Fuzzy Logic Speed Controller Implementation to A Supercapacitor Based-Regenerative Brake System

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***Abstract*—During the braking process, the efficiency for the electric vehicles is improved through the recovery of energy by the regenerative brake system. The mechanical energy is lost and converted to heat when the conventional contact brake system is used. In this study, fuzzy-logic speed controller for a regenerative brake system using supercapacitors was designed, prototyped and tested. The prototype is mainly composed of a suspended wheel driven by a DC motor whose speed is varied and controlled through fuzzy logic algorithm. This study aimed at improving and maintaining the speed of the wheel to a set-point as compared with an open-loop system. This study also aimed to compare the performance of the proposed system that utilizes supercapacitor bank against a conventional system that uses a battery based on the recovered energy and the braking time. According to the experimental results, the proposed system improved its speed control through the fuzzy logic method as compared against an open-loop system. The data also showed that the proposed system using supercapacitor bank is significantly better in energy recovery and braking compared to the conventional system using a battery. On the average, the system using battery achieved 4.81% reduction in stopping time, while the system using supercapacitor achieved 30.29% in reducing the stopping time of the wheel during coasting. In a single braking, the average recovered energy using the battery is 0.01 J while 0.69 J of energy is recovered using the supercapacitor bank. Therefore, the system using supercapacitor recovered an average of 0.68 J more energy than using a battery in a single braking.**

***Index Terms*—Regenerative Brake System; Fuzzy Logic; DC Moto; Energy; Supercapacitor.**

I. INTRODUCTION

We live in a fast-changing world driven by emerging technologies that aid us in order to make our lives easier. Along with advancement in the field of science, engineering and technology is the rise in the global consumption of energy. Energy utilization should be taken into consideration.

Motor vehicles as products of technology consume a large part of our energy. Energy in the form of petroleum or electricity drives the engine of every vehicle. This energy is converted into mechanical work, but what happens to the energy wasted when stopping the vehicle? This wasted heat energy from the friction needed in order to stop the wheel only contributes to global warming. In urban driving, about one third to one half of energy of the total energy is consumed during braking according to studies. Regenerative brake energy recovery system converts the vehicle's potential and kinetic energy to electrical energy through the motor-generator during the braking process. The recovered energy is then stored to an electricity storage element.

A need for a system that utilizes wasted energies from stopping the wheel of vehicles is realized in this study. Studies show that regenerative braking is an efficient method to achieve better fuel economy, reduced energy consumption and decreased environment pollution.

The objective of this study is to develop and construct a fuzzy logic controlled wheel drive prototype that is capable of recovering energy through regenerative braking action. The system is aimed at developing and implementing a fuzzy-logic algorithm in a microcontroller that drives the wheel at different speeds and directions (i.e. forward and reverse); controls and maintains the speed of the wheel within a specified range; and decelerates and stops the wheel. The study includes the design of circuits for the power drive of the motor, input switch, relay, and a supercapacitor bank that will store electrical energy captured during the process. A test evaluates the performance of the fuzzy logic control method in achieving and maintaining the desired speed as compared to the open-loop method in forward and reverse directions. Another test evaluates and compares the performance of the regenerative brake system that uses supercapacitor bank in recovering energy and slowing the wheel compared to a system that uses battery based on the recovered energy and the braking time.

Upon successful implementation of this project, the system greatly contributes to utilization of energy and trims down the consumption of energy among vehicles. Conventionally, a regenerative braking system uses the battery of vehicle to gain charge. With the help of the proposed system, much more energy is recovered through the use of a supercapacitor bank. The braking time is also improved through the use of the supercapacitor bank.

The study includes the design and implementation of a controller for the motor-generator system whose components are limited to driving the wheel, stopping it, storage of electric energy to the supercapacitor bank. The study employs a prototype for the purpose of demonstrating the concept. The model is limited to a single bicycle wheel driven by a motor-generator which is powered by a 24 VDC power supply and is controlled through a microcontroller and H-Bridge driver circuit which could achieve 173 rpm as the maximum speed. Electric discharge mechanism to avoid overcharging the capacitor is not considered in this study. The test equipment used in this study to measure voltage, current and average power is limited to a digital multimeter. There is no data acquisition system to use due to its unavailability. The study does not cover the effects of the aerodynamic structure of a vehicle in stopping it. It does not consider the physical parameters of the vehicle that may affect the performance of the system such as mass, momentum, number of passengers, coefficient of friction of the tire used and the number of wheels in consideration. The system is not capable of providing the same braking power as the conventional friction-based brake plates. The study does not cover the process of transferring energy from the supercapacitor bank to the battery.

