Regenerative Braking

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Objective

- To study the history of Regenerative Braking
- To delve deeper into the working principle of Regenerative Braking
- To analyze its practical working using a simulink model
- To discuss some of its applications in present day scenarios

Introduction

Braking is a process in which a mechanical or electrical device inhibits motion. It is often necessary to brake the motor rapidly and smoothly according to a given speed schedule. Braking torque may be applied by electrical or mechanical methods or combination of both.

For both of these processes, a retarding torque is required, which may be supplied mechanically or electrically. Electrical methods are more precise than mechanical methods, where accurate and smooth control of the stopping instant is possible. In electrical braking the kinetic energy of the rotating parts of the equipment gets converted into electric energy.

The methods of braking employed in electrical drives can be classified as:

- Regenerative
- Plugging and
- Dynamic braking.

In this study, we have discussed the advanced regenerative braking.

Also, a comparative study has been carried out by considering various motor drives and we finally concluded that the BLDC motor is the most suitable one for performing regenerative braking operation. The proposed scheme is implemented using MATLAB and the results are illustrated.

Regenerative Braking

Regenerative braking is an energy recovery mechanism that slows down a moving vehicle or object by converting its kinetic energy into a form that can be either used immediately or stored until needed. In this mechanism, the electric traction motor uses the vehicle's momentum to recover energy that would otherwise be lost to the brake discs as heat. This contrasts with conventional braking systems, where the excess kinetic energy is converted to unwanted and wasted heat due to friction in the brakes, or with dynamic brakes, where the energy is recovered by using electric motors as generators but is immediately dissipated as heat in resistors. In addition to improving the overall efficiency of the vehicle, regeneration can significantly extend the life of the braking system as the mechanical parts will not wear out very quickly.

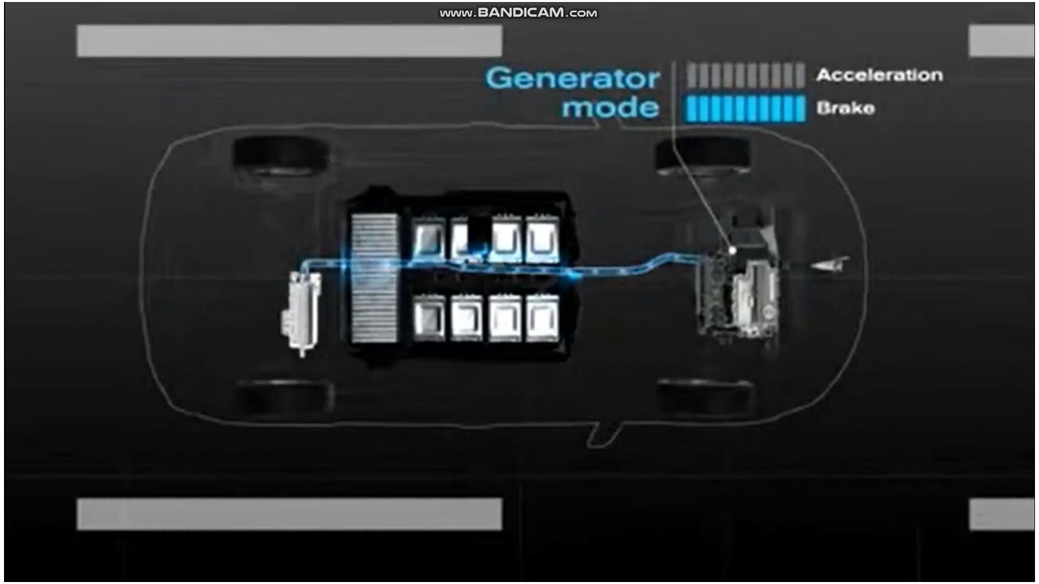
History

- Regenerative Braking seems to have become a topic of discussion among pioneers of automobile engineering in recent times but its foundations were already being applied in train engines dating back to 1950s.
- Back then it was called Dynamic Braking which made use of braking produced by electrical means. A generator would make use of the rotational kinetic energy of the wheels and converting it into electrical energy bringing a stop to the motion of train.
- This technology was a milestone back then because it saved a lot of money spent on braking system maintenance of heavy vehicles as prior to this technology, friction was the main stopping force called into play. By introduction of this technology, wear and tear of the wheels as well as braking pads was reduced but back then the electrical energy would just be made to lose in the form of Resistive losses in air.
- Recent technologies have found the use of this electrical energy in charging batteries, thus the name Regenerative Braking.

Working principle

- The most common form of regenerative brake involves an electric motor functioning as an electric generator.
- Electric motors, when used in reverse, function as generators and will then convert mechanical energy into electrical energy. Vehicles propelled by electric motors use them as generators when using regenerative braking, braking by transferring mechanical energy from the wheels to an electrical load.
- When the driver steps on the brake pedal of an electric or hybrid vehicle, these types of brakes put the vehicle's electric motor into reverse mode, causing it to run backwards, thus slowing the car's wheels. While running backwards, the motor also acts as an electric generator, producing electricity that's then fed into the vehicle's batteries

Regenerative Action



Practical Regenerative Braking

Regenerative braking is not by itself sufficient as the sole means of safely bringing a vehicle to a standstill, or slowing it as required, so it must be used in conjunction with another braking system such as friction-based braking.

- The regenerative braking effect drops off at lower speeds, and cannot bring a vehicle to a complete halt reasonably quickly with current technology, although some cars like the Chevrolet Bolt can bring the vehicle to a complete stop on even surfaces when the driver knows the vehicle's regenerative braking distance. This is referred to as One Pedal Driving.
- Current regenerative brakes do not immobilize a stationary vehicle; physical locking is required, for example to prevent vehicles from rolling down hills.
- Many road vehicles with regenerative braking do not have drive motors on all wheels (as in a two-wheel drive car); regenerative braking is normally only applicable to wheels with motors. For safety, the ability to brake all wheels is required.
- The regenerative braking effect available is limited, and mechanical braking is still necessary for substantial speed reductions, to bring a vehicle to a stop, or to hold a vehicle at a standstill.

Choice of Motor used

A comparison is drawn among the Brushed, Brushless and Induction type motors on the basis of efficiency, service, specific cost, heat rejection, torque-speed behaviour and some other miscellaneous factors.

Brushed DC Motor

Brushless DC motor

Induction Motor

Brushed DC Motor

In a brushed DC, the field is a permanent magnet and the rotor is an electromagnet. The commutator is charged by the brushes to the reverse polarity, which in turn causes the rotor to rotate. By reversing the polarity of the brushes, the direction of rotation can be altered. Efficiency is very less here.

Induction Type

When the speed of the motor is more than the synchronous speed, relative speed between the motor conductors and air gap rotating field reverses, as a result the phase angle because greater than 90° and the power flow reverse and thus regenerative braking takes place. If the source frequency is fixed then the regenerative braking of induction motor can only take place if the speed of the motor is greater than synchronous speed, but with a variable frequency source regenerative braking of induction motor can occur for speeds lower than synchronous speed. The major advantage of this type of braking is that the power generated is usefully employed and the major disadvantage is that the for fixed frequency sources, braking operation cannot be performed below synchronous speeds. Speed control of induction motors is quite difficult

Brushless DC Motor

Efficiency is a primary selling feature for BLDC motors. As in case of BLDC motor, the rotor is the only bearer of magnets, hence it does not require any, i.e. no commutator, no connection and no brush is required for the operation and hence there is no sparking produced in the process. In place of these, the motor employs control circuitry. In order to determine the position of the rotor at different times, a hall sensor is used along with the controllers.

Comparison of Motors

In terms of efficiency,

- **Brushed**:
  - DC- Motor (80%),
  - DC controller (94%, passive fly back),
  - NET (75%)
- **BLDC**:
  - Motor (93%),
  - inverter (97%, synchronous fly back or hysteretic control),
  - NET (90%)
- **Induction**:
  - Motor (91%),
  - inverter (97%, synchronous fly back or hysteretic control),
  - NET (88%)

In terms of service,

- **Brush-DC**: Periodic replacement for brushes and bearing are required
- **BLDC**: No replacement of bearing is required
- **Induction**: Same as in the case of BLDC MOTOR

In terms of Specific Cost,

- **Brush-DC**: The cost is low
- **BLDC**: The high power permanent magnets are indeed expensive
- **Induction**: The cost is moderate in this case.

In terms of Heat rejection,

- **Brush-DC**: The removal of heat is difficult
- **BLDC**: Heat rejection is comparatively is easier. Magnets on the rotor have low-moderate eddy current induced heating
- **Induction**: Windings on stator make stator heat rejection straightforward. The current induced in the rotor can be cooled by oil when implemented in high power applications.

For Torque/speed behavior,

- **Brush-DC**: It has infinite zero speed torque, but the torque drops down gradually with increasing speed.
- **BLDC**: The motor has a constant torque up to base speed and power is constant up to the maximum speed. Automotive applications are viable with a single ratio gearbox.
- **Induction**: Here the torque remains constant up to base speed and the power is constant up to maximum speed. Automotive applications are viable with a single ratio gearbox. The torque builds up after some delay when current is applied.

