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Designing electric braking system for brushless direct current motor as an electric bicycle propulsion

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ABSTRACT

One of the problems arising in the conversion of pedal-based bicycles into electric bicycles using brushless direct current (BLDC) motors is how to provide an electric braking system for the BLDC motor. Published research on braking systems for electric bicycles from a practical perspective was still limited. The objective of the article is to develop an electric braking system for BLDC motor as a propulsion of electric bicycle converted from pedal-based bicycle from the empirical point of view. The pedal-based bicycle was converted to the electric bicycle by fully replacing its rear wheel including its chain system with the BLDC motor. The braking system was developed by adding a DC motor as a load for BLDC in the braking mode. Test was conducted by turning on the acceleration handle and then the braking action was applied. The stoppage time was recorded from the start of braking action until the wheel was fully stopped. The test results showed that the addition of a direct current (DC) motor as a load can shorten stoppage time of the electric bicycle dramatically, i.e., needs 1.65 seconds compared to 10.14 seconds and 3.09 seconds for without braking and with braking but without DC motor as a load respectively.

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1. INTRODUCTION

Research on electric vehicles (EV) including cars, motorcycles, and bicycles is increasingly widespread along with the increasing demand and development of electric transportation modes because EV offer many advantages such as having much higher energy conversion compared to oil-fueled engines and can reduce air pollution in the environment [1]. However, what is considered the most fundamental key component in the development of EV is still on the energy supply side, namely the battery and related matters such as the charging process and battery management system thus attracting great attention from researchers [2], [3]. Besides electric cars and motorcycles, the demand for electric bicycles has also gained popularity in society because it has advantages such as can be used in congested traffic or narrow streets in urban environments [4]. There are two general forms of electric bicycle namely electric assisted conventional bicycle such as proposed in [5] which still has pedal based propulsion system and full electric bicycle which is without pedal based propulsion system. In principle, the works of the electric motorcycle and electric bicycle are very similar. The difference is mainly in its dimension, an electric bicycle is usually smaller than an electric motorcycle. Besides being developed from scratch such as proposed in [6], electric bicycles also can be converted from already existing pedal based bicycles such as proposed by [7], [8].

A direct current (DC) motor is an electric motor that is driven using DC current [9]. There are several types of DC motors which are widely used in various areas of life as actuators/drivers, for example the brushless direct current (BLDC) motor which is used as a driver in EV including electric cars, electric motorcycles, and electric bicycles. Every mode of transportation, including EV, must be equipped with a braking system to reduce its speed or even stop it when necessary. In principle, braking on EV is divided into two types, including mechanical braking which uses the principle of brake lining friction and electrical braking which is an effort to reduce the rotational speed of the electric motor as a driver as quickly as possible [10]. Electric braking can be done very quickly, is more reliable and more economical compared to mechanical braking. For electric braking, the parameters commonly used to measure its performance include the time required to stop (stoppage time) and the distance required to stop (stoppage distance) [11].

Researches in the field of electric braking system for DC motor families have been carried out in various fields of application for example in braking on permanent magnet DC motors used to drive light systems [12] as well as braking for DC motors to drive large loads such as for pure EV or hybrid electric cars as reported in [13]. Generally, electric braking on EV can be grouped into three types, namely plugging, rheostatic/dynamic braking, and regenerative braking [10]. Of these three types of braking, the most studied by researchers are dynamic and regenerative braking systems [14].

The main advantage of regenerative braking is that the kinetic energy from the motor during braking can be used to charge the battery [15] although the research results in [16] suggested that the saved electrical energy was still arguably very low. Another advantage of regenerative braking is that it can minimize brake lining wear, increase mileage, and reduce maintenance costs significantly [17]. With these various advantages, the regenerative braking system has attracted the interest of researchers to be applied to various EV, including electric dump trucks [18]. To increase braking performance while still maximizing energy storage, a combination of braking types can be used, such as a combination of plugging and regenerative braking [19]. One of the things that must be considered in regenerative braking is that its performance will be greatly influenced by the condition of the battery, including battery capacity and temperature [20]. In order to find optimum electrical conversion, researchers proposed optimization algorithms for electric braking on DC motors for example using a combination of artificial neural network (ANN) algorithms and proportional-integral (PI) controllers [21], and the radial basis function algorithm implemented in electro-mechanical systems [22]. From a practical perspective, the electric braking system on DC motors can be implemented using various methods, for example by using electromagnetic relays and timers [23], and pulse width modulation (PWM) [24], [25].

