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Regenerative Braking for Bicycles on Hilly Roads

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***Abstract*: When travelling uphill, electric vehicles that run in hilly areas accumulate potential energy. Through the use of regenerative braking, energy can be recovered to charge the battery as the vehicle descends. Regenerative braking used in bicycles will support upward movement and increase range. Implementing a low-cost regenerative braking circuit is the goal. People who frequently travel through mountainous locations in search of a financially viable solution can benefit from this. In addition to the current pedal drive, this setup makes use of a battery and a motor drive. The bicycle's speed setting is changed by a throttle. This will create a more dependable and effective transportation system by incorporating this circuit into the bicycle.**

***Keywords*: Boost converter, Buck converter, MOSFET, PI controller, PWM, Regeneration.**

1. Introduction

The document is a template for Microsoft *Word* versions 6.0 or later. The bicycles riding in steep terrain, where stopping frequently during descends results in a large energy loss. Kinetic energy generation in traditional brake systems generated by the moving bicycle is released as heat, particularly while riding up steep hills. By using an electric motor that doubles as a generator during braking, this concept aims to remedy that inefficiency by turning some of the wasted kinetic energy into electrical energy. Regeneration is a technique to increase the battery's range. For instance, driving range can be increased by using Regenerative Braking System in the place of traditional braking when the wheels are retarding. Because it transforms the kinetic energy of the wheel into electrical energy and feeds the power source as the vehicle is braking, which is known as "regenerative" braking.

This technology allows users to twist the throttle to select different speed numbers based on their preferences. The battery and motor are connected via a bidirectional DC to DC converter. It will run in motoring mode when the needed speed exceeds the actual speed. In driving mode, the converter will function as a buck converter and power will move from the battery to the motor. Power will move from the motor to the battery in the regeneration mode when the needed speed is lower than the actual speed. The converter will function as a boost converter when in regeneration mode.

In order to improve overall energy management and lessen dependency on external power sources, the generated electricity is stored in a battery and can be used again to help the rider during difficult uphill climbs. Furthermore, this method seeks to expand the prolongs the life of conventional mechanical brake parts by lowering wear and usage. Bicycle performance and sustainability are improved by the suggested regenerative braking system, which offers cyclists an affordable and ecologically friendly option, especially in areas with different elevations. By using this strategy, the project tackles energy recovery issues and provides useful advantages for both conventional and e-bike applications in hilly areas.

2. Related Work

Numerous studies have been carried out to improve the regenerative braking system. The current studies highlighting their contribution to sustainability and energy efficiency. In order to maximize power flow between the motor and battery during braking and acceleration, several research have investigated various DC-DC converters, including buck and boost converters. By controlling voltage and guaranteeing effective energy transmission, these converters reduce losses. Furthermore, studies on electric vehicle energy management techniques have produced sophisticated control algorithms that dynamically modify power distribution in response to current circumstances. Regenerative braking is an essential component of contemporary electric mobility solutions because of these control systems, which also increase battery longevity, boost performance, and optimize energy recovery during brake events.

Research on the systems which uses multiple energy storage systems, such as combining batteries and super capacitors to better manage energy fluctuations, is another important area of regenerative braking. According to studies, response time can be greatly increased and reliable power delivery can be ensured by using pulse-width modulation (PWM) techniques and optimal converter designs. Nonetheless, issues including accurate brake force control, voltage regulation, and system integration continue to be crucial factors. Regenerative braking systems can become more dependable and successful by addressing these issues with creative circuit designs and astute control techniques, which will make them a practical and affordable option for bicycles riding on hills.

The study [5] examines how non-isolated DC-DC converters integrate and function in regenerative braking systems, especially in electric cars where effective energy management is essential. In the context of regenerative braking, the studies provide a thorough analysis of several converter topologies, including buck, boost, and buck-boost converters, and go over their working principles. These converters are crucial for absorbing the kinetic energy produced as a car slows down, turning it into electrical energy, and sending it to super capacitors or batteries for storage. Regenerative braking is a crucial part of sustainable transportation technology since it increases overall energy efficiency and helps electric cars get farther on their driving missions.