Other parameters

- **Brush-DC**: At high voltages arcing can be problematic. Regenerative braking is tricky and requires a more complex speed controller.
- **BLDC**: BLDC motors are ideal for low power applications. Regenerative braking comes essentially for free.
- **Induction**: Cost is low and implementation for automotive application is cheaper. Regenerative braking comes essentially for free.

Boost Converter

A boost converter (step-up converter) is a DC-to-DC power converter that steps up voltage (while stepping down current) from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) containing at least two semiconductors (a diode and a transistor) and at least one energy storage element: a capacitor, inductor, or the two in combination. To reduce voltage ripple, filters made of capacitors (sometimes in combination with inductors) are normally added to such a converter's output (load-side filter) and input (supply-side filter).

The key principle that drives the boost converter is the tendency of an inductor to resist changes in current by either increasing or decreasing the energy stored in the inductor magnetic field. In a boost converter, the output voltage is always higher than the input voltage.

Operation of Boost Converter

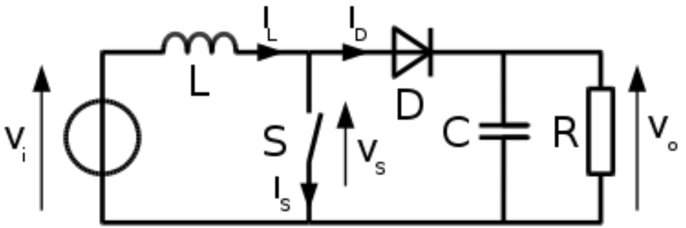
- When the switch is closed, current flows through the inductor in the clockwise direction and the inductor stores some energy by generating a magnetic field. Polarity of the left side of the inductor is positive.
- When the switch is opened, current will be reduced as the impedance is higher. The magnetic field previously created will be reduced in energy to maintain the current towards the load. Thus the polarity will be reversed. As a result, two sources will be in series causing a higher voltage to charge the capacitor through the diode D.

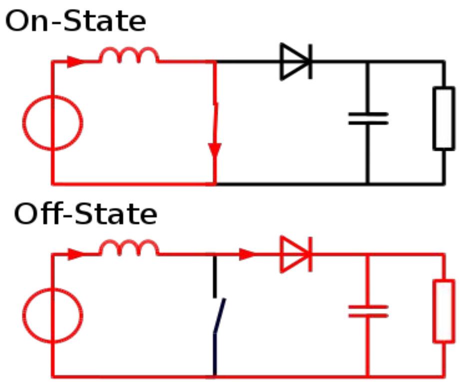
If the switch is cycled fast enough, the inductor will not discharge fully in between charging stages, and the load will always see a voltage greater than that of the input source alone when the switch is opened. Also while the switch is opened, the capacitor in parallel with the load is charged to this combined voltage. When the switch is then closed and the right hand side is shorted out from the left hand side, the capacitor is therefore able to provide the voltage and energy to the load. During this time, the blocking diode prevents the capacitor from discharging through the switch. The switch must of course be opened again fast enough to prevent the capacitor from discharging too much.

The basic principle of a Boost converter consists of 2 distinct states :

- in the On-state, the switch S is closed, resulting in an increase in the inductor current;
- in the Off-state, the switch is open and the only path offered to inductor current is through the flyback diode D, the capacitor C and the load R. This results in transferring the energy accumulated during the On-state into the capacitor.

The input current is the same as the inductor current as can be seen in. So it is not discontinuous as in the buck converter and the requirements on the input filter are relaxed compared to a buck converter.





Duty Cycle

A duty cycle or power cycle is the fraction of one period in which a signal or system is active. Duty cycle is commonly expressed as a percentage or a ratio. A period is the time it takes for a signal to complete an on-and-off cycle. A duty cycle (ratio) may be expressed as:

$$D = PW/T$$

where PW is the pulse width (pulse active time), and T is the total period of the signal.

Thus, a 60% duty cycle means the signal is on 60% of the time but off 40% of the time. The "on time" for a 60% duty cycle could be a fraction of a second, a day, or even a week, depending on the length of the period. Duty cycles can be used to describe the percent time of an active signal in an electrical device.
The duty factor for periodic signal expresses the same notion, but is usually scaled to a maximum of one rather than 100%

State Of Charge

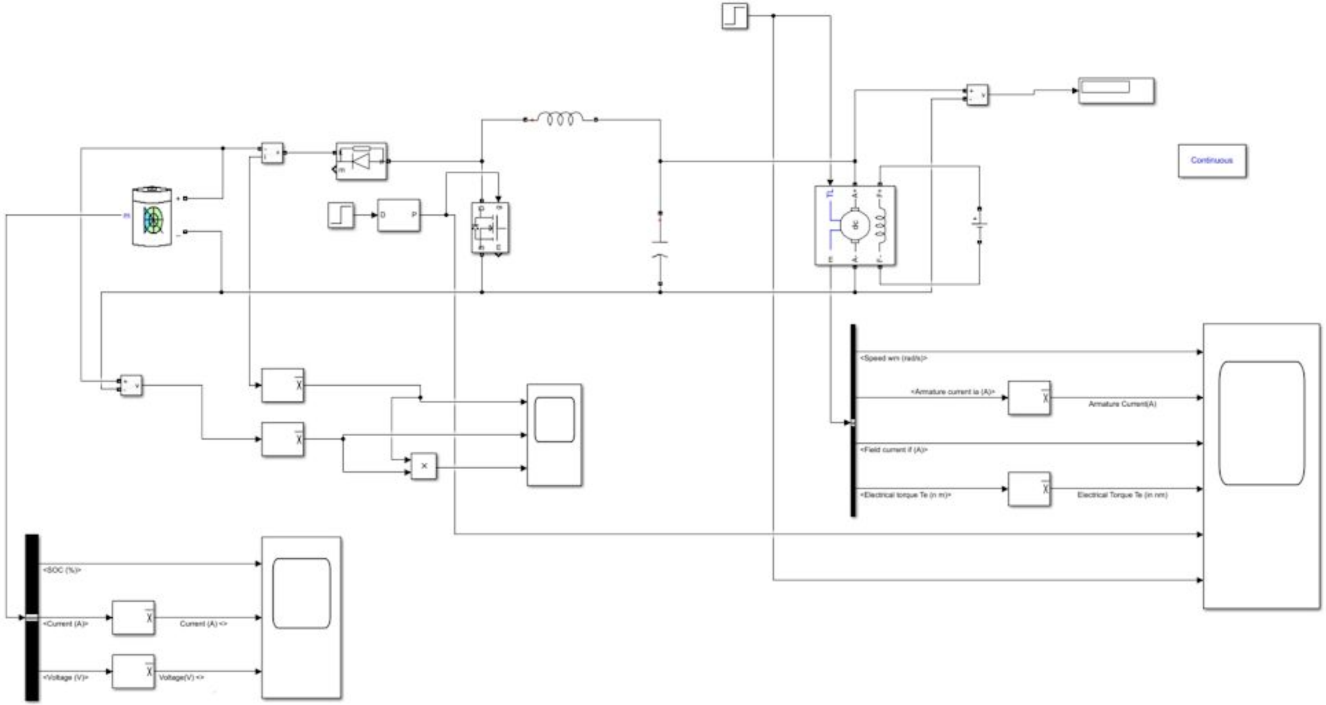
State of charge (SoC) is the level of charge of an electric battery relative to its capacity. The units of SoC are percentage points (0% = empty; 100% = full). An alternative form of the same measure is the depth of discharge (DoD), the inverse of SoC (100% = empty; 0% = full). SoC is normally used when discussing the current state of a battery in use, while DoD is most often seen when discussing the lifetime of the battery after repeated use.

In a battery electric vehicle (BEV), hybrid vehicle (HV), or plug-in hybrid electric vehicle (PHEV), SoC for the battery pack is the equivalent of a fuel gauge. It is important to mention that state of charge, presented as a gauge or percentual value at any vehicle dashboard, especially in plug-in hybrid vehicles, may not be representative for a real level of charge. In that particular case, some noticeable amount of energy stored in the electric battery is not shown at the dashboard, and it is reserved for hybrid-work operations. It permits a vehicle to accelerate with electric motor(s) mainly using battery energy, while engine serves as a generator is used to recharge the battery to the minimum level needed for such operation.

