Four-Quadrant DC Motor Controller

1 Objectives

- Understand pulse width modulation (PWM) for speed control of dc motors.
- Understand one- and four-quadrant operation of dc motors.
- Decide which features are implemented by the controller and which features are delegated to digital logic.
- Implement a simple finite-state machine using VHDL.
- Simulate the operation of the FSM.

2 Introduction

The controller to be designed controls the operation of a dc motor. This application is used in many areas such as to control the rudder of an airplane, electric bicycle or an electric car. Figure 1 shows a simplified brush dc motor construction. The motor is built from a stationary magnet (called *stator*) and rotating coils (called *rotors*). The brushes supply electric current to the coil that is close to the motor magnet pole pieces. As the rotor turns, the polarity of each coil is reversed and sustained rotation of the motor is achieved.

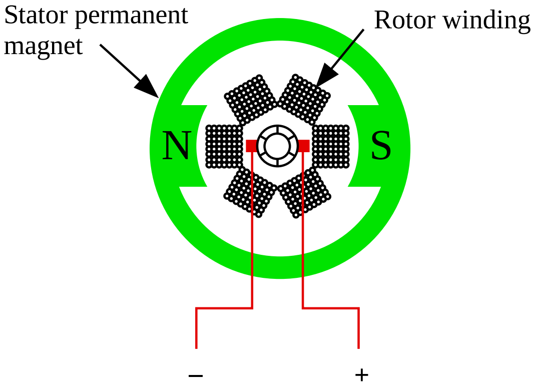

Figure 1: Simplified construction of a brush dc motor.

The direction of rotation depends on the polarity of the brushes. The torque applied on the rotor depends on the current passing through the coils. The steady speed depends on the current flowing through the coils and load being driven by the motor.

2.1 One-quadrant motor operation

Figure 2 shows one-quadrant mode of operation. In this mode, the polarity of the brushes is fixed and the motor spins in the same direction. The figure shows that the torque applied is clockwise (CW) and hence the resulting speed is clockwise also.

Increasing the current through the coils increases the torque and speed increases as a consequence. Slowing down the motor, however, is achieved only by reducing the current through coil and the motor slows down through the natural friction and load inertia. Hence, one-quadrant mode of operation does not provide strong control over the motor operation.

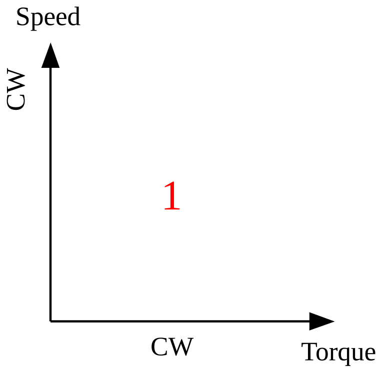

Figure 2: One quadrant mode of operation for a dc motor.

2.2 Four-quadrant motor operation

Figure 3 shows four-quadrant mode of operation. In this mode, the polarity of the brushes can be reversed. The motor can spin in the same direction as the applied torque or it can spin in the opposite direction. The figures shows that the torque applied could be clockwise or counter clockwise (CCW).

Quadrant 1 is CW speed and torque. Power is supplied to the motor to propel the motor. Quadrant 3 is CCW speed and torque. Power is supplied to the motor to propel the motor.

Quadrant 2 is CW speed and CCW torque. Torque is actively used to apply brakes to the motor to slow it down. The motor is generating power instead of consuming it. The generated power could be used to recharge the batteries that might be used to drive the motor. Quadrant 4 is CCW speed and CW torque. Torque is actively used to apply brakes to the motor to slow it down. The motor is generating power instead of consuming it. The generated power could be used to recharge the batteries that might be used to drive the motor.

