



Design and Implementation of an Electromechanical Brake System

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HIGHLIGHTS

- Pad wear result is affected by the nature of calculating the coefficient of friction.
- The dissipated heat due radiation has small effect on the total heat loss and the wear.
- The EMB braking force path changes dramatically when including the pad wear.

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ABSTRACT

Nowadays, hydraulic brakes are already being replaced by electromechanical brakes (EMB) to improve quick-response brakes, efficient fuel consumption, environmentally sound, simple maintenance, and enhanced safety design. It is suggested that the electromechanical brake will be one of the most important brake systems in the future. This study focuses on designing and implementing an electromechanical brake based on a brushless DC (BLDC) motor and position controller to generate and control the required braking force at a variable friction coefficient between disc and pad. A feedback controller equipped with a measuring sensor is usually utilized to control this type of brake. Thus, three controllers for current, speed, and position were implemented in successive loops to control the motor movement. This system has current, speed, and force sensors. Due to implementation difficulties and cost issues of braking, the clamping sensor should be replaced with a position sensor with some modification where a position controller has been designed and implemented. The results showed that the clamping force of the brake system can follow the target accurately and it has good performance. Also, it is shown that this system can adjust the brake force more accurately and quickly compared with the traditional.

1. Introduction

Brakes are one of the most essential components and main safety systems in the vehicle. According to the crash report [1, 2] of automobiles, about 22% of car accidents are caused by brake failure. Brakes are mechanical or electrical components that help slow down and eventually stop the vehicle ascertain distance and a certain time [3]. A vehicle [4] requires a brake system to adjust its speed or stop as traffic and road conditions change. The primary idea used in braking systems is the conversion of the vehicle's kinetic energy into another form of energy. For example, the kinetic energy is converted into heat in friction braking, while it is converted into electricity, compressed air, etc. in regenerative braking. Two types of the friction-based braking system are commonly used, roller and disc brake [5]. The request for improved safety design, simplified system assembly, faster brake responding, easy maintenance, better fuel economy, and more environmentally friendly led to discover the electromechanical brakes (EMBs) as they have already started to replace the hydraulic brake in automotive. The electro-mechanical implementation came as an alternative to the electromechanical system. The EMB technique is usually known as Brake-by-Wire, in case of hydraulic system cancellation [6, 7]. This technique has not appeared in any production models because of the critical safety nature of the braking systems. However, it has undergone a broad search and testing. Compared to electro-hydraulic brakes, the EMB system has electronic components. Instead of using hydraulic-slave cylinders, the calipers contain electronic actuators, and everything is governed by a controller instead of using a master cylinder with high pressure. The EMB uses electromagnetic force to slow or stop motion. These systems also need a set of additional equipment, such as clamp force, actuator position, and temperature sensors in each caliper. The EMB shown in Figure 1 is a type of Brake-by-wire (BBW) where the driver's brake command results in an electric signal that will be communicated via micro-controllers to the brake actuator [5,8].

