UNIVERSITY OF CAPE TOWN

Department of Electrical Engineering

EEE4117F – Electrical Machines and Power Electronics

Flywheel Project

Ronak Mehta – MHTRON001

05th June 2020

Declaration

1. I know that plagiarism is wrong. Plagiarism is to use another's work and pretending that it is one's own.
2. I have used the IEEE convention for citation and referencing. Each contribution to, and quotation in, this report from the work(s) of other people has been attributed, and has been cited and referenced.
3. This report is my own work.
4. I have not allowed, and will not allow, anyone to copy my work with the intention of passing it of as their own work or part thereof.

Name: Ronak Mehta Student Number: MHTRON001

Signature: RMehta

Table of Contents

AIM:

This project was divided into two major parts, namely the analysis of a flywheel and the practical section. In this report, we are going to discuss the later which aims to determine the DC machine constants using No-load test and also by loading the machine at various speeds.

OBJECTIVE:

To calculate the DC machine constant, $K_a\phi$ using its relationship with the back-emf E_a.The theory states that E_a is directly proportional to the speed, ω_m and if plotted linearly against each other, then the slope of this graph would result in the machine constant, $K_a\phi$. This report would thus put the theory into practice and calculate $K_a\phi$ and other DC machine parameters. To determine this constant using a No-load test, the following set up must be established.

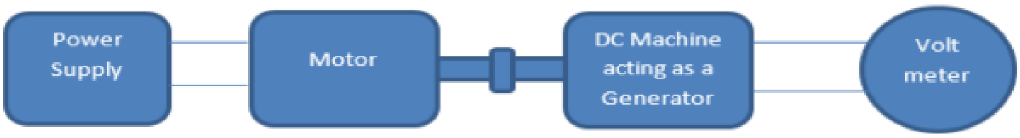


Figure 1: Set up for No-load test

EXPERIMENTATION:

This section was divided into three tasks, in which each of the task had a specific goal to be achieved.

TASK 1:

An Arduino was used to produce a PWM for the H-bridge which controls the DC motor. This was a 1kHz PWM signal with a duty cycle from 50% to 100%. A Pulse Width Modulation (PWM) is a technique which enables the control of an analog circuit using a series of digital pulses by altering the duty cycle. The code documented for this specific PWM signal is appended below:

```
#include <PWM.h>           // adds the PWM library to control frequency
int LEDpin = 9;            // define the pin of the
int32_t frequency = 1000; // sets the frequency to 1kHz
int brightness = 127;      // initial value of LED brightness at 50% duty cycle [0.5*255]
int fadeAmount = 10;       // stepping through the duty cycle by this value

void setup() {
  pinMode(LEDpin, OUTPUT);  // define the LEDpin as output pin
  InitTimersSafe();         // sets all timers to available
  SetPinFrequencySafe(LEDpin, frequency); // sets up the led pin at the frequency
}

void loop() {
  pwmWrite(LEDpin, brightness);  // sets LED brightness as PWM signal(starts at 50% duty cycle)
  brightness = brightness + fadeAmount; // Increasing the duty cycle
  // keeps the duty cycle from 50% to 100%
  if (brightness <= 127 || brightness >= 255) {
    fadeAmount = -fadeAmount;
  }
  delay(30);
}
```

Figure 2: Code for generating the PWM signal

The PWM signal output from the Arduino was tested on an LED and as expected, the duty cycle ranged from 50% to 100% which was visible by observing the LED brightness.

