جامعة خليفة
Khalifa University

Smart Monitoring and Control of Plug-in Electric Vehicle (PEV) Powertrain

BY

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General overview

Theoretical background

Design concepts

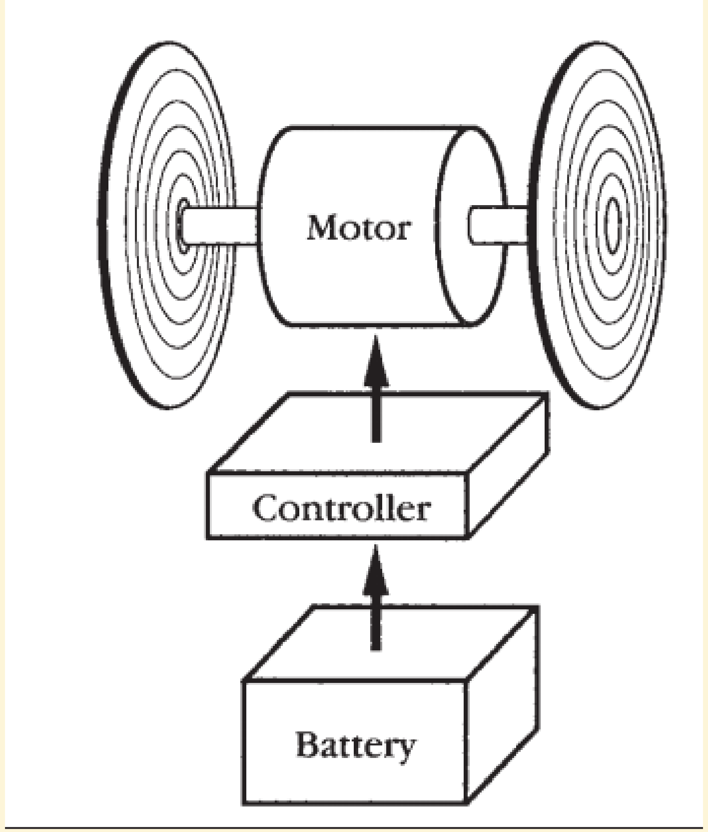
Implementation and testing: Simulation and Prototype

Conclusion

General overview: plug in EV

- Electric vehicles are emerging rapidly
- EVs were around before internal combustion engine vehicles.

Internal combustion engine vehicle	Electric Vehicle
Requires fuel	Requires only electricity and water
Average 20% thermal Efficiency	About 70% efficiency
Generate toxic gas: greenhouse effect	Zero emission: no greenhouse effect

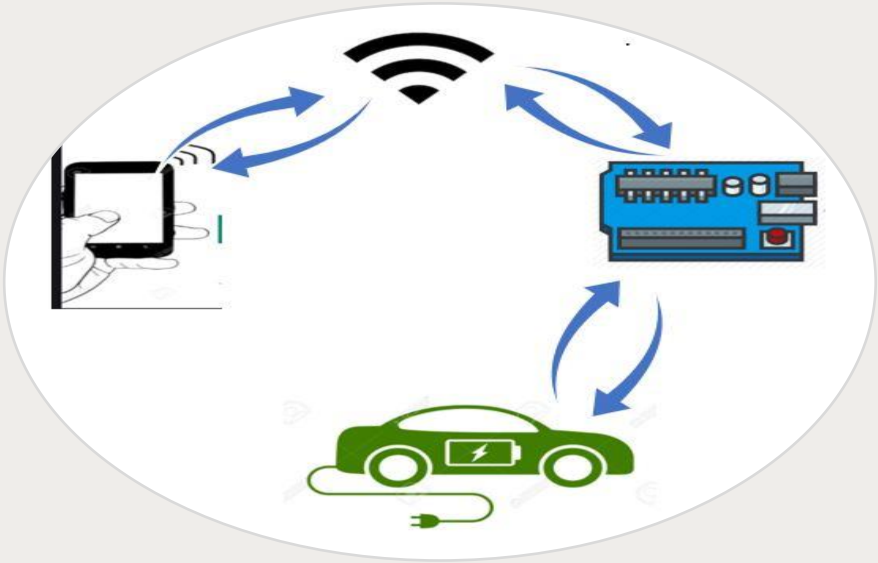


General overview

Goals

Build a smart monitoring and control system

For a DC powered Plug-in Electric Vehicle (PEV) powertrain



Objectives

Design the whole system on a software

Achieve a desired simulation of the system

Build a prototype of a DC powered Plug-in Electric Vehicle (PEV) powertrain

Create monitoring system and a speed controller

Evaluate the performance of the PEV based on the data of the monitoring system obtained through WIFI.

Technical Overview

Main components

Internet of Things (IoT) concepts will be implemented in the project. One of the main ideas is to design a speed controller. The following will be used for this task:

- Bidirectional DC-DC converter
- H-bridge
- Microcontroller and WiFi module
- A speed sensor built on Magnetic Hall Effect
- Vehicle body frame (with transmission drive and braking system)
- DC Motor
- Batteries

General overview

System requirements

- Safety
- Simplicity
- Accuracy and reliability
- Cost

System specifications

- The PEV powertrain should handle a weight of 200 kg (including passengers)
- Battery should be rechargeable
- Should be able to operate at the rated power for at least 1 hour
- Speed control and monitor should be as accurate as possible
- System will be controlled and monitored remotely via Wi-Fi or Bluetooth

Power Rating Calculation

Specifications

- Total mass(m) = 200 kg
- Max. Velocity(Vmax) = 20 km/h = 5 m/s
- Acceleration(acc) = 1 m/s2
- Wheel radius(Rwheel) = 15 cm = 0.15 m
- Max. inclination angle(θmax) = 4 degrees
- Gravity(g) = 9.8 m/s2
- Working Surface (Csf) = poor (0.02)
- Air Density (ad) = 1.23
- Front Area(fa) = 0.5 m2
- Aero Drag Coefficient(adc) = 0.38
- Sprocket Ration = 5/6/7/8

Requirements

- Total Tractive Effort(TTE)
- Wheel Torque(Wτ)
- Power
- Motor torque(Mτ)
- Motor Speed(ω)

Calculations

- *Total Tractive Effort(TTE) = Rolling Resistance(RR) + Grade Resistance(GR) + Acceleration Force(AF) + Aerodynamics Drag(AD)*

$\Rightarrow RR = m * g * Csf = 260 * 9.8 * 0.02 = 50.96\ N$

$\Rightarrow GR = m * g * Sin\ (\theta max) = 260 * 9.8 * 0.0698 = 177.74\ N$

$\Rightarrow AF = m * a = 260 * 1 = 260\ N$

$\Rightarrow AD = 0.5 * ad * adc * fa * Vmax2 = 0.5 * 1.23 * 0.38 * 0.5 * 25 = 3\ N$

$\Rightarrow TTE = 50.96 + 177.74 + 260 + 3 = 491.7\ N$

$\Rightarrow W\tau = TTE * Rwheel = 491.7 * 0.15 = 74\ Nm$

$\Rightarrow$ 1 wheel revolution = 2*pi * Rwheel = 0.9425 m

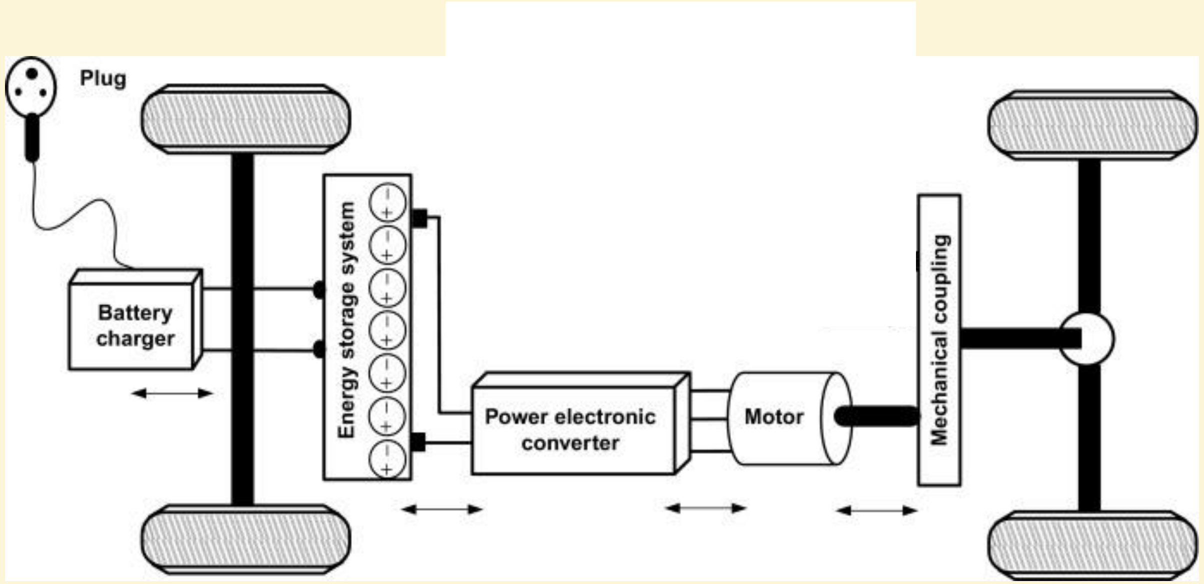
$\Rightarrow$ Therefore, ω = 20 km/h = ((20,000 m)/ (0.9425 m/rev))/60 min = 354 rpm

$\Rightarrow$ Power = (2*pi * Wτ * ω) / (60) = 2758.67 W

Concept Generation and Design Evaluation

Introduction

- ✓ This section we will compare three different design concepts that we came up with.
- ✓ We will build a pair-wise comparison chart to properly compare the design concepts.
- ✓ The design with the highest score in the end will be selected for implementation.



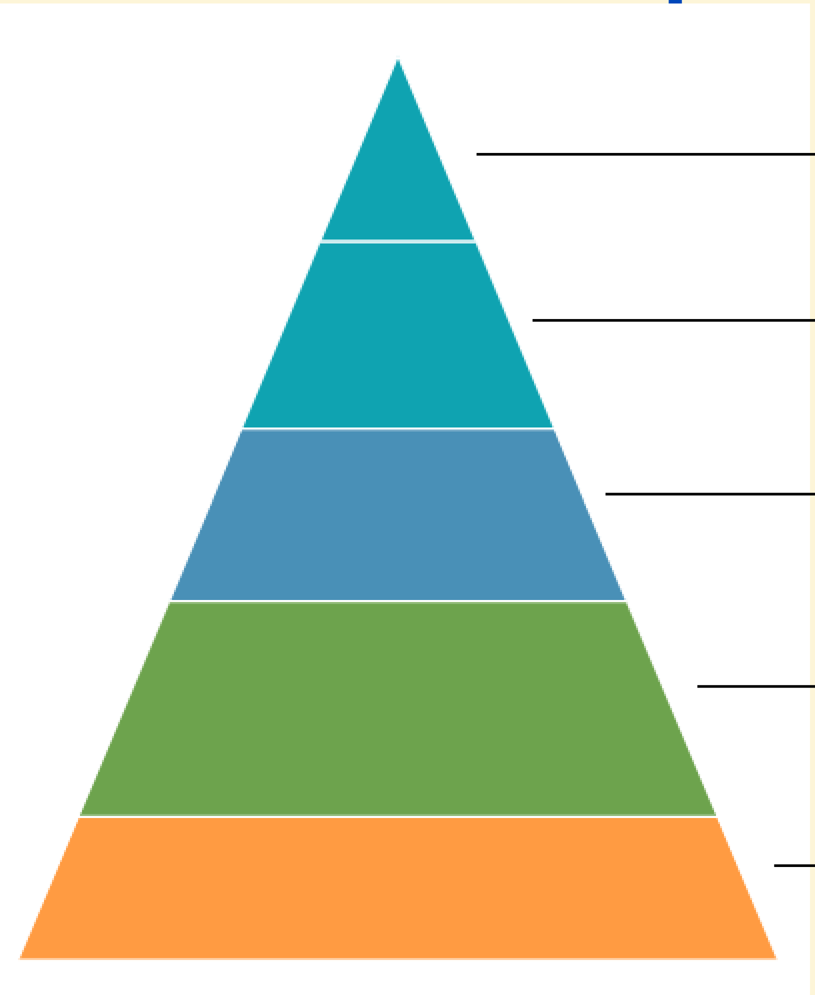
Existing products

- ✓ Many huge companies manufacture PEV powertrain system.
- ✓ Some examples are BMW i3, Chevy bolt, Chevy Spark, Nissan LEAF, Hyundai Ioniq, and of course Tesla model cars.
- ✓ Of course our model is in much smaller scale, however the basic mechanism is very similar.

Pair-wise comparison chart

Goals	Safety	Low Cost	Low Power Consumption	Accuracy and Reliability	Ease of Build	Score
Safety		1	1	1	1	4 (40%)
Low Cost	0		½	0	½	1 (10%)
Low Power Consumption	0	½		0	½	1 (10%)
Accuracy and Reliability	0	1	1		½	2.5 (25%)
Ease of Build	0	½	½	½		1.5 (15%)

Pair-wise comparison chart



Safety (40%)

Accuracy and Reliability (30%)

Ease of Build (15%)

Low Cost (10%)

Low Power Consumption (10%)

Design-1: Permanent Magnet DC Motor PEV Powertrain

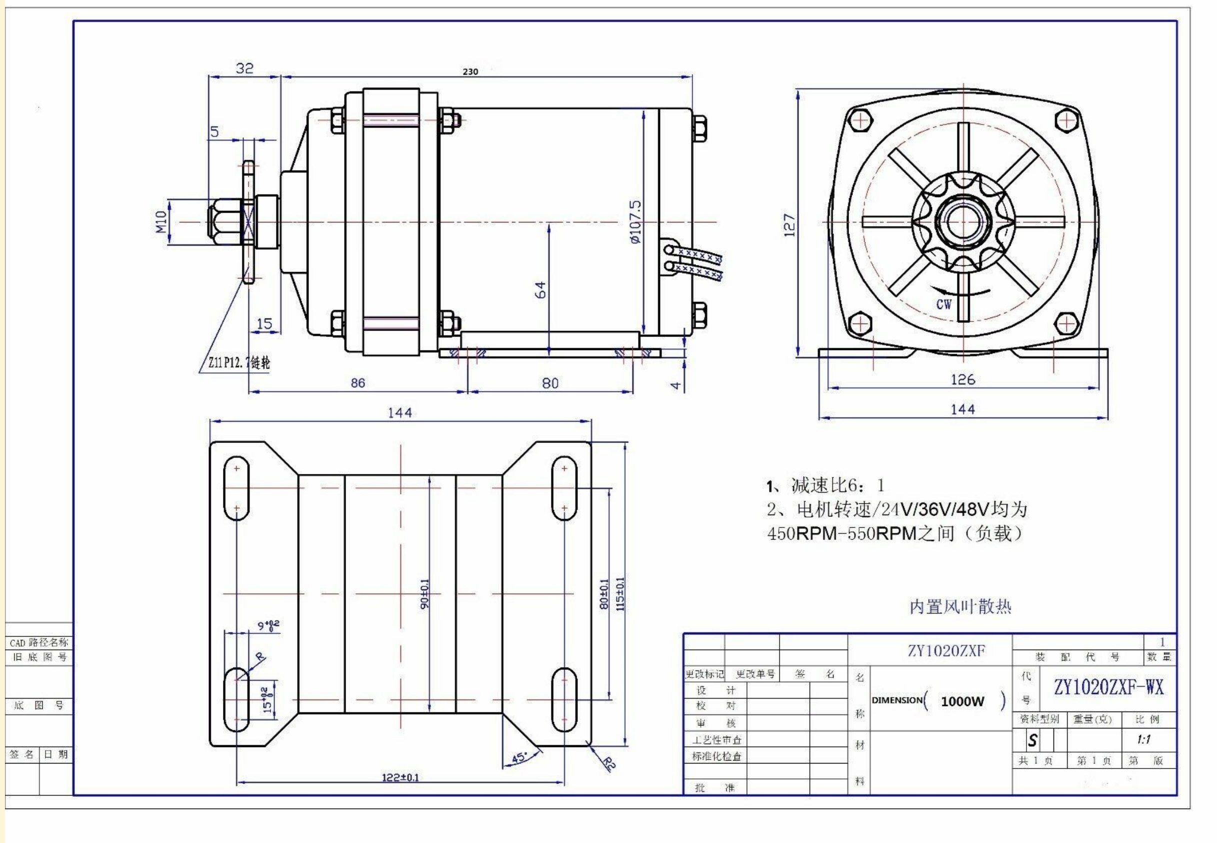
Kart Body Frame:

- Estimated maximum weight: 200 kg (including the whole system and a passenger)
- The kart will be designed for a single passenger only.
- Already have a steering wheel attached to the kart.

Design-1: Permanent Magnet DC Motor PEV Powertrain

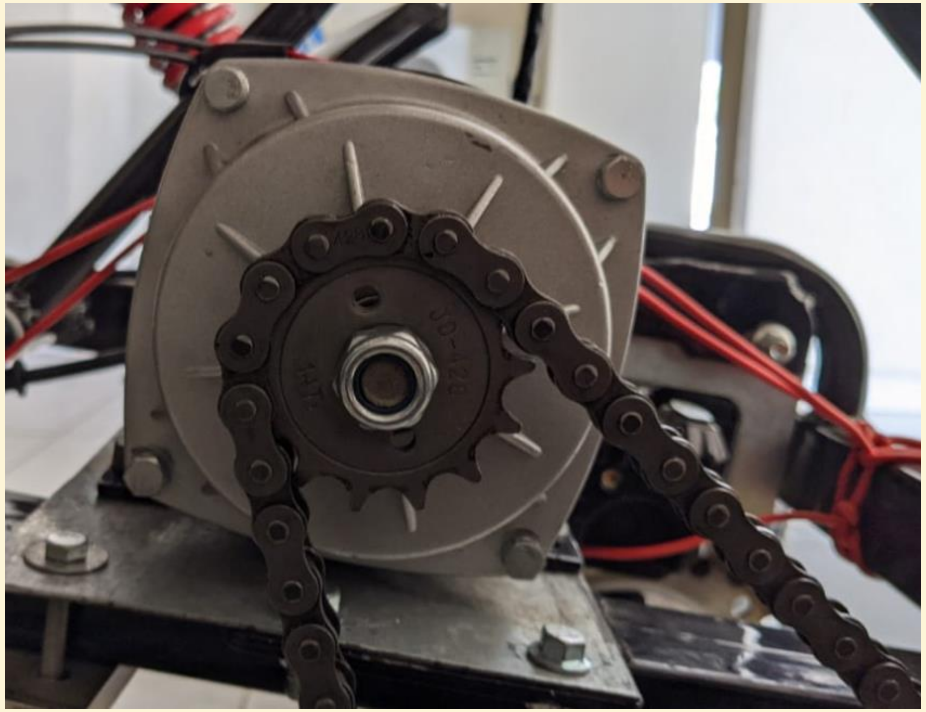
DC Motor:

1kW@48V Brushed PMDC Motor



Design-1: Permanent Magnet DC Motor PEV Powertrain

Drive Transmission Method:

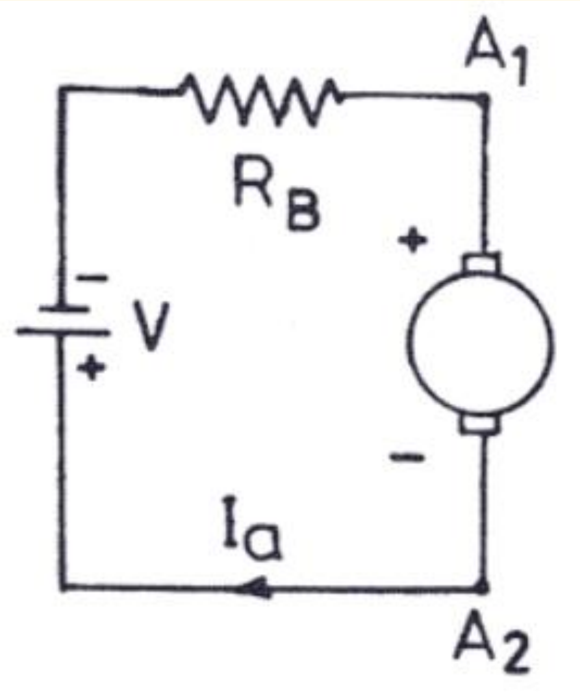


Chain drive attached to DC motor and driver shaft

Design-1: Permanent Magnet DC Motor PEV Powertrain

Vehicle Braking System:

Hydraulic disc brake



Regenerative braking

Design-1: Permanent Magnet DC Motor PEV Powertrain

Battery Storage System:

4x12V Lead-Acid in series at 26AH

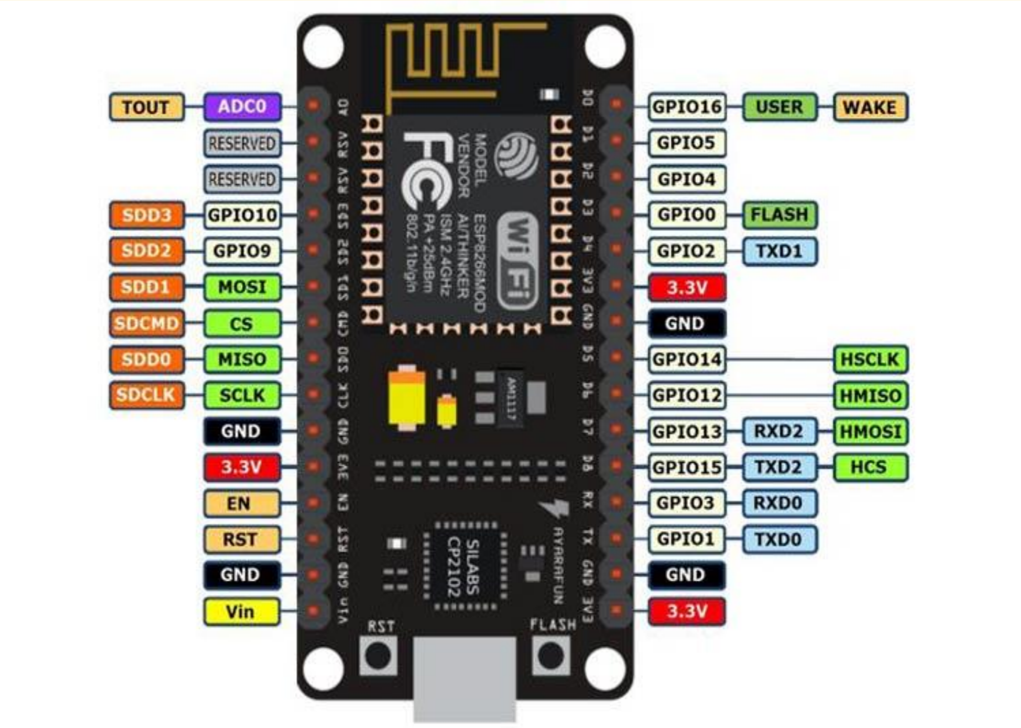
Design-1: Permanent Magnet DC Motor PEV Powertrain

Battery Charger:

12V charger supplying at 2.6A

Design-1: Permanent Magnet DC Motor PEV Powertrain

Microcontroller:



NodeMCU Board

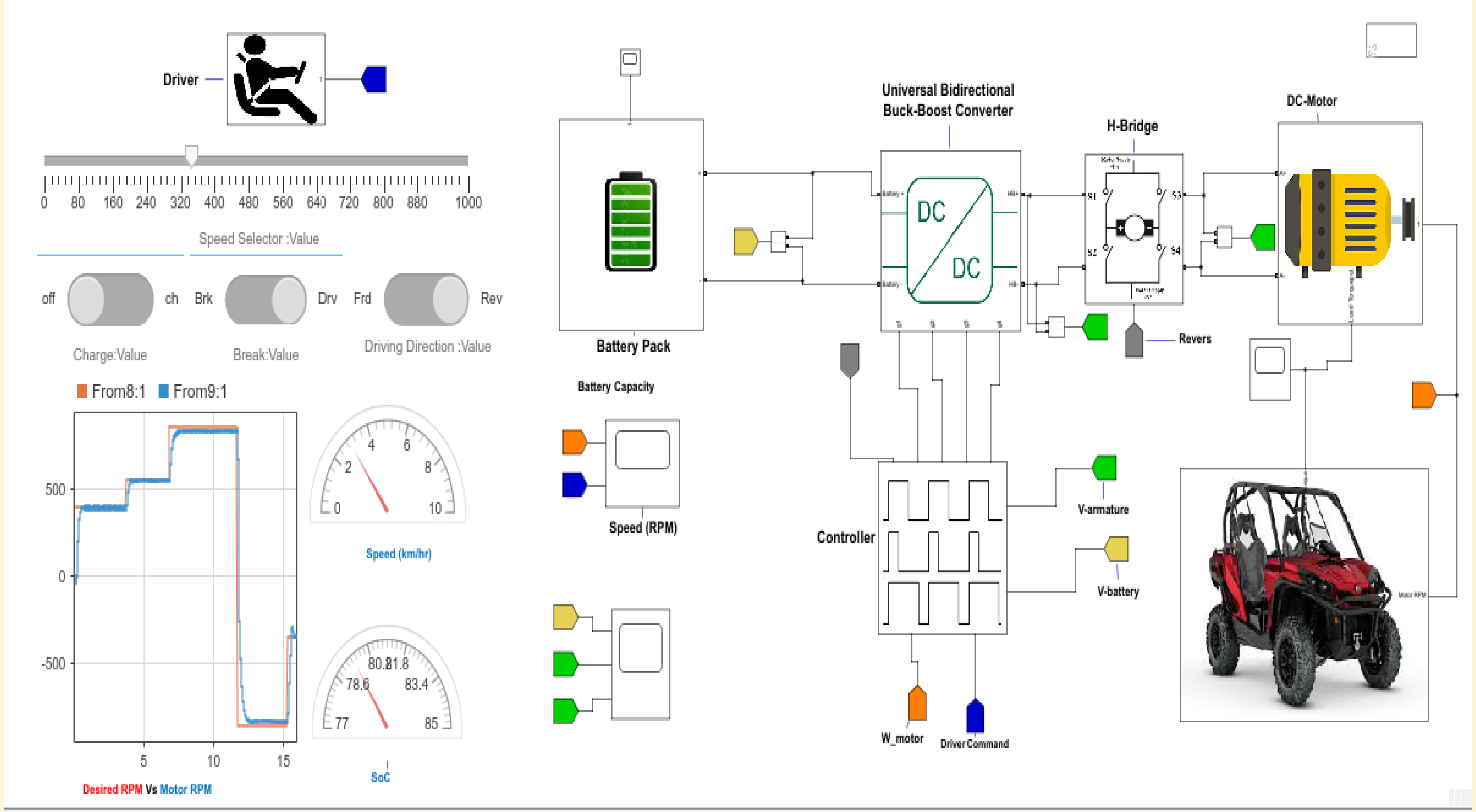
Design-1: Permanent Magnet DC Motor PEV Powertrain

Microcontroller:

300A PWM-controllable speed controller with regenerative braking

Design-1: Permanent Magnet DC Motor PEV Powertrain

Design Simulation:



Design-2: Separately Excited DC Motor PEV Powertrain

Kart Frame:

- Maximum weight: 260 kg (including the whole system and passengers)
- The kart will be designed for two passengers.
- Already have a steering wheel attached to the kart.

Design-2: Separately Excited DC Motor PEV Powertrain

DC Motor:

3kW@48V SepEx Brushed DC Motor

Design-2: Separately Excited DC Motor PEV Powertrain

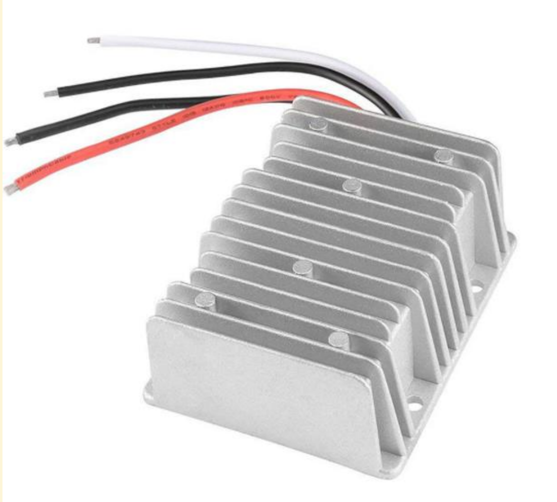
Battery Storage System:

Lithium-ion batteries 48V@100Ah with charging contacts

Design-2: Separately Excited DC Motor PEV Powertrain

Other Components:

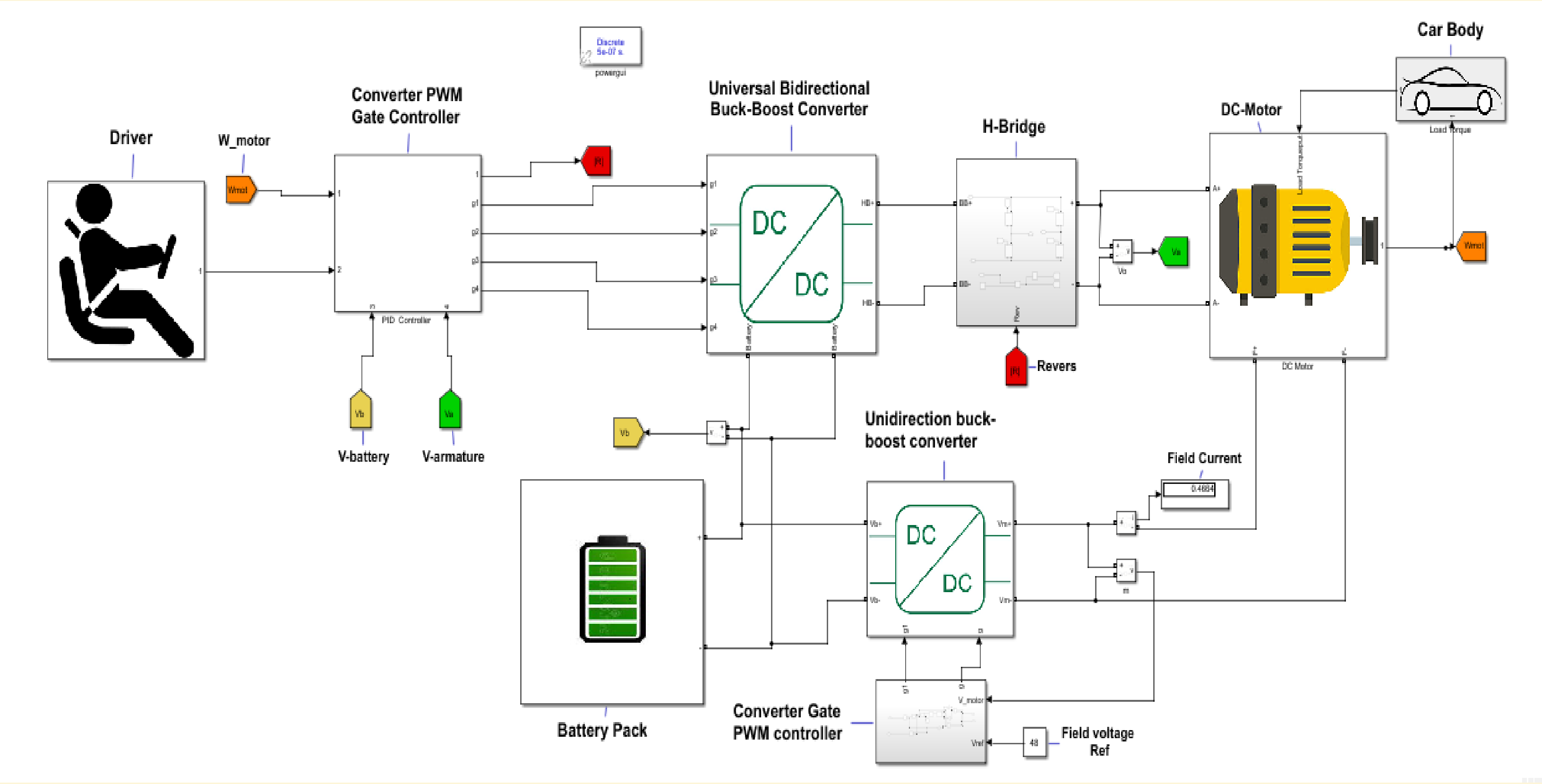
All other components will be the same as design concept #1, which includes the drive transmission method, the braking system, the microcontroller, and the speed controller. But it will have an additional component to power up the field windings of the separately excited DC motor.



Buck-boost converter to power up field coils.

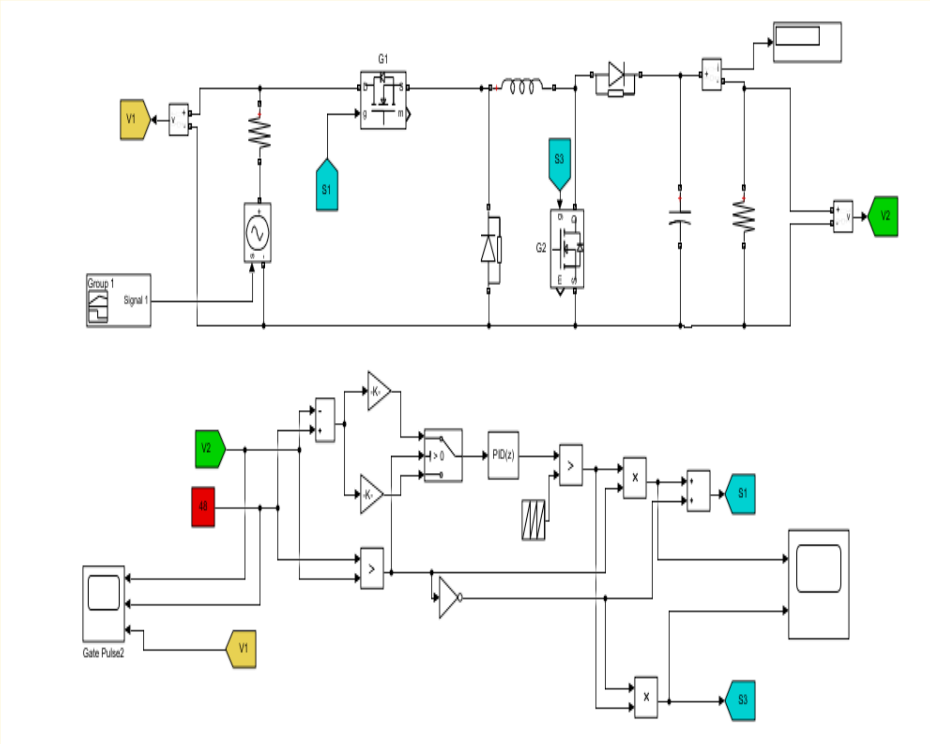
Design-2: Separately Excited DC Motor PEV Powertrain

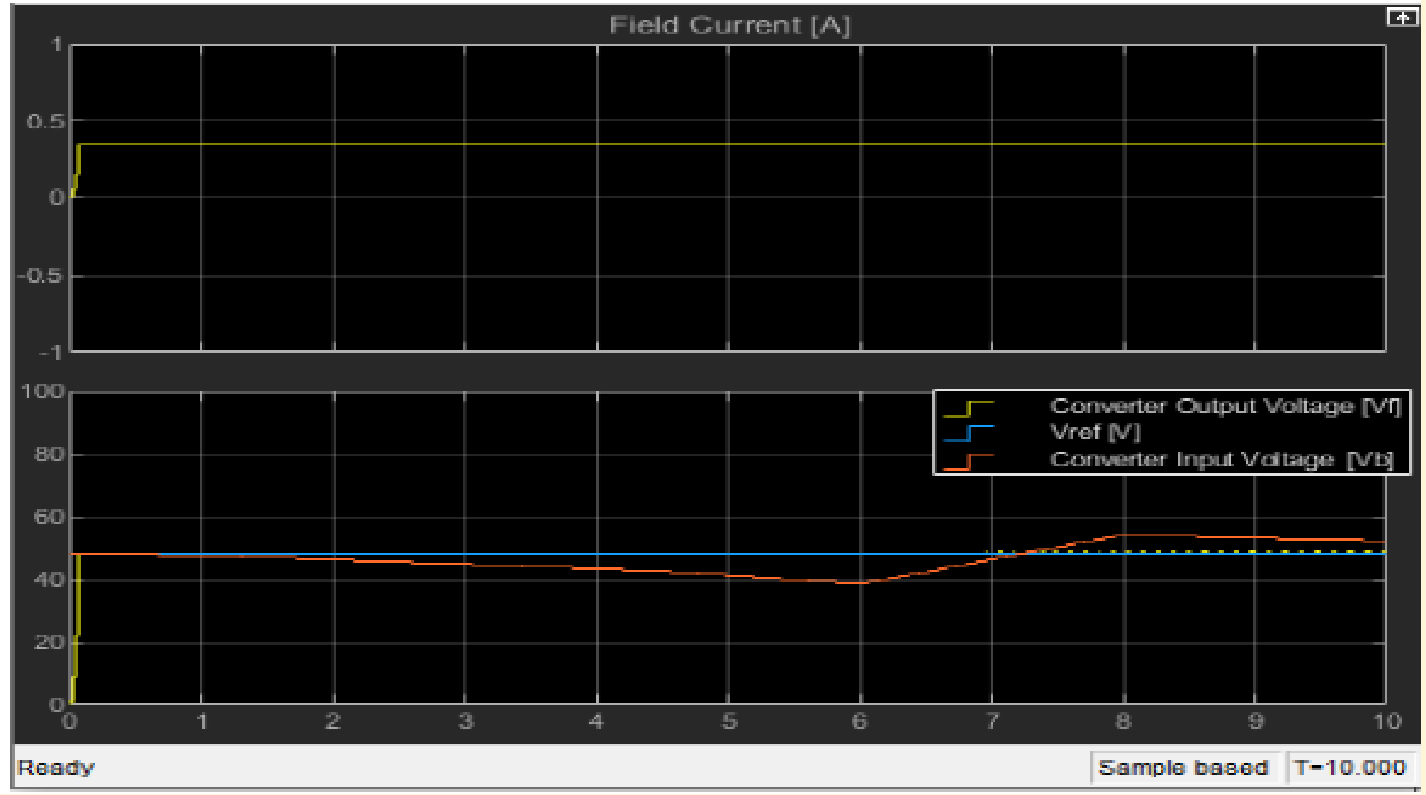
Design Simulation:



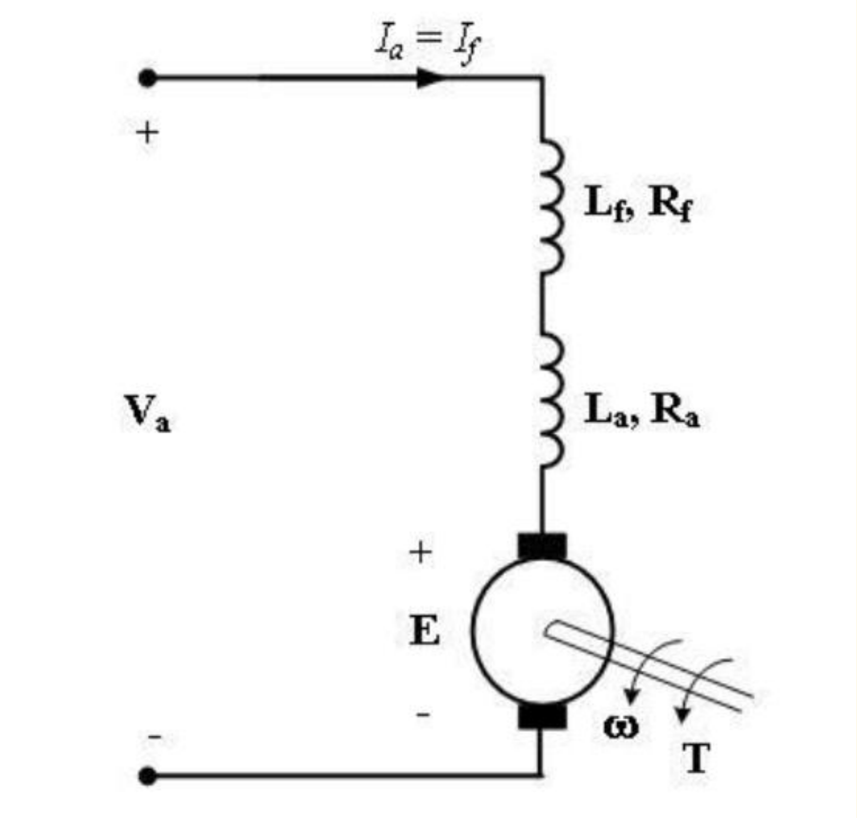
Design-2: Separately Excited DC Motor PEV Powertrain

Unidirection buck-boost converter:





Design-3: Series-wound DC motor PEV powertrain



Equivalent Circuit of a Series Excited DC Motor

Design-3: Series-wound DC motor PEV powertrain

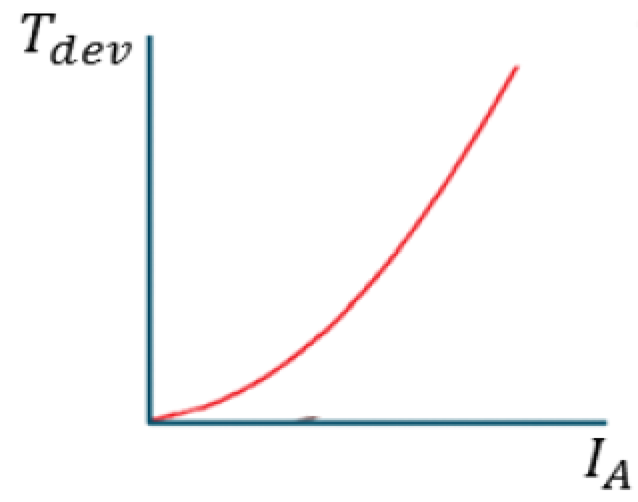
- ✓ The design uses the same vehicle structure, battery type, and motor power and voltage ratings. However the excitation of the motor will be series-wound.
- ✓ Speed control method also is either through supply voltage control or armature/field resistance control.
- ✓ PID control for speed control is much more complicated since the speed is inversely proportional to the square root of the torque which presents non-linearity in the dynamic equation.