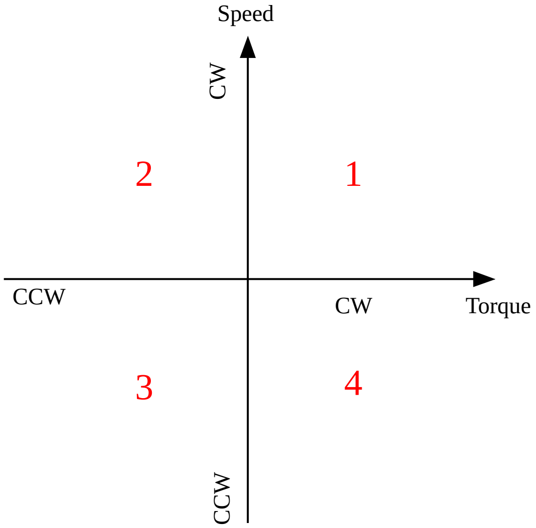

Figure 3: Four quadrant mode of operation for a dc motor.

3 Pulse Width Modulation (PWM) Drive

By applying a train of pulses to the motor windings, it is easy to control the speed of the dc motor without wasting too much energy. Pulse width modulation (PWM) varies the duty cycle of the pulse train. Four-quadrant control of the motor is achieved by varying the duty cycle and polarity of the applied pulses.

Figure 4 shows the polarities applied across the dc motor windings due to the totem pole bridge rectifier for a four-quadrant (4Q) motor control system. Figure 4(a) shows the case when switch pair $S1$ is closed and $S2$ is open. Figure 4(b) shows the case when switch pair $S2$ is closed and $S1$ is open.

Figure 5 shows the current flowing through the motor winding during one period of the pulse train. Switches $S1$ open and close in unison since the same signal is applied to them. Switches $S2$ open and close simultaneously also but they are activated by the *complement* of the pulse train as shown.

We have to ensure that pulses applied to $S1$ and $S2$ are not overlapping. There is a *deadtime* around the pulses rising and falling edges so that switches $S1$ and $S2$ are never open at the same time to ensure that the power supply will not be shorted.

The duty cycle of the pulse train is given by the equation

$$\text{Duty Cycle \%} = \frac{T_1}{T} \times 100 \tag{1}$$

where T_1 is the duration of pulses applied to the switch pair $S1$ and T is the pulse period. The figure shows the case when the duty cycle for $S1$ is approximately 50% and the pulses supplied to switches $S1$ and $S2$ are equal in duration. In that case the average current passing through the motor winding is zero and the motor will not move. If the duty cycle is

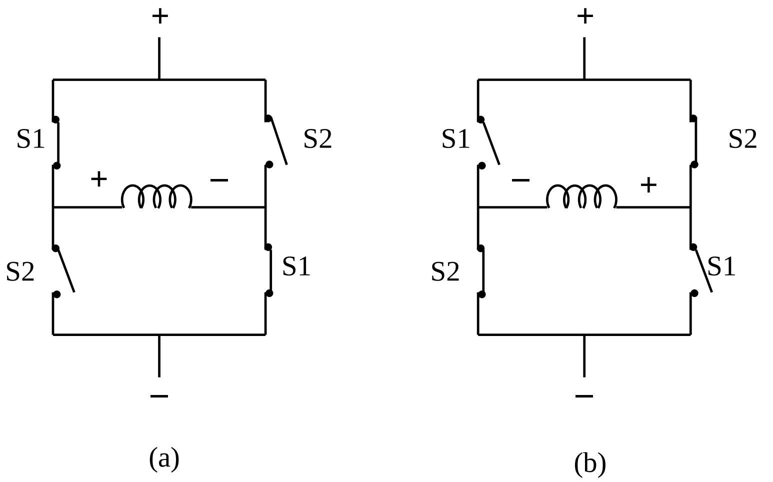

Figure 4: Motor winding polarity during operation of a four-quadrant system. (a) When switch pair $S1$ is closed and $S2$ is open. (b) When switch pair $S2$ is closed and $S1$ is open.

