



MOTOR VEHICLE TECHNOLOGY

ELECTRIC MOTORS AND DRIVE SYSTEMS IN ELECTRIC VEHICLES

2023-2-TR01-KA210-VET-000180148

New Applications in Electric Vehicles Technology According to 4.0 Standards



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EXPLANATIONS

AREA	Motor Vehicle Technology
JOB	Electric Vehicles
MODULE NAME	Electric Motors and Drive Systems in Electric Vehicles
MODULE DESCRIPTION	This module is a learning material that provides basic knowledge and skills regarding electric motors and drive systems, and includes the structure, operating principle and control applications for motor systems used in electric vehicles.
COMPETENCE	To know the components of the motor and drive systems used in electric vehicles, to determine maintenance requirements according to their operating principles, to perform basic maintenance practices and to install the relevant systems.
PURPOSE OF THE MODULE	<p>General purpose</p> <p>With this module, you will be able to recognize the basic components of electric motors and drive systems, determine the maintenance requirements specific to electric vehicles, and perform the installation and basic maintenance of the systems.</p> <p>Objectives</p> <ol style="list-style-type: none"> 1. Be able to recognize the structures and functions of electric motors and drive systems. 2. Be able to compare the maintenance needs of electric and internal combustion vehicle engines. 3. Be able to perform basic maintenance of motor and drive systems used in electric vehicles. 4. Be able to perform installation and maintenance of technological components such as inverters, batteries and sensors.

1. DIRECT CURRENT MOTORS

1.1. Magnetism

Materials that have the ability to attract materials such as iron, nickel and cobalt are called magnets. There are two types of magnets: permanent magnets and electromagnets. Permanent magnets are also of two types: natural magnets and artificial magnets. Permanent magnet and electromagnet are shown in Figure 1.1.

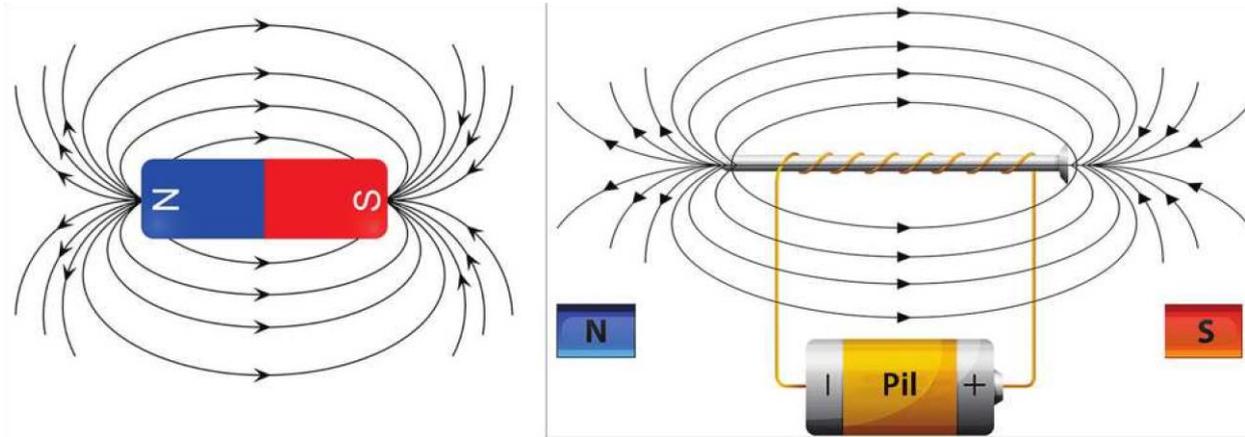


Figure 1.1: Permanent magnet and electromagnet

Magnets have two poles, the North Pole and the South Pole. There are magnetic lines of force between these poles. The density of magnetic lines of force is called magnetic flux. Magnetic flux is an electrical charge movement. The direction of magnetic flux is from the South Pole (S) to the North Pole (N) inside the magnet, and from the North Pole to the South Pole outside the magnet. Magnetic flux is shown with the symbol " ϕ ". The unit of magnetic flux is Weber (Wb) in the MKS (meter, kilogram, hour) unit system and Maxwell (M) in the CGS (centimeter, gram, second) unit system. (1 Weber = 10^8 Maxwell)

The amount of magnetic flux per unit surface is called the magnetic field. The intensity of the magnetic field changes according to the density of the magnetic flux contacting the conductor or surface.

The symbol for the magnetic field is "B". Accordingly; " $B = \phi / A$ ". "A" is the area affected by the magnetic flux. Magnetic field intensity: The magnitude of the effect of the magnetic field on the substance in it.

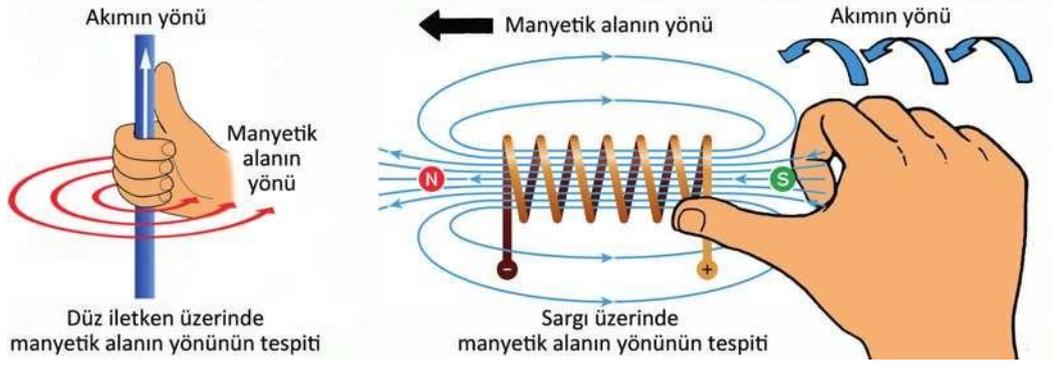


Figure 1.2: Finding the direction of the magnetic field using the right hand rule

The direction of the magnetic field is determined according to the right hand rule. When we hold the conductor with the right hand so that the thumb points in the direction of the current, the other fingers show the direction of the magnetic field. When we hold the coil with the right hand so that the four fingers point in the direction of the current, the thumb shows the direction of the magnetic field. Figure 1.2 shows the direction of the magnetic field on a straight conductor and on the coil.

1.1.1. Magnetic permeability

The degree of magnetization of materials under the influence of a magnetic field is called magnetic permeability (μ). According to their relative magnetic permeability, substances are divided into three groups, these are;

- **Ferromagnetic Material:** These are substances whose relative permeability is much greater than “1”. Substances such as iron, nickel and cobalt are in this group.
- **Paramagnetic Material:** These are substances whose relative permeability is less than “1”. Substances such as aluminum and air are in this group.
- **Diamagnetic Material:** These are substances whose relative permeability is less than “1”. Copper and carbon are in these substances.

1.1.2. Principles and Definitions

Various basic principles will be explained and various definitions will be made in the book in order to understand the structure and working principles of electric motors that will be covered.

1.1.2.1. Ampere principle

A magnetic field is formed around a conductor through which electric current passes (Figure 1.3). The intensity of the magnetic field around the conductor is directly proportional to the current passing through the conductor.

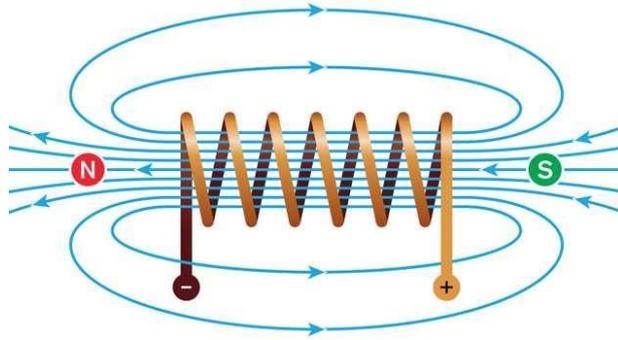


Image 1.3: Ampere principle

1.1.2.2. Faraday's Induction Principle

When a conductor is inserted into a magnetic field, an electric current is induced on the conductor. An induced voltage (electromotive force) is formed on the conductor (Figure 1.4). This is called Faraday's induction principle.

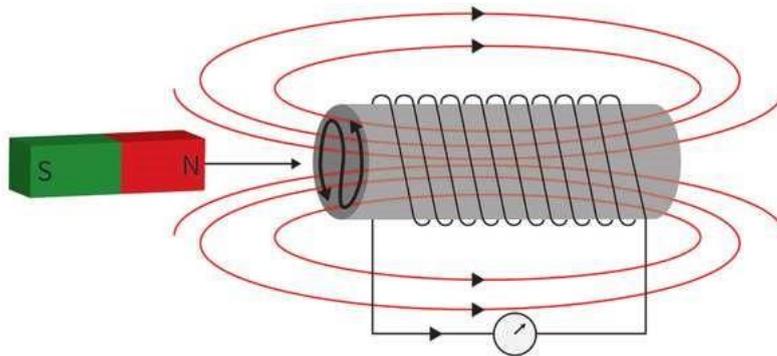


Figure 1.4: Faraday principle

The net voltage (potential difference) provided by a generator or battery to an electric circuit is called electromotive force (EMF). EMF means the force that moves electrons. It is shown with the symbol “ \mathcal{E} ” and its unit is volt.

$\mathcal{E} = N \cdot \Delta\phi / \Delta t$	
\mathcal{E} : Electromotive force	$\Delta\phi$: Variable magnetic flux
N : Number of turns in conductor winding	Δt : Variable time

For induction to occur, there must be a time-varying magnetic flux. If our magnetic field source is a magnet, either the conductor must be moved over the magnet or the magnet must be moved over the conductor.

1.1.2.3. Lenz principle

Electric current is obtained by induction on a conductor in a magnetic field. An EMK is formed as a result of induction on the conductor. The EMK formed creates resistance against the magnetic flux that creates itself. In other words, the magnetic flux formed as a result of induction resists the change of the magnetic flux that creates itself. This phenomenon is called Lenz principle.

1.1.2.4. Lorentz principle

If a conductor with current passing through it is placed in a magnetic field, a force (F) is formed on the conductor. The direction of the force is found with the left hand rule (Visual 1.5). "I" is the symbol for electric current, "B" is the symbol for magnetic field.