II. DESIGN

Shown in Figure 1 are the procedural steps used in conducting this research study.

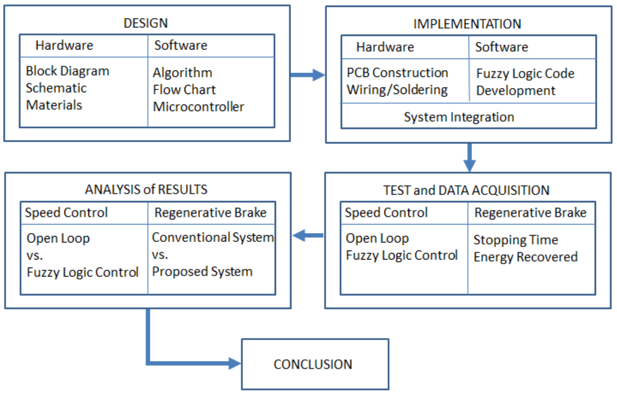

Figure 1: Methodology

The conceptual framework of the system is shown in Figure 2.

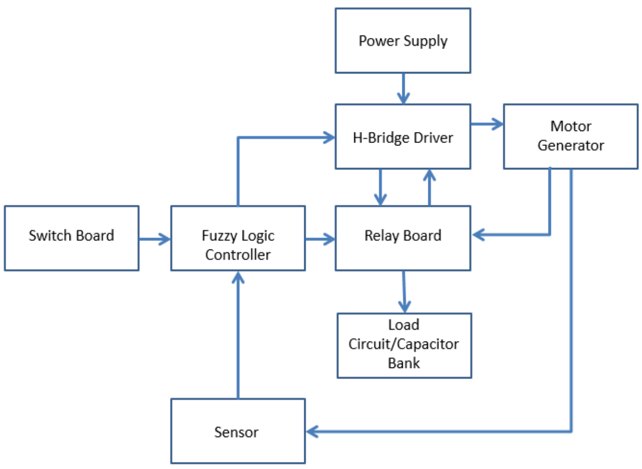

Figure 2: Conceptual framework

Speed control is performed through the following process. First, the desired speed is set through the switchboard. The output of the switchboard is fed to the fuzzy logic controller. The controller sends PWM signal to the H-Bridge driver that drives the wheel to the desired speed. The motor gets power from power supply/battery through the H-Bridge driver which limits the power supplied to the motor based on the PWM signal. The actual speed is never equal to the desired speed since the system is still at the open loop mode. Referring to Figure 2.2, the sensor is used to monitor the speed of the wheel which in turn sends a feedback signal to the controller. The Fuzzy logic algorithm performs operations using the desired speed and the feedback signal as inputs. Consequently, the output of the controller is the compensated PWM signal that will improve the speed of the wheel against the previous actual speed.

Regenerative braking, on the other hand, is performed through the following process. At the time that the compensated speed is achieved and maintained through the fuzzy logic control, the wheel could now be stopped. The stop switch is engaged to send a signal to the microcontroller which controls the relay board. While the wheel is maintaining its speed, the motor terminals are connected to the H-Bridge driver. This time, when the regenerative brake is applied, the relay board switches the motor terminals to the supercapacitor bank that will introduce the braking action to the motor. The motor will now become a generator that stores electrical energy to the supercapacitor bank.

III. IMPLEMENTATION

A. Hardware

The most important element considered in the design of the system is the motor/generator. It puts a limit on the system's maximum speed and power. The maximum speed of the motor is 84 rpm. This speed rating was increased by removing the gear box which is originally attached to the motor. In order to drive the wheel, the motor was coupled to the suspended motorcycle wheel using metal chains. In the set-up shown in Figure 3, the wheel achieved 173 rpm as the maximum speed using a power supply whose rated output is 24 VDC at 3.2 Amperes

Figure 3: Motor-generator and wheel set-up

The next step was to define the membership function that will convert raw data values into linguistic terms. Triangular shape functions represent the input and output membership functions.