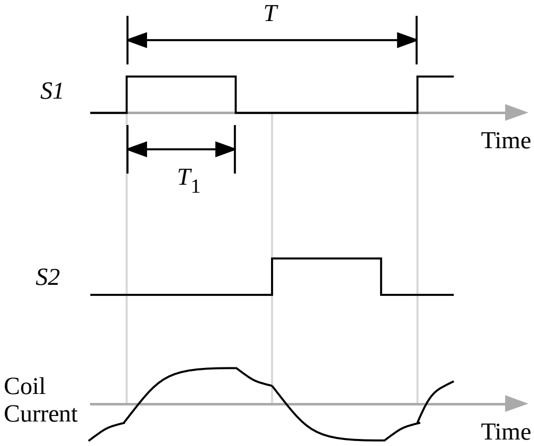

Figure 5: Current flowing through motor winding.

between 50%–100%, the motor will spin clockwise. Conversely, if the duty cycle is between 0%–50%, the motor will spin counter clockwise. Therefore, it is possible to obtain precise control of the motor speed and direction of rotation in spite of the load being driven.

3.1 Motor Operation

A user typically selects a desired steady state velocity and rotation direction. The motor controller has to supply the proper pulses with proper duty cycle. However, the controller must ensure that the changes in pulse duty cycle are done gradually so as to limit the amount of current swings through the motor windings. This is done to ensure that the torque applied to the motor is not excessive and also to ensure that the motor does not accelerate or decelerate suddenly in either direction. This is accomplished through the use of proper sensors attached to the motor to monitor its speed and winding current values.

Figure 6 shows the overall speed control system which is composed of the motor controller and the sensor electronics. Note that employing lots of electronic hardware simplifies the task of designing the FSM.

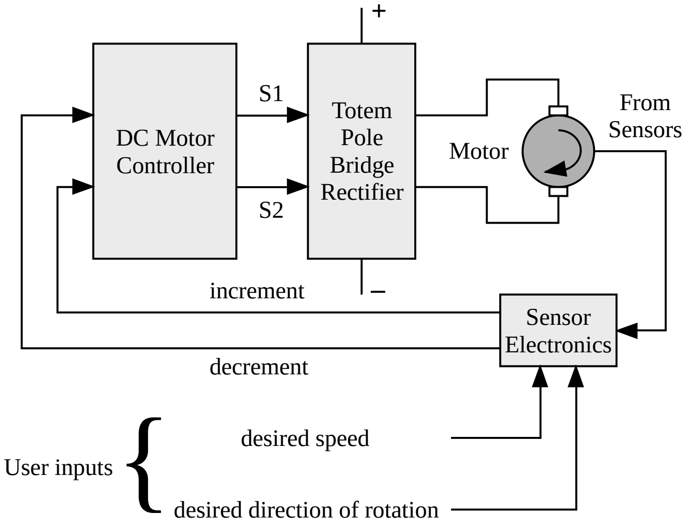

Figure 6: Sensors attached to the motor monitor motor speed and winding current and send signals to the motor controller.

The sensors monitor the speed of the motor, its direction of rotation, and the current flowing through its windings. The sensor electronics also receive from the user the desired motor speed and direction of rotation. Based on these inputs the sensor electronics generate two signals *increment* and *decrement* to increment or decrement the duty cycle of the pulse train for $S1$ signal. Increasing or decreasing the duty cycle of $S1$ will have the opposite effect on $S2$ since this signal is complementary to $S1$.

4 DC Motor Controller Details

Figure 7 shows the main components of the dc motor controller.

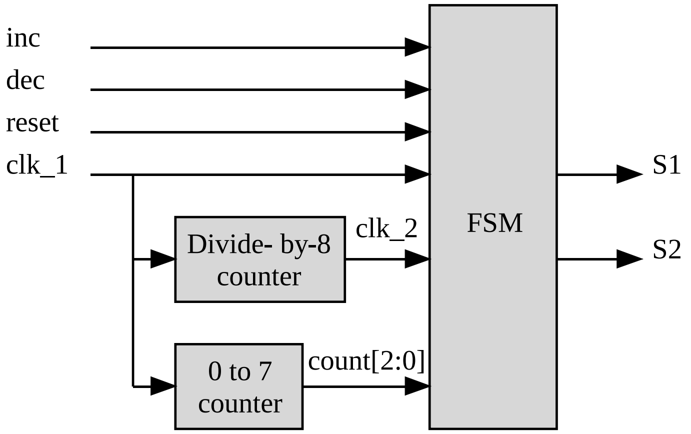

Figure 7: The main components of the dc motor controller.