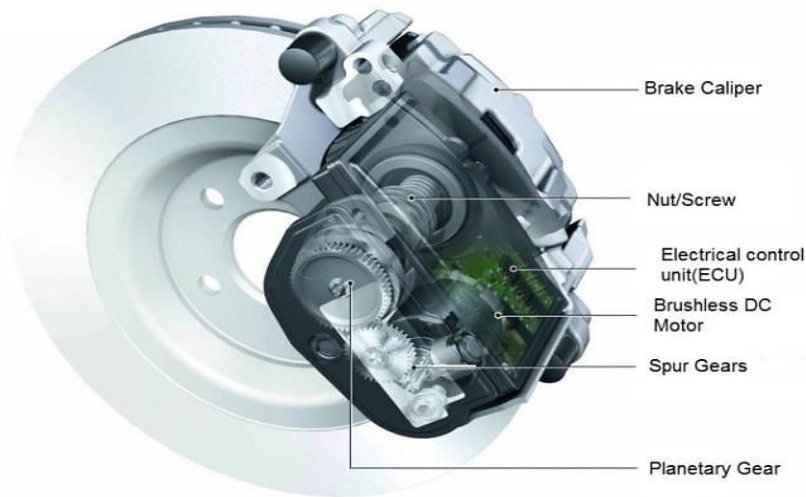


Figure 1: Electromechanical Brake, EMB

The brake-by-wire applications is requiring high-quality motors with a high torque/size ratio, high dynamic capacity, low inertia, fast braking response, low torque pulsations, and low radial forces [9, 10]. In this paper, a permanent magnet synchronous motor (PMSM) is considered an electrical drive for the EMB system. The braking force is generated by this motor in each wheel brake. These motors are controlled by an electronic control unit and are executed by signals coming from the electronic pedal module where the input of the driver is again received from a suitable sensor in a way similar way to the operation of the electro-hydraulic system. Moreover, an actuator in the inputs such as the brake pedal would send a feedback signal to the driver. The EMB has many advantages over conventional brake [11] such as; reducing mechanical parts, being nature friendly, and less maintenance. The EMB mechanical part performs by transforming the motor rotational motion into linear displacement by which it controls the braking force. The electrical part processes feedback signals transmitted to the control chip via sensors to ensure optimal response time [12].

Some researchers in the literature focused on the issue of the EMB system and are interested in designing and improving its performance. Yang et al. [13] had designed an actuator and controller of EMB. Mat lab/Simulink was used to build the EMB model. The control unit design of the braking system had adopted control architecture with three successive loops, which are force loop, speed loop, and current loop. Computer simulations were performed based on three typical conditions for step input, pulse input, and half cosine input. Liao [14] analyzed the EMB system in detail. The researchers introduced the theory of the EMB system and its advantages composition. They offered the Electronic Braking System (EBS) hardware and assessed the design of the electrical machine and electronic pedal of the EMB system. Eventually, they specifically analyzed the system software. This study has great meaning for the braking system researchers and maintainers of the automobile. Nayak et al. [15] had designed a new concept of an electromechanical parking-brake system with simple and low-cost characteristics. Traditional parking brake systems have been replaced by a fully electric component system. This brake is accomplished by replacing traditional links with electric units driven by an electric motor. The braking force of each wheel can be directly generated by using high-performance electric motors as well as gear reduction. Beak et al. [16] theoretically and experimentally evaluated the clamping force performance for an EMB in a high-speed train. A three-phase surface permanent magnet synchronous motor (SPMSM) is used for generating this force. A Proportional Integral (PI) current control was applied to control motor torque. Moreover, an anti-windup fast current tracking controller was proposed to improve the torque output. It was found that the peak clamping force is enhanced by about 4.8% when the PI current controller is combined with the anti-windup controller. An interior three-phase permanent magnet synchronous motor (IPMSM) was used to drive the EMB. A speed controller, position controller, and current controller based on the PI control were utilized for driving the motor. The control principle with maximum torque per ampere (MTPA) was implemented on the current controller for effective control performance. The experimental results showed that applying the MTPA control reduces the current consumption in the EMB system. At the same time, the clamping force reduced the total input power by ~40%.

In the present study, an EMB system has been designed and implemented based on building a position controller to evaluate the clamping force. This system depends on a brushless DC (BLDC) motor and position controller to generate the required braking force at the variable coefficient of friction between the disc and pad.

2. Experimental Work

This section focuses on designing, assembling, and implementing the EMB system based On BLDC motor position controller [17]. Three controllers in cascade loops; the current controller, speed controller, and position controller are implemented to control the motion of the BLDC motor. Therefore, the EMB system must have three sensors for current, speed, and force. Due to the lack of a high-power sensor, it was replaced by a position sensor where a position controller was implemented. The goal of the experimental work is to control the angular position of the motor shaft. All the details

and procedures of the design and implementation of the parts of the EMB system will be demonstrated in the following sections.

2.1 Electrical Part

The electrical part consists of a micro-controller, sensors, BLDC motor, BLDC driver, power supply, and host-personal computer (PC). An Adriano micro-controller was chosen to be communicated with a PC via USB port, and with sensors and motor via its input and output pins. It receives signals from sensors for processing and sends the drive signal through one of the PWM output pins. An Adriano Mega 256 was chosen because of its fast response and large memory. Code will not be written, instead, Matlab/Simulink software along with Adriano support package was used to build the required blocks and then generate and deploy code to the arguing board. Analog and digital pins will be used as inputs to read signals of sensors and sliding switches. ACS712, 20A current sensor module shown in Figure 2 was chosen to be compatible with the proposed motor and arguing. This motor draws a current that reaches 18A. The sensor is connected between the ground of the power source and the BLDC drive. The sensor is powered via a 5 volts pin and ground pin from the arguing board. The sensor signal is connected to analog pin 0.

