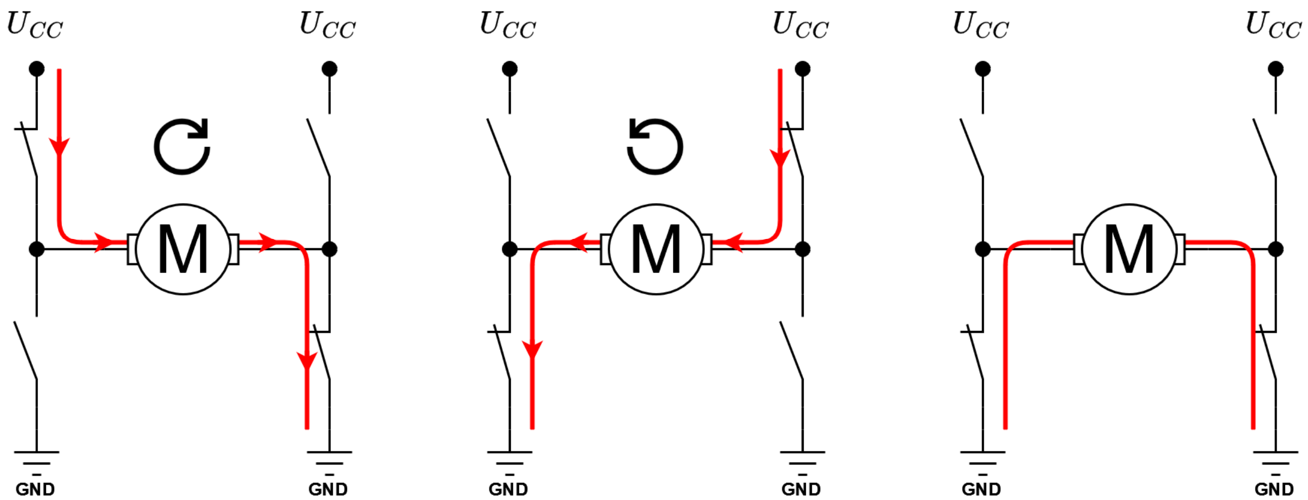
DC Motor Driver

Requirements for the exercise (issues and skills necessary to complete the task):