From previous publications mentioned above, it can be noted that most of the research on electric braking systems was focusing on passenger cars, trucks, or motorcycles. The work of braking systems development devoted to electric bicycles, especially electric bicycles converted from pedal-based bicycles, is still limited. Therefore, research on the braking system for electric bicycles is very urgent to do in order to provide a braking system which is safe and comfortable for the rider. The objective of the article is to result in an electric braking system for BLDC motor as a propulsion of electric bicycle converted from pedal-based bicycle. The electric brake was intended to be used to decelerate BLDC motor speed which in turn decreases the speed of the electric bicycle before being braked by using an existing mechanical brake. Therefore, the problem that will be solved in this article is what kind of braking system is precise in terms of stoppage time. The importance of the article is to give a contribution on the providing alternative braking system model for the electric bicycle in the practical form.

2. METHOD

2.1. General development steps

The braking system development steps can be outlined as follows. First, a pedal-based bicycle was converted to an electric bicycle by removing its chain based propulsion system and then replacing it with a BLDC motor available in the market. Second, an electronic hardware including processor, display and battery as the main power source were mounted in the body of the bicycle. Third, the proposed braking system was constructed on the resulting bicycle. Finally, the performance of the developed braking system was assessed based on its stoppage time.

2.2. Converting pedal-based bicycle into electric bicycle

The development of the control and braking system of the electric bicycle developed in this article can be broken down into two main steps. The first step was performing mechanical work for converting the pedal-based bicycle into electric bicycle step while the second step was designing electronic hardware and software of control and electric braking system step. Different from the mechanical construction which was using DC motor and still using chain-based propulsion systems proposed in [26], the mechanical work for converting the pedal-based bicycle into electric bicycle in the article was done by replacing the rear wheel and its chain based propulsion system completely with the same size rim of BLDC motor powered wheel. The BLDC motor was chosen because it has higher efficiency and lower maintenance compared to general DC motors [27].

After the mechanical construction was finished, the control circuit was designed in order to give acceleration to the BLDC motor for moving the electric bicycle as a whole and the braking system for decreasing its speed or stopping it. The concept of the designed braking system is that there will be two brakes in the developed electric bicycle involving electric braking which is applied in the rear wheel to decrease the BLDC motor speed and the existing mechanical braking which is applied in the front wheel to stop the electric bicycle mechanically by using friction principle. The electric brake has to be applied first before the mechanical brake because if the BLDC motor is in full speed which means the electric bicycle also in full speed and if mechanical brake in the front wheel is applied directly it will make the electric bicycle will stop abruptly which cause the rider feeling uncomfortable or perhaps can caused an accident.

2.3. General architecture of the braking system

The developed control and braking system on the electric bicycle was built based on the electronic components available in the market. The Arduino Uno microcontroller was used as the main processor to read and process the data from acceleration handle, brake handle, and BLDC motor sensor. Arduino Uno microcontroller was chosen because it is a popular board which has been used in various research applications such as for automatic controlling of lamp [28] and electric power of home appliances control [29]. The computed value of data from all sensors were then displayed in the liquid crystal display (LCD). Electrically, the acceleration handle is constructed mainly from a potentiometer component so that the position of its handle from 0 to 100% of scale results in resistance value from zero to its maximum value in Ohm. This resistance value was then converted into the voltage value for powering the BLDC motor as a propulsion of the electric bicycle via the driver to determine its speed.

In theory, when the BLDC motor received the voltage input it will convert the voltage input into the movement of its rotor to become speed stated in the revolution per minute (RPM) and if the voltage input is turned off then the BLDC can be able to convert the movement of its rotor to become voltage output. This voltage output then can be used for charging back the battery as load so that it will decrease the BLDC speed to form regenerative braking. However, the BLDC motor used in the developed system provided only very small output voltage so that it cannot be used for charging the battery to implement general regenerative braking. To overcome this problem, a DC motor was proposed as a load of the BLDC motor in the braking period whose function was to fast decelerate of the BLDC motor speed. The DC motor as a load was connected to the BLDC motor by using pulley and V-belt (also called as van belt). The general architecture of the developed braking system is depicted in the block diagram of Figure 1.