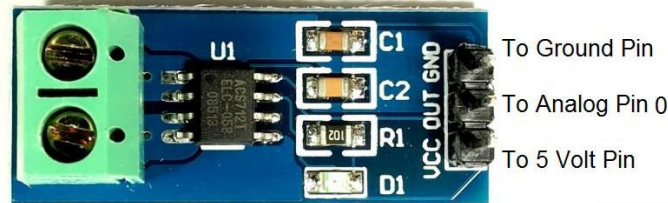


Figure 2: Current sensor

It was found that the raw readings of the current sensor start at 512, so a calibration has been performed on it to make its readings vary between 0 and 1024. Also, it was found that the sensor reading is accompanied by noise, so a low-pass filter (RC) represented by the "S-function" block was used as shown in Figure 3. The current signal is doubled using a "converter block" so it can be processed by the current PI controller.

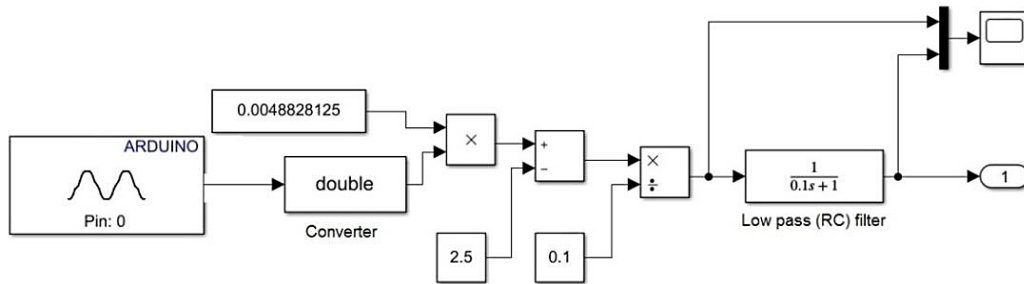


Figure 3: Current sensor calibration block

The BLDC motor proposed in this work is a sensor-powered motor, which means that it has three built-in Hall sensors used to control the rotation of the motor as shown in Figure 4. One of the three sensors can be used as a speed sensor and the signal is connected to the arguing digital pin 2.

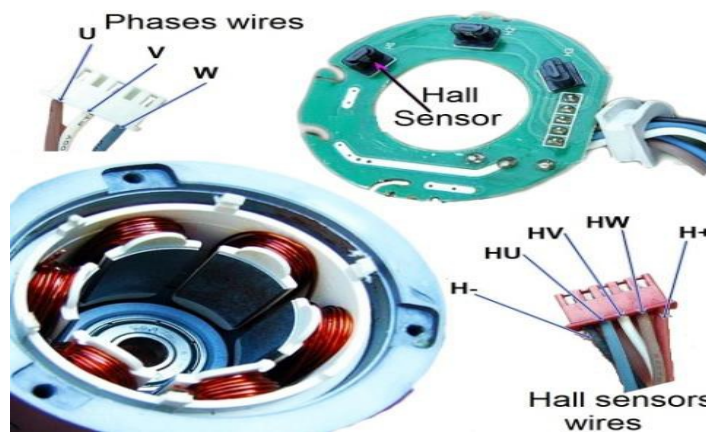


Figure 4: BLDC components

Hall sensor readings are in tics every time the rotor pole passes. For that reason, a block called "speed sensor" in the arguing library is used. Also, the sensor reading has noise, so a low-pass filter is used as an S-function block, as shown in Figure 5. The signal is doubled using a converter block, so it can be processed by the PI speed controller.

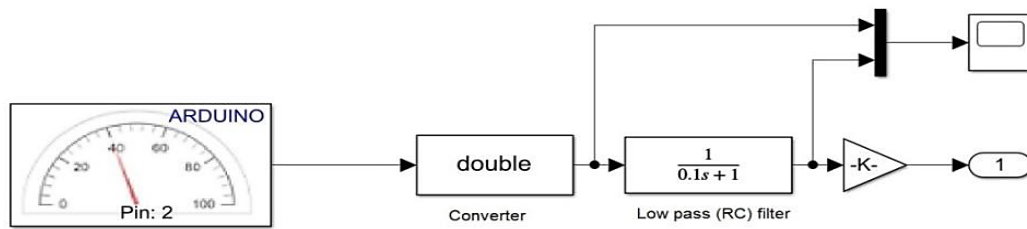


Figure 5: Speed sensor block

Normally, to read the angular position sensor, an encoder or rotary sensor is used. However, for the narrow space between the motor and other components, the speed sensor signal is integrated to get the angular position signal. The integrator block used is shown in Figure 6.

