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وزارة التعليم العالي و البحث العلمي

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جامعة عمار ثليجي – الأغواط

University Amar Telidji of Laghouat

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Domain :Technology

Field : Electrical Engineering

Speciality : Automatic

Course Handout (Lectures)

Intended for students of: of: Bachelor Level: 3rd Year

Actuators

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Course of Actuators for 3Licence Automatic

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2025/ 2026

Preface

This course entitled *Actuators* has been designed for undergraduate students in the field of automation engineering. It provides a comprehensive presentation of electric, pneumatic, and hydraulic actuators used in modern industrial systems.

This course on Actuators is primarily intended for third-year students enrolled in the Bachelor's degree program in Automation, in accordance with the L.M.D. training framework (2025/2026). It is part of the Fundamental Teaching Unit (UEF 3.2.1) and is delivered over a total duration of 45 hours, including lectures and tutorial sessions, spread across 15 weeks.

The main objective of this course is to provide students with the theoretical foundations and practical knowledge required for the proper selection and integration of pneumatic, hydraulic, , and electric actuators in industrial systems. Emphasis is placed on understanding the operating principles, performance characteristics, and design constraints of various actuation technologies.

By the end of the course, learners will be able to analyze actuator requirements, evaluate technical and operational constraints, and select appropriate solutions for automation applications. The course also aims to develop a critical understanding of current challenges and technological advancements in the field of industrial actuation.

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Contents

0.1 Introduction

The actuator belongs to the operative part of an automated system, where its role is to convert received energy into work (force or torque) to change the behavior or state of a system. Another definition is that an actuator is a device capable of producing a physical action from the energy received. Actuators can be classified on the basis of the energy used or the usable physical phenomenon. An actuator can be electric (electric motor), hydraulic (hydraulic cylinder for linear movements or hydraulic motor for rotational movements) or pneumatic (cylinder for linear movements or pneumatic motor for rotational movements). The choice of an actuator depends on several parameters, but generally the required force dictates such a choice. The various types of commonly used actuators and their areas of application are illustrated in the figure below.

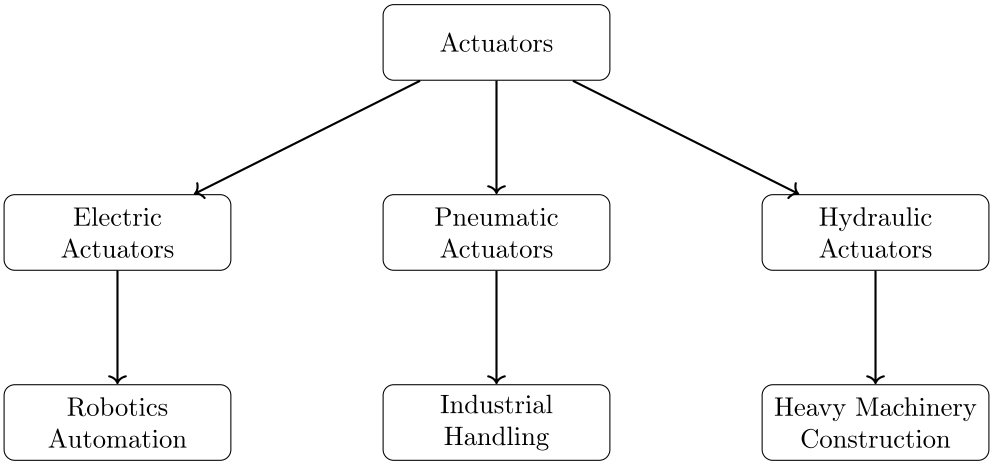


Figure 1: Common types of actuators and their typical areas of application.

An automated system, as illustrated in the figure 2, includes :

- The **Operative Part (O.P)** is the mechanical and physical part of the system that performs the required operations, such as motion or force generation. It consists of actuators including electric motors and pneumatic or hydraulic cylinders, which convert electrical, pneumatic, or hydraulic energy into mechanical energy.
- The **Interface Part (I.P)** is located between the Control Part and the Operative Part. It ensures the adaptation, transmission, and translation of commands and information. It includes sensor interfaces, signal conditioning circuits, power interfaces (pre-actuators), and human–machine interfaces (HMI).
- The **Control Part (C.P)** coordinates and supervises the sequence of actions applied to the Operative Part in order to accomplish a well-defined task. It typically consists of programmable controllers, control algorithms, and decision-making logic.

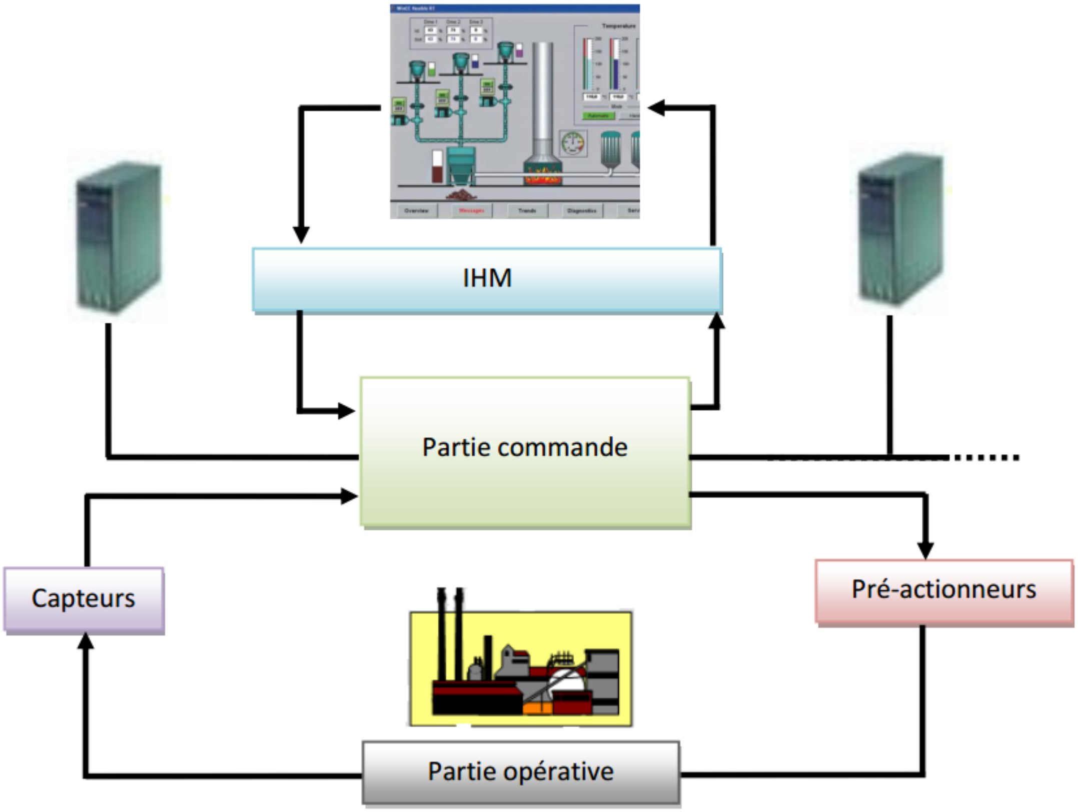


Figure 2: Structure of an Automated System

Chapter 1

Basics of Actuators

After completing this chapter,students will be able to:

- Define actuators and explain their role in automation systems
- Classify actuators based on energy source and motion type
- Identify typical actuator applications
- Compare electric, pneumatic, and hydraulic actuators

1.1 Introduction

Automation systems rely on the coordinated interaction of sensors, controllers, and actuators. Among these components, actuators play a crucial role as they are responsible for converting control signals into physical actions. This chapter introduces the fundamental concepts of actuators, their roles in automation, and their main classifications.

1.2 Definition and Role of Actuators in Automation

An **actuator** is a device that converts energy and a control signal into **mechanical motion** or force. The input signal is usually electrical (analog or digital), while the output is a physical action such as linear displacement, rotary motion, or applied torque.

In an automation chain, actuators are considered the **final control elements**. After a sensor measures a physical quantity and the controller processes the information, the actuator executes the controller's command on the process.

1.2.1 Main Roles of Actuators

The primary roles of actuators in automation systems include:

- Converting energy into mechanical motion
- Executing control commands from PLCs, microcontrollers, or computers
- Regulating position, speed, acceleration, and force
- Interfacing between control systems and mechanical processes

1.2.2 Examples of Actuator Applications

Actuators are widely used in many industrial and domestic applications, such as:

- Industrial robots and manipulators
- Conveyor belts and automated production lines
- Valves and flow control systems
- CNC machines and positioning systems
- Automotive and aerospace systems

1.3 Classification Based on Energy Source

Each energy source offers specific advantages and is selected according to application requirements such as power, precision, speed, and environmental conditions. Based on the energy source used, actuators can be classified as:

- Electrical actuators

- Hydraulic actuators
- Pneumatic actuators
- Thermal actuators
- Piezoelectric actuators

This course focuses on the three most common categories of actuators used in automation: electric, pneumatic , and hydraulic actuators.

1.3.1 Electric Actuators

Electric actuators convert **electrical energy** into mechanical motion. They are the most widely used actuators in modern automation due to their cleanliness, ease of control, and compatibility with electronic systems.

Common Types of Electric Actuators

- DC motors (brushed and brushless)
- AC motors (induction and synchronous motors)
- Stepper motors
- Servo motors
- Solenoids

Advantages

- High precision and repeatability
- Easy integration with control systems
- Low maintenance requirements
- Clean operation (no fluid leakage)

Limitations

- Limited force compared to hydraulic actuators
- Sensitivity to harsh environments (temperature, humidity)

1.3.2 Pneumatic Actuators

Pneumatic actuators operate using **compressed air**. They are commonly used in industrial automation where fast and repetitive motion is required.

Types of Pneumatic Actuators

- Pneumatic cylinders (single-acting and double-acting)
- Pneumatic rotary actuators

Advantages

- Simple and low-cost design
- High operating speed
- Clean and safe operation

Limitations

- Limited force compared to hydraulic systems
- Lower positioning accuracy due to air compressibility

1.3.3 Hydraulic Actuators

Hydraulic actuators use **pressurized liquid** (usually oil) to generate motion. They are especially suitable for applications requiring very high force and power.

Types of Hydraulic Actuators

- Hydraulic cylinders (linear motion)
- Hydraulic motors (rotary motion)

Advantages

- Very high force and torque capability
- Smooth and precise motion under heavy loads
- Suitable for harsh industrial environments

Limitations

- Complex and bulky systems
- Risk of fluid leakage
- Higher maintenance requirements

1.4 Classification Based on Working Principle

Actuators can also be classified according to the type of motion they produce.

1.4.1 Linear Actuators

Linear actuators generate motion along a straight line. Examples include hydraulic cylinders, pneumatic cylinders, and electric linear actuators.

1.4.2 Rotary Actuators

Rotary actuators produce rotational motion. Typical examples are electric motors, hydraulic motors, and pneumatic rotary actuators.

1.5 Comparison of Actuator Types

Actuators can be broadly classified into electric, hydraulic, and pneumatic types, each with distinct characteristics and applications. As illustrated in table 1.1, electric actuators offer high precision and cleanliness, making them ideal for robotics and automation, while hydraulic actuators provide a very high power density suitable for heavy-duty applications such as presses and construction machinery. Pneumatic actuators are simple, fast, and cost-effective, commonly used in industrial handling systems, but they provide lower force and precision compared to the other types. The following table summarizes a comparison of these actuator types based on key performance criteria.

Criterion	**Electric Actuators**	**Hydraulic Actuators**	**Pneumatic Actuators**
Cost	Moderate	High	Low
Power Capability	Medium	Very High	Low to Medium
Precision	Very High	High	Low
Maintenance Requirement	Low	High	Moderate
Response Speed	High	Medium	Very High
Energy Efficiency	High	Medium	Low
Stiffness	Medium	Very High	Low
Cleanliness	Very Clean	Oil Leakage Possible	Clean
Noise Level	Low	Medium	High
System Complexity	Low	High	Medium
Weight / Size Ratio	Compact	Heavy but Powerful	Lightweight
Typical Applications	Robotics, CNC machines, EV drives	Heavy machinery, aircraft systems	Pick-and-place systems, automation lines

Table 1.1: Comparison between Electric, Hydraulic and Pneumatic Actuation Systems

1.6 Conclusion

This chapter presented the fundamental concepts of actuators in automation systems. The definition, role, main types, and classification criteria of actuators were discussed. Understanding these basics is essential for selecting the appropriate actuator for a given automation application and forms the foundation for more advanced topics in actuator control and system integration.

Chapter 2

Electric Actuators

After completing this chapter,students will be able to:

- Explain electromagnetic energy conversion principles
- Distinguish between DC and AC motors
- Describe operation of brushed DC, stepper, and BLDC motors
- Explain induction motor power flow and efficiency
- Interpret star and delta motor connections
- Select electric actuators based on technical constraints

2.1 Introduction to Electric Motors

Electric actuators are the most widely used actuators in modern automation systems due to their precision, flexibility, and ease of integration with electronic control systems. At the heart of electric actuators are electric motors, which convert electrical energy into mechanical energy through electromagnetic interactions.

Electric motors are commonly used to generate rotary motion, which can be directly applied to a load or converted into linear motion using mechanical transmission elements such as gears, belts, screws, or racks.