Zilog! Encore microcontroller was chosen for the system since it is capable of performing the fuzzy-logic algorithm. It also has an adequate number of I/O terminals for the interfacing as required by the system.

The speed was monitored by a laser tachometer manufactured by Compact Instruments. This type of sensor was chosen for having an RS232 signal output since the microcontroller communication port to where the tachometer was attached required an RS232 signal. The actual analog speed signal was captured by the tachometer and was converted to digital form. This signal was fed back to the microcontroller communication port with ± 0.1 % accuracy.

The supercapacitor bank is composed of fifty 0.01-F (5.5 Vdc) supercapacitor in series-parallel connection. The total capacitance of the bank was 1.25 F (11 Vdc). This was used as the load circuit to capture energy during the braking process. Shown in Figure 4 is a picture of the supercapacitor bank of the system.

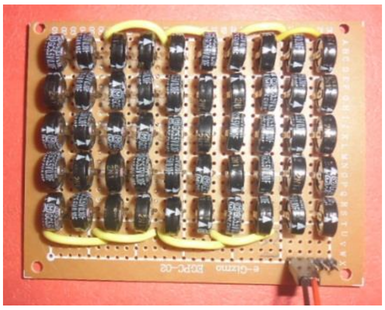

Figure 4: Supercapacitor bank

B. Software

The software component of the system was implemented in the microcontroller based on the process flow chart shown in Figure 5.

Fuzzy logic was chosen as the control algorithm. The process variable was the speed of the motor. The set-point was the speed defined by the user at the start of the operation. The input is the difference between the actual and desired speeds (Error_RPM). The output of the PWM signal adjustment (PWM_Adjust) for the motor driver, the microcontroller compared the actual speed to the set-point to yield an error signal. This error signal was then used as the reference for the necessary adjustment for the PWM signal output. The membership functions for both input and output were necessary in creating the rule for this control method. The linguistic terms used to represent the input and output values are VL, L, H MH, VH and VVH.

The next step was to define the membership function that will convert raw data values into linguistic terms. Triangular shape functions represented the input and output membership functions shown in Figure 6.

Instead of mathematical formulas, the algorithm used fuzzy logic rules to make decisions and control action in the form of if-then statements. Figure 7 shows the rules being implemented by the algorithm. If the error signal is L, then the PWM adjust is L. If the error signal is VVH, then the PWM adjust will also be VVH. The same rule is applied to all the membership functions.

Summarizing the output from all the fuzzy rules, a surface plot of PWM Adjust vs. RPM Error was created shown in Figure 8. When there was an error signal, there was a corresponding adjustment to the PWM signal output of the controller. This set of rules was developed an adjusted after comparing the actual output to the expected output as a result of several tests. The actual tested prototype is also shown in Figure 9.