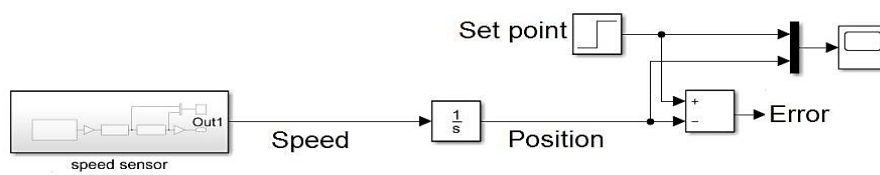


Figure 6: Position sensor blocks

Six channels MOFSET driver circuit is used to drive the BLDC motor. Each phase of the three BLDC motor phases is driven by two MOFSETs as shown in Figure 7. The MOFSETs receive signals from the driver circuit in the form of PWM to control the power of BLDC motor by switching on and off.

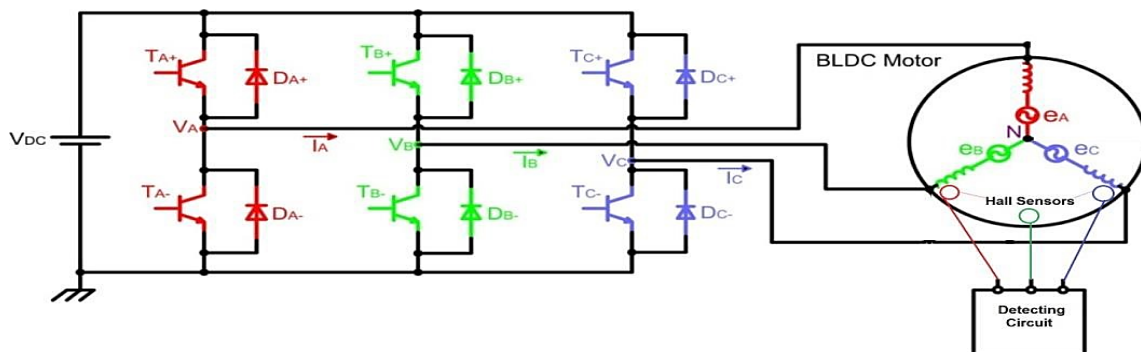


Figure 7: BLDC motor drive diagram

The drive circuit receives command signals as a DC voltage ranging between 0 and 2.5 V, and because the arguing only delivers PWM signals, an RC filter of 10k Ω resistor and 100 μ F capacitor are used to smooth the PWM. Four poles 300 W, 18 V, 18 A BLDC motor is used in this work. The motor specifications are listed in Table 1. Obit PXC 18V/4Ah Lithium-Ion Battery is used as the power source which is compatible with the BLDC motor rated power. Host-PC or laptop is used to be communicated with the system in real-time to observe the results of the outputs and inputs via software displays (scopes). The host computer has been interfaced with the BLDC motor driver as shown in Figure 8 and motor current and speed are captured by arguing Mega microcontroller.