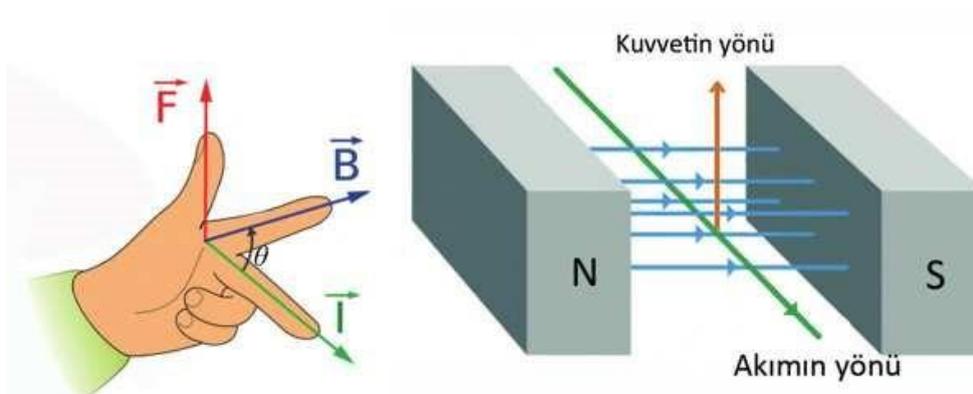


Image 1.5: Lorentz Principle (Finding the direction of the force with the left hand rule)

1.1.2.5. Inductance

The voltage (EMF) induced in a coil is directly proportional to the change in current flowing through the coil with respect to time. Inductance is the coefficient that provides equality in this proportion. Inductance is also called the ability of an inductor to store energy in a magnetic field. It is shown with the symbol "L". Its unit is "Henry".

$\mathcal{E} = L \cdot \Delta I / \Delta t$	
\mathcal{E} : Induced voltage	ΔI : Time varying current
L : Inductance	Δt : Variable time

1.1.2.6. Magnetomotive force

The physical force that creates the magnetic flux in a magnetic circuit is called “magnetomotive force”. It is shown with the symbol “F”. According to Ohm’s principle ($E = I \cdot R$), it replaces the voltage in the electric circuit.

1.1.2.7. Reluctance

The difficulty shown against the magnetic flux in magnetic circuits is called reluctance (\mathcal{R}). According to Ohm’s principle, it is the equivalent of resistance in the electric circuit.

$F = \Phi \cdot \mathcal{R}$	
F: Magnetomotive force	Φ: Magnetic Flux
\mathcal{R}: Reluctance	

Electric machines have undertaken important tasks in the development of industry and technology since the 1800s. These machines have a very wide range of uses, from daily life to dams, from automobiles to factories. Electric machines are widely used in both mechanical energy production and electrical energy production.

The foundations of electric machines were laid in the 1800s with the emergence of concepts related to magnetism. In 1820, Hans Christian Oersted (Hans Kristian Orsted) revealed that electric current creates a magnetic field. In 1831, Michael Faraday (Maykıl Feredey) invented the generator with the concept of electromagnetic induction, and in 1832, Thomas Davenport (Tamıs Devinport) invented the electric motor. With these developments, the first electric vehicles emerged in the 1800s and did not attract attention over time due to their disadvantages. Today, with the development of technology, electric machines are actively used in the automotive sector.

Electrical machines are divided into three as electric motor, generator and transformer. An electric motor is a machine that converts electrical energy into mechanical energy. Generators are machines that convert mechanical energy into electrical energy. Transformers are stationary machines that convert electric current and voltage by electromagnetic induction. Electric motors are used for propulsion purposes in electric vehicles. In addition, starter motors, wiper motors, fuel pump motors, etc. used in vehicles are electric motors. The alternator, which is a charging system element in vehicles, is a generator. In hybrid and electric vehicles, the electric motor acts as a generator and is used to obtain electricity in regenerative braking systems. The

ignition coils used in hybrid vehicles are also transformers. It increases the battery voltage and provides spark formation in the spark plug.

With the spread of hybrid and electric vehicles in the automotive sector, there has been a variety of motors used for propulsion purposes. The general classification of electric motors used in the automotive sector is shown in Visual 1.6.

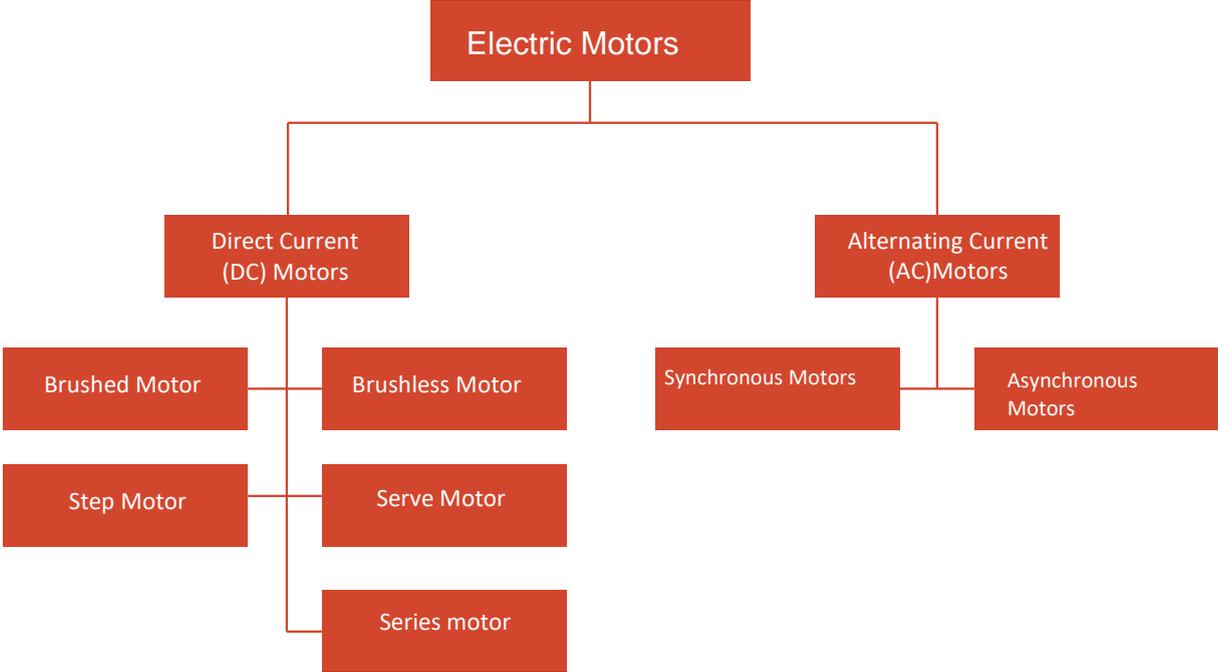


Figure 1.6: General classification of electric motors

1.2. Direct Current Motors

Direct current motors are electrical machines that convert electrical energy with direct current (DA or DC) properties into mechanical energy. They are also called DC motors or DA motors. They are preferred in many areas due to their advantages such as high torque at low speeds, easy controllability, simple structure, linear torque-speed characteristics and high efficiency. Since direct current motors operate with direct current, they are easy to control. Therefore, there is no need for complex power electronic elements. The biggest disadvantage of direct current motors is the use of collector-brush assembly for rotor current. Brushes wear out over time and require maintenance, while also causing motor efficiency to decrease. With technological developments, this disadvantage has been eliminated and brushless DC motors have been developed.

Brushed and brushless DC motors have a wide range of use in the automotive sector. These are; drive motors in electric vehicles, starter motors, throttle valve motors, wiper motors, fuel pump motors, radiator fan motors, window and mirror motors, air conditioning fan motors, idle motors, etc. Direct current motors generally consist of the following parts: Stator (inductor), rotor (armature), body and covers, brush mechanism, bearings and bearings.

1.2.1. Stator (Inductor)

It is a fixed and non-moving part of the motor. It is also called an inductor. The function of the stator is to create a magnetic field. It consists of a body, core and poles. The stator core is made of silicon sheets. A winding or magnet is used to create a magnetic field in the stator. The stator winding consists of insulated copper wires. An electromagnetic field is created by giving electric current to the windings. Natural magnets produced at appropriate angles are used to position the stator body. A fixed magnetic field is obtained with these magnets. The stator body, which forms the outer part of the motor, houses the core and windings or magnets.



Figure 1.7: Stator

1.2.2. Rotor (Endüvi)

The rotating, moving part of the motor. It is also called armature and armature. It consists of core, shaft and winding parts. The rotor core is made of steel sheets. The rotor winding consists of insulated copper wires. A magnetic field is created by giving electric current to the rotor winding. In order to give current to the rotor, the winding ends are connected to collector (commutator) rings made of copper slices. Current passes to the collector through brushes (coals). A magnetic field is created in the windings and it is ensured that it interacts with the magnetic field in the stator windings. As a result of this interaction, rotational movement and torque occur in the rotor.



Figure 1.8: Rotor

1.2.3. Collector (Commutator) and Brushes (Coals)

Collectors and brushes are used to create a magnetic field in rotor windings. The collector is the part of the rotor consisting of copper slices to which the winding ends are connected. It is mounted on the rotor shaft and rotates with the rotor. Brushes are the intermediate transmission elements that are in contact to transmit electric current to the collector. The change of direction of the current with the collector-brush mechanism in rotor windings is called commutation. Brushes of different hardness are used according to the current and voltage values of the motors. Brush springs are used to ensure that the brushes come into contact.

Brushes are usually made of carbon alloys. That's why they are also called coal. Brushes are used in this type of motors called brushed DC motors (Brush DC motor-brush teeth motor). Collectors and brushes wear and deform over time depending on use. This reduces motor efficiency and causes the brushes to make noise and sparks. That's why brushed DC motors need periodic control and maintenance.

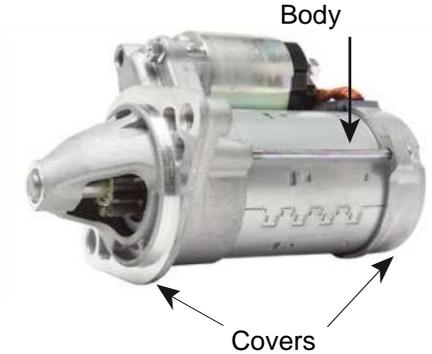
With technological advances, DC motors that do not use collectors and brushes (Brushless DC motor-Bıraşlıs disı motor) have been developed.



Image 1.9: Collector and brush holder

1.2.4. Body and Covers

They form the outer part of the motor together with the stator to protect the electric motor from external effects. They are made of aluminum and iron alloy. Covers ensure that the rotor is centered and placed in the stator and protect the inner part of the motor from external effects.



Visual 1.10: Body and covers

1.2.5. Bearings and Housings

Bearings are used on the rotor shaft to support the rotor. The bearings are placed in the bearings on the covers and ensure that the rotor rotates efficiently. Care should be taken with the bearings during disassembly and assembly. Bearings make noise and wear out over time due to lack of lubrication. Worn bearings cause friction losses, reducing the efficiency of the motor.