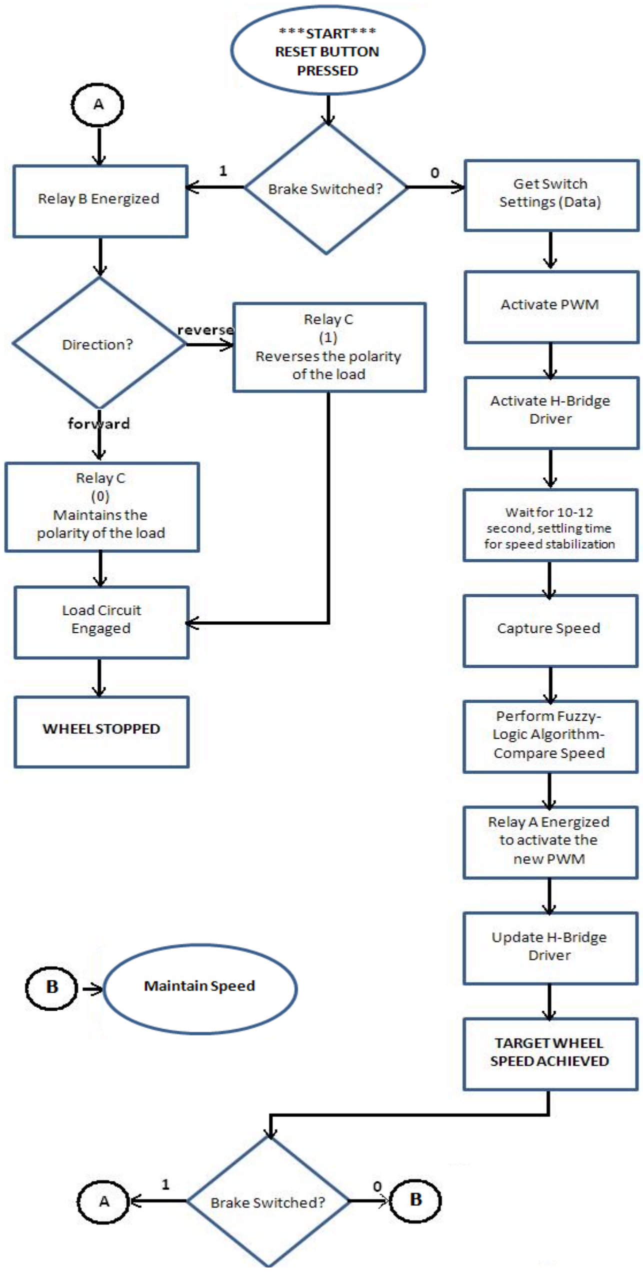

Figure 5: Process flow chart

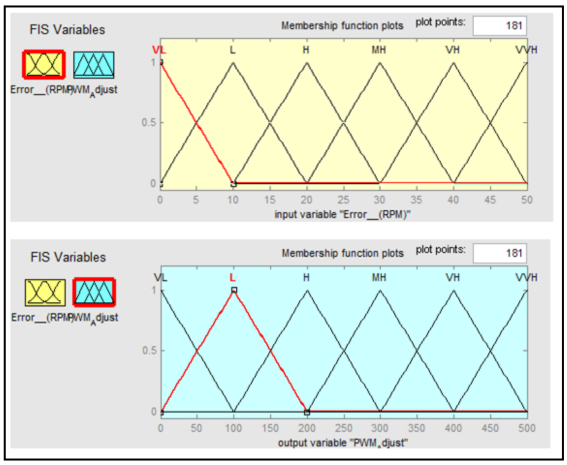

Figure 6: Membership functions of input and output

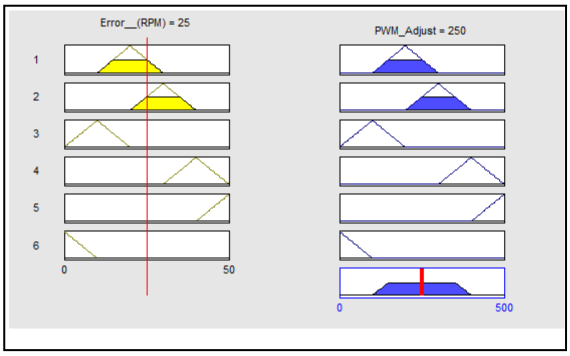

Figure 7: Fuzzy logic rules

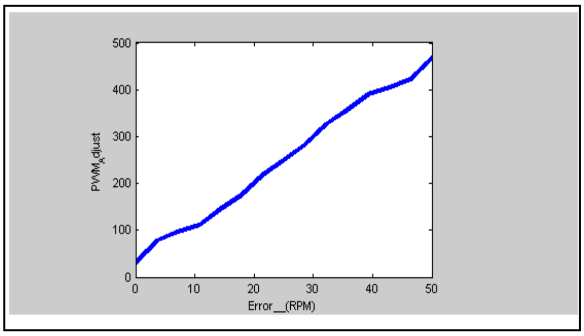

Figure 8: Surface plot

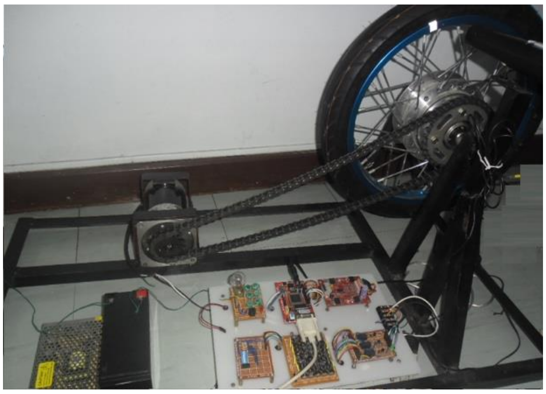

Figure 9: Actual tested prototype

C. Test and data Acquisition

a. Test the fuzzy logic speed control

A test was done to evaluate the performance of the fuzzy logic control method in achieving and maintaining the desired speed as compared to the open-loop method in forward and reverse directions. There were eight trials made on this test each at different wheel speeds. The fuzzy logic control was evaluated by comparing the wheel speed before and after the compensation process. Actual rpm speed values were gathered before and after the compensation for each input switch settings. The data were gathered using A2108 software from the tachometer provider. At the end of the test, the effectiveness of the control algorithm was evaluated by comparing the results with the expected rpm speed values.

b. Test for the regenerative brake and energy harness

Another test was done to evaluate and compare the performance of the regenerative brake system that uses supercapacitor bank in recovering energy and slowing the wheel compared to a system that uses battery based on the two parameters: recovered energy and the braking time.

The recovered energy in the supercapacitor bank was measured using the following formula, (Kuruppu, 2010):

$$E_{recovered} = E_{final} - E_{initial} \quad (1)$$

where:

$E_{recovered}$ = total energy captured by the supercapacitor on a single braking in Joules

E_{final} = energy of the capacitor after the braking into full stop

E_{final} = energy of the capacitor before braking

$$E_{final} = \frac{1}{2} C V_{final}^2 \quad (2)$$

where:

E_{final} = energy of the supercapacitor after braking in Joules

V_{final} = voltage across the supercapacitor after braking in Volts

C = total capacitance of the supercapacitor bank, 1.25 F

$$E_{initial} = \frac{1}{2} C V_{initial}^2 \quad (3)$$

where:

$E_{initial}$ = energy of the supercapacitor before braking, Joules

$V_{initial}$ = voltage across the supercapacitor before braking, Volts

C = total capacitance of the supercapacitor bank, 1.25 F

The wheel speed was set to maximum (i.e. 173 rpm). Before braking, the voltage across the supercapacitor was measured using a digital multimeter. Then, the brake switch was engaged until it reached full stop. The voltage across the supercapacitor was then measured again. Using the formula for the initial and final energy of the capacitor, the energy recovered (change in energy) was calculated for a single braking process. Ten trials were made in measuring the voltage, current and time needed to compute for the recovered energy.

Meanwhile, the recovered energy (change in energy) in the battery was measured through the derived formula below:

$$P = IV \quad (4)$$

$$E = Pt \quad (5)$$

where:

E = energy of the battery after braking, Joules

P = power, watts

V = difference in the voltage across the battery before and after the braking, Volts

I = peak current measured through the battery during the braking process

t = time to stop the wheel, seconds

IV. Data and Results

Figure 10 shows the compensation that took part in the improvement of the speed level.

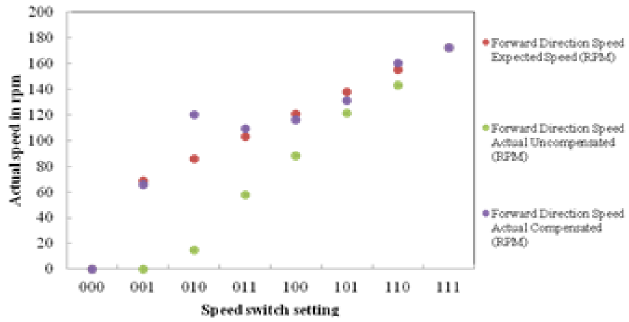

Figure 10: Compesated vs uncompensated forward speed

	No Load	Battery	Supercapacitor
	8.6400	8.2000	5.8900
	8.7100	7.4900	5.5600
	8.2800	8.2200	5.7400
	8.6100	7.8700	6.1500
	8.5700	8.7000	5.9200
	8.3700	8.1100	6.2500
	8.7100	8.5300	6.3300
	8.3900	8.0900	5.5600
	8.3600	8.0400	6.0900
	8.6700	7.9600	5.9800
Average	**8.5310**	**8.1210**	**5.9470**

