NATIONAL UNIVERSITY OF SINGAPORE
Department of Electrical and Computer Engineering
AY 2021-22
EE4502 Project-Based Lab Experiments

Exp 1: DC Drive System

Main objective:

In this part of the mini project, DC drive system will be investigated. The experiment starts with the unregulated AC power source such as utility supply mains converted into DC power source and then supplies to the two-quadrant, Class-C converter to drive a DC motor. In the midst of these conversion processes, important factors like dynamic response of the drive system, harmonics and power factor would be evaluated. The two-quadrant operation of the DC drive system incorporating ***forward motoring*** and ***forward braking*** mode of operations would also be investigated. In the last part of the experiment, closed-loop speed control of the DC drive system will be investigated.

Discussions

Introduction to Chopper-Fed DC Motor Drive for Two Quadrant Operation

A **buck (step-down)** chopper converts a fixed dc input voltage to a *lower* variable output dc voltage. Similarly, a **boost (step-up)** chopper converts a fixed dc input voltage to a *higher* variable dc output voltage. When these two converters are connected together and it is possible to create a two-quadrant (CLASS-C) converter. The converter allows **two-quadrant operation** as the current can flow in either directions as shown in Figure .1.

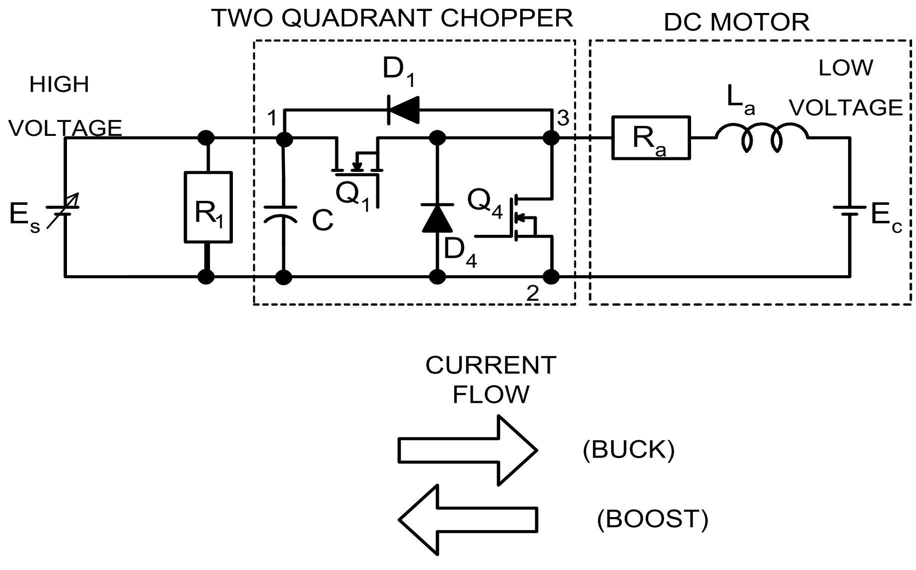


Figure.1: A two quadrant converter driving a dc motor

In Figure.1, switch Q_1 and diode D_4 form the buck converter and switch Q_4 and diode D_1 compose the boost converter. The addition of the boost section to the buck converter circuit provides braking torque capability by allowing the regenerated energy to be sent back towards the source.

When the switch Q_4 turns ON, the dc motor back-emf contributes to reversing the armature current, converting mechanical energy into electrical form. When the switch Q_4 is turned OFF, energy stored in the armature inductor together with the rotational kinetic energy is sent back to the source through diode D_1, as switch Q_1 is being blocked. Energy is then dissipated across the power resistor, R_1. This resistor limits the dc link voltage to be maintained within the allowable limits. Please take note that no energy is sent back to the ac power source.

DC Motor Characteristic Equations:

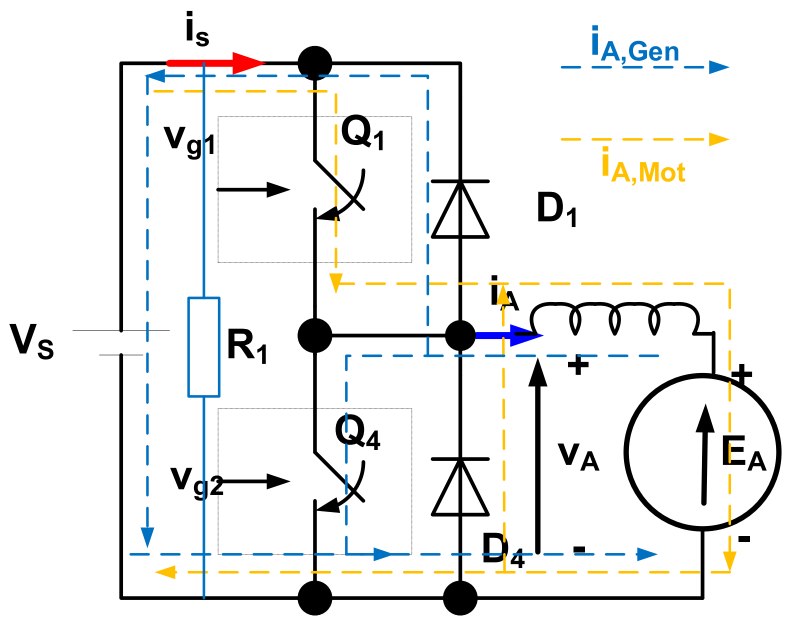


Figure 2: A two quadrant converter driving a dc motor

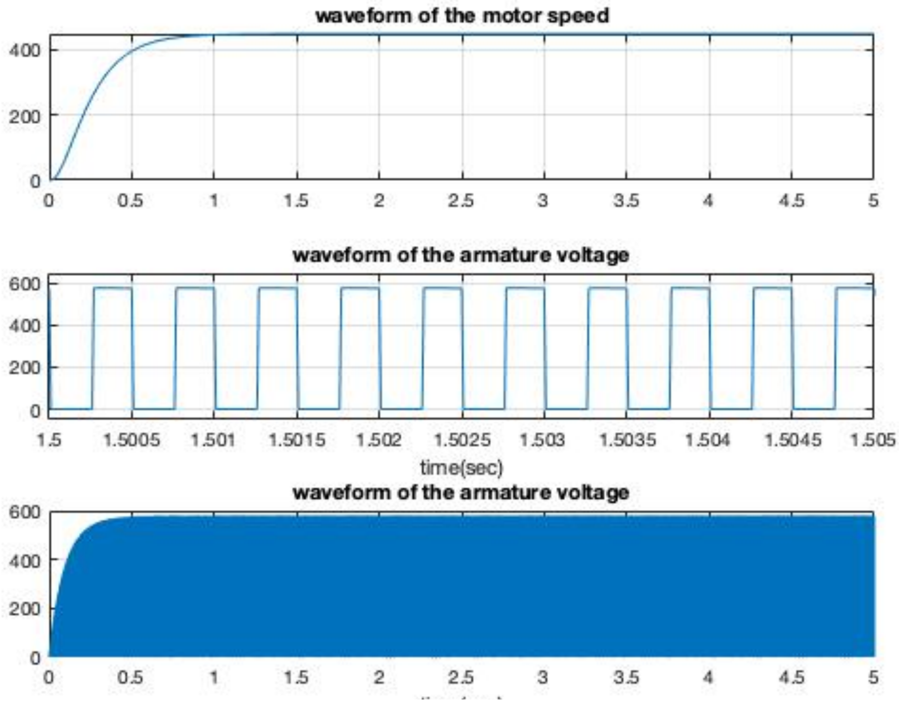
$$E_a = k\phi_f \omega_m = K_E \omega_m$$
$$T_e = k\phi_f I_a = K_T I_a$$
$$K_T = K_E = k\phi_f = kL_{af} I_f$$
$$V_a = E_a + I_a R_a$$
$$\omega_m = \frac{E_a}{K_E} = \frac{V_a - I_a R_a}{K_E} = \frac{V_a}{K_E} - \frac{T_e R_a}{K_E^2}$$

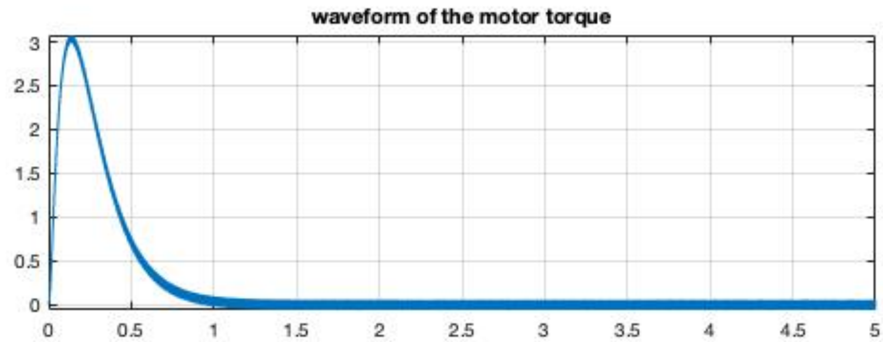