Apart from analysing converter types, the study articles [2] concentrate on design factors that are especially pertinent to regenerative braking, like maximizing efficiency, guaranteeing quick reaction to power variations, and putting in place efficient methods of control. While quick reaction times are critical for adjusting to the fluctuating power demands during deceleration events, high efficiency is necessary for limiting energy losses and optimizing energy recovery. The investigations also point out problems including energy losses, voltage regulation, and thermal management and suggest technological fixes to lessen them. The usefulness of these converters is illustrated in real-world situations through case studies and real-world applications. By comparing converter performance parameters across various designs, comparative evaluations reveal which strategies work best for a given regenerative braking scenario hypothetical situations. Finally, the paper highlights possible directions for further study to improve converter technology and raise the effectiveness, dependability, and sustainability of regenerative braking system in electric cars.

3. Working

Figure1 indicates the block diagram representation of the circuit. The main elements and their interactions are depicted in the block diagram of the Regenerative Braking for Bicycle on Hilly Roads system. A bidirectional DC-DC converter, which functions in two modes—boost mode during regenerative braking and buck mode during motoring—is at the heart of the system. The main power source is the battery, which provides energy to the motor when it needs it, particularly while climbing hills. A controller processes the speed requirement that is set by the throttle when the bicycle is moving. The controller modifies the operation mode in accordance with the difference between the necessary and actual speeds. The system switches to motoring mode when the needed speed exceeds the actual speed. In this mode, the converter lowers the battery voltage to power the motor. On the other hand, when braking or moving downhill, the motor functions as a generator, transforming kinetic energy into electrical energy. The generated voltage is then amplified and sent to the battery for storage when the converter transitions to boost mode. Furthermore, a current sensor keeps track of the motor's armature current and reports back to the controller, guaranteeing safe operation and effective energy flow. This regenerative braking technique increases battery life, boosts energy efficiency, and makes riding more enjoyable overall—especially on mountainous terrain.

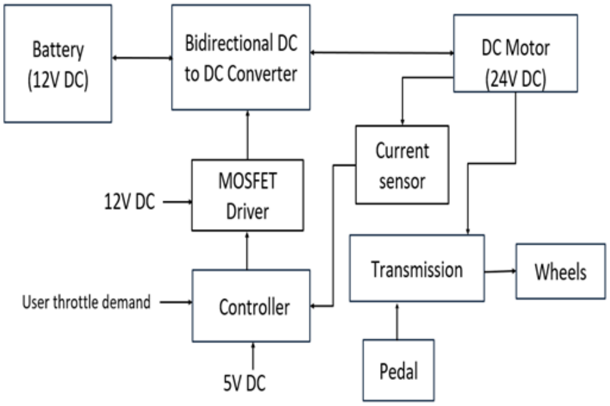

Fig.1. Block diagram of regenerative braking for bicycle

4. Modes Of Operation

The circuit represented in Figure 2 shows a non-isolated DC-DC converter with two modes of operation: buck (charging) and boost (discharging). It is typically used in regenerative braking systems, particularly in electric bicycles for hilly terrains. During motoring mode, the converter will act as buck converter and power flow takes place from battery towards the motor. During regeneration power flow takes place towards the battery.

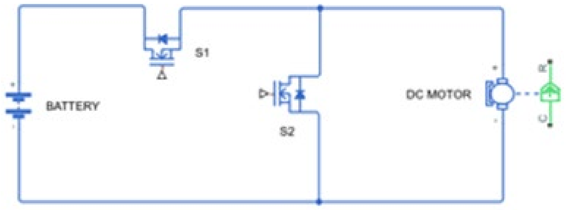

Fig. 2. Circuit diagram

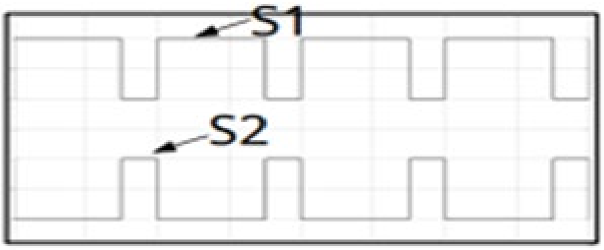

Fig. 3. Gate pulse

The operation of converter in various modes can be done by varying the gate pulse given the MOSFETs. Whatever gate pulse we give to switch S1, the same pulse is given to switch S2 through a NOT gate. So the two switches will be never ON at the same time. Figure 3 shows an example of gate pulse given. From the figure it is evident that when switch S1 is ON, S2 is OFF and vice versa.