They are suitable for high-dynamic and high-precision applications. The variety of technologies in this type of actuators, along with their ease of control, has allowed them to easily penetrate the industrial world. Furthermore, electrical energy is easy to use and readily lends itself to automatic controls and adjustments. The objective of this chapter is to understand the principle working of electric motors. We will explore concepts such as power, losses, and efficiency, as well as the characteristics of each type of electric motor.

2.1.1 Principle of Operation

The operation of electric motors is based on the interaction between a magnetic field and a current-carrying conductor. When an electric current flows through a conductor placed in a magnetic field, a force is generated according to Lorentz's law, producing motion.

2.1.2 DC Motors and AC Motors

Electric motors can be broadly classified into DC motors and AC motors based on the type of electrical supply used as illustrated in figure 2.1.

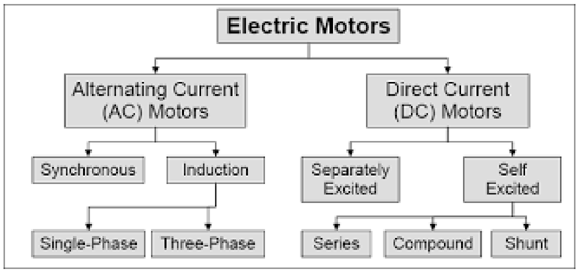


Figure 2.1: Types of electric motors

2.1.3 Main Characteristics of Electric Motors

Key parameters used to characterize electric motors include:

- Rated voltage and current
- Rated power and torque
- Speed range and efficiency

- Duty cycle
- Control method (open-loop or closed-loop)

2.2 DC Motors

A DC (Direct Current) motor is an electro-mechanical device that converts electrical energy from direct current into mechanical energy, resulting in rotary motion. It operates based on the interaction between a magnetic field and electric current in a wire winding to produce a torque that drives the motor's shaft. DC motors are commonly used in various applications such as robotics, electric vehicles, conveyor systems, and many other industrial and consumer devices. DC machines can operate as either motors or generators. Currently, their use as generators is limited due to the widespread use of AC power.

- Large DC Motors: find application in machine tools, printing presses, fans, pumps, cranes, paper mills, traction systems, and textile mills.
- Small DC Machines (Fractional Horsepower Rating lower than one kilo Watts: Primarily are used primarily as control device-such as tach generators for speed sensing and servomotors for position and tracking, and used in Robots.

1.Types of DC Motors

DC motors can be brushed, using mechanical brushes and a commutator, or brushless, which use electronic controllers for higher efficiency, longer life, and lower maintenance. different types of DC motor are summarized in 2.2.

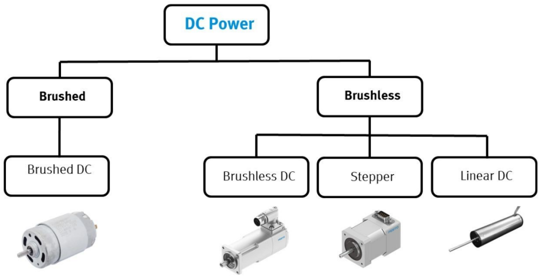


Figure 2.2: Types of DC Motors

Advantages of DC Motors

- Simple speed control over a wide range
- High starting torque
- Good dynamic response (Rapid acceleration and deceleration)
- Suitable for demanding applications (traction motors, electric trains, electric cars, etc.)

Limitations of DC Motors

- Brush wear and maintenance (brushed motors)
- Limited lifespan compared to AC motors
- Unsuitable for use in explosive areas
- Higher initial cost for BLDC and Servo DC

2.2.1 Brushed DC motor

1.Operating Principle of a DC Motor

A DC motor converts direct current electrical energy into mechanical rotational energy through the interaction between a magnetic field and a current-carrying conductor. When a DC voltage is applied to the armature, current flows in the conductors placed within the stator magnetic field. According to the Lorentz force law, each conductor experiences a force, generating an electromagnetic torque that causes the rotor to rotate.

The electromagnetic torque is given by:

$$T = k_t \, \Phi \, I_a$$

where Φ is the magnetic flux and I_a is the armature current.

2. Brushed DC motor construction

The construction of a DC (Direct Current) motor involves several key components that work together to convert electrical energy into mechanical motion. As mentioned in figure 2.3, the main components and their functions in a typical DC motor are:

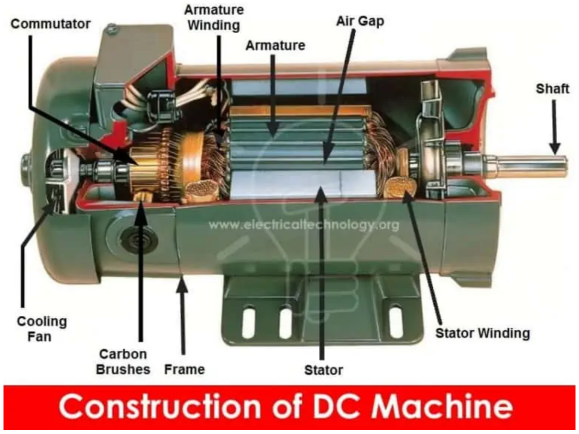


Figure 2.3: Construction of DC motor

- Stator: is the stationary part of the motor which consists of a magnetic frame or core made of laminated iron. The stator provides a magnetic field necessary for the motor's operation.

- Rotor: is the rotating part of the motor which is usually made of a coil or coils of wire wound around a core. When a current flows through the rotor windings, it interacts with the magnetic field, generating a torque that causes the rotor to turn.
- Commutator: is a rotary switch which consists of segments (usually copper bars) insulated from each other. The commutator, whose function is to facilitate the collection of current from the armature, It consists of copper segments tightly fastened together with mica/micanite insulating separators on an insulated base. The whole commutator forms a rigid and solid assembly of insulated copper strips and can rotate at high speeds. Each commutator segment is provided with a 'riser' where the ends of the armature coils get connected.
- Brushes: are conductive elements (often made of carbon) that maintain electrical contact with the commutator. They allow the current to flow from the external power source to the rotor windings.
- Brush Holders: are structures that hold the brushes in place and provide a path for electrical connection.
- Field Coils: In some DC motors, especially larger ones, the stator may have field coils instead of a permanent magnet. These field coils are energized to create a magnetic field, replacing the need for a permanent magnet.
- Housing or Frame: it encases and protects the motor's internal components. Also, it provides structural support and can also include features for mounting the motor.
- Bearings: it supports the rotor shaft, allowing it to rotate smoothly.

3.Types of Excitation of DC Motors

DC motors are classified according to the method used to produce the magnetic field in the stator. The excitation determines the motor characteristics such as torque, speed regulation, and applications.

Separately Excited DC Motor

In a separately excited DC motor, the field winding is supplied by an independent external DC source as shown in 2.4. This allows precise control of the field current and motor speed. These motors are widely used in applications requiring accurate speed control.

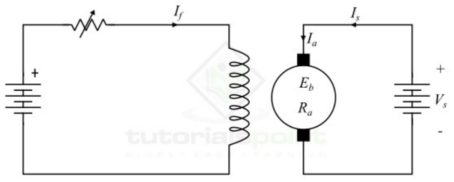


Figure 1 - Separately Excited DC Motor

Figure 2.4: Separately Excited DC Motor

Self-Excited DC Motors

In self-excited DC motors, the field winding is powered by the motor's own armature supply. They are classified as follows:

Shunt DC Motor

The field winding is connected in parallel with the armature as shown in figure 2.5. Shunt DC motors provide nearly constant speed under varying load conditions and are commonly used in machine tools and fans.

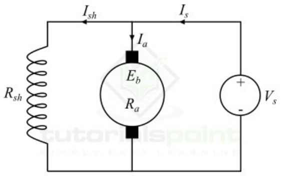


Figure 3 - Shunt DC Motor

Figure 2.5: Shunt DC Motor

Series DC Motor

The field winding is connected in series with the armature as shown in figure 2.6. This configuration produces a very high starting torque but poor speed regulation, making it suitable for traction, cranes, and hoists.

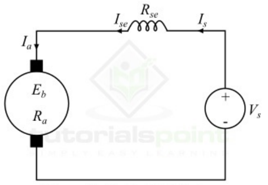


Figure 2 - Series DC Motor

Figure 2.6: Series DC Motor

Compound DC Motor

Compound DC motors combine shunt and series field windings (see fig2.7, 2.8) to achieve good starting torque and better speed regulation. They are classified into flowing.

- Short-shunt compound DC motor
- Long-shunt compound DC motor

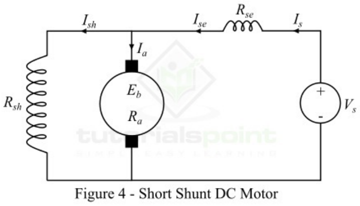


Figure 2.7: Short-shunt compound DC motor

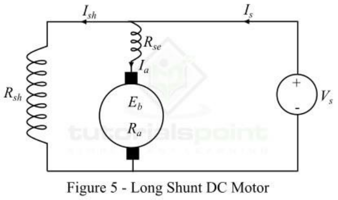


Figure 2.8: Long-shunt compound DC motor

Permanent Magnet DC motors (PMDCM)

In permanent magnet DC motors, the stator magnetic field is produced by permanent magnets instead of field windings as shown in figure 2.9. These motors are compact, efficient, and commonly used in low-power applications such as robotics and small actuators.

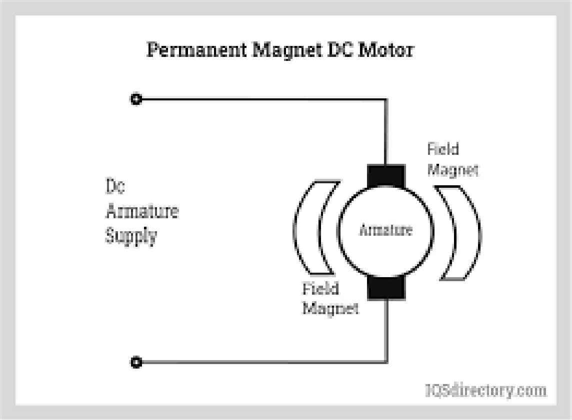


Figure 2.9: Permanent Magnet DC Motor

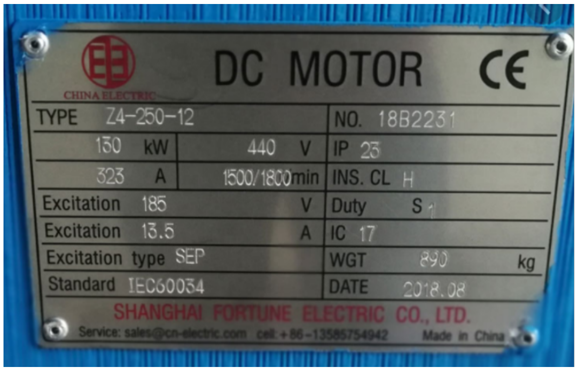
4.Motor Nameplate and Standardized Information

A *motor nameplate* is a metal or plastic label permanently attached to the housing of an electric motor as illustrated in figure 2.10. It provides essential information about the electrical, mechanical, and thermal characteristics of the motor. The nameplate serves as a primary reference for installers,

Table 2.1: Torque–Speed Characteristics of DC Motors According to Excitation Type

DC Motor Type	**Torque Characteristic**	**Speed Characteristic**	**Typical Applications**
Separately Excited DC Motor	Torque proportional to armature current	Wide and precise speed control	Variable-speed drives, laboratory drives
Shunt DC Motor	Moderate starting torque	Nearly constant speed with load variation	Machine tools, fans, blowers
Series DC Motor	Very high starting torque	Speed varies greatly with load; dangerous at no-load	Traction, cranes, hoists
Cumulatively Compounded DC Motor	High starting torque	Better speed regulation than series motor	Elevators, rolling mills
Differentially Compounded DC Motor	Lower starting torque	Speed increases with load (unstable)	Rarely used
Permanent Magnet DC Motor	Torque proportional to armature current	Good speed regulation within rated load	Robotics, small actuators

operators, maintenance, personnel and engineers to ensure proper installation, safe operation, and effective maintenance throughout the service life of the motor. Motor nameplates play a crucial role in motor selection and system design, as they allow users to verify compatibility with power supplies, protection devices, and load requirements. They also assist in troubleshooting, performance evaluation, and compliance with safety standards.



TYPE Z4-250-12
NO. 18B2231
150 kW
440 V
IP 23
323 A
1500/1800 min
INS. CL H
Excitation 185 V
Duty S 1
Excitation 13.5 A
IC 17
Excitation type SEP
WGT 890 kg
Standard IEC60034
DATE 2018.08
SHANGHAI FORTUNE ELECTRIC CO., LTD.
Service: sales@cn-electric.com cell: +86-13585754942 Made in China

Figure 2.10: DC motor nameplate

Motor Standards and Regulatory Bodies

Although motor standards may vary from one country to another, most industrial motors comply with standards defined by one of the following organizations:

- **International Electrotechnical Commission (IEC)**
- **National Electrical Manufacturers Association (NEMA)**

Motor nameplates are designed according to the specifications established by these organizations, ensuring uniformity, safety, and interchangeability.