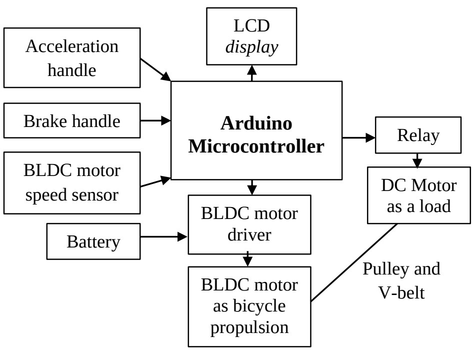


Figure 1. Block diagram representing the general architecture of the developed braking system

2.4. Electronic hardware configuration

The general architecture in Figure 1 was then implemented into a schematic diagram depicted in Figure 2. In the developed system, Arduino Uno R3 board which was built based on ATMega328 microcontroller was used. LM2596 is a driver module for BLDC motors. The driver has input operating voltage between 12 V and 36 V with current maximum of 500 mA. The driver has output voltage from 0.1 V to 5 V which will be passed to the BLDC motor. The developed system used the 27 V/10 A DC battery as the main power source. For the Arduino Uno microcontroller, this battery was connected to the step down circuit to decrease to 5 V since the operating voltage of the microcontroller is 5 V. This 5 V voltage was then connected to the Vin pin of Arduino Uno microcontroller while the ground path of the battery was connected to the ground pin of the Arduino. The Vcc pin of Arduino Uno was connected to the voltage input of the I2C LCD while serial data line (SDA) and serial clock line (SCL) pins of I2C were also connected to SDA and SCL pins of Arduino respectively. The data pin of the BLDC motor driver was connected to pins D2 and D9 of the Arduino while the data path from the acceleration handle was connected to pin A0 of the Arduino. Finally, RST pins of the driver were connected to RST cables of the BLDC motor.

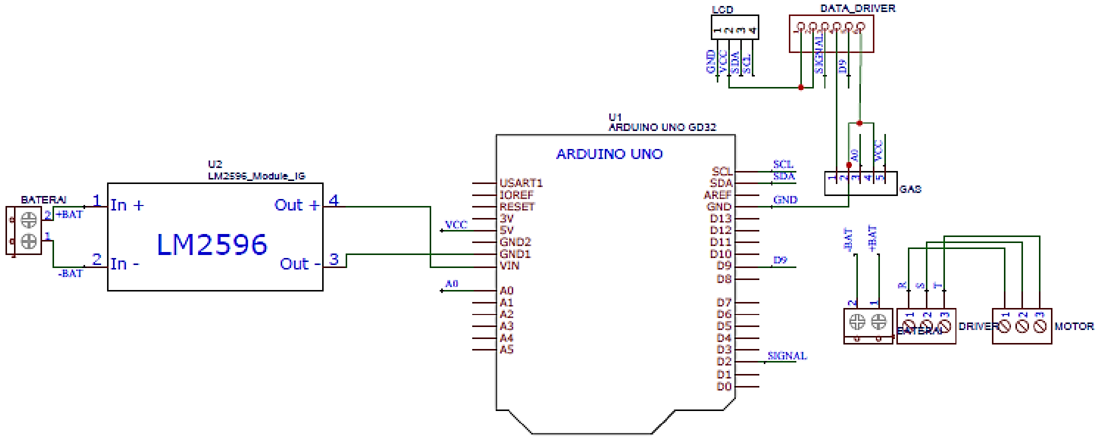
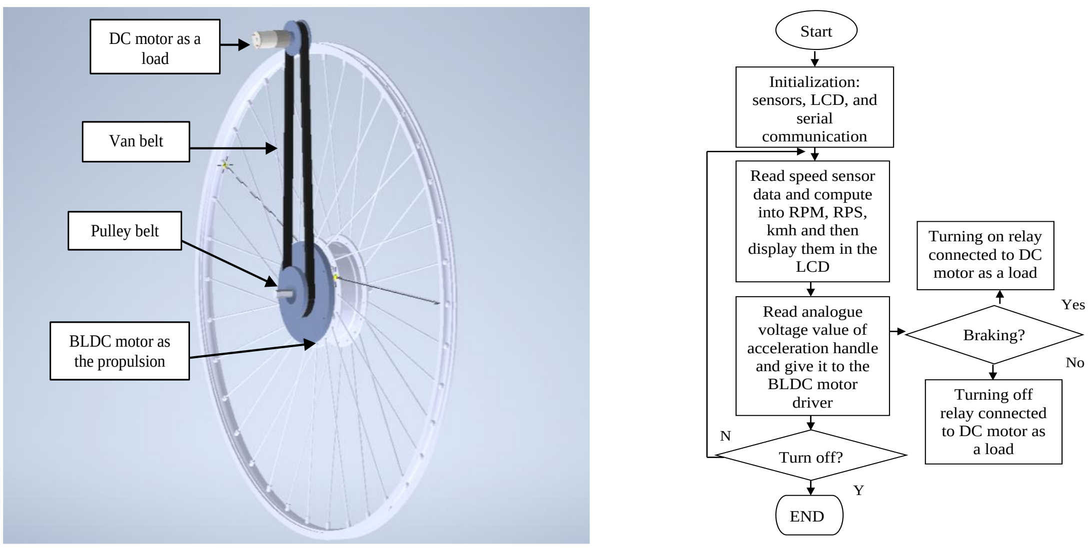