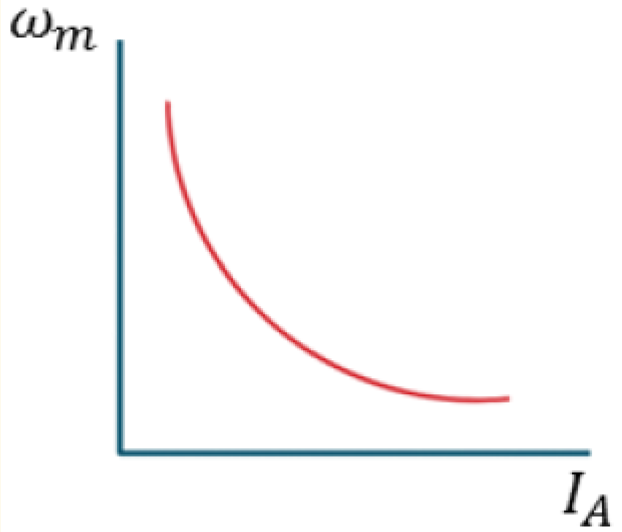
$$T_{dev} = KcI_A^2$$

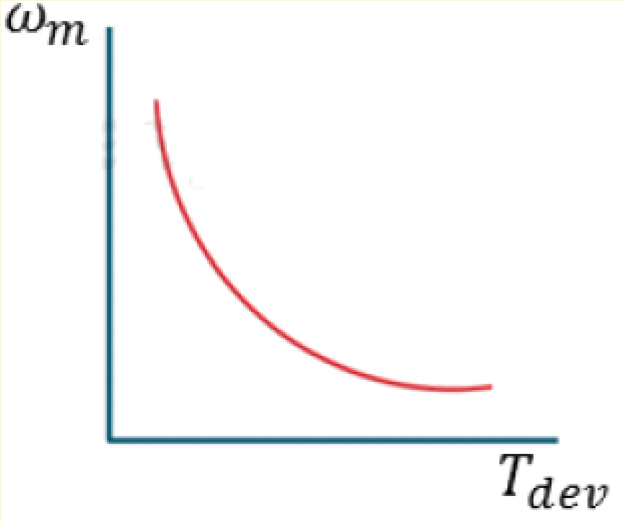
$$T_{dev} = KcI_A^2 \quad \ggg \quad I_A = \frac{\sqrt{T_{dev}}}{\sqrt{Kc}} \quad \ggg \quad \omega_m = \frac{V_s}{\sqrt{Kc}\sqrt{T_{dev}}} - \frac{(R_A+R_s)}{Kc}$$

Design-3: Series-wound DC motor PEV powertrain

- ✓ The speed is inversely proportional to the armature current as shown in the speed-armature current curve.
- ✓ When armature current is very small the speed becomes dangerously high. That is why a series motor should never be started without some mechanical load.

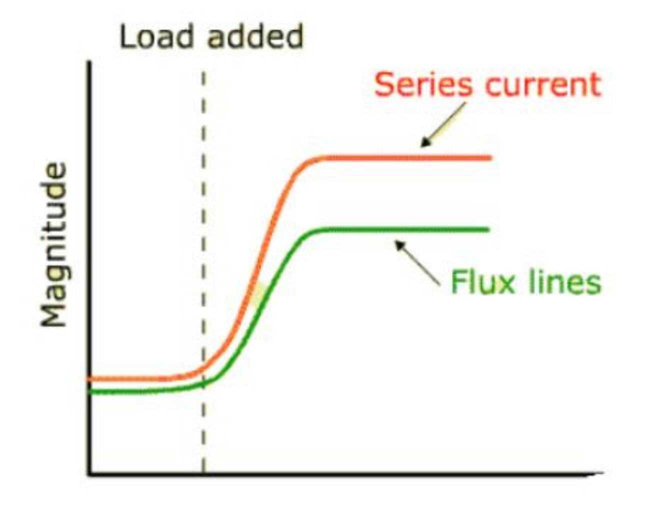






Design-3: Series-wound DC motor PEV powertrain

- ✓ Good for high startup torque application.
- ✓ Bad for accurate speed control.
- ✓ As the motor is loaded, the speed decreases, which causes back EMF to decrease and both the armature and the field current will increase. But the current eventually becomes high enough which causes saturation of the magnetic field.
- ✓ The flux between the armature and stator won’t be able to keep up and thus the motor won’t be able to produce enough torque to bring the speed back to its desired value.



Assessment of Design Concepts

Objectives Design	Safety 40%	Accuracy and Reliability 25%	Ease of Build 15%	Low Power Consumption 10%	Low Cost 10%	Score
Design #1: PMDC motor PEV	1 40%	1 25%	1 15%	0.9 9%	0.7 7%	**96%**
Design #2: SepEx motor PEV	0.9 36%	0.9 22.5%	0.5 7.5%	0.6 6%	0.9 9%	81%
Design #3: Series-wound motor PEV	0.5 20%	0.5 12.5%	0.8 12%	0.5 5%	0.9 9%	58.5%

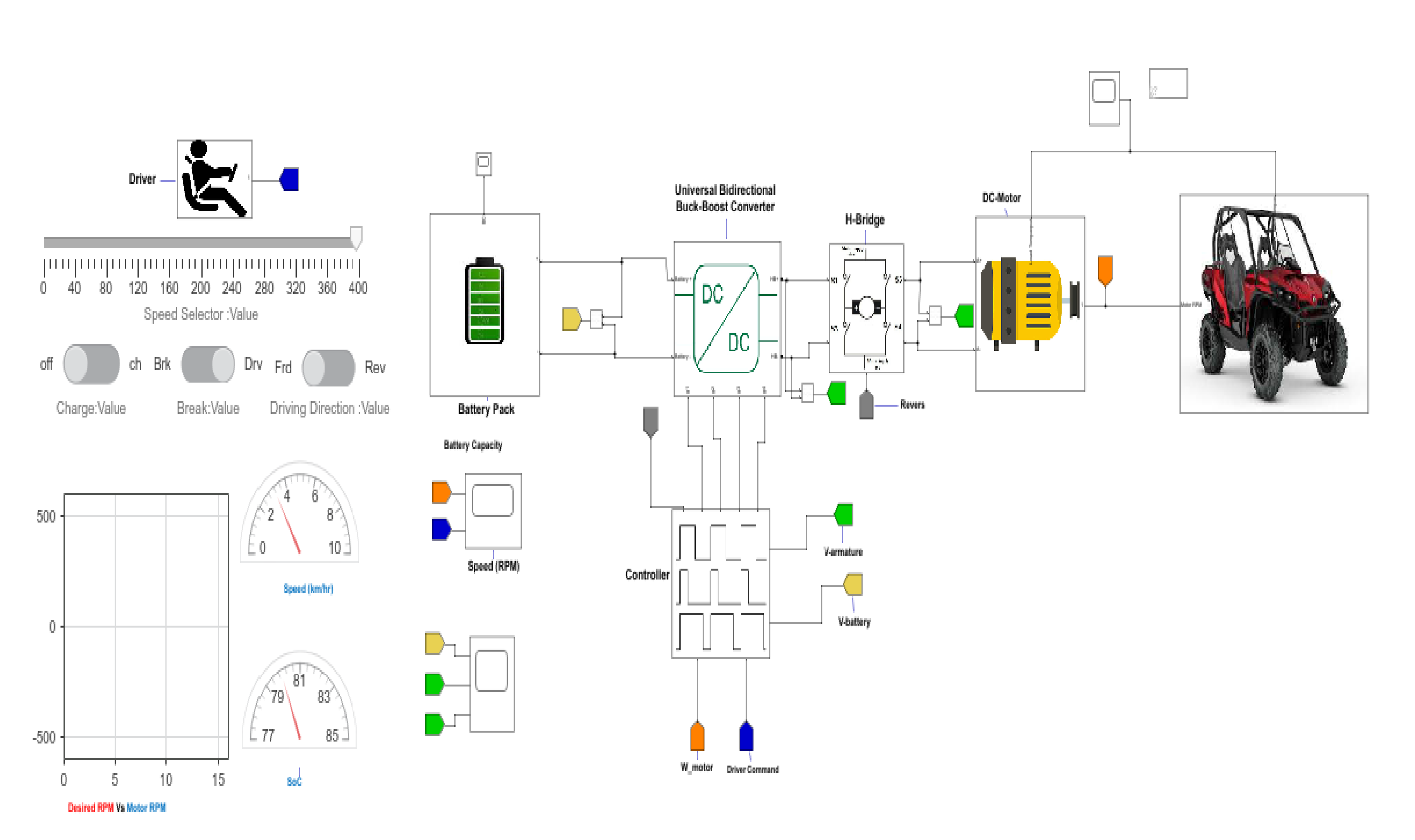
Implementation

Simulation and Testing

Design Simulation

PEV with a permanent Magnet DC motor

- **Components**
  - Car body
  - Motor
  - Motor controller
    - DC-DC converter
    - Converter Controller
    - H-Bridge
  - Battery block
    - battery pack
    - battery charger
  - Driver block



Design Simulation

PEV with a permanent Magnet DC motor

Car body

-200 kg, go kart was assumed for the simulation &

- Simulink model that represents all the resistive forces such as aerodynamic drag, gradient force , rolling resistance etc was built and the corresponding toque was used to as a load input for the motor

Design Simulation

PEV with a permanent Magnet DC motor

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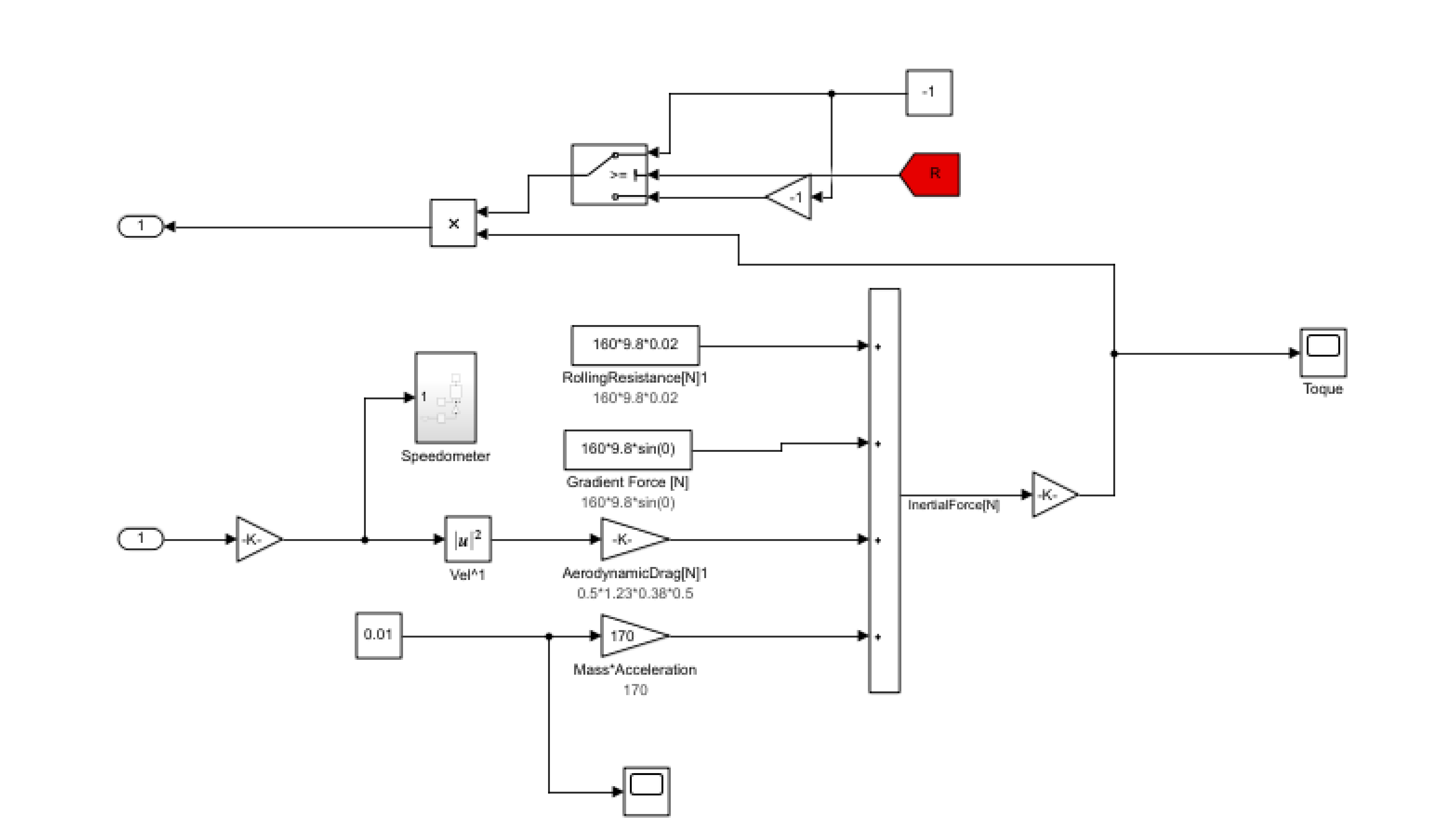
- Simulink model that represents all the resistive forces such as aerodynamic drag, gradient force , rolling resistance etc was built and the corresponding toque was used to as a load input for the motor

- A Simscape multibody block that represents the kart was also constructed to visualize the kart motion



Go Kart Vehicle Body [surce: google images]

Design Simulation

PEV with a permanent Magnet DC motor

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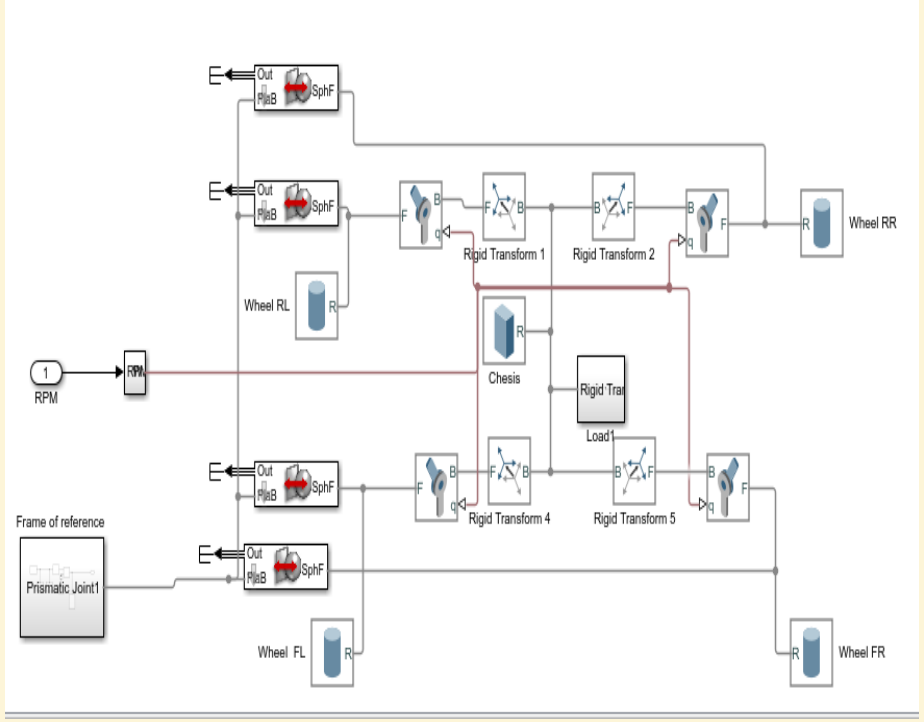
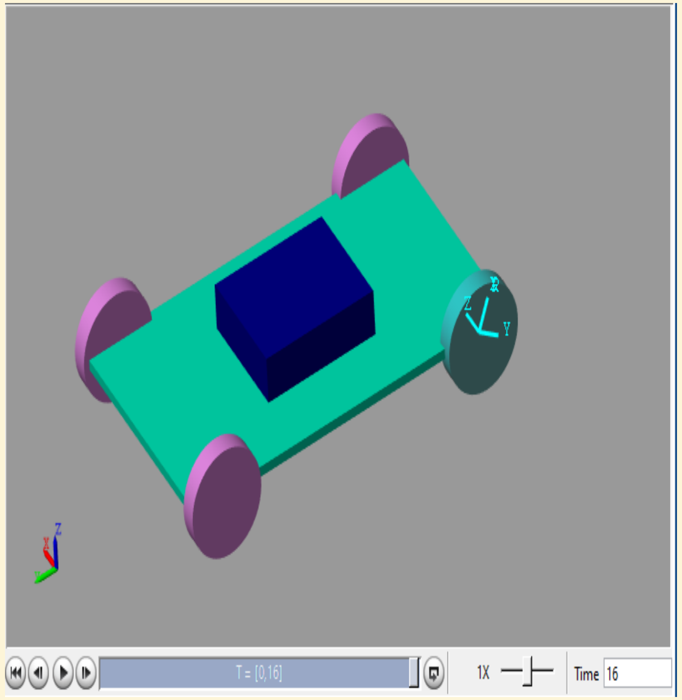




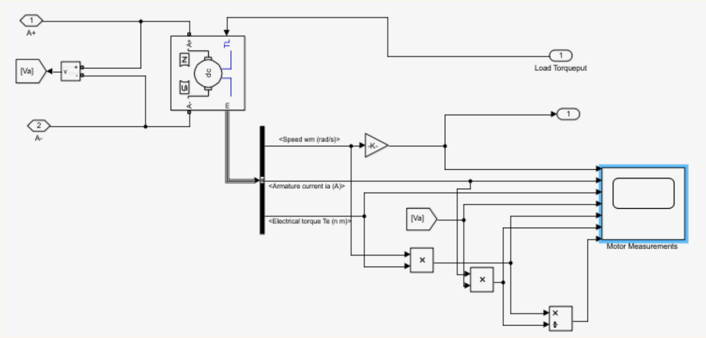
Go Kart Vehicle Body [surce: google images]

Design Simulation

PEV with a permanent Magnet DC motor

Motor

- based on the kart dynamic calculations , a 3kW, 48V brushed PMDC motor was required, but due to delivery issues we could only get 48 V, 1 kw PMDC motor



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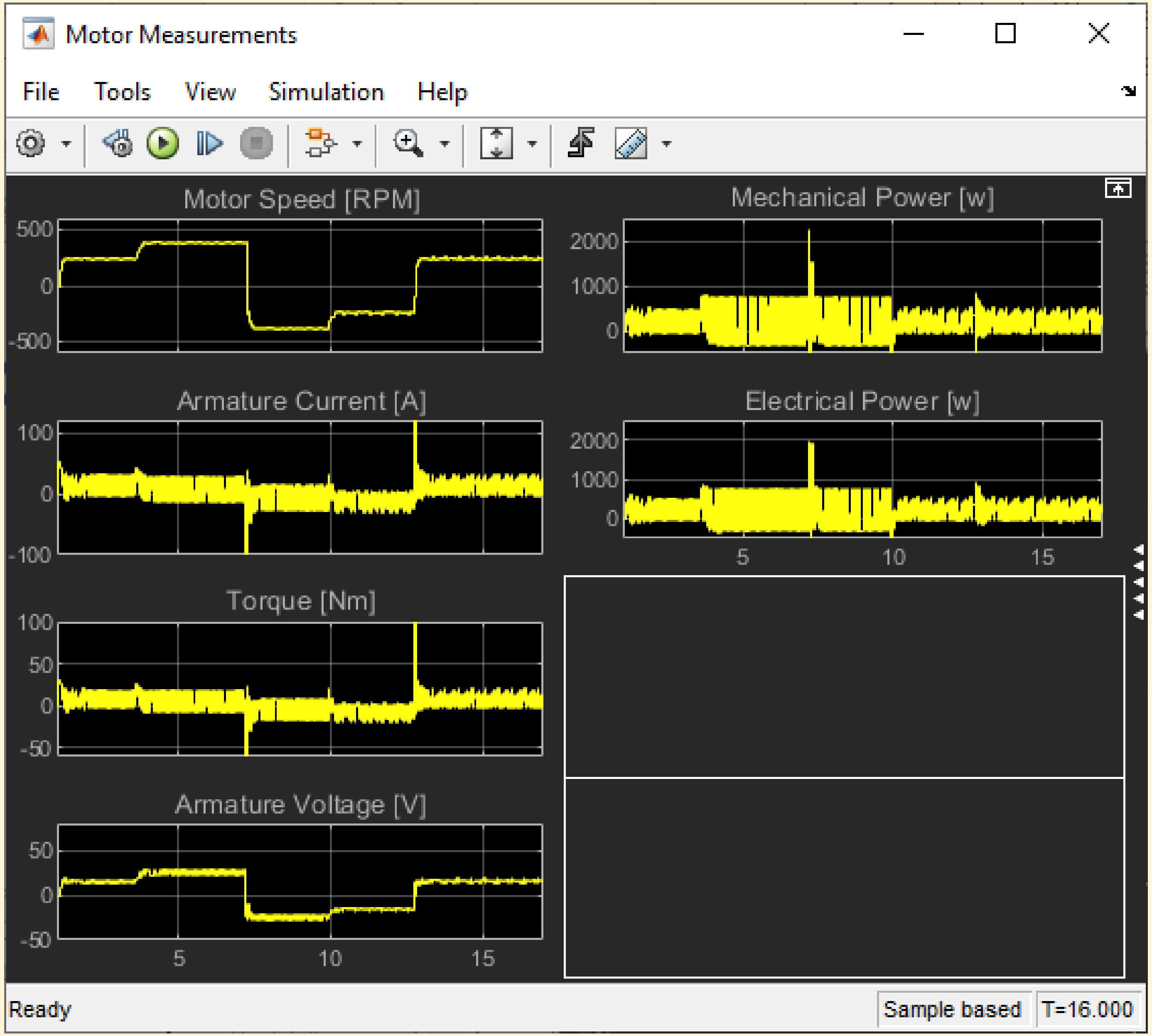