Typical Information on a Motor Nameplate

The key information commonly found on a motor nameplate includes:

- **Manufacturer and Model**: Identifies the motor brand and specific model.
- **Power Rating**: Indicates the rated output power, typically expressed in kilowatts (kW) or horsepower (HP).
- **Rated Voltage**: Specifies the nominal supply voltage for proper operation.
- **Rated Current**: Indicates the current drawn by the motor at full load.
- **Frequency**: For AC motors, specifies the supply frequency (e.g., 50 Hz or 60 Hz).
- **Rated Speed**: Given in revolutions per minute (RPM) under rated conditions.
- **Efficiency**: Indicates how effectively electrical energy is converted into mechanical energy.
- **Insulation Class**: Specifies the thermal endurance of the winding insulation.
- **Enclosure Type**: Describes the motor housing and environmental protection.
- **Ambient Temperature**: Maximum surrounding temperature for safe operation.
- **Service Factor**: Indicates the motor's ability to operate under temporary overload conditions.
- **Serial Number and Date of Manufacture**: Used for identification, traceability, and warranty purposes.

Insulation Class

The *insulation class* defines the maximum allowable temperature that the motor's insulation system can withstand without degradation. It is a standardized classification used for electrical machines, transformers, and cables to ensure thermal safety and reliability.

Insulation classes are designated by letters and correspond to specific maximum temperature limits:

- **Class A**: 105 °C
- **Class B**: 130 °C
- **Class F**: 155 °C
- **Class H**: 180 °C

Selecting an appropriate insulation class is essential in applications involving high ambient temperatures, frequent overloads, or severe operating conditions.

Enclosure Type and Ingress Protection (IP)

The enclosure type defines the level of protection provided by the motor housing against environmental influences. Common enclosure types include:

- Open Drip-Proof (ODP)
- Totally Enclosed Fan-Cooled (TEFC)
- Explosion-Proof (XP)

In addition, motors are often rated using the **Ingress Protection (IP)** classification, which specifies protection against solid objects and water ingress. The IP rating consists of two digits:

- The **first digit** indicates protection against solid particles such as dust.
- The **second digit** indicates protection against water.

For example, an **IP54** rating means:

- Protection against limited dust ingress (dust-protected)
- Protection against water splashes from any direction

The appropriate IP rating depends on the motor's operating environment and application requirements.

5. Efficiency and Power Flow of a DC Brushed Motor

A DC motor converts electrical energy into mechanical energy, with some losses occurring due to copper, iron, and mechanical effects. The electrical input power to the motor is given by:

$$P_{\text{electrical}} = V_a \, I_a$$

where V_a is the armature voltage and I_a is the armature current.

Power Losses

The main losses in a brushed DC motor are:

- **Armature copper loss:** $P_a = I_a^2 R_a$
- **Field winding copper loss:** $P_f = I_f^2 R_f$
- **Mechanical losses:** friction and windage, P_{mech}
- **Core (iron) losses:** hysteresis and eddy current, P_{core}
- **Brush contact losses:** P_{brush}

The total power loss is therefore:

$$P_{\text{loss}} = P_a + P_f + P_{\text{mech}} + P_{\text{core}} + P_{\text{brush}}$$

Mechanical Output Power

The mechanical power delivered to the shaft is:

$$P_{\text{mech}} = T\,\omega$$

where T is the electromagnetic torque and ω is the angular speed in rad/s.

Efficiency Calculation

The efficiency η of the DC motor is defined as the ratio of mechanical output power to electrical input power:

$$\eta = \frac{P_{\text{mech}}}{P_{\text{electrical}}} = \frac{P_{\text{electrical}} - P_{\text{loss}}}{P_{\text{electrical}}} = 1 - \frac{P_{\text{loss}}}{P_{\text{electrical}}}$$

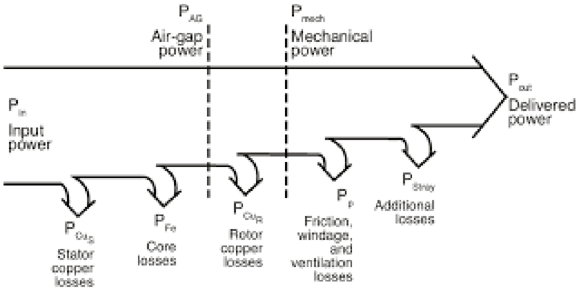


Figure 2.11: Power Flow Diagram

Example

Consider a DC motor supplied at $V_a = 200$ V and $I_a = 10$ A, with the following losses:

- Armature copper loss: $P_a = 60$ W
- Field copper loss: $P_f = 40$ W
- Mechanical, core, and brush losses: $P_{\text{mech+core+brush}} = 50$ W

The total electrical input power is:

$$P_{\text{in}} = V_a\,I_a = 200 \times 10 = 2000 \text{ W}$$

The total losses are:

$$P_{\text{loss}} = 60 + 40 + 50 = 150 \text{ W}$$

The mechanical output power is:

$$P_{\text{mech}} = P_{\text{in}} - P_{\text{loss}} = 2000 - 150 = 1850 \text{ W}$$

The efficiency of the motor is then:

$$\eta = \frac{P_{\text{mech}}}{P_{\text{in}}} = \frac{1850}{2000} = 0.925 = 92.5\%$$

2.2.2 Stepper motor

A stepper motor (figure 2.12) is a brushless electromechanical actuator that converts electrical pulses into discrete angular movements. Each input pulse corresponds to a fixed mechanical step, making stepper motors particularly suitable for precise position and speed control in open-loop systems.

Figure 2.12: Stepper motor

1. Applications of Stepper Motors

Stepper motors are widely used in applications requiring accurate positioning, repeatability, and low-speed torque. Typical applications include:

- Computer peripherals such as printers, scanners, and disk drives
- CNC machines and 3D printers
- Robotics and automated positioning systems
- Medical equipment (infusion pumps, imaging systems)
- Camera positioning and focus control systems
- Industrial instrumentation and valve actuators

2. Typical Power Range of Stepper Motors According to NEMA Size

Stepper motors are commonly classified by the **NEMA (National Electrical Manufacturers Association)** frame size, which defines the motor's mounting dimensions rather than its electrical performance. However, each NEMA size is generally associated with a typical power and torque range.

3. Types of Stepper Motors According to Rotor Structure

Based on the rotor construction, stepper motors are classified into three main types:

Table 2.2: Typical Power Range of Stepper Motors by NEMA Size

NEMA Size	Frame Size (in)	Typical Power Range	Typical Applications
NEMA 8	0.8×0.8	1 – 5 W	Precision instruments, optics
NEMA 11	1.1×1.1	5 – 15 W	Small automation, cameras
NEMA 14	1.4×1.4	10 – 30 W	Office equipment
NEMA 17	1.7×1.7	20 – 60 W	3D printers, robotics
NEMA 23	2.3×2.3	60 – 150 W	CNC machines, automation
NEMA 34	3.4×3.4	150 – 300 W	Industrial positioning
NEMA 42	4.2×4.2	300 – 500 W	Heavy-duty motion systems

Variable Reluctance (VR) Stepper Motor

As illustrated in figure 2.13, the rotor of a variable reluctance stepper motor is made of soft iron with salient poles and contains no permanent magnets. Torque is produced by the tendency of the rotor to align with the minimum reluctance path of the magnetic circuit.

- Simple and robust construction
- High step resolution
- Low torque compared to other types

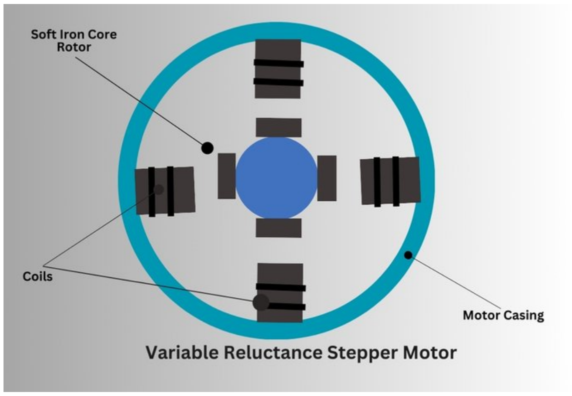


Figure 2.13: Variable Reluctance (VR) Stepper Motor construction

Number of Steps and Step Angle of Variable Reluctance Stepper Motors

A Variable Reluctance (VR) stepper motor consists of a toothed soft-iron rotor and a stator with salient poles arranged in phases. The rotor has no permanent magnets. Motion is obtained by sequentially energizing the stator phases, causing the rotor to align with the minimum reluctance position.

Number of Steps per Revolution

Let:

- N_r be the number of rotor teeth
- N_s be the number of stator teeth
- m be the number of stator phases

For a VR stepper motor, the number of steps per mechanical revolution is given by:

$$N_{\text{steps}} = m \times N_r$$

Step Angle

The step angle α is defined as the angular displacement of the rotor for each input pulse. It is expressed as:

$$\alpha = \frac{360^\circ}{N_{\text{steps}}}$$

Substituting the expression for the number of steps:

$$\alpha = \frac{360^\circ}{m\,N_r}$$

Example

Consider a VR stepper motor with:

- Number of phases: $m = 3$
- Number of rotor teeth: $N_r = 12$

The number of steps per revolution is:

$$N_{\text{steps}} = 3 \times 12 = 36$$

The corresponding step angle is:

$$\alpha = \frac{360^\circ}{36} = 10^\circ$$

Remarks

- Increasing the number of rotor teeth reduces the step angle and improves positioning resolution.
- VR stepper motors typically have larger step angles compared to hybrid stepper motors.
- The step angle depends only on the motor geometry and number of phases.

Permanent Magnet (PM) Stepper Motor

A permanent magnet stepper motor has a stator with wound, salient (projecting) poles and a cylindrical rotor made of permanently magnetized material (see figure 2.14), typically magnetically hard ferrite or rare-earth magnets. The rotor is radially magnetized, forming alternating north and south poles around its circumference. When the stator windings are energized, they generate a magnetic field that interacts with the rotor's magnetic field to produce electromagnetic torque. The rotor aligns with the energized stator poles, resulting in step-by-step motion, and the direction of rotation depends on the sequence and polarity of the stator current excitation.

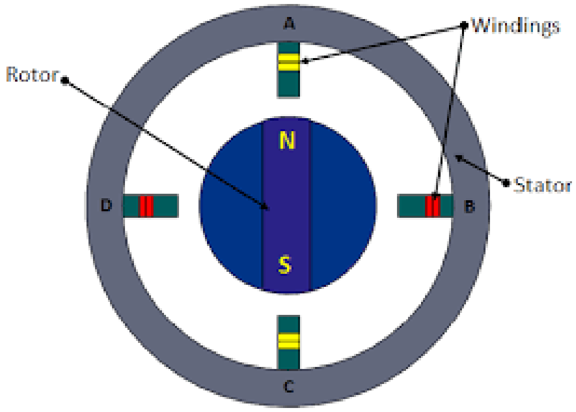


Figure 2.14: Permanent Magnet (PM) Stepper Motor construction

- Higher torque than VR stepper motors
- Larger step angle
- Moderate positioning accuracy

Step Angle and Number of Steps of Permanent Magnet (PM) Stepper Motors

In permanent magnet stepper motors, the rotor consists of a cylindrical permanent magnet with alternating north and south poles, while the stator has wound salient poles. The step angle α is the angular displacement of the rotor for each input pulse, determined by the rotor and stator geometry.

Let:

- N_r = Number of rotor poles (permanent magnet poles)
- m = Number of stator phases

The number of steps per revolution is:

$$N_{\text{steps}} = m \times N_r$$

The step angle is calculated as:

$$\alpha = \frac{360^\circ}{N_{\text{steps}}} = \frac{360^\circ}{m\,N_r}$$

Example: Consider a PM stepper motor with:

- $m = 2$ phases
- $N_r = 6$ rotor poles

Then the number of steps per revolution is:

$$N_{\text{steps}} = 2 \times 6 = 12$$

and the step angle is:

$$\alpha = \frac{360^\circ}{12} = 30^\circ$$

Remarks:

- PM stepper motors generally have **medium step angles** between 7.5° and 15°.
- Increasing the number of rotor poles or stator phases reduces the step angle and improves positioning resolution.
- They are widely used in **medium-precision positioning applications** such as office automation, cameras, and small actuators.

Hybrid Stepper Motor

A hybrid stepper motor combines the operating principles of variable reluctance and permanent magnet stepper motors to achieve high torque and high positioning accuracy. The rotor consists of a permanent magnet magnetized axially and sandwiched between two toothed soft-iron rotor cups. The stator has toothed salient poles equipped with concentrated windings.

When the stator phases are sequentially energized, a rotating magnetic field is produced. The rotor aligns itself with successive minimum reluctance positions, resulting in step-by-step motion. Due to its toothed rotor and stator structure, the hybrid stepper motor exhibits a small step angle, typically 1.8° or 0.9°, making it the most widely used stepper motor in precision motion control applications.

Hybrid stepper motors are commonly employed in CNC machines, robotics, 3D printers, and industrial automation systems where accurate positioning and high holding torque are required.

- High torque and high precision
- Small step angle (typically 1.8° or 0.9°)
- Most widely used type in industrial applications

Step Angle and Number of Steps of Hybrid Stepper Motors

The step angle α of a hybrid stepper motor is the angular displacement of the rotor for each input pulse. It depends on the rotor and stator geometry.

