Sheikh Hasina University, Netrokona

Department of Computer Science and Engineering

CSE-2205: Introduction to Mechatronics

Lec-18: Electrical Actuation System

Md. Ariful Islam

Assistant Professor

Dept. of Robotics and Mechatronics Engineering

University of Dhaka

&

Adjunct Faculty

Sheikh Hasina University, Netrokona

Department of Computer Science and Engineering

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DC Motor

A DC motor is an **electromechanical energy conversion** device, which converts electrical energy input into the mechanical energy output.

The operation of the DC motor is based on the principle that when a current carrying conductor is placed in a magnetic field, a mechanical force acts on the conductor. The magnitude of the force is given by,

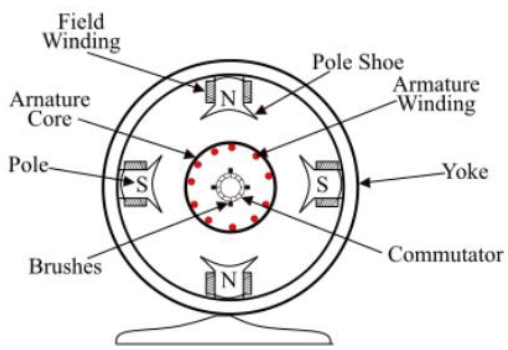
$$F=BIl \text{ Newtons}$$

The direction of this is given by the **Fleming's left hand rule**.

Fleming's left hand rule: If we stretch the first finger, second finger and thumb of our left hand to be perpendicular to each other, and the direction of magnetic field is represented by the first finger, direction of the current is represented by the second finger, then the thumb represents direction of the force experienced by the current carrying conductor.

Construction of a DC Motor

Here is the schematic diagram of a DC Motor



1. **Yoke:** The outer frame provides structural support and serves as a protective cover for the motor. It also completes the magnetic circuit and directs the magnetic flux produced by the field winding.

2. **Magnetic Field System:** This is the stationary part of the motor, producing the main magnetic flux. It consists of pole cores with field windings. The pole cores are laminated to reduce eddy current losses, and the field coils are connected in series.

3. **Armature Core:** Mounted on the shaft, it rotates between the field poles. The armature core is made of laminated soft steel to reduce eddy current losses. Armature conductors are placed in slots on the outer surface.

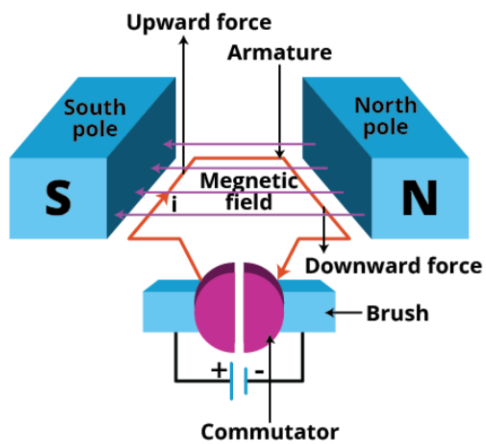
4. **Armature Winding:** The insulated conductors in the armature core slots, suitably connected, form the armature winding. There are two common types of armature windings: wave winding and lap winding.

5. **Commutator:** A mechanical rectifier converting the DC input from the source into alternating current in the armature winding. It consists of copper segments insulated from each other and connected to the armature coils.

6. **Brushes:** Mounted on the commutator, brushes inject current from the DC source into the armature windings. The brushes, typically made of carbon, are supported by a brush holder. The pressure on the commutator is adjusted by springs.

Working principle of DC Motor

The working principle of a DC motor is based on the interaction of magnetic fields and electric currents, leading to the conversion of electrical energy into mechanical energy. Here's a step-by-step explanation:



1. **Creation of Magnetic Field:**
    - The DC motor consists of a stationary magnetic field, typically generated by a field winding on the stator (stationary part) of the motor.
    - The field winding produces a magnetic field with north and south poles within the motor.
2. **Armature and Magnetic Field Interaction:**
    - The armature, a part of the motor rotor (rotating part), carries a winding that is connected to a DC power source.
    - When a DC voltage is applied to the armature winding, an electric current flows through the winding, creating its own magnetic field.
3. **Lorentz Force on Armature Conductors:**
    - The magnetic field produced by the armature winding interacts with the stationary magnetic field generated by the field winding.
    - According to the Lorentz force principle, when a current-carrying conductor (armature winding) is placed in a magnetic field, a mechanical force is exerted on the conductor.
    - This force causes the armature to rotate.
4. **Commutator Action:**
    - As the armature rotates, the commutator (a rotary switch) on the rotor also rotates.

- The commutator reverses the direction of the current in the armature winding as it rotates. This reversal ensures that the magnetic forces on the armature conductors consistently produce a torque in the same direction, allowing continuous rotation.

5. **Conversion of Electrical to Mechanical Energy:**

- The continuous interaction between the magnetic fields of the armature and the stationary field winding leads to the continuous rotation of the motor shaft.