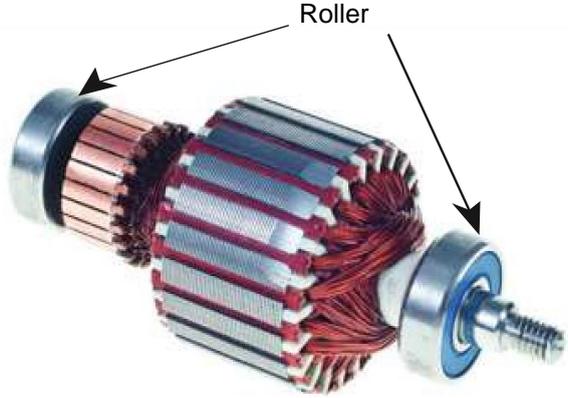
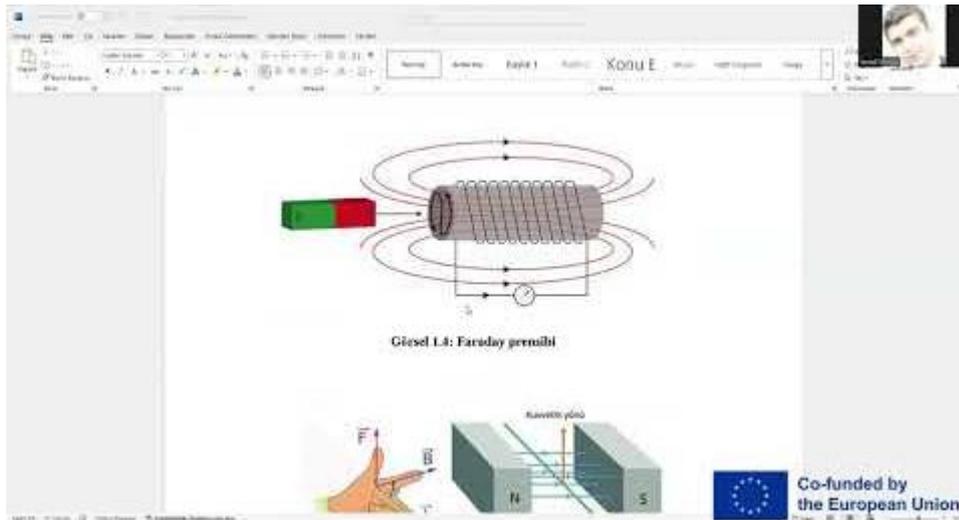


Image 1.11: Bearing



To play the video, click on the image or click the link below and open it with your browser.

<https://youtu.be/HBKBZwPzyc0>

DC motors may have different winding-magnet positions in rotor and stator structurally. Designs that have magnets in the stator, windings in the rotor, windings in the stator, windings in the rotor, and windings in the stator and magnets in the rotor are used. Despite the structural changes, the operating principle is the same.

1.3. Direct Current Motor Types

1.3.1. Brushed DC Motor

In brushed DC motors, current is transmitted to the rotor windings by means of the collector-brush mechanism. Its structure was explained in the previous topic. It is widely used in many areas of industry due to its affordable cost and easy motor management. Due to the use of collectors and brushes, wear and sparks occur in the motor over time. This causes the motor efficiency to decrease over time. It was used for propulsion in the first developed electric vehicles. Brushed DC motors are used in vehicles as starter motors, wiper motors, ventilation fan motors, radiator fan motors, and fuel pump motors. There are also Brushless DC motor varieties of these motors.



Image 1.12: Starter motor and wiper motor

1.3.2. Brushless Direct Current Motor (BLDC)

Brushless DC motors have been developed due to the disadvantages of brushed DC motors such as low efficiency and maintenance requirements. Since the collector-brush mechanism is not used, they are called Brushless DC Motors (BLDC). Permanent magnets are used for the rotor magnetic field and windings are used for the stator magnetic field. A control system containing an electronic controller and sensors are needed to detect the rotor position are needed for operation. Optical or Hall-effect (Hol efekt) sensors are used as sensors. Due to its high efficiency, high starting torque and silent operation, it is used for propulsion purposes in electric vehicles. It is also used as a starter motor, wiper motor, fuel pump motor, air conditioning fan motor and radiator fan motor in vehicles.

Brushless DC motors are structurally divided into two types: inner rotor and outer rotor.

1.3.2.1. Inner Rotor Brushless Direct Current Motor (Inrunner-Inrunner BLDC)

Like traditional motors, the rotor is at the center of the motor and the stator is outside. These motors require power transmission elements due to their structure. They are widely used in three-wheeled micro electric vehicles.

1.3.2.2. Outer Rotor Brushless Direct Current Motor (Outrunner-Autranır BLDC)

Although the working principle of external rotor motors is the same, they have structural differences. While the rotor is located outside the motor, the stator is in the center of the motor. This structure is also called a hub motor. There are permanent magnets on the rotor. The windings are wrapped around the stator. The rotor is rotated by controlling the stator current. In systems with this motor, the movement is transferred directly to the wheels without using the transmission organs. In this way, it is widely used in vehicles such as electric bicycles-motorcycles, three-wheeled micro vehicles, etc. that are desired to be light.



Figure 1.13: Brushless DC motor with internal rotor

1.3.3. Series motor

In series motors, windings are used for the stator and rotor magnetic fields. Motors in which the stator windings and rotor windings are connected in series are called series motors. They have the same parts as brushed DC motors. The stator windings are thicker and have fewer windings than other DC motors. When current is supplied from the power source, current flows first to the stator windings and then to the rotor windings. These motors, which draw high current, have high starting torque. They are widely used in rail transportation vehicles and cranes that require high torque during start-up. In vehicles, they are used as starter motors to give the internal combustion engines their first start.



Figure 1.14: External rotor brushless DC motor

1.3.4. Servo Motor

Servo motors are DC motor systems that operate by providing feedback with power electronic elements. The structure of the servo motor consists of a DC motor, gears, control circuit, potentiometer or encoder.

The speed and position values of the rotor shaft are measured by a potentiometer or encoder and this information is called the feedback signal. The control circuit constantly controls the operating status of the motor by comparing the input signal with the feedback signal. Various DC motors can be used in the servo motor structure. It is used in various areas in the industry because it provides precise positioning, speed control and high torque at low speed. It is not used for drive purposes in electric vehicles.

The most common use in vehicles is the electronically controlled throttle motor. Electronically controlled throttle systems are systems that use a DC motor that operates with feedback. The signal from the electronic control unit moves the throttle motor. The movement of the rotor shaft is measured from the throttle position potentiometer located opposite the reduction gears and the feedback signal is obtained. The throttle position is verified by comparing the motor input signal with the feedback signal.



Image 1.15: Starter motor windings



Image 1.16: Electronic throttle

1.3.5. Step Motor

Stepper motors are motors that rotate at certain angles according to the signals applied to their inputs. Stepper motors are also called step motors. They are simpler than servo motors and have no feedback. Since permanent magnets are used in the rotor, they are brushless motors. There are windings in the stator. Stepper motors can move at 90° , 45° , 18° , 7.5° , 1.8° or different angles. The angle/number of step movements depends on the number of poles in the stator. Stepper motors, which provide precise positioning with their movements at different angles, are used in various areas in the industry because they provide speed control and high torque. Stepper motors are stepper motors that move in stages such as idle motors and exhaust gas recirculation (EGR) motors in vehicles.



Image 1.17: Idle and EGR engine

1.4. Operation of Direct Current Motors

1.4.1. Operation of Brushed DC Motors

It is known that magnets have a natural magnetic field and that magnetic fields are obtained artificially with the help of windings. Repulsion and attraction movements occur between magnetic fields due to the poles. While opposite poles attract each other, the same poles repel each other. The operation of DC motors depends on this basic principle.

A magnetic field is created in the rotor and stator of DC motors with the help of magnets and windings. As a result of the interaction of magnetic fields, a rotational movement occurs in the rotor as a result of the repulsion and attraction. While the magnetic field created by the winding or magnet in the stator is fixed, the magnetic field created by the winding in the rotor is mobile. The electric current changes direction in the rotor windings with the collector-brush mechanism. This direction change process is called commutation. With commutation, the poles in the rotor windings are changed and continuous interaction with the stator magnetic field is achieved.

According to Faraday's Law, a current is induced in a conductor moving in a fixed magnetic field. As the rotor conductors move in the stator magnetic field, they cut the magnetic force lines and an EMK (electromotive force) is induced. The EMK is in the opposite direction to the voltage applied to the rotor. That's why it is called the back EMF.

Back EMF allows the motor to operate with low current. If one pole in the stator is energized, the rotor will rotate at a certain angle and stop. To eliminate this situation, both poles are energized and the rotor is allowed to rotate continuously.

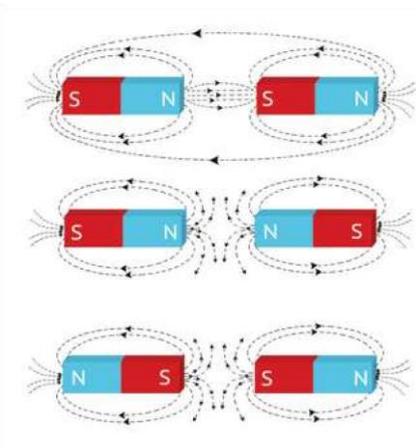
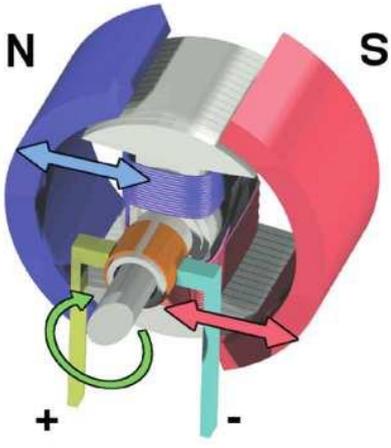