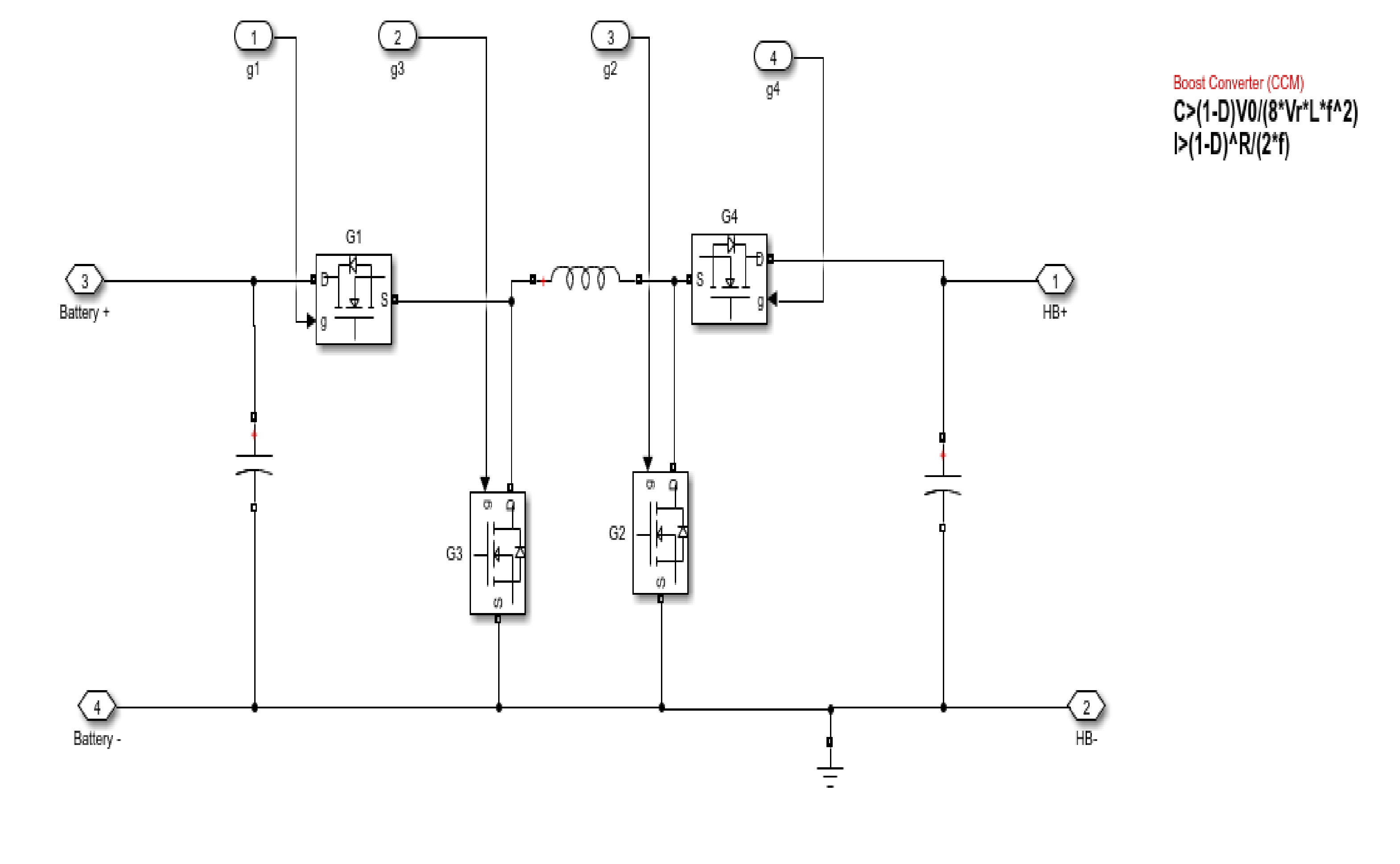
Motor Simulation Result under full load

Design Simulation

PEV with a permanent Magnet DC motor

Motor Speed controller DC-DC Converter

- Non-Isolated Universal Bidirectional Cascaded DC-DC converter was used
- It Provides Easy Voltage control It's controlled using PWM signal, which can be generated easily, and it's well studied
- Has four modes of operation



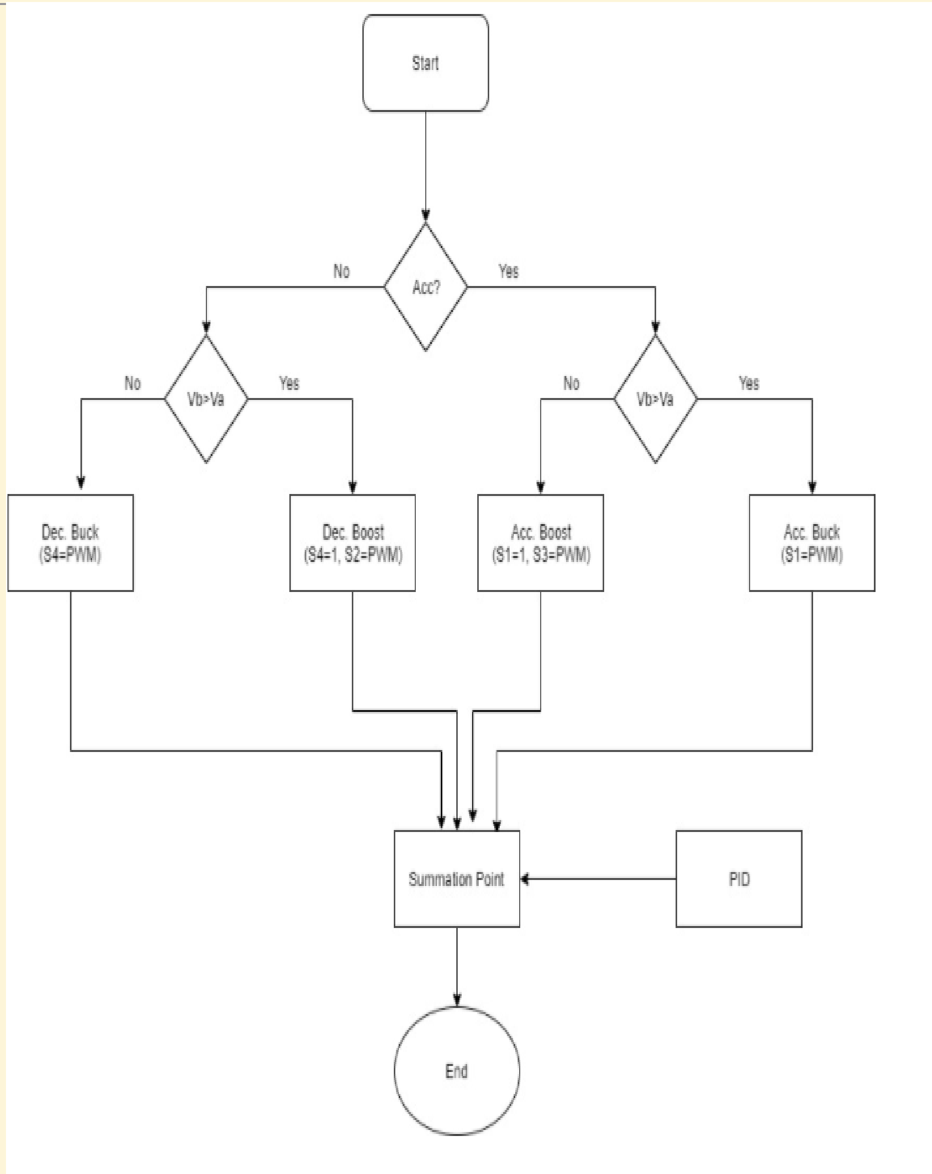
Converter Circuit Diagram

Design Simulation

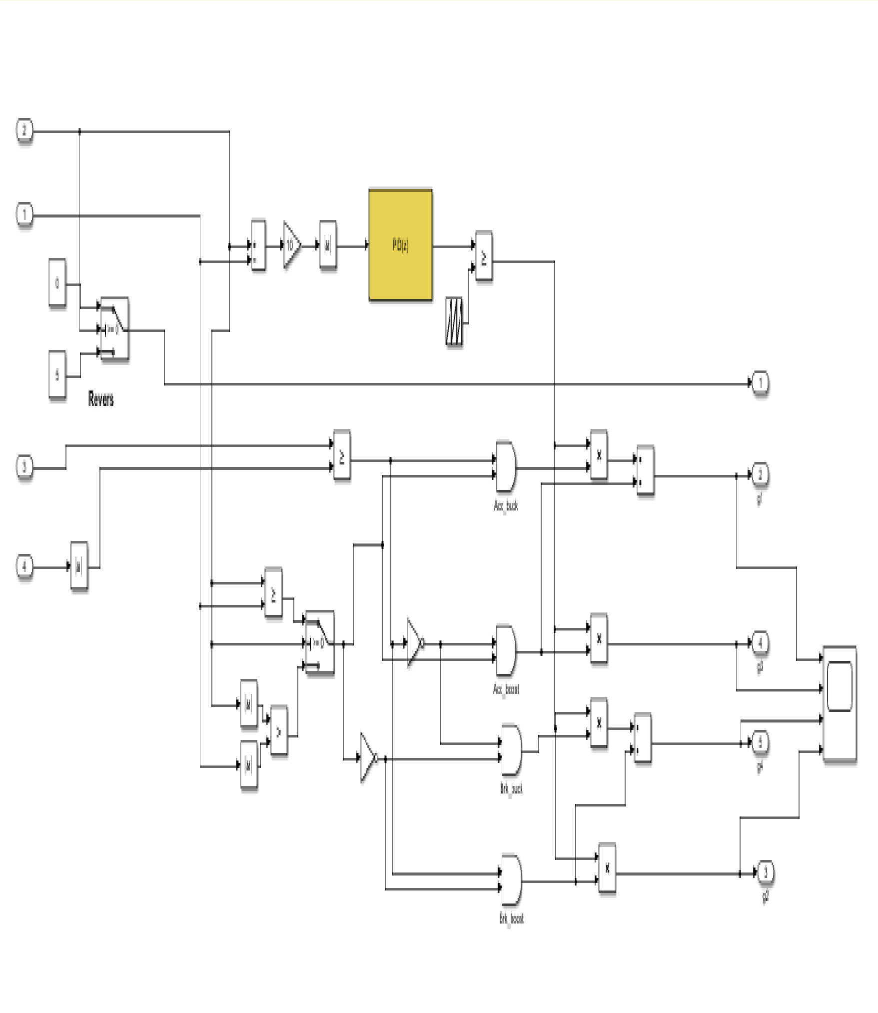
PEV with a permanent Magnet DC motor

Converter Control

- Modes of operation are based on the converter control algorism
- PID controller is used to generate PWM signal and control its duty cycle for every mode of operation



Control algorism



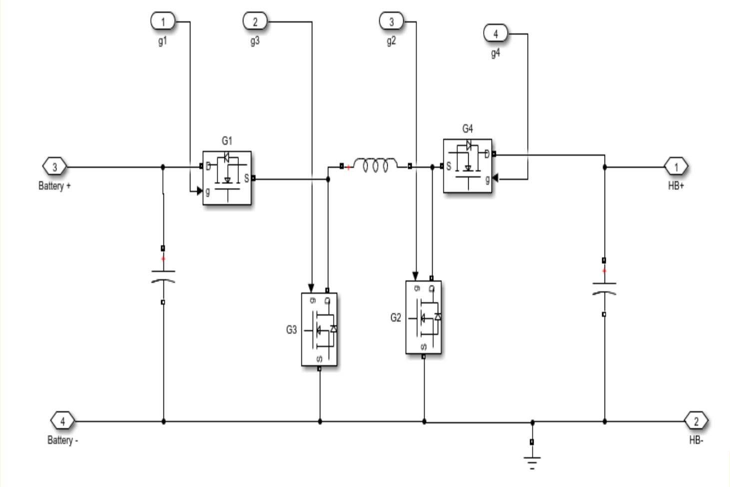
Controller Circuit Diagram

Design Simulation

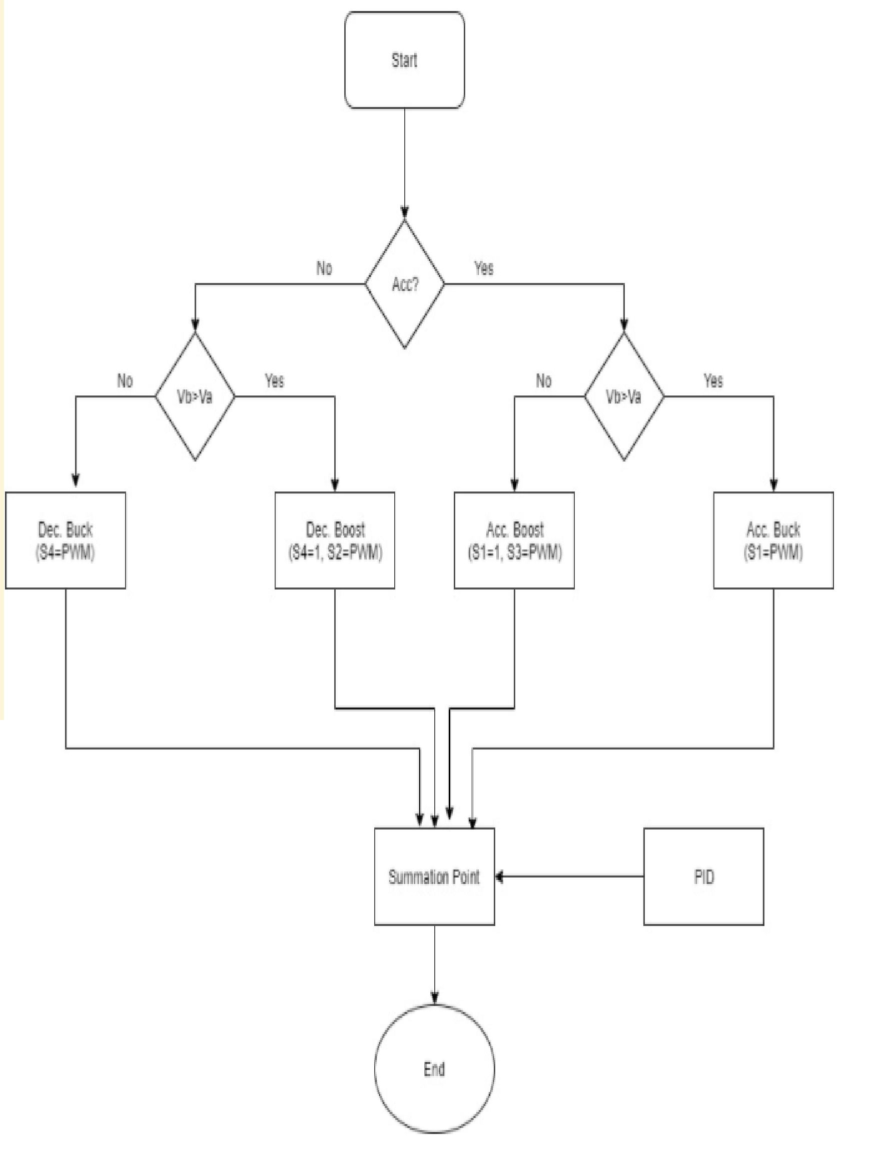
PEV with a permanent Magnet DC motor

Modes of Operation

- Acc. Buck
- Acc. Boost
- Brk Boost
- Brk Buck Mode



Buck Boost Converter



Control algorism

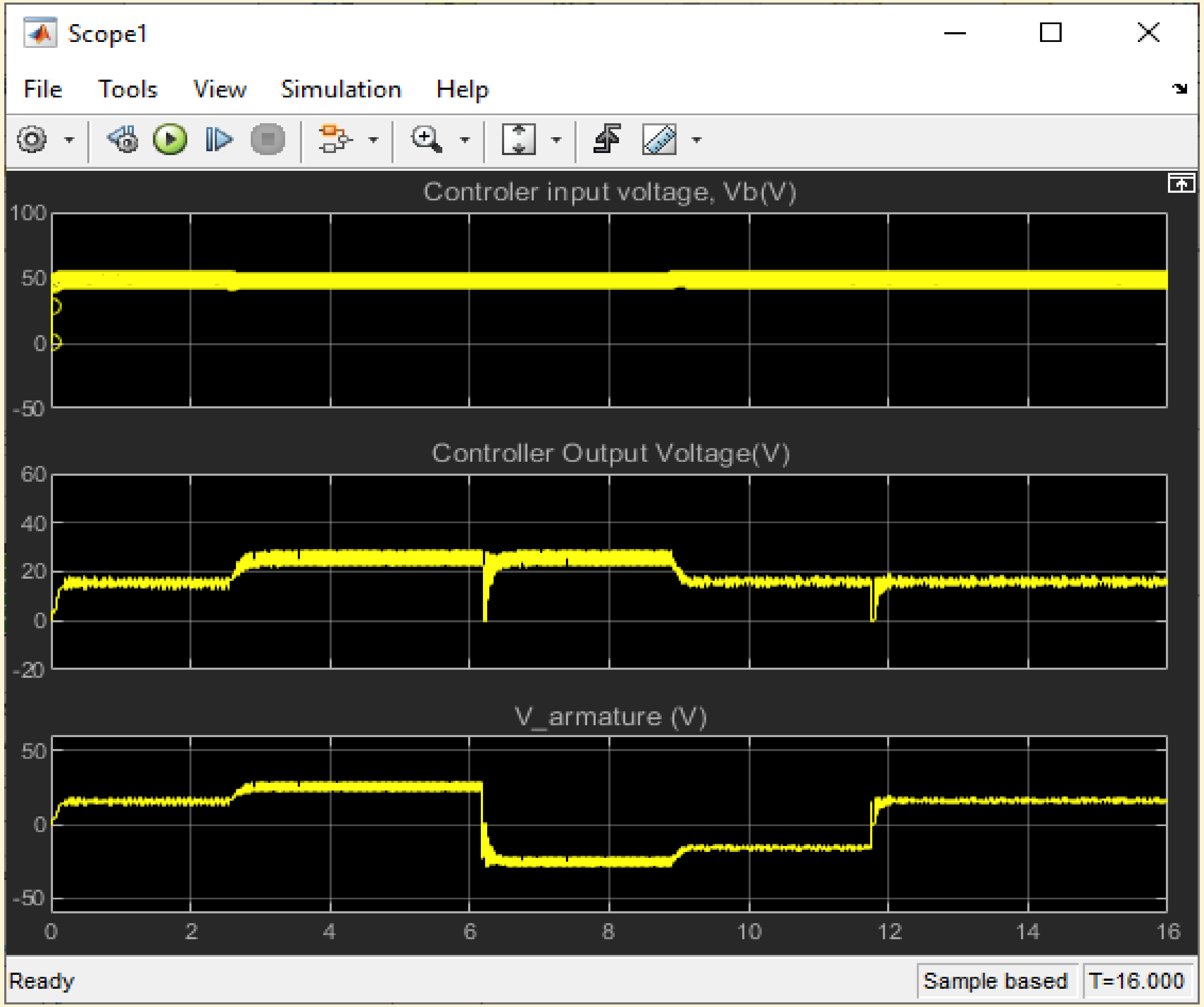
	Condition	G1	G2	G3	G4
Acc. buck mode	Wrf>Wm Vi>Vo	PWM	0	0	0
Acc. boost mode	Wrf>Wm Vi<Vo	1	PWM	0	0
Break boost mode	Wrf<Wm Vi>Vo	0	0	PWM	1
Break buck mode	Wrf<Wm Vi<Vo	0	0	0	PWM