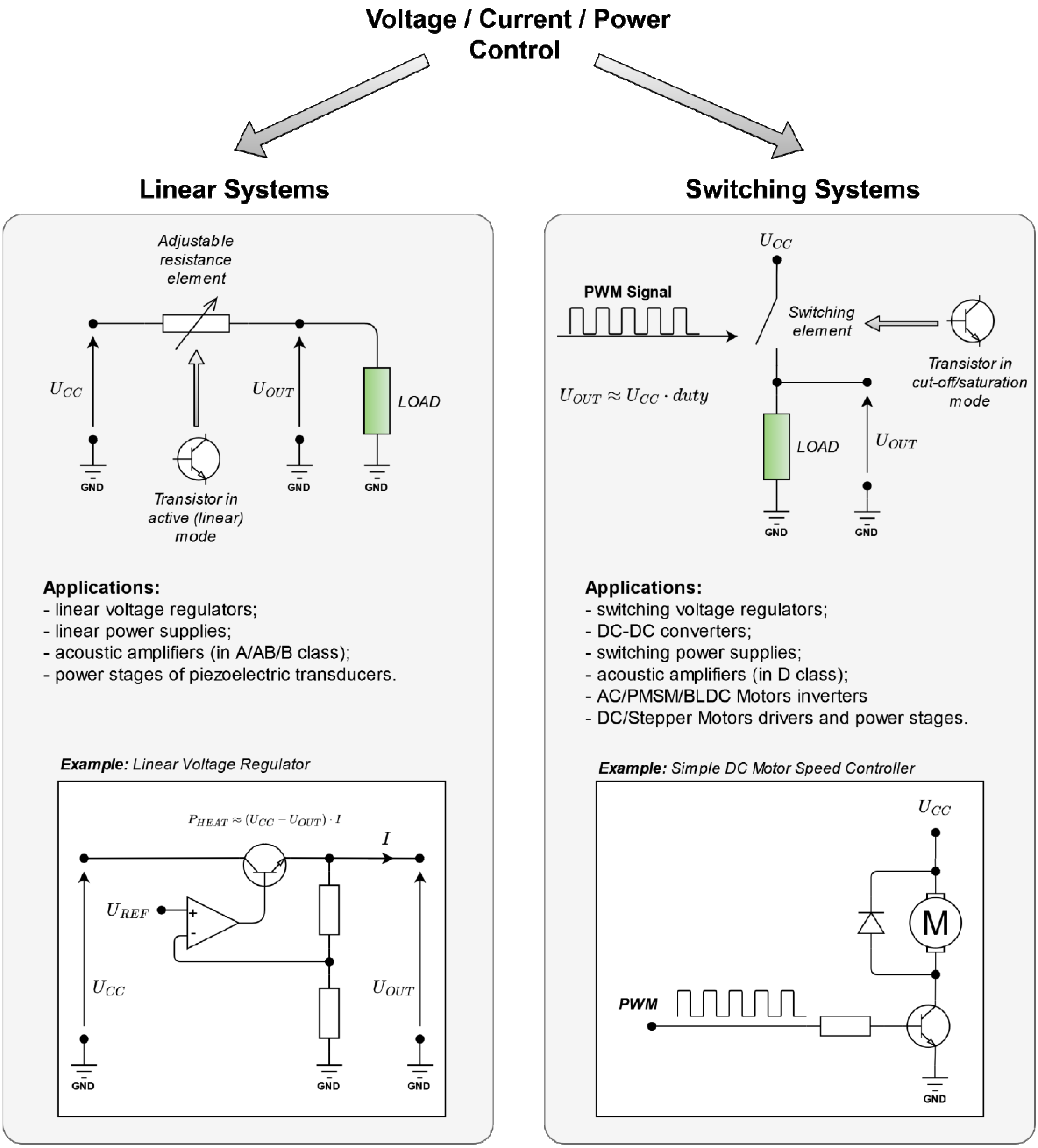
- **representation of numbers in decimal, binary and hexadecimal systems;**
- **setting up a new project in Quartus Prime;**
- **creating a hardware module (symbol) in Quartus Prime based on a schematic file (*.bdf);**
- **creating a hardware module (symbol) in Quartus Prime based on a source code file (eg. *.vhd);**
- **ability to simplify a logical expressions using the Karnaugh Map method;**
- **ability to implement a scheme with logic gates based on an algebraic equation;**
- **design mod 2^N counter.**



Clockwise rotation	Counterclockwise rotation	Dynamic Braking

1. PWM Modulation

PWM modulation is a commonly used method of generating control signals in impulse systems. The PWM signal has a fixed frequency and amplitude, the variable parameter is the pulse width (duty).



Advantages: ⊕ simpler and more robust construction; ⊕ low level of generated ripples and interference EMC/EMI; ⊕ cheap for low power applications. **Disadvantages:** ⊖ **low efficiency (~ 50%);** ⊖ low power-to-weight (and power-to-volume) ratio for high power applications; ⊖ expensive solution for high power applications.	**Advantages:** ⊕ high efficiency (~80 – 90%); ⊕ good power-to-weight (and power-to-volume) ratio; ⊕ cheap solution for high power applications. **Disadvantages:** ⊖ more complex construction; ⊖ high level of generated ripples and interference EMC/EMI.