Figure 1.18: Interaction of magnet poles

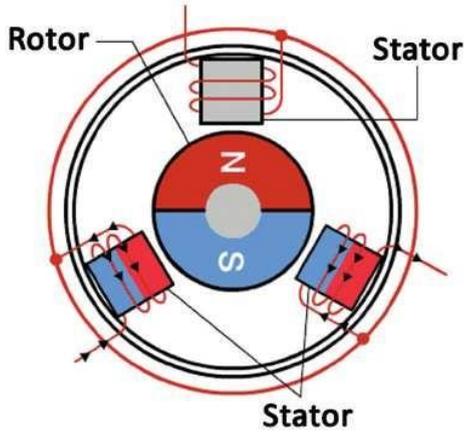


Visual 1.19: DC motor operation

1.4.2. Working of Brushless DC Motors

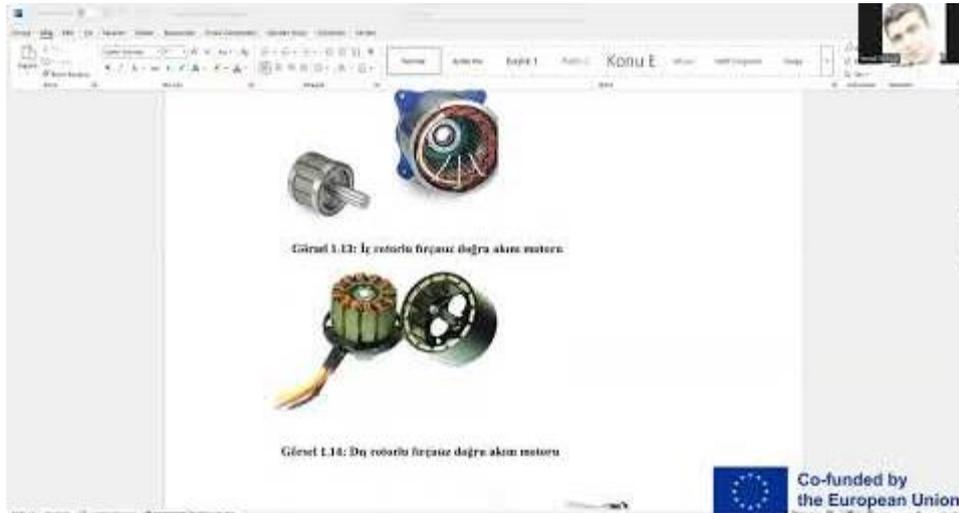
Brushless DC motors have structural differences compared to brushed DC motors. The methods of creating magnetic fields in the rotor and stator have changed. A fixed magnetic field is obtained by using permanent magnets in the rotor. A rotating magnetic field is obtained by using windings in the stator.

Brushless DC motors require power electronic components to operate. An electronic controller



is needed to drive the motor and sensors are needed for rotor position information. Hall effect sensors are generally used to detect the rotor position. The controller provides electric current to the stator poles in order according to the information received from the sensor. The rotor rotates and torque is created by the push-pull interaction between the rotor magnetic field and the stator magnetic field. The torque created depends on the strength of the magnetic fields.

Visual 1.20: Brushless DC motor operation



To play the video, click on the image or click the link below and open it with your browser.

<https://youtu.be/y0PT6MaL8Fs>

2. ASYNCHRONOUS MOTORS

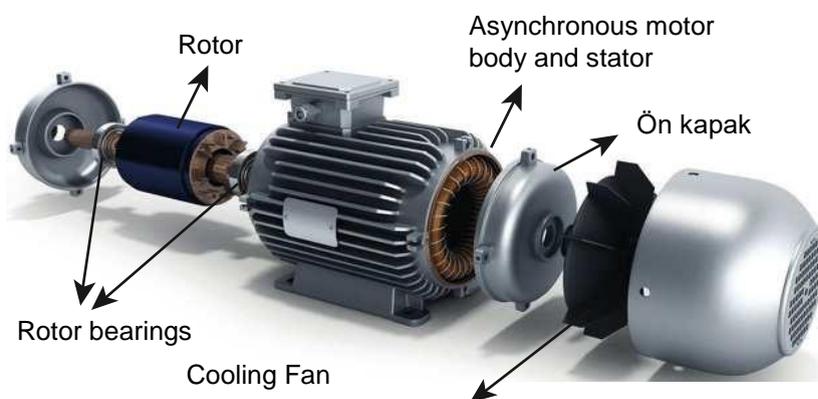
Invented by Nikola Tesla, asynchronous motors operate with alternating current. These motors are preferred in electric vehicles due to their simple structure, high reliability, robustness, low cost and easy maintenance features. These motors are also called induction motors due to their working principle. During operation, no electric arc occurs between the collector slices of DC motors, as is the case. An asynchronous motor cross-section is shown in Visual 2.1.



Visual 2.1: Asynchronous motor cross-section

2.1. Structure of Asynchronous Motors

Since three-phase asynchronous motors are preferred in electric vehicles, the structure of these motors will be examined. Asynchronous motors consist of two main parts, the stator and the rotor. Apart from these main parts, there are bearings that allow the rotor to be supported by the body.



Visual 2.2: Parts that make up an asynchronous motor

2.1.1. Stator

The stator is the fixed part of the motor. Grooves are opened on its inner surface, high conductivity silicon steel sheet plates are combined and placed inside the body.



Figure 2.3: Motor body and stator

Sheet metal plates provide the reinforcement of the magnetic field. There are three windings (coils) placed in the grooves on the combined plates at an angle of 120° (Visual 2.3, Visual 2.4 and Visual 2.5). The winding ends in the stator are connected in star or delta. In asynchronous motors used in electric vehicles, star connection is preferred.



Figure 2.4: Motor body and stator plates



Figure 2.5: Motor body and stator windings

2.1.2. Rotor

The rotor is the moving part of the asynchronous motor. As in the stator, the squirrel cage rotor is connected to the rotor shaft by high conductivity silicon steel sheet plates. As in the stator, the plates provide the reinforcement of the magnetic field formed on the rotor. Aluminum or copper rods are passed through the grooves on these steel plates. The rods are connected to both sides of the rotor shaft by aluminum or copper rings at their ends and a short circuit is

made. It is called a squirrel cage rotor because of its appearance resembling a squirrel cage. The rotor shaft is supported by bearings at the beginning and end of the motor body.



Figure 2.6: Rotor squirrel cage structure and rotor steel plates

In rotor wound (ring) motors, there are windings on the rotor and rings to which the ends of these windings are connected. Brushes are placed on these rings. Starting and speed adjustment are made with these rotating rings. The cross-section and rotor of the motor are given in Visual 2.7.

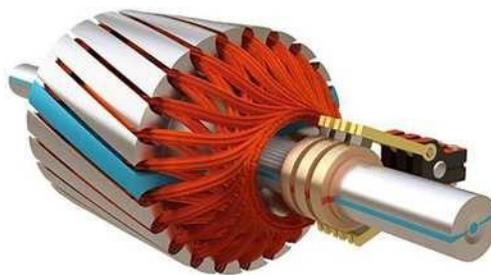


Figure 2.7: Ring (rotor winding) rotor

2.1.3. Connection Types of Stator and Rotor Windings of Asynchronous Motors to the Electric Source

In the stator of three-phase asynchronous motors, one winding is placed for each phase at an angle of 120° . These windings are connected to the power supply circuits with star or delta connection.

2.1.3.1. Star Connection

Star connection is preferred in asynchronous motors used in electric vehicles. The input, output terminals and connection type of the windings in motors produced for industrial purposes are given in Visual 2.8. In electric vehicle motors, there are only three terminals for three-phase input. The output terminals are combined and insulated at a suitable point of the windings.

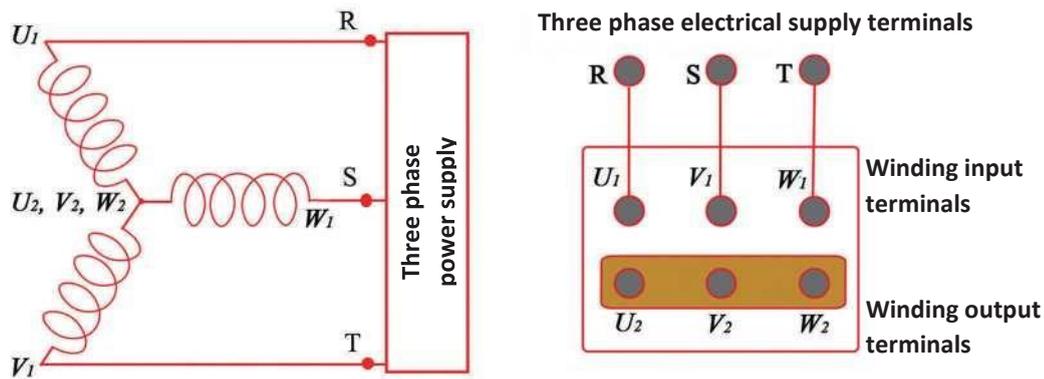
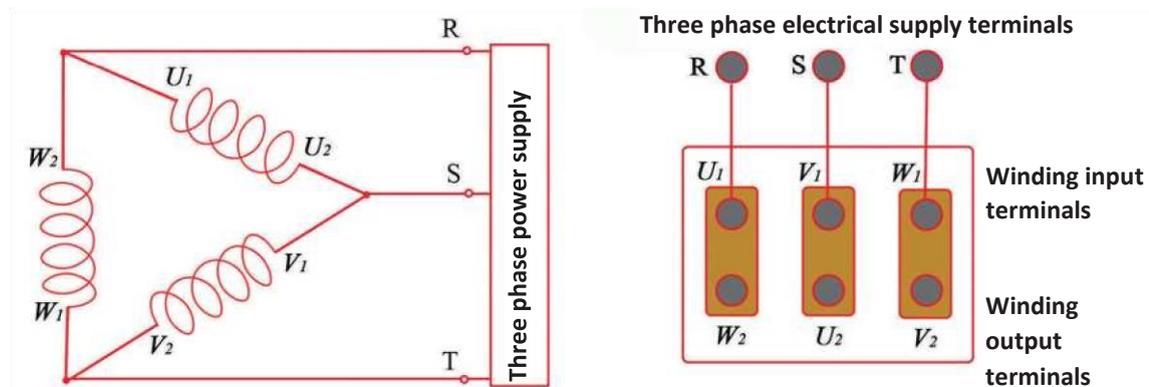


Figure 2.8: Star connection circuit and terminal connection status

In star connection, the winding output ends are combined. Each of the winding input ends is connected to the terminals of the three-phase electrical power source as in Figure 2.7. In star connection, the voltage going to each winding drops by about 40%.

2.1.3.2. Triangle Connection

In this connection, the output of each winding is combined with the input of the other winding, and three common terminals are formed. These terminals are connected to the three-phase electrical power supply terminals. In this connection, the voltage applied to the windings is the same as the power supply voltage, it does not change.



Visual 2.9: Delta connection circuit and terminal connection status

2.2. Types of Asynchronous Motors

2.2.1. Asynchronous Motors According to Their Phases

There are two types: single-phase and three-phase asynchronous motors.

2.2.1.1. Single Phase Asynchronous Motors

Since these motors are produced for industrial purposes, they only operate with 220 V AC voltage. Since their torque is low, they are not preferred as electric vehicle motors.