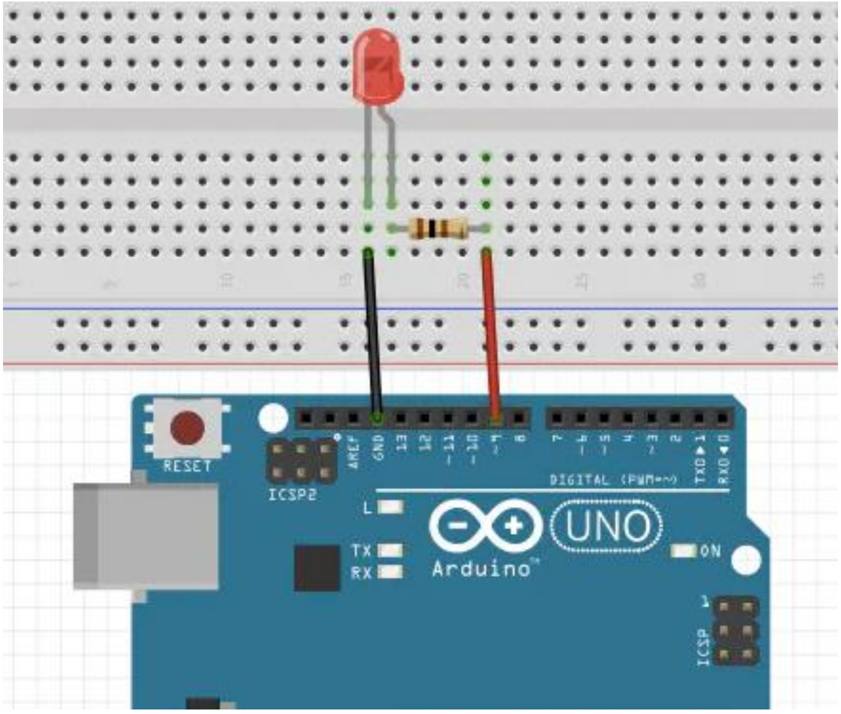


Figure 3: Testing the PWM code on an LED

The PWM signal was further tested on an oscilloscope and Figure 4 below shows the screenshot of the readings of the PWM from the oscilloscope.

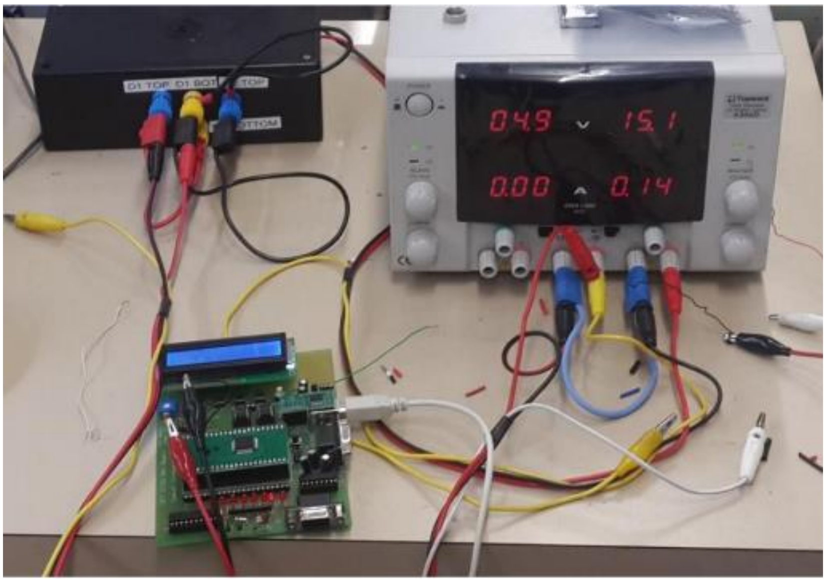


Figure 4: Screenshot of Readings of PWM from the oscilloscope

The H-bridge is a circuit used in electronic control of high current devices, particularly where the device polarity may be reversed, e.g. DC Motors [2]. While using an H-bridge, it is vital to ensure that two of its switches in the same leg are never closed at the same time as it creates a short circuit which might damage the device. For a working operation of the H-bridge, two opposite mosfets as shown in Figure 5 must be ON to drive the motor in the respective direction [3].