where, E_a is the back emf, V_a is the armature voltage, ω_m is speed, I_a is armature current, R_a is armature resistance, L_f is the mutual inductance, T_{em} is the electromagnetic torque, and I_f is the field current. Neglect the brush voltage drop.

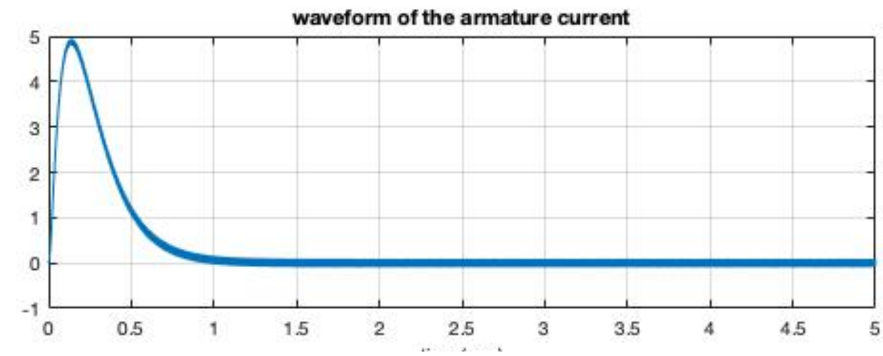
Simulations

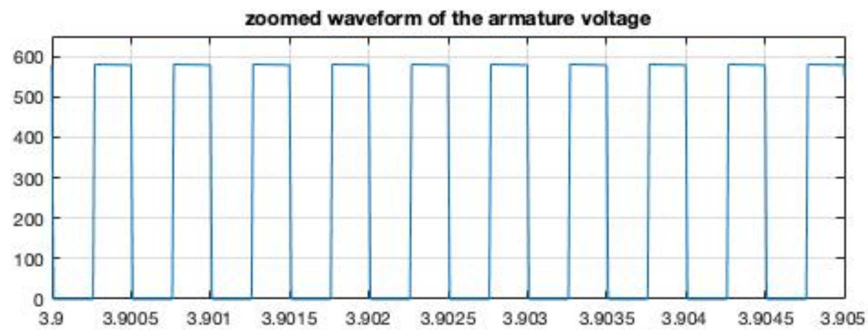
Simulation 1: Introduction to Chopper-Fed of DC Motor Drive under open-loop control