- The mechanical energy produced by the rotation of the motor shaft can be used to perform various tasks, such as driving machinery, fans, or wheels in an electric vehicle.

Back EMF in DC Motor

When the current-carrying conductor placed in a magnetic field, the torque induces on the conductor, the torque rotates the conductor which cuts the flux of the magnetic field. According to the Electromagnetic Induction Phenomenon **"when the conductor cuts the magnetic field, EMF induces in the conductor"**.

The Fleming right-hand rule determines the direction of the induced EMF.

According to Fleming Right Hand Rule, if we hold our thumb, middle finger and index finger of the right hand by an angle of 90°, then the index finger represents the direction of the magnetic field. The thumb shows the direction of motion of the conductor and the middle finger represents the emf induces on the conductor.

On applying the right-hand rule in the figure shown below, it is seen that **the direction of the induced emf is opposite to the applied voltage.** Thereby the emf is known as the *counter emf or back emf*.

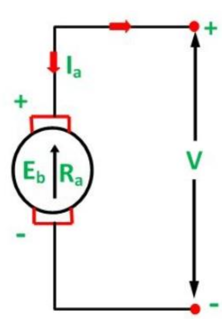
The back emf is developed in series with the applied voltage, but opposite in direction, i.e., the back emf opposes the current which causes it.

The magnitude of the back emf is given by the same expression shown below:

$$E_b = \frac{NP\varphi Z}{60\ A}$$

Where E_b is the induced emf of the motor known as Back EMF, A is the number of parallel paths through the armature between the brushes of opposite polarity. P is the number of poles, N is the speed, Z is the total number of conductors in the armature and ϕ is the useful flux per pole.

A simple conventional circuit diagram of the machine working as a motor is shown in the diagram below:



In this case, the magnitude of the back emf is always less than the applied voltage. The difference between the two is nearly equal when the motor runs under normal conditions.

The current induces on the motor because of the main supply. The relation between the main supply, back emf and armature current is given as $E_b = V – I_aR_a$.

The back emf makes the DC motor self-regulating machine, i.e., **the back emf develops the armature current according to the need of the motor.** The armature current of the motor is calculated as:

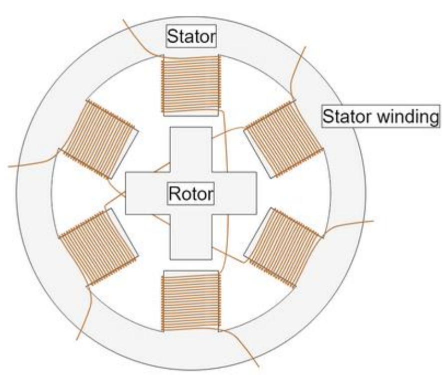
$$I = \frac{V - E_b}{R_a}$$

Let's understand how the back emf makes motor self-regulating.

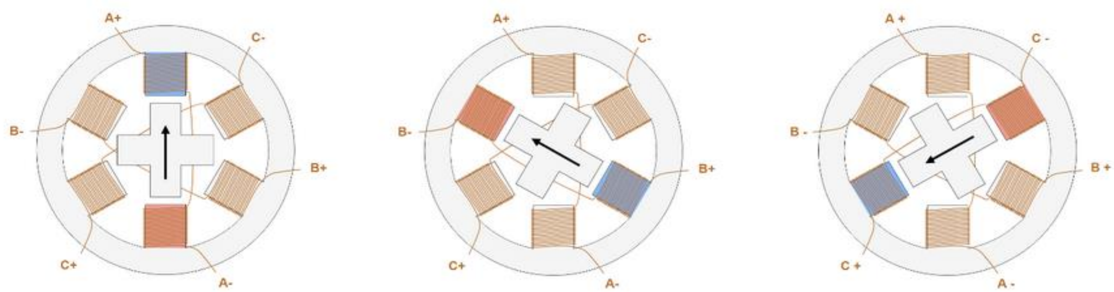
- Consider the motor is running at no-load condition. At no load, the DC motor requires small torque for controlling the friction and windage loss. The motor withdraws less current. As the back emf depends on the current their value also decreases. The magnitude of the back EMF is nearly equal to the supply voltage.
- If the sudden load is applied to the motor, the motor becomes slow down. As the speed of the motor decreases, the magnitude of their back emf also falls down. The small back emf withdraw heavy current from the supply. The large armature current induces the large torque in the armature, which is the need of the motor. Thus, the motor moves continuously at a new speed.
- If the load on the motor is suddenly reduced, the driving torque on the motor is more than the load torque. The driving torque increases the speed of the motor which also increases their back emf. The high value of back emf decreases the armature current. The small magnitude of armature current develops less driving torque, which is equal to the load torque. And the motor will rotate uniformly at the new speed.

Stepper Motor

1. **Structure of Stepper Motor:**
    - Stepper motors have a stationary part called the stator and a moving part called the rotor.
    - The stator has teeth on which coils are wound, and the rotor can be either a permanent magnet or a variable reluctance iron core.



