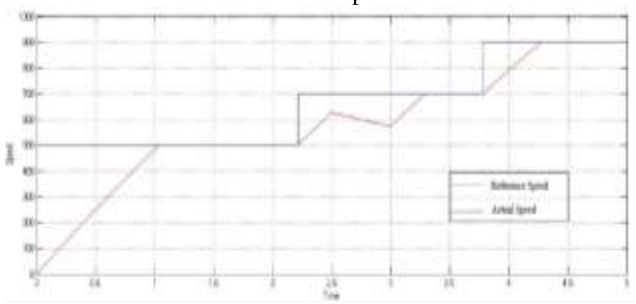

Fig. 16: Speed response using fuzzy controller when the motor is loaded and speed is varying

C. Regenerative Braking

The simulation diagram for regenerative braking of the system is given in fig 17. The battery charging circuit subsystem is shown in fig 18.

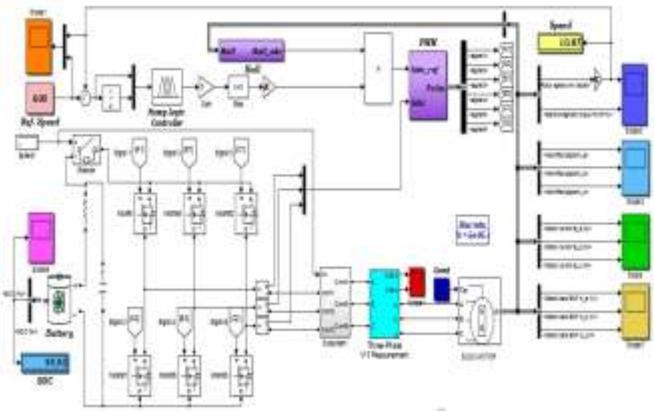

Fig. 17: Simulation block diagram for regenerative braking

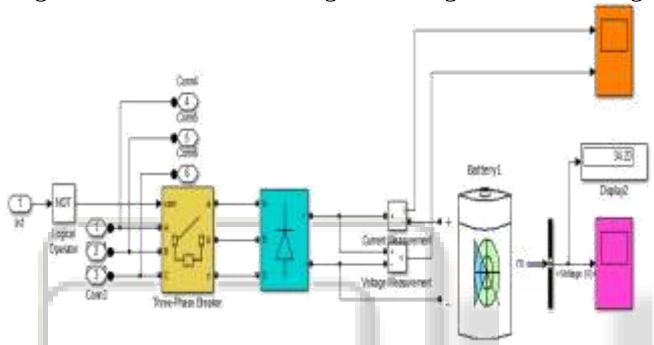

Fig. 18: Battery charging subsystem

Here the brake signal is applied at 2 seconds and the speed of the motor starts decreasing. At this time the battery in charging circuit which is initially at 24 V is charged to around 34 V. The speed waveform and charging circuit waveform during regenerative braking is given in fig 19 and fig 20.

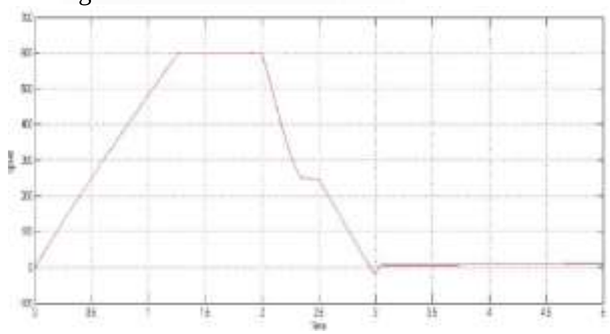

Fig. 19: Speed response during regenerative braking

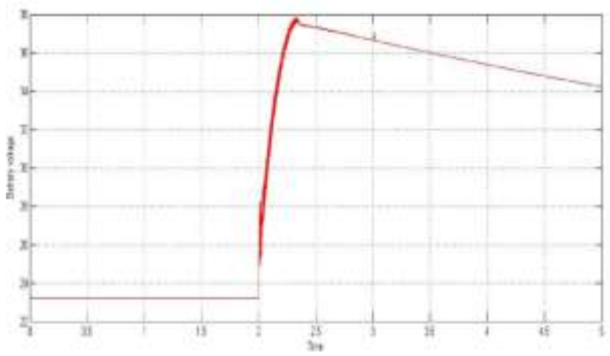

Fig. 20: Battery voltage in charging circuit during regenerative braking

VI. SIMULATION RESULTS

The simulation study shows that fuzzy controller gives better performance than the PI controller. Fuzzy controller is faster and has no overshoots compared to PI controller. The Fuzzy Logic approach applied to speed control leads to an improved dynamic behavior of the motor drive system and shows less fluctuation under load perturbations and parameter variations. So from the simulations it is clear that fuzzy controller is a better and efficient controller for the E-bike application. Also by the method of regenerative breaking the useful kinetic energy that is wasted during braking is converted to electric energy and is used to charge the battery.

VII. CONCLUSION

Many Speed controlling techniques are available for BLDC hub motor nowadays. PI and Fuzzy controllers are the most commonly used controlling techniques. Hence comparative study of PI and fuzzy controller is done to find out the suitable speed controller for hub motor. The simulation is done using MATLAB/SIMULINK. From the simulations it is clear that fuzzy controller is a better and efficient controller for the E-bike using BLDC hub motor. Regenerative method of braking of an electric bicycle helps in charging the battery using the power that is wasted during braking and thus helps in efficient utilization of battery power to increase the range of the vehicle.

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