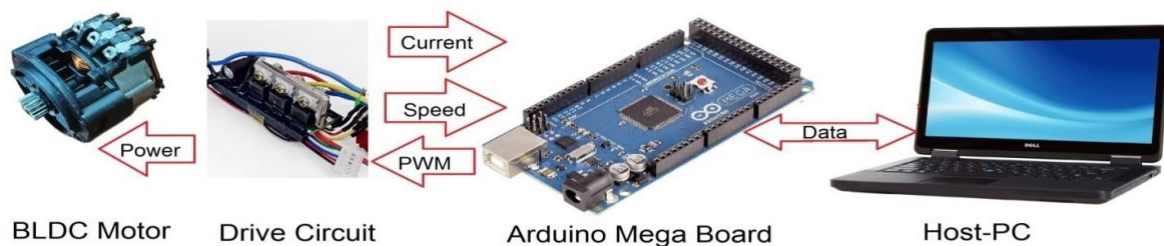


Figure 8: arguing Communications with BLDC motor and PC

A sliding switch button is connected to directly switch arguing, so the command can be sent externally if desired, and not from the host computer. The switch is connected to the ground pin, 3 V pin, and analog pin 1. For the caliper piston to move forward and backward, 2-Channel 250 V 10 A TOGLING Relay module is used. The motor motion then will be in two directions, clockwise (CW) and counter-clockwise (CCW). The motor driver has two wires, white and red to alter the rotation. When one wire is grounded, the motor rotates in one direction, and when the other wire is grounded, the motor will rotate in the opposite direction.

2.2 Mechanical part

The mechanical part consists of a brake caliper, piston, lever gears, planetary gears, and Ball Screw. A single-piston brake caliper is used in the EMB system as shown in Figure 9. The caliper was modified in a lathe shop, so the planetary gear can be placed inside the caliper, and then the motion can be transferred freely from the spur gears to the planetary gear and finally to the piston. Very hard metal planetary gears are used, so they will be capable of affording high torque and pressure. The planet carrier is connected (welded) to the screw which will drive the screw into the nut at the piston. The reduction ratio of the final planetary gear is about 8/1. The main purpose of the spur gears is to transfer the motor motion in the opposite direction from where the motor is placed, so the motion can be directed toward the caliper piston. It is also used to reduce the motor speed and increase the torque, the reduction ratio off spur gears is 4/1. The brake piston was modified by having a nut welded and whole drilled at the center, so the screw rotational motion can be transferred to the piston linear motion to create the required force.

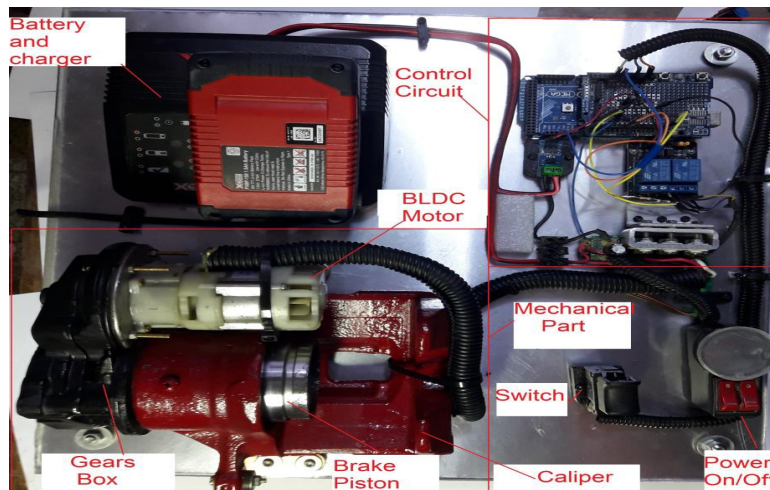


Figure 9: The main component of the EMB

3. Experimental setup

To collect the experimental input and output data for the implemented EMB system, the Arguing Mega has been programmed with an arguing block-set developed by MATLAB to send command signals to the motor driver. The motor speed and current measurements are received from the motor, or the signal can be sent from the sliding push button if needed. The EMB system has three controllers (current, speed, and position) connected in series and feedback in the cascade as shown in Figure 10.