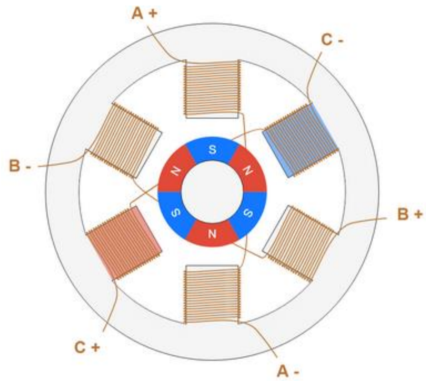
2. **Working Principle:**
   - When one or more phases of the stator coils are energized, a magnetic field is created.
   - The rotor aligns itself with the magnetic field created by the energized coil(s).
3. **Step Rotation:**
   - By sequentially energizing different phases in a specific sequence, the rotor can be rotated in fixed steps.
   - Each step corresponds to a specific angular movement, and the motor can be controlled to move in a precise and controlled manner.



4. **Sequential Energization:**
   - For example, when coil A is energized, the rotor aligns with the magnetic field it produces.
   - Subsequently energizing coil B causes the rotor to rotate anti-clockwise by a fixed angle (e.g., 60°) to align with the new magnetic field.
   - The same principle applies when coil C is energized, causing further rotation.
5. **Direction of Rotation:**
   - The direction of rotation is determined by the sequence in which the coils are energized.
   - The colors of the stator teeth indicate the direction of the magnetic field generated by the corresponding stator winding.
6. **Control and Positioning:**
   - Stepper motors are widely used in applications where precise control over the position and rotation of the motor is required.
   - The step-by-step movement allows for accurate positioning, making stepper motors suitable for applications such as robotics, 3D printers, CNC machines, and more.

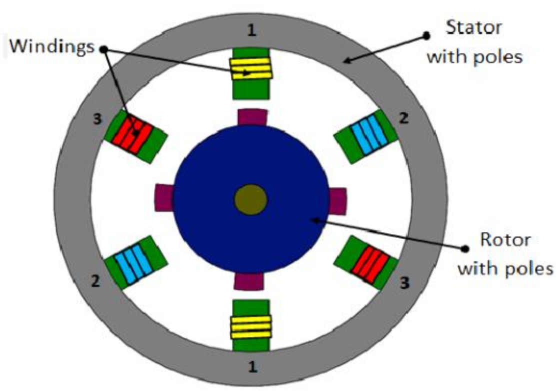
Types of Stepper Motor

1. **Permanent Magnet (PM) Rotor:**



- **Description:** The PM rotor is constructed with permanent magnets.
- **Operation:** These magnets align with the magnetic field generated by the stator, creating a strong interaction that produces torque for rotation.
- **Detent Torque:** PM stepper motors exhibit detent torque, meaning they resist changing their position even when no coils are energized. This provides stability in holding a position.
- **Drawbacks:**
    - Lower speeds compared to other stepper motor types.
    - Lower resolution, impacting precision in positioning.

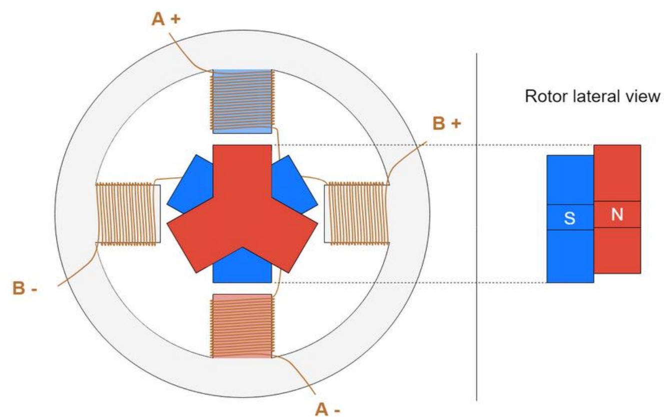
2. **Variable Reluctance Rotor:**



- **Description:** The rotor in a variable reluctance stepper motor does not contain permanent magnets. Instead, it is made of a material attracted to the stator's magnetic field.
- **Operation:** The shape of the rotor is designed to maximize reluctance at certain positions, causing it to rotate when stator coils are energized.
- **Advantages:**

        - Higher speeds and better resolution compared to PM motors.
    - **Limitations:**
        - May not provide as much holding torque or detent torque, making them less suitable for applications requiring position holding.