Let:

- N_r = Number of rotor teeth

- N_s = Number of stator teeth per phase
- m = Number of stator phases

The number of steps per revolution is:

$$N_{\text{steps}} = m \times N_r$$

The step angle is then calculated as:

$$\alpha = \frac{360^\circ}{N_{\text{steps}}} = \frac{360^\circ}{m\,N_r}$$

Example: Consider a hybrid stepper motor with:

- $m = 2$ phases
- $N_r = 50$ rotor teeth

Then the number of steps per revolution is:

$$N_{\text{steps}} = 2 \times 50 = 100$$

and the step angle is:

$$\alpha = \frac{360^\circ}{100} = 3.6^\circ$$

Hybrid stepper motors usually have small step angles, typically 1.8° or 0.9°, providing **high positioning accuracy**.

Comparison of Stepper Motor Types

Stepper motors are classified into Permanent Magnet (PM), Variable Reluctance (VR), and Hybrid types. PM stepper motors provide moderate torque and resolution with simple construction. VR stepper motors offer fast response but lower torque and no holding torque. Hybrid stepper motors combine both technologies, delivering higher torque, finer resolution, and better positioning accuracy, making them the most widely used in precision applications.

3. Types of Stepper Motors to arrangement of stator windings

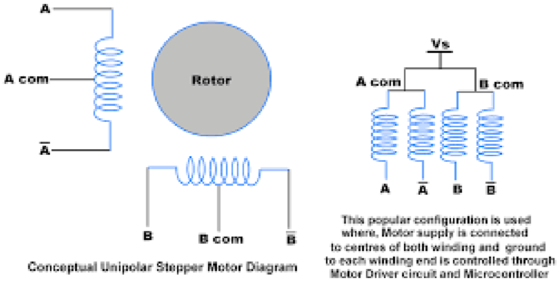
The stator of a stepper motor (SM) contains multiple windings, and the configuration of these windings is the primary factor that distinguishes different types of stepper motor from an electrical perspective. Accordingly, stepper motors can be designed with unipolar or bipolar windings, as described below.

Unipolar stepper motors

Unipolar stepper motors consist of two windings, each with a center tap, resulting in five or six external wires as shown in figure 2.15. The center tap(s) are connected to a power supply, while the coil ends are alternately grounded to drive the motor. Although sometimes called a "four-phase motor," a more accurate name is "dual-phase, 6-wire stepper motor", reflecting that it has two phases with center-tapped coils.

Table 2.3: Comparison of VR, PM, and Hybrid Stepper Motors

Feature	**Variable Reluctance (VR)**	**Permanent Magnet (PM)**	**Hybrid**
Rotor Type	Soft iron, no magnet	Permanent magnet, cylindrical	Permanent magnet + toothed rotor
Stator Type	Wound salient poles	Wound salient poles	Wound toothed poles
Step Angle	Large (> 15°)	Medium (7.5–15°)	Small (0.9–1.8°)
Torque	Low	Medium	High
Positioning Accuracy	Moderate	Moderate	High
Applications	Low-cost positioning, instruments	Office automation, small machines	CNC, robotics, 3D printers, industrial automation



Conceptual Unipolar Stepper Motor Diagram

This popular configuration is used where, Motor supply is connected to centres of both winding and ground to each winding end is controlled through Motor Driver circuit and Microcontroller

Figure 2.15: Unipolar stepper motors

Bipolar stepper motors

A bipolar stepper motor has one winding per stator phase and typically four lead wires for a two-phase motor (see figure 2.17). Unlike unipolar motors, it has no common center tap, and the current flows through the entire coil, producing higher torque for the same motor size. Although the structure is simple, driving a bipolar stepper is more complex because the current must be reversible, requiring a positive and negative supply and an H-bridge driver circuit. The polarity of each coil must be switched to reverse the magnetic field, and a two-phase bipolar motor usually needs eight transistors (two H-bridges) to operate.

The power stage for stepper motors depends on the winding type. Unipolar motors use simpler drivers, as only half of each coil is energized at a time, requiring a single supply and basic switching transistors. Bipolar motors need bidirectional current in the windings, which requires H-bridge circuits per phase, making the driver more complex but delivering higher torque and efficiency. Both types can use microstepping drivers for smoother motion and finer positioning.

Types of Stepper Motor Supplying (Driving) Methods

Stepper motors are supplied using electronic drivers that control the sequence and magnitude of currents in the stator windings. The main driving methods are:

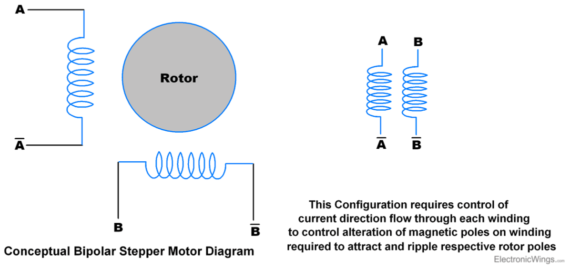


Figure 2.16: Biploar stepper motor

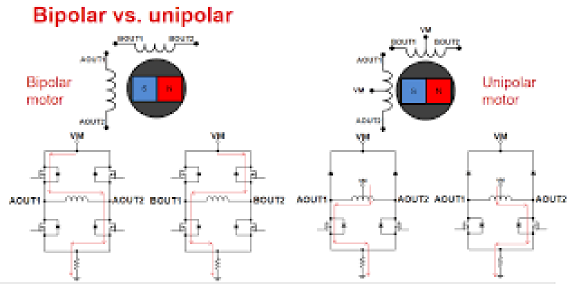


Figure 2.17: Biploar Vs uniploar

Wave stepping drive (one-phase-on)

As shown in figure 2.18 Wave stepping (one-phase-on) energizes only one stator phase at a time, advancing the motor step by step through a sequential excitation. It offers simple control and low power consumption but produces lower torque and holding capability than full-step (two-phase-on) excitation.

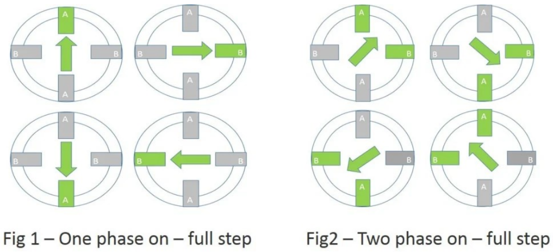


Fig 1 – One phase on – full step

Fig2 – Two phase on – full step

Figure 2.18: one/two phase drive method

Full stepping Drive (two-phase-on)

In full-step operation, the motor moves one full step per input pulse. Two phases are usually energized simultaneously to increase torque.

- Simple control
- High torque
- Lower positioning resolution

Half stepping Drive (one/two-phase-on)

As illustrated in figure2.19, half-step driving alternates between one-phase and two-phase excitation, effectively halving the step angle.

- Improved resolution compared to full-step mode
- Reduced torque ripple
- Moderate control complexity

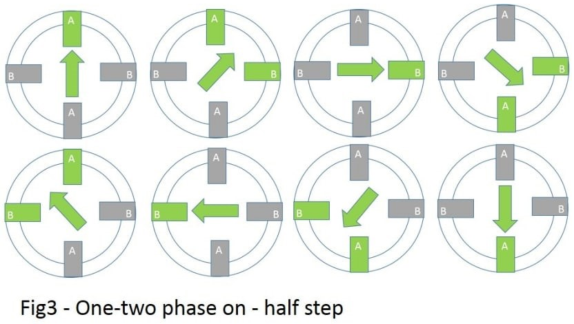


Figure 2.19: Half stepping drive method

Microstepping Drive

In microstepping mode, the phase currents are controlled with sinusoidal waveforms, allowing the rotor to move in very small increments.

- Very smooth motion
- High positioning accuracy
- Reduced vibration and noise
- More complex driver and control circuitry

4. Effective Step Angle of Stepper Motors

The **effective step angle** of a stepper motor depends not only on its intrinsic construction but also on the **type of winding** (unipolar or bipolar) and the **driving method** (full-step, half-step, microstepping).

A. Intrinsic Step Angle

The physical step angle of a motor is determined by its rotor and stator structure:

$$\theta_{\text{phys}} = \frac{360^\circ}{N_s \cdot N_r} \tag{2.1}$$

where N_s is the number of stator phases (or pole pairs per phase) and N_r is the number of rotor teeth. This represents the angle moved per excitation step in the simplest driving mode.

B. Effect of Motor Type and Driving Method

- **Unipolar Motor:**
  - *Full-step:* $\theta_{\text{step}} = \theta_{\text{phys}}, \quad \text{Steps/rev} = \frac{360^\circ}{\theta_{\text{phys}}}$
  - *Half-step:* $\theta_{\text{step}} = \theta_{\text{phys}}/2, \quad \text{Steps/rev} = 2 \cdot \frac{360^\circ}{\theta_{\text{phys}}}$
- **Bipolar Motor:**
  - *Full-step:* $\theta_{\text{step}} = \theta_{\text{phys}}/2, \quad \text{Steps/rev} = 2 \cdot \frac{360^\circ}{\theta_{\text{phys}}}$
  - *Half-step:* $\theta_{\text{step}} = \theta_{\text{phys}}/4, \quad \text{Steps/rev} = 4 \cdot \frac{360^\circ}{\theta_{\text{phys}}}$
- **Microstepping (any motor type):** Divides each step into n microsteps:

$$\theta_{\text{microstep}} = \frac{\theta_{\text{step}}}{n}, \quad \text{Steps/rev} = n \cdot \frac{360^\circ}{\theta_{\text{step}}} \tag{2.2}$$

C. Remarks

- Bipolar motors effectively *double* the number of steps per revolution compared to unipolar motors when using full-step driving, because both coil directions are utilized.
- Half-stepping and microstepping further increase the resolution and smoothness of motion.

5.Advantages and Limitations of Stepper Motors

Advantages:

- Precise position control without feedback
- High holding torque at standstill
- Simple control using digital pulses

Limitations:

- Torque decreases rapidly at high speeds
- Lower efficiency compared to BLDC motors
- Risk of missed steps in open-loop operation

2.2.3 Brushless DC (BLDC) Motors

Brushless DC (BLDC) motors are a modern type of DC motor in which the traditional mechanical commutator and brushes are replaced by an electronic controller. This design eliminates brush friction and wear, resulting in higher efficiency, reliability, and reduced maintenance.

1. Principle of Operation

BLDC motors operate on the same basic principle as DC motors: a current-carrying conductor placed in a magnetic field experiences a force, producing torque. In a BLDC motor:

- The rotor contains permanent magnets, generating a constant magnetic field.
- The stator windings are energized sequentially by an electronic driver.
- Hall effect sensors or sensorless control determine rotor position to switch the current at the correct time.

This electronic commutation replaces the mechanical commutator used in conventional DC motors.

2. Construction

A Brushless Direct Current (BLDC) motor is mainly composed of (see figure figure2.20):

- **Rotor:** Permanent magnets mounted on a rotating shaft.
- **Stator:** Wound with three-phase coils, typically in a star (Y) configuration.
- **Electronic Controller:** Converts DC supply into properly timed phase currents.

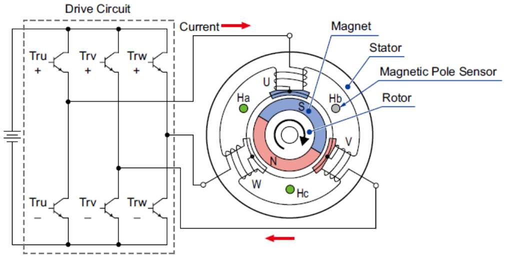


Fig. 2.8 Simplified Model of a Brushless Motor

Figure 2.20: Construction of BLDC motor

3.Advantages of BLDC Motors

- High efficiency and power density
- Long operational life due to no brushes

- Low maintenance requirements
- Precise speed and position control
- Reduced electrical noise and sparking

4. Applications

BLDC motors are widely used in:

- Robotics and automation actuators
- Electric vehicles (EVs) and drones
- Computer peripherals (hard drives, fans)
- Industrial drives requiring high precision and reliability

Table 2.4: BLDC vs. Brushed DC Motor Characteristics

Feature	**Brushed DC Motor**	**BLDC Motor**
Commutation	Mechanical (brushes)	Electronic
Maintenance	High	Low
Efficiency	Moderate	High
Lifetime	Limited (brush wear)	Long
Speed Control	Simple	Precise, programmable
Noise / Sparking	High	Low

2.3 AC Motors

AC motors operate using alternating current (AC) electrical supply and are widely employed in industrial environments due to their robustness, high efficiency, and suitability for continuous operation. They are particularly valued for their simple construction, low maintenance requirements, and ability to deliver reliable performance under varying load conditions.

Advantages of AC Motors

- Robust construction
- Low maintenance
- Suitable for high-power applications

Limitations of AC Motors

- More complex speed control
- Lower starting torque without control devices

2.3.1 Classification of AC Motors

AC motors are electrical machines supplied by alternating current. They are broadly classified into:

- Single-phase AC motors
- Three-phase AC motors
- Synchronous motors

2.3.2 Single-Phase AC Motors

Single-phase motors operate from a single-phase AC supply (typically 220–240 V, 50/60 Hz) (see figure2.21). They are widely used in residential and light commercial applications.

A major characteristic of single-phase motors is that they are **not self-starting**.