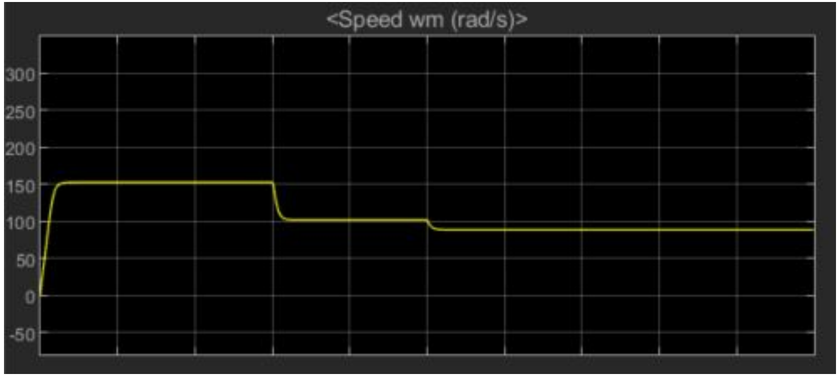
Simulink Simulation

We have simulated open-loop control and closed loop control for regenerative braking

Open Loop system



DC Machine Parameters

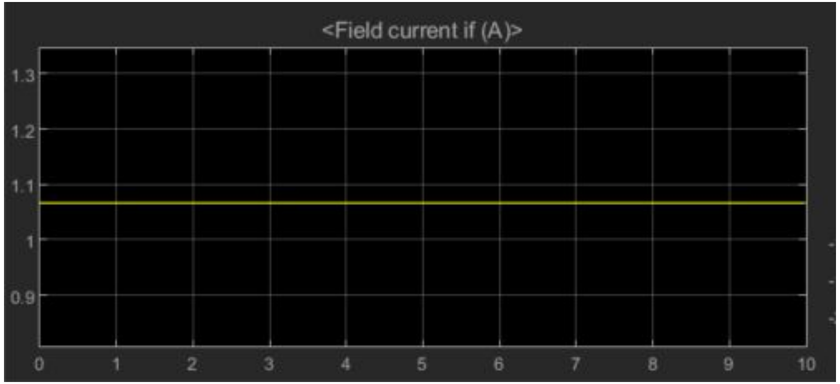


Trace Selection

<Speed wm (rad/s)>

Signal Statistics

	Value	Time
Max	1.527e+02	3.000
Min	1.000e+00	0.000e+00
Peak to Peak	1.517e+02	
Mean	1.050e+02	
Median	8.876e+01	
RMS	1.083e+02	



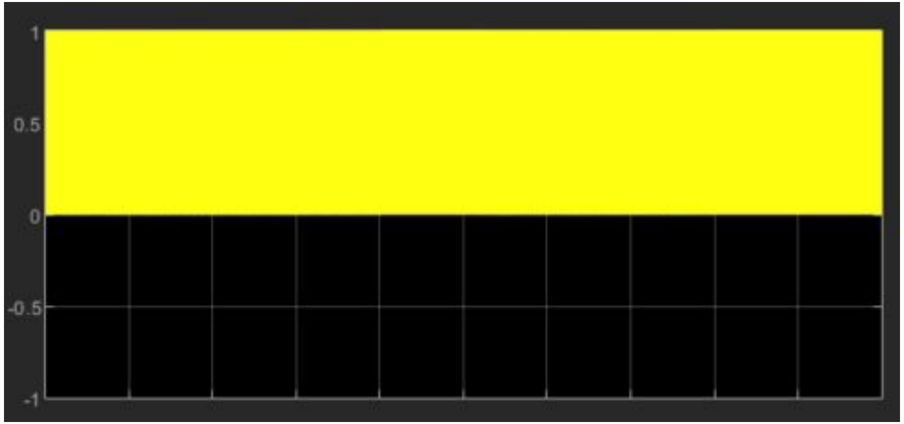
Trace Selection

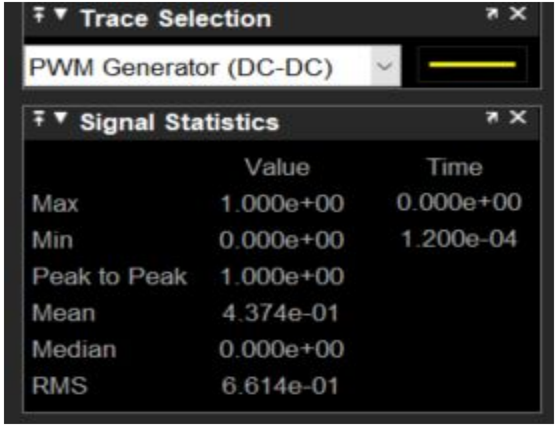
`<Field current if (A)>`

Signal Statistics

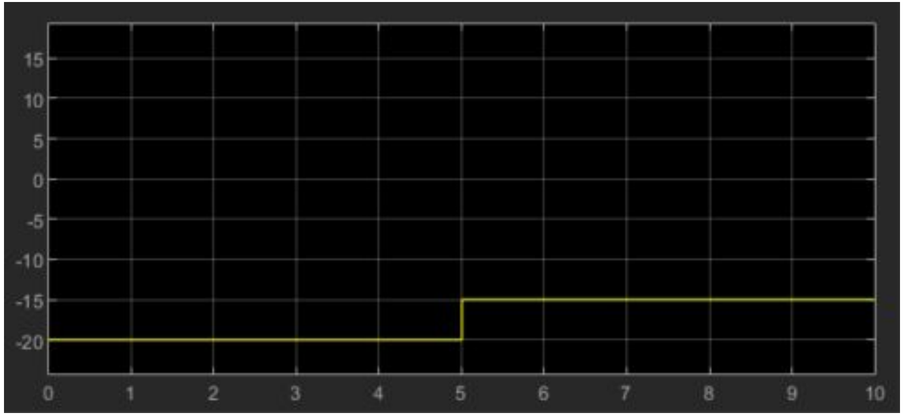
	Value	Time
Max	1.066e+00	7.831
Min	1.066e+00	5.157
Peak to Peak	9.592e-13	
Mean	1.066e+00	
Median	1.066e+00	
RMS	1.066e+00	

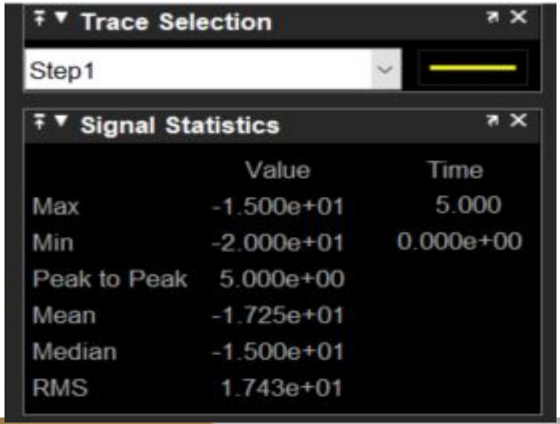
DUTY CYCLE

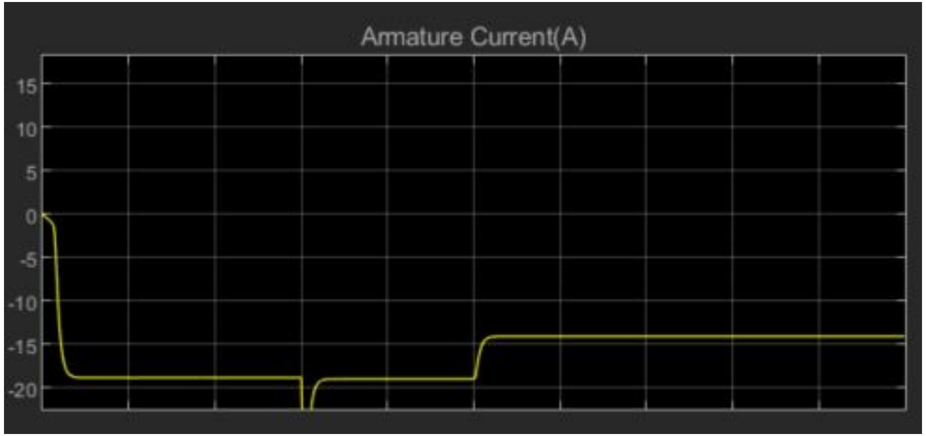




TORQUE IMPULSE





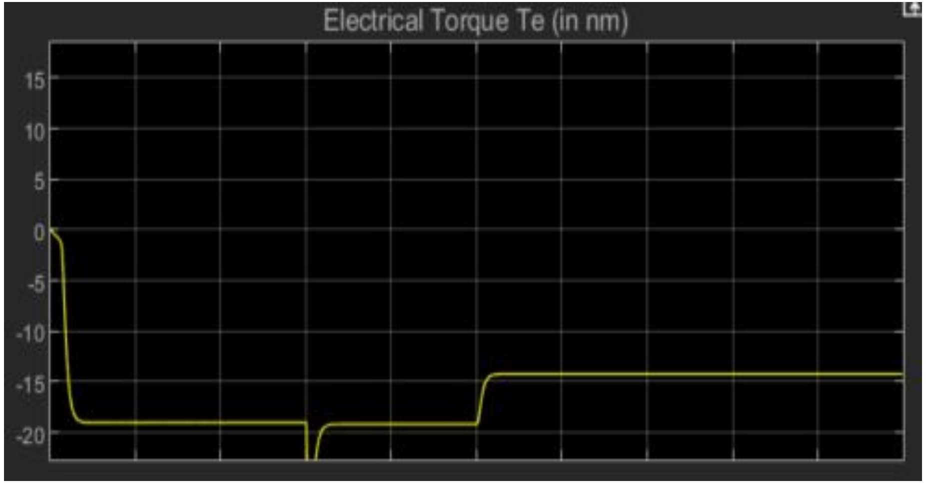


Trace Selection

Armature Current(A)

