Web-based Flywheel Battery Control System with Regenerative Braking

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Abstract: This paper describes the framework and methodology behind the construction of a web-based flywheel battery control system. This remotely triggered setup has been created to enable mechanical engineering students to understand the principles of regenerative braking by means of a flywheel battery as a laboratory experiment supplementing their regular course work. Students can remotely control and monitor adding energy to and extracting energy from the rapidly rotating flywheel using an AC motor and a bi-directional AC motor controller, with regenerative braking capability. This work demonstrates the important concept of recovering mechanical energy through regenerative braking, such as those used in electric vehicles. The experiment is hosted online, making it freely accessible for universities and students around the world.

Keywords: controller, data acquisition, energy storage, flywheel, regenerative braking.

Introduction

With increasing consumption of energy, continuously decreasing sources and serious concerns about climate change, the choices we make about the sources of energy and the careful usage once we have 'captured' it are becoming increasingly important for the well-being of future generations. Energy conservation can be achieved by reducing the level of services used. Energy can be conserved by replacing less efficient equipment with more energy efficient equivalents, for example by replacing an incandescent lamp with a fluorescent lamp.

Flywheel batteries are a method of storing energy in a rapidly rotating mechanical disc or cylinder called a flywheel, whereby energy efficiency can be increased by energy conservation. Flywheel batteries have been used as highly efficient backup power supplies for buildings, spaceships and in Formula1 racecars to increase efficiency. The battery is “charged” by using electricity to power a motor, increasing the rotational speed of the disc. The system is “discharged” by regenerative braking, using the motor as a generator. During discharge, the flywheel’s kinetic energy is converted back to electrical energy when the flywheel slows down, storing the restored energy onto an electrochemical battery like a lead acid battery. Regenerative braking can be utilized to recover wasted rotational or kinetic energy for many different systems. This has been found to smooth out transmission systems [1] and increase efficiency in hybrid and pure electric vehicles.

The application of such electro-mechanical systems is extremely important for a modern day mechanical engineer. We have developed an experiment for mechanical engineers to understand this important concept using a motor controller with regenerative braking [2]. The system extracts energy from an electrochemical battery bank when accelerating by means of a three phase induction motor, storing the extracted energy in a flywheel as kinetic energy. When the flywheel is decelerating, the motor becomes a generator, re-charging the electrochemical battery bank.

Developing such a laboratory setup can be challenging and expensive, for the regular engineering curriculum. Virtual and remote laboratories are one of the latest developments to address the lack of high quality and expensive labs. Virtual and remote labs allow remote access of laboratories with the help of information and control technology, and have helped improve technical education [3].

Virtual and Accessible Laboratories (VALUE@Amrita) is a strong initiative of Amrita University to develop virtual and remote laboratories science education [4]. As part of this initiative, over 43 labs with 350 experiments have been created by Amrita. In the area of mechanical engineering, a full lab dedicated to the experimentation of energy storage technologies, as part of the renewable energy course, has been developed. The lab allows students to use the platform at their convenience and redo the experiments any number of times to understand the underlying concepts. Teachers can use the content and materials in Virtual Labs as supplements to their teaching, saving time and improving student performance [5].

System Description

The system consists of a 150kg cast iron flywheel directly coupled with a 30 HP, three phase AC induction motor/ generator powered by a 48V, 100Ah battery bank through a bi-directional AC motor controller from Curtis. Data acquisition for the computer interface is performed using a National Instruments USB-6009 Data Acquisition card (DAQ). The battery charge/discharge current is sensed by a HASS 200-S transducer from LEM. Fig. 1 shows image and Fig.2 shows the block diagram of the system.