2.2.1.2. Three Phase Asynchronous Motors

Their torque is high. These motors operate with three-phase AC voltage. Motors produced for industrial purposes operate with 380 volts. Motors used in electric vehicles operate with 400 volts, 480 volts or different voltages depending on the manufacturer's brand.

2.2.2. Asynchronous Motors According to Their Structure

There are two types. In terms of the structure of asynchronous motors, motor types have been examined according to their structures. The stators of these motors are similar to each other. However, the structures of their rotors are different.

2.2.2.1. Squirrel Cage Asynchronous Motors

Grooves were opened on it, high conductivity sheet metal plates were combined and fixed to the rotor shaft. The rods passed through the plate grooves were short-circuited by connecting them to the plates from both sides. Due to this connection type, these motors are called short-circuit asynchronous motors or squirrel cage asynchronous motors (Visual 2.6, Visual 2.10).

Maintenance and production costs are low compared to other electric motors. For this reason, they are more preferred as electric vehicle motors. Their starting torque is low but their starting current is high. Frequency changer systems are needed for speed control. In electric vehicles, speed and torque are adjusted according to need with the inverter management group.



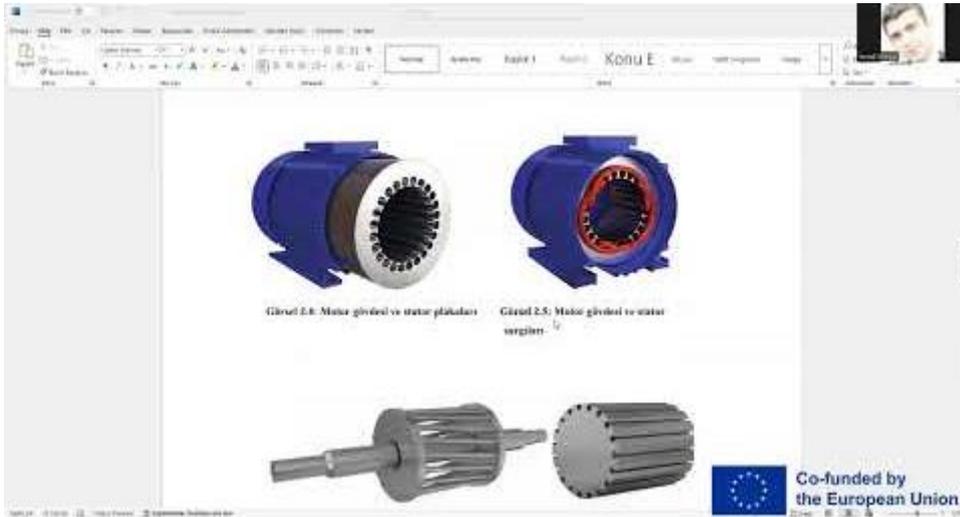
Visual 2.10: Squirrel cage rotors

2.2.2.2. Ring (Rotor Wound) Asynchronous Motors

It is used in places where high torque is required. Speed adjustment is simpler than squirrel cage motors. Starting torques are also high. Due to its brushed structure, maintenance intervals are more frequent and costly than squirrel cage motors. In this respect, squirrel cage asynchronous motors are more preferred for electric vehicles.



Image 2.11: Slip-ring asynchronous motor



To play the video, click on the image or click the link below and open it with your browser.

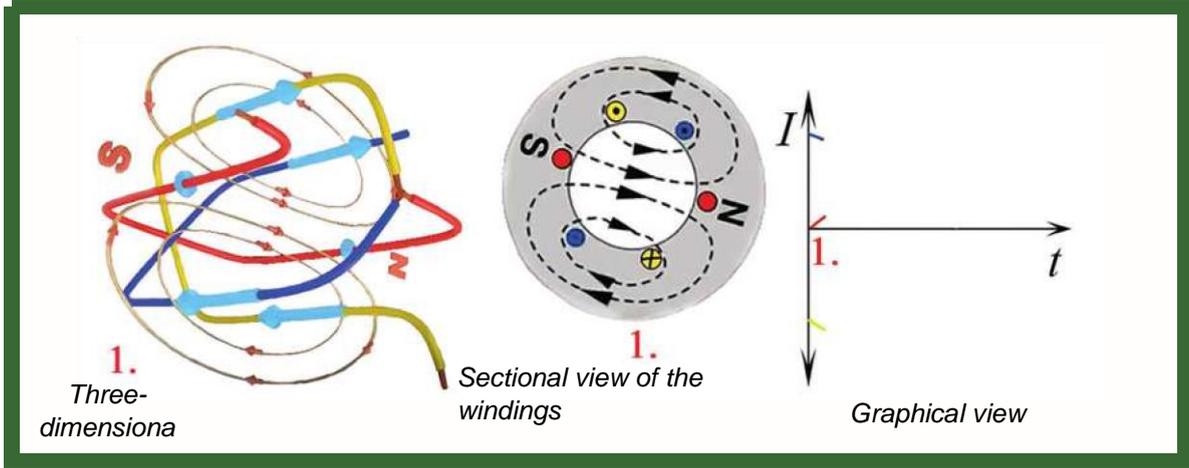
<https://youtu.be/CW4kE3pDIPU>

2.3. Operation of Asynchronous Motors

With the supply from the three-phase electric power source, a rotating magnetic field is formed in the stator windings. The speed of the rotating magnetic field is called synchronous speed.

The passage of the voltage from the three separate phases of the power source through each winding is shown on the model in the images. The formation of the rotating magnetic field is explained in stages in Visuals 2.12, 2.13 and 2.14.

In Visual 2.12, the formation of the magnetic field is given as a three-dimensional model image, two-dimensional and graphic. In the first stage, the magnetic field is formed in the windings represented in blue and yellow colors opposite each other.



Görsel 2.12: Döner manyetik alanın oluşması (1. aşama)

Then, current passes through the windings represented in yellow and a magnetic field is created (Figure 2.13). In the second stage, the same thing happens and the magnetic field is displaced a little.

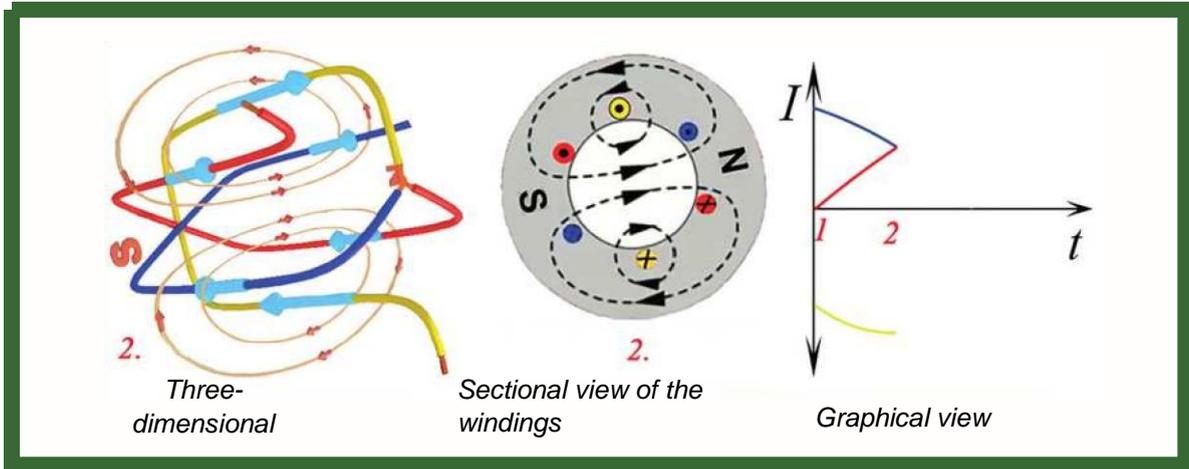


Figure 2.13: Formation of the rotating magnetic field (2nd stage)

In the third stage, a magnetic field is formed in the windings represented in yellow and red (Figure 2.14). The magnetic field changes its place a little more compared to its last position. A magnetic field is formed sequentially on all winding segments (poles) in the stator. The magnetic field continuously changes its place and completes the cycle (360°) by making a tour around the rotor and then a new cycle begins.

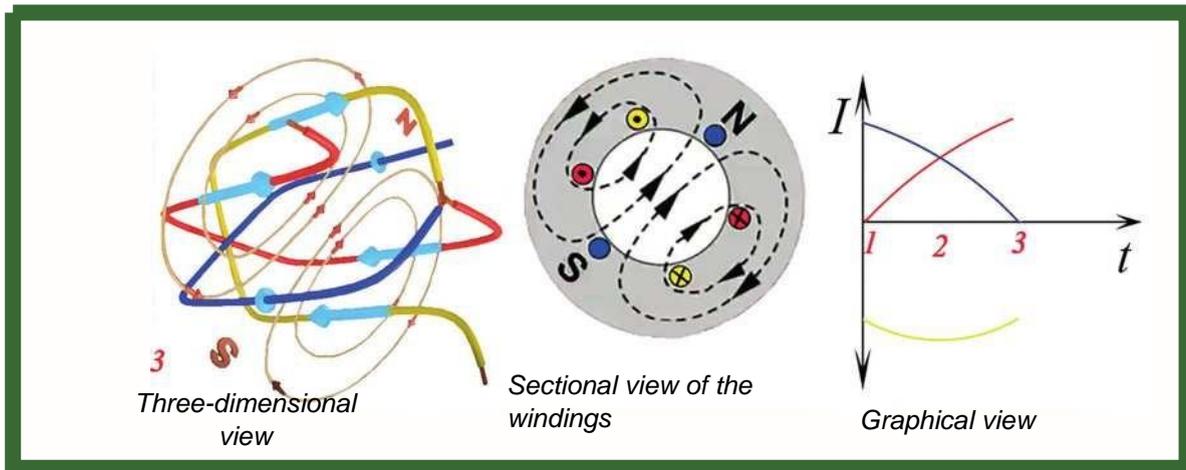


Figure 2.14: Formation of the rotating magnetic field (3rd stage)