The controller is composed mainly of the finite-state machine (FSM), a divide-by-8 counter, and a 0-to-7 counter. The FSM generates the desired waveforms for outputs $S1$ and $S2$. The divide-by-8 block generates a new clock (clk_2) that is 8 times slower than the system clock. The slower clock facilitates generating the different waveforms. The 0-to-7 counter counts the number of clk_1 pulses in each clk_2 period. This counter is used to control the duty cycle of signals $S1$ and $S2$. In effect, Clock clk_1 and the 0-to-7 counter are used to control the duty cycle of outputs $S1$ and $S2$. Clock clk_2 determines the period of the waveforms.

Figure 8 shows the $S1$ and $S2$ waveforms for the case when the duty cycle is 3/8. Note that the duty cycle of each signal $S1$ or $S2$ is controller by counting the number of clk_1 pulses. On the other hand, the period of the waveforms, i.e. the pulse rate, is equal to the period of clk_2.

Therefore, the controller is able to provide 8 levels of pulse widths of Signal $S1$:

$$T_1/T = \ 0 \quad 1/8 \quad 2/8 \quad 3/8 \quad 4/8 \quad 5/8 \quad 6/8 \quad 7/8 \quad 1$$

If we require more transition levels and perhaps even control the deadtime, then we could have used a divide-by-16 counter or even a divide-by-32 counter.

4.1 FSM Specifications

The FSM for the dc motor controller has the following specifications.

1. The default state is when the duty cycle for $S1$ and $S2$ is 50%.

2. When *decrement* and *increment* are both zero FSM does not change its state.

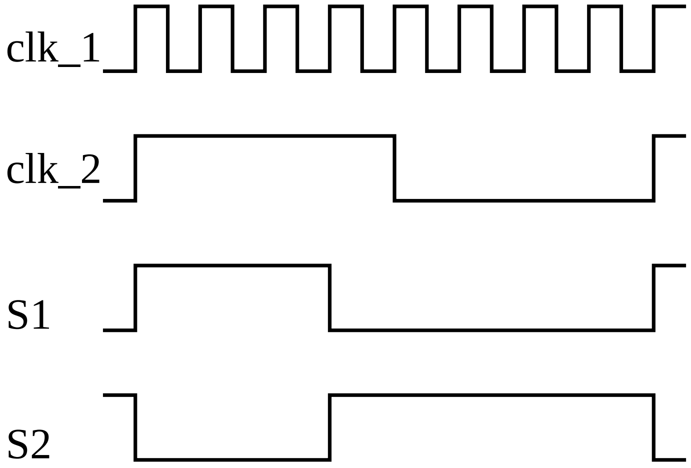

Figure 8: The relation of waveforms for $S1$ and $S2$ and the two clocks clk_1 and clk_2 when the duty cycle for $S1$ is 3/8.

3. When *decrement* and *increment* are both one FSM does not change its state.
4. When *increment* is asserted, FSM increases duration of $S1$ by one clk_1 pulse and decreases $S2$ duration by one clk_1 pulse.
5. When *decrement* is asserted, FSM decreases duration of $S1$ by one clk_1 pulse and increases $S2$ duration by one clk_1 pulse.

5 Pre-Lab Report

Draw a Mealy-style state diagram which covers all legal state transitions of the FSM.

6 Project Requirements

In this project you are required to design, model and simulate the finite-state machine for the traffic light controller.

1. Use a three-process FSM VHDL coding style. Make sure you have adequate and clear comments in your code.
2. Write a testbench to verify the operation of the FSM. The testbench should try different scenarios for motor accelerating, running at a constant speed, and decelerating.
3. Simulate the behavior of the FSM using the testbench you developed.

7 Lab Report

1. Refer to the lab report grading scheme for items that must be present in your report.
2. Provide a table indicating all the input and output signals of the dc motor controller and the controller FSM.
3. Draw a neat Mealy-style state-diagram with all the states used and the transitions clearly labeled. Write a brief note about what is being done in each state.