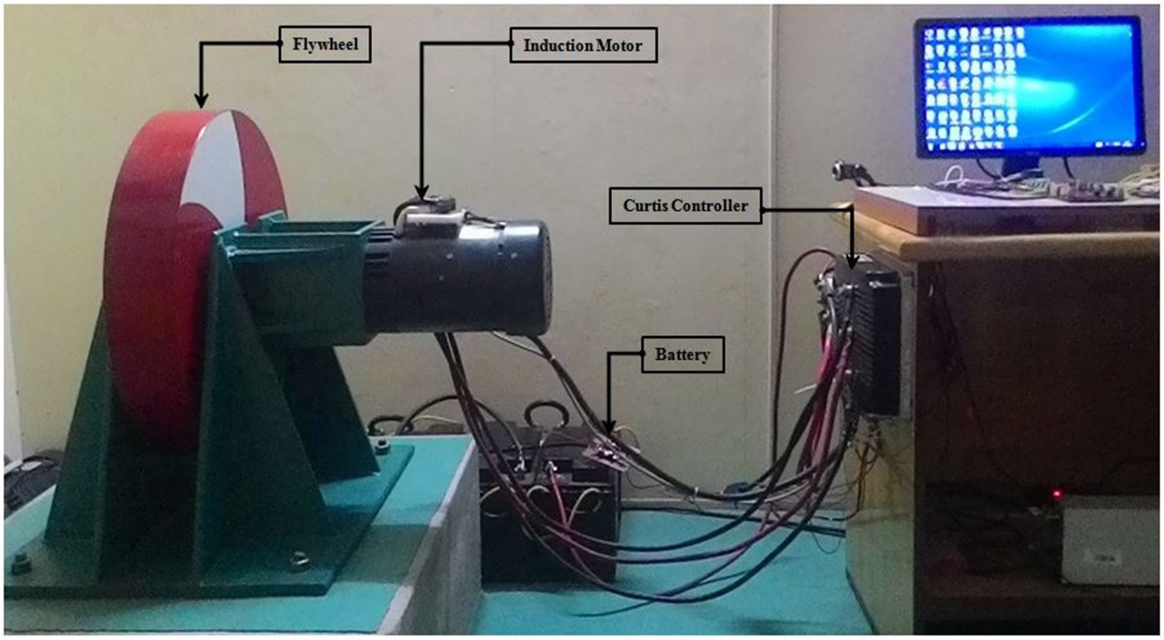

Figure 1. Remote Triggered Flywheel with regenerative braking installed at Amrita Virtual Laboratories for Mechanical Engineering

Voltage is sensed using a voltage divider. The rotational speed of the flywheel is measured using an E5 optical encoder from US Digital. All parameters of the motor and controller can be observed through the Curtis 1314 programming station.

Three phase AC motor

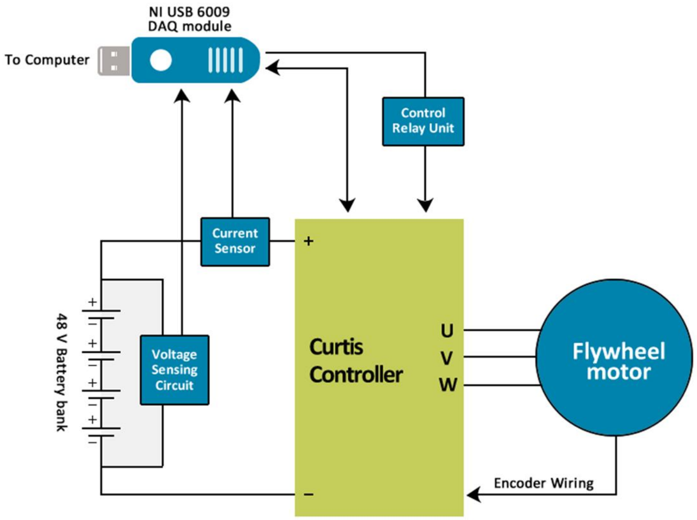

Figure 2. Block diagram of the regenerative braking control system

The flywheel battery allows energy to be stored mechanically and transferred to and from an electrochemical battery using an electrical machine. The electrical machine works as a motor to transfer electrical energy to and from the flywheel. When acting as a motor, the electrical energy supplied to the motor is converted into mechanical energy, increasing the speed of the flywheel. In generator mode, the kinetic energy stored in the flywheel is converted into electrical energy. The motor coupled to the flywheel is a low voltage AC 3 phase motor, rated 72 Volt, 300 Ampere, 30 HP, with peak power at 6800 rpm. An application of this kind of drive system is in small electric vehicles such as golf carts.

