Feasibility Study and Implementation of Low Cost Regenerative Braking Scheme in Motorized bicycle Using Supercapacitors

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Abstract

This paper presents an implementation of a regenerative braking system in an electrically operated two wheeler using supercapacitors (SC), thus partially salvaging the heat energy previously dissipating due to friction. Kinetic energy is converted into useful energy in the developed system which gets converted in to heat energy in conventional braking. Regenerative braking is demonstrated on a motorized bicycle to establish its concept for electric two wheelers. The charging behaviour of the supercapacitor bank is studied under a regenerative environment to implement it in motorized bicycle. The supercapacitor bank provides assistance to the battery during starting/acceleration, thereby improving the life of the battery.

Keywords

supercapacitor, ultracapacitor, regenerative braking, motorized bicycle, electric two wheeler

1. INTRODUCTION

Due to rapid development, economic growth, high population density, and tropical climate, scooters/ motorcycles are the most popular vehicles in many under developed countries [Chen et al., 2007]. However, in order to cope with the harmful effects on the environment such as serious air and noise pollution in urban areas and depleting energy resources, the development of zero-emission electric scooters is gaining importance on a global scale. Zero-emission vehicles are defined as vehicles with no gaseous emissions, such as NOx, CO, HC and particulate matter [Morrison et al., 2009]. Cities around the world have set ambitious emissions reduction targets [Patil et al., 2008]. Electric, hybrid, and fuel-cell vehicles are gaining popularity among vehicle constructors, governments, and consumers [Chan et al., 2010]. Electric vehicles produce no pollution at the user end. Energy storage and power boost are major problems in the development of electric vehicles [Jinrui et al., 2006]. Electric vehicles are associated with different dynamic conditions such as start stop operation, sudden acceleration and different drive cycle parameter variations. Regenerative braking is an essential feature in most of the electric vehicles.

An electric two wheeler demands both continuous and pulse power. A battery is designed to give continuous power supply. But when it comes to pulse power demand, especially during motor starting/acceleration it has problems regarding the supply of high initial current and drop in voltage. Batteries are used to provide continuous power and supercapacitor can be used to meet the instantaneous power demand [Voorden et al., 2007; Khaligh et al., 2010]. An electrically powered vehicle needs a better power source which can feed pulse power and continuous power efficiently. The current electrically operated models suffer from certain drawbacks, related to insufficient energy density resulting in a short cruising distance, excess charging time for the battery pack and a reduced life of battery. Hence, it is imperative to urgently find a commercially viable, eco-friendly solution which eliminates the fore- mentioned flaws. Energy management plays an important role in such a solution. Energy regeneration which is an essential part of any energy management system is a widely used technique in electric vehicle manufacture, where the kinetic energy is pushed back into storage units during braking [Peng et al., 2006]. The system can convert the kinetic energy to electrical energy and store it in some electrical device, and provide the extra push required during start and acceleration [Zhang et al., 2009]. The electrical device mentioned could be a supercapacitor-battery system as the efficiency of both lead acid battery and that of supercapacitor are in the range of 85 % to 95 %.

A supercapacitor which is regarded as a new-style energy storage element has the characteristics of large capacitance, high energy density, long life cycle and quick charge/ discharge compared to traditional capacitors [Li et al., 2008]. This paper documents a solution including a brief description of the demonstration model for regeneration based on the use of a supercapacitor-battery combination. The individuality of this work lies in the use of supercapacitors to augment the regenerative effect on an electrically operated two wheeler. The supercapacitor is a device which can charge or discharge almost instantaneously which is a necessity in regenerative braking and the subsequent acceleration that follows the retardation. The recovery of the braking energy by means of the supercapacitor technology reduces stress on the battery pack, resulting in a longer battery life. It substantially increases the range of the vehicle and salvages lost energy. Such a solution is commercially available on electric four wheelers and electric trains. It is required to be extended to electrically powered two wheelers. Confirmation of feasibility of regenerative braking using supercapacitors can lead us in optimization of each subsystem and component involved in the system.

This paper is organized as: Section 2; describes the scope of regenerative braking in two wheelers. Section 3; deals with the description of the demonstration model of the motorized bicycle and the problems associated with it along with solutions. Section 4; presents the electrical parameter variations in various practical situations. Section 5; presents the electrical parameter variations with standard initial conditions. Sections 6; deals with energy transformations taking place during braking. Section 7; presents the conclusion.