Signal Statistics

	Value	Time
Max	0.000e+00	0.000e+00
Min	-3.329e+01	3.035
Peak to Peak	3.329e+01	
Mean	-1.600e+01	
Median	-1.406e+01	
RMS	1.640e+01	



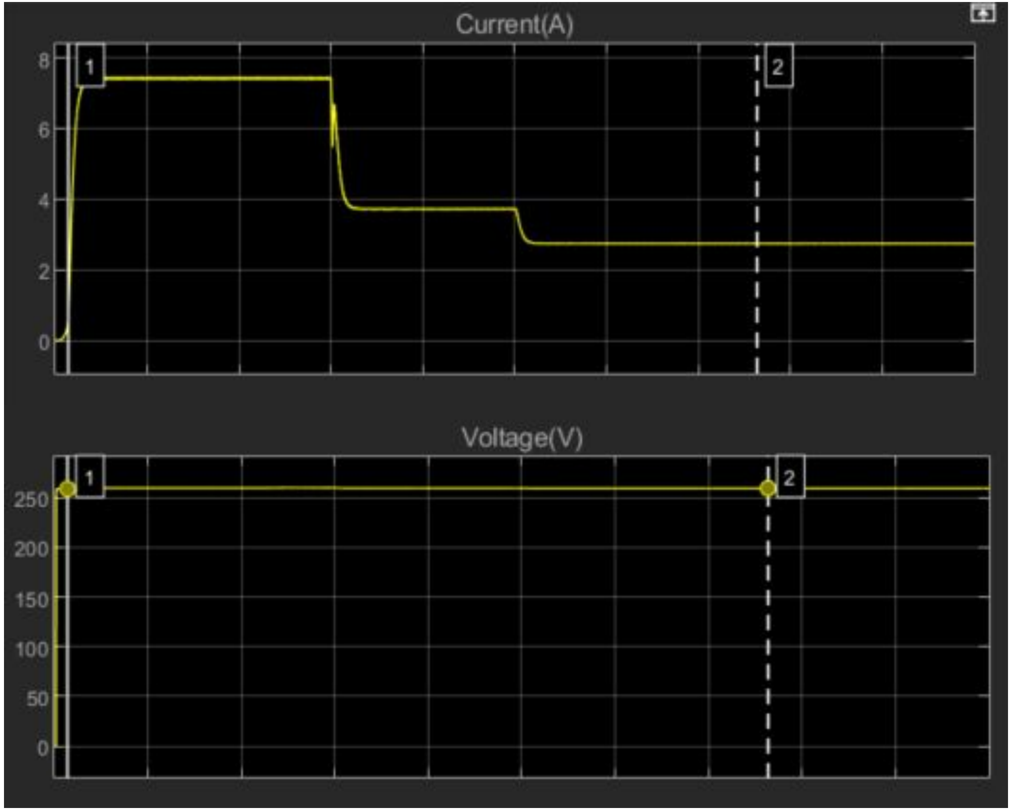
Trace Selection

Electrical Torque Te (in nm)

Signal Statistics

	Value	Time
Max	0.000e+00	0.000e+00
Min	-3.367e+01	3.035
Peak to Peak	3.367e+01	
Mean	-1.619e+01	
Median	-1.422e+01	
RMS	1.659e+01	

Charging Circuit Parameters



Trace Selection

Current(A)

Signal Statistics

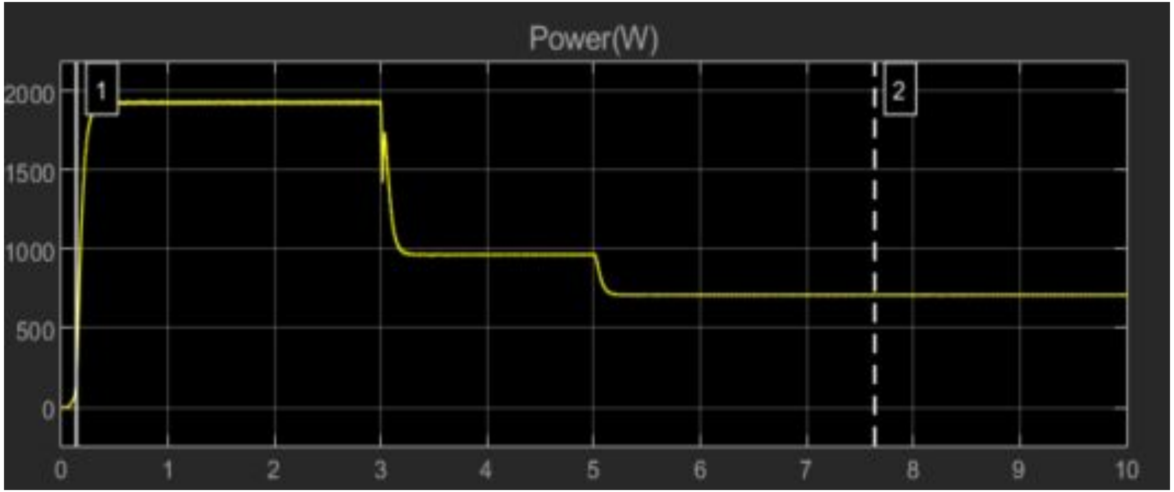
	Value	Time
Max	7.456e+00	1.033
Min	-3.160e-03	0.017
Peak to Peak	7.459e+00	
Mean	3.913e+00	
Median	2.755e+00	
RMS	4.355e+00	

Trace Selection

Voltage(V)

Signal Statistics

	Value	Time
Max	2.597e+02	3.000
Min	0.000e+00	0.000e+00
Peak to Peak	2.597e+02	
Mean	2.585e+02	
Median	2.592e+02	
RMS	2.589e+02	


Power(W)
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1000
500
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0
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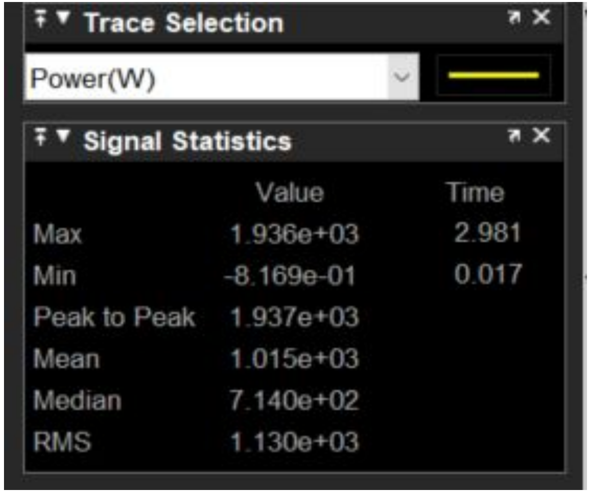
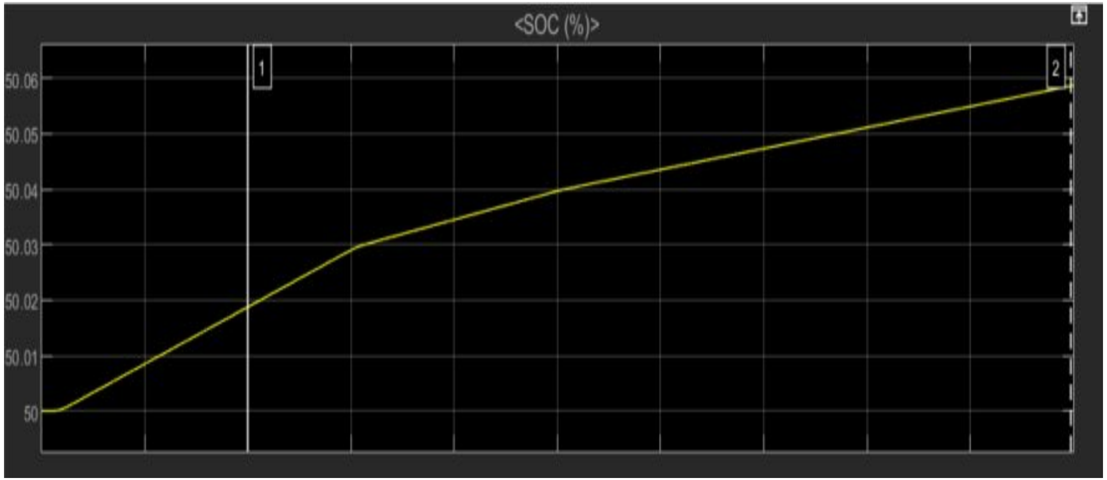
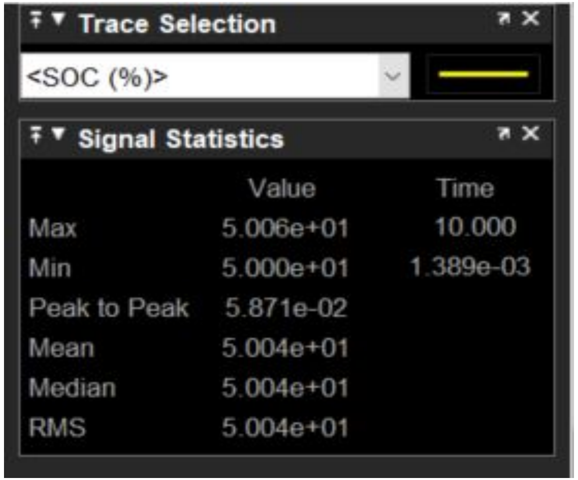
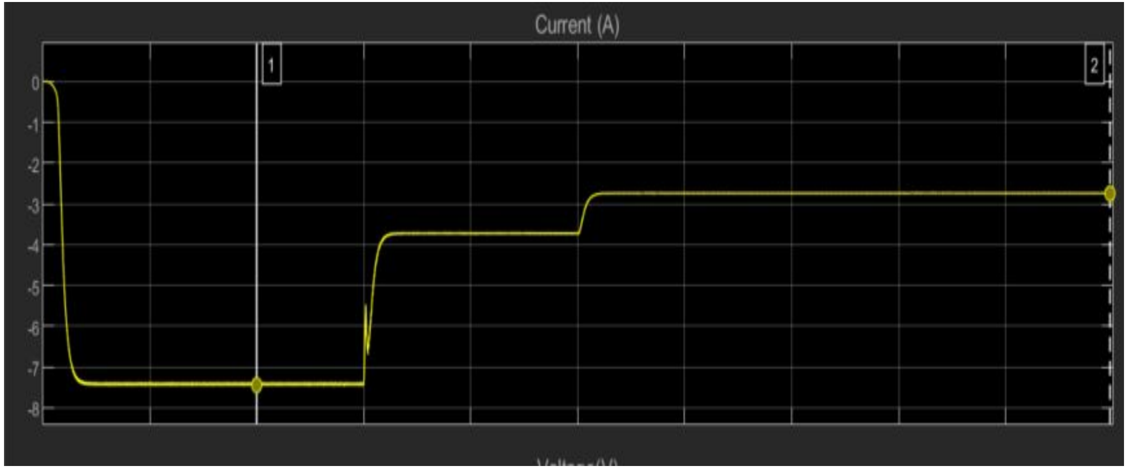
2
3
4
5
6
7
8
9
10
1
2