3. **Hybrid Rotor:**

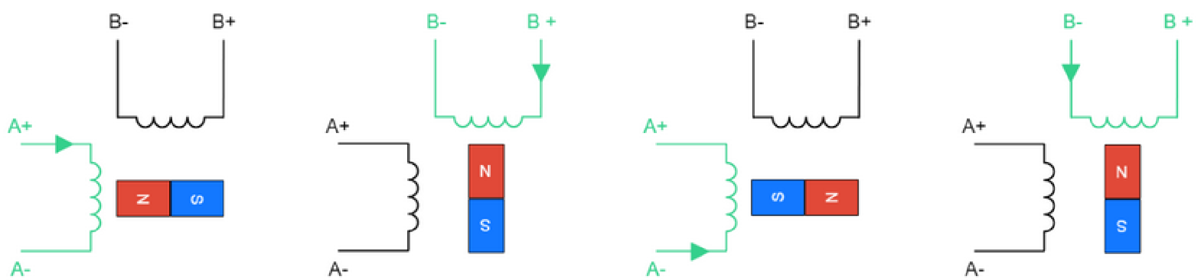


- **Description:** Hybrid stepper motors combine elements of both PM and variable reluctance designs.
- **Construction:** They often have a permanent magnet rotor with additional features like teeth or slots to enhance reluctance.
- **Benefits:**
    - Benefit from the advantages of both PM and variable reluctance designs.
    - Improved performance in terms of speed, resolution, and torque compared to individual types.

Stepper Motor Driving Techniques

There are different driving techniques for a stepper motor:

Wave mode:

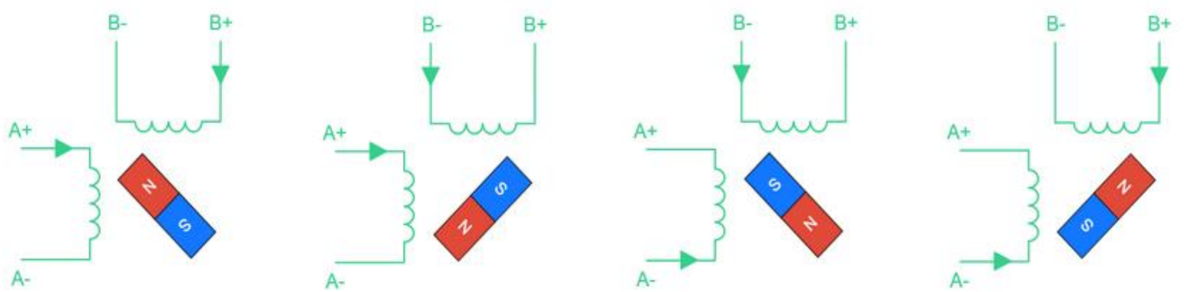


1. **Positive Direction (A+ to A-):**
    - Starting Position: The current flows only in phase A in the positive direction.

- Result: The rotor, represented by a magnet, aligns with the magnetic field generated by phase A.

2. **Positive Direction (B+ to B-):**
    - Next Step: The current flows only in phase B in the positive direction.
    - Result: The rotor spins 90° clockwise to align with the magnetic field generated by phase B.
3. **Negative Direction (A- to A+):**
    - Subsequent Step: Phase A is energized again, but the current flows in the negative direction.
    - Result: The rotor spins again by 90°, changing its position.
4. **Negative Direction (B- to B+):**
    - Final Step: The current flows negatively in phase B.
    - Result: The rotor spins again by 90°, completing one full step.