Design Simulation

PEV with a permanent Magnet DC motor

Converter Simulation results

- Converter input/output voltages
- Converter Gate Control signals



Controller input/output Simulation results

Design Simulation

PEV with a permanent Magnet DC motor

Converter Simulation results

- Converter Gate Control signals
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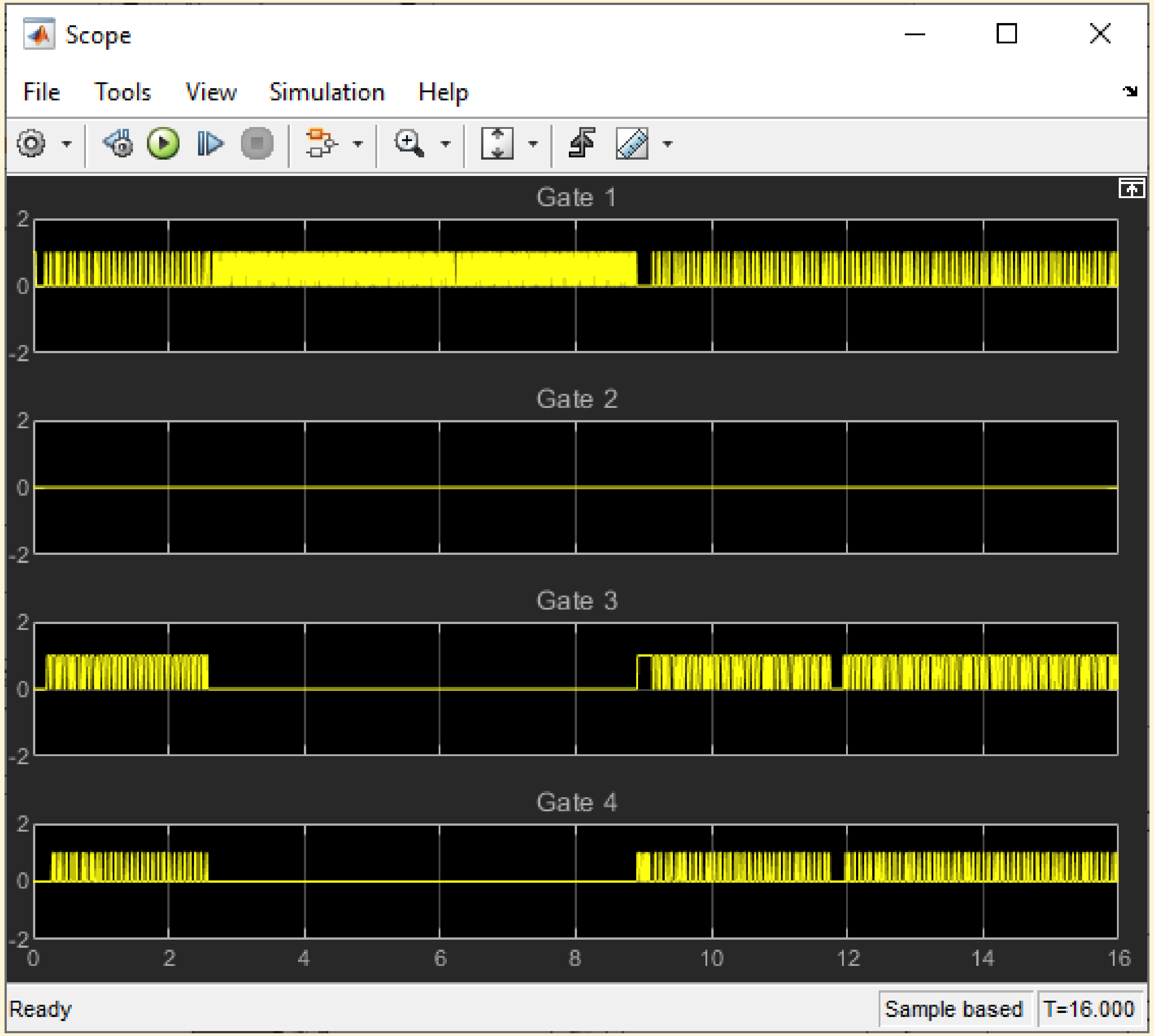
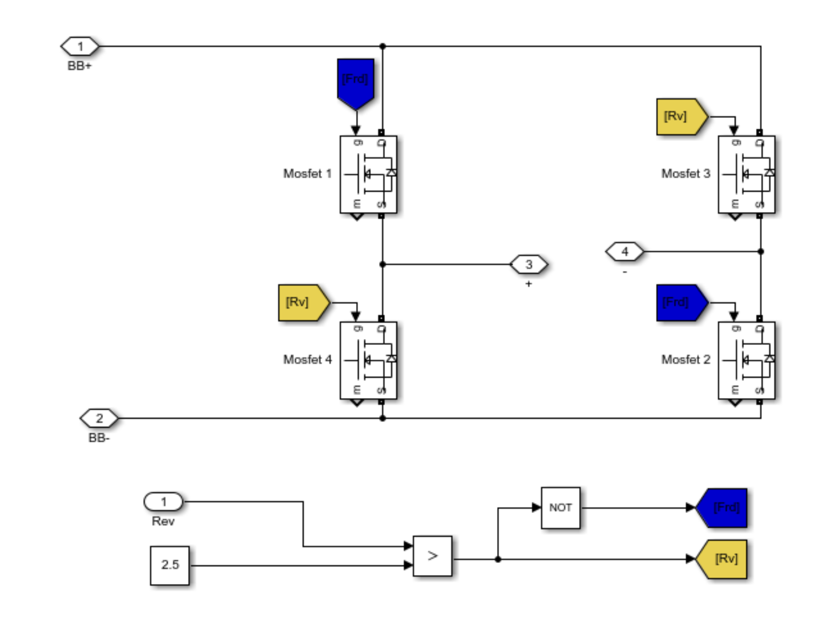


