Homework #3

Background Information

An electric scooter, an example shown in Fig. 1, is a personal transportation device that has recently gained popularity. It is suitable for use in cities and urban areas since it is convenient, easy to use, and environmentally friendly. Also, it is usually preferred to have fun and for short trips in the campus.

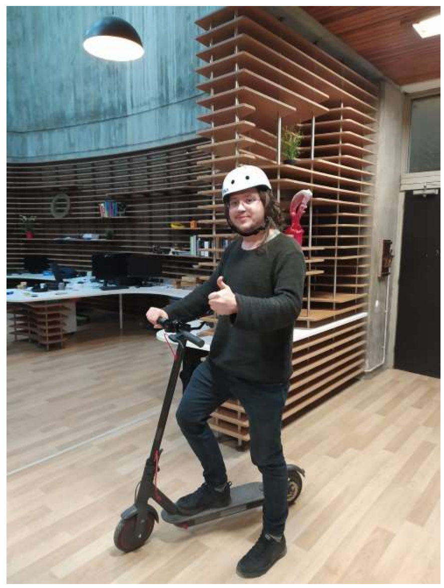

Figure 1 An electric scooter

Electric scooters are made up of electrical, mechanical, and auxiliary parts such as a motor, battery, controller, throttle, wheels, brakes, handlebars, deck, suspension, and display. In this homework, we are interested in only electrical parts which are explained as follows:

1. **Motor**: The motor is responsible for propelling the scooter forward. It is usually located in the hub of the front wheel. Electric scooters typically use either AC or DC motors. AC motors are typically more efficient, but they are also more expensive and require a more complex drive system. Therefore, DC motors are usually preferred.
2. **Battery**: Electric scooters typically use lithium-ion batteries, which are a type of rechargeable battery that is known for its high energy density and low self-discharge rate. Other types of batteries that may be used in electric scooters include lead-acid batteries, nickel-metal hydride batteries, and nickel-cadmium batteries, but lithium-ion batteries are also relatively lightweight and efficient, making them a good choice for use in electric scooters.

3. **Controller**: The controller is the "brain" of the scooter. It receives signals from the throttle and governs the motor drive.

4. **Motor driver**: The motor drive is an electronic device that controls the speed and torque of an electric motor. It receives signals from a controller and converts them into electrical currents to power the motor. Motor drives typically consist of several components, such as converters, control electronics, and cooling systems. They may also have features such as current and voltage sensing, overcurrent protection, and thermal protection to ensure safe and reliable operation. There are several types of motor drives, including brushed and brushless motor drives, AC and DC motor drives, and servo and stepper motor drives.

Part I: Simplified System Structure and Electrical Circuit Parameters

In this homework, we are interested in an electric scooter with a permanent magnet DC motor. The electrical equivalent circuit and system parameters are presented in Fig. 2, and Table 1.