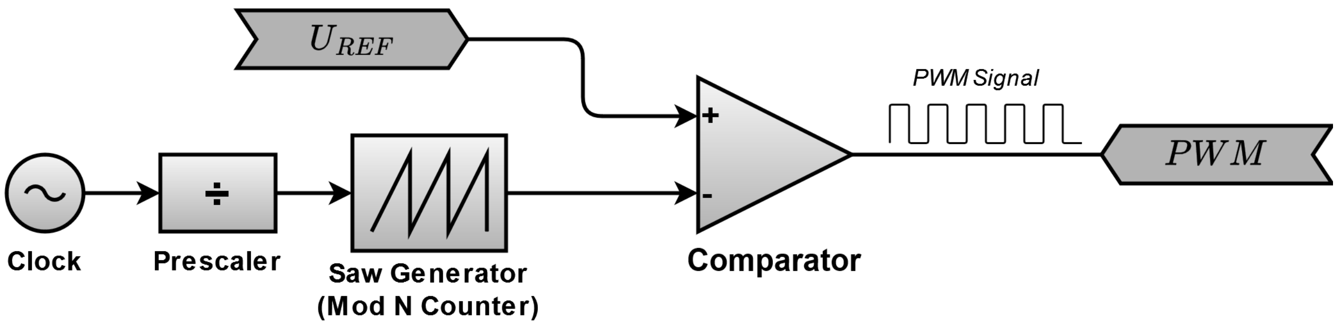


Fig. 1: Block diagram of a PWM modulator

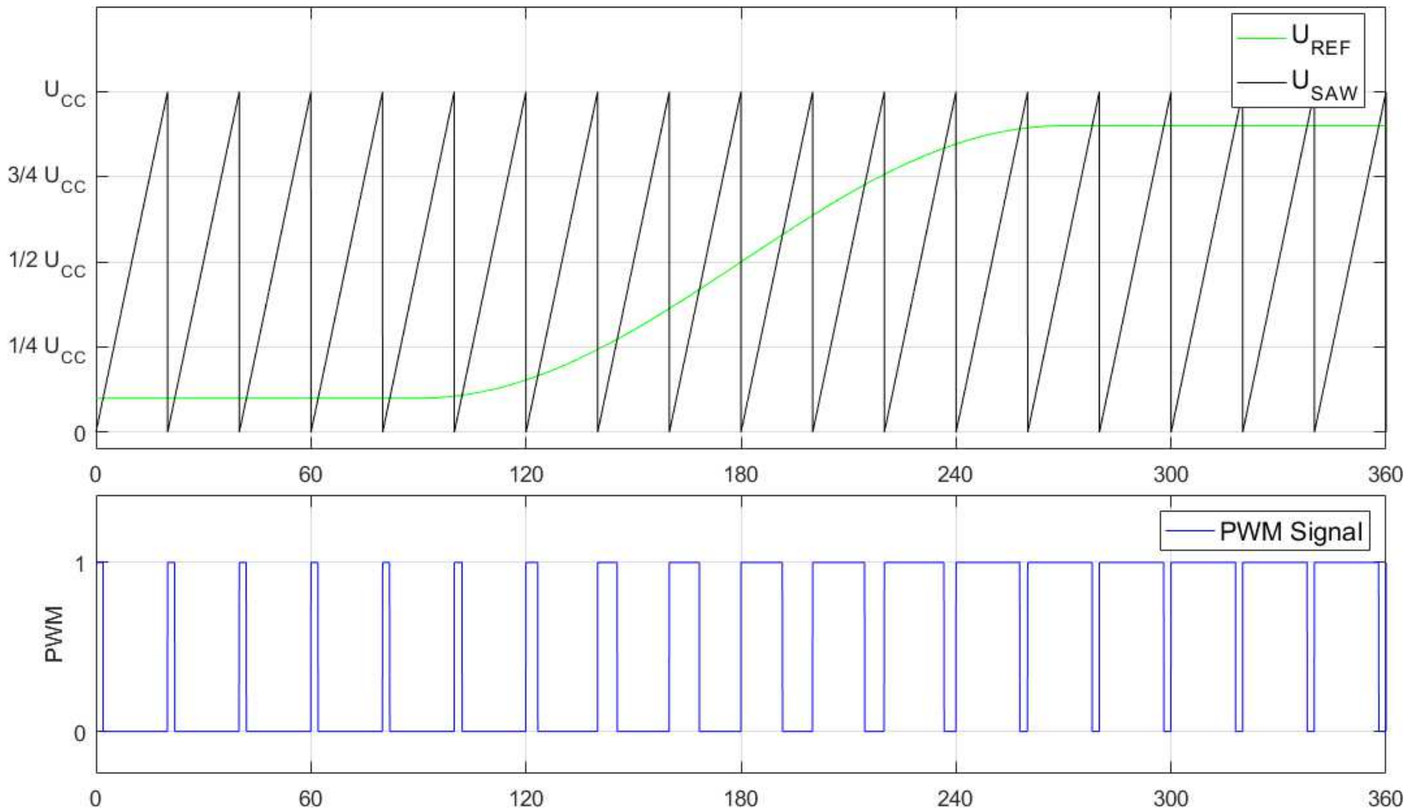


Fig. 2: The principle of generating the PWM signal

2. DC Motor

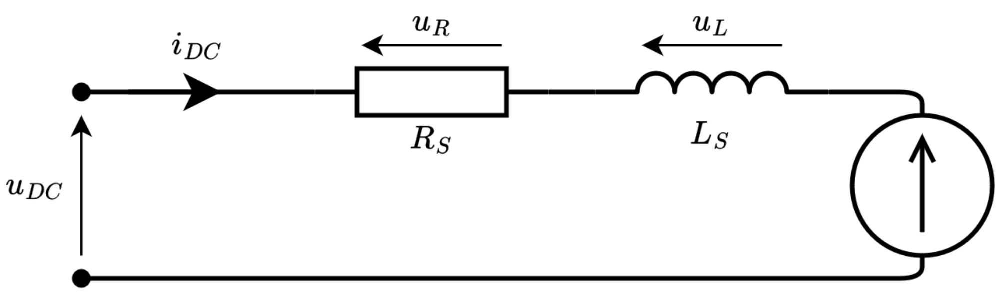
A DC motor is commonly used in mechatronic devices and systems (typically of small to medium power) due to its ease of speed and torque control. Due to the relatively low torque output, these motors are often paired with gearboxes (e.g., planetary gears) that increase torque at the expense of reducing speed. The ease of regulating the rotational speed (approximately proportional to the voltage) and torque (proportional to the current), as well as the simplicity of changing the direction of rotation by reversing the polarity of the voltage, is particularly noteworthy. Additionally, DC motors can achieve very high rotational speeds (up to several tens of thousands of revolutions per minute). The primary disadvantage of a DC motor is the use of a mechanical commutator in its construction. This results in the generation of an electric arc, which prevents the use of such motors in hazardous environments, and necessitates the maintenance and replacement of brushes.

Advantages:
- easy control (via DC voltage/current);
- linear relationship between generated torque and current;
- approximately linear relationship between speed and voltage;
- high rotational speeds (even over 20,000 RPM);
- inexpensive and simple controllers.

Disadvantages:
- requires a gearbox to achieve high torque;
- necessary maintenance and replacement of brushes;
- during commutation of winding sections, an electric arc is generated, which intensifies as brushes wear out;
- not recommended for hazardous environments due to the possibility of open electric arc formation.

Applications:
automation; automotive industry; household appliances; high-speed spindle drives; simple CNC machines (3D printers, milling machines, plotters).

Simplified Mathematical Model:



$$\varepsilon = k_e \cdot \omega_m$$

$$T = k_m \cdot i_{DC}$$

$$u_{DC} = u_R + u_L + \varepsilon$$

$$u_{DC} = i_{DC} \cdot R_S + \frac{di_{DC}}{dt} L_s + k_e \cdot \omega_m$$

- u_{DC} – motor supply voltage
- i_{DC} – motor phase current
- R_S – winding resistance
- L_S – winding inductance
- ε – electromotive force (EMF)
- ω_m – rotor angular speed
- k_e – electrical constant
- k_m – mechanical constant (torque constant)
- T – torque