Bi-directional motor controller

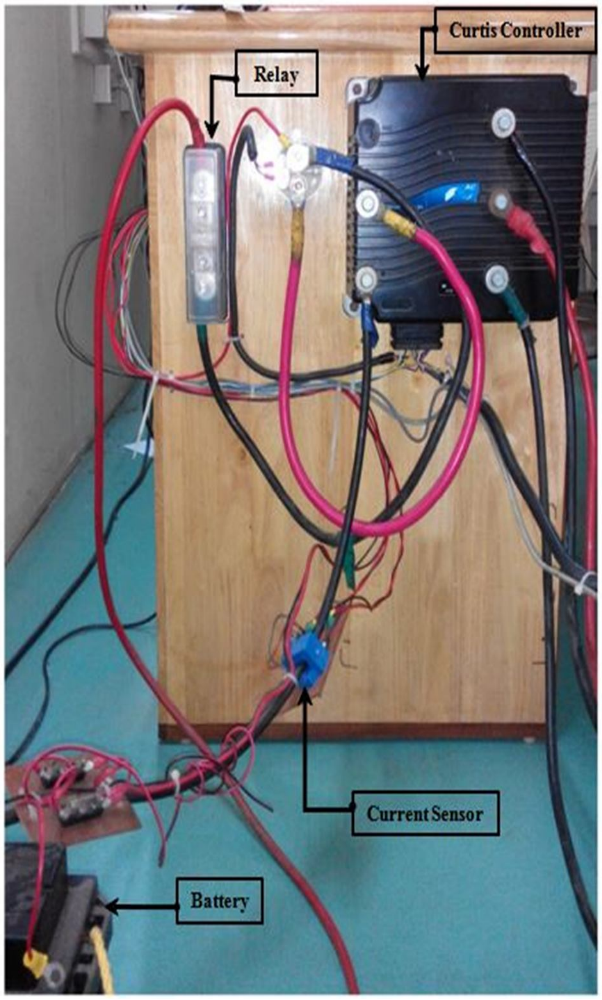

Figure 3. Motor Controller and related accessories

The main requirement of any energy recovery setup is a bi-directional motor controller which will act both as a power converter and as a motor controller. During the acceleration of the flywheel, the power converter converts the DC power from battery to AC, supplying it to the AC induction motor. During deceleration of the flywheel, the converter converts the AC power generated by the motor to DC, supplying it to the battery. The motor controller controls the speed and direction of the motor by varying the frequency, voltage and current. The motor is controlled by a Curtis 1238-6501 motor controller as shown in Fig. 3, with a voltage rating of 48-80V and a current rating of 550A. This controller can convert DC battery power into low voltage 3 phase AC power simultaneously controlling motor torque, speed and direction.

The controller does regenerative braking, motor controlling and converting the motor/generator’s AC output into DC to charge the batteries. This type of controller is used in industry to provide advanced control of AC induction motors performing as vehicle traction drives. The battery is connected to the controller through a fuse and DC contactor for protection. The contactor is enabled and disabled by the control circuit, for which the signals are given from the LabVIEW program through USB 6009 DAQ. There are two main input signals given to the controller - namely, the key switch input voltage, which is the 48 V from battery to enable the dc contactor and the throttle input. The throttle input to the controller is given as a voltage corresponding to the RPM value at which we need to rotate the flywheel.