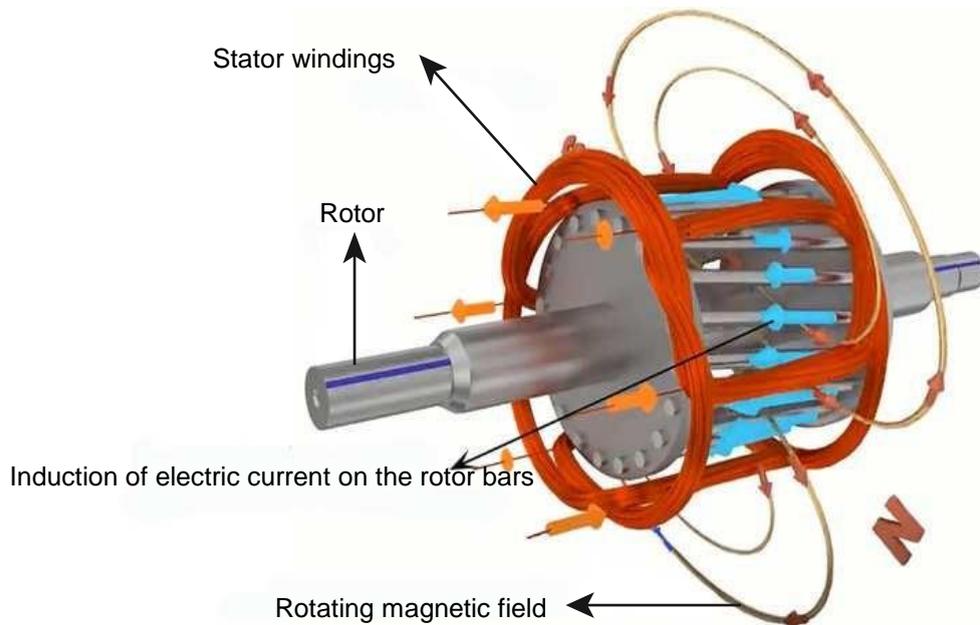


Figure 2.15: Induction on the rotor

Electric current is induced on the rotor bars that remain within the rotating magnetic field formed in the stator. For this reason, these motors are also called induction motors. Electromotive force (EMF) occurs on the rotor and a magnetic field is formed. The rotor starts to rotate (Figure 2.14).

The speed of the rotor is not equal to the synchronous speed. The synchronous speed is always higher than the rotor speed. If the speed is equal, there will be no induction since the rotating magnetic field will rotate at the same speed as the rotor. The difference between the

synchronous speed and the rotor speed is called slip. Since the rotor speed is not equal to the synchronous speed, these motors are called asynchronous motors.

2.3.1. Starting of Asynchronous Motors

The current drawn by asynchronous motors used in industry at the starting moment (start) is high. This situation causes voltage drops in the electrical network. The current drawn by asynchronous motors at the starting moment is called starting current. The ways in which starting current is limited are called starting. The starting methods are as follows:

1. Direct starting
2. Low voltage starting
 - a. Starting with resistance
 - b. Star-delta starting
 - c. Starting with auto transformer
3. Starting with microprocessors
 - a. Soft starting (with soft starter)
 - b. Starting with frequency changer (inverter)

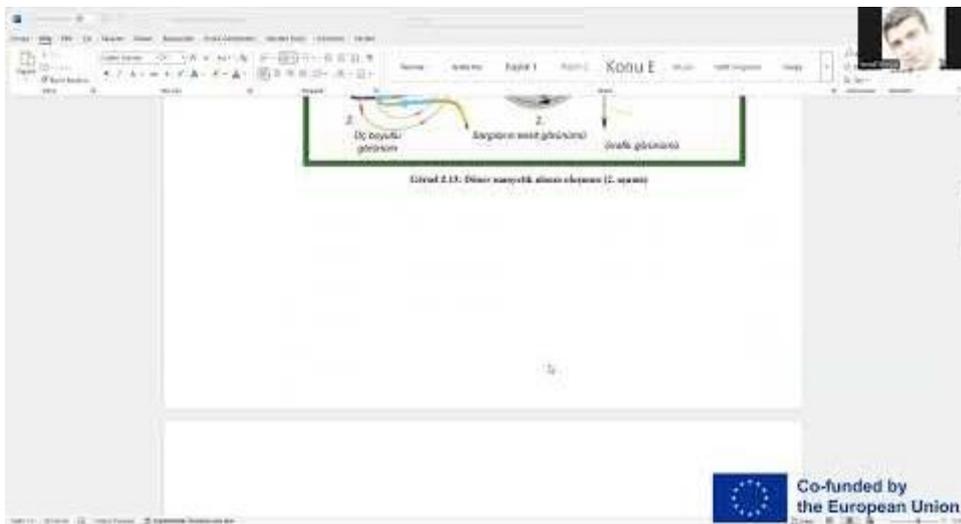
Electric vehicles do not use fixed-speed motors, such as asynchronous motors used in industry. In other words, it is necessary to adjust the speed of the vehicle according to the road and load conditions. In addition, there is no such thing as a load on the network. However, the speed of the motor is adjusted by changing the frequency only according to the need and in a controlled manner from the vehicle's electrical source.

2.3.1.1. Starting with Frequency Changer (Inverter)

Systems that convert direct current (DC) to alternating current (AC) and can adjust frequency and voltage are called inverters. In electric vehicles, it adjusts speed and torque according to road conditions and engine operating conditions. Inverters are covered extensively in the "converters" learning unit.



Image 2.16: Inverter



To play the video, click on the image or click the link below and open it with your browser.

<https://youtu.be/NCYjOwDnAll>

3. RELUCTANCE MOTORS

The emergence of reluctance motors dates back to the 1840s. These motors, which were not used for years due to their disadvantages, have recently started to be used in important areas of the industry with the development of power electronics. Especially in the electric vehicle sector, reluctance motor development studies and the use of these motors are increasing day by day. Companies want to reduce the use of windings, magnets and their varieties on electric motors, reduce costs and reduce their dependence on them.

3.1. Structure of Reluctance Motors

Reluctance is the resistance shown against the passage of magnetic flux in the magnetic circuit. Reluctance motors are motors that operate with alternating current according to the reluctance principle and have developed power electronics. In these motors, windings are used for the stator magnetic field, while windings, magnets, collectors and brushes are generally not used in the rotor. The rotor consists of silicon steel laminated sheets. Permanent magnets are used in the rotors of reluctance motors specially developed for electric vehicles.

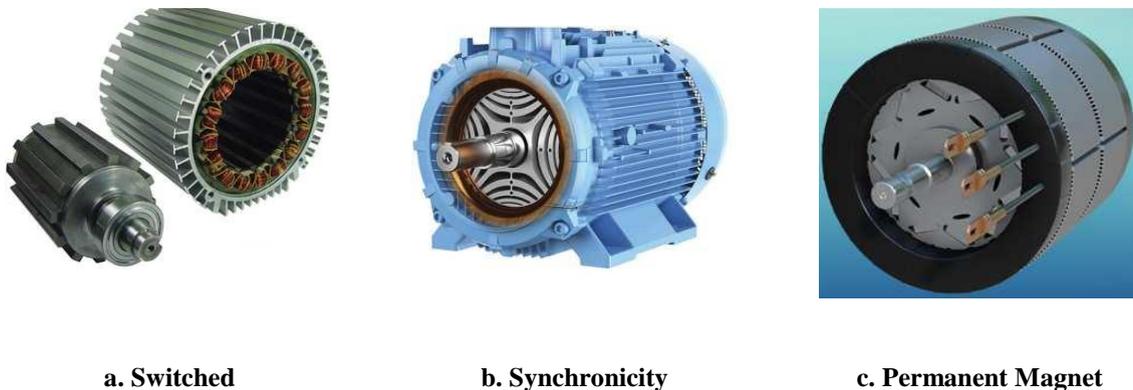


Figure 4.1: Reluctance motors

Reluctance motors are an alternative to other electric motors, especially permanent magnet motors, with their simple structure, cheap manufacturing, easy use, high speed and efficiency features. Since brushless and windingless rotors are used, these motors can reach high speeds. They have an advantage over other motors because they have high torque values without drawing much current in the first run. Another advantage is that they have high torque output in small sizes.

In order for the motor to operate properly, it must produce continuous torque. For continuous torque production, the stator and rotor pole positions must be detected by position sensors and fed in the appropriate phase order. Therefore, power electronic elements are used. These

elements are; inverter, position or speed, temperature sensors and controller. The inverter converts the direct current (DC) from the battery to alternating current (AC) and enables the motor to operate with current and frequency adjustment. Temperature sensors measure the temperature of the motor and provide information to protect the motor against risky situations. Position or speed sensors measure the speed and position of the rotor. Resolver, encoder and Hall-effect type sensors are used for position and speed measurement.

The general parts of reluctance motors are; stator, rotor, body, covers, bearings and power electronic elements. The stator and rotor, which are different from other motors, will be emphasized.

3.1.1. Stator

It is the fixed part that creates a rotating magnetic field in the motor and does not move. It consists of the core and windings. The stator core is made of laminated steel sheets. The stator windings are made of thin or thick insulated copper wires with multiple windings.

A rotating magnetic field is created in the windings with alternating current. It is desired that the flux in the magnetic field flows towards the rotor and affects the poles according to the reluctance principle. Therefore, the stator poles are also designed in accordance with the reluctance principle. The windings can be wound on protruding poles or in the dispersed type.

The aluminum alloy motor body is located on the outside of the stator. There are cooling fluid channels and power electronics connection points on the body.



Görsel 3.2: Stator

3.1.2. Rotor

It is the rotating, moving part of the motor. It rotates due to the pulling effect of the magnetic field formed in the stator. It consists of the core, shaft and bearings. The rotor core is usually made of steel laminated sheets. Bearings are used on the motor body so that the rotor shaft can rotate efficiently. There are different types of rotor structures.

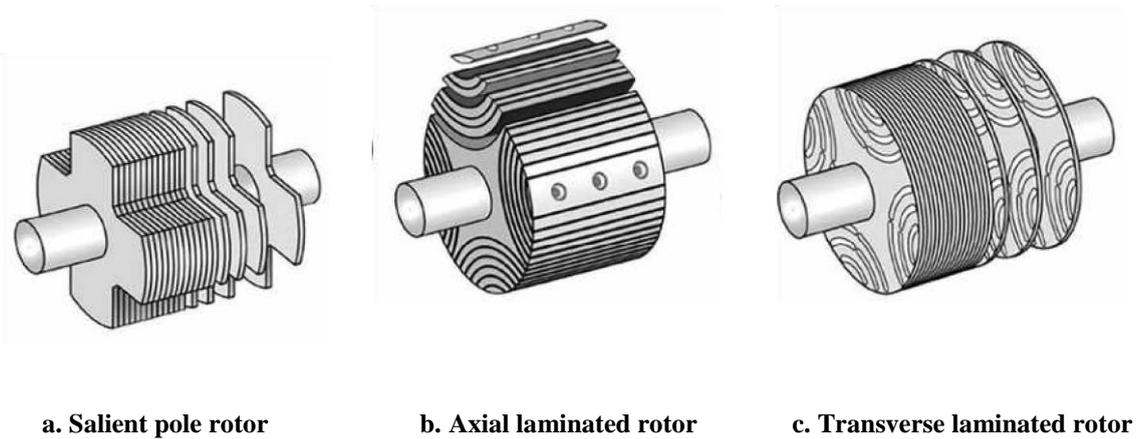


Image 3.3: Rotor structures

The poles on the rotor are designed for low reluctance values. The reluctance value of air is high. Air channels are used on the rotor to direct the magnetic flux. These channels are called flux barriers. Windings, magnets, collectors and brushes are not used in classical reluctance motors. The magnetic field formed in the stator flows through the pole heads on the rotor and allows the rotor to rotate. While salient pole rotors are generally preferred in switched reluctance motors, axial and transverse laminated rotors are used in synchronous reluctance motors. Transverse laminated rotors are preferred more **for ease of manufacturing**.