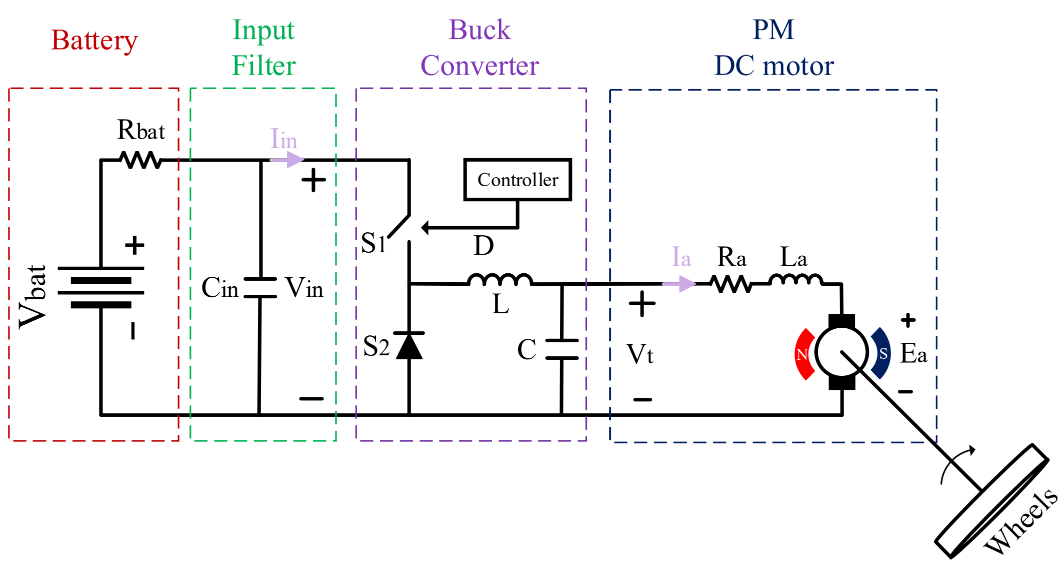

Figure 2 Electrical equivalent circuit of the electric scooter.

Table 1 System Parameters

System Parameters	**Values**
Battery voltage (V_{bat})	$52\ V$
Battery internal resistance (R_{bat})	$0.2\ \Omega$
Input capacitance (C_{in})	$100\ \mu F$
Buck converter inductance (L)	$400\ \mu H$
Buck converter capacitance (C)	$100\ \mu F$
Armature resistance (R_a)	$73.8\ m\Omega$
Armature inductance (L_a)	$120\ \mu H$
Machine constant (K_a)	$0.3416 \frac{V}{rad/sec}$
Motor rated terminal voltage (V_a)	$48V$
Motor inertia (J_a)	$0.0130\ kg.m^2$
Motor rated power	$250W$

a) Assume that the rated mechanical load (included mechanical losses of the motor) is given as follows:

$$P_{mec} = 250\ W$$

Find the rated current, input power, and rated speed of the motor while 48 V is applied to terminal.

b) Assume that the mechanical losses can be defined as a function of the rotational speed as given:

$$P_{loss} = 7.8 + 0.2\omega + 0.002076\omega_{mech}^2$$

Find the mechanical losses for the rated speed, and calculate the efficiency of the motor.

c) The shaft of the electric motor is directly connected to the wheel which of a diameter is 10 cm. Find the rated speed of the scooter in $\frac{km}{h}$ for the full-load condition.

d) The duty cycle of the switch (S1) is given as *D*. The load current is given as I_a. The switching period is given as *T*. Assume the converter is working in continuous conduction mode. Assume the input voltage of the buck converter (battery voltage) is constant and the output voltage (terminal voltage) ripple is very small.
Sketch the following waveforms for two switching periods. Align the time axis of all graphs. Express axis values in terms of V_{in}, Vt, I_a, D, T, L, and C.
   i. Sketch inductor current i_L and inductor voltage v_L on the same time axis.
   ii. Sketch the current waveform i_C of the capacitor.
   iii. Sketch the voltage and current waveform of switch S1 on the same time axis.
   iv. Sketch the voltage and current waveform of diode S2 on the same time axis.
   v. Determine the maximum instantaneous voltage and the maximum instantaneous current for diode S2 and switch S1.

(Attention: You can ignore the battery internal resistance for this question, but actually a drop in the battery voltage which is due to the battery current exists.)

e) Find the required range of the duty cycle to be able to apply the full range voltage (0 to 48V) to the motor terminal for the given battery parameters.
(Attention: You can ignore the battery internal resistance for this question, but actually a drop in the battery voltage which is due to the battery current exists.)

f) Assume that the rated voltage (48 V) is applied to the terminal voltage when the motor is standstill with no load (also no friction). For this situation, plot the motor current and motor speed with respect to time. No numerical values are required.

g) Write some of the disadvantages of high starting current (in part e) in respect of both the motor and the drive, and suggest any control methods to limit this starting current.

Part II: Modelling of Electric Scooter in Simulink

We established a setup, as given in Fig. 3, to simulate the control of the electric scooter in Simulink. In this simulation, we can control our terminal voltage by the duty cycle of S1, and also, we can achieve the scooter ride modeling in the different road characteristics by changing the load torque of the DC motor.