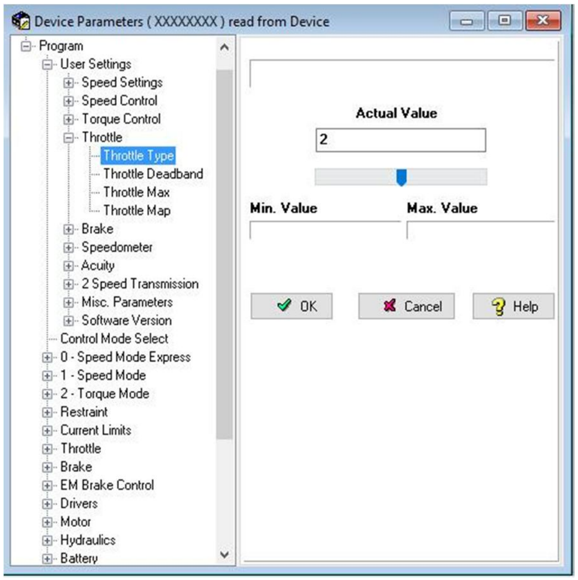

Figure 4. User tuned parameters from the Curtis programming Station

The controller has a large number of parameters that can be adjusted using Curtis 1314 programming station, as shown in Fig. 4. The programmable parameters allow the performance for the motor and controller to be customized to fit the needs of specific applications. The programming station also allows many parameters to be monitored, as shown in Fig. 5. The corresponding data can be saved onto a spreadsheet for monitoring and analysis purposes. Depending on the selected mode of control, various related variables can be tuned. For example, in the speed controller menu, there are sub-menus for speed setting, brakes and throttle.

Motor response characteristics can be tuned through two control modes depending on the application, namely speed mode and torque mode. Speed mode is used for applications where throttle input corresponds to motor speed output where the control mode value is one. Torque mode can be used for applications where throttle input corresponds to motor torque output. We chose speed control where the throttle type is 2 as shown in Fig. 4 for our setup that adjust the flywheel speed by adjusting the motor speed which is made possible by making the controller throttle input to correspond to the motor speed output and we do not have experimental setup to control the torque.

There is proportional (Kp) and integral (KI) gain control constants that can be set for adjusting the level of speed control. The proportional gain constant determines how aggressively the speed controller will match the motor speed to the set speed. We optimized the Kp value such that it will not have oscillations at high values and will not exhibit sluggish behavior at low values. ‘KI’ term correspond to zero steady state error. Again, the value has been optimized for avoiding oscillations at high values and time taken to approach the exact commanded speed. Speed mode has fine tuning options for acceleration, deceleration and braking. These parameters were adjusted such that the current drawn by the controller is optimal.

Battery bank

Four rechargeable Exide 12 volt, 100Ah batteries are connected in series to form a 48V, 100Ah battery bank. While accelerating the flywheel the motor consumes power from the battery and while decelerating power is fed back into the battery. The battery and the motor are connected to the motor controller.

Current measurement

The DC current flowing to and from the battery is measured using a HASS 200-S current transducer, capable of measuring current flow up to 200A. The output voltage of the transducer corresponding to the current flow is fed into the data acquisition device.

Voltage measurement

The DC battery voltage is measured using a voltage divider circuit, which linearly converts a large voltage into a small quantity. The voltage divider is designed in such way that its output voltage is kept less than 5V, which is fed into the data acquisition device, as shown in the block diagram in Fig. 2.