Operating Principle

A single-phase supply produces a pulsating magnetic field rather than a rotating magnetic field.

According to the double revolving field theory, a pulsating magnetic field can be decomposed into two rotating magnetic fields:

- Equal magnitude
- Opposite directions
- Same synchronous speed

At standstill:

$$T_{forward} = T_{backward}$$

Therefore,

$$T_{starting} = 0$$

An auxiliary winding is required to create a phase shift and generate starting torque.

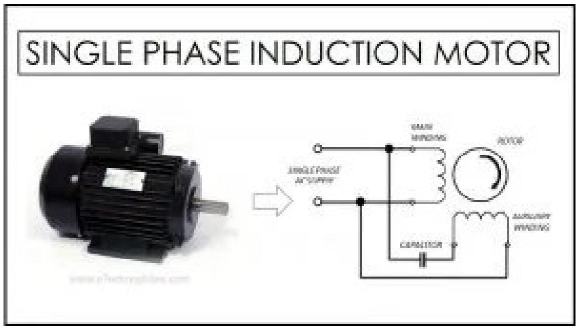


Figure 2.21: Single phase Induction Motor

Types of Single-Phase Motors

1) Split-Phase Motor

- Auxiliary winding with higher resistance
- Moderate starting torque
- Centrifugal switch disconnects auxiliary winding

Applications: Fans, small pumps, washing machines.

2) Capacitor-Start Motor

- Capacitor connected in series with auxiliary winding
- High starting torque
- Used for heavier loads

3) Capacitor-Start Capacitor-Run Motor

- Two capacitors (start + run)
- High starting torque
- Improved efficiency and power factor

4) Shaded Pole Motor

- Shading coil produces weak rotating field
- Low starting torque
- Very simple construction

Applications: Small fans, clocks, small household appliances.

2.3.3 Three-Phase AC Motors

Introduction

A three-phase induction motor, also called an asynchronous motor, operates on the principle of electromagnetic induction, where the rotor current is induced by the rotating magnetic field of the stator to produce torque. It may use either a squirrel-cage rotor or a wound rotor. Its defining feature is that the rotor speed is slightly lower than the synchronous speed, which makes it highly reliable and widely used in industrial and commercial applications. They are widely used in industrial applications due to their:

- High efficiency
- High reliability
- Self-starting capability
- Smooth torque production

Rotating Magnetic Field

A balanced three-phase supply produces a rotating magnetic field with constant magnitude.

The synchronous speed is given by:

$$n_s = \frac{120f}{P}$$

where:

- f = supply frequency (Hz)
- P = number of poles

1) Three-Phase Induction Motor There are basically 2 types of rotor construction

- Rotor types:
  - Squirrel-cage rotor : no windings and no slip rings
  - Wound rotor :It has 3 phase windings, usually Y connected, and the winding ends are connected via slip rings. Wound rotor are known to be more expensive due to its maintenance cost to upkeep the slip rings, carbon brushes and also rotor windings.
- Operates with slip: Induction motor rotor always rotate at a speed less than synchronous speed. The difference between the main flux speed (n_s) and their rotor speed (n_r) is called slip. It is usually expressed as a percentage of synchronous speed (n_s) and is represented by s.

$$s = \frac{n_s - n_r}{n_s}$$

where n_r is rotor speed. The difference between synchronous speed and rotor speed is called slip speed i.e., Slip speed = $n_s - n_r$

2.3.4 Power Flow in an Induction Motor

As illustrated in figure2.22, the power flow in an induction motor can be summarized as follows:

- **Input Power (P_{in}):** Three-phase electrical power supplied to the stator.
- **Stator Copper Losses (P_{SCL}):** I^2R losses occurring in the stator windings.
- **Core (Iron) Losses (P_{core}):** Losses due to hysteresis and eddy currents, mainly in the stator core. Represented in the equivalent circuit by the resistance R_C (or conductance G_C).
- **Air-Gap Power (P_{AG}):** Power transferred from the stator to the rotor across the air gap.
- **Rotor Copper Losses (P_{RCL}):** I^2R losses occurring in the rotor windings.
- **Converted Power (P_{conv}):** Electrical power converted into mechanical power.
- **Mechanical Losses:**

  - Friction and windage losses ($P_{F\&W}$)
  - Stray losses (P_{misc})
- **Output Power (P_{out}):** Remaining mechanical power available at the motor shaft.

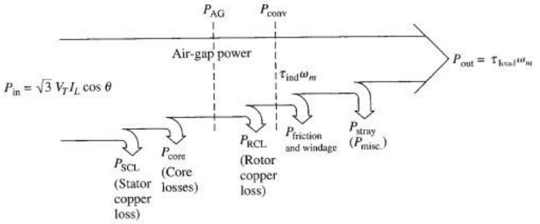


Figure 2.22: induction motor power folow diagram

Note on Core and Rotational Losses

- Core losses originate from both stator and rotor, but rotor core losses are very small since the rotor operates near synchronous speed.
- Therefore, core losses are generally lumped at the stator side in the power-flow diagram.
- Friction, windage, and stray losses are often grouped with core losses and called **rotational losses**.
- Rotational losses are commonly assumed constant because some components increase with speed while others decrease.

2.3.5 Example: Induction Motor Power Flow and Efficiency Calculation

Given Data

A three-phase induction motor has the following data:

- Input power: $P_{in} = 50\,\text{kW}$
- Stator copper losses: $P_{SCL} = 2\,\text{kW}$
- Core losses: $P_{core} = 1.5\,\text{kW}$
- Rotor copper losses: $P_{RCL} = 1.2\,\text{kW}$
- Mechanical losses (friction and windage): $P_{mech} = 0.8\,\text{kW}$

Step 1: Air-Gap Power

The air-gap power is the power transferred from stator to rotor:

$$P_{AG} = P_{in} - P_{SCL} - P_{core}$$

$$P_{AG} = 50 - 2 - 1.5 = 46.5\,\text{kW}$$

Step 2: Converted Mechanical Power

The converted power is:

$$P_{conv} = P_{AG} - P_{RCL}$$

$$P_{conv} = 46.5 - 1.2 = 45.3\,\text{kW}$$

Step 3: Output Power

$$P_{out} = P_{conv} - P_{mech}$$

$$P_{out} = 45.3 - 0.8 = 44.5\,\text{kW}$$

Step 4: Efficiency Calculation

Motor efficiency is defined as:

$$\eta = \frac{P_{out}}{P_{in}}$$

$$\eta = \frac{44.5}{50} = 0.89$$

$$\eta = 89\%$$

Power Flow Summary

$$P_{in} \to P_{SCL},\, P_{core} \to P_{AG} \to P_{RCL} \to P_{conv} \to P_{mech} \to P_{out}$$

Slip Verification (Optional)

Since rotor copper losses are related to slip:

$$P_{RCL} = s \cdot P_{AG}$$

$$s = \frac{P_{RCL}}{P_{AG}} = \frac{1.2}{46.5} = 0.0258$$

$$s \approx 2.6\%$$

This confirms normal industrial operation near synchronous speed.

2.3.6 Star (Y) and Delta (Δ) Connections

Three-phase motors can be connected in either **Star (Y)** or **Delta (Δ)** configuration depending on **the supply voltage** and desired **operating conditions**.

Star (Y) Connection

In a star connection, one end of each phase winding is connected to a common neutral point, while the other ends are connected to the three supply lines as shown in figure2.23.

- Line voltage: $V_L = \sqrt{3}\, V_{ph}$
- Line current: $I_L = I_{ph}$

Characteristics:

- Lower phase voltage
- Reduced starting current
- Reduced starting torque
- Suitable for high-voltage operation

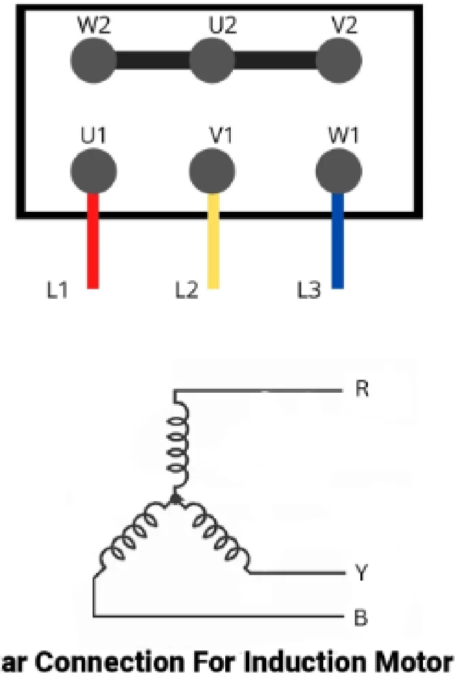


Figure 2.23: Star connection

Star connection is commonly used during motor starting in star-delta starters to limit inrush current.

Delta (Δ) Connection

In a delta connection, the end of each phase winding is connected to the beginning of the next phase, forming a closed loop (see figure2.24).

- Line voltage: $V_L = V_{ph}$
- Line current: $I_L = \sqrt{3}\, I_{ph}$

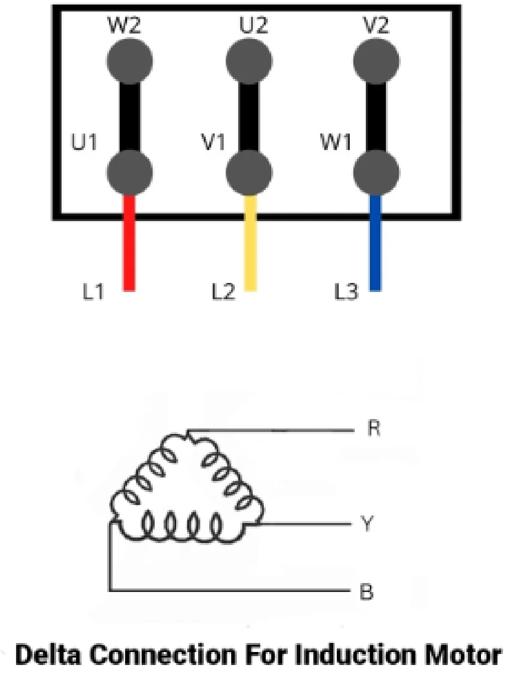


Figure 2.24: Delta connection

Characteristics:

- Higher phase voltage
- Higher starting current
- Higher starting torque
- Suitable for low-voltage, high-power operation

Comparison Between Star and Delta Connections

Feature	Star (Y)	Delta (Δ)
Phase Voltage	$V_L/\sqrt{3}$	V_L
Line Current	I_{ph}	$\sqrt{3}\,I_{ph}$
Starting Current	Lower	Higher
Starting Torque	Lower	Higher
Typical Use	Motor Starting	Normal Operation

2.4 Selection Criteria for Electric Actuators

The selection of an electric actuator depends on several technical and economic factors.

2.4.1 Technical Criteria

- Required torque and power
- Speed and acceleration requirements
- Positioning accuracy and resolution
- Load characteristics (inertia, friction)
- Operating environment

2.4.2 Economic and Practical Criteria

- Cost of the actuator and drive system
- Maintenance requirements
- Energy efficiency
- Reliability and lifespan

2.5 Conclusion

This chapter presented a comprehensive overview of electric actuators, with particular emphasis on electric motors, their operating principles, and their classification. DC motors, AC motors, stepper motors, and servo motors were analyzed and compared in terms of performance characteristics and typical applications. Furthermore, the power flow diagrams of the DC brushed motor and the three-phase motor were discussed in detail to highlight energy conversion and loss mechanisms. Finally, key selection criteria were introduced to assist engineers in choosing the most appropriate electric actuator for a specific automation application.

Chapter 3

Pneumatic and Hydraulic Actuators

After completing this chapter,students will be able to:

- Explain physical principles of pneumatic systems
- Describe pneumatic cylinders and motors
- Identify industrial pneumatic applications
- Explain hydraulic actuation principles
- Compare single-acting and double-acting cylinders
- Evaluate advantages and limitations of hydraulic systems

3.1 Introduction

Pneumatic actuators are devices that convert the energy of compressed air or gas into a mechanical motion that regulates one or more final control elements. Pneumatic actuators are widely used in industrial automation systems because of their simplicity, reliability, and rapid response. They operate by converting the energy of compressed air into mechanical motion through pressure differences acting on a piston, vane, or diaphragm. The most common pneumatic actuators are cylinders for linear motion and air motors for rotary motion.

These actuators are particularly suitable for repetitive, high-speed operations such as clamping, positioning, sorting, and material handling. Their robust construction and inherent safety make them ideal for harsh or explosive environments, since compressed air does not create fire hazards. Moreover, compressed air is readily available in many industrial facilities, which facilitates system integration.

The objective of this chapter is to present the operating principles of pneumatic actuators, including air preparation, pressure–force relationships, and motion control. Different types of pneumatic actuators will be examined, along with their performance characteristics, advantages, limitations, and typical industrial applications.

3.2 Pneumatic actuators

3.2.1 Physical Principles of pneumatic systems

The fundamental principles of pneumatic systems rely on the properties of air, particularly its compressibility, pressure characteristics, and flow rate behavior. Since air is a compressible fluid, its pressure, volume, and temperature are interrelated according to the ideal gas law, which provides a theoretical framework for analyzing pneumatic processes under practical engineering assumptions. In pneumatic actuators, pressure generates force according to the relation $F = P \times A$, where P is the air pressure and A is the effective piston area. This force produces motion when it overcomes opposing loads, establishing a direct relationship between pressure, force, and mechanical displacement in pneumatic systems.