2. SCOPE OF REGENERATIVE BRAKING IN TWO WHEELERS

Regenerative braking is not a new concept or innovation with electrically powered heavy vehicles such as trains and buses. The kinetic energy of any body depends on its mass as well as its velocity. Since these vehicles are very heavy, their kinetic energy is also large even at moderate speeds. Therefore, a huge amount of kinetic energy is wasted in frictional braking. In the current scenario of depleting oil reserves and increasing pollution, this is alarming. Also, in these vehicles, the space occupied by the system and the weight of the system are not key issues. In the recent past, it has been applied to medium and small sized cars also. These vehicles are either hybrids or completely electric in nature.

In two wheelers though, this concept has not grown much. The basic reason for this is that, two wheelers are light and kinetic energy associated with them is less. Thus, the energy recovered will also be less. This concept is not studied in academic research. Industrial reseach is not focusing in this area due of limited energy recovery. However, because of the huge number of two wheelers the amount of energy that could be recovered is significant. There are more than 35 million two wheelers in a country like India [Chiplankar, 2006]. In the future, it is possible that many of these two wheelers would be electrically powered and even if a small amount of energy can be recovered from every such electric two wheeler, the overall energy savings would be tremendous. In the long run its contribution towards energy saving will be important.

If regenerative braking is applied to electric two wheelers, it will not only help in saving energy, but will also increase the range of the electric two wheeler. Our aim in conducting a study on regenerative braking is to implement a system- (1) That would recover at least 50 % of the kinetic energy during braking. (2) That would be able to push this recovered energy back into the motor while starting/acceleration with minimum losses.

The concept is demonstrated on a motorized bicycle.

3. MOTORIZED BICYCLE

A supercapacitor based regenerative braking system in two wheelers can have a lot of impact in the field of energy conservation. Its effect is increase in battery life and reduction in its size, thereby making a more environmentally acceptable system. Implementation of this system has many issues such as selection of motor, drive system, optimum selection of supercapacitor-battery pack combination, control mechanism and other system elements. Theoretical analysis and mathematical modelling will be the correct approach to get an optimum regenerative system for two wheel-

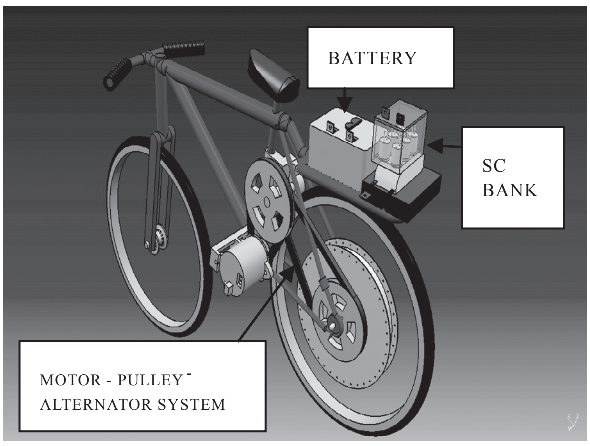

Fig. 1 Motorized bicycle for demonstration of regenerative braking

ers. However, for establishing the concept of regenerative braking in two wheeler systems from a feasibility point of view, theoretical knowledge and availability were the two aspects considered for selection of components. Following section deals with these aspects. Figure 1 shows the different components of the motorized bicycle.

3.1 Electric motor

Brushless or brush type DC hub motor are the options. Brush type DC motors have an inherent problem of sparking and their brushes wearing out. Therefore, even though it is not the best choice, a low voltage brushless DC (BLDC) motor is selected which is less expensive compared to other type of motors used in traction applications. Researchers are working on an efficient BLDC motor with regenerative capabilities [Taechyung et al., 2006].

3.2 Alternator with rectifier

Ideally the motor used to drive the system; itself should operate as a generator to facilitate regeneration. However, the availability of such a BLDC hub motor was an issue and hence, the use of generator was inevitable. Low speed, low voltage (24 V to 48 V, < 300 rpm) generators of smaller capacity are not used in many applications. Thus, the only choice that remains is the use of existing high speed generators. As a result, a standard alternator with rectifier of a Maruti Suzuki 800 manufactured by Lucas-TVS was used along with a speed reduction system in the form of a two stage pulley system described subsequently. From here on, alternator refers to alternator with rectifier..