DC Motor Control – H Bridge

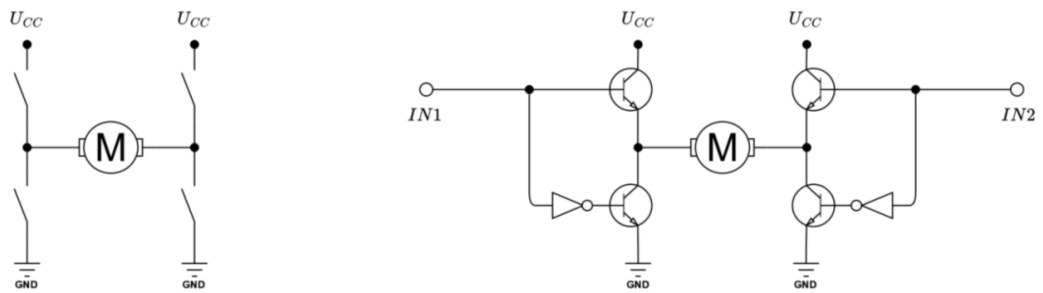
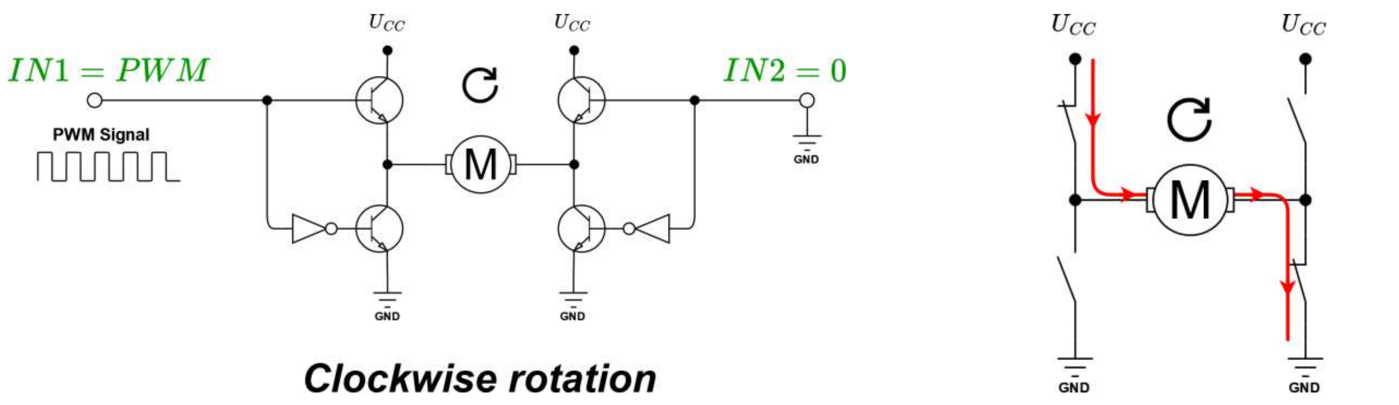