Figure 11: Battery vs supercapacitor on stopping time in seconds

Figure 11 shows the improved stopping time of the wheel using the supercapacitor bank as compared with the no load condition and when using battery as the load. The average of the stopping time without the load for all the tests is 8.531 seconds while 8.121 seconds using the battery and 5.947 seconds using the capacitor bank. The equations 6 and 7 show the percent reductions of stopping time using the battery and supercapacitor respectively.

$$R_{battery}(\%) = \frac{S_{noload} - S_{battery}}{S_{noload}} x100 = \frac{8.531 - 8.121}{8.531} x100 = 4.81\% \quad (6)$$

$$R_{supercapacitor}(\%) = \frac{S_{noload} - S_{supercapacitor}}{S_{noload}} x100 = \frac{8.531 - 5.947}{8.531} x100 = 30.29\% \quad (7)$$

On the average, the system using battery achieved 4.81% reduction in stopping time, while the system using supercapacitor achieved 30.29% in reducing the stopping time of the wheel during coasting.

Figure 12 shows the improved energy recovery from the regenerative braking using the supercapacitor bank as compared from the no load condition and when using battery as the load. Obviously, there was no energy recovered without the load and when the wheel was stopped through freewheeling. On the other hand, the average energy recovered using the battery is 0.01 J while 0.69 J of energy was recovered using the supercapacitor bank for a single braking.

	No Load	Battery	Supercapacitor **(in Seconds)**
	0.0000	0.0170	0.6954
	0.0000	0.0139	0.8108
	0.0000	0.0178	0.0609
	0.0000	0.0091	0.8897
	0.0000	0.0125	0.9810
	0.0000	0.0109	0.9338
	0.0000	0.0133	0.2670
	0.0000	0.0119	1.0688
	0.0000	0.0123	0.9672
	0.0000	0.0111	0.2016
Average	**0.0000 s**	**0.0130 s**	**0.6876 s**

Figure 12: Battery vs supercapacitor on the recovered energy (change in energy) in Joules

Figure 12 shows the improved energy recovery from the regenerative braking using the supercapacitor bank as compared from the no load condition and when using battery as the load. Obviously, there was no energy recovered without the load and when the wheel was stopped through freewheeling. On the other hand, the average energy recovered using the battery is 0.01 J while 0.69 J of energy was recovered using the supercapacitor bank for a single braking. Therefore on the average, the system using supercapacitor recovered 0.68 J more energy than using a battery in a single braking as shown in Equation 8.

$$\Delta E = E_{Supercapacitor} - E_{battery} = 0.69 - 0.01 = 0.68J \quad (8)$$

A statistical analysis was done in determining which between the supercapacitor bank and the battery is better in terms of the stopping time. Since the data were gathered from two distinct systems which were independent from each other, the t-test for two-sample assuming unequal variances could be used to conclude the findings of the study. Microsoft Excel data analysis function was used in performing this test. The alpha used was 0.05. Based on the t-test data, the probability value (P) was extremely small (less than $\alpha = 0.05$) which became a strong evidence against the null hypothesis (H0 : $\mu0 = \mu1$). Therefore, the alternative hypothesis (H0 : $\mu0 > \mu1$) is true and hence the conclusion can be made that using the supercapacitor bank is better than using the battery in terms of reducing the stopping time.

Another statistical analysis was done in determining which between the supercapacitor bank and the battery is better in terms of the performance in energy recovery. Since the data were gathered from two distinct systems which were independent from each other, the t-test for two-sample assuming unequal variances could be used to conclude the findings of the study. Microsoft Excel data analysis function was used in performing this test. The alpha used was 0.05.

Based on the t-test data, the probability value (P) was extremely small (less than $\alpha = 0.05$) which became a strong evidence against the null hypothesis (H0 : $\mu0 = \mu1$). Therefore, the alternative hypothesis (H0 : $\mu0 < \mu1$) is true and hence the conclusion can be made that using the supercapacitor bank is better than using the battery in terms of recovering energy.