The mechanical force generated by a pneumatic actuator is governed by Pascal's law and is expressed as:

$$F = P \times A$$

where F is the force, P the applied pressure, and A the effective piston area. When this force exceeds the external load and friction forces, motion is produced, establishing the fundamental relationship between pressure, force, and mechanical displacement in pneumatic actuators.

3.2.2 Applications and Advantages of Pneumatic Actuators

3.2.3 Industrial Applications

- Manufacturing and assembly systems
- Packaging machines

- Pick-and-place mechanisms
- Automotive and food industries

3.2.4 Advantages of Pneumatic Actuators

- Simple and robust design
- High operating speed
- Clean and safe operation
- Low maintenance cost

3.2.5 Limitations of Pneumatic Systems

- Limited force capability
- Low positioning accuracy
- Energy efficiency issues
- Noise generation

3.2.6 Pneumatic Actuators: Cylinders and Motors

3.2.7 Classification of Pneumatic Actuators

Pneumatic actuators are classified according to the type of motion they produce and their construction principles. They are generally divided into linear actuators and rotary actuators. Linear pneumatic actuators, commonly known as pneumatic cylinders, generate straight-line motion and are further categorized as single-acting or double-acting depending on whether compressed air acts on one or both sides of the piston.

Rotary pneumatic actuators produce angular motion and include vane-type actuators and rack-and-pinion mechanisms. Pneumatic motors, which provide continuous rotational motion, also belong to this category. This classification facilitates the selection of an appropriate actuator based on motion requirements, load characteristics, precision, and application constraints.

3.2.8 Pneumatic Cylinders

Structure and Operating Principle

As shown in figure3.1, the main components of a pneumatic cylinder include the barrel, piston, piston rod, and end caps.
subsectionTypes of Pneumatic Cylinders

Pneumatic cylinders are classified based on their motion, actuation method, and mechanical construction. The main types include:

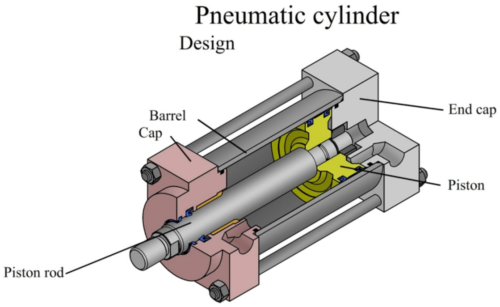


Figure 3.1: Pneumatic cylinder

Single-Acting Cylinders

Single-acting cylinders are pneumatic actuators that use compressed air to move the piston in only one direction. Return stroke is usually accomplished by a **spring** or an **external load**. These cylinders are simple, compact, and cost-effective, making them suitable for applications such as clamping, ejection, or light push tasks.

Construction and Components: As shown in figure3.2, a typical single-acting cylinder consists of:

- **Cylinder barrel:** Houses the piston and guides its motion.
- **Piston:** Converts air pressure into linear motion.
- **Piston rod:** transmits force from the piston to the external load.
- **End caps:** Seal the ends of the cylinder and provide mounting points.
- **Seals:** Prevent air leakage and reduce friction.
- **Spring (return mechanism):** Returns the piston to its original position when air is released.

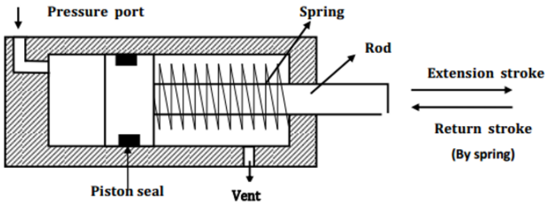


Figure 3.2: Single acting cylinder

Force Calculation: The output force of a single-acting cylinder is determined by the applied air pressure and the piston area:

$$F = P \times A$$

where:

- F = output force (N)
- P = air pressure (Pa)
- A = piston effective area (m^2)

Example: For a piston diameter $D = 50\,\text{mm}$ and air pressure $P = 6\,\text{bar} = 6 \times 10^5\,\text{Pa}$,

$$A = \frac{\pi D^2}{4} = \frac{\pi (0.05)^2}{4} \approx 1.963 \times 10^{-3}\,\text{m}^2$$

$$F = P \times A = 6 \times 10^5 \times 1.963 \times 10^{-3} \approx 1178\,\text{N}$$

Double-Acting Cylinders

Double-acting cylinders are pneumatic actuators in which compressed air is applied alternately to both sides of the piston, allowing motion in both directions (see figure3.3). Unlike single-acting cylinders, the return stroke does not rely on a spring or external force, which provides greater control over speed, position, and force. These cylinders are widely used in industrial automation applications where precise bidirectional motion is required, such as robotic arms, presses, and material handling systems.

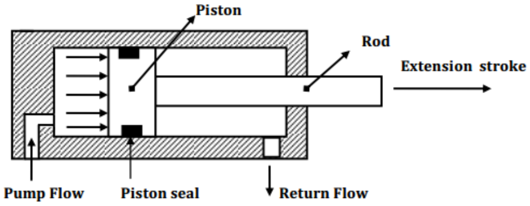


Figure 3.3: Double acting

Construction and Components: The main components of a double-acting cylinder include:

- **Cylinder barrel:** Houses the piston and guides its movement.
- **Piston:** Converts pneumatic energy into mechanical motion in both directions.
- **Piston rod:** Transmits force to the external load.
- **End caps:** Seal the cylinder ends and provide ports for air supply.
- **Seals:** Prevent air leakage and reduce friction for smooth operation.
- **Air ports:** Two ports, one at each end, for air supply and controlled actuation.

Force Calculation: The output force depends on the piston area and the air pressure. For a cylinder with diameter D:

$$F = P \times A = P \times \frac{\pi D^2}{4}$$

If the piston rod occupies part of the piston area on the rod side, the effective area for the retract stroke is reduced:

$$A_{retract} = \frac{\pi D^2}{4} - \frac{\pi d^2}{4}$$

where d is the rod diameter. This means the retract force is slightly lower than the extend force.

Example: For a piston diameter $D = 50\,\text{mm}$, rod diameter $d = 20\,\text{mm}$, and air pressure $P = 6\,\text{bar} = 6 \times 10^5\,\text{Pa}$:

$$A_{extend} = \frac{\pi(0.05)^2}{4} \approx 1.963 \times 10^{-3}\,\text{m}^2$$

$$F_{extend} = 6 \times 10^5 \times 1.963 \times 10^{-3} \approx 1178\,\text{N}$$

$$A_{retract} = \frac{\pi(0.05)^2}{4} - \frac{\pi(0.02)^2}{4} \approx 1.635 \times 10^{-3}\,\text{m}^2$$

$$F_{retract} = 6 \times 10^5 \times 1.635 \times 10^{-3} \approx 981\,\text{N}$$

To illustrate the differences between common pneumatic actuators, Table 3.1 presents a comparative study between single-acting and double-acting pneumatic cylinders. The table summarizes key features including motion type, force generation, return mechanism, control complexity, typical applications, and advantages and limitations. This comparison helps to select the most suitable cylinder type based on application requirements and operational constraints.

Design Considerations for Pneumatic Cylinders

When designing pneumatic cylinders, several key factors must be taken into account to ensure proper operation, durability, and performance. These considerations apply to both single-acting and double-acting cylinders:

- **Maximum load and required force:** Ensure that the cylinder can generate sufficient force to move the intended load in one or both directions.
- **Stroke length:** Determine the required movement range of the piston to complete the task. For single-acting cylinders, this also includes the spring return distance.
- **Cylinder mounting and alignment:** Choose appropriate mounting methods and ensure proper alignment to prevent side loads, bending, or misalignment that could damage the cylinder.
- **Air supply pressure and flow rate:** Provide sufficient pressure and airflow to achieve the desired speed, acceleration, and smooth operation.

Table 3.1: Comparative Study: Single-Acting vs. Double-Acting Pneumatic Cylinders

Feature	**Single-Acting Cylinder**	**Double-Acting Cylinder**
Motion	Produces motion in one direction only	Produces motion in both directions
Force Generation	Force generated during working stroke only, proportional to pressure and piston area	Force generated in both extension and retraction strokes, proportional to pressure and piston area
Return Mechanism	Spring or external force returns the piston	Air pressure applied to opposite side of piston controls return stroke
Control	Simple, requires fewer valves	More complex, requires directional control valves for bidirectional motion
Applications	Pressing, ejection, lifting light loads where return stroke is passive	Robotics, material handling, clamping, and other tasks requiring controlled bidirectional motion
Advantages	Simple design, cost-effective, compact	Flexible motion, precise control, capable of continuous bidirectional operation
Limitations	Limited to unidirectional work; spring limits stroke and force	More components, higher cost, slightly larger footprint

- **Sealing materials and lubrication:** Select seals and lubrication suitable for the operating environment to minimize leakage, wear, and maintenance needs.

- **Rod diameter and return mechanism:** For double-acting cylinders, rod diameter affects retract force and mechanical strength. For single-acting cylinders, spring strength and type must be selected to ensure reliable return motion.

Specialized Pneumatic Actuators

In addition to single-acting and double-acting cylinders, there are several specialized types of pneumatic actuators designed for specific applications. These include **telescopic cylinders** for long strokes in limited space, **rodless cylinders** for compact linear motion without an extended piston rod, **guided cylinders** which provide precise, rotation-free movement under lateral loads, and **pneumatic motors**, which convert compressed air into rotary motion for applications requiring continuous rotational output.

- **Telescopic Cylinders:** Telescopic cylinders consist of multiple nested stages that extend sequentially, providing a long stroke from a compact retracted length. They are ideal for applications requiring long extension in limited installation space, such as lifting mechanisms and dump trucks.

- **Rodless Cylinders:** Rodless cylinders do not have a traditional piston rod; instead, the piston moves within the cylinder and transmits motion via a magnetic coupling or mechanical carriage along the cylinder body. They are useful when a long stroke is needed without increasing the overall length of the cylinder, such as in conveyor or material handling systems.

- **Guided Cylinders:** Guided cylinders include additional guide rods or bushings to prevent rotation of the piston or payload. They provide higher accuracy and stability, making them suitable for applications requiring precise linear motion under lateral loads, such as pick-and-place operations or tooling movements.

- **Pneumatic Motors:**

  Pneumatic motors convert compressed air into rotational motion by applying air pressure to internal moving elements. The main types are **vane motors**, **piston motors**, and **gear motors**, each with characteristic torque-speed behavior, typically high torque at low speeds. They offer advantages such as simple construction, fast response, and safe operation in hazardous environments, but are limited by lower efficiency and the need for clean, dry air.

3.3 Hydraulic Actuators

3.3.1 Physical Principles of Hydraulic Systems

Hydraulic systems operate by using an incompressible fluid (see figure3.3) , typically oil, to transmit power from one location to another and to generate controlled motion. When a pump supplies pressurized fluid into a cylinder or motor, the pressure acts on a piston or rotary element, producing a force or torque according to the relationship

$$F = P \times A$$

where F is the output force, P is the hydraulic pressure, and A is the piston or actuator area. Because the fluid is nearly incompressible, pressure is transmitted almost instantaneously throughout the system, allowing precise and powerful actuation. Hydraulic systems can generate very high forces and torques in relatively compact components, and the motion can be controlled accurately by regulating fluid flow and pressure using valves and other control elements. The combination of incompressible fluid, pressure multiplication, and flow control makes hydraulic systems highly efficient for applications requiring heavy loads, precise positioning, or smooth motion.

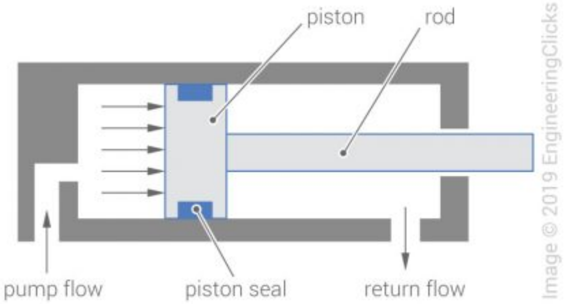


Figure 3.4: Hydraulic actuator

3.3.2 Applications and Advantages of Hydraulic Actuators

Hydraulic actuators are widely used in industries that require high force, precise control, and compact design. Typical applications include **industrial presses**, **construction machinery** such as excavators and loaders, **robotic manipulators**, and **aerospace systems**. Their primary advantages stem from the ability of hydraulic systems to generate very high forces and torques from relatively small actuators, provide smooth and accurate motion control, and transmit power over long distances with minimal mechanical complexity. Additionally, hydraulic actuators can be designed to withstand harsh operating conditions, making them suitable for heavy-duty and continuous industrial operations.

3.3.3 Limitations of Hydraulic Systems

Despite their high power density and precision, hydraulic systems have several limitations. They are prone to **fluid leaks**, which can reduce efficiency and create environmental hazards. Regular **maintenance** is required to prevent wear of seals, pumps, and valves. **Fluid contamination** by dirt, water, or air can impair performance and damage components. Additionally, some energy is lost due to **fluid friction and heat generation**, making hydraulic systems generally less energy-efficient compared to purely mechanical or electrical actuators.