3.3 Pulley system

A BLDC hub motor of 300 rpm, 24 V and an alternator of 2100 rpm minimum speed, 12 V was used. As the speeds of both machines were not matching, various methods of mechanical power transmission were considered and V-belt drive was considered to be the best [He et al., 2009; Spots, 1998]. To match the speeds, as shown in Figure 2 a pulley arrangement consisting of 4 pulleys increasing the speed in the ratio 1:4 and 1:4 giving a total speed ratio of 1:16 is used. The intermediate shaft of the two stage pulley system is designed on strength basis for static and fatigue loading [Paul, 1968].

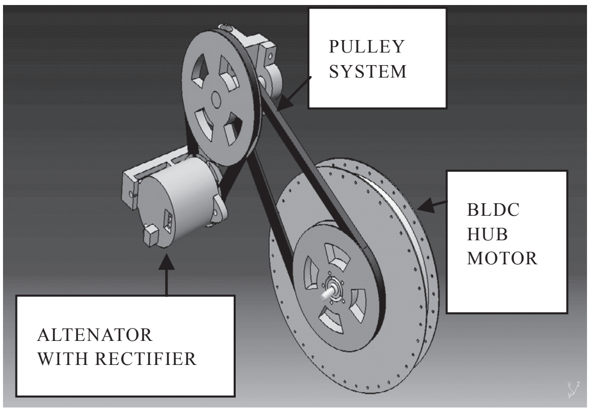

Fig. 2 Pulley system

3.4 Battery and supercapacitor

Lead acid battery is the most cost effective solution as it has high efficiency in the range of 85 to 95 %, but maintenance is an important issue with this battery. [Brown, 1999] Supercapacitors are of two types-aqueous and non-aqueous type. Aqueous supercapacitor technology is still developing [Karandikar, 2010] whereas non aqueous technology has been present for over a decade now. Non aqueous type supercapacitors are used in the presented work. Sizing of supercapacitor modules is out of scope of the work at present and hence, two 15 V, 20 F banks that use six non-aqueous Maxwell supercapacitors each are used. The banks are connected one by one across the alternator during charging i.e. regeneration and during discharging they are in series to obtain 30 V across the 24 V BLDC hub motor to feed the starting or acceleration current.

Self-discharge problem can be addressed by a PV system [Karandikar, 2009]. Work for inclusion of photo voltaic system in the demonstration model is in progress.

3.5 Control scheme

The demonstration bicycle consists of the following parts- (1) BLDC Hub Motor, 24 V, 250 W, 250 rpm, (2) Belt and pulley system, (3) Alternator with rectifier 24 V, 2000 RPM, (4) Cycle frame, (5) Two supercapacitor Banks 20 F, 15 V, (6) Two lead acid batteries 12 V, 7 Ah each. The performance and cost of the regenerative braking system are required to be balanced as this type of vehicle targets the common man. Hence, low cost components are selected which meet the minimum performance requirements of the system.

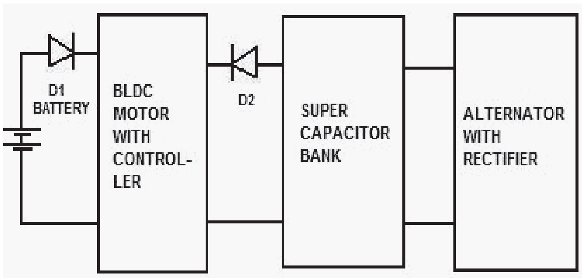

Fig. 3 Regenerative braking scheme using supercapacitor bank

The supercapacitor bank is connected across the alternator to store the energy generated during braking. Figure 3 shows the regenerative braking scheme using supercapacitor bank.

4. ELECTRICAL PARAMETER VARIATIONS IN A PRACTICAL SITUATION

During regenerative braking, the supercapacitor bank may possess any voltage and from that, it is required to get fully charged to use the stored charge for subsequent starting/ acceleration. Table 1 summarizes the results from a similar testing situation.

Table 1 Performance parameters of regenerative scheme in a practical situation

Initial Voltage of the SC bank (Volts)	Increase in voltage of SC bank (Volts)	Peak charging current (Amp)	Energy regenerated (Joules)
0	4.49	9.6	201.60
4.21	6.72	12.9	274.343
6.53	8.04	14.5	220.007
7.75	8.9	14.5	191.475
8.61	9.49	11.9	159.28
9.36	10.5	8.5	226.404
10.35	11.1	14.2	160.875
10.97	11.61	11.7	144.512
11.47	12.1	7.9	148.491

For the practical testing of the demonstration model and recording of necessary observations, instruments like digital storage oscilloscope (DSO) would not prove feasible because the setup is mobile. Therefore, an apparatus is made consisting of a clamp meter for measuring current, a digital multi meter for measuring voltage and a digital camera to record the readings of the two meters. The video captured by the camera is later played back and the readings of current, voltage and average speed were tabulated. The above mentioned procedure is used for all the results presented.