PWM Gate Signals

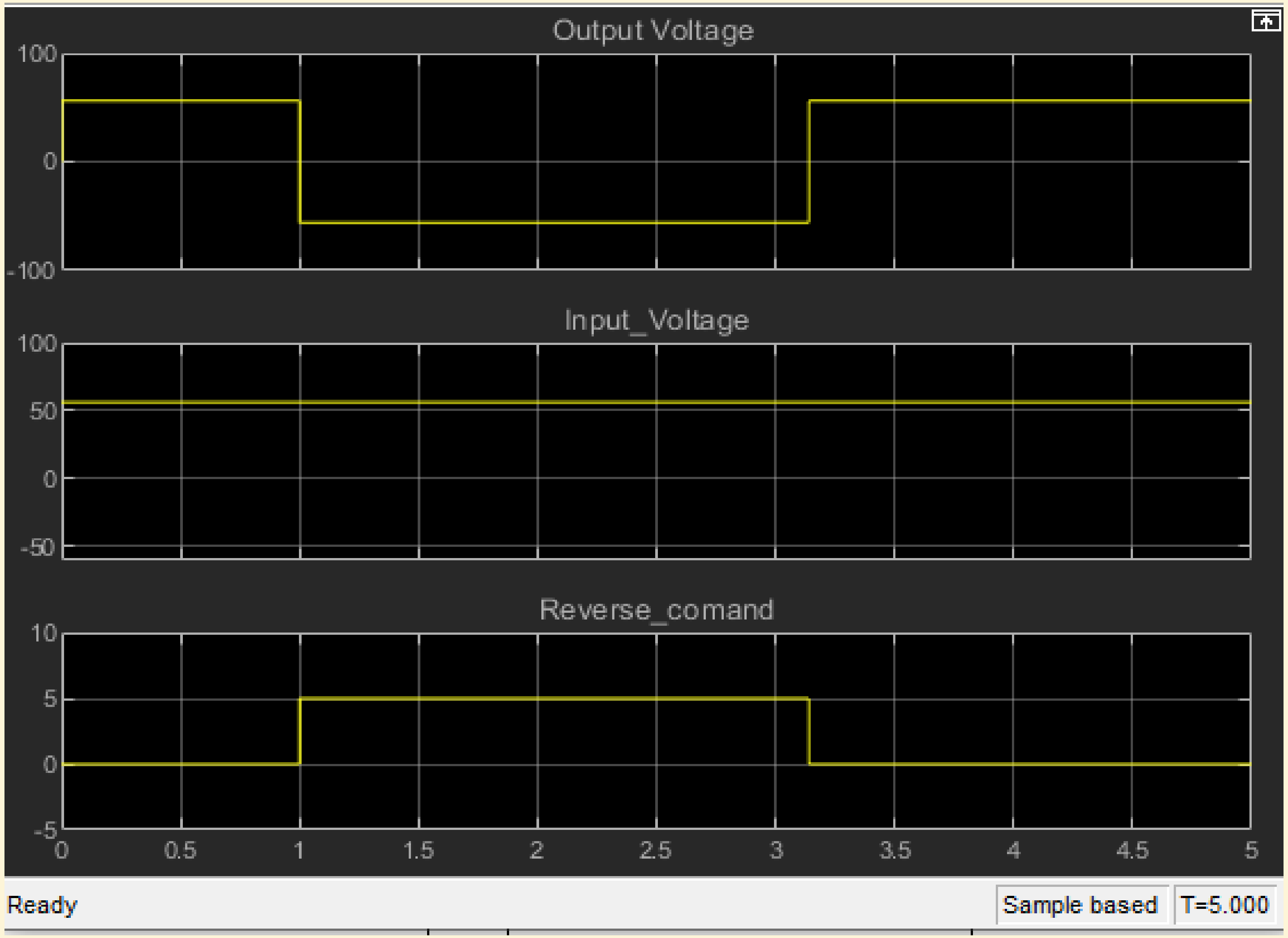
Design Simulation

PEV with a permanent Magnet DC motor

H-Bridge



H-Bridge Circuit Diagram



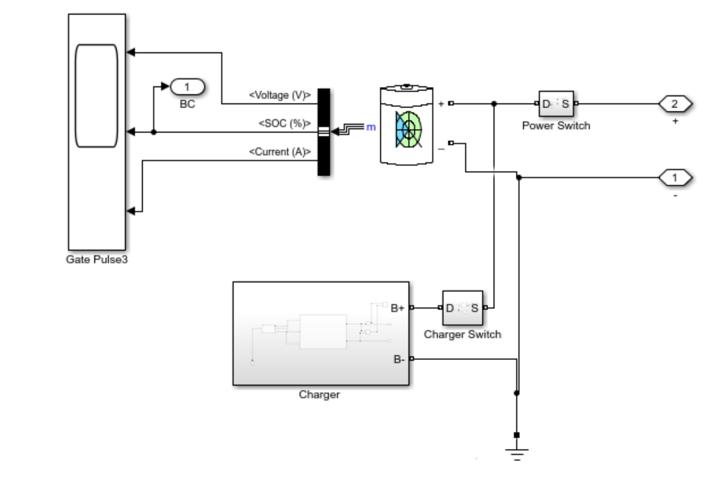
H-Bridge Simulation Result

Design Simulation

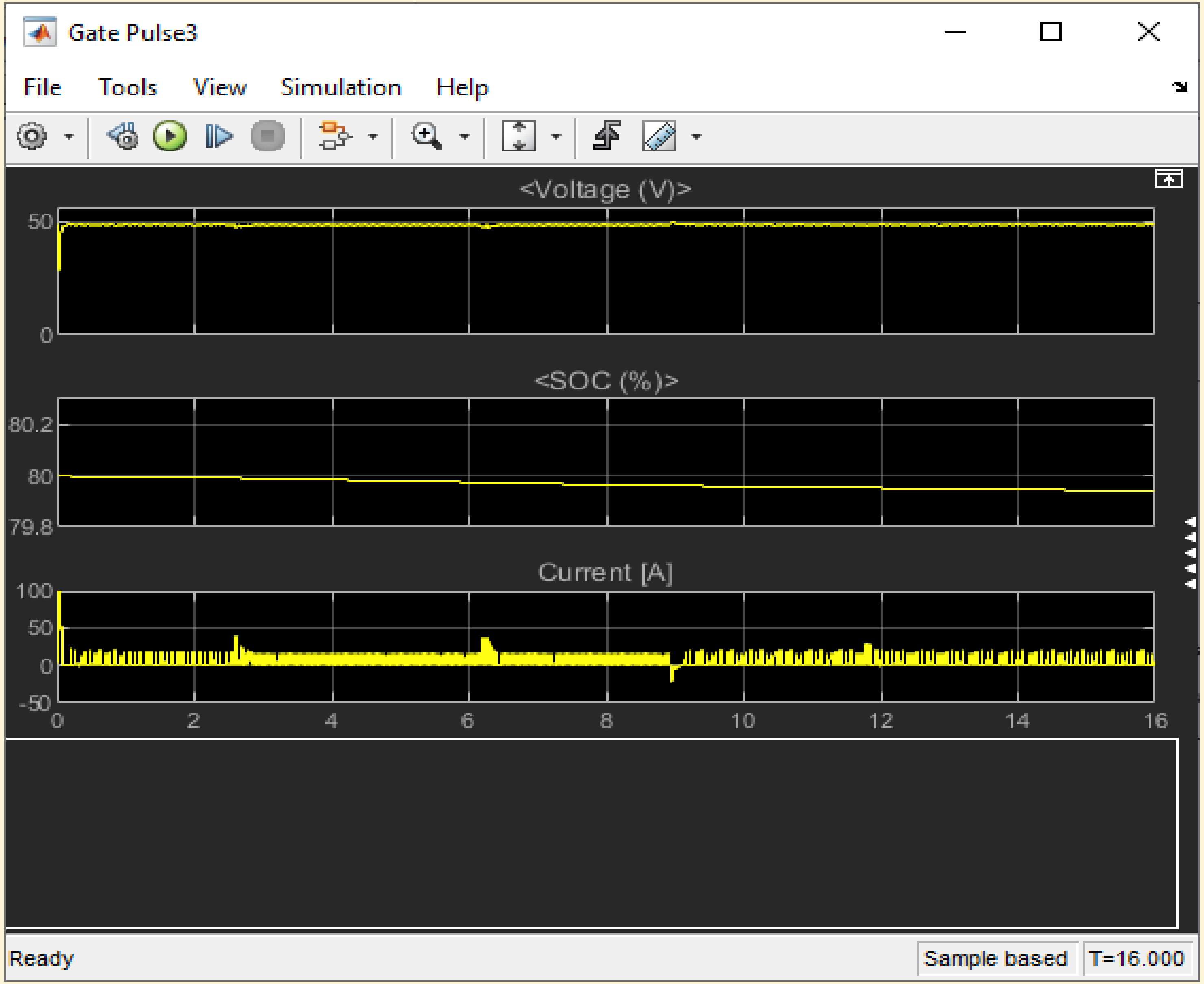
PEV with a permanent Magnet DC motor

Battery Block: Battery Pack

- 4 , 12V , 26 AH lead acid batteries connected in series were used



Battery block



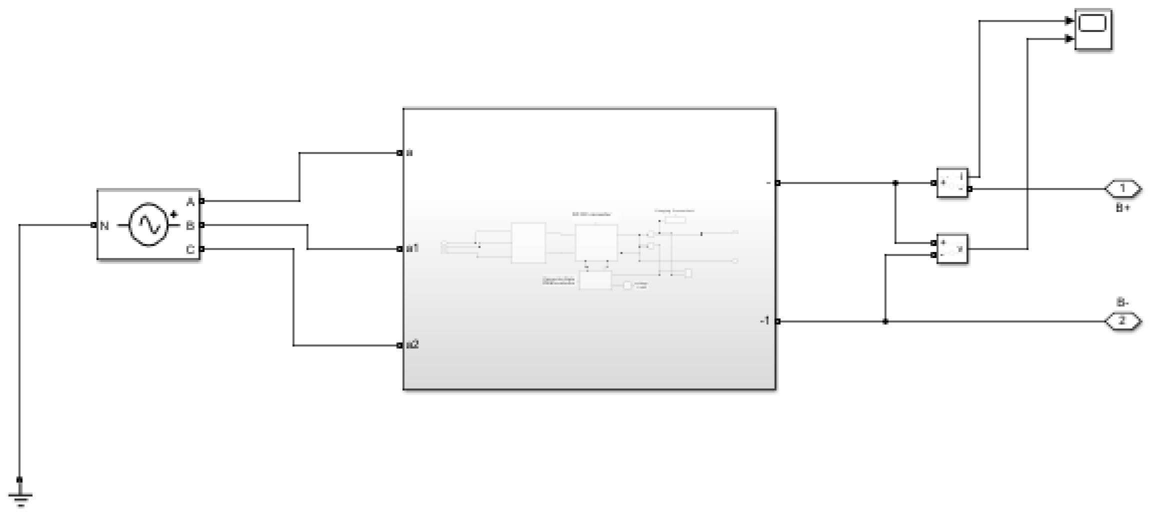
Simulation Results

Design Simulation

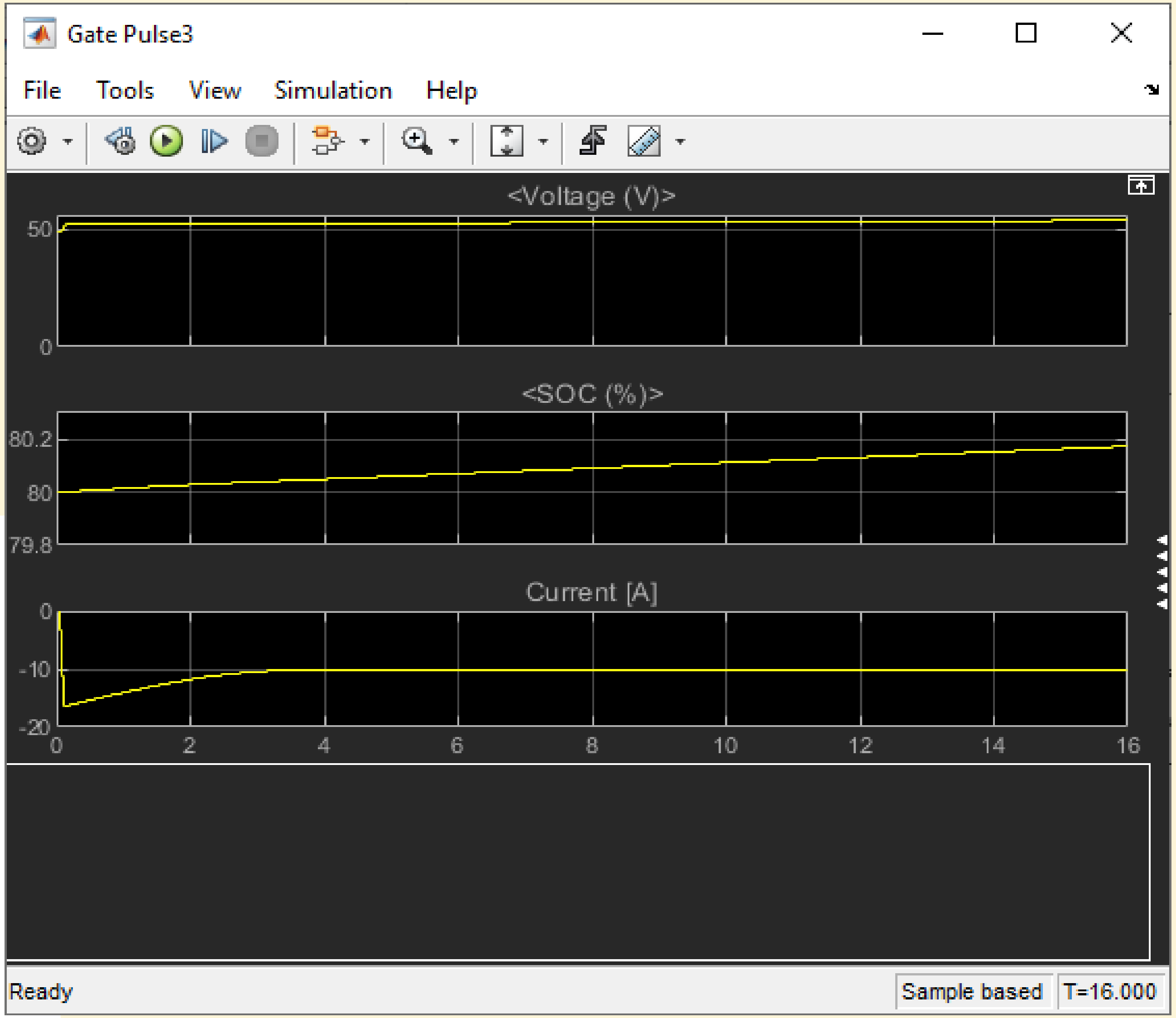
PEV with a permanent Magnet DC motor

Battery Block: Battery Charger

- 60 V, 10 A , battery charger



Battery block



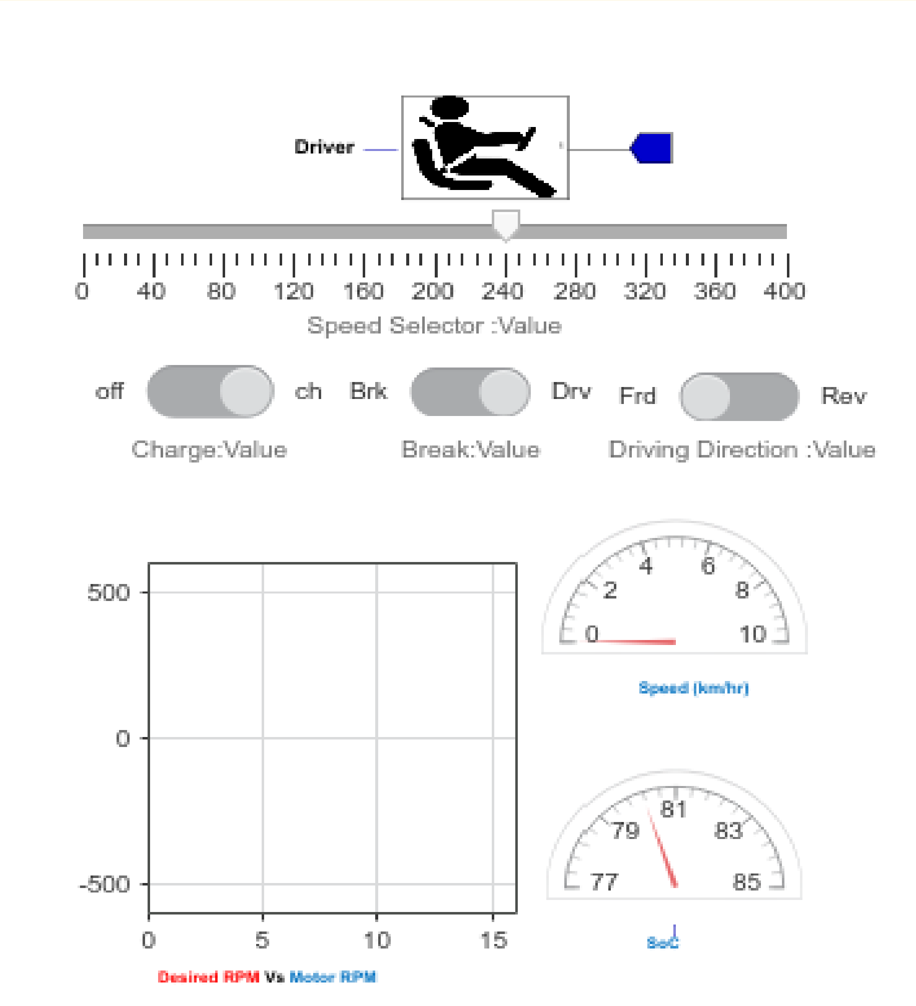
Simulation Results

Design Simulation

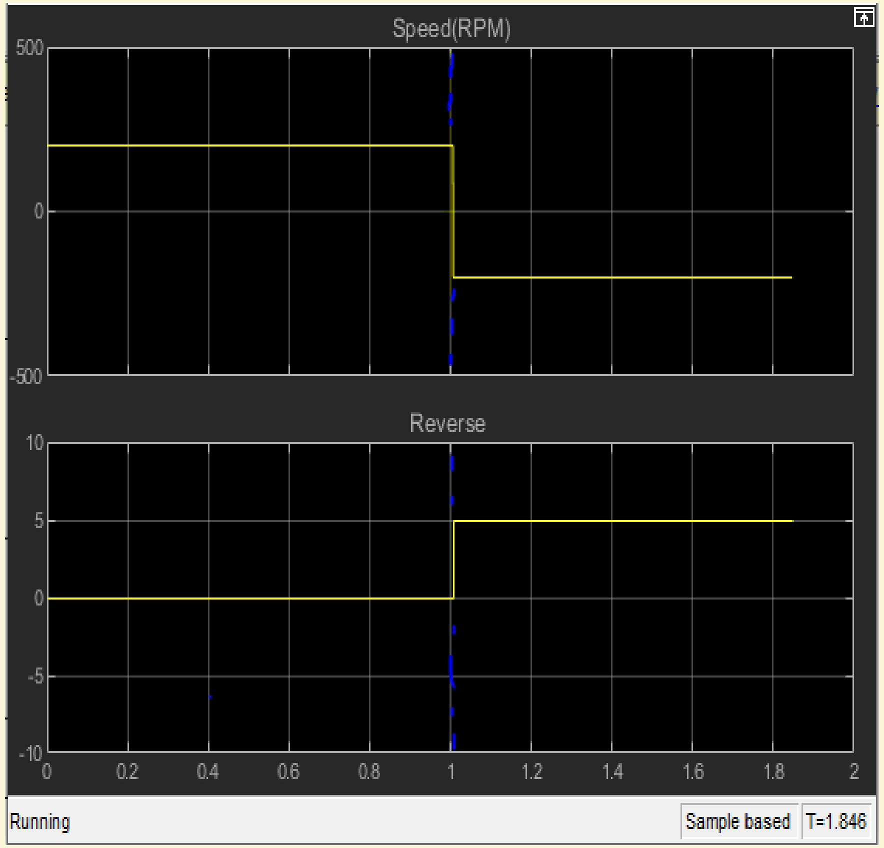
PEV with a permanent Magnet DC motor

Driver Block

- Speed , driving direction charge & break command



Driver Dashboard



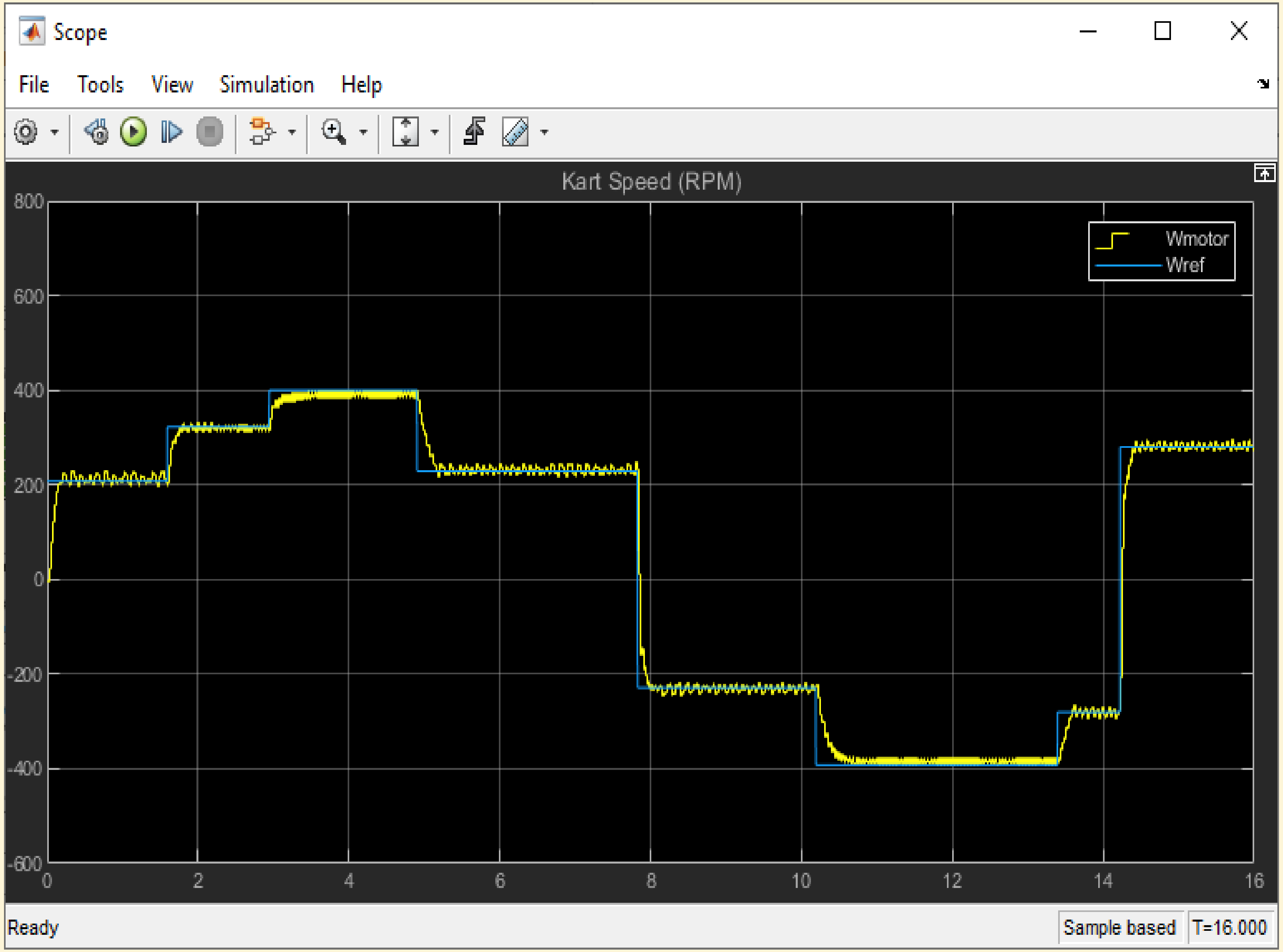
Simulation Result

Design Simulation

PEV with a permanent Magnet DC motor

Speed Control Result

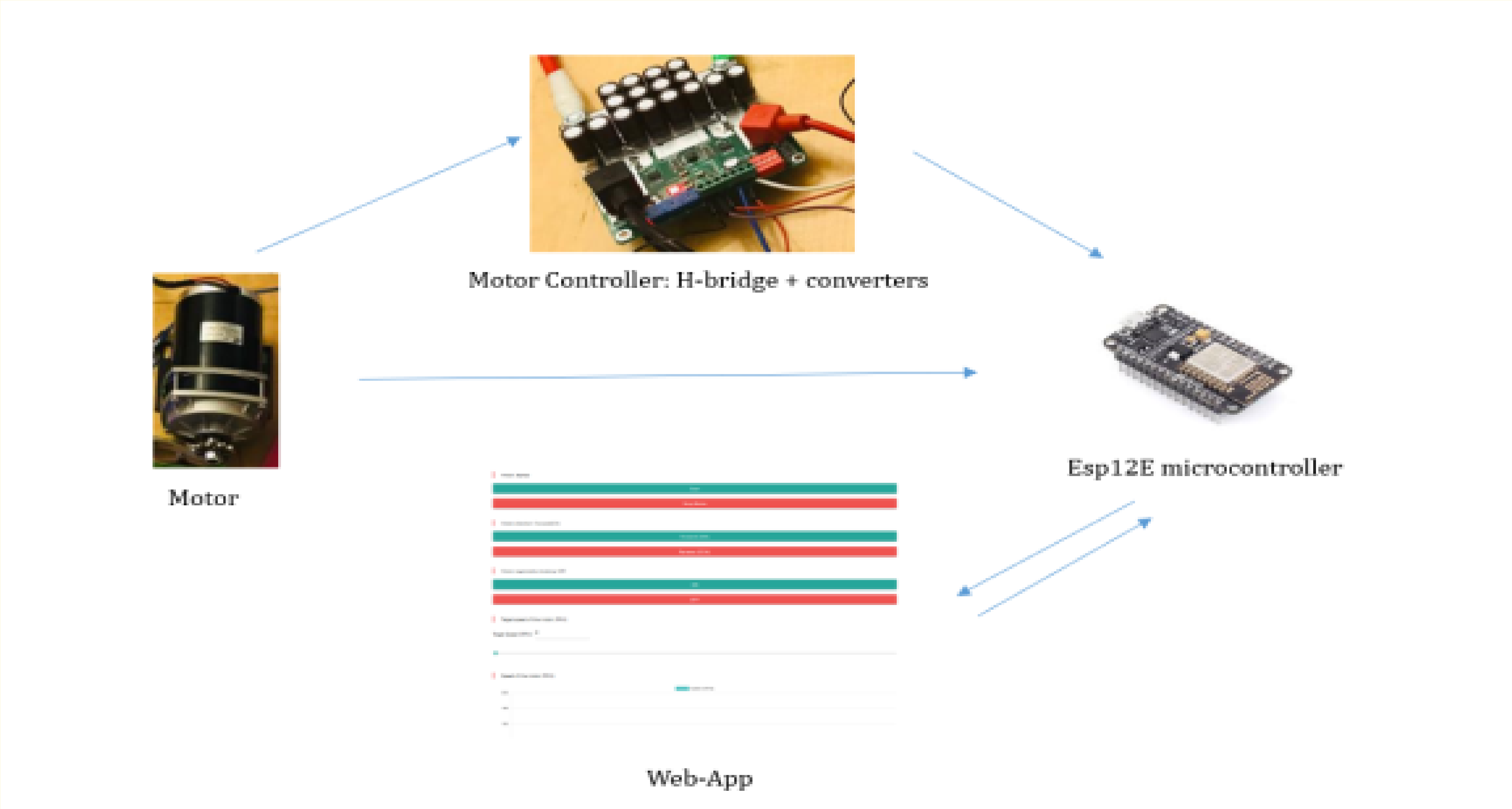
- Speed was Controlled almost as required



Implementation

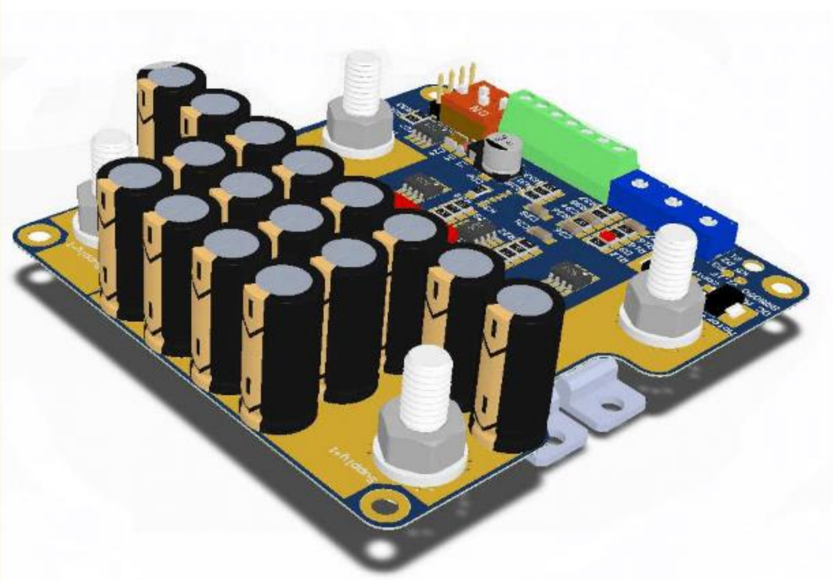
Prototype and Testing

Overall View of the Control mechanism



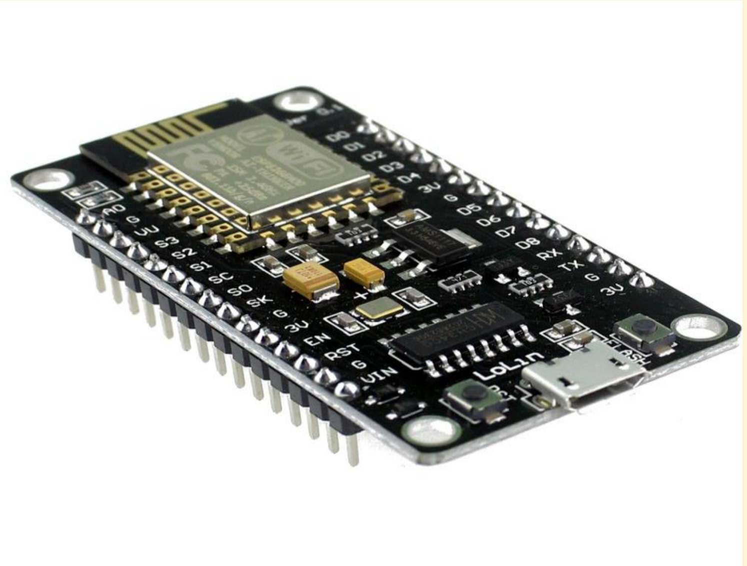
The motor Controller

- 60 V 100A max., 50A continuous current
- H-bridge + Converters (Power Electronics)
- H-bridge: introduces direction change capabilities
- Segregates High-Voltage System from Low-Voltage System



Esp12E - NodeMCU microcontroller

- Microcontroller with built-in Wi-Fi capabilities
- Bigger memory storage than Arduino Uno but fewer analog and digital pins than Arduino Uno.
- Outputs 3.3V.
- All computation takes place here.

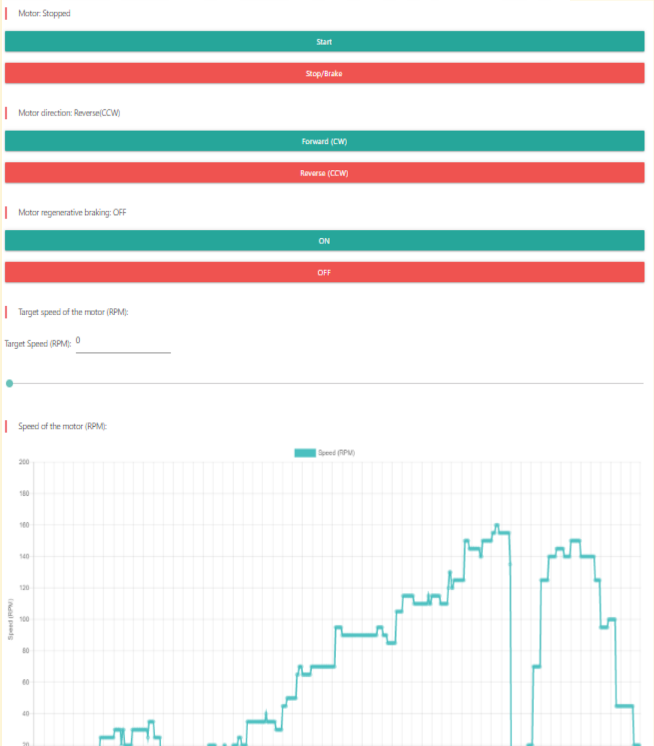


The Hall-Effect Sensor

- Applies Hall-Effect principle: magnets passes near and it triggers the sensor
- Made for smaller motors thus has low resolution which isn't reliable for our project.
- Attached magnets to the rotor by ourselves and couldn't use enough because of interference.

The Web-App

- An app to control the speed of the motor via Wi-Fi.
- Has motor enable, an direction control buttons.
- It also has a slider to control the speed with a text box right above it to control it via input text
- Graphs the real-time speed of the motor



Main Code Functions

- Small, concise, and reusable code structure followed
- The main functions of the code are the following:

The Timer

- Sets timer for an timer overflow interrupt to take place.
- Gives the interrupt a priority.
- Esp12E is capable of providing a hardware timer interrupt but Wi-Fi function was used at the same time which may result in conflict in timing. Thus software interrupt was chosen.

```
/********************************Timer Interrupt Code****************************************/

void user_init(void) {

  os_timer_setfn(&myTimer, Timer_ISR, NULL);      // os_timer_setfn - Define a function to be called when the timer fires

  os_timer_arm(&myTimer, 1000, true);     // Enable a millisecond granularity timer

} // End of user_init
```

The Encoder Interrupt Code

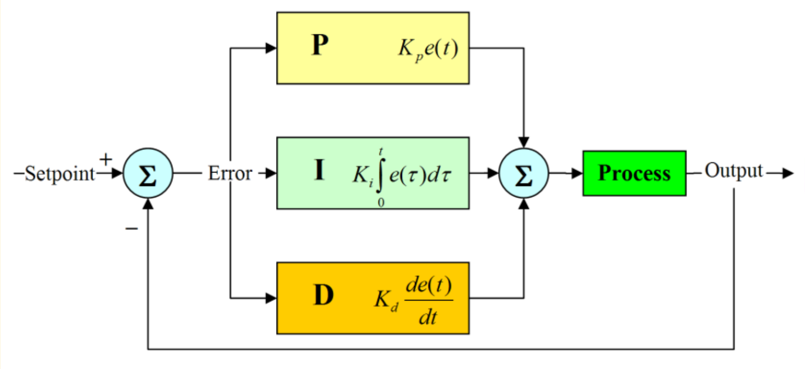
- Voltage pulse is detected the moment a magnet runs near the sensor.
- Increases the counter every time the sensor comes in contact with a magnetic field
- This counter will be used to calculate the rpm of the motor as follows:

```
currentSpeed = 60.0 * (encoder / number of sampling magnets used)/Sampling time;
```

```
/*******************************Encoder Interrupt Code*****************************************/

void IRAM_ATTR Encoder_Interrupt() {
  encoder = encoder + 1;                    // increasing encoder at new rising pulse
}//End of Encoder_Interrupt
```