3.3.4 Hydraulic Actuators: Cylinders and Motors

Hydraulic actuators convert the energy of pressurized fluid into mechanical motion and are generally classified into two main types. **Linear actuators**, or hydraulic cylinders, produce straight-line motion and are widely used for lifting, pushing, or clamping applications. **Rotary actuators**, commonly known as hydraulic motors, generate continuous or limited rotational motion and are employed in applications requiring high torque and controlled angular displacement, such as conveyors, winches, and industrial machinery.

3.3.5 Hydraulic Cylinders

A hydraulic cylinder is a linear actuator that converts hydraulic energy into mechanical motion. The main components of a hydraulic cylinder include the **cylinder barrel**, which houses the piston and guides its movement; the **piston**, which separates the pressure chambers and transmits force to the piston rod; the **piston rod**, which delivers the output force to the external load; and the **end caps**, which seal the cylinder and provide ports for fluid entry and exit. **Seals** are used to prevent fluid leakage and ensure smooth operation.

3.3.6 Single-Acting Cylinders

Single-acting hydraulic cylinders generate motion in only one direction using hydraulic pressure, while the return motion is typically achieved by a spring or an external load as illustrated in figure3.5. These cylinders are simple, compact, and cost-effective, suitable for applications such as lifting, ejection, or light pushing.

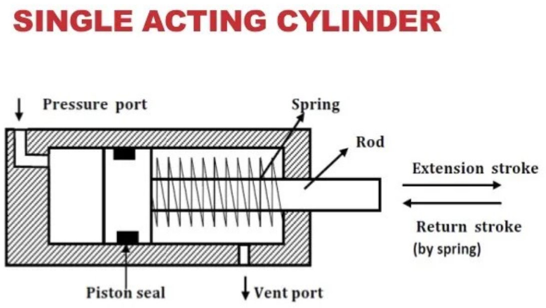


Figure 3.5: Single-Acting Hydraulic Cylinders

Force Calculation: The output force of a single-acting cylinder is calculated using:

$$F = P \times A$$

where:

- F = Cylinder force [N]
- P = Fluid pressure [Pa]
- $A = \pi D^2/4$ = Piston cross-sectional area [m^2]
- D = Piston diameter [m]

Design Parameters: Key parameters to consider when designing or selecting a single-acting cylinder include:

- Maximum load to be moved
- Required stroke length for the working motion
- Spring strength for return stroke
- Cylinder mounting type and alignment
- Working fluid pressure and flow rate to achieve desired speed
- Seal type and material to reduce leakage and wear

Example: Single-Acting Cylinder

Problem: A single-acting hydraulic cylinder has a piston diameter of 50 mm and operates at a pressure of 6 MPa. Determine the output force during the working stroke. Assume the return stroke is spring-operated.

Solution:

$$A = \frac{\pi D^2}{4} = \frac{\pi (0.05)^2}{4} = 1.9635 \times 10^{-3}\ \text{m}^2$$

$$F = P \times A = 6 \times 10^6 \times 1.9635 \times 10^{-3} \approx 11781\ \text{N} \approx 11.78\ \text{kN}$$

Answer: The single-acting cylinder produces a force of approximately 11.78 kN in the working stroke.

—

3.3.7 Double-Acting Cylinders

Double-acting hydraulic cylinders generate motion in both directions by applying hydraulic pressure alternately to each side of the piston, allowing controlled extension and retraction of the piston rod (see figure3.3). This allows for controlled bidirectional motion, making them suitable for high-precision, high-load, and continuous operations, such as presses, robotic actuators, and industrial machinery.

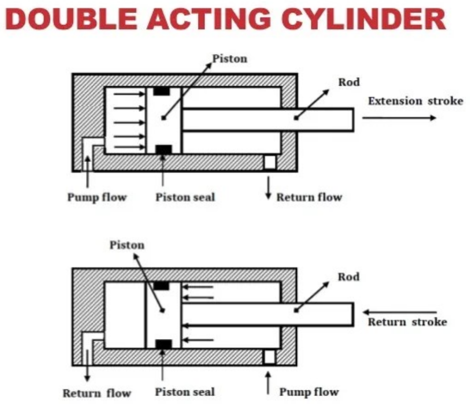


Figure 3.6: Double Acting hydralic cylinder

Force Calculation: For double-acting cylinders, the output force differs between the extension and retraction strokes because of the piston rod area:

$$F_{\text{extend}} = P \times A$$

$$F_{\text{retract}} = P \times (A - A_r)$$

where:

- A = Piston cross-sectional area [m^2]
- $A_r = \pi d_r^2/4$ = Piston rod cross-sectional area [m^2]
- d_r = Rod diameter [m]
- P = Fluid pressure [Pa]
- F_{extend} = Force during extension
- F_{retract} = Force during retraction

Design Parameters: Key parameters for double-acting cylinders include:

- Maximum load and required bidirectional force
- Stroke length for complete motion
- Cylinder mounting type and alignment to avoid side loads
- Working fluid pressure and flow rate to achieve desired speed and acceleration
- Seal materials and lubrication for durability
- Piston rod diameter, which affects retraction force and mechanical strength

Example: Double-Acting Cylinder

Problem: A double-acting hydraulic cylinder has a piston diameter $D = 80$ mm and a rod diameter $d_r = 30$ mm. The system pressure is 5 MPa. Calculate the extension and retraction forces.

Solution:

Piston area:

$$A = \frac{\pi D^2}{4} = \frac{\pi (0.08)^2}{4} = 5.027 \times 10^{-3} \text{ m}^2$$

Rod area:

$$A_r = \frac{\pi d_r^2}{4} = \frac{\pi (0.03)^2}{4} = 7.069 \times 10^{-4} \text{ m}^2$$

Extension force:

$$F_{\text{extend}} = P \times A = 5 \times 10^6 \times 5.027 \times 10^{-3} \approx 25.14 \text{ kN}$$

Retraction force:

$$F_{\text{retract}} = P \times (A - A_r) = 5 \times 10^6 \times (5.027 \times 10^{-3} - 7.069 \times 10^{-4}) \approx 21.63 \text{ kN}$$

Answer: The cylinder generates approximately 25.14 kN during extension and 21.63 kN during retraction.

Design Considerations for Hydraulic Cylinders

When designing hydraulic cylinders, several key factors must be taken into account to ensure proper performance, durability, and safety. The **maximum load and required force** determine the piston diameter and hydraulic pressure rating. The **stroke length** must be sufficient for the intended motion, while the **mounting method and alignment** are critical to prevent side loads or bending of the piston rod. The **hydraulic pressure and flow rate** must match the actuator specifications to achieve the desired speed and acceleration. Proper **seal selection** is essential to prevent fluid leakage and maintain efficiency, and the **type of hydraulic fluid** must be compatible with the system materials and operating temperature. Finally, the **operating environment**, including exposure to contaminants, temperature extremes, or corrosive conditions, influences material selection, cylinder protection, and maintenance requirements.

3.3.8 Hydraulic Motors

Hydraulic motors are rotary actuators that convert pressurized fluid energy into rotational mechanical motion. They are commonly classified into three main types: **vane motors**, in which vanes slide within a rotor to generate torque; **piston motors**, which use multiple pistons arranged radially or axially to convert fluid pressure into high-torque rotation; and **gear motors**, where pressurized fluid drives inter-meshed gears to produce rotary motion (see figure3.7) . Each type exhibits distinct **torque-speed characteristics**, typically providing high torque at low speeds, with speed increasing as torque decreases. Hydraulic motors offer several advantages, including compact size, high power density, precise speed and torque control, and suitability for heavy-duty applications. They can operate under high pressures, providing large output torque in a relatively small package. However, limitations include potential leakage, sensitivity to fluid contamination, maintenance requirements, and energy losses due to fluid friction and heat generation.

Figure 3.7: Different-Types-of-Hydraulic-Motors

3.3.9 Applications of Hydraulic Motors

Hydraulic motors are widely used in industrial, mobile, and energy applications where high torque, compact size, and precise control are required. They convert hydraulic energy (pressure and flow) into rotational mechanical motion, making them suitable for a variety of tasks. Key application areas include:

- **Mobile Equipment:** Hydraulic motors are commonly used in construction, agriculture, and mining machinery such as excavators, loaders, tractors, and conveyors. They drive wheels, tracks, augers, and lifting mechanisms.

- **Industrial Machinery:** They are applied in presses, injection molding machines, material handling systems, and industrial mixers, providing high torque at low speed and smooth rotational motion.
- **Marine and Offshore Systems:** Hydraulic motors power winches, cranes, steering systems, and thrusters on ships and offshore platforms due to their reliability and ability to operate under harsh conditions.
- **Energy and Renewable Systems:** They are used in hydroelectric plants and wave energy converters for rotational actuation and energy conversion.
- **Automation and Robotics:** Hydraulic motors provide precise rotational control in robotic arms, actuated joints, and other automated handling systems, especially when high force or torque is required in a compact form factor.
- **Specialty Vehicles:** Applications include forklifts, fire trucks, and airport ground support vehicles, where high torque and controllable motion are critical.

Hydraulic motors are particularly advantageous in applications requiring compact high-torque output, variable speed operation, and robustness under heavy-duty conditions. Their combination with hydraulic pumps and valves allows flexible motion control in complex systems.

To better understand the functional differences and applications of hydraulic actuators, Table 3.2 presents a comparative study between hydraulic cylinders and hydraulic motors. The table highlights key aspects such as motion type, force and torque generation, control methods, typical applications, advantages, and limitations. This comparison provides a clear overview for selecting the appropriate actuator type based on system requirements and operational constraints.

3.4 Conclusion

This chapter presented a comprehensive overview of pneumatic and hydraulic actuators, focusing on their operating principles, structural components, and performance characteristics. Pneumatic cylinders and motors were examined in terms of simplicity, speed, and suitability for light to medium industrial applications. Hydraulic actuators, including cylinders and motors, were analyzed for their high force and torque capabilities, robustness, and suitability for heavy-duty operations.

The fundamental equations governing force and torque generation were discussed to highlight the relationship between pressure, flow rate, and mechanical output. In addition, key design considerations such as load requirements, pressure rating, sealing, mounting configuration, fluid selection, and environmental constraints were presented.

Finally, a comparative perspective was introduced to assist engineers in selecting the most appropriate fluid power actuator based on application requirements, efficiency considerations, precision needs, and maintenance constraints.

Table 3.2: Comparative Study: Hydraulic Cylinders vs. Hydraulic Motors

Feature	**Hydraulic Cylinder**	**Hydraulic Motor**
Function	Converts hydraulic energy into linear motion	Converts hydraulic energy into rotary motion
Output Motion	Linear (push/pull along a straight path)	Rotational (torque around shaft)
Force/Torque Generation	Produces force proportional to pressure and piston area: $F = P \times A$	Produces torque proportional to pressure and displacement: $T = P \times D$
Applications	Lifting, pressing, clamping, material handling, industrial presses	Wheels, tracks, conveyors, winches, mixers, robotics
Control	Direction controlled via directional control valves; speed adjusted via flow control	Direction and speed controlled via flow and pressure control; torque depends on load and displacement
Mechanical Design	Piston, rod, barrel, seals, end caps	Vane, gear, or piston type rotors; shaft; housing; seals
Advantages	Simple, robust, high force capability, easy to integrate in linear applications	Compact, high torque output, precise rotational control, flexible speed range
Limitations	Limited to linear motion; requires linkages for rotary motion	Limited to rotational motion; higher complexity for sealing; sensitive to contamination

Chapter 4

Preactuators in Automation Systems

After completing this chapter,students will be able to:

- Define the function of preactuators in control chains
- Identify manual, automatic, and electronic control methods
- Interpret actuator control schematic symbols
- Describe electric motor driving interfaces
- Explain electro-pneumatic and electro-hydraulic valve operation
- Analyze actuator control architectures in automation systems

4.1 Introduction

In automated systems, actuators are responsible for converting energy into mechanical motion. However, the signals generated by control systems such as programmable logic controllers (PLC), microcontrollers, or computers are generally low-power signals.

These signals cannot directly drive actuators that require higher electrical, pneumatic, or hydraulic power. Therefore, an intermediate device called a **preactuator** is used.

A **preactuator** is a device that receives a control signal from a controller and converts it into a suitable power signal capable of driving an actuator.

Preactuators therefore act as an interface between the information processing system (controller) and the energy conversion system (actuator).

Depending on the type of actuator, preactuators can be classified into three main categories:

- Electric preactuators
- Pneumatic preactuators
- Hydraulic preactuators

4.1.1 Preactuators in Automation Systems

In industrial automation, **preactuators** act as the interface between the low-power control signals from the controller and the high-power actuators. Different actuator technologies (electric, pneumatic, hydraulic) require different preactuators, but all share the same purpose: signal amplification, isolation, and reliable actuation.

Function and Role

- Convert low-power control signals into signals suitable for actuators.
- Protect controllers from high-power circuits (safety and isolation).
- Ensure actuators operate with precision and responsiveness.
- Allow a single controller to operate multiple types of actuators.

Illustrative Multi-Technology Diagram

Explanation: In this system:

- The **controller** receives measurements and operator commands, producing low-power control signals.
- **Preactuators** convert these signals into suitable energy forms for each type of actuator: electric, pneumatic, or hydraulic.
- **Actuators** perform the mechanical action on the process.
- **Feedback** signals from the process enable closed-loop control.