The motorized bicycle is driven to a rated speed of 21 km/h and electrical brakes are applied to capture the braking energy which is pushed into one supercapacitor bank of 15 V, 20 F. In the actual proposed model, two such banks would be charged one by one and later connected in series to obtain 30 volts.

The voltage by which the supercapacitor bank charges follows a certain trend. In the first braking, the supercapacitors are charged to 4.49 volts, but in the next braking, the supercapacitor bank is charged to 6.72 volts (follow the same way: charge should vary). This means that in the second braking, the supercapacitor bank charges by only 2.23 volts. Similarly in the subsequent braking, the voltage by which the supercapacitor bank charges, decreases. However, the energy recovered is dependent on the difference in squares of the final and initial voltage on the supercapacitor bank. As a result, the average energy recovered in each braking is about 200 Joules.

However, the performance parameters have to be standardized and thus, we performed the above mentioned test again, but this time with fixed initial conditions.

5. ELECTRICAL PARAMETER VARIATION WITH VARIOUS INITIAL CONDITIONS OF SUPERCAPACITOR

The performance of a supercapacitor bank under braking dynamics of a motorized bicycle is studied by charging the supercapacitor bank at different standard initial conditions. Table 2 shows the performance parameters of the regenerative braking system with the supercapacitor bank charged to different initial conditions.

Table 2 Performance parameters of regenerative scheme with various initial conditions of supercapacitor

Initial Voltage of the SC bank (Volts)	Increase in voltage of SC bank (Volts)	Peak charging current observed (Amp)	Energy regenerated (Joules)
0	4.49	9.6	201.6
2	5.71	9.8	286.60
4	6.9	14	316.1
6	7.84	15.5	254.66
8	9.18	15.1	202.72
10	11.1	14.2	232.10

Thus, it is observed that more energy can be regenerated if the supercapacitor bank is partially charged because power is the product of voltage and current. Initially voltage is less, thus power is less. Later on, as the supercapacitor bank keeps charging to different voltage levels, power again starts decreasing. This is because of the charging characteristics of a capacitor (rate of charging keeps decreasing). Hence, it is advisable to charge the supercapacitor bank through a battery to about 30 % of its maximum value and then regenerate energy in every braking to use it for subsequent starting/acceleration.

6. ANALYSIS OF RECOVERY OF ENERGY DURING REGENERATIVE BRAKING AND ITS EFFECT ON STARTING CURRENT

6.1 Energy analysis

The energy recovered is the energy that has been

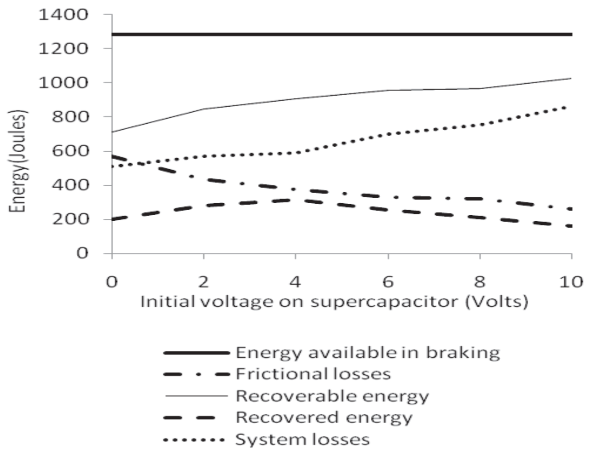

Fig. 4 Distribution of energy during regeneration

pushed in the supercapacitor bank. Figure 4 shows the distribution of energy during braking.
Total mechanical energy available is calculated by

$$Energy_{available} = \frac{1}{2} mv_f^2 - \frac{1}{2} mv_i^2 \quad (1)$$

Where m – mass, v_f – final velocity and v_i – initial velocity
Velocity decreases from 21 km/h to 3 km/h during our trials and the mass of the complete system with the weight of the person is 79.9 kg. Due to the presence of the additional alternator, whose weight is 4 kg, a small amount of additional energy is regenerated but its value is about 5 % only.
The rotational energy of the wheels is very less compared to the kinetic energy and hence we have neglected it.
Losses in friction are given by

$$Losses_{friction} = \mu N = \mu mg \quad (2)$$

Where μ - coefficient of friction and g – acceleration due to gravity
μ between tyre and road for rolling is 0.015 [Thomas, 2008].
The recovered energy is calculated by measuring the change in voltage across the supercapacitor bank.