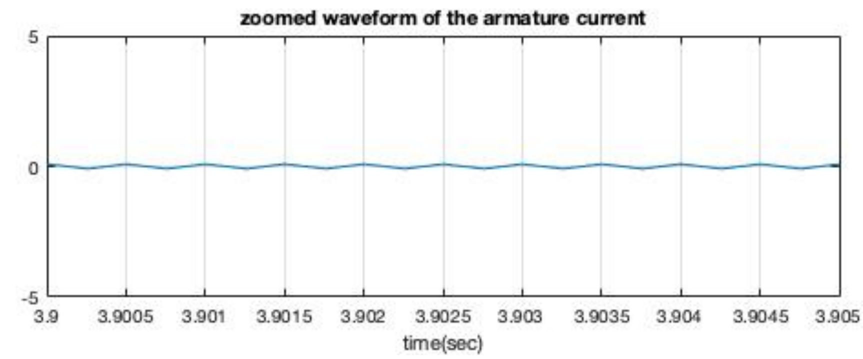
1) When the duty cycle is fixed at 0.5 and no external mechanical load torque is applied, observe the corresponding motor torque, speed, current and voltage waveforms and provide detailed explanations of your observations.







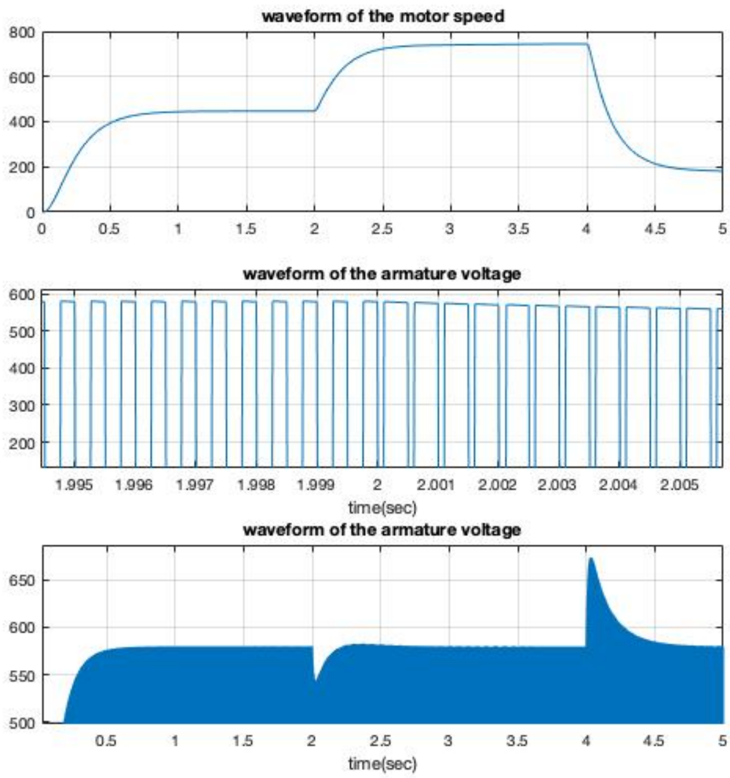


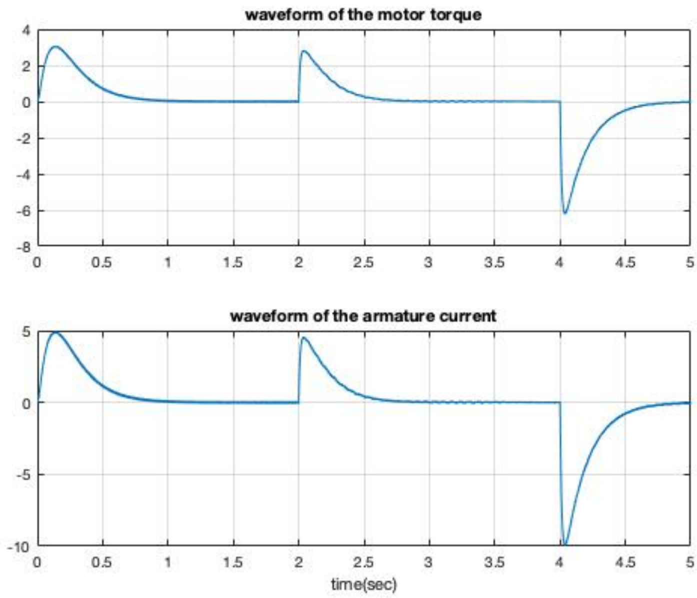


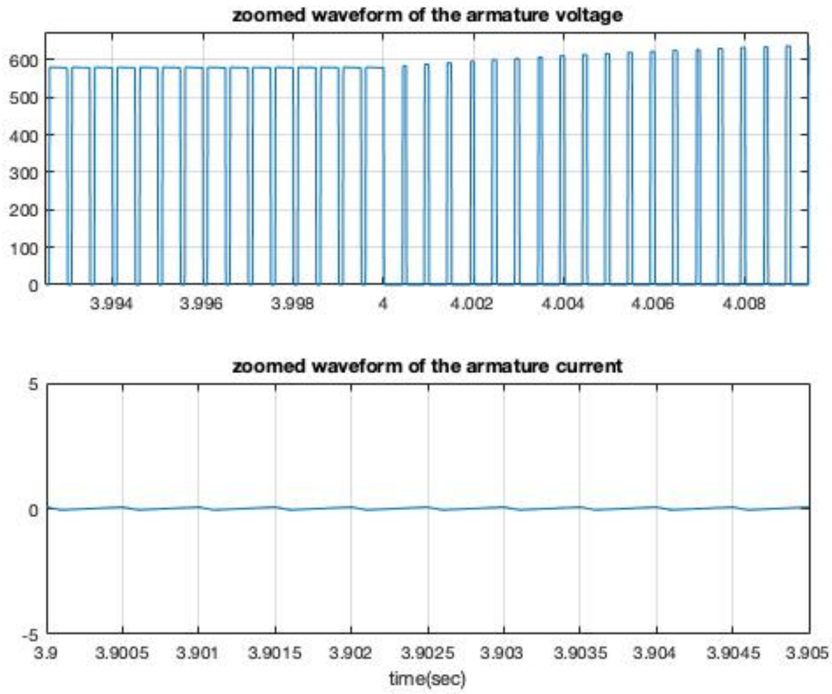
Explanation: The armature current rises almost immediately, peaks and then falls until around 1second due to the motor overcoming its inertia and accelerating. The motor torque needs to be higher than the load torque in order to accelerate. Since the current is proportional (*Kt) to the motor torque, the Armature current Waveform and the Motor torque Waveform have identical shape but values differing by a factor of Kt.

Since there is no external load applied to the motor, once the motor reaches it's no load speed, the motor torque becomes 0 and the motor current becomes 0.

2) Investigate the performance of the drive system when the *duty cycle* is step-changed from 0.5 to 0.8 at t = 2 sec and from 0.8 to 0.2 at t = 4 sec. Please note that no external mechanical load is applied.