Trace Selection
Power(W)
Signal Statistics
Value
Time
Max 1.936e+03 2.981
Min -8.169e-01 0.017
Peak to Peak 1.937e+03
Mean 1.015e+03
Median 7.140e+02
RMS 1.130e+03

Battery Parameters






Current (A)
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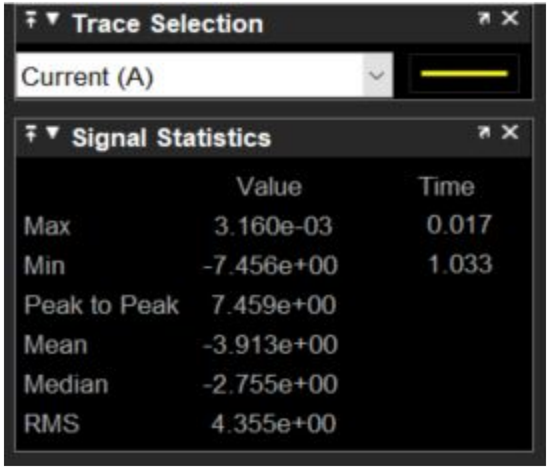
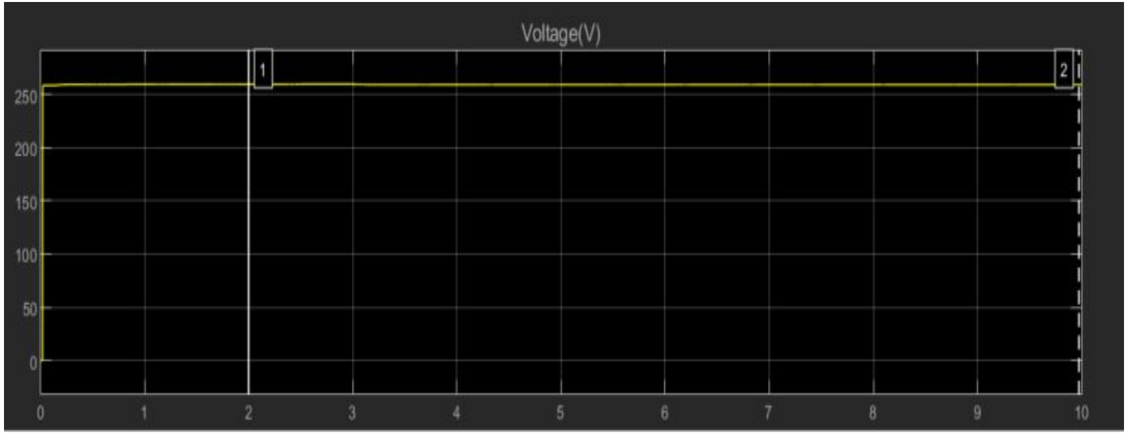
-2
-3
-4
-5
-6
-7
-8
1
2


Trace Selection
Current (A)
Signal Statistics
Value Time
Max 3.160e-03 0.017
Min -7.456e+00 1.033
Peak to Peak 7.459e+00
Mean -3.913e+00
Median -2.755e+00
RMS 4.355e+00


Voltage(V)
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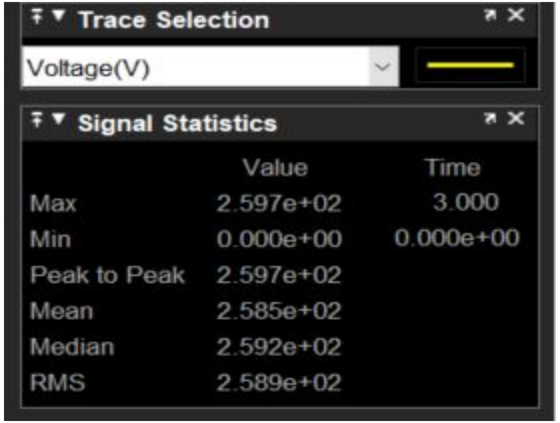
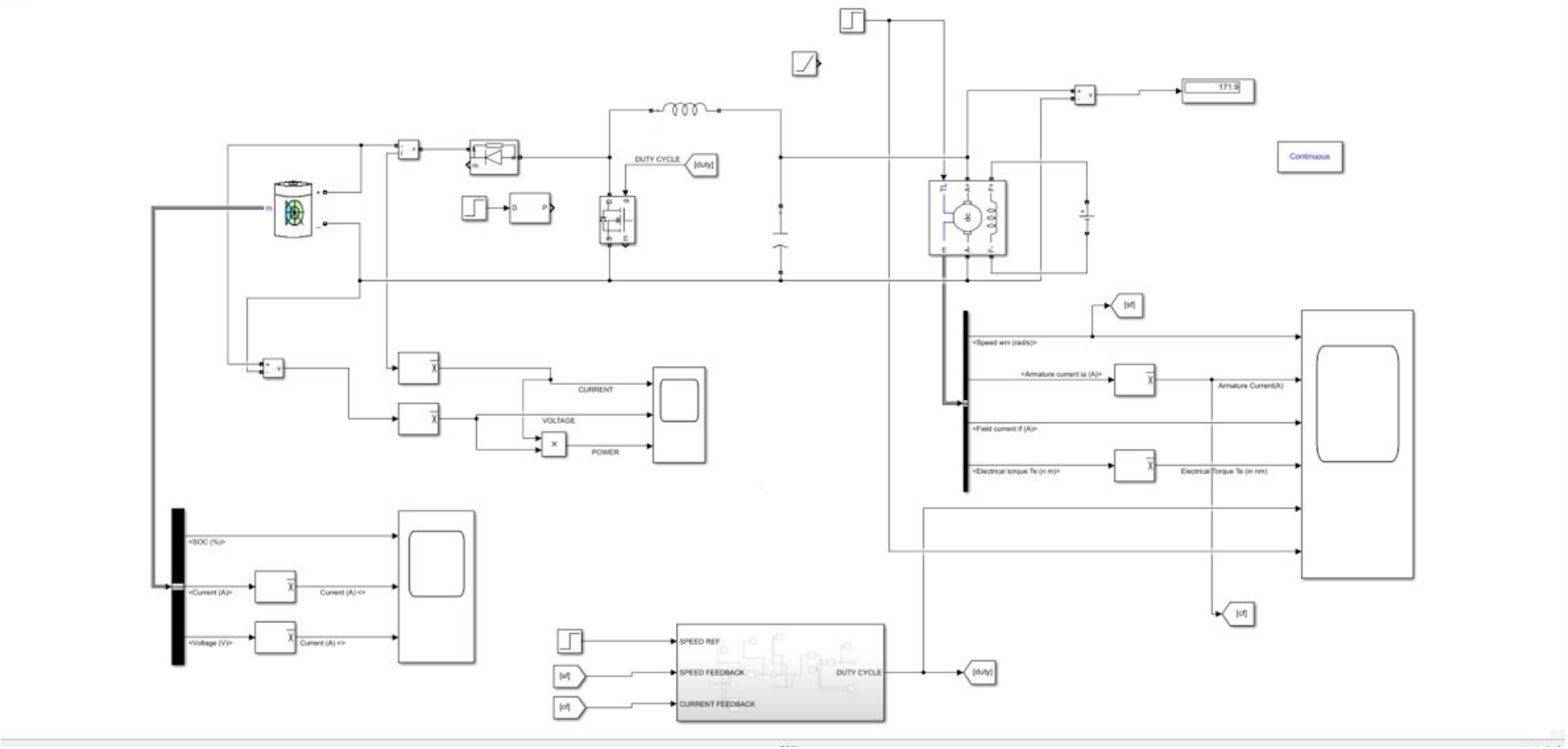
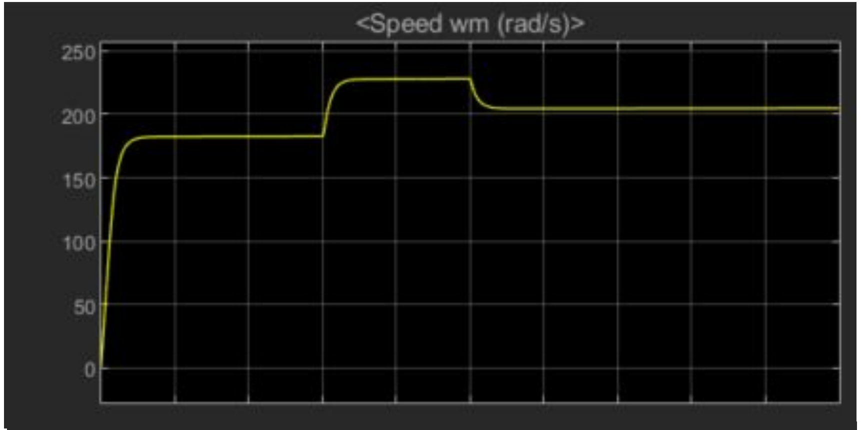
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10