Permanent magnets are used in reluctance motors specially developed for electric vehicles. Therefore, these motors are called permanent magnet reluctance motors (PMSRM).



Figure 3.4: Flux barriers

3.2. Reluctance Motor Types

Different reluctance motors are used in different sectors of the industry and in the electric vehicle sector. These can be listed as switched, synchronous and permanent magnet reluctance motors. Although the operating principles of these motors are the same, there are differences in the stator and rotor structures.

3.2.1. Switched Reluctance Motor (SRM)

It is a reluctance motor with protruding stator and rotor poles. The number of rotor poles is less than the number of stator poles. This eliminates torque ripple. It is similar to stepper motors. Due to the protruding poles, the magnetic flux is more intense at the protruding points. This creates a pulling force and allows the rotor to rotate. The stator windings are wound on the protruding pole heads.



Image 3.5: Switched reluctance motor

3.2.2. Synchronous Reluctance Motor (SynRM)

This motor, which has structural similarities with asynchronous motors, is a reluctance motor designed for synchronous operation. A transversely laminated rotor is generally used as the rotor structure. The rotor is made of laminated steel sheets. The stator windings are wound in a distributed manner on the stator body. Three-phase alternating current is applied to the stator.

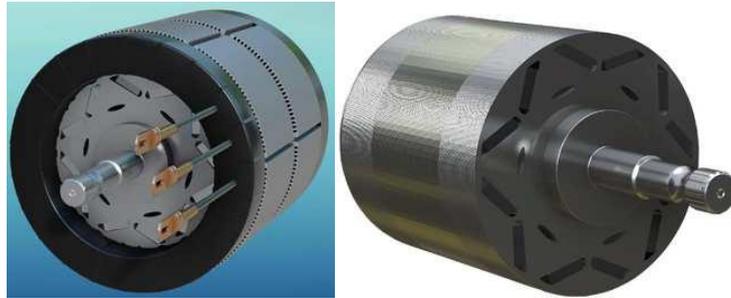


Image 3.6: Synchronous reluctance motor

3.2.3. Permanent Magnet Synchronous Reluctance Motor (PMSynRM)

These are motors specially developed by electric vehicle companies. It is a motor that combines the advantages of reluctance motor and permanent magnet synchronous motor. Magnets and conductors are not used in the rotors of standard reluctance motors. In such motors, permanent magnets are placed in the rotor. Nickel-cobalt-iron, ferrites, neodymium-iron-boron magnets are preferred as magnets. In this way, both the reluctance principle and the magnetic field effect of the magnet are used. With permanent magnet placement, the disadvantage of reluctance motors, torque fluctuation, is eliminated and torque values are increased.

Generally, a transversely laminated flux barrier type is preferred as the rotor structure. Although the placement design of permanent magnets varies from brand to brand, it is designed in a way that will contribute the most to the reluctance torque



Görsel 3.7: Permanent magnet synchronous reluctance motor (PMSynRM) and its rotor

Over time, it is planned to reduce the magnetic field-induced torque in motors and increase the reluctance torque. Thus, it is planned to reduce the use of magnets and conductors in motors and reduce costs.

3.3. Operation of Reluctance Motors

3.3.1. Working of Reluctance Motor

It is a known physical phenomenon that magnets or electromagnets attract metal objects towards themselves under the influence of their magnetic fields. In reluctance motors, unlike in classical electric motors, there is no push-pull movement together, only a pulling movement occurs. The pulling movement here is the effect that occurs when a magnet is brought close to a metal part.

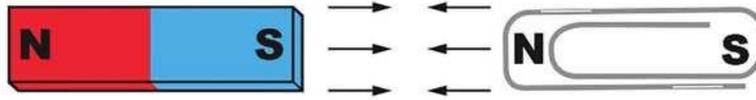


Figure 3.8: The magnetic field of a magnet attracting a metal

Reluctance is the resistance against the passage of magnetic flux in the magnetic circuit. When alternating current is applied to the stator winding, magnetic flux is formed in the windings. When the magnetic flux passes through a place with a large air gap, it encounters high resistance (reluctance). When it passes through a place with a small air gap, it encounters less resistance. Therefore, the magnetic flux begins to flow towards the place with less resistance. The stator poles, where the magnetic flux is dense, attract the rotor poles, causing the rotor to rotate. The rotation resulting from the pulling motion creates a reluctance torque.

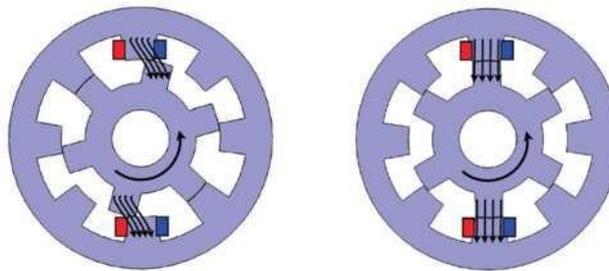


Figure 3.9: Rotation of the rotor due to reluctance effect.

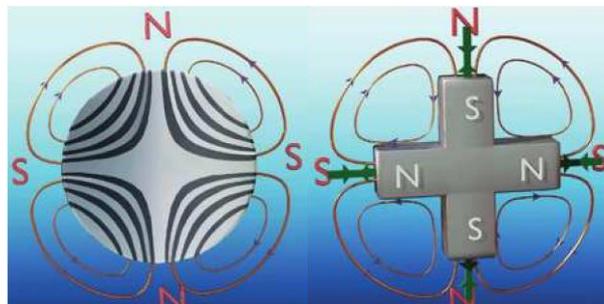


Figure 3.10: Magnetic field effect on rotor structures

By changing the phase sequence of the stator poles with power electronics, the rotor poles are continuously rotated. While the magnetic field in the stator windings rotates counterclockwise, the rotor rotates clockwise.

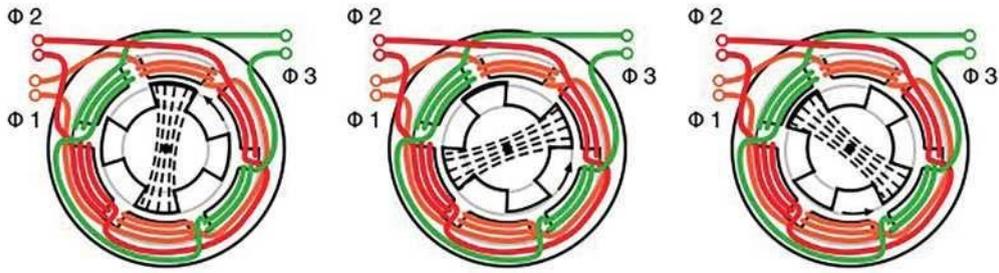


Figure 3.11: Operation of reluctance motor

3.3.2. Working of Permanent Magnet Reluctance Motor

Reluctance motors are motors developed by using permanent magnets in their rotors. In addition to the reluctance effect, the magnetic field is increased by permanent magnets. Thus, this motor combines the advantages of both the reluctance motor and the permanent magnet synchronous motor. The magnetic flux applied to the rotor with permanent magnets is strengthened and thus the reluctance torque is increased. The torque ripple disadvantage of the reluctance motor is eliminated.

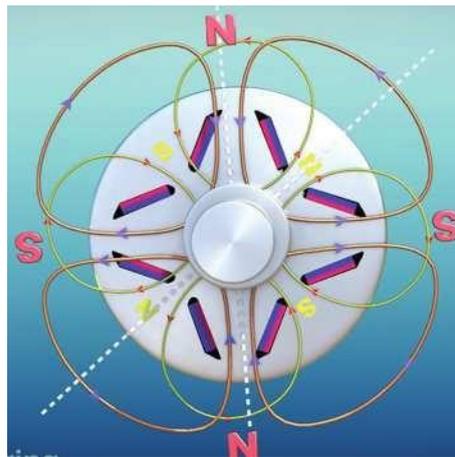
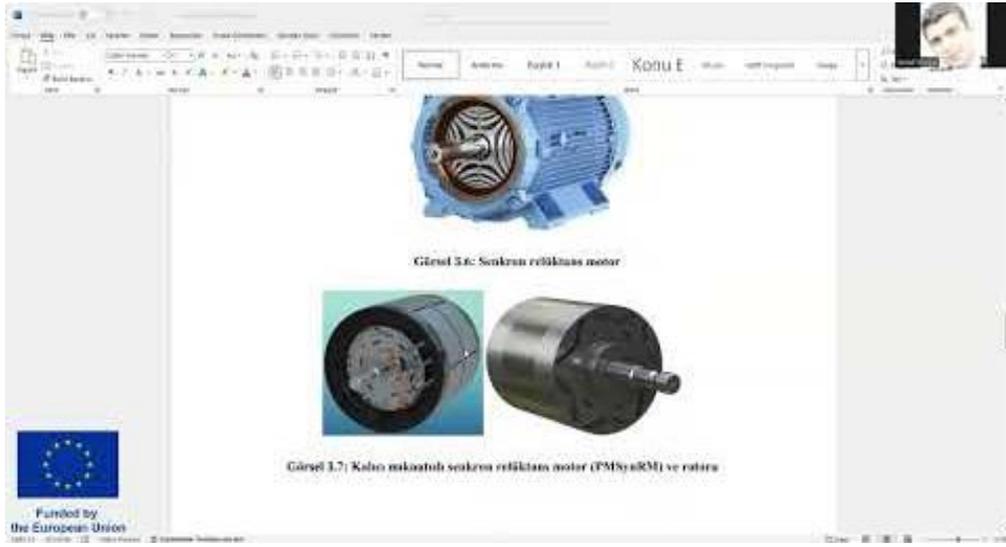


Figure 3.12: Operation of permanent magnet synchronous reluctance motor



To play the video, click on the image or click the link below and open it with your browser.