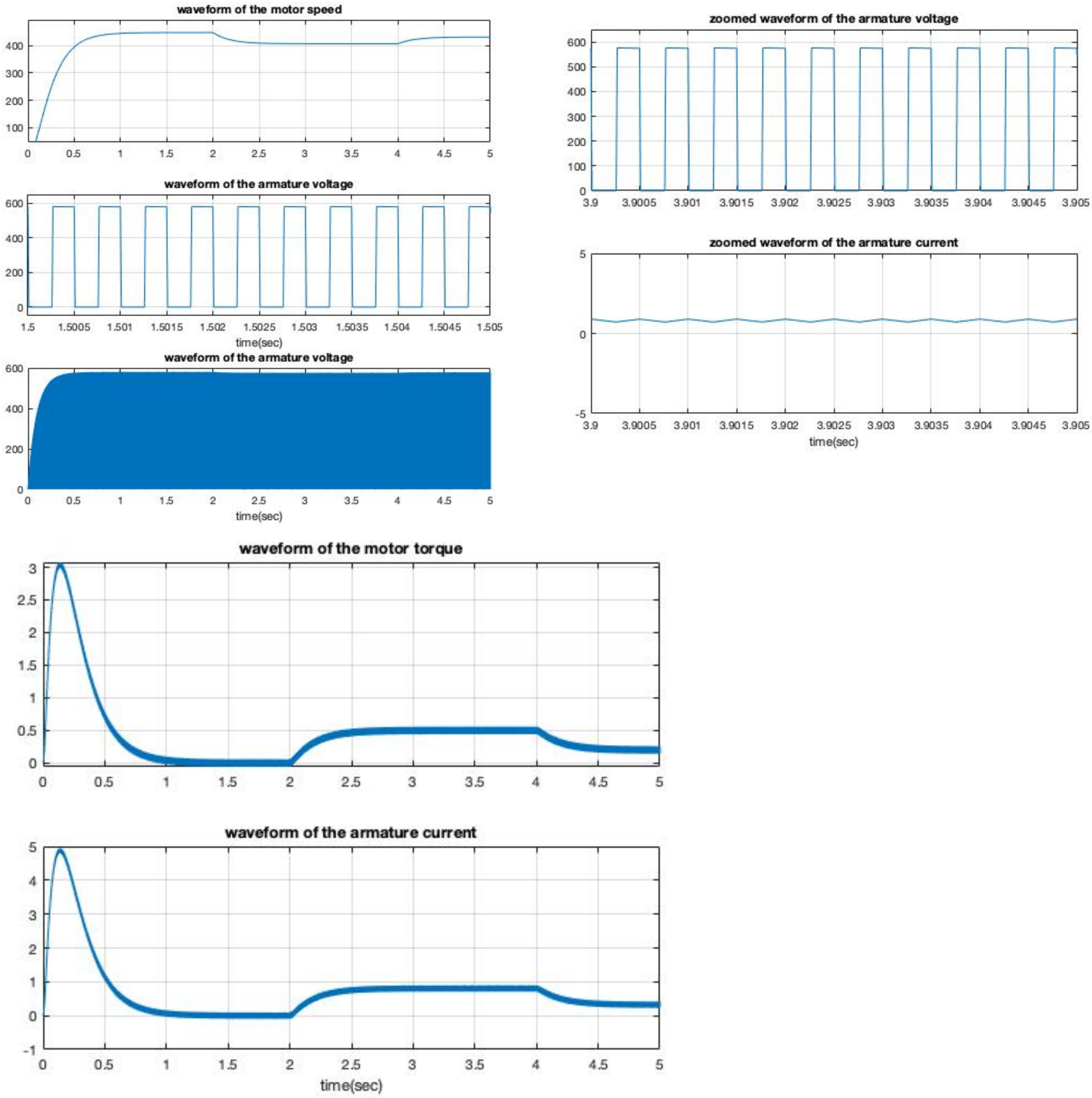




The change in duty cycles can be observed in the figures above. At t = 2s, the duty cycle is increased to 80%, which then increases the current flowing through the armature. The increased current results in a higher motor torque than the motor load, therefore acceleration takes place until the speed. At rated output, for a current increase, the voltage has to decrease, which explains the dip in armature voltage seen at t = 2 seconds.

When the duty cycle is decreased to 20% at t = 4s, the armature current drops to -10A which provides a negative torque to the motor. The motor is operating in the forward braking region. During forward braking, energy stored in the armature inductor and the rotational kinetic energy of the motor is transferred back to the source, this is why a voltage spike is seen in the armature voltage. The armature voltage spike reduces as the speed of the motor reduces and flattens when the motor is at steady state.

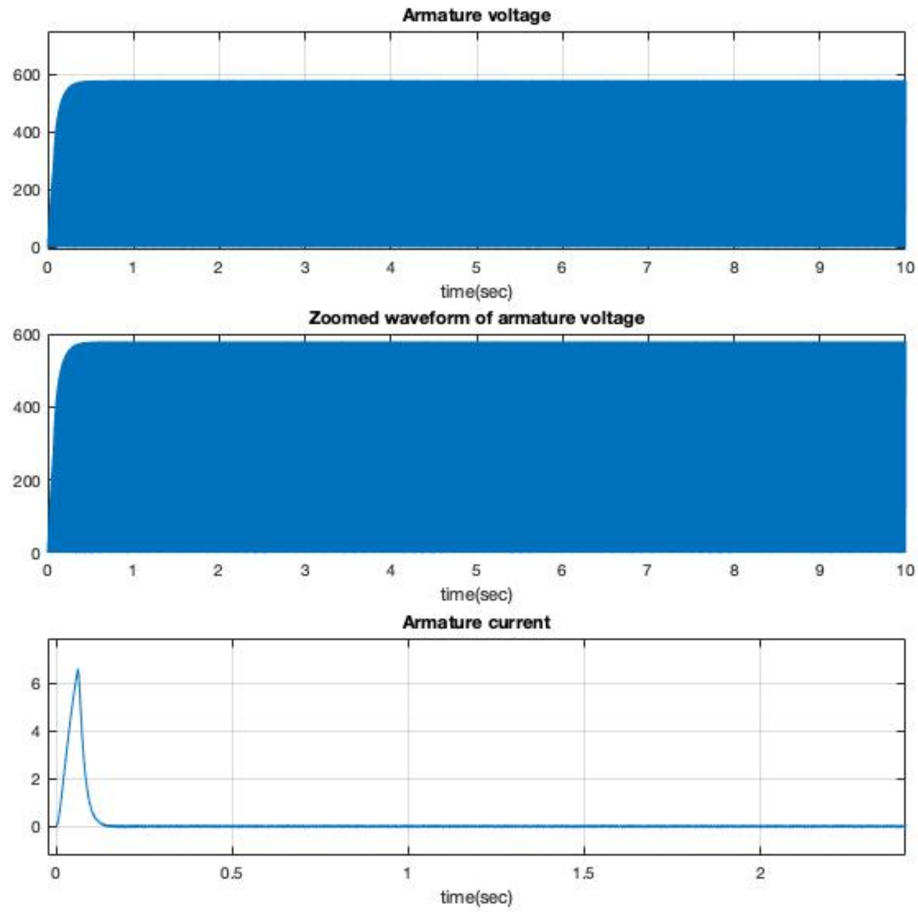
3) Investigate the performance of the drive system when the *load torque* is step-changed from 0 to 0.5 N.m at $t = 2.0$ sec and from 0.5 N.m to 0.2 N.m at $t = 4.0$ sec. Please note that the duty cycle is kept constant at 0.5.