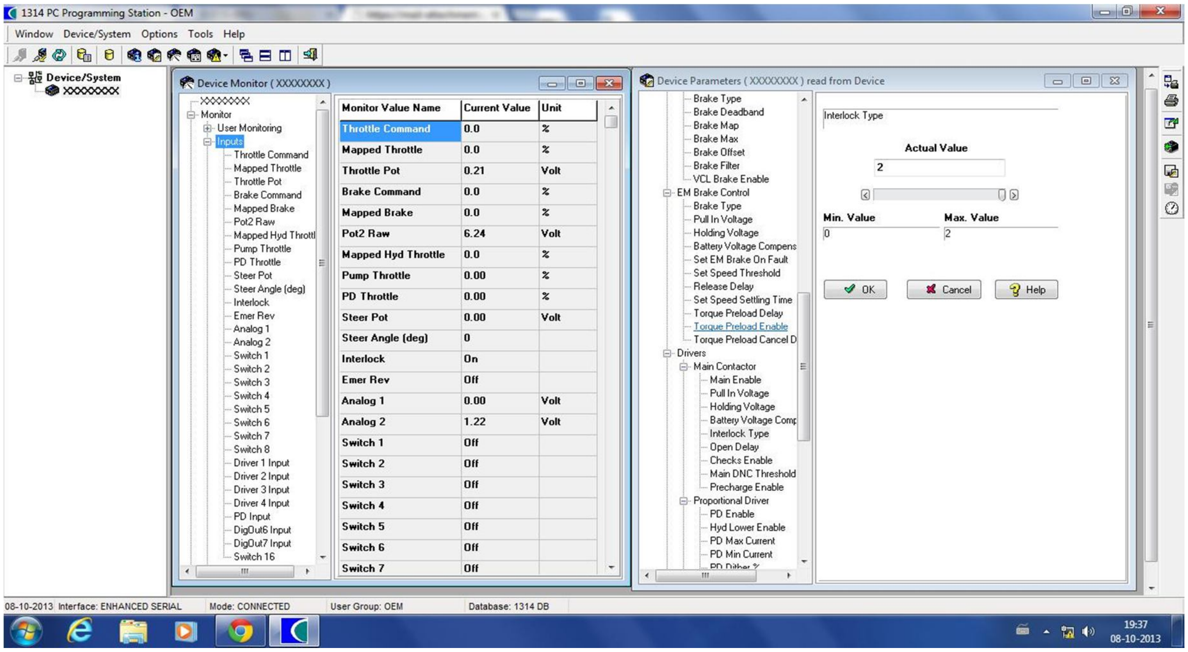

Figure 5. Parameter monitoring from Curtis Programming Station

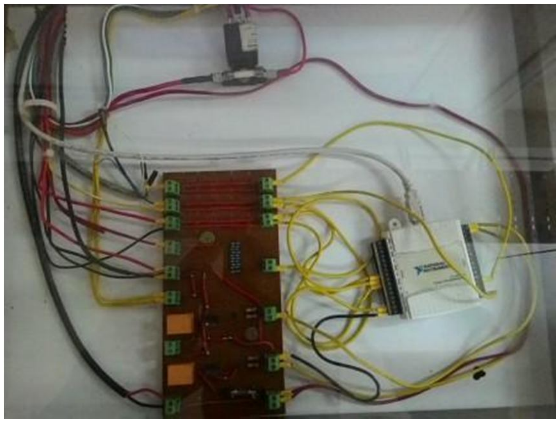

Figure 6. Data acquisition system with sensors

RPM measurement

The rotational speed of the flywheel is measured using an E5 optical rotary encoder from US Digital, installed on the motor shaft. The measured RPM is fed into the motor controller and into the data acquisition device, to be used in the LabVIEW control program and shown on the GUI.

Data Acquisition (DAQ)

The National Instruments USB 6009 module is used for data acquisition. It is connected to the host computer using a USB cable. This DAQ card is chosen because it has suitable analog inputs with sufficient resolution digital inputs and outputs and is easy to use for the specific requirement. Output of the current, voltage, and RPM sensors is connected to the DAQ card. It also gives the control signals for the controller. LabVIEW software is used to develop the program for control and data acquisition.

Communication Interface

The basic communication structure for all virtual lab experiments has client-server architecture [6] with the setup as shown in Fig 7. The flywheel experiment connects to a LabVIEW web server which interfaces with the remaining communication system through a serial port.