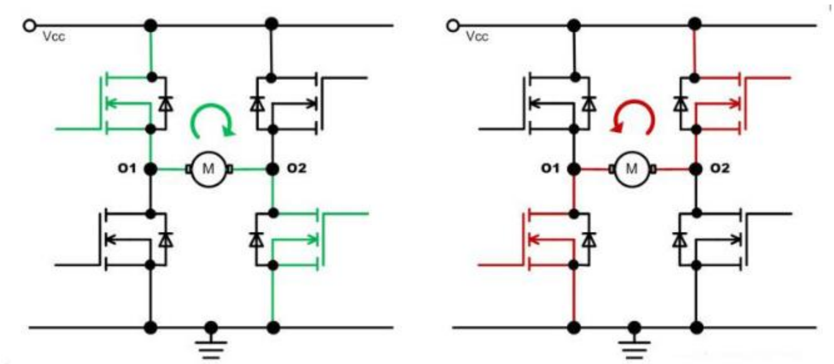


Figure 5: Working operation of H-bridge

The H-bridge has a tendency of accepting two PWM signals where one is the inverse of the other as shown below. This is because, for the non-inverted signal, you are running the motor in forward direction but for the motor to run in reverse direction, we have to invert the duty cycle as it is the low-part of the duty cycle that turns the motor on in the reverse direction.

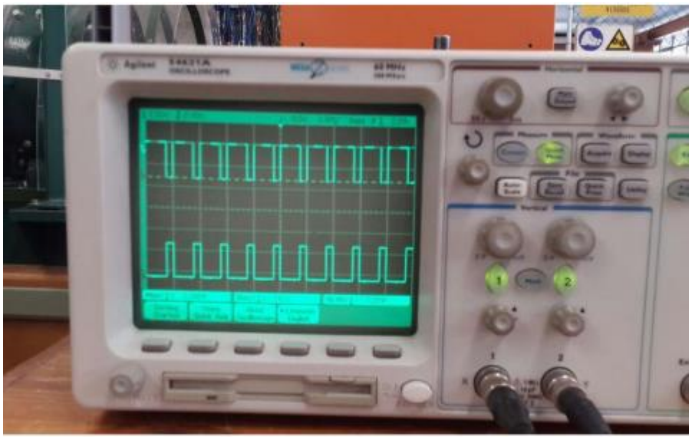


Figure 6: Oscilloscope showing one signal as the inverted version of the other

This however becomes a problem when there is a slight ON or OFF delay of the complementary mosfets which might result in a short circuit due to both switches of the same leg being closed at the same time. This can be solved by having a dead band with the advanced PWM controller in complementary mode. This avoids the overlapping in the switching phase of the H-bridge driving [3] as shown in Figure 7.

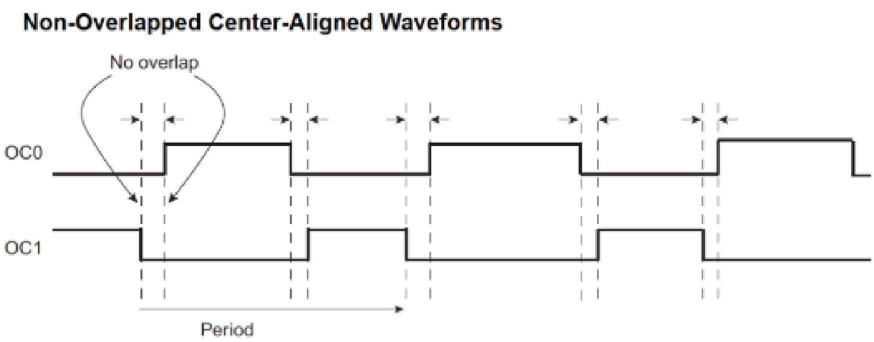


Figure 7: Solution to the above problem

Another solution can be to add a transistor as shown in Figure 8 to the circuit that only connects to the bottom rail of the H-bridge to the negative supply. Pulsing this will make the motor run only while the control is high so PWM on this would make an overall speed control without having to worry about which direction the motor is running [2].