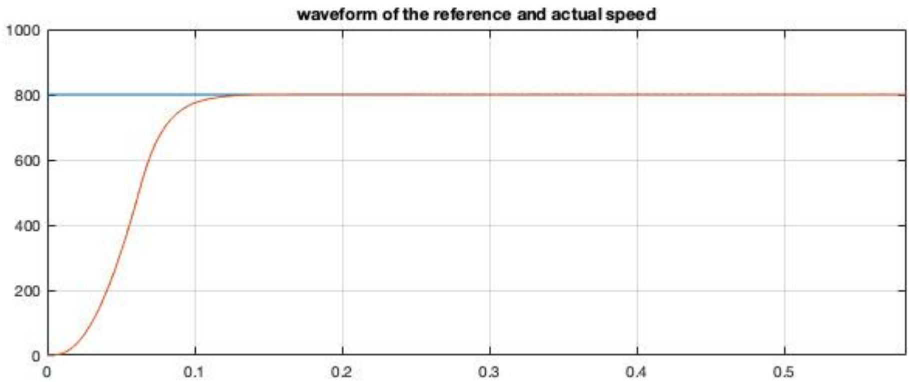


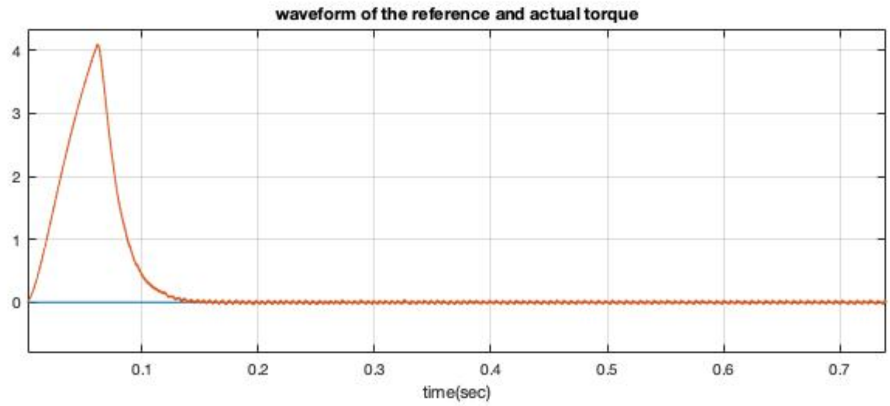
The motor load is increased at t = 2seconds, therefore by the equation of motion, if load torque is higher than motor torque, deceleration would occur. When the armature current decreased, the armature voltage decreased slightly as seen in the figure above. At rated power output, a rise in current would cause a drop in voltage which explains the drop in armature voltage seen at t = 2 seconds.

Simulation 2: Introduction to Chopper-Fed DC Motor Drive with Closed-loop Outer Speed Control Loop and Inner Current Control Loop

1) **The Current controller P gain used was 0.4366 and the I gain used was 32.4626. The Speed controller P gain used was 0.0256 and the I gain used was 0.0163.**
2) When the reference speed is fixed at 800 rpm and no external mechanical load is applied, observe the corresponding motor torque and speed waveforms and explain the results.