Figure 2. Electronic wiring diagram of developed braking system

2.5. Mechanical construction and software design

The mechanical construction design of the developed braking system and flowchart of the program coded in the Arduino Uno microcontroller has logic which is represented in the flowchart in Figures 3(a) and (b) respectively. The developed braking system was implemented on the rear wheel of the electric bicycle. The rim of the wheel size is 27.5 inches. The BLDC motor operating voltage is 36 V with maximum power is 350 Watts with weight 4.5 kilograms (Kgs). As a propulsion, this BLDC motor is able to make the electric bicycle to run between 20 and 30 kilometers per hour (kmh). The DC motor as a load has an operating voltage of 12 V with maximum speed of 200 RPM. Its torque was 6.5 kilograms while its weight was just 90 grams. Its dimension is 68 millimeters in length with a diameter of 25 millimeters. Its rotor axis is 9.5 millimeters with a diameter of 4 millimeters. The DC motor was mounted in the back seat of the electric bicycle and then its rotor was connected to the pulley. The pulley of the DC motor as a load was then connected to the BLDC motor using a van belt.



(a) (b)

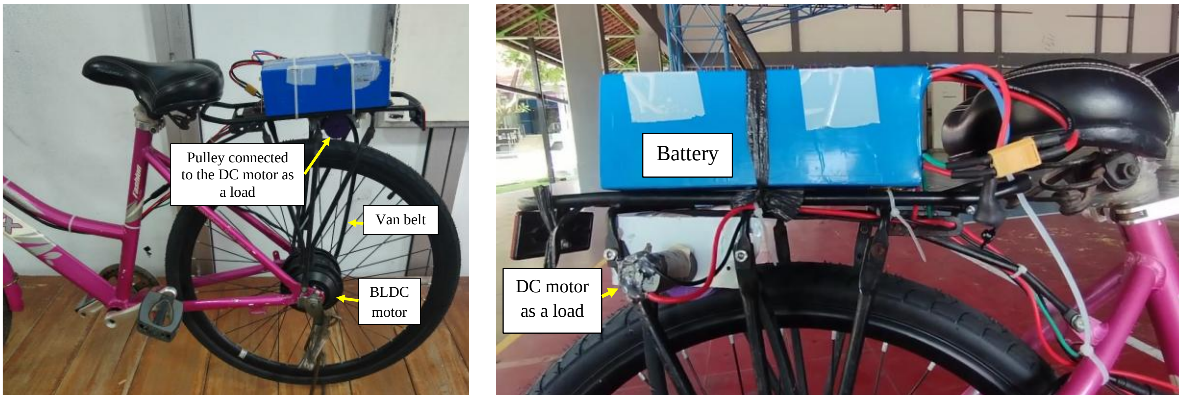
Figure 3. Mechanical and software design: (a) sketch of the mechanical construction of the developed braking system and (b) flowchart which is representing the logic of the program in the Arduino Uno microcontroller

The flowchart depicted in Figure 3(b) can be explained as follows. After the developed system was started, the Arduino Uno microcontroller performed an initialization step to check the availability of sensors, LCD, and serial data communication. After that, the microcontroller then read the data from the speed sensor to compute its speed stated in revolution per second (RPS), RPM, and kmh which were then displayed in the LCD continuously. The Arduino microcontroller reads analogue voltage value resulted by potentiometer of acceleration handle position and passes this value to the driver of the BLDC motor. The speed of the BLDC motor was supposed to be proportionally linear to this voltage value. At the same time, based on the voltage value, the Arduino Uno microcontroller decides whether the BLDC motor is in the braking mode or not, if yes then the relay connected to the DC motor as a load will be turned on otherwise it will be turned off. The program of the microcontroller was written by using Arduino integrated development environment (IDE). Arduino IDE is a multipurpose software development environment which can be used not only for Arduino board families but also other boards such as NodeMCU board used for remote water monitoring [30].