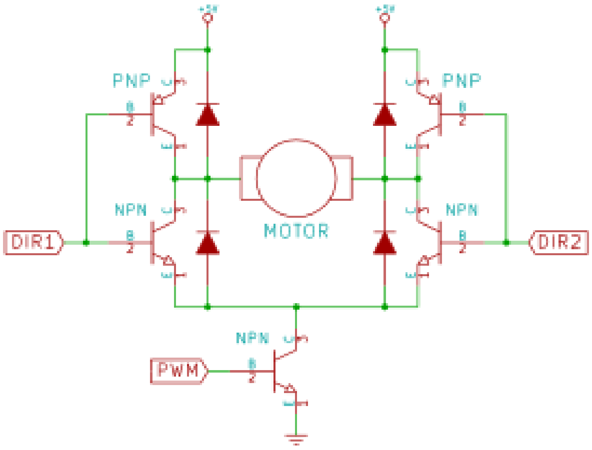


Figure 8: Second solution to the above problem

Finally, one can also use logic as shown in Figure 9 to filter the control lines so that the PWM signal is combined with the direction signals [2].

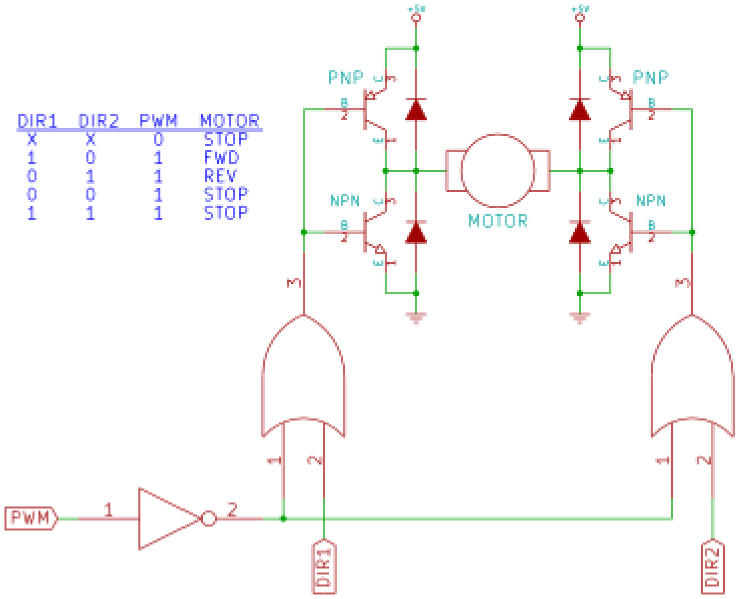


Figure 9: Third solution to the above problem

TASK 2:

The microcontroller was now connected to the drive system and the flywheel was run at 300 rpm by slowing increasing the duty cycle of the PWM signal. The following parameters were recorded from the system as shown in Figure 10 and tabulated below in Table 1.

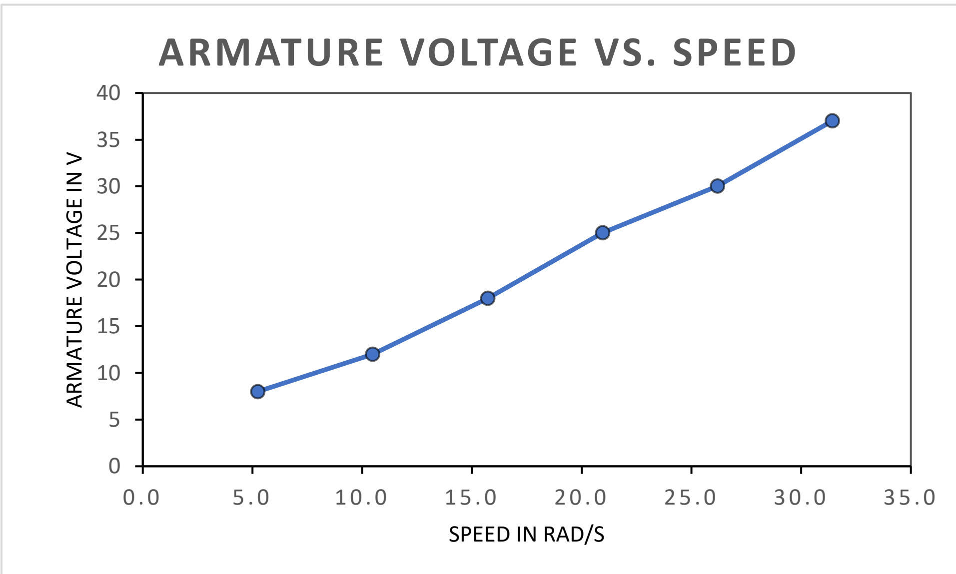
Figure 10: Readings from the drive system