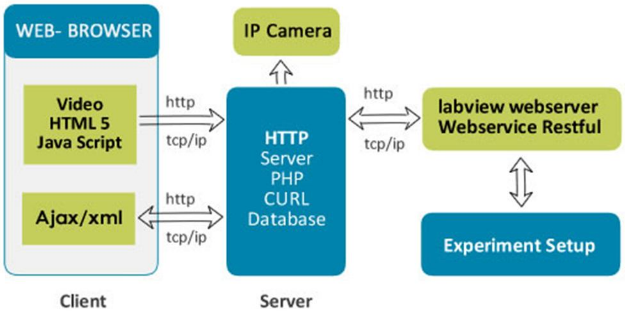

Figure 7. Communication Interface for remote triggered flywheel

Web Interface

Users can login to the Amrita Virtual lab website, vlab.amrita.edu, and select the AC Flywheel Battery experiment from the Energy Storage lab under Mechanical Engineering. Users are advised to go through the theory, procedure and self-evaluation tabs before entering the RT (remote-trigger) tab, which has the remote control GUI for the experiment, as shown in Fig. 8. The Start button should be clicked to switch on the motor controller and other related hardware, and to start the experiment. The experiment can be viewed live using the webcam option. The graphical view will provide a picture of the setup, if there are problems with live streaming due to slow internet connection.

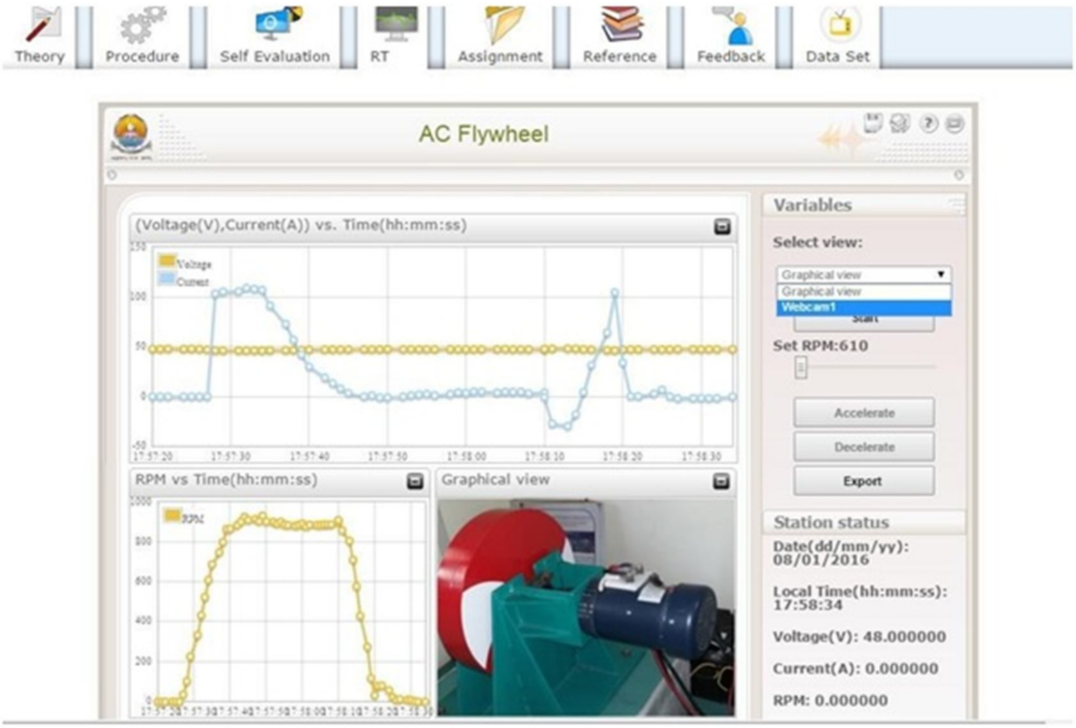

Figure 8. Remote Trigger tab on flywheel experiment webpage, after completing the experiment

After selecting an rpm using the rpm slider, the accelerate button should be clicked to accelerate the flywheel to the desired rpm. During this period the controller converts the DC power from the battery into AC power and supplies it to the AC machine, which will act as a motor and convert the electrical energy into mechanical energy, increasing the speed of the flywheel thereby storing energy in the flywheel.