3. RESULTS AND DISCUSSION

3.1. The developed system

The obtained developed braking system can be seen in Figures 4 and 5; Figure 4(a) shows the developed system from the left-hand side view, Figure 4(b) shows the developed system from the upper right-hand view, while Figure 5(a) shows from the lower right-hand side view, showing the position of the van belt and cable from the driver to the BLDC motor. The battery as the power source was placed in the back seat of the electric bicycle. This obtained system is mainly aimed as a prototype and proof of concept so that the placement of the battery has not considered the ergonomic factor yet. The electronic hardware circuit including the microcontroller and LCD was placed in the plastic box and then was mounted in the steering handle bar of the electric bicycle. The 4×20 LCD used in the developed system displays the speed of the BLDC in RPM and RPS, the speed of the electric bicycle in kmh, and the position of the acceleration handle in percent. There are two brake handles in the steering handle bar (shown in Figure 5(b) namely mechanical brake handle (right brake handle) which is the existing braking system of a pedal based bicycle and electrical brake handle (left brake handle) which is the developed system. When the electric brake handle is squeezed on, it will activate the developed electric braking system.

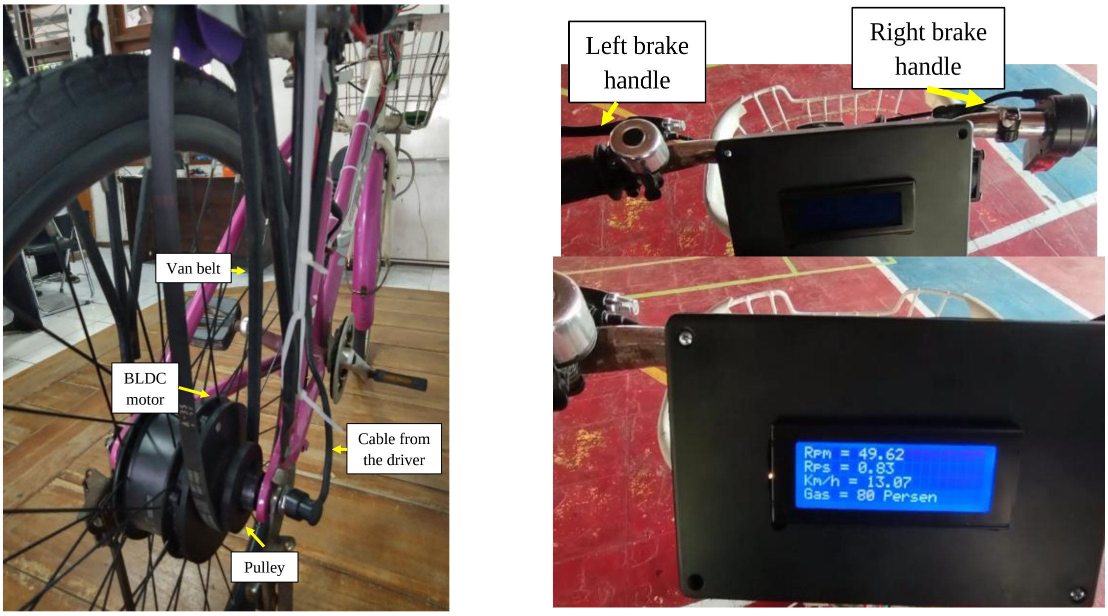


(a) (b)

Figure 4. Construction of the obtained system: (a) the obtained braking system and (b) the obtained braking system showing the position of the DC motor as a load mounting in more detail

3.2. Brushless direct current motor stopping characteristics without braking

The test on speed acceleration and natural stopping characteristics was performed on the BLDC motor before it was constructed to become an electric bicycle. The BLDC motor with the rim wheel of the bicycle was placed in the position as can be seen in Figure 6(a). The initial condition was the BLDC motor with the rim wheel was in resting/full stop condition. The acceleration handle was then turned on step by step until 100% of its position from its resting position (0%). After the acceleration handle position was at 100%, it was released directly so that its position came back to its resting position (0%). The stoppage time was recorded starting from the release of the acceleration handle from 100% of its position until the BLDC motor was in full stop condition. The experiment was done several times and the recorded stoppage time was between 28 and 30 seconds.