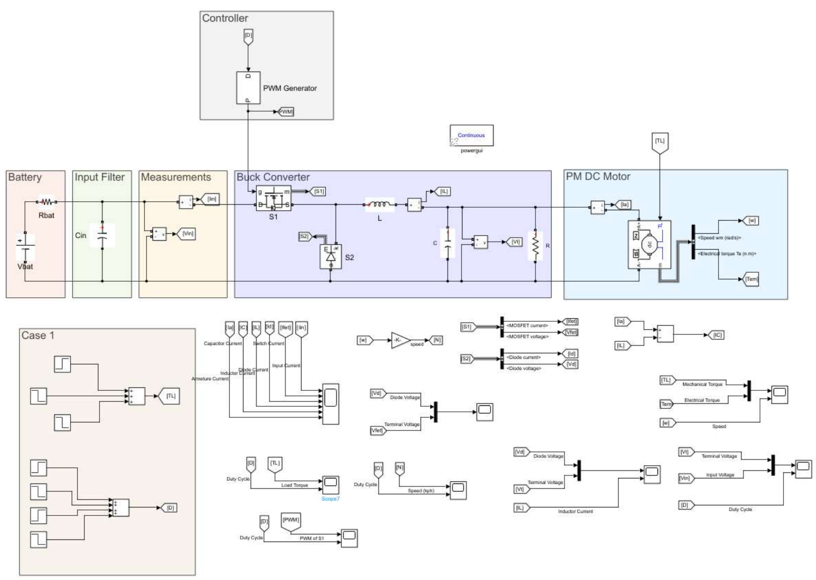

Figure 3 Simulink Model of an Electrical Scooter

In the first case, we have varying load torques and duty cycles with respect to time as shown in Fig. 4.

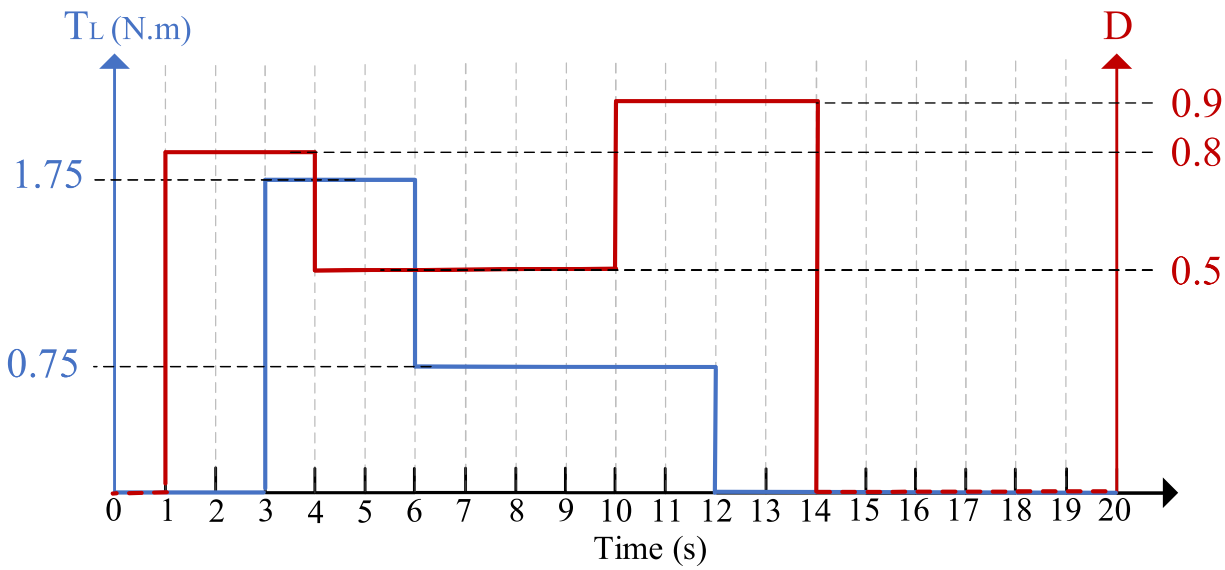

Figure 4 Varying load torques and duty cycles with respect to time for Case 1

a) Which kind of change do you expect in the rotational speed for these duty cycles and load torques? No numerical values are required, you can only give trends time by time.