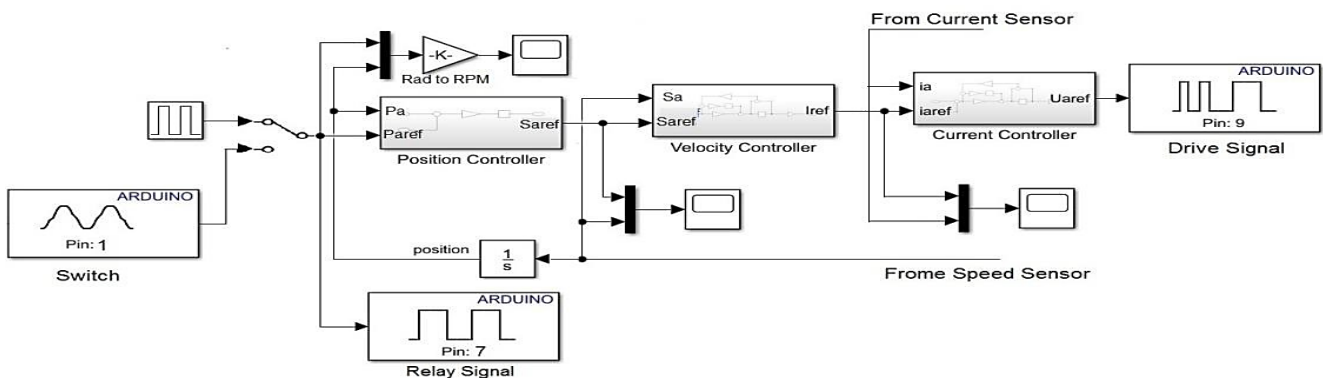


Figure 10: EMB arguing Blocks

The current controller and speed controller are PI with an anti-windup back-calculation controller, while the position controller is only a proportional (P) controller, as shown in Figures 11 and 12. After trying different controller formations of P, PI, PID, and PD, the PI controller for current and speed, and P controller for the position are found to be more suitable to the

system response. When the anti-windup scheme is activated, it prevents the controller output from wandering away. The Anti-windup scheme is effective in removing ripples from the signal. Controllers' gains are tuned using the trial and error method. Starting by increasing P gain until the response comes close to the signal and stops increasing when no significant change occurs. Then the I gain is increased until the response match signal with some ripples and lastly, the anti-windup gain is increased until the ripples disappear. The motor specifications are shown in Table 2 and the controllers' gains are shown in Table 3.

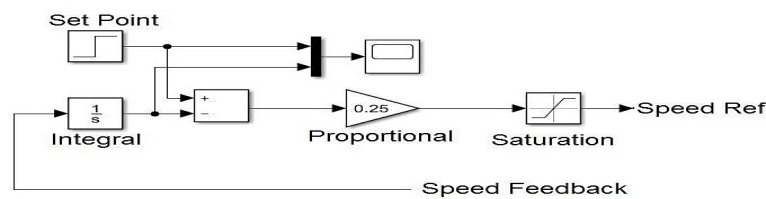


Figure 11: Position Controller

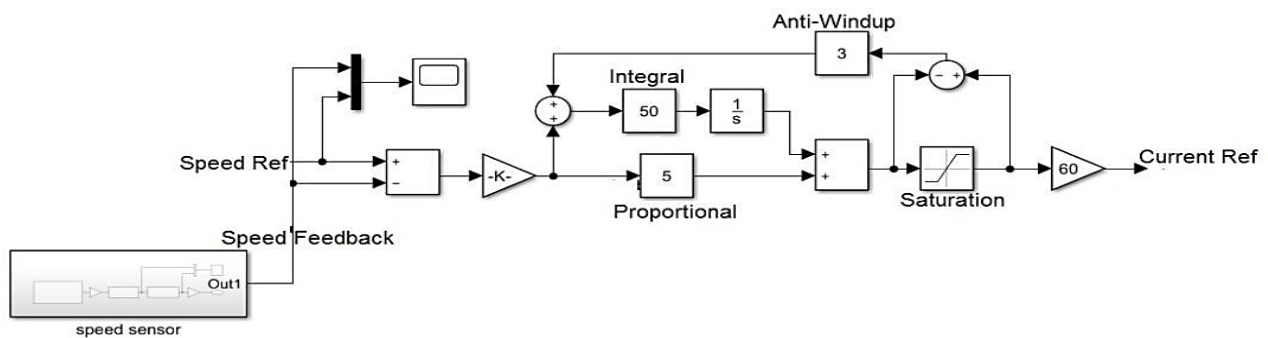


Figure 12: Speed Controller

The limits of the saturation block in the current controller are between 0, and 20 as the motor rated voltage, while arguing PWM output pin limits are between 0 and 256, and for that reason, again block of 64 is added, so the signal goes to pin 9 is between 0 and 128, which means the PWM voltage is between 0 and 2.5 V and that is what the drive circuit is accepting as shown in Figure 13.