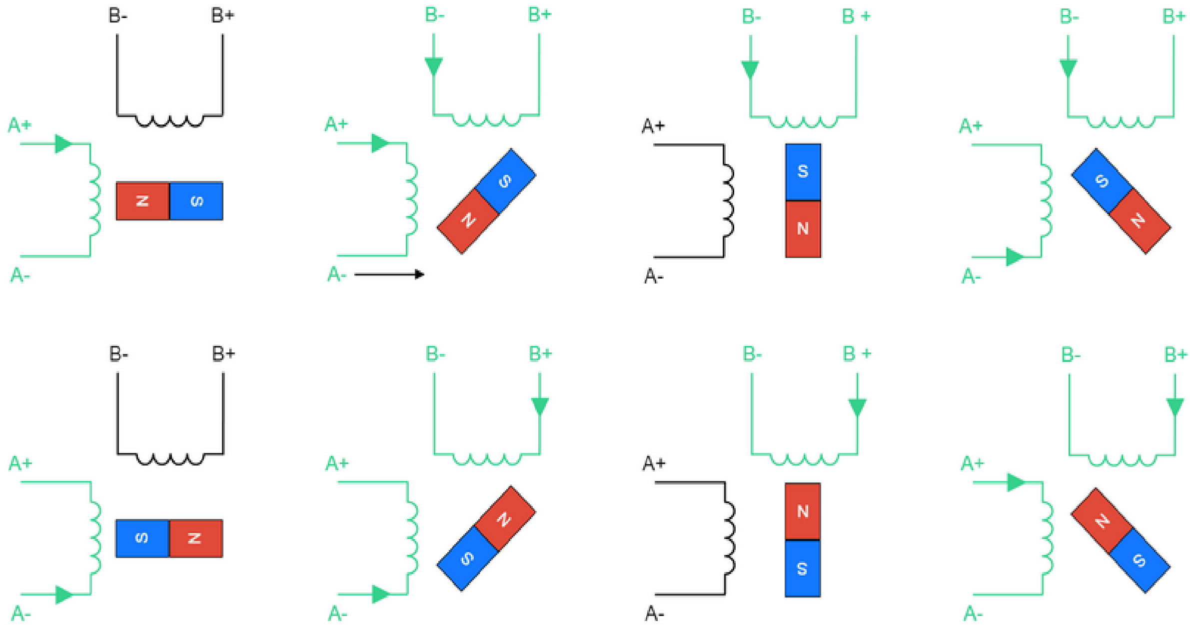
Full step Mode



1. **Step 1:**
    - Current flows positively in both phases A and B.
    - Result: The rotor aligns with the combined magnetic fields of both phase A and phase B.
2. **Step 2:**
    - Current continues to flow positively in both phases A and B.
    - Result: The rotor spins 90° clockwise to align with the combined magnetic fields of phase A and phase B.
3. **Step 3:**
    - Current flows negatively in both phases A and B.
    - Result: The rotor spins again by 90°, changing its position.
4. **Step 4:**

- Current continues to flow negatively in both phases A and B.
- Result: The rotor spins again by 90°, completing one full step.

Half step Mode



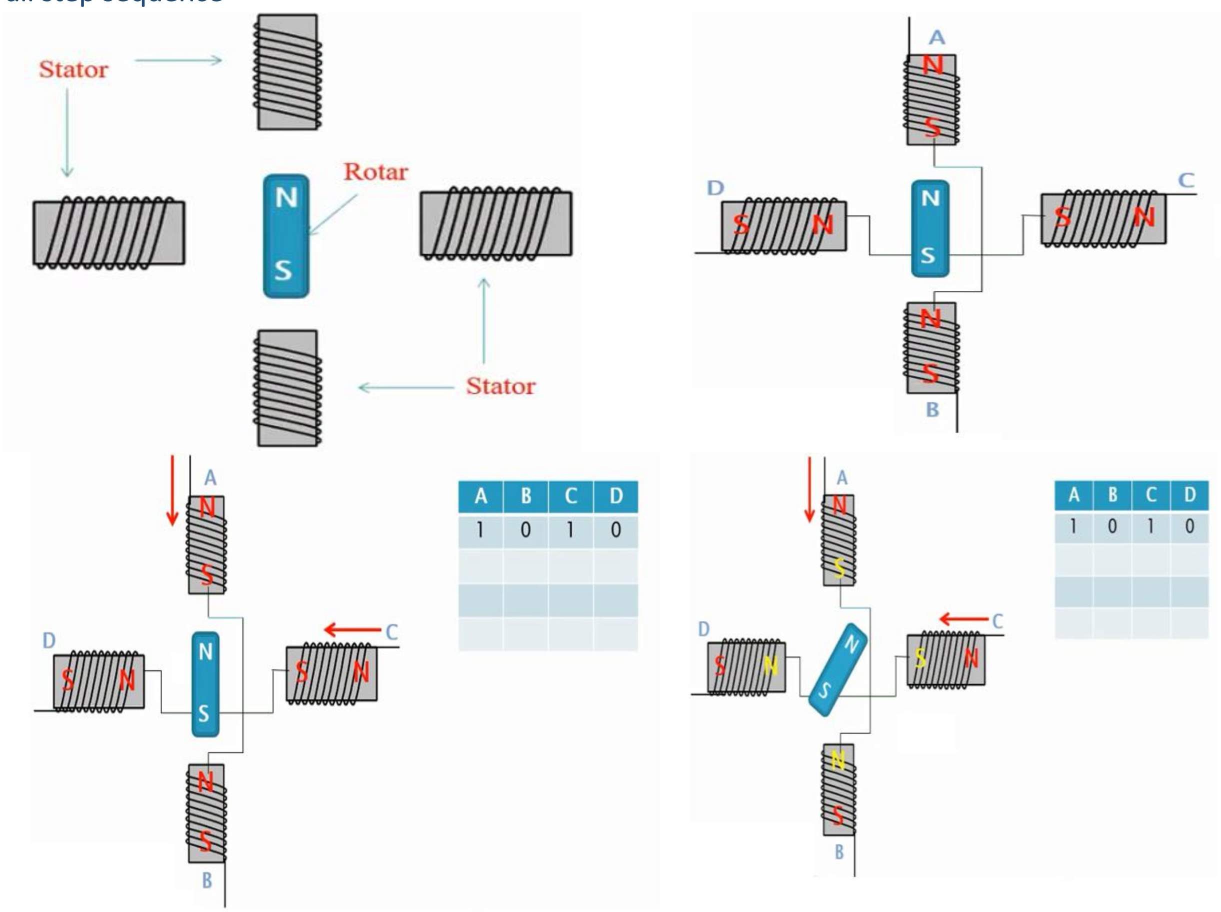
1. **Step 1:**
    - Current flows positively only in phase A.
    - Result: The rotor aligns with the magnetic field of phase A.
2. **Step 2:**
    - Current flows positively in both phases A and B.
    - Result: The rotor spins 45° clockwise, aligning with the combined magnetic fields of phase A and phase B.
3. **Step 3:**
    - Current flows positively only in phase B.
    - Result: The rotor spins another 45° clockwise, aligning with the magnetic field of phase B.
4. **Step 4:**
    - Current continues to flow positively in both phases A and B.
    - Result: The rotor spins 45° clockwise, aligning again with the combined magnetic fields of phase A and phase B.
5. **Step 5:**
    - Current flows negatively only in phase A.