A. Buck Mode (Discharging)

In buck mode (discharging), the system draws energy from battery to power the motor. In this mode, battery serves as the energy source. The buck converter steps down the battery voltage to the voltage needed. The key to this process is the switching operation, where the inductor plays a crucial role. Upon closing the switch, the inductor gets charged. When switch is turned off, the inductor discharges. Duty cycle in this mode controls the extent of the voltage buck. By adjusting the duty ratio, the power converter ensures the required input is delivered to motor efficiently, especially in challenging conditions like hilly terrains or during acceleration.

B. Boost Mode (Charging)

In boost mode (charging), the main aim is conversion of the kinetic energy generated while the bicycle is going downhill and store this energy in the battery. During regenerative braking, the motor functions like generator, generating a DC voltage. The energy thus produced should to be converted to a voltage suitable for charging the battery, and this is where the boost converter comes into play. The converter's switches operate to step up this input voltage level by controlling the duty ratio of the semiconductor devices. This duty ratio determines the relationship between input and output voltage. The voltage developed by regeneration is not a huge value, so we will have to provide boost converter to feed it to battery. Thus, by adjusting the duty cycle, the boost converter ensures that the battery is charged at the appropriate voltage level.

C. Regenerative Braking in Hilly Areas

1) Uphill Climbing (Buck Mode)

When climbing hills or accelerating, the system switches to buck mode, where it draws energy from the battery and feeds the voltage to drive the motor and assist the cyclist. The cyclist gets required pedal assistance which increases the comfort of driving especially in hilly regions due to its steep climbs.

2) Downhill Braking (Boost Mode)

When going downhill, the motor generates excess electrical energy. The DC-DC converter operates in boost mode, stepping up the voltage and storing the recovered energy into the battery. This action will improve the range of battery.

5. Design of Boost Converter

Boost converters are DC-DC converters that are designed to increase a lower input voltage to a greater output value. For uses such as regenerative braking in electric bicycles, the converter is set up to maximize stability and efficiency.

Reliable performance is ensured by calculating important design parameters such as input voltage, desired output voltage, and maximum output current. Through the determination of ideal values for the output capacitance, duty cycle, and inductor ripple current, the converter is made to provide a reliable and effective power source appropriate for a range of input circumstances, increasing its suitability for low-power applications.

Figure 4 shows the configuration of a boost converter where the voltage is stepped up. It is made bidirectional by replacing the diode by switch. All equations of this circuit except the heat dissipation across diode can be taken into consideration.

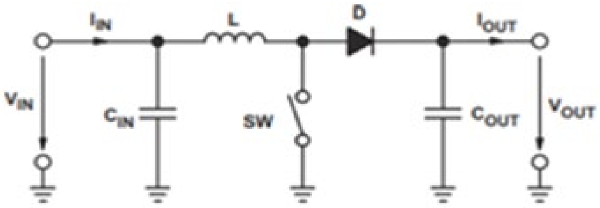

Fig. 4. Boost converter

The following parameters are used to calculate the power stage:

1. *Input Voltage*: Vin
2. *Nominal Output Voltage*: Vo
3. *Maximum Output Current*: Ioutmax

The first step is determination of the duty ratio, D, for the input voltage. The minimum input voltage is used since it causes the maximum switch current.

$D = 1 - Vin \times \eta / Vo = 1 - 12 \times 0.9 / 24 = 55\%$ (5.1)

where,
Vin = minimum input voltage
Vo = desired output voltage
Efficiency of the converter, $\eta = 90\%$

The efficiency is considered here in duty ratio calculation, because the converter has to provide also the energy dissipated. This calculation gives a realistic and reliable duty ratio than just the equation without considering the efficiency.

The maximum output current is given by

$Ioutmax = P/V = 250 / 24 = 10.416A$ (5.2)

The next step is to determine the inductor ripple current. It can be taken as 20 to 40 percentage of the output current.

$\Delta IL = (0.2 \text{ to } 0.4) \times Ioutmax \times (Vout / Vin)$
$= (0.3) \times Ioutmax \times (Vout / Vin)$
$= (0.3) \times 10.416 \times (24 / 12) = 6.2496A$

The value of inductance can be determined by,

$L = Vin \times (Vout - Vin) / \Delta IL \times fs \times Vout$
$= 12 \times (24 - 12) / 6.2496 \times 30000 \times 24$
$= 32\mu H \approx 33\mu H, 5A$

Where,
Vin = typical input voltage
Vout = desired output voltage
fs = minimum switching frequency of the converter
ΔIL = estimated inductor ripple current

Next step is to find output capacitor values for a desired output voltage ripple. To calculate capacitance value various parameters such as duty ratio, switching frequency, maximum output current are considered.