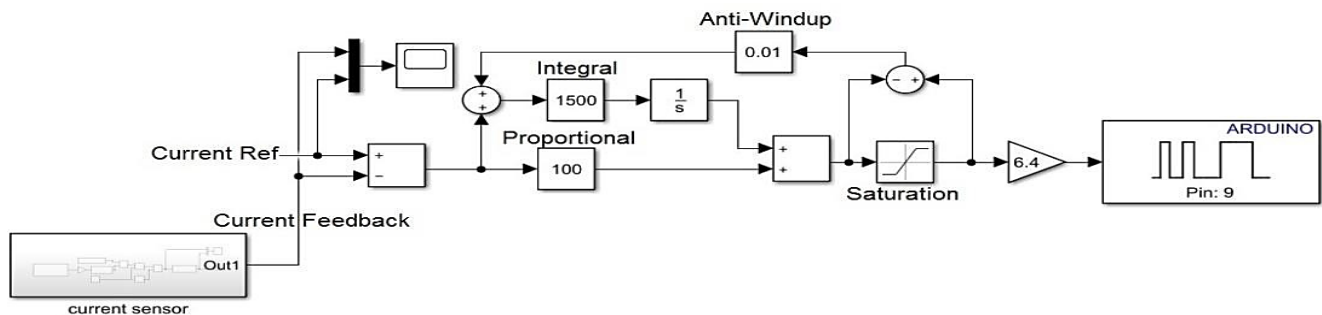


Figure 13: Current Controller

Table 1: Motor Specifications

Parameter	Value
Output power	240 W
No. of poles	4
No. of phases	3
Stator resistance	0.1 Ω
Stator inductance	0.02 H
Rated voltage	18V
Rated speed	30000 rpm
Holding torque	0.6 N.m
Peak current	18 A
Torque constant	0.007 N.m/A
Moment of inertia	0.00002 Kg.M ²

Table 2: Controller gains

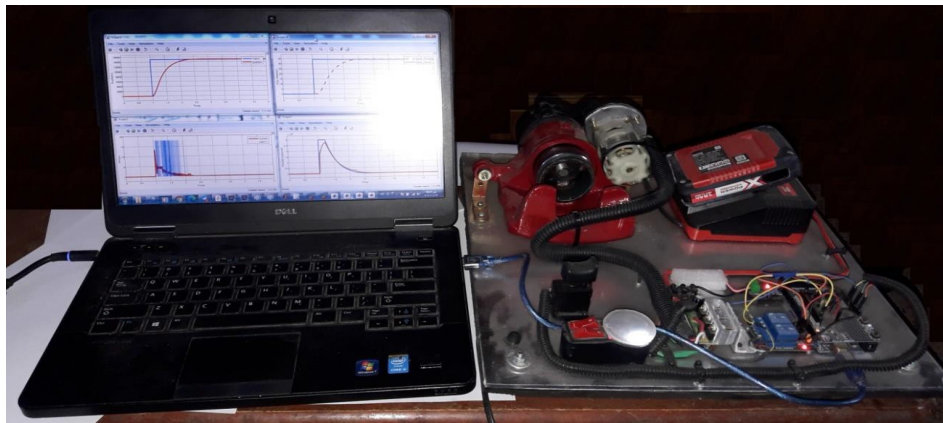
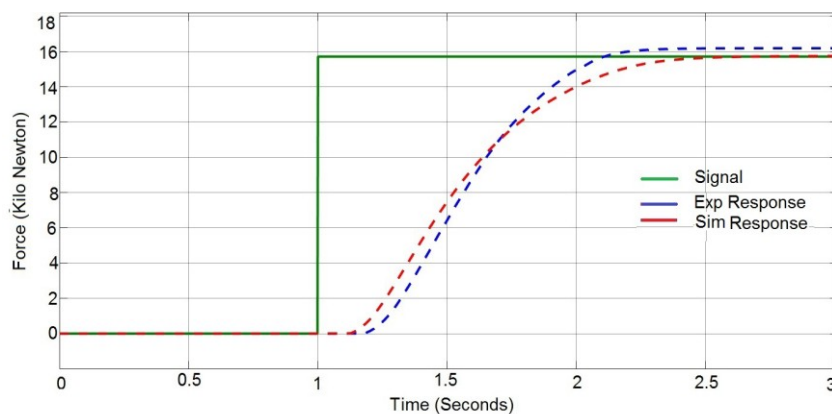
Controller	Gains		
	P	I	Anti-windup
Current controller	100	1500	0.01
Speed controller	5	50	3
Force Controller	2.5		

Table 3: Thermal model parameters

Parameter	Value		
Vehicle mass	1000 kg		
Rotor mass	3 kg		
Rotor eff. radius	0.28 m		
Vehicle speed	30 (m/s)	50	40