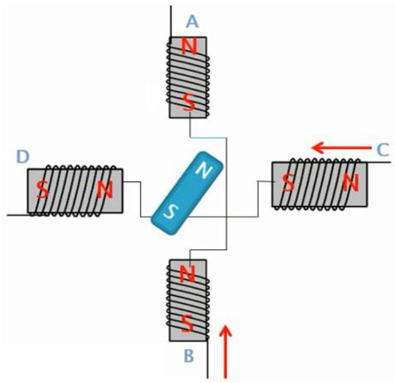
- Result: The rotor spins another 45° clockwise, aligning with the magnetic field of phase A.

6. **Step 6:**
    - Current continues to flow negatively in both phases A and B.
    - Result: The rotor spins 45° clockwise, aligning with the combined magnetic fields of phase A and phase B.
7. **Step 7:**
    - Current flows negatively only in phase B.
    - Result: The rotor spins another 45° clockwise, aligning with the magnetic field of phase B.
8. **Step 8:**
    - Current continues to flow negatively in both phases A and B.
    - Result: The rotor spins 45° clockwise, aligning again with the combined magnetic fields of phase A and phase B.

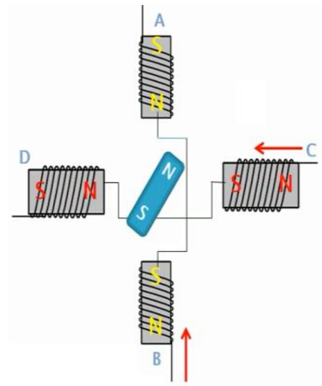
Stepper motor program and working

Full step sequence

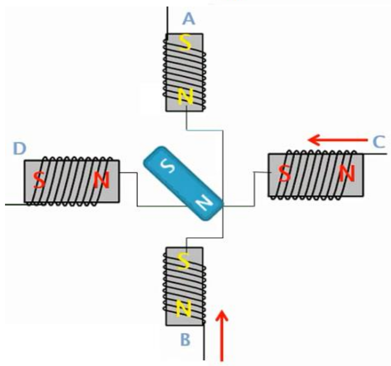




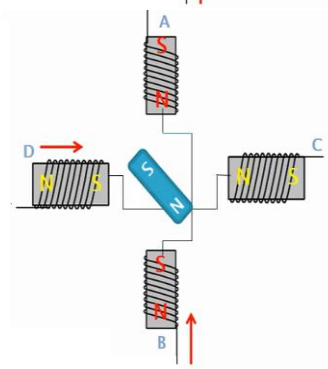
A	B	C	D
1	0	1	0
0	1	1	0



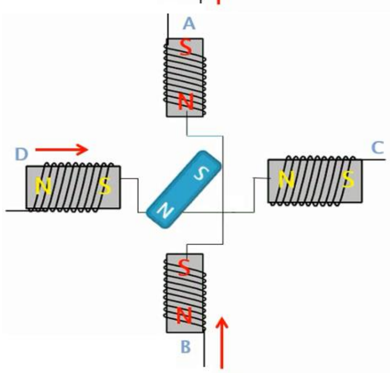
A	B	C	D
1	0	1	0
0	1	1	0



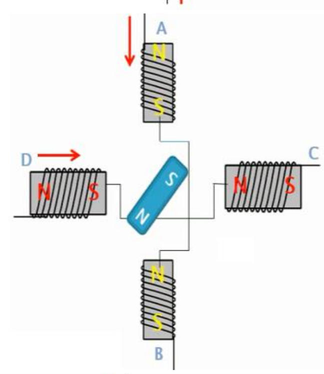
A	B	C	D
1	0	1	0
0	1	1	0



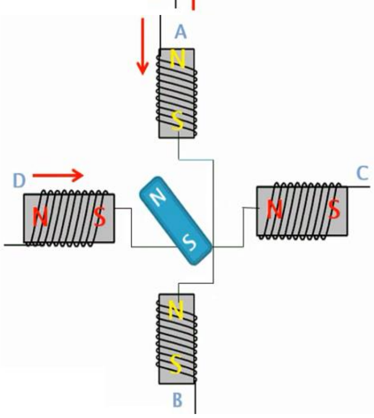
A	B	C	D
1	0	1	0
0	1	1	0
0	1	0	1