V. Conclusion

A prototype for the proposed system was successfully constructed and tested. Fuzzy logic algorithm was successfully implemented for the control of the wheel speed.

Compared with an open loop system, the speed control which was achieved through the fuzzy logic algorithm of the proposed system is better based on the experimental results. Moreover, the data show that the proposed system is significantly better in energy recovery and braking compared to the conventional system using a battery. On the average, the system using battery achieved 4.81% reduction in stopping time, while the system using supercapacitor achieved 30.29% in reducing the stopping time of the wheel during coasting. In a single braking, the average energy recovered using the battery is 0.01 J while 0.69 J of energy was recovered using the supercapacitor bank. On the average, the system using supercapacitor recovered 0.68 J more energy than using a battery in a single braking.

REFERENCES

[1] Burke A.F. 2000. Ultracapacitors: Why, How, and Where is the Technology?. *J. Power Sources.* 91: 37-50.

[2] Carsdirect. 2010. Common Regenerative Brake Problems. HybridCars.

[3] Chen J., Li Y., Wu Y. and Liao R. 2006. The FLC Policy Research and Simulation in HEV. *Automotive Engineering*. 1: 8.

[4] Compact Instruments. 2012. Tachoprobe Operating Instructions A2108 Series. A2108/LSR/232.

[5] Continental Automotive. 2010. Innovations for a mobile automotive future. *Automotive Group.*

[6] Ehsani, M., Gao Y. and Emadi A. 2010. Modern Electric, Hybrid and Fuel Cell Vehicles. Florida: CPC Press.

[7] E-Gizmo. 2012. 6.0A H-Bridge Driver for DC Motor User Manual. Taft Ave., Manila.

[8] Junzhi, Z., Xin L., Shanglou C. and Pengjun Z. 2008. Coordinated Control for Regenerative Braking System. *State Keylab of Automotive Energy and Safety*, Tsinghua University, Beijing, China.

[9] Sandun Kuruppu 2010. Implementation and Performance Evaluation of a Regenerative Braking System Coupled to Ultracapacitors for a Brushless DC Hub Motor Driven Electric Tricycle, Purdue University, West Lafayette, Indiana.

[10] Sison, L. 2004. UP IRC SlimBoard Set User Manual. University of the Philippines, Diliman.

[11] Sison, L. and Burgos O. 2004. Designing with the Z8 Encore! Microcontroller. University of the Philippines, Diliman.

[12] Tsai, M. 2002. Choosing a Microcontroller for Embedded Systems Applications. *Application Note*, Michigan State University.

[13] Toyota Technical Training. 2010. Brake system. *Toyota Hybrid System Diagnosis.*

[14] Voser, P. 2009. The Future of Mobility is Hybrid. Shell World Philippines, 1: 4.

[15] Dorf R. and Bishop R. 1998. *Modern Control Systems.* New York: Addison Wesley Longman Inc.

[16] Dunn, W. 2005. *Fundamentals of Industrial Instrumentation and Process Control.* USA: McGraw-Hil, 1: 243-248.

[17] Giambattista, A., Richardson B. and Richardson R. 2007. College Physics. New York: McGraw-Hill. 2: 187.

[18] Grob, B. 2006. *Basic Electronics.* New York: McGraw-Hill. 10: 55-70.

[19] Bian, Y., Lijing Z. and Xinming X. 2010. Regenerative Brake System in Electric hoist with ultracapacitor, *International Conference on Electrical and Control Engineering, Shanghai, China*.

[20] Cikanek S. R. and Bailey K. E. 2002. Regenerative Braking System For A Hybrid Electric. *Proceedings of the American Control Conference, Anchorage, Ford Research Laboratory Dearbom*, MI 48121-2053.

[21] Jing-ming, Z., Bao-yu S. and Shu-mei C. 2009. Fuzzy Logic Approach to Regenerative Brake System. *2009 International Conference on Intelligent Human- Machine Systems and Cybernetics, Harbin, Heilongjiang Province, China*.

[22] Takahashi, Y. and Seki H. 2009. Fuzzy Logic Based Regenerative Braking Control System of Electric wheelchair for Senior Citizen. *2009 IEEE 11th International Conference on Rehabilitation Robotics Kyoto International Conference*, Japan.