Speed in RPM	Speed in rad/s	Bridge Current	Bridge Voltage	Armature Current, Ia	Armature Voltage, Vt	Torque, T
50	5.2	0.2	45	0.9	8	0.16
100	10.5	0.4	43	1.0	12	0.23
150	15.7	0.5	42	1.0	18	0.26
200	20.9	0.7	41	1.1	25	0.27
250	26.2	0.9	41	1.1	30	0.32
300	31.4	1.1	40	1.1	37	0.35
	Average	**0.633**	**42**	**1.033**	**21.667**	**0.265**

Table 1: Tabulated readings from the system

Questions:

1. Plot the graph of Armature Voltage vs. Speed



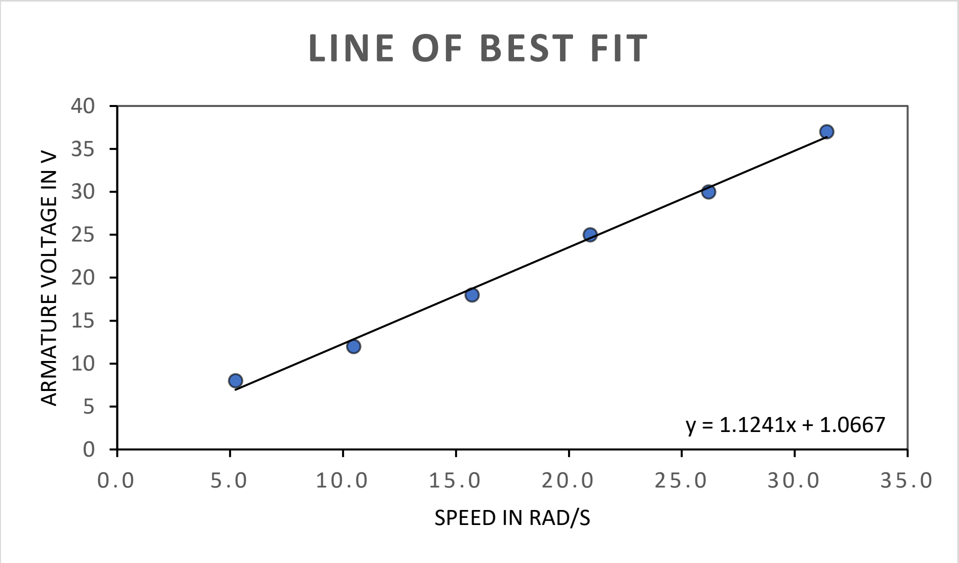
2. Determine from the graph plotted; $K_a\phi$ and armature resistance Ra

$V_t = E_a + I_aR_a$

But, $E_a = K_a\emptyset\omega_m$

Thus;

$$V_t = K_a\emptyset\omega_m + I_aR_a$$
$$y = m \quad x + c$$



From the graph above, we see that the equation of the best fit line is:

$$y = 1.1241x + 1.0667$$

which clearly indicates that:

Gradient, m = $K_a\phi$ = 1.1241 Vs/rad

and y-intercept, c = I_aR_a = 1.0667

with Average Ia = 1.033 A, we can calculate, Ra = c/Ia = 1.033 Ω

Thus; $K_a\phi$ = <u>1.1241 Vs/rad</u> and armature resistance, Ra = <u>1.033 Ω</u>