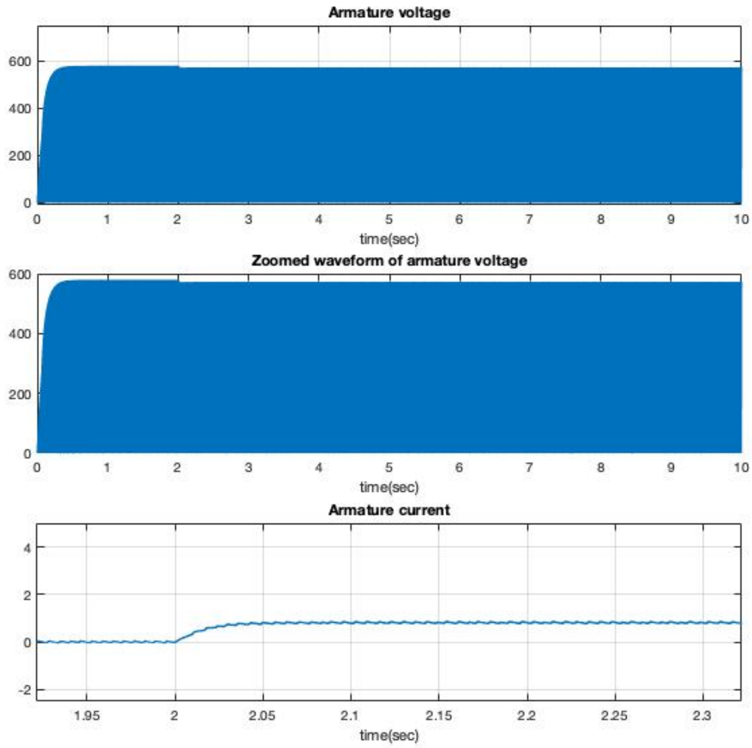


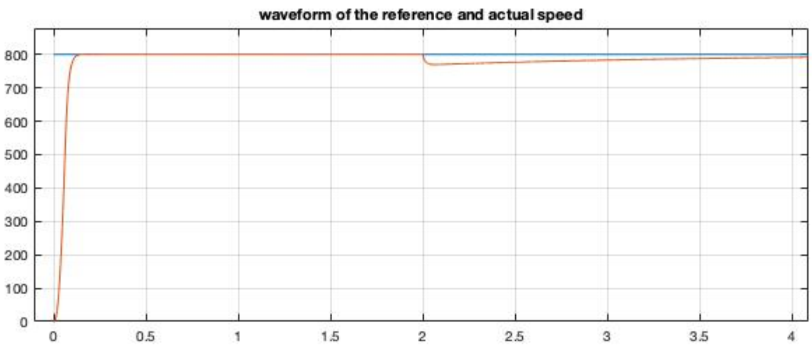


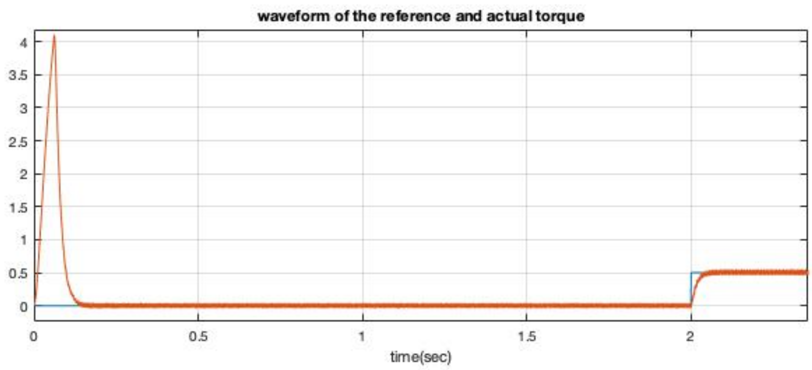


The armature current increases to increase the motor torque which then increase the speed of the motor. However, the response time to reach the desired speed value is much faster compared to the open loop controlled motor. The armature current also has a higher peak value compared to the open loop controlled motor. The motor reaches steady state speed in approximately 0.1 seconds, which is also when the actual load matches the reference value of the load.

3) Investigate the performance of the drive system when the load torque has step-changed by a disturbance of 0.5 N.m at t = 2 sec. Please note that the reference speed is kept constant at 800 rpm.







The response time for the speed reference to adjust back to the setpoint is approximately 4 seconds. This difference between the closed loop and the open loop is that when an external load is applied, the speed will return back to the setpoint in the closed loop however the open loop motor speed is constant and does not return to the setpoint value. In both scenarios, when the armature current is increased, the armature voltage is decreased due to P = V*I.

Experiments

Introduction to Speed Control of Chopper-Fed DC Motor Drive for two quadrant operation (forward motoring and forward braking).

1-A. Open loop speed control of the DC motor

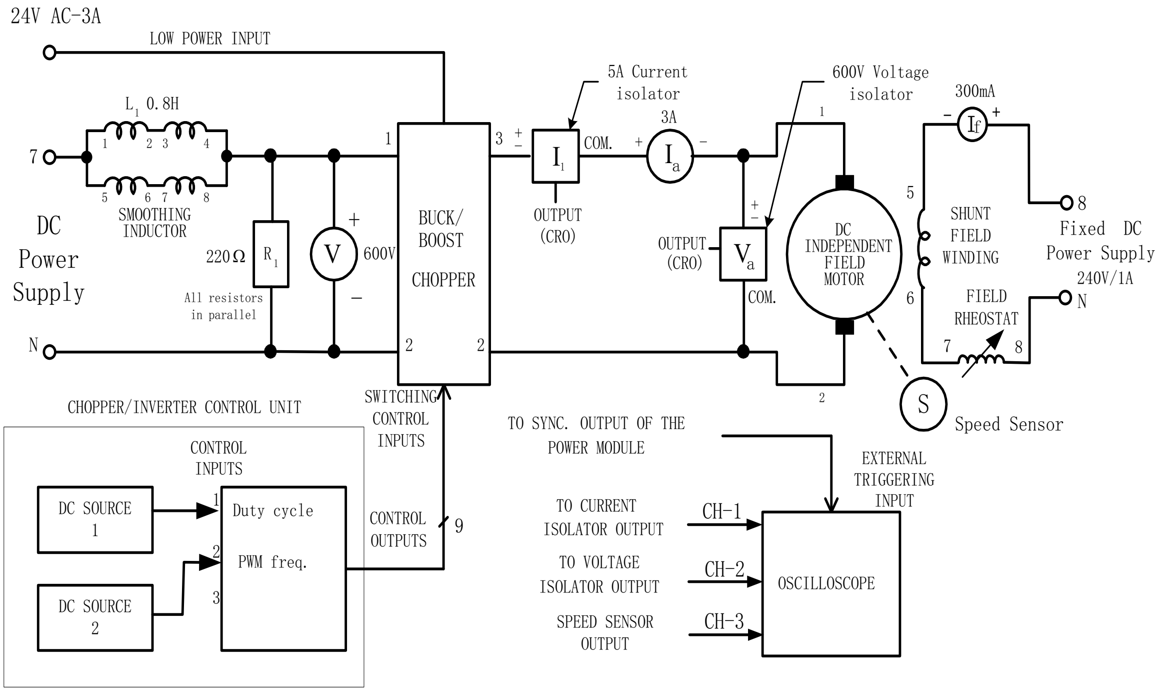


Figure.3: Circuit of a two quadrant converter driving a dc motor drive system

Question 1. Explain the relationship between the PWM duty cycles and the DC motor voltage and speed. Try to discuss about how the current changes when increasing speed or decreasing the motor speed.