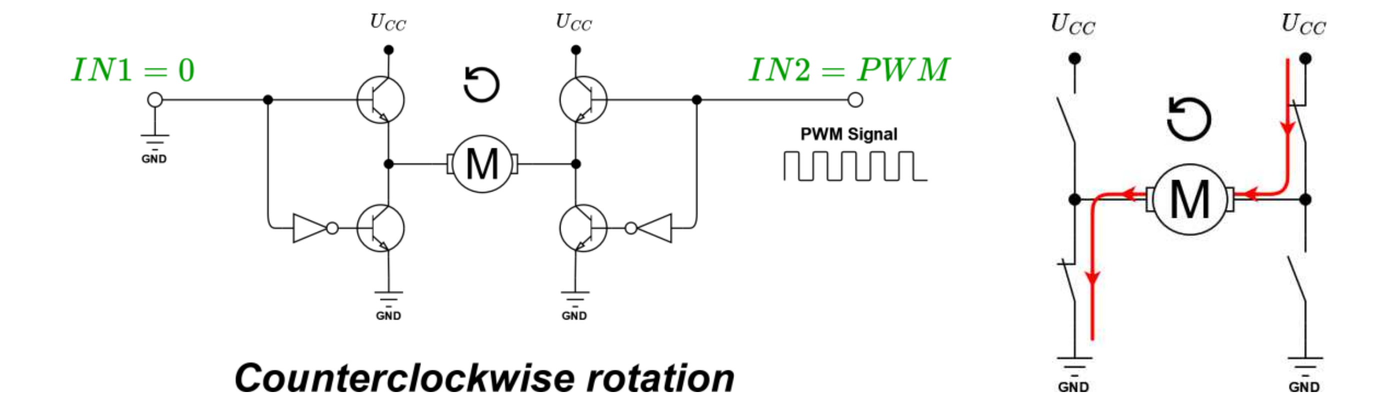
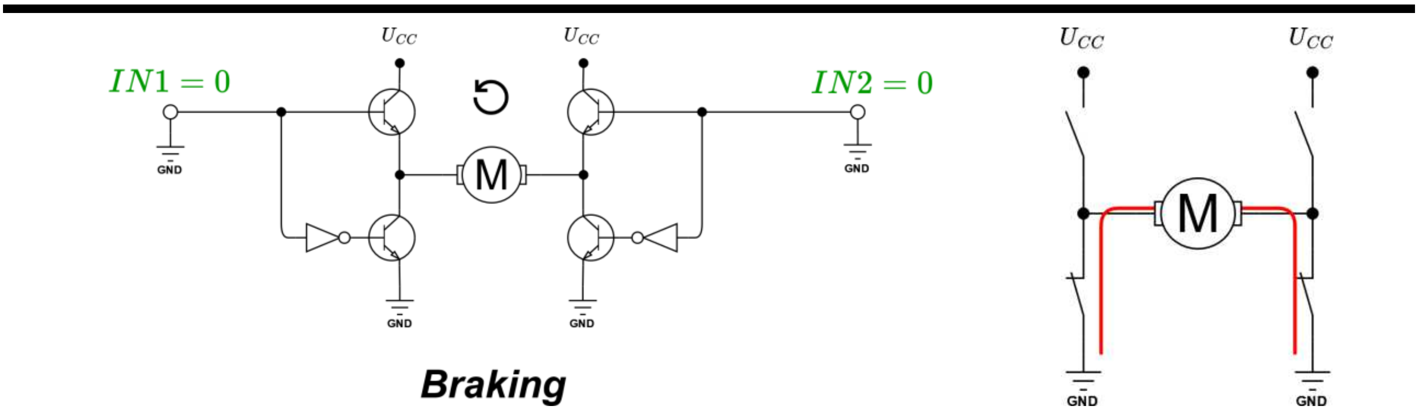