$Cout(min) = Ioutmax \times D / fs \times \Delta Vout$
$= 10.416 \times (0.55) / 30000 \times 0.24$
$= 795.66\mu F \approx 820\mu F, 100V$ (4.6)

where,
Cout = minimum output capacitance
Ioutmax = maximum output current of the application

D =duty cycle calculated with Equation 4.1

fs= minimum switching frequency of the converter

Vout = desired output voltage ripple taken as 1% of Vo

The design of the boost converter, incorporating both buck and boost operations, provides a versatile and efficient solution for voltage regulation in various applications. In boost operation, the converter steps up the input voltage to achieve a higher output voltage, ensuring stable power delivery even with a variable input. Conversely, in buck operation, the converter can step down the voltage to meet specific lower output requirements, offering flexibility for different energy conversion needs. By optimizing key parameters such as duty cycle, inductor ripple current, and output capacitance, the converter maintains high efficiency, minimizing power losses. This dual-mode functionality, combined with precise design calculations, ensures reliable and efficient working over a wide range of input and output conditions, making it ideal for applications like regenerative braking in electric bicycles and other low-power systems.

6. Simulation

Throughout the simulation, different test scenarios are introduced via the Signal editor, which generates various operating conditions like changes in speed demand. The system's ability to adapt to these conditions is evaluated by monitoring key outputs such as motor speed, battery voltage, and current flow. The PI controllers dynamically adjust the power flow and ensure that the motor responds appropriately to these changing inputs, keeping the system operating within desired parameters. Finally, at the end of the simulation, the results are analyzed by evaluating battery SOC, battery voltage, battery current. It is clear from the results that during regeneration current flows from load to source.

Figure 5 shows the simulation circuit where different drive scenarios are given from a signal generator.

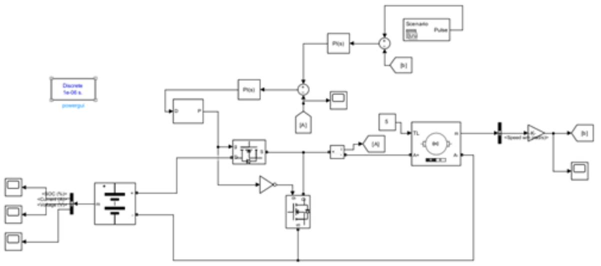

Fig. 5. Simulation diagram

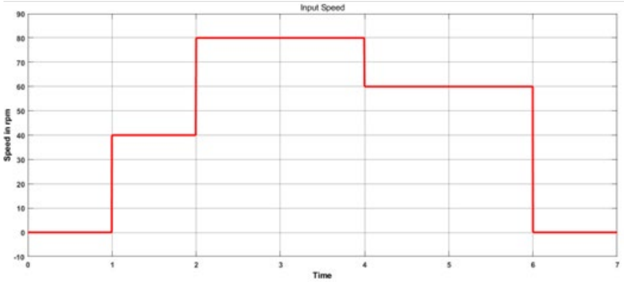

Fig. 6. Motor speed input

Figure 6 shows input speed signal given from a signal editor. Figure 7 shows speed output of motor.

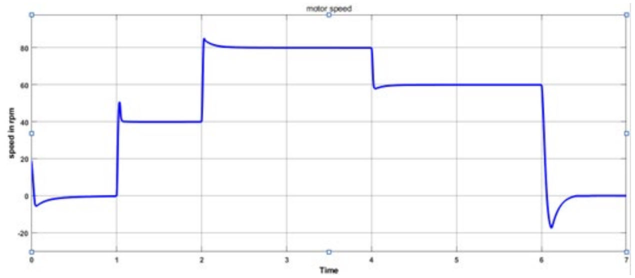

Fig. 7. Motor speed output

Figure 8 shows the battery current where during regeneration. Figure 9 shows battery voltage. There is an increase in battery voltage during regeneration. Figure 10 shows battery SOC