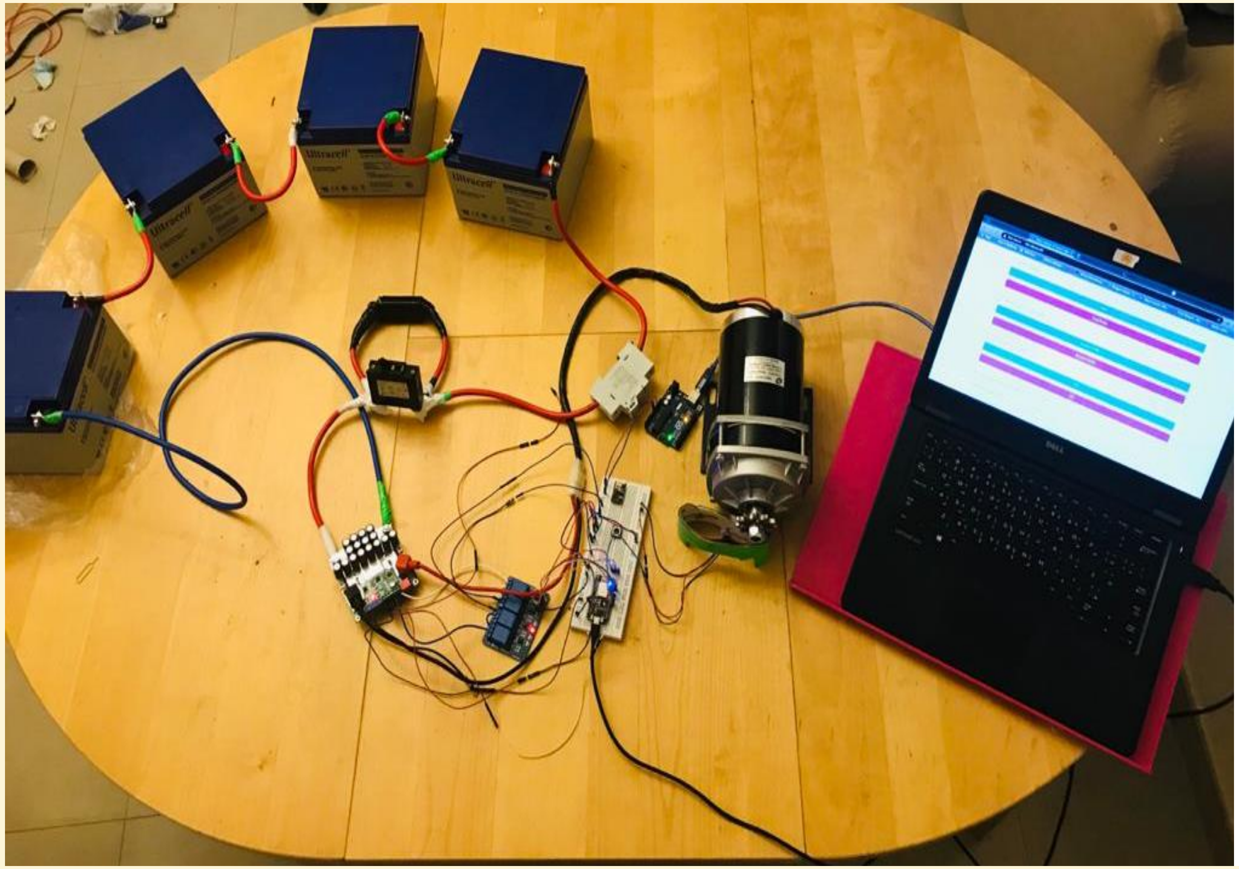
The Digital PID Controller Code

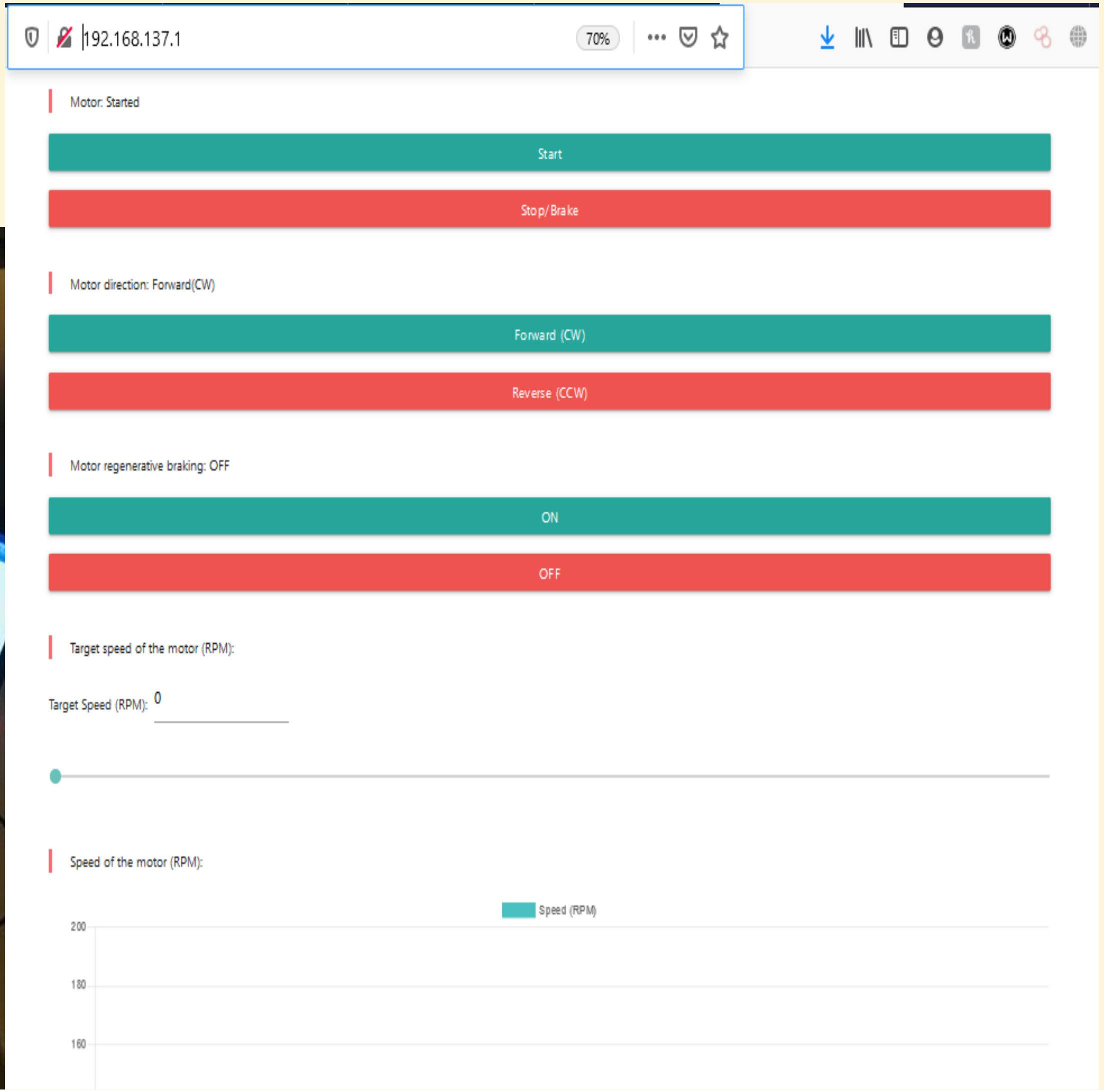
- Stabilize the system.
- Make the system start fast but smooth, eliminates overshoots, and eliminates steady-state errors based on the control parameters.




```
if (MotorStart) {

  /*************************************PID Controller Code*********************************/

     ErrorSpeed = targetSpeed - currentSpeed;
     PWMValue = ErrorSpeed * Kp + ErrorSpeedSum * Ki + (ErrorSpeed - PreErrorSpeed) * Kd;
     PreErrorSpeed = ErrorSpeed;                              //save last (previous) error
     ErrorSpeedSum += ErrorSpeed;                             //sum of error
     if (ErrorSpeedSum > 600) ErrorSpeedSum = 600;
     if (ErrorSpeedSum < -600) ErrorSpeedSum = -600;

 /*******************************************************************************************/

}
else {
  ErrorSpeed = 0;
  PreErrorSpeed = 0;
  ErrorSpeedSum = 0;
  PWMValue = 0;
}
```

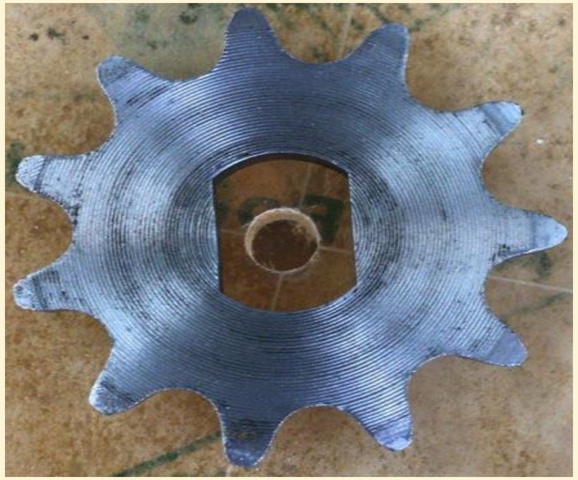
Practical Results





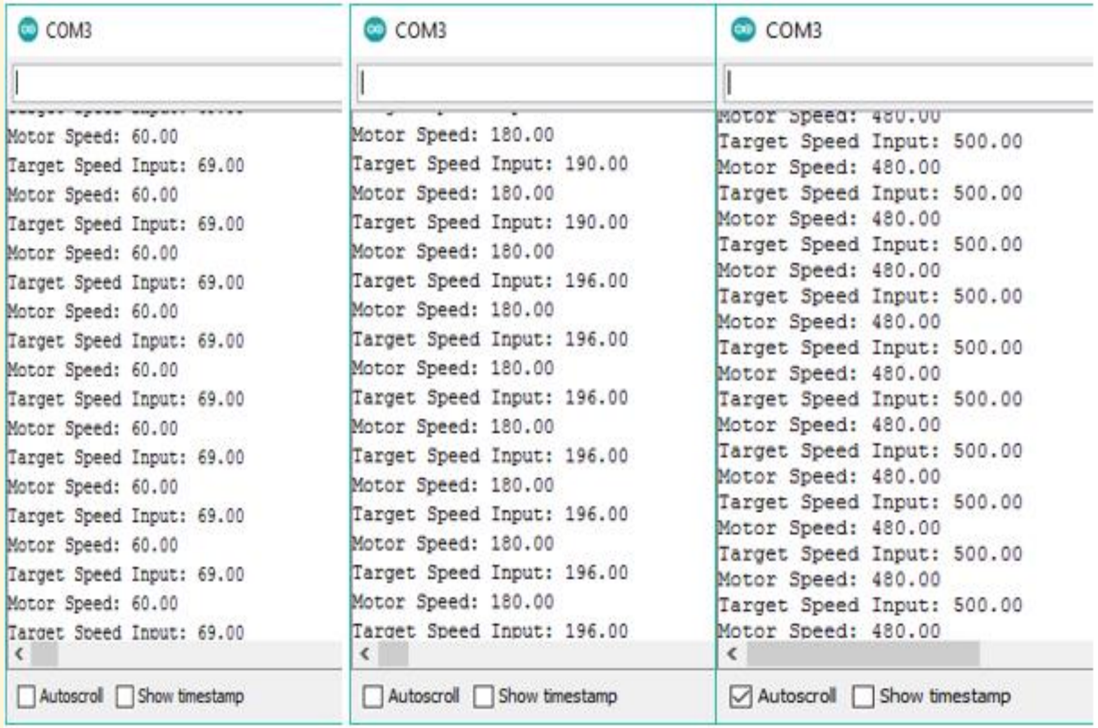
Results Using PID Controller

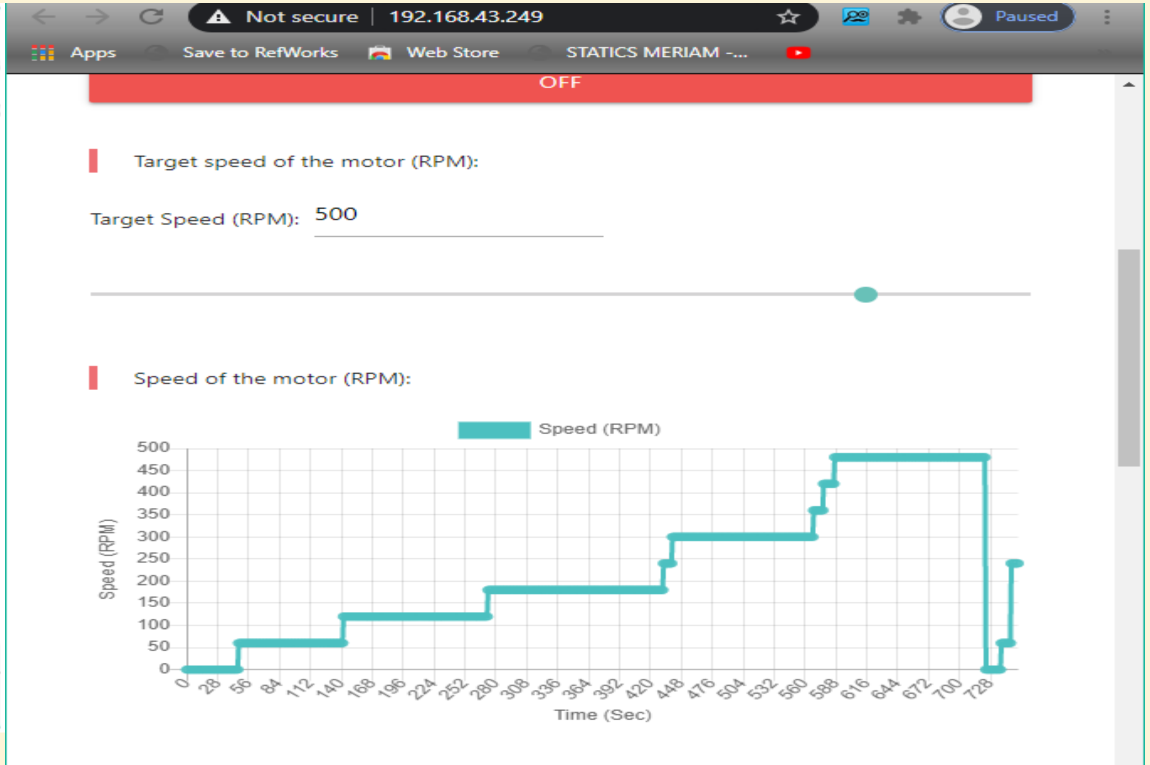
- Resulted into swinging speed control
- Difficult to make the system unstable because the resolution of the sensor we were using was too low for such applications i.e. we were using external magnets and they were too few for the speed resolution.
- Low resolution resulted into big error margin = +- 60



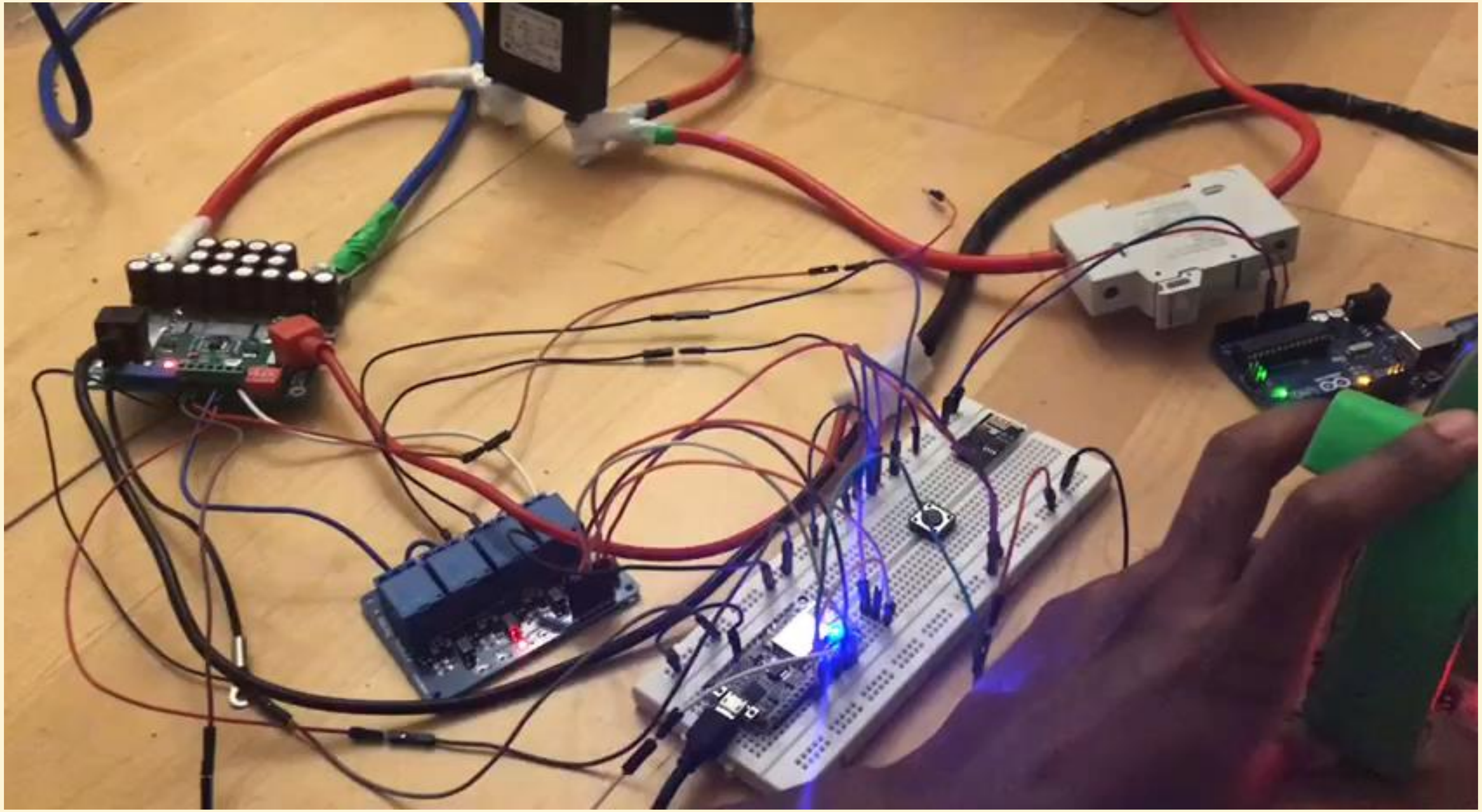
Results of Speed Control using Mapping

- **PWMValue = map (targetSpeed, minSpeed, maxSpeed, minPWM, maxPWM)**
- No feedback control mechanism instead the timer was set into very small intervals of 0.1 second thus this ensured that the motor is fed with the same PWM signal value every timer the target speed is given.
- Not reliable for varying load.