Fig. 3: H-Bridge Construction: a) conceptual diagram; b) simplified electrical schematic







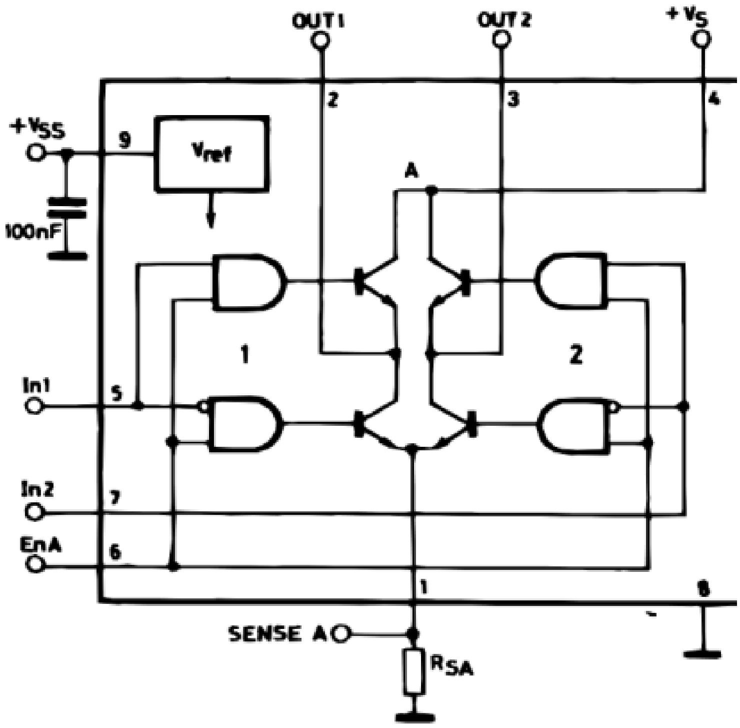


Fig. 4: H bridge – L298N circuit

DC Motor Braking

- **Dynamic Braking** – In this method, an external resistor is connected across the motor terminals (in the special case of zero resistance, the terminals are short-circuited). The value of this external resistance limits the motor phase current, thereby controlling the braking torque. During dynamic braking, the motor acts as a generator, converting kinetic energy into electrical energy. This energy is then dissipated (converted into heat) through the motor winding resistance and the external resistance. Dynamic braking is a relatively inefficient method of braking and is dependent on the motor's rotational speed.
- **Reverse Current Braking** – This method involves using the control system to apply a phase current opposite to the direction of rotation. This creates a braking torque (proportional to the current) that opposes the rotational direction. The supply voltage and the electromotive force (EMF) act in the same direction, so the effective voltage across the rotor is their sum. Consequently, the rotor current is reversed, producing a high braking torque. Although reverse current braking is highly effective, it requires additional power from the power source.
- **Regenerative Braking** – This braking method allows the motor's kinetic energy to be returned to the power supply. This type of braking is possible when the driven load forces the motor to operate at a speed higher than that determined by the supply voltage. The motor's EMF exceeds the supply voltage, reversing the direction of the rotor current. In this mode, the motor acts as an electric generator. Regenerative braking is also a relatively inefficient method, with effectiveness depending on the motor's rotational speed.

3. TASK

Design and implement a DC motor speed controller in an FPGA system consisting of a MultiPrescaler module, a modulo-16 counter, a 4-bit comparator, and a combinational control module. The mod-16 counter should be built using flip-flops connected in a toggle mode configuration, as shown in Figure 6. The 4-bit comparator should be implemented based on the Karnaugh map provided below (Table 1). The control module should be implemented based on the truth table (Table 2). For the reference value for the modulator, use a 4-bit number read from the SW[3..0] switches located on the DE10-Lite board.

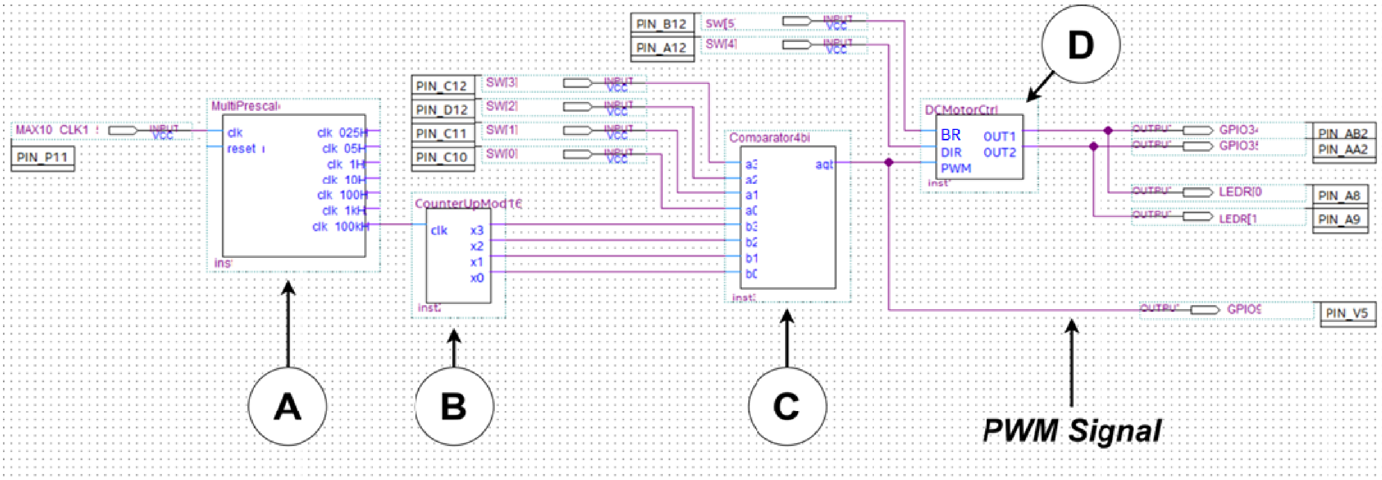


Fig. 5: DC Motor Driver schematic in Quartus Prime.

(A) MultiPrescaler

Prescaler module implemented in VHDL.

(B) CounterUpMod16

Modulo-16 counter implemented based on the diagram in Figure 6.