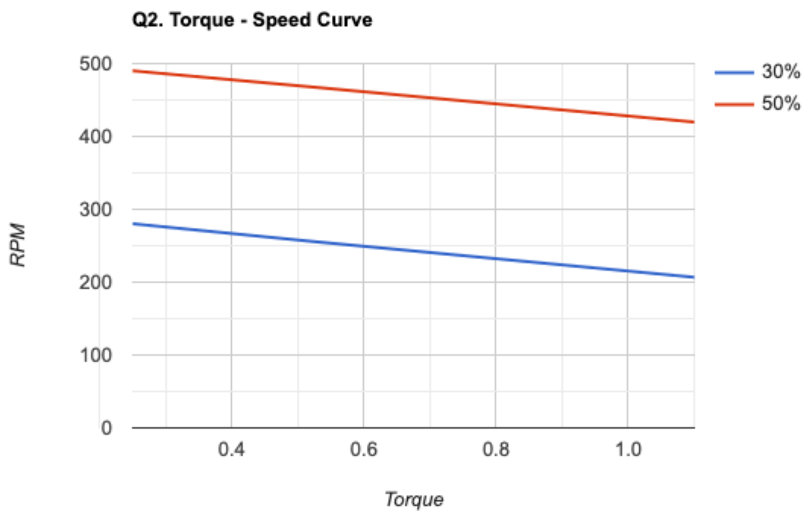
The PWM Duty Cycle varies the DC Voltage supplied to the motor. If the duty cycle is increased, the voltage supplied is increased, if the duty cycle is decreased, the voltage supplied is decreased. The equation is given by Va = dVs, where Va is the voltage supplied to the motor, d is the duty cycle, and Vs is the Voltage from the voltage supply.

When the motor is increasing or decreasing speed, the current increases. However, the direction of current is different. When the motor is increasing in speed, the current Ia is increasing in the positive direction, when the motor is decreasing in speed, Ia is increasing in the negative direction.

1. Set the duty cycle at 30%. Now, load the motor manually by adjusting the load setting of the dynamometer. Slowly increase the load setting and the effect on the motor speed. Take three to four points. Repeat this experiment for duty cycle at 50%.

Duty cycle	**Torque (Nm)**	**Speed (RPM)**
30%	**0.25**	**280**
	0.53	**255**
	1.1	**207**
50%	**0.25**	**490**
	0.53	**467**
	1.1	**420**

Question 2. Plot the torque – speed characteristics of the motor for the two duty cycles and discuss about the nature these curves.



The gradients on the torque – speed curve are similar. Higher PWM provides more armature voltage which then provides a higher speed for a given torque. Therefore, controlling the armature voltage through PWM is suitable for speed control below the base speed.

1-B. Study the effect of field current on the torque-speed characteristics of DC motor:

2. Turn the dynamometer load setting to minimum value.

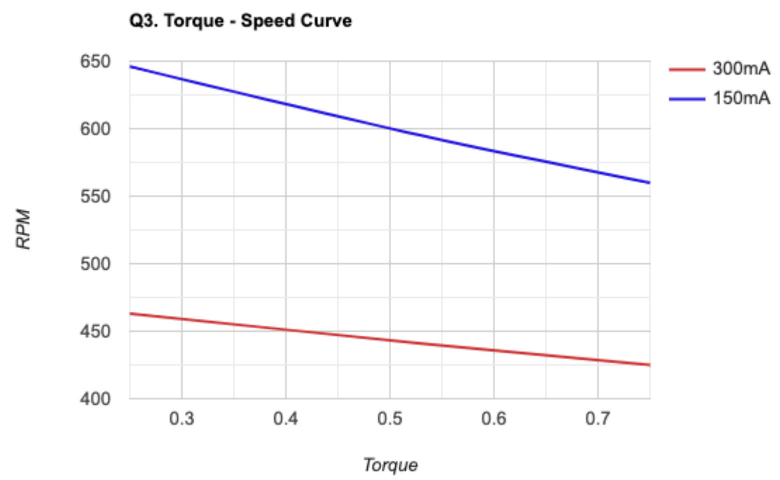
3.(Under No load Conditions) Set the duty cycle to 50%. Adjust the field current to 100mA. Note down the speed of the motor. Repeat this experiment for field current of 200mA and 300mA.

150mA = 681rpm
200mA = 595rpm
250mA = 528rpm

4. (Under Loading Conditions). Set the field current to 300mA, and adjust the duty cycle to 50%. Now, load the motor manually by adjusting the load setting of the dynamometer. Slowly increase the load setting and the effect on the motor speed. Take three to four points. Repeat this experiment for field current at 150mA.

Field Current	**Torque (Nm)**	**Speed (RPM)**
300mA	**0.25**	**463**
	0.53	**441**
	0.75	**425**
150mA	**0.25**	**646**
	0.53	**595**
	0.75	**560**

Question 3. Plot the torque – speed characteristics of the motor for two field currents and discuss about the nature these curves.



The gradients in this control method are different for the same applied voltage. It can be noted that lower flux produces higher speeds for the given torque. Therefore, flux control is not a suitable way to control the speed when the motor speed is below the base speed. This method also increases power losses.

Please answer the following questions and attach the relevant waveforms in the Report

Simulations:

1. Open Loop Control of DC Motor Drive
    a. Attach the motor speed, armature voltage waveform
    b. Attach the motor torque, armature current waveform
    c. Attach the armature voltage and armature current waveform
    d. Comment your observations (how changing duty cycle and load torque affects the armature voltage, armature current, torque and speed and why)

2. Closed Loop Control of DC Motor Drive – speed and current control loop
    a. Mention the speed and current control loop PID parameters used
    b. Attach the speed and torque waveforms
    c. Comment your observations on how changing the load torque affects speed and why?

Experiments:

1-A. Open Loop Control of DC Motor – effect of duty cycle on speed

a. Attach three waveforms of speed variation with duty cycle
b. Answer question Q1 and Q2 and comment your observations

1-B. Open Loop Control of DC Motor – effect of field current

a. Attach torque-speed variation waveforms for two different field currents
b. Answer Q3 and comment your observations