4. Results and discussion

After implementing the electromechanical brake, it is combined with the Laptop to collect the findings as shown in Figure 14. Due to the high cost of the clamping force sensor, it is recommended to replace this sensor with an accurate and simple algorithm. Also, it should be noted that the sensor has low accuracy with complex structural issues and high temperatures. The clamping force is obtained using the relationship between the stiffness curve and linear displacement. Motor angular position is obtained from the integration of the speed signal and then multiplied by the effective gear ratio to obtain the linear position in the millimeter. The force in the EMB system was experimentally evaluated as shown in Figure 15. The blue dotted line represents the experimental response of the actual braking force with a delay time of 1.2 sec and time rise of about 2sec and at a steady-state, it exceeds the green-colored desired signal because of some technical issue (interference noise).

**Figure 14:** Overall setup of the EMB system**Figure 15:** Force generated

In Figure 16, the experimental response for piston displacement is plotted. The response has a similar shape to the force response (as force is a result of the linear displacement), but they start climbing faster and the reason for that is caused by the stiffness curve function, as when displacement is less than 0.125mm, the relationship is linear.

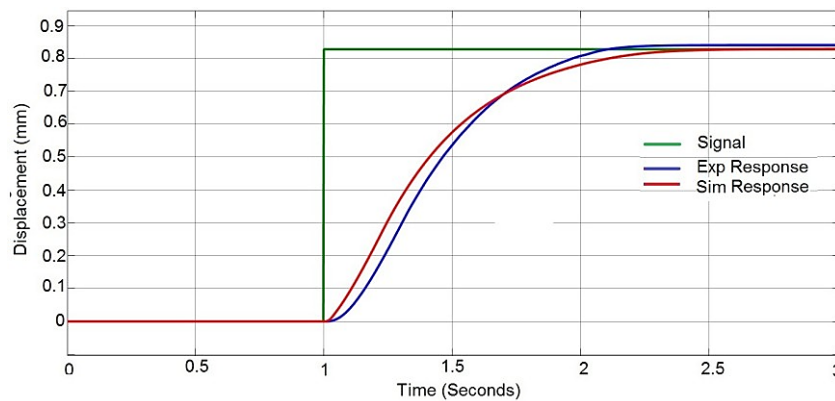


Figure 16: Piston displacement

In Figure 17, the experimental response for speed is plotted. The experimental signal is plotted with the light blue line, while the experimental response is plotted with the blue line. The actual speed reaches about 90% of the desired maximum speed during about 1.25s. After the braking action, the speed is quickly dropped to zero speed only in 1.5 seconds.

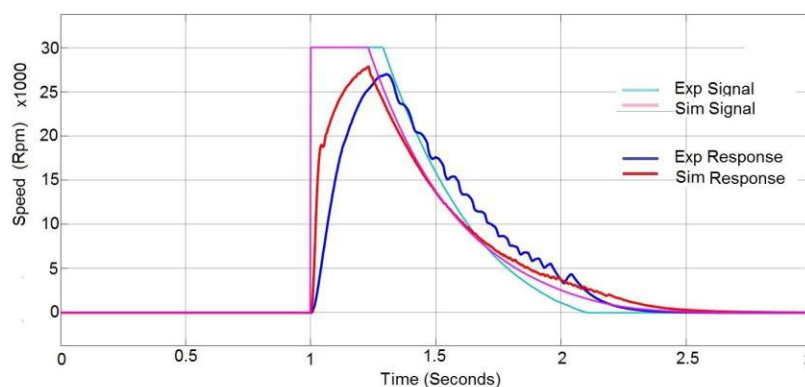


Figure 17: Motor Speed

5. Conclusions

Some conclusions have been drawn:

- 1) The friction coefficient has a major role in the calculation of the braking force required in the EMS and the accumulated wearing during breaking.
- 2) The braking force required is high when using a variable friction coefficient.
- 3) The constant friction coefficient leads to higher wear than the variable friction coefficient.
- 4) The observed difference in response between experimental and simulation systems is insignificant and convincing. Some overshoot is happening in the experimental response occurs due to some technical issue like noise.
- 5) It can be noted from the results that the response rise time and settling time in the simulation model is shorter than in the experimental one by about 17% and 8%, respectively.

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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