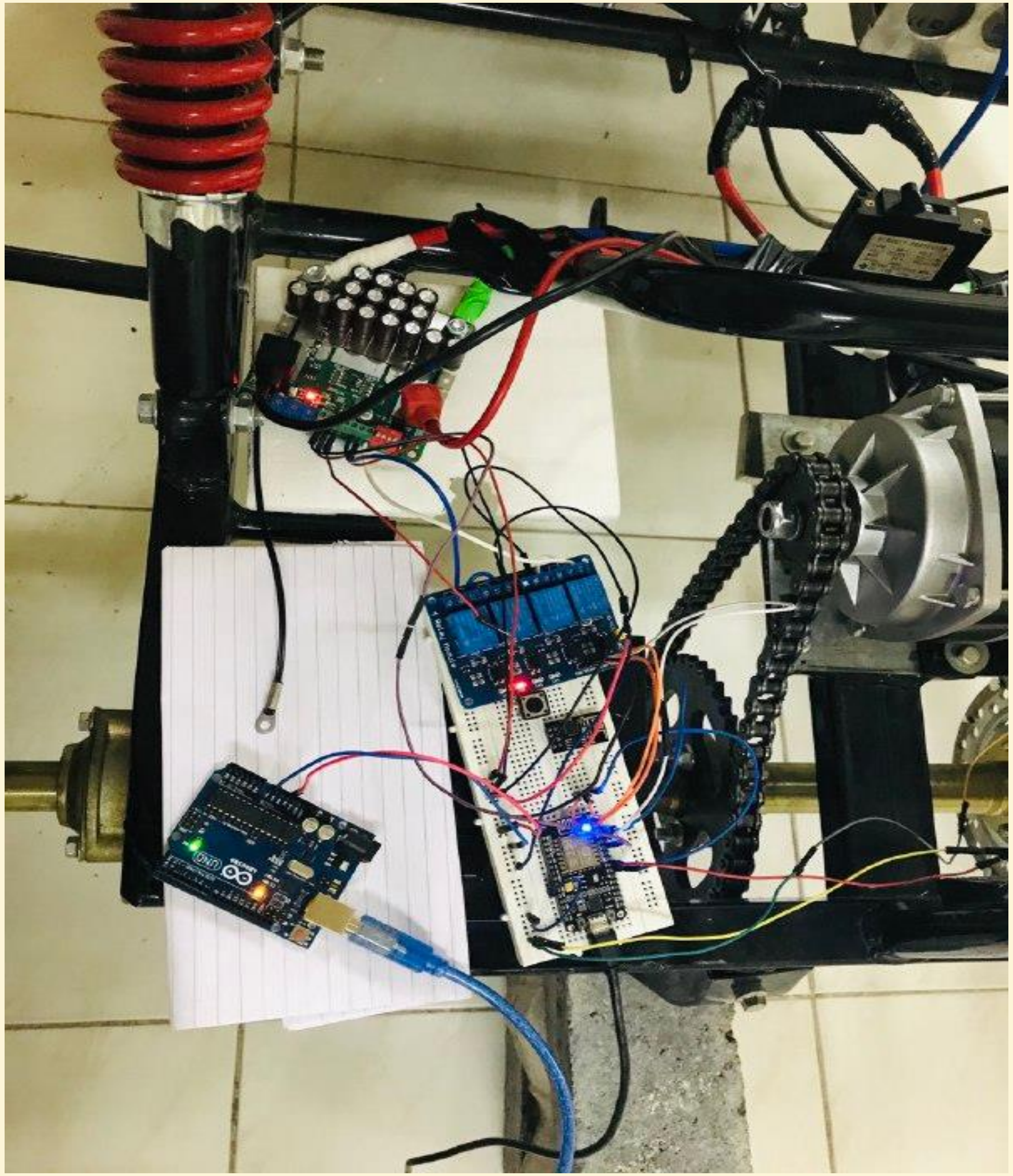


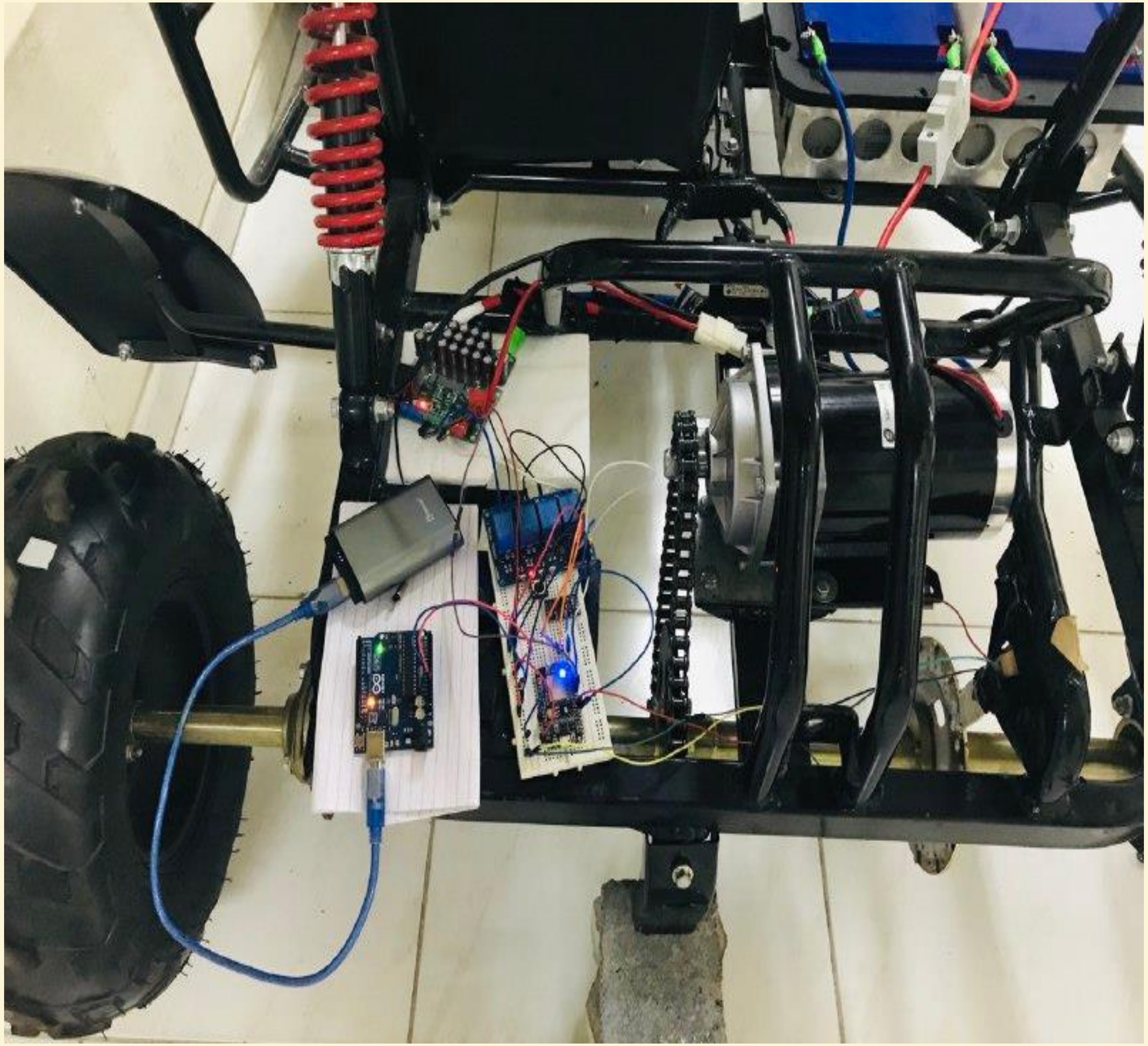


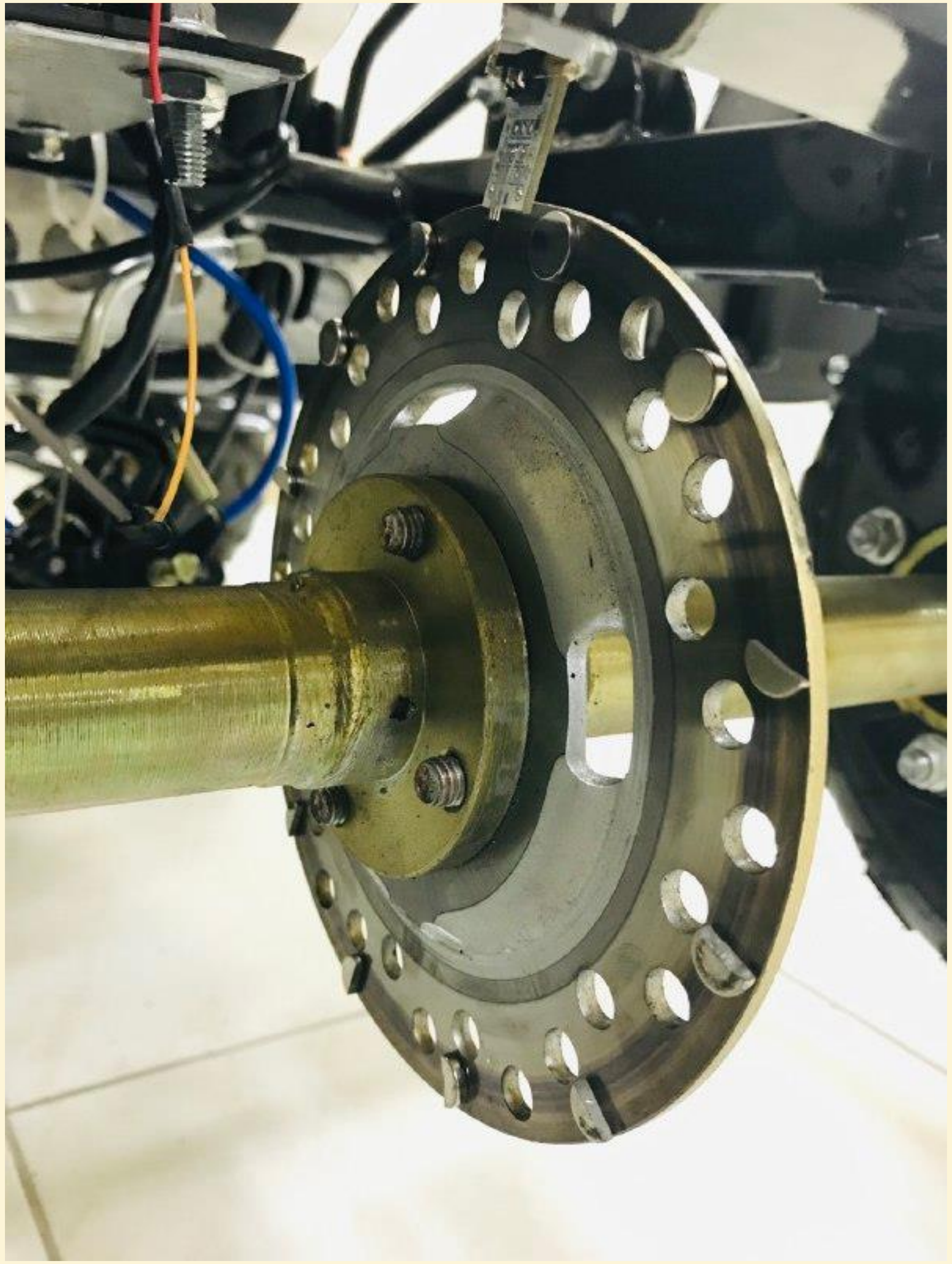
Video of Speed Control using Mapping

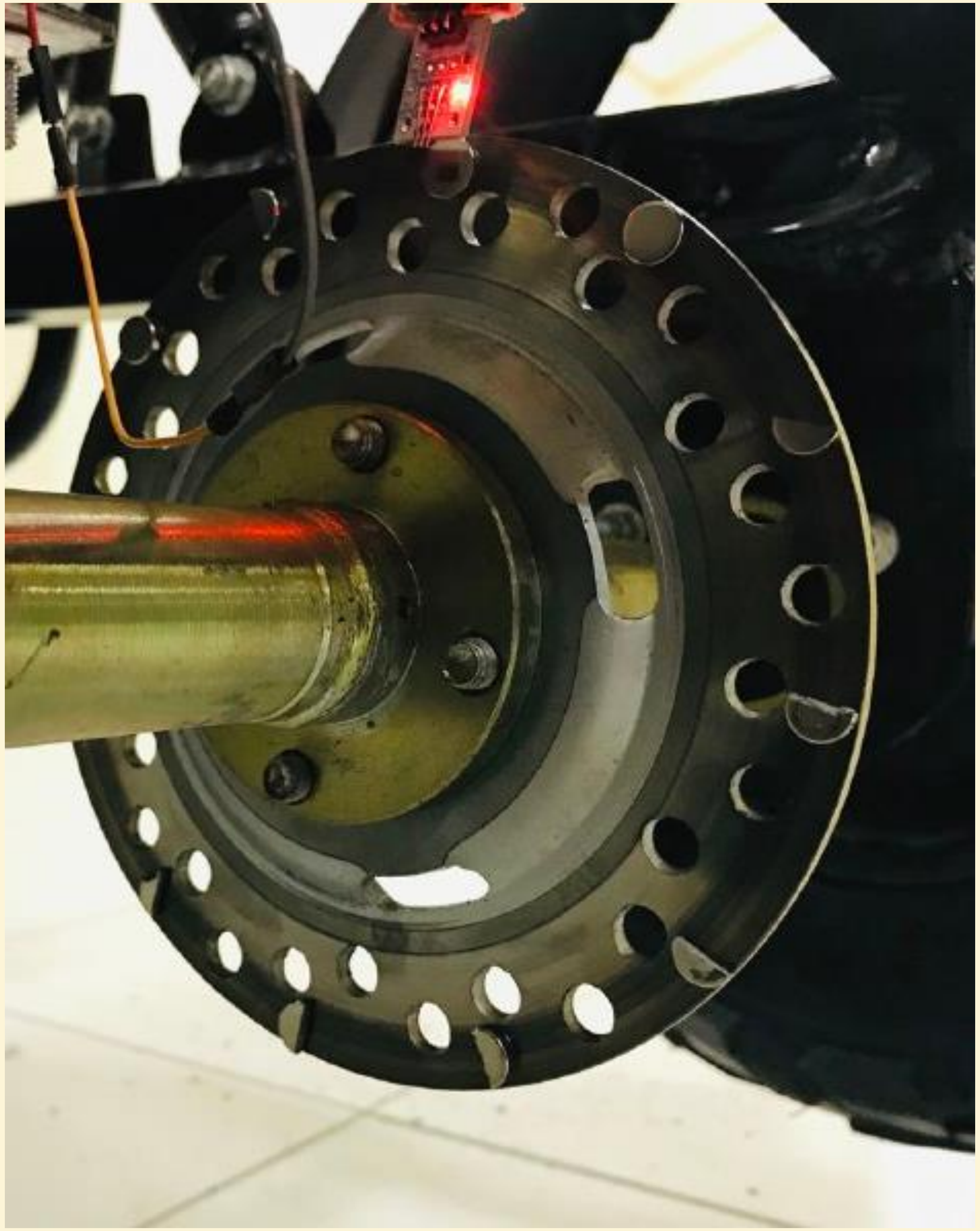


Implementation on The Kart

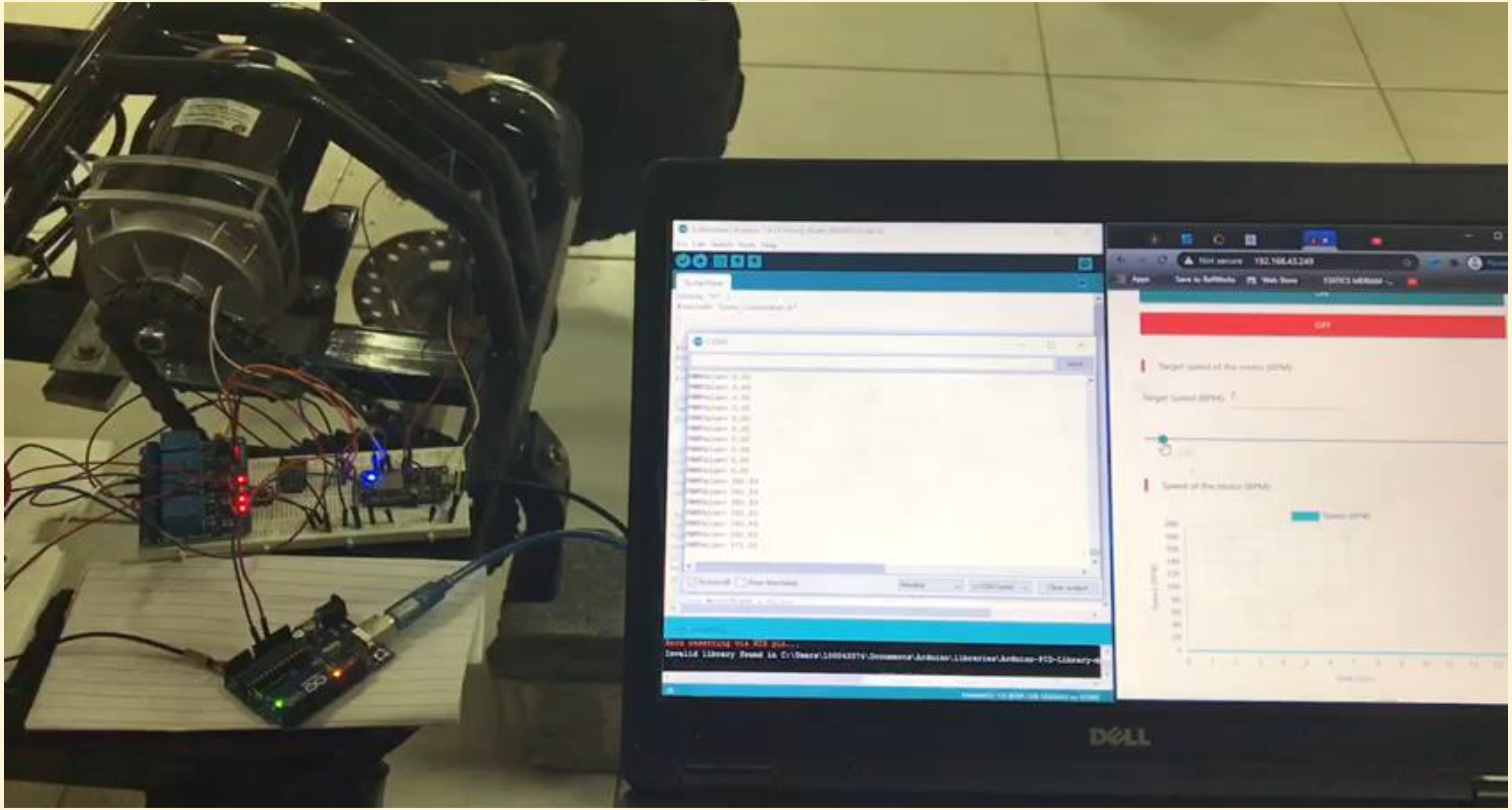


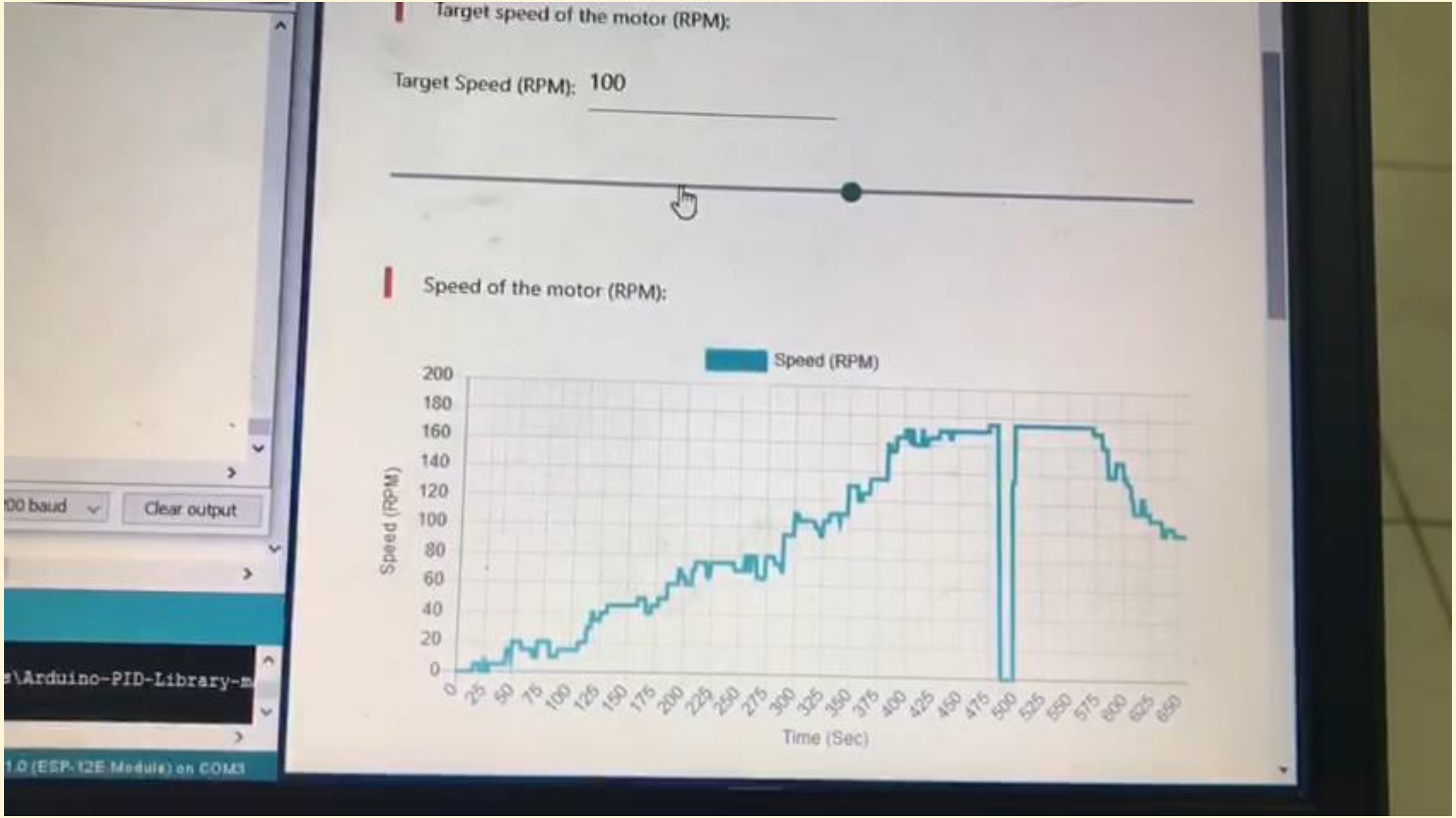


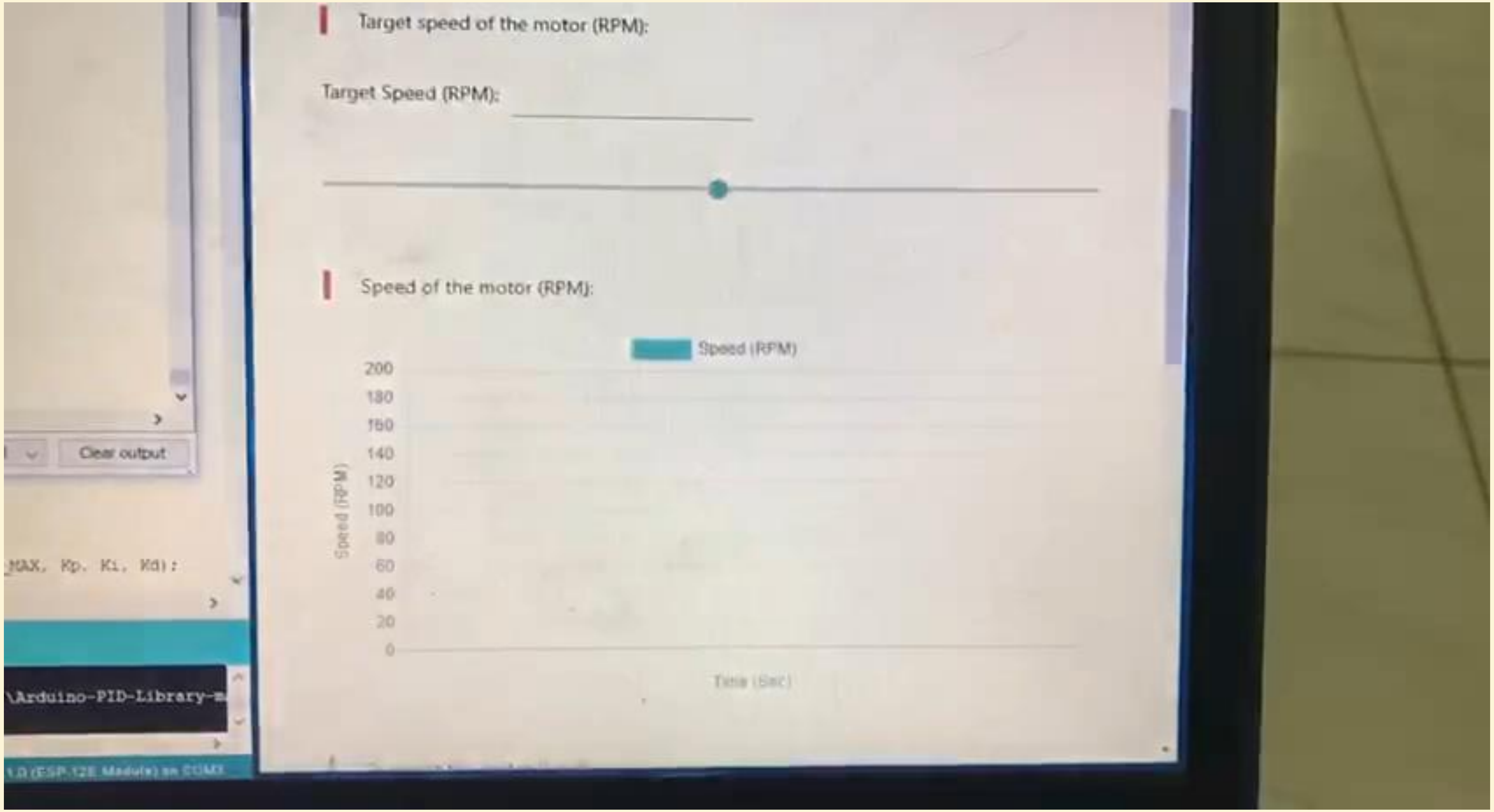




PID Controlled Wireless Speed monitoring of the Kart




Target speed of the motor (RPM):
Target Speed (RPM): 100
Speed of the motor (RPM):
Speed (RPM)
Speed (RPM)
Time (Sec)
00 baud
Clear output
\Arduino-PID-Library-m
1.0 (ESP-12E Module) on COM3


Target speed of the motor (RPM):
Target Speed (RPM):
Speed of the motor (RPM):
Speed (RPM)
200
180
160
140
120
100
80
60
40
20
0
Speed (RPM)
Time (Sec)
Clear output
_MAX, Kp, Ki, Kd):
\Arduino-PID-Library-m

The Final Design

Conclusion

Overview

- **Project**: DC powered Plug-in Electric Vehicle P(EV) powertrain
- **Design objectives**: Safety, low cost, low power consumption, accuracy, reliability, and ease of build
- **MOTOR**: brushed permanent magnet PMDC motor at 1k@48V
- **Battery:** lead-acid battery 48V
- **Control**: H-bridge + Converters.
- **NodeMCU** as microcontroller.
- **Cable:** 12AWG 600/1000V insulated with PVC (Polyvinyl Chloride)
- **The Hall-Effect Sensor:** to detect the speed of the motor
- **Website:** interface to control the system remotely

Conclusion

Difficulties we faced:

Primarily the pandemic caused

- Shipment issues
- Hard to find electrical components in local stores
- Couldn’t access the lab, limited resources and tools.

Acknowledgment

- our supervisors Dr. Tarek El Fouly and Dr. Bashar Zawawi
- Mr. Syed Faisal, Lab engineer from SAN campus

Budget Table

Material	Unit Price (AED)	Total Price (AED)
48V brushed PMDC Motor	833.77	1 x 833.77
Speed controller	936.62	1 x 936.62
Battery storage unit + battery charger	990	1 x 990
Wires, Relays, Resistors, Sprocket & Chain, Wi-Fi shield, Lugs, Connectors, Transistors, Equipment, Wires, Spare Controller, Arduino UNO	1208.95	1 x 1208.95
Go Kart 125 CC Gasoline Engine Powertrain Frame	5439	1 x 5439
TOTAL		9408.34

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Khalifa University

Thank You

Q/A