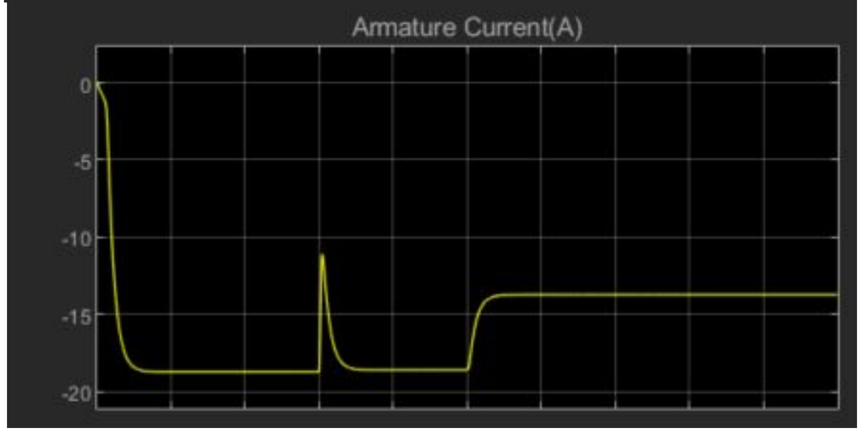

Trace Selection
Voltage(V)
Signal Statistics
Value Time
Max 2.597e+02 3.000
Min 0.000e+00 0.000e+00
Peak to Peak 2.597e+02
Mean 2.585e+02
Median 2.592e+02
RMS 2.589e+02

Closed Loop System



DC Machine Parameters





Trace Selection

<Speed wm (rad/s)>

Signal Statistics

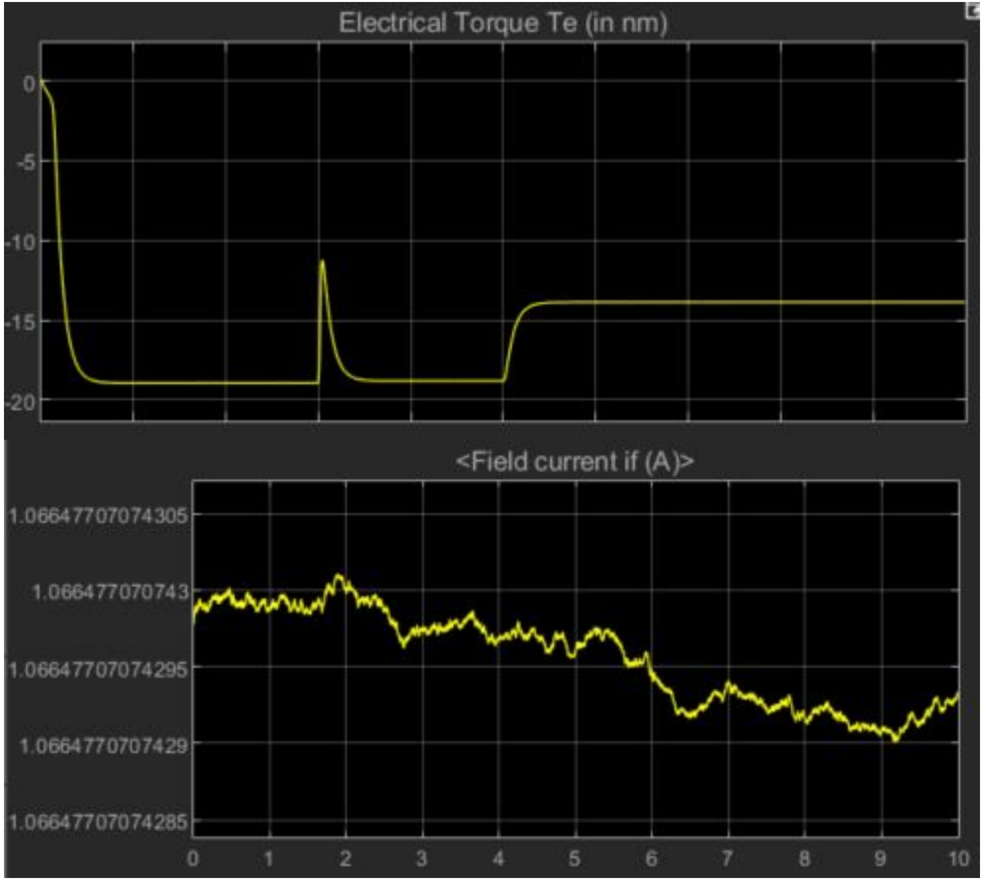
	Value	Time
Max	2.282e+02	5.000
Min	1.000e+00	0.000e+00
Peak to Peak	2.272e+02	
Mean	1.981e+02	
Median	2.047e+02	
RMS	2.000e+02	

Trace Selection

Armature Current(A)

Signal Statistics

	Value	Time
Max	0.000e+00	0.000e+00
Min	-1.873e+01	1.741
Peak to Peak	1.873e+01	
Mean	-1.578e+01	
Median	-1.490e+01	
RMS	1.613e+01	



Trace Selection

Electrical Torque Te (in nm)

Signal Statistics

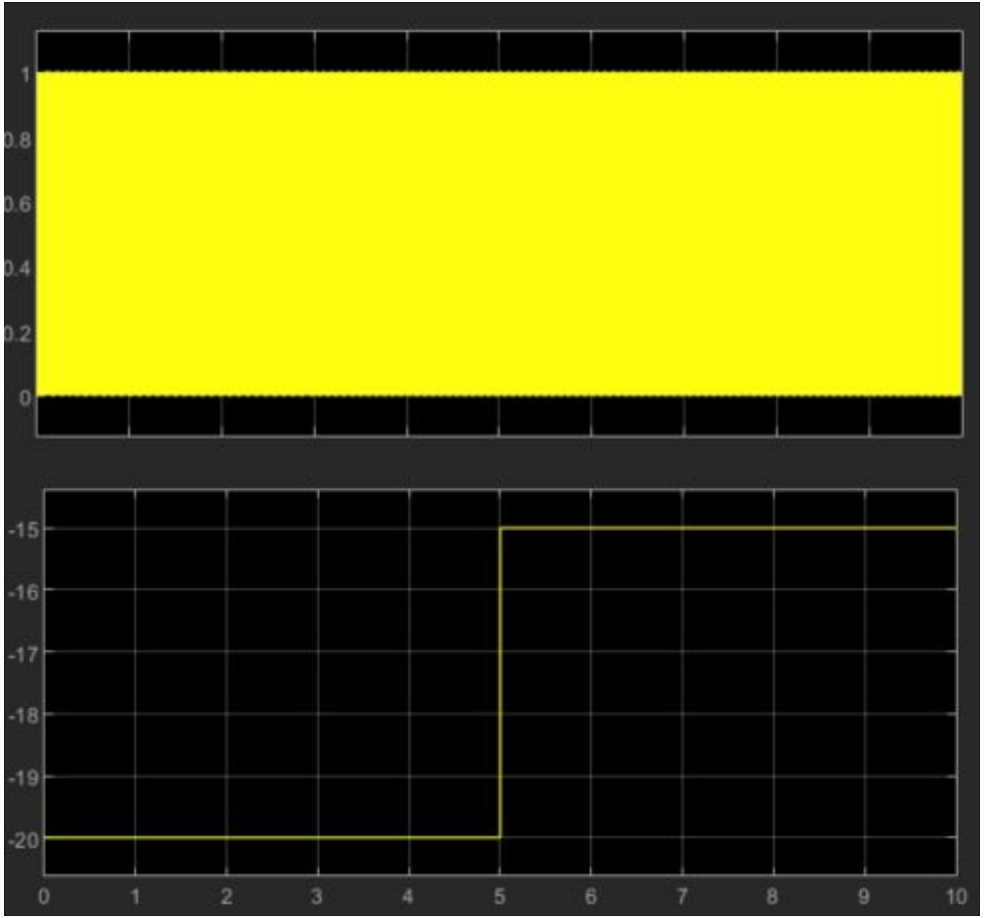
	Value	Time
Max	-1.124e+01	3.044
Min	-1.894e+01	2.649
Peak to Peak	7.704e+00	
Mean	-1.598e+01	
Median	-1.389e+01	
RMS	1.616e+01	