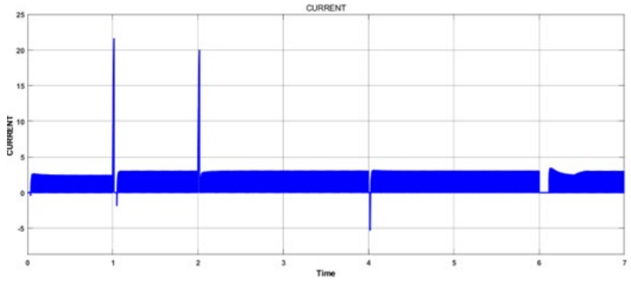

Fig. 8. Battery current

wherein there is a slight increase during regeneration

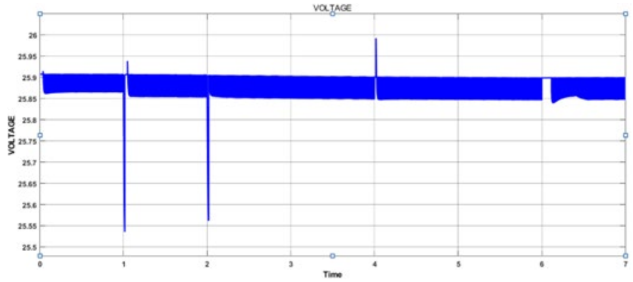

Fig. 9. Battery voltage

The SOC of battery is assumed to be 60 percentage initially. It is evident that SOC of the battery had an increase during regeneration.

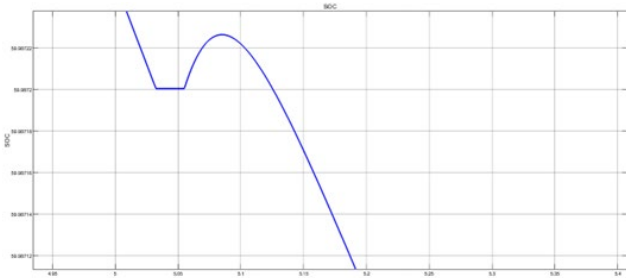

Fig. 10. Battery SOC

In this table, the performance analysis conducted in the simulation model is presented. The efficiency of regenerative

Table 1
Performance analysis

Speed	Increase in SOC	Increase in voltage	Increase in current
80 to 20 m/s	6*10^-5	22.865 to 26.1 V	2.07 to -11.5 A
60 to 20 m/s	4*10^-5	25.87 to 26.06 V	1.85 to -9 A
40 to 20 m/s	1.79*10^-5	25.87 to 26 V	1.6 to -5.5 A
30 to 20 m/s	6.6*10^-5	25.88 to 25.961 V	1.52 to -3.2 A
20 to 10 m/s	3.3*10^-5	22.8 to 25.94 V	1.4 to -2.4 A

action can be well understood from this analysis. Different scenarios of speed input are given into the motor from signal editor in the unit meter per second corresponding increase in SOC, increase in voltage, increase in current is noted.

From the simulation done, the results obtained during regeneration are:

Battery voltage increases from 25.851 V to 26.05V

Battery current goes from +2.79 A to -8.8 A

SOC increases from 59.99218 to 59.99223

From the performance analysis carried out it is evident that regeneration can be achieved even in shifting between speeds as low as 20 to 30 m/s. So, the idea of incorporating electrical components to a bicycle can be considered as a potential idea on the basis of results obtained.

7. Hardware

A single layer PCB is used. Hardware implementation sends PWM signals to the motor driver circuit, which consists of MOSFETs, capacitors, and a heat sink. The motor drive regulates the power supplied to the motor based on these control signals.

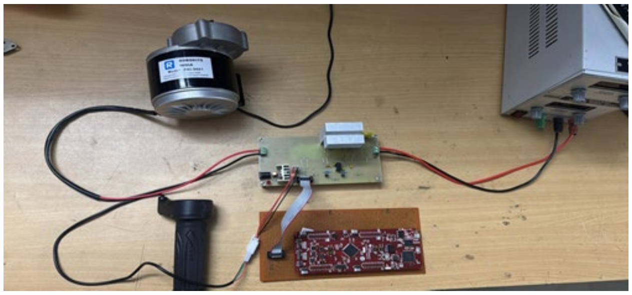

Fig. 11. Tabletop setup

Fig. 12. Hardware

A current sensor is integrated into the circuit to monitor the current flowing through the motor, providing feedback to the microcontroller for efficient control and safety. By the use of a multi meter to monitor the voltage, slight increase in the battery voltage was observed after downhill travel by regenerative braking. The assistance offered by motor was also noticed.

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