Initially, the current will be very high to bring the motor and flywheel to the desired rpm, as can be observed on Fig. 8 and 9. The current starts decreasing as the flywheel rpm increases. When the flywheel attains the set rpm, the current becomes constant. Users can observe regenerative braking on the graphs in Fig. 8 and 9, with the current going in the negative direction. After the flywheel attains the desired rpm, the user can click on the decelerate button to decelerate the flywheel. At this time, the motor controller is in regenerative braking mode when the motor will act as a generator converting the

mechanical energy stored in the flywheel into electrical energy and feed it back to the battery. The user can observe the rpm, voltage and current values plotted on the graphs in Fig. 8, 9 and 10.
After completing the experiment, the user can click on the export button to export the detailed sensor data for further analysis. If the system is down due to any technical mishap, a provision to observe and analyze a sample data has been made available on the dataset folder, which also allows exporting of data. Users can evaluate their understanding of the system and experiment by going through the assignment folder and answering the questions there.

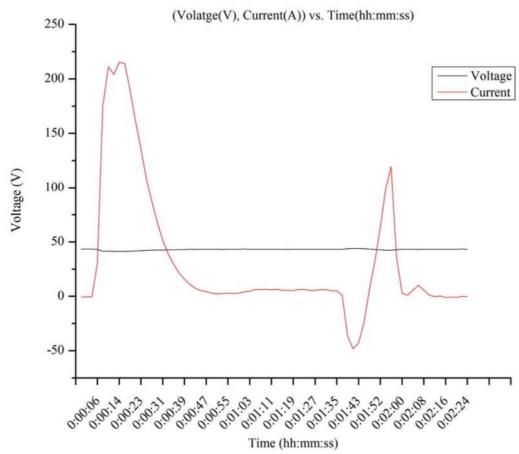

Figure 9. Current and Voltage measured during the course of the experiment

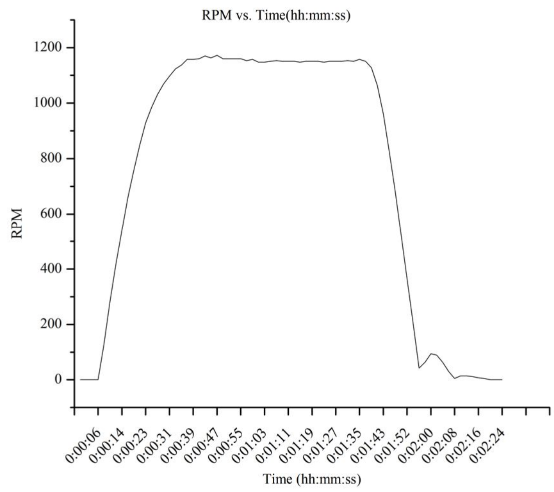

Figure 10. RPM sensed during the course of the experiment

Conclusion and Future Work

The Virtual Lab Flywheel experiment to understand regenerative braking has been successfully created, fabricated and implemented. A dynamic braking experiment [7] was developed before developing the regenerative braking experiment. Thus we have two experiments demonstrating two types of braking for energy storage and recovery. We have developed experiments in the energy storage labs using different technologies [8] to test batteries with their characteristics as well.
Ideally, in the regenerative braking mode the current should be negative until the flywheel comes to rest. However, in the results of our work, observation could be done on the graph (fig 8 and 9) that the current is negative for some time and then switches to positive, because of the sudden decrease in speed of the flywheel. The controller circuit needs this oscillation in the transient region before attaining a steady-state. New circuits could be designed to support the motor controller to reduce this oscillation.

Acknowledgment

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