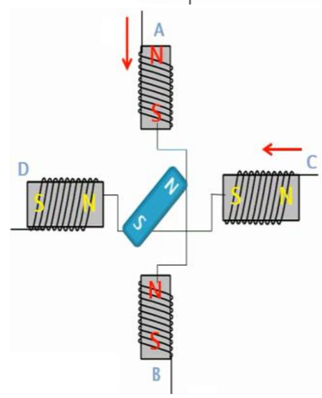
A	B	C	D
1	0	1	0
0	1	1	0
0	1	0	1



A	B	C	D
1	0	1	0
0	1	1	0
0	1	0	1
1	0	0	1

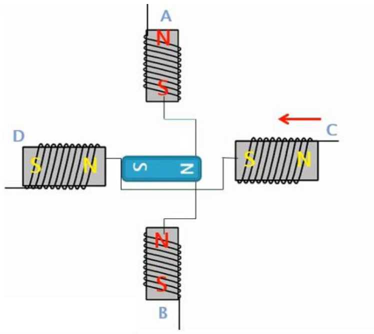


A	B	C	D
1	0	1	0
0	1	1	0
0	1	0	1
1	0	0	1

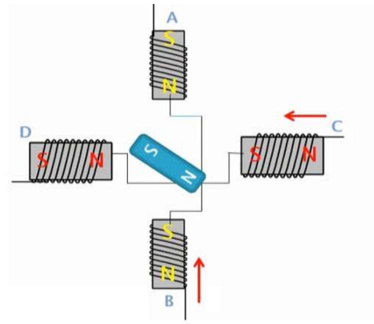


A	B	C	D	
1	0	1	0	0A
0	1	1	0	06
0	1	0	1	05
1	0	0	1	09

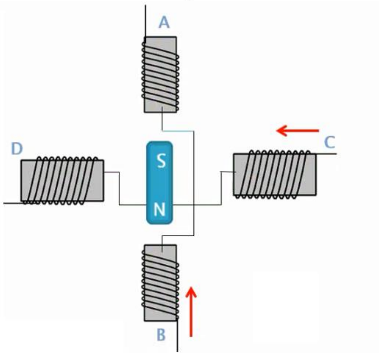
Half step sequence



A	B	C	D	
1	0	1	0	0A
0	0	1	0	02
0	1	1	0	06
0	1	0	1	05
1	0	0	1	09



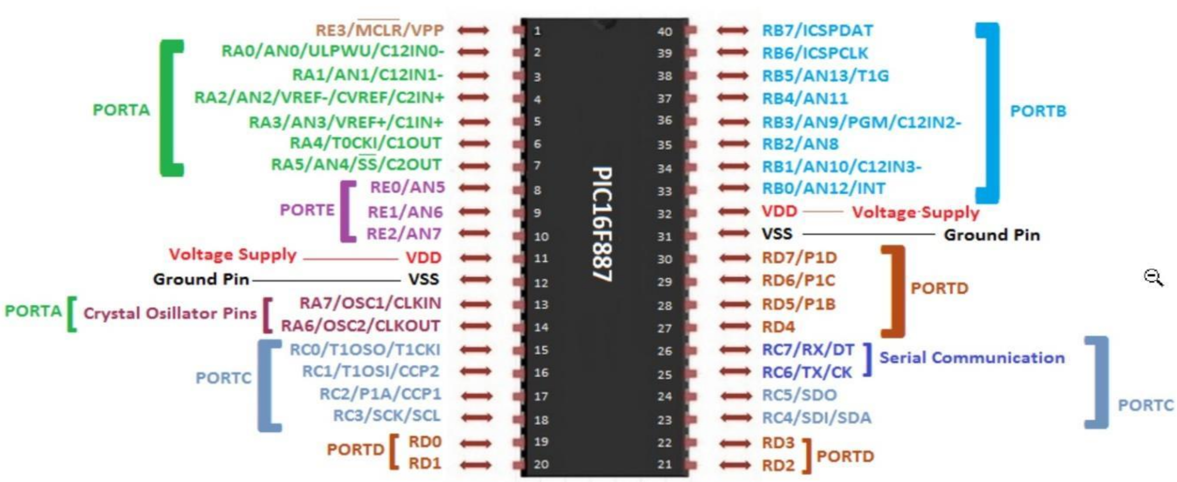
A	B	C	D	
1	0	1	0	0A
0	0	1	0	02
0	1	1	0	06
0	1	0	1	05
1	0	0	1	09



A	B	C	D	
1	0	1	0	0A
0	0	1	0	02
0	1	1	0	06
0	1	0	0	04
0	1	0	1	05
1	0	0	1	09

A	B	C	D	
1	0	1	0	0A
0	0	1	0	02
0	1	1	0	06
0	1	0	0	04
0	1	0	1	05
0	0	0	1	01
1	0	0	1	09
1	0	0	0	08

PIC Microcontroller



In PIC microcontrollers, including the PIC16F877, the TRIS (Tri-state) registers are used to configure the direction of individual I/O pins as either input or output. Additionally, the PORT registers are used to read or write digital values to those pins. Let's take a closer look at the concepts of TRIS registers and PORT registers in the context of the PIC16F877 microcontroller.