(a) (b)

Figure 5. Construction of the obtained system: (a) the obtained braking system and (b) brake handle of the electric bicycle (upper), the electronic hardware circuit placed inside the box and LCD mounted in the steering handle bar of the electric bicycle (lower)

3.3. Testing on developed braking system in static condition

Testing was conducted on the obtained braking system mainly to unveil its performance focusing on its stoppage time. The test was conducted by placing the bicycle in the resting condition as can be seen in Figure 6(b). In the test, the acceleration handle was turned on until its full position (100%) after that it was released. The stoppage time was then recorded by using a stopwatch.

(a) (b)

Figure 6. Rim and bicycle position in testing: (a) position of testing BLDC motor stopping characteristics without any braking action before constructed to become an electric bicycle and (b) the electric bicycle in the resting condition in the testing

There are three conditions in the experiment. Firstly, the acceleration handle was turned on 100% and then it was released until the BLDC motor in full stop condition without any braking action. Secondly, the acceleration handle was turned on 100% and then it was released until the BLDC motor was in full stop condition with electric brake handle (left handle brake) was turned on but without DC motor as a load. Thirdly, the acceleration handle was turned on 100% and then it was released until the BLDC motor in full stop condition with left brake handle was turned on with DC motor as a load. The experiment was conducted several times and three recorded data was summarized in Table 1. From the testing results on the Table 1 it can be noted that the average stoppage time braking action with DC motor as a load has superior performance in the stoppage time, i.e., 1.65 seconds compared to without braking action, i.e., 10.14 seconds. The developed braking system was able to decelerate the electric bicycle almost ten times faster compared to without braking. Compared to braking action without DC motor as a load, braking action with DC motor as a load was also superior in that it can stop the electric bicycle around twice faster, i.e., with stoppage average 1.65 seconds compared to 3.09 seconds. However, the limitation of this stoppage time results was that the experimentation was performed in resting condition or static mode.

Table 1. The testing results of a developed braking system in static mode

No.	Testing condition	Stoppage time (seconds), attempt			
		1st	2nd	3rd	Average
1	Without braking action	10.3	9.84	10.29	10.14
2	Braking action without DC motor as a load	2.89	3.11	3.29	3.09
3	Braking action with DC motor as a load	1.84	1.6	1.53	1.65

3.4. Testing on developed braking system in actual condition

After being tested in a static mode, the developed braking system was tested in actual condition. The electric bicycle was ridden by an actual human rider. The testing environment was a flat pavement road. The acceleration handle was positioned 100% (maximum speed) and then the braking system was applied. The stoppage time was then recorded. After that the experimentation was repeated for 75% and 50% position of the acceleration handle. The data test results summarized in Table 2 shows that the stoppage time is between 26.30 and 27.75 seconds depending on the speed of the electric bicycle, in general the faster speed the longer the stoppage time.

Table 2. The testing results of a developed braking system in actual environment

No.	Acceleration handle position (%)	Stoppage time (s)
1.	100	27.75
2.	75	27.47
3.	50	26.30

3.5. Discussion

While many previous research articles are focusing on the theoretical point view with software simulation environments such as proposed in [31]-[33], the developed braking system was focusing on an experimental approach on a real electric bicycle. The developed braking system has been tested in a real electric bicycle, different from the braking system proposed in [34] which was applied for a small size BLDC motor without being constructed as a real electric bicycle. In the developed system, the braking system was applied in the rear wheel where the BLDC motor was installed differently from the front-wheel drive electric bicycle proposed in [35]. The developed braking system was also different from the braking system proposed by [36] where the speed of the wheel was used to compress air for further pneumatic action. In the developed electric braking system, the rotation of pulley and van belt was able to rotate the rotor of the DC motor as a load. Further study needs to be done to see its potential in order to develop new instruments or circuits for regenerative braking system strategy as suggested in [37], [38] and its dynamic characteristic regarding the mechanical construction as suggested in [39].

4. CONCLUSION

An electric braking system for BLDC motor as electric bicycle propulsion has been developed. The electric bicycle was built by converting a pedal based bicycle. The existing rear wheel of the pedal-based bicycle was fully replaced by a BLDC motor powered rim wheel. The electric braking system was developed by giving a DC motor as a load which was connected to the BLDC motor by using pulley and van belt. The performance of the developed braking systems was tested in three conditions namely without braking action, with braking action without DC motor as a load and with braking action with DC motor as a load. The test results showed that the addition of a DC motor as a load can shorten stoppage time of the electric bicycle dramatically, i.e., needs 1.65 seconds only compared to 10.14 seconds and 3.09 seconds for without braking and with braking but without DC motor as a load respectively. Further study including its performance in various actual street conditions, and regenerative braking system strategy should be addressed.

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