b) Run the Simulink model of Case 1. Plot the armature, inductor, and switch currents in the Simulink model. Do you have overshoots in the currents? If yes, why do we have these overshoots? Explain.

c) Plot the load torque, electrical torque, and rotational speed with time. How does the speed relate to load torque and electrical torque? Explain.

d) Plot the duty cycle, input voltage and terminal voltage with time. Does terminal voltage depend on the duty cycle?

In the second case, we have varying load torques and duty cycles with respect to time as shown in Fig. 5.

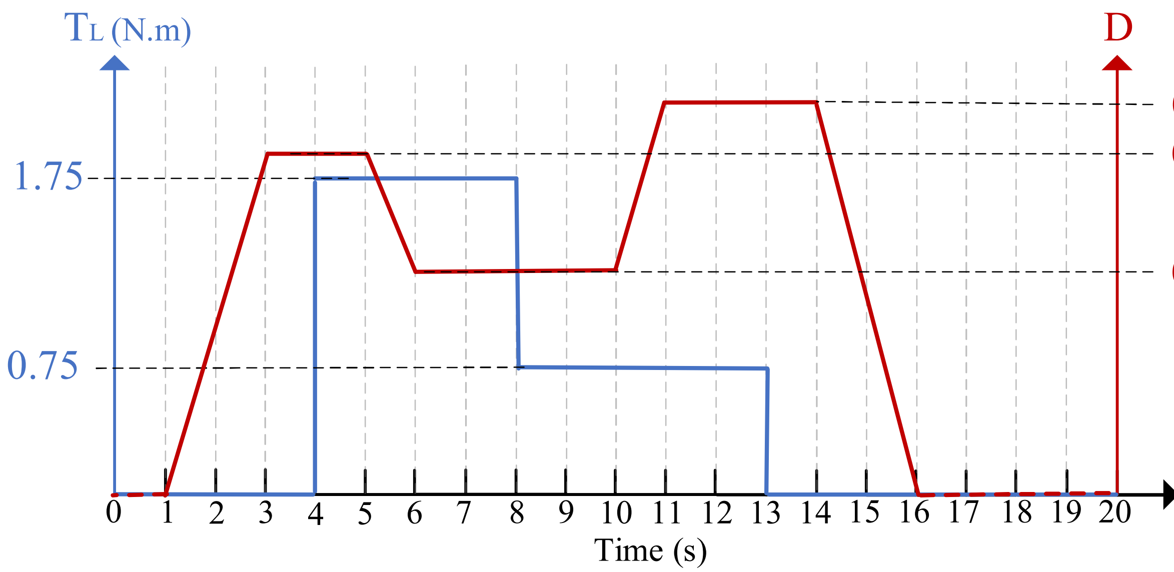

Figure 5 Varying load torques and duty cycles with respect to time for Case 2

e) Which kind of change do you expect in the rotational speed for these duty cycles and load torques? No numerical values are required, you can only give trends time by time.

f) Run the Simulink model of Case 2. Plot the armature, inductor, and switch currents in the Simulink model. Compare the overshoots in the currents with the previous case. In this case, do you think that the motor is soft-started?

g) Plot the load torque, electrical torque, and rotational speed with time.

h) Plot the duty cycle, input voltage and terminal voltage with time.

i) Considering both cases,
   A) Does the terminal voltage of the motor (output voltage of the Buck converter) depend on the motor current? Explain.
   B) For the constant duty cycle, does the speed of the motor depend on the motor current? Explain.
   C) Is the motor current directly related to terminal voltage? Explain.
   D) It is observed that an instantaneous increase in the load torque causes a motor current to over-shoot transiently. How can this over-shoot be avoided?