$$Energy_{recovered} = \frac{1}{2} CV_f^2 - \frac{1}{2} CV_i^2 \quad (3)$$

Where C – capacitance, V_f – final voltage and V_i – initial voltage
In the above equation C = 20 F, as we used standard Maxwell capacitor bank of 20 F - 15 V.
During six trials, the following average values of various energy transformations taking place were obtained.

The system losses are a major component and are due to air resistance, losses in the pulley mechanism, losses in the bearings of the wheels and losses in the alternator. Table 3 shows that 18 % of the total energy is recovered. Our aim was to recover 50 % of the energy as mentioned in section II. However due to technical and commercial difficulties mentioned in section 3, we could recover only 18 % of the energy. If we could minimize the system losses, then a higher percentage of the braking energy can be recovered.

Table 3 Average values of all the energy transformations

Distribution of energy (avg)	Energy (Joules)	% of Total Mech. Energy
Total mech. Energy	1284	100 %
Frictional losses	381.41	30 %
Recoverable energy	902.58	70 %
Energy recovered	237	18 %
System losses	665.58	52 %

6.2 Current sharing

A battery and a supercapacitor working together can reduce the demand on the battery alone. The average energy consumption of a vehicle with a supercapacitor in a regenerative environment is much less than that of a vehicle without a regenerative system and the mileage in one charge of the electric vehicle gets affected notably.
Current sharing of the supercapacitor bank and battery is studied by starting the motorized bicycle with fully charged supercapacitor bank. The current sharing is shown in Figure 5.
Maximum current is drawn by a motor during starting, thereby stressing the batteries. A supercapacitor can

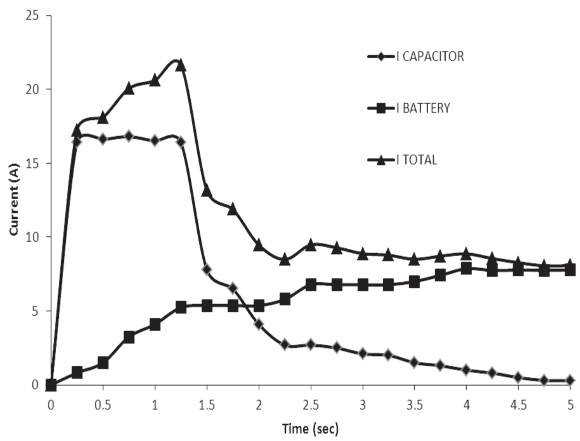

Fig. 5 Current sharing by supercapacitor bank and battery in starting operation of motor

improve the acceleration performance of the vehicle by providing a large current in a short time and delivering extra energy to meet the energy requirement when it is needed.

The two supercapacitor banks are charged to 15 V each and then connected in series to obtain 30 V and then connected through diodes to assist the batteries during the starting of the motor. As seen in Figure 5, the supercapacitor bank is supplying most of the current during the initial few seconds, i.e. during starting. Their share slowly reduces as they discharge. During the 1st second after starting, the supercapacitor bank provides almost 90 % of the current required by the motor.

In the motorized bicycle under study, without the aid of the supercapacitor bank the batteries will have to supply almost 21 A of current during starting. The supercapacitor bank limits this value to a mere 5-7 A. This not only increases the range (in terms of distance) of the system but also prolongs battery life, by reducing the peak current being supplied by the battery. Hence battery maintenance and battery replacement frequency reduces which reduces the running cost of the bicycle.

6.3 Impact on range

This study was conducted aiming at a system that could regenerate power in every braking and push the power back in the subsequent starting/acceleration. But due to the limitations in the alternator with rectifier and the supercapacitor bank, although regeneration is possible in every braking, it may not be possible to use this regenerated power immediately. The supercapacitor bank has to be charged above a threshold value, specifically, 0.7 volts above the battery bank in order to assist. There is a problem regarding self-discharge of the supercapacitor bank since it is not an ideal device. But even then the results are encouraging.