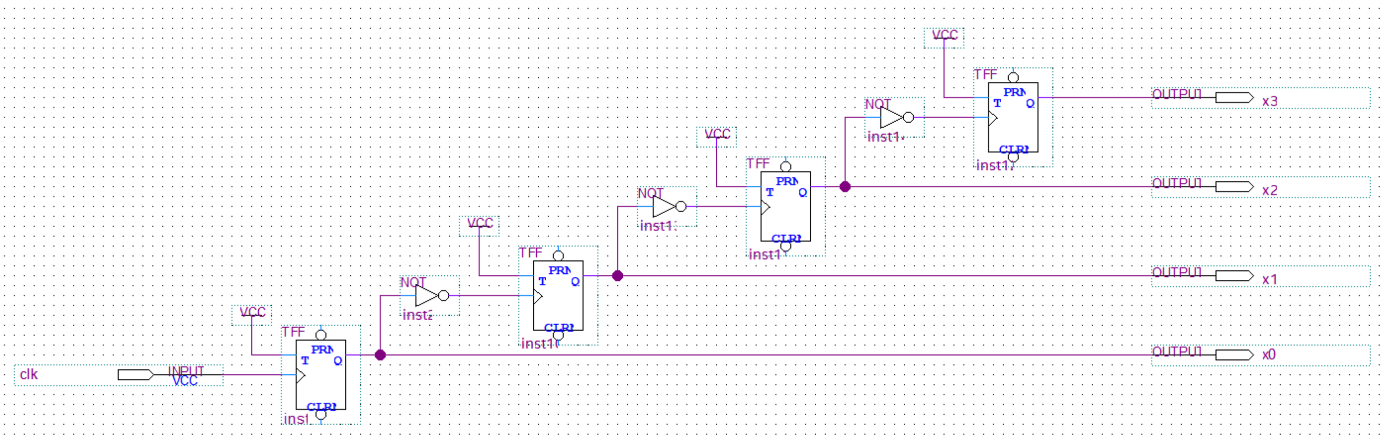


Fig. 6: Modulo-16 Up Counter

(C) Comparator4bits

4-Bit Comparator Module Implemented Using Karnaugh Map.

Is A > B ? (1 – Yes, 0 – No)

$$A_{DEC} = (a_3\ a_2\ a_1\ a_0)_{BIN};$$

$$B_{DEC} = (b_3\ b_2\ b_1\ b_0)_{BIN};$$

$b_3\ b_2\ b_1\ b_0$ / $a_3\ a_2\ a_1\ a_0$	0000 (0_{DEC})	0001 (1_{DEC})	0011 (3_{DEC})	0010 (2_{DEC})	0110 (6_{DEC})	0111 (7_{DEC})	0101 (5_{DEC})	0100 (4_{DEC})	1100 (12_{DEC})	1101 (13_{DEC})	1111 (15_{DEC})	1110 (14_{DEC})	1010 (10_{DEC})	1011 (11_{DEC})	1001 (9_{DEC})	1000 (8_{DEC})
0000 (0_{DEC})	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0001 (1_{DEC})	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0011 (3_{DEC})	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
0010 (2_{DEC})	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0110 (6_{DEC})	1	1	1	1	0	0	1	1	0	0	0	0	0	0	0	0
0111 (7_{DEC})	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0	0
0101 (5_{DEC})	1	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0
0100 (4_{DEC})	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
1100 (12_{DEC})	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1
1101 (13_{DEC})	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1
1111 (15_{DEC})	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
1110 (14_{DEC})	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1
1010 (10_{DEC})	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1
1011 (11_{DEC})	1	1	1	1	1	1	1	1	0	0	0	0	1	0	1	1
1001 (9_{DEC})	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1
1000 (8_{DEC})	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0

Tab. 1: Karnaugh map of the 4-bit comparator

(D) DCMotorCtrl

DC Motor Control Module. A combinational logic circuit with three inputs:

- BR – brake (1 - enabled, 0 - disabled);
- DIR – direction change;
- PWM – PWM signal;

and two outputs (OUT1 – signal for controlling one half-bridge, OUT2 – signal for controlling the other half-bridge). The DCMotorCtrl module should be implemented based on the following truth table.

Inputs of the Combinational Circuit			Outputs of the Combinational Circuit	
BR (Brake)	**DIR** (Direction)	**PWM** (PWM Signal)	**OUT1** (Connected to IN1 of the H-bridge)	**OUT2** (Connected to IN2 of the H-bridge)
0	0	0		
0	0	1		
0	1	0		
0	1	1		
1	0	0		
1	0	1		
1	1	0		
1	1	1		

Tab. 2: Truth table for the DCMotorCtrl module