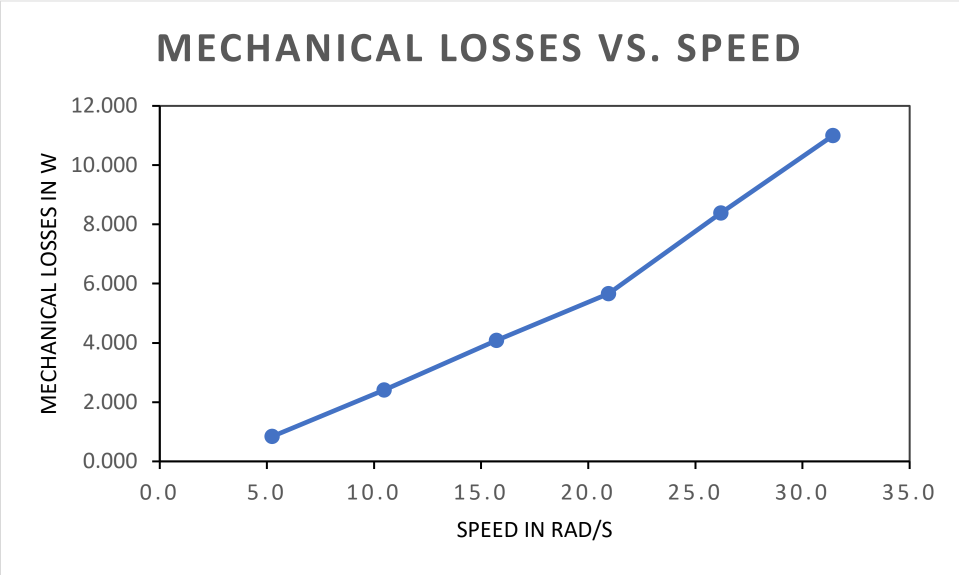
3. Determine the losses due to the armature winding

$P_{Loss} = I_a^2 * R_a$

$P_{Loss} = (1.033)^2 * 1.033 = 1.102$

<u>P_{Loss} = 1.102 W</u>

4. Plot the graph of Mechanical losses vs. Speed
   Mechanical losses are directly proportional to the torque and also to the Speed.



5. Calculate the average bridge losses
   Avg. Bridge Loss = Avg. Bridge Current * Avg. Bridge Voltage
   = (0.633 * 42) = 26.6
   Avg. Bridge Loss = 26.6 W

⇨ A run-down test was now performed on the flywheel by allowing power to dissipate over the set resistors and it recorded a time of 83.40 seconds to decelerate to 0 rpm as shown in Figure 11.

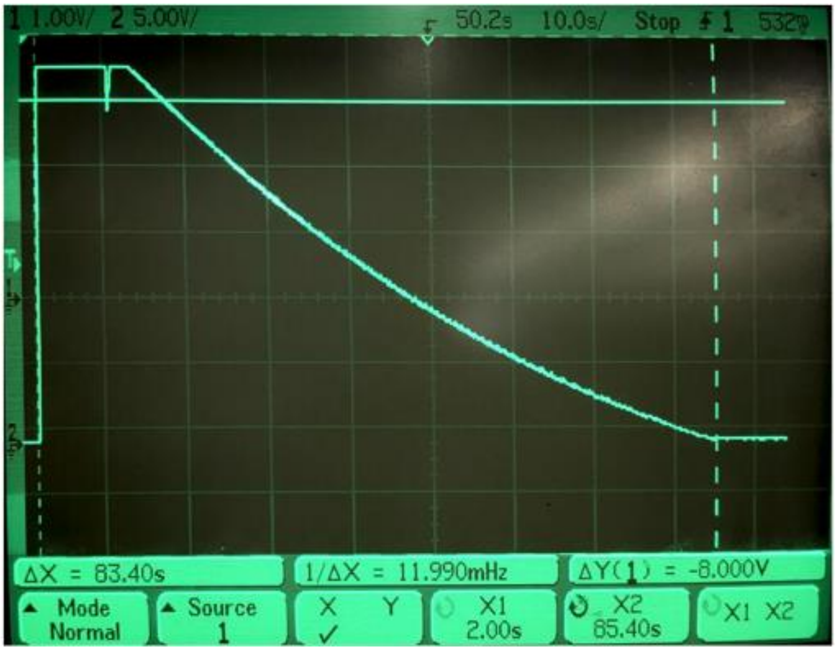


Figure 11: Graph from the run-down test

TASK 3:

A flywheel is a mechanical storage device which emulates the storage of electrical energy by converting it to mechanical energy. This stored energy is in the form of rotational kinetic energy [1]. There are numerous application areas of the flywheel energy storage system ranging from large scale to small scales. Some of these applications are explained below:

i. UPS Energy Storage:

In an Uninterruptible Power Supply [UPS] application, the flywheel is used as a back-up storage device during power outages. The flywheel device contains a rotary flywheel spinning at fast speeds, which converts electrical energy into stored kinetic energy which it releases during a power outage as DC power and sends it back to the UPS to supply the facility as AC power. Additionally, the flywheel device used here, contains a magnetic bearing as opposed to mechanical bearings which greatly improves the overall efficiency.

Advantages of using this system:

- Flywheels have a very long lifespan. Unlike batteries, the energy storage and performance of flywheels does not diminish with repeated use and thus increases its durability and also saves cost. Flywheels tend to usually have a lifespan of roughly around 20 years depending on the application and functionality.
- Flywheels have a fast charging and discharging rates. A flywheel can normally deliver its stored energy and recharge quickly, in a matter of seconds. It usually discharges its entire capacity in 15 to 20 seconds which is sufficient to meet the load demands to run a system until the power source is restored or a standby power source comes online.
- Another advantage is that flywheels have a comparatively smaller size and weigh less than the zinc batteries used in the competitive UPS market.

Disadvantage of using this system:

- Flywheel self-discharges at a much higher rate than other storage mediums which would not be beneficial if power outages last longer than 15 to 20 seconds.

ii. Flywheels in Transportation:

In transportation, flywheels are used in a variety of systems ranging from electric cars, bullet trains to roller coasters; but for simplicity of this report, we will refer to the application of flywheel energy storage system in hybrid/electric cars. The components of the flywheel device used are the spinning rotor, motor/generator, bearings, power electronics interface and a housing case. The flywheel device in an electric car is mainly used to store energy by using the regenerative braking phenomenon. i.e. energy from regenerative braking during vehicle slowdown is stored in flywheels and released when a boost is required during acceleration or moving up steep hills [1].

Advantages of using this system:

- Flywheels are environmentally friendly as there are no emissions during its operation, since the materials used are not hazardous to the environment.
- Flywheels have a high efficiency and can cope well with fluctuating power consumption which is vital in regenerative braking system and hence have an edge over batteries.

Disadvantage of using this system:

- Flywheel rotors can be hazardous if not designed properly. These rotors can malfunction easily and cause calamities.

CONCLUSION:

This report has explained the testing and performance analysis of the DC motor drive and flywheel by first conducting tests on the generated PWM signal for the H-bridge which controls the DC motor. Detailed calculations for determining the DC machine constants were made through conducting no-load test, loading the machine at different operating points and a run-down test. Finally, the report discusses the applications of flywheel as an energy storage system and the effects it has on other related fields.

REFERENCES:

[1] M. Amiryar and K. Pullen, "A Review of Flywheel Energy Storage System Technologies and Their Applications", *Applied Sciences*, vol. 7, no. 3, p. 286, 2017. Available: 10.3390/app7030286.

[2] "nathandumont.com : H-Bridge Tutorial", *Nathandumont.com*, 2020. [Online]. Available: https://nathandumont.com/blog/h-bridge-tutorial. [Accessed: 04- Jun- 2020].

[3] S. Tanzilli, "How to design the PWM circuitry", *Acmesystems.it*, 2020. [Online]. Available: https://www.acmesystems.it/pcb_pwm. [Accessed: 04- Jun- 2020].