1. **TRIS Registers:**
    - Each port (like PORTA, PORTB, etc.) has a corresponding TRIS register (TRISA, TRISB, etc.).
    - The TRIS register is used to configure the direction of each pin in the associated port.
    - If a bit in the TRIS register is set (logic 1), it configures the corresponding pin as an input.
    - If a bit in the TRIS register is cleared (logic 0), it configures the corresponding pin as an output.

Example:

BSF TRISA, 0 ; Set the first bit of TRISA, configuring it as an input

BCF TRISB, 4 ; Clear the fifth bit of TRISB, configuring it as an output

2. **PORT Registers:**

- Each port has a corresponding PORT register (PORTA, PORTB, etc.).
- The PORT register is used to read or write digital values to the pins of the associated port.
- When a pin is configured as an input (TRIS bit set), reading from the PORT register will give the logic level on that pin.
- When a pin is configured as an output (TRIS bit cleared), writing to the PORT register will set or clear the corresponding pin.

Example:

MOVF PORTA, W ; Move the value on PORTA to the W register

MOVWF Variable ; Move the value in W to a variable

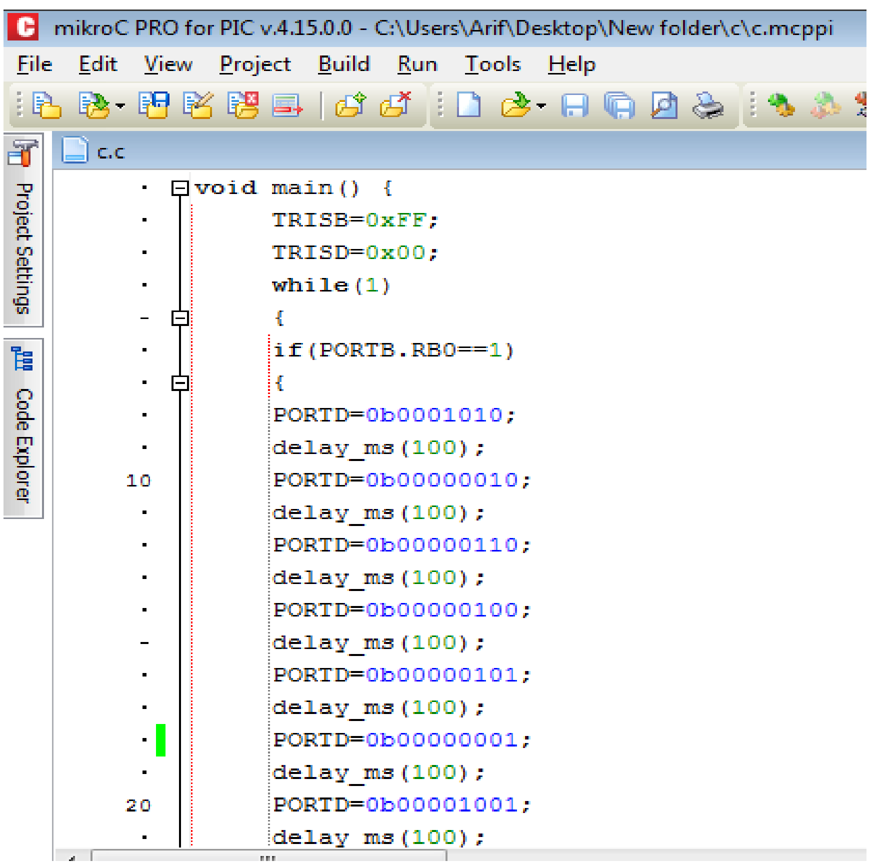
BCF PORTB, 2 ; Clear the third bit of PORTB, setting the corresponding output pin to logic 0

BSF PORTC, 5 ; Set the sixth bit of PORTC, setting the corresponding output pin to logic 1

C Programming to control the stepper motor

```
void main() {
  // Configure Port B pins as inputs and Port D pins as outputs
  TRISB = 0xFF; // Set all Port B pins as inputs (assuming RB0-RB7)
  TRISD = 0x00; // Set all Port D pins as outputs (assuming RD0-RD7)
  while (1) {
    // Check if RB0 (Port B, Pin 0) is high
    if (PORTB.RB0 == 1) {
      // If RB0 is high, execute the following stepper motor sequence
      // Step 1
      PORTD = 0b0001010;
```

```
        delay_ms(100);
        // Step 2
        PORTD = 0b00000010;
        delay_ms(100);
        // Step 3
        PORTD = 0b00000110;
        delay_ms(100);
        // Step 4
        PORTD = 0b00000100;
        delay_ms(100);
        // Step 5
        PORTD = 0b00000101;
        delay_ms(100);
        // Step 6
        PORTD = 0b00000001;
        delay_ms(100);
        // Step 7
        PORTD = 0b00001001;
        delay_ms(100);
        // Step 8
        PORTD = 0b00001000;
        delay_ms(100);
      }
    }
}
```



Actuation System