Trace Selection

Field current if (A)

Signal Statistics

	Value	Time
Max	1.066e+00	1.888
Min	1.066e+00	9.183
Peak to Peak	1.099e-13	
Mean	1.066e+00	
Median	1.066e+00	
RMS	1.066e+00	



Trace Selection

Subsystem

Signal Statistics

	Value	Time
Max	1.000e+00	3.257
Min	0.000e+00	3.257
Peak to Peak	1.000e+00	
Mean	5.230e-01	
Median	1.000e+00	
RMS	7.232e-01	

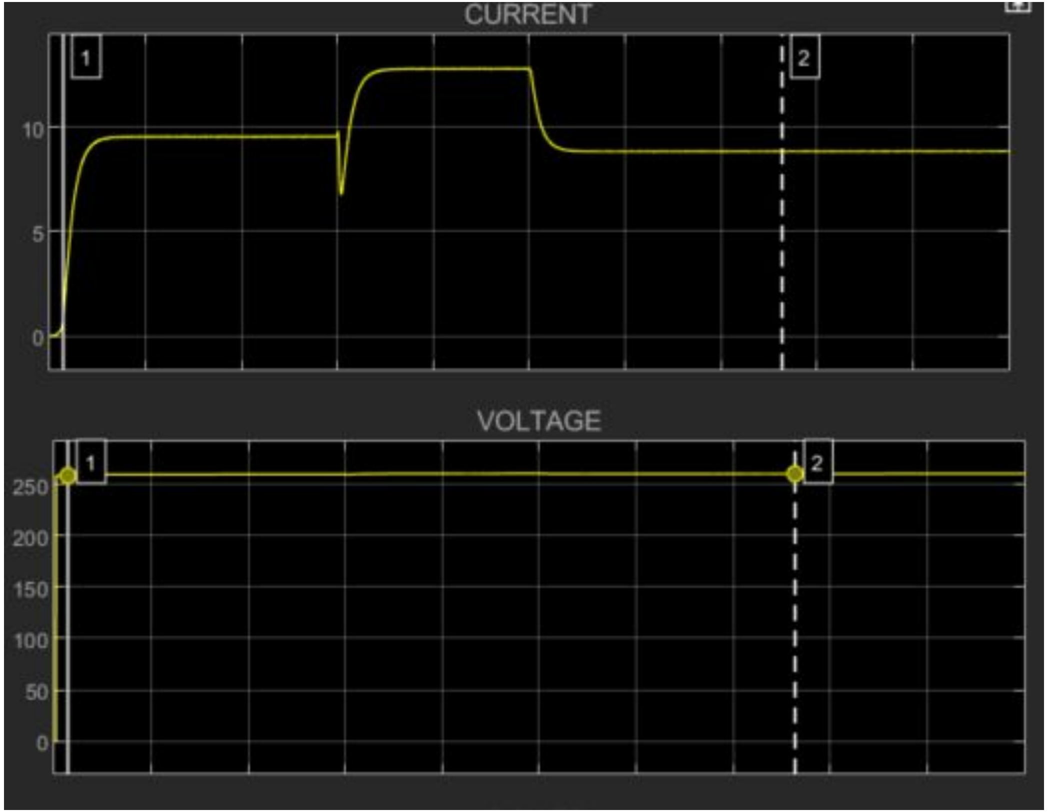
Trace Selection

Step1

Signal Statistics

	Value	Time
Max	-1.500e+01	5.000
Min	-2.000e+01	3.257
Peak to Peak	5.000e+00	
Mean	-1.692e+01	
Median	-1.500e+01	
RMS	1.709e+01	

Charging Circuit Parameters



Trace Selection

CURRENT

Signal Statistics

	Value	Time
Max	1.285e+01	4.997
Min	-3.256e-03	0.017
Peak to Peak	1.285e+01	
Mean	9.515e+00	
Median	9.041e+00	
RMS	9.740e+00	

Trace Selection

VOLTAGE

Signal Statistics

	Value	Time
Max	2.607e+02	5.003
Min	0.000e+00	0.000e+00
Peak to Peak	2.607e+02	
Mean	2.595e+02	
Median	2.603e+02	
RMS	2.599e+02	


POWER
1
2
0
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2000
3000
0
1
2
3
4
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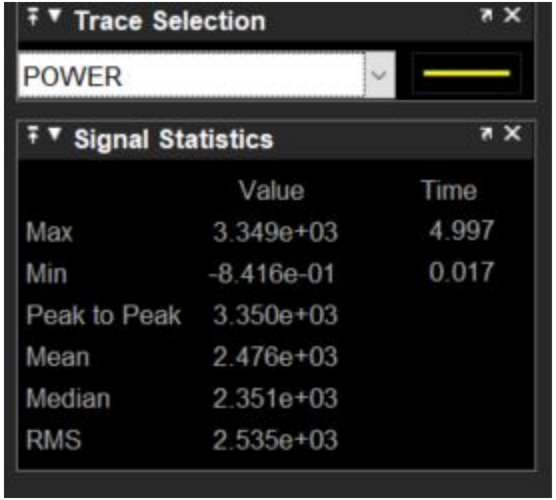
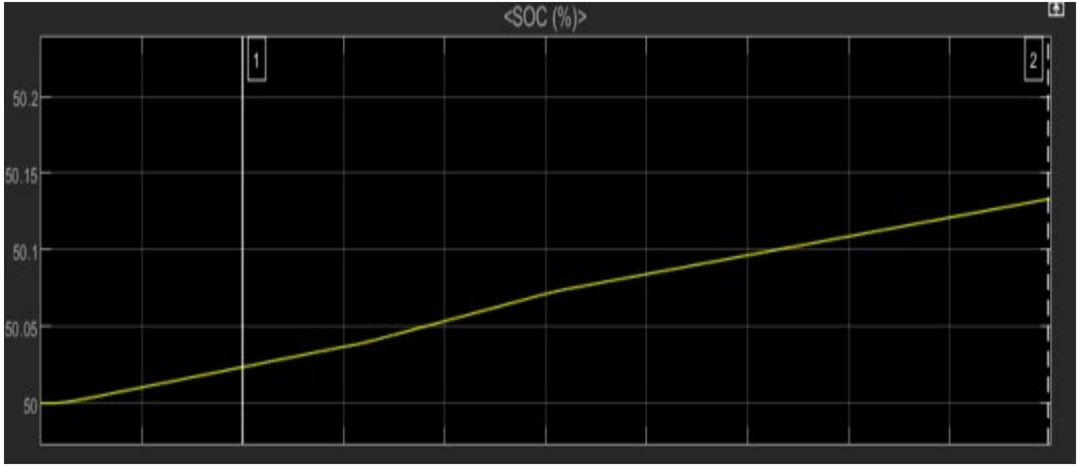
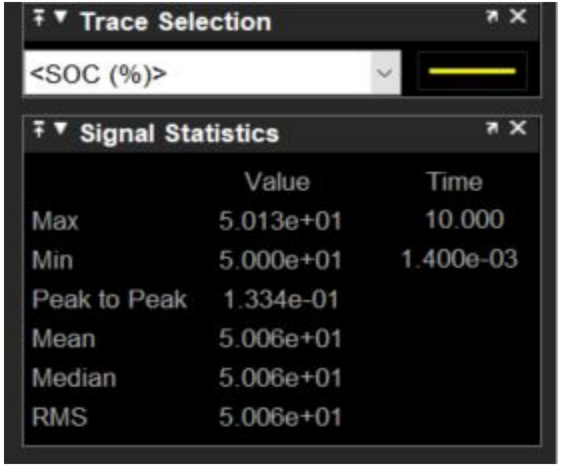
6
7
8
9
10