Two points A and B, 40m apart are selected. The bicycle is run from point A to point B. On reaching point B, brakes are applied. The experiment is repeated with the bicycle now going from point B to point A. The distance travelled by the cycle increased to 1.68 km (42 times the cycle was run from A to B and back with regenerative braking and assist) from 1.60 km (40 times the cycle was run without regenerative braking). This increase in the range is just about 5 %, however with improvement in the system by using single machine capable of regenerating power and DC-DC convertor in control scheme along with optimum size of supercapacitor and battery, this range is likely to increase substantially. Work in this regard is in progress. This proves that, it is feasible to implement regenerative braking using supercapacitor to increase the range of the vehicle in electric two wheelers.

6.4 Braking distance

The braking distance varies from 22 m to 37 m depending on the charge on the supercapacitor bank at the time when the brakes are applied. This distance is needed for the bicycle to come to a complete rest with just the electronic brake. But in the true sense, this is deceleration and not braking. We have to use frictional brakes along with electronic brakes to reduce the braking distance. In case the bicycle has to stop immediately, frictional brakes are applied along with the electronic brakes; otherwise just the electronic brakes provide the deceleration. This is achieved through an innovative mechanism shown in Figure 6. Various springs were tried out and the best suitable spring was selected for this new mechanism during the trials. The proper design and placement of this spring can give a sophisticated and accurate handle for better control of the vehicle.

If the rider wants to just decelerate, then he applies the brakes lightly and electronic brakes are applied through the momentary action SPST switch. The SPST switch connects the circuit that provides field current to the alternator. If the rider wants to stop immediately, he applies the brakes completely and both electronic and mechanical brakes are engaged. The spring constant of the spring in the momentary action SPST switch is less than the spring constant of spring *S*. This ensures that only if the switch is closed when the brakes are engaged, the spring *S* gets compressed and mechanical brakes are applied. Therefore, electronic brakes are engaged before mechanical brakes.

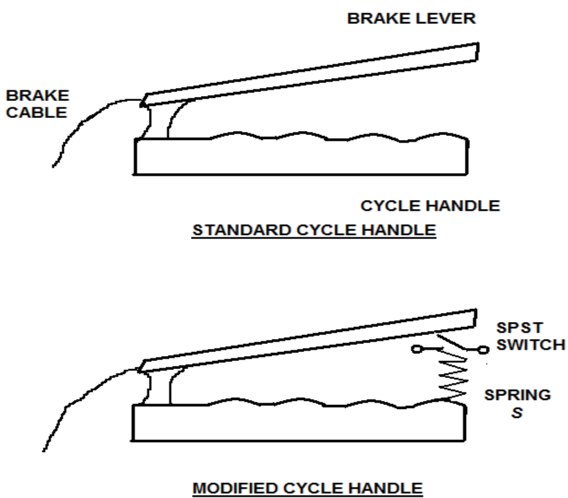

Fig. 6 Cycle handle of a standard bicycle and of the motorized bicycle

7. CONCLUSION

Although regenerative braking already exists in heavy vehicles such as four wheelers, keeping in mind the energy crisis and rapidly depleting conventional energy reserves, it is imperative to develop an energy saving system on a smaller scale such as a two wheeler. Use of supercapacitor is not a new concept. However results of use of supercapacitors based regenerative braking for two wheelers are not documented in academic research. System used for regeneration may be complex but the results presented will give proper direction for development of an improvised system. Despite many technical and commercial difficulties, regenerative braking using supercapacitors is successfully implemented on a motorized cycle and the results are encouraging. This scheme can be extended to any electric two wheelers with some modifications. However for effective implementation of this scheme, low speed and low voltage DC hub type motor and a cost effective machine is required along with a DC-DC convertor in the control scheme consisting of a battery and a supercapacitor bank. This can eliminate the mechanical power transmission system, a separate generator and thereby recapture energy during regeneration more efficiently. Although our initial aim was to recover 50 % of the kinetic energy we could recover only 18 % due to high system losses. The attempt to push the recovered energy in the system is successful. Self-discharge of the supercapacitor is another hurdle in the implementation of this scheme in electric two wheelers. Considering the values of recovered energy, it is recommended to partially charge the supercapacitor bank to maximize the regenerated energy. Results show that, it is feasible to implement regenerative braking on an electric two wheeler. After establishing the concept of regenerative braking on an electric two wheeler, modeling and design aspects can be considered for component selection and optimum performance. We are working on optimum selection of various components.

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