This architecture highlights the central role of **preactuators** as the interface between the low-power **information chain** and the high-power **energy chain**, ensuring that industrial actuators operate with **safety, precision, and flexibility**.

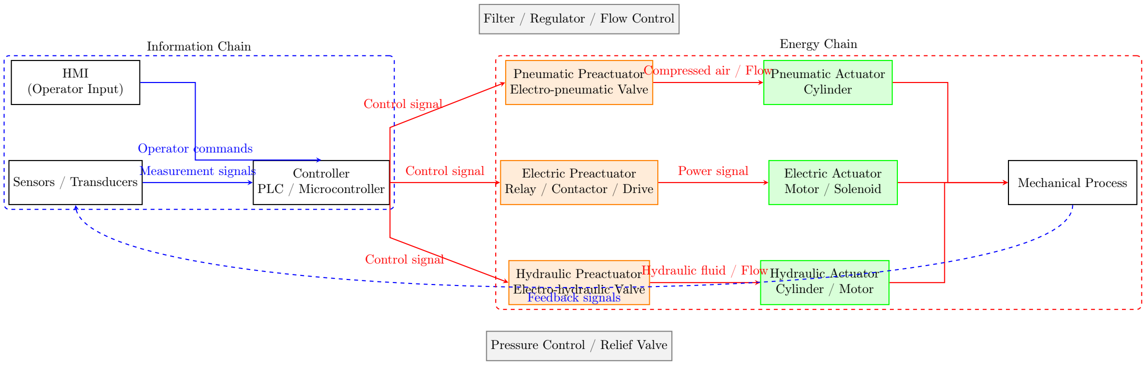


Figure 4.1: Industrial automation system showing electric, pneumatic, and hydraulic preactuators and their role in the energy chain.

4.2 General Control and Driving Methods

Preactuators may be controlled using several methods depending on the system design.

4.2.1 Manual Control

Manual control involves direct operation by an operator.

Examples include:

- Push buttons
- Switches
- Circuit breakers

This type of control is mainly used in simple systems or maintenance operations.

4.2.2 Automatic Control

Automatic control uses signals generated by controllers such as:

- PLC
- Microcontroller
- Industrial computer

These signals activate preactuators automatically according to the programmed logic.

4.2.3 Electronic Control

Electronic control relies on power electronic devices to regulate electrical energy.

Examples include:

- MOSFET drivers
- IGBT power modules
- Electronic speed drives

Electronic control allows high-speed switching and precise power regulation.

4.3 Standardized Symbols

Industrial automation diagrams use standardized symbols defined by international standards such as IEC and ISO.

Standard symbols are used to represent:

- Relays
- Contactors
- Circuit breakers
- Solenoid valves
- Hydraulic valves

These symbols ensure that electrical and fluid diagrams are easily interpreted by engineers worldwide.

4.4 Electric Preactuators

Electric preactuators are used to control electric actuators such as motors, solenoids, and electromagnetic devices.

They are responsible for switching or regulating electrical power supplied to the actuator.

4.4.1 Manual Switching Devices

Circuit Breaker

A circuit breaker is a protective switching device that interrupts the electrical circuit in case of abnormal current conditions.

Its main functions are:

- Protection against overload
- Protection against short circuits
- Manual switching and isolation

Motor Circuit Breaker

A motor circuit breaker (MCB) provides automatic protection against overloads and short circuits, while a contactor is a heavy-duty switch used for frequently controlling (starting/stopping) the motor. MCBs protect, whereas contactors switch, often working together (breaker for safety, contactor for switching)

It provides protection against:

- Overcurrent
- Short circuits
- Phase failure

Motor circuit breakers are commonly installed in motor control panels.

4.4.2 Automatically Controlled Switching Devices

A) Relay

A relay is an electromechanical switching device used to control electrical circuits using a low-power control signal.

It consists of:

- an electromagnetic coil
- a movable armature
- fixed and movable contacts

When the coil is energized, the magnetic field attracts the armature, which changes the position of the contacts and switches the electrical circuit.

Relays are widely used to control:

- low-power electrical loads
- signal switching in control circuits
- interface circuits between controllers and actuators

Contactor

A contactor is an electromechanical switching device used to control high-power electrical loads. It consists of:

- an electromagnetic coil
- movable contacts
- fixed contacts

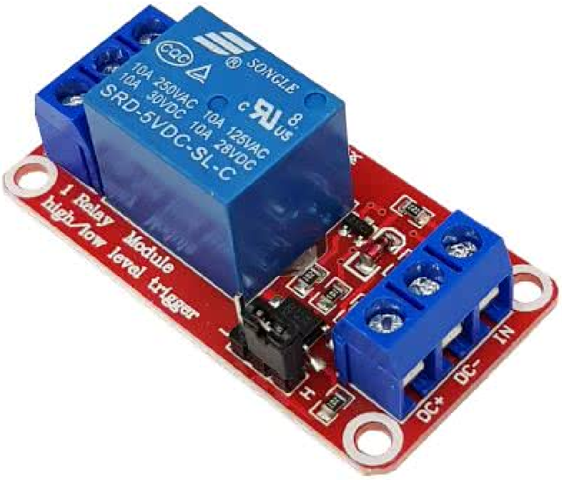


Figure 4.2: Relay

Figure 4.3: Contactor 12A, 230 V

When the coil is energized, the contacts close and allow electrical current to flow through the load.

Contactors are widely used to control:

- electric motors
- heating systems
- lighting installations

4.4.3 Electronically Controlled Devices

Electronic preactuators employ semiconductor devices, such as transistors, thyristors, or MOSFETs, to precisely regulate and control the electrical power supplied to actuators. By modulating voltage, current, or frequency, they enable smooth, efficient, and responsive operation of electric motors or other electrical loads, while providing protection and isolation for the control system.

4.4.4 Electronically Controlled Devices for DC and AC Motors

Concept

Electronically Controlled Devices (ECDs) are preactuators that use **semiconductor components** to control the power delivered to electric motors. They replace traditional electromechanical devices (relays, contactors) when precise, fast, and efficient control is required.

ECDs allow:

- Smooth variation of motor speed and torque
- Direction control of DC and AC motors
- Protection of the motor and control circuit
- Energy-efficient operation

They are widely used in **automation systems**, from conveyor belts to robotic manipulators.

Types of Electronically Controlled Devices

For DC Motors:

- **Chopper Circuits:** Control the average voltage supplied to the motor by high-frequency switching.
- **PWM Drives (Pulse Width Modulation):** Adjust the duty cycle to control motor speed and torque.
- **H-Bridge Circuits:** Allow bidirectional control of DC motors.

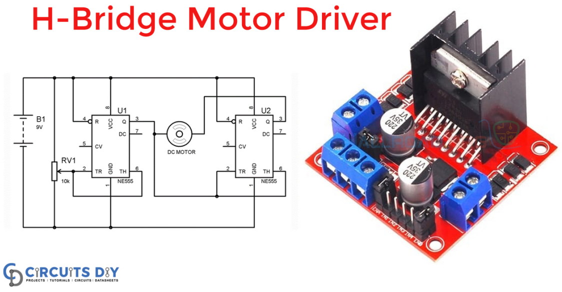


Figure 4.4: ECD circuit for DC motor

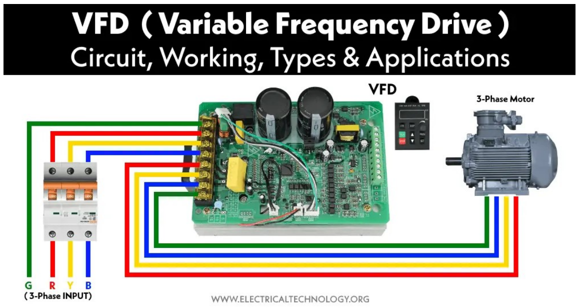


Figure 4.5: Variable Frequency Drives (VFDs)

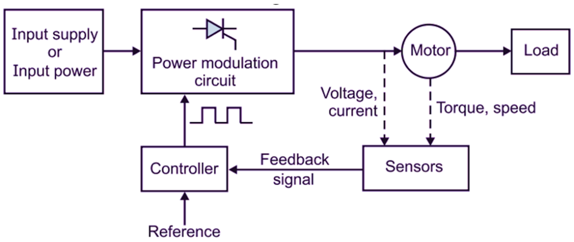


Figure 4.6: General block diagram of Electronically Controlled Device

For AC Motors:

- **AC Voltage Controllers:** Use thyristors to vary RMS voltage for speed control.
- **Variable Frequency Drives (VFDs):** Control motor speed and torque by adjusting voltage and frequency
- **Servo Drives:** Enable precise position, speed, and torque control in closed-loop systems.

Position in an Automation System

Electronically Controlled Devices act as **preactuators** between the controller and the motor. They receive low-power control signals from the controller (e.g., PLC, microcontroller) and convert them into the required voltage, current, and frequency to drive the motor efficiently.

The controller generates low-power signals based on sensor feedback or programmed commands. The ECD (power modulation circuit) receives these signals and delivers the appropriate voltage, current, and frequency to the motor. This ensures smooth, efficient, and precise motor operation while protecting both the motor and the control system.

Summary

Electronically Controlled Devices are essential preactuators for modern DC and AC motors, enabling:

- High-speed and precise actuation
- Energy-efficient operation
- Flexible control of motor speed, torque, and direction
- Safe interfacing between low-power controllers and high-power motors

4.5 Pneumatic Preactuators

The flow of compressed air is controlled by devices known as **pneumatic distributors**, which act as pneumatic preactuators.

4.5.1 Electro-Pneumatic Distributors

Electro-pneumatic distributors combine electrical control with pneumatic flow control.

They are also called **solenoid valves**.

When an electrical signal energizes the solenoid coil, a magnetic field moves the valve spool and redirects the airflow.

4.5.2 Types of Pneumatic Valves

Common pneumatic distributors include:

- 2/2 valve (two ports, two positions)
- 3/2 valve (three ports, two positions)
- 4/2 valve (four ports, two positions)
- 5/2 valve (five ports, two positions)

The 5/2 valve is widely used for controlling double-acting cylinders.

4.5.3 Distribution Auxiliary Components

Pneumatic systems often include auxiliary components such as:

Pressure Regulators

Pressure regulators maintain a constant air pressure level.

Flow Control Valves

These valves regulate airflow to control actuator speed.

Filters

Filters remove particles and moisture from compressed air.

4.6 Hydraulic Preactuators

Hydraulic actuators are used in applications requiring high force and power density.

Hydraulic preactuators control the direction, pressure, and flow rate of hydraulic fluid.

4.6.1 Electro-Hydraulic Valves

Electro-hydraulic valves convert electrical signals into hydraulic control actions.

Examples include:

- Directional control valves
- Pressure control valves
- Flow control valves

4.6.2 Servo Valves

Servo valves are high-performance electro-hydraulic valves used in precision control systems.

They are widely used in:

- aerospace systems
- industrial robotics
- heavy machinery

Servo valves allow precise control of:

- flow rate
- pressure
- actuator position

4.7 Application Examples

4.7.1 Electric Motor Control System

In an industrial motor control system:

- The PLC sends a command signal.
- The contactor or electronic drive acts as the preactuator.
- The motor receives electrical power.
- Mechanical motion is produced.

4.7.2 Pneumatic Cylinder Control

In a pneumatic automation system:

- The PLC sends a signal to a solenoid valve.
- The valve redirects compressed air.
- The pneumatic cylinder extends or retracts.

4.7.3 Hydraulic Cylinder Control

In a hydraulic system:

- The controller sends a signal to an electro-hydraulic valve.
- The valve directs hydraulic fluid.
- The hydraulic cylinder produces high mechanical force.

4.8 Conclusion

Preactuators are essential components in modern automation systems. They provide the necessary interface between low-power control signals and high-power actuators.

Three major categories of preactuators are commonly used:

- Electric preactuators
- Pneumatic preactuators
- Hydraulic preactuators

Each technology offers specific advantages depending on the application requirements in terms of power, speed, and precision.

Advances in power electronics, electro-pneumatic technology, and electro-hydraulic systems continue to improve the efficiency and performance of industrial automation systems.

General Conclusion

This course provided a comprehensive study of actuators used in modern automation systems, covering electric, pneumatic, and hydraulic technologies. Each category was analyzed from both a theoretical and practical perspective, including operating principles, mathematical modeling, performance characteristics, and application domains.

Electric actuators, particularly DC and AC motors, stepper motors, and servo systems, were examined in terms of precision, controllability, and energy efficiency. Pneumatic actuators were presented as simple, fast, and cost-effective solutions suitable for repetitive and lightweight industrial tasks. Hydraulic actuators were studied for their high power density, robustness, and ability to generate large forces and torques in demanding environments.

The fundamental equations governing force, torque, speed, and power conversion were introduced to establish a clear understanding of energy transformation mechanisms. In addition, actuator selection criteria were discussed, taking into account load requirements, dynamic performance, environmental conditions, maintenance constraints, and economic considerations.

Overall, this course highlights that no single actuator technology is universally optimal; the appropriate choice depends on the specific requirements of the automation system. A solid understanding of actuator principles, modeling, and control strategies enables engineers to design efficient, reliable, and high-performance automated systems.

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