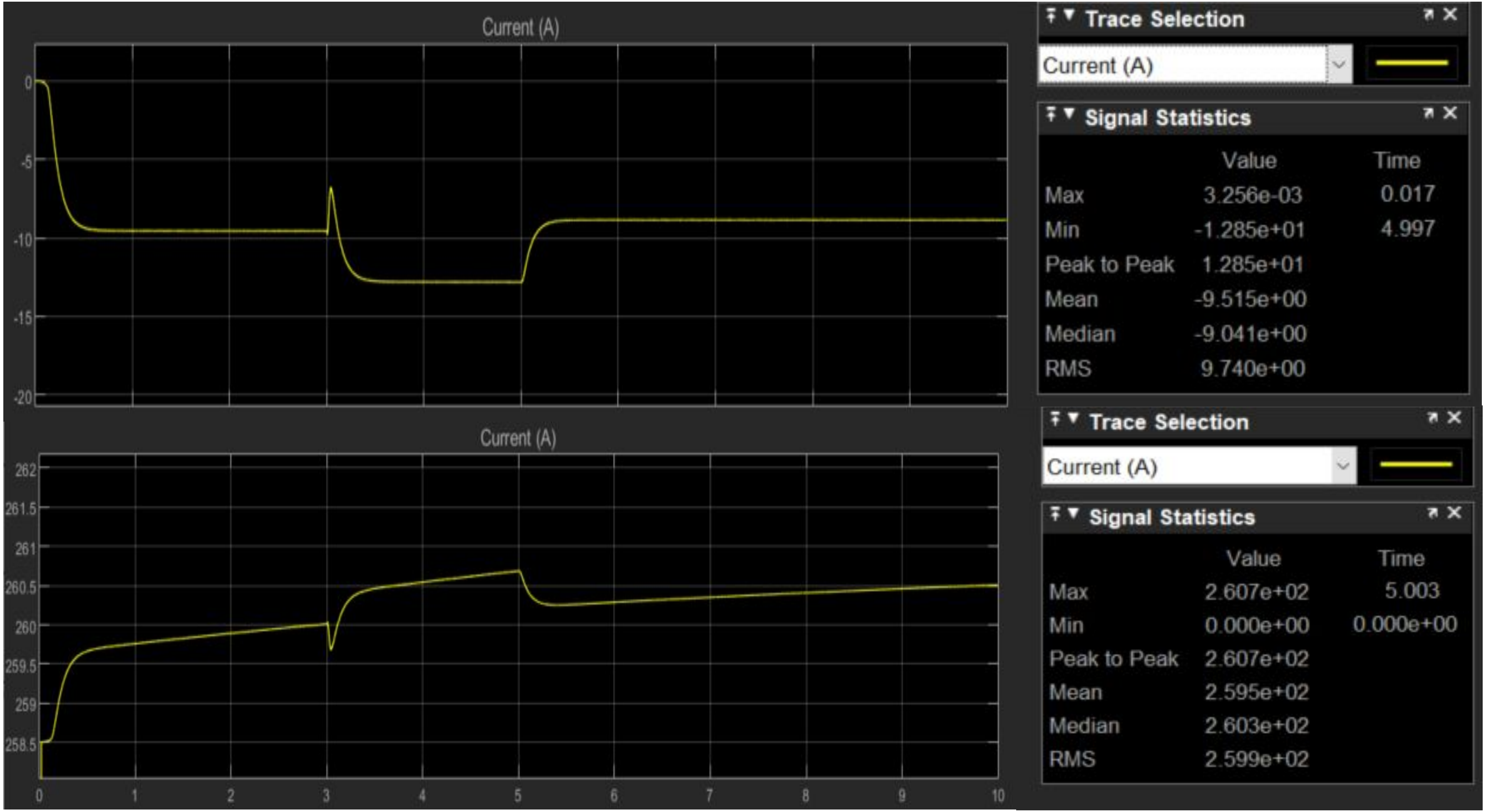

Trace Selection
POWER
Signal Statistics
Value
Time
Max 3.349e+03 4.997
Min -8.416e-01 0.017
Peak to Peak 3.350e+03
Mean 2.476e+03
Median 2.351e+03
RMS 2.535e+03

Battery Parameters

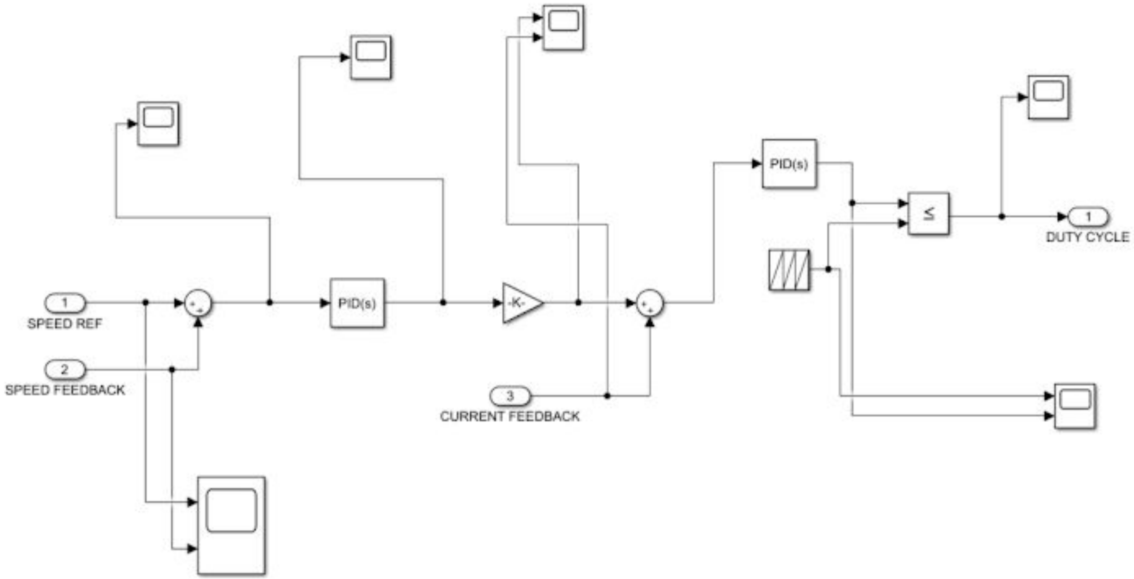




	Value	Time
Max	5.013e+01	10.000
Min	5.000e+01	1.400e-03
Peak to Peak	1.334e-01	
Mean	5.006e+01	
Median	5.006e+01	
RMS	5.006e+01	


Current (A)
0
-5
-10
-15
-20
Trace Selection
Current (A)
Signal Statistics
Value
Time
Max
3.256e-03
0.017
Min
-1.285e+01
4.997
Peak to Peak
1.285e+01
Mean
-9.515e+00
Median
-9.041e+00
RMS
9.740e+00
Current (A)
262
261.5
261
260.5
260
259.5
259
258.5
0
1
2
3
4
5
6
7
8
9
10
Trace Selection
Current (A)
Signal Statistics
Value
Time
Max
2.607e+02
5.003
Min
0.000e+00
0.000e+00
Peak to Peak
2.607e+02
Mean
2.595e+02
Median
2.603e+02
RMS
2.599e+02

Subsystem



1
SPEED REF
2
SPEED FEEDBACK
PID(s)
-K-
3
CURRENT FEEDBACK
PID(s)
≤
1
DUTY CYCLE

Applications

Trains

Dynamic Braking first found its major application in Trains and Metros. Even today Regenerative Braking finds use in trains. The stored electrical energy from braking action is used in providing electricity in lighting, fans, cooling, and sockets that we use for charging etc in trains.

Hybrid Vehicle

Hybrid vehicles still depend on fuel for running of vehicle but make use of Regenerative Braking by switching to it when when brake operation is initiated by a smart controller.
The power generated by this braking is then stored in a battery that provides electrical energy for headlights, horn, charging port, etc.

Elevators

When elevators are required to descend from a height, they make use of regenerative braking to achieve stable speeds of descent along with some production of electricity.

Powerful Electrical Vehicles

Powerful Electrical Vehicles require more power hence more electrical energy. If the electric vehicles is used intensively, the electrical power will drain out rapidly, limiting the usage time for the vehicle.

Many of the Powerful Electrical Vehicles in today's market are trying to overcome this problem by making the machine to depend more on Regenerative Braking, and reducing its assistance from classic mechanical braking system and only depending on the latter in case of failure of the electrical braking.

F1 Cars

Formula 1 cars require high starting power to reach high speeds in less time. This is achieved by a small motor that mechanically aids the fuel powered motion by providing higher torque that helps the Racing Car achieve higher acceleration. This motor is powered by a small battery.

When a car is required to slow down on sharp turns the car uses effective regenerative braking to again charge the small battery an aid in acceleration on the straight road after the turn.

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Acknowledgment

Mr. Krishna Dutt (Professor, Department of Electrical Engineering, DTU) was appointed to me as my instructor of the course EECT(Electromechanical Energy Conversion and Transformers) during the time of pandemic. Since then he has guided me into the deeper concepts of this course.

I would like to heartily thank Mr. Krishna Dutt for his tremendous contribution to this project. Without his efforts and guidance this project wouldn’t have had been anywhere near its current shape.