<https://youtu.be/oNGXXycRe6E>

4. SYNCHRONOUS MOTORS

4.1. Synchronous Motors

Synchronous literally means equal time. Since the rotating magnetic field formed in the stator and the rotor rotate at the same speed, these motors are called synchronous motors. Synchronous generators and synchronous motors are included in the synchronous machine group. Synchronous motors and synchronous generators are identical in structure. If electrical energy is applied to the input of a synchronous machine and mechanical energy is obtained from its output, it is called a synchronous motor; if mechanical energy is applied to the input of a synchronous machine and electrical energy is obtained from its output, it is called a synchronous generator. In this learning unit, only information about synchronous motors will be given. Synchronous generators will be covered in another learning unit.

4.1.1. Structure of Synchronous Motors

The synchronous motor consists of two main parts. These are the stator (armature) which is the fixed part and the rotor which is the moving part. Apart from these, the synchronous motor has a housing, bearings and a cooling system. Visual 4.1 shows a synchronous motor in a hybrid vehicle.



Image 4.1: Synchronous motor

4.1.1.1. Stator

It is the part where the rotating magnetic field is formed. The stator is a circular structure consisting of magnetic sheets insulated from each other with varnish. Copper windings fed with three-phase alternating currents are wound on the channels on the sheet plates. In the

connection of these windings to each other, a triangle or star connection type is used. In synchronous motors, the star connection type is most commonly used.

4.1.1.2. Rotor

The moving part of the synchronous motor is the rotor. In order for the rotor to rotate at synchronous speed, it must have a magnetic field. The magnetic field in the rotor is created either by an independent direct current source feeding the rotor winding or by permanent magnets placed in the rotor.

4.2. Types of Synchronous Motors

Synchronous motors have many types as they are used in different industries. However, the type used in electric vehicles is permanent magnet synchronous motors. Permanent magnet alternating current motors are divided into two classes according to the waveform of the induced electromotive force: sinusoidal and trapezoidal. Trapezoidal excited motors are called Brushless Direct Current Motors (FDAM) and sinusoidal excited motors are called Permanent Magnet Synchronous Motors (PMSM). In this learning unit, only permanent magnet synchronous motors will be discussed.

4.2.1. Structure of Permanent Magnet Synchronous Motors (PMSM)

Permanent magnet synchronous motors, like other electric motors, have a moving rotor and a fixed stator. In order to rotate a synchronous motor at synchronous speed, it is necessary to create a magnetic field in both the stator and the rotor. The rotating magnetic field in the stator windings is created with three-phase AC (alternating current) current. Two methods are used to create the magnetic field in the rotor. The first of these is the rotor windings fed with DC (direct current) current, and the second method is permanent magnets mounted on the rotor. Since it is necessary to use brush and ring arrangements to create a magnetic field in the rotor windings fed with direct current, these types of synchronous motors have not been used in electric vehicles. The use of permanent magnets in rotors has eliminated rotor copper losses and excitation circuit maintenance needs. Electric motors using permanent magnets are also called brushless type motors. A picture of a permanent magnet synchronous motor is shown in Visual 4.2.

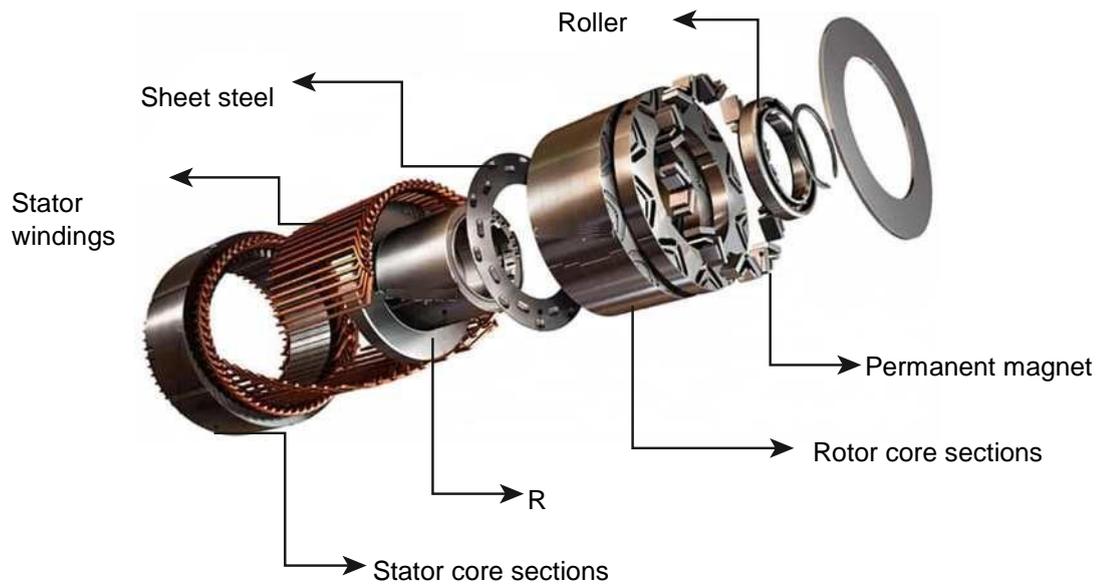


Figure 4.2: Parts of a permanent magnet synchronous motor

4.2.1.1. Stator

The stators used in permanent magnet synchronous motors are similar in structure to the stators used in other electric motors. Generally, stator windings consist of three-phase windings placed in the stator slots. Stator windings can be wound on magnetic sheets in two ways: scattered-winding type and lumped-winding type. The windings are connected to each other in two ways: delta and star connection. The most commonly used connection type is star connection. The stator of a permanent magnet synchronous motor used in a hybrid vehicle is seen in Figure 4.3.



Figure 4.3: Dispersed winding type stator

4.2.1.2. Rotor

The magnetic fields of the rotors used in permanent magnet synchronous motors are created by permanent magnets. The use of permanent magnets in the rotor has been very convenient for synchronous motors in terms of structure and operating principle. Because there is no need for a current source, windings and brush ring arrangement to create a magnetic field. The use of permanent magnets has made it possible to manufacture rotors with smaller dimensions and

stronger magnetic fields. In permanent magnet synchronous motors; rare earth element permanent magnets (REPM) such as Samarium-Cobalt ($\text{Sm}_2\text{Co}_{17}$) or Neodimium-Iron-Boron (Nd-Fe-B) are used. Visual 4.4 shows the rotor of a permanent magnet synchronous motor used in a hybrid vehicle.

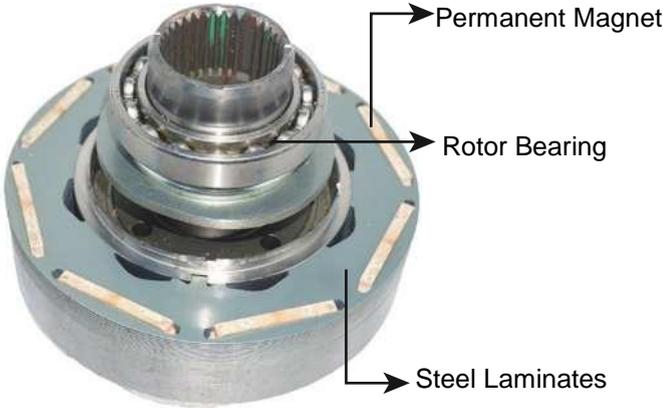


Figure 4.4: Permanent magnet rotor

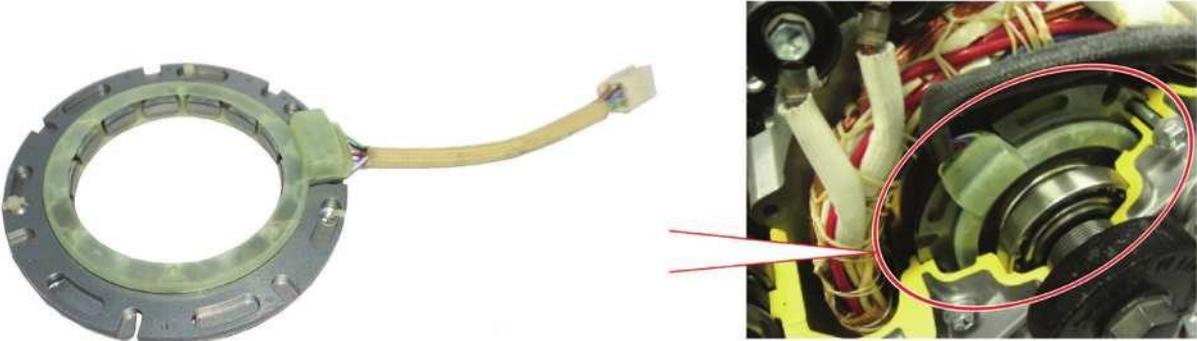


Figure 4.5: Rotor position and speed sensor

4.2.1.3. Rotor Position and Speed Sensor

In order for a synchronous motor to work, the position of the rotor must be known. Because the inverter determines the frequency of the alternating current according to this data. For this reason, there is a sensor that determines the position of the rotor and measures its speed in synchronous motors used in electric vehicles. These sensors may have different structures. However, they all do the same job. In Visual 4.5, the location of the sensor on the motor that determines the speed and position of the rotor used in a hybrid vehicle is seen.

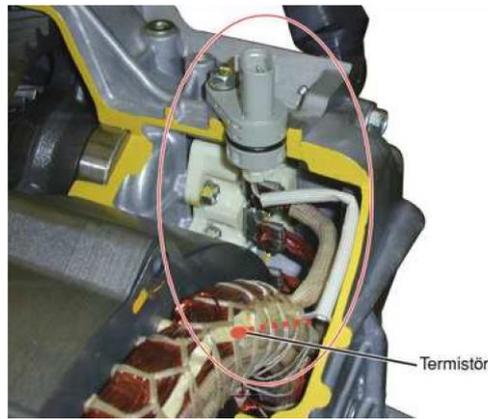


Figure 4.6: Stator winding temperature sensor

4.2.1.4. Stator Windings Temperature Sensor

The temperature sensor continuously measures the temperature in the stator windings and sends the data to the electronic control unit. When the temperature in the windings increases, the electrical control unit reduces the motor output power and causes the temperature to drop. This sensor is a negative coefficient (NTC) thermistor. The location of the sensor that measures the temperature of the stator windings in the synchronous motor is shown in Figure 4.6.

4.2.2. Classification of Permanent Magnet Synchronous Motors

Permanent magnet synchronous motors are classified according to where the permanent magnets are placed in the rotor and the stator winding arrangement.

4.2.2.1. Permanent Magnet Synchronous Motors According to Stator Winding Arrangement

Two types of winding arrangements are used in stator windings. These are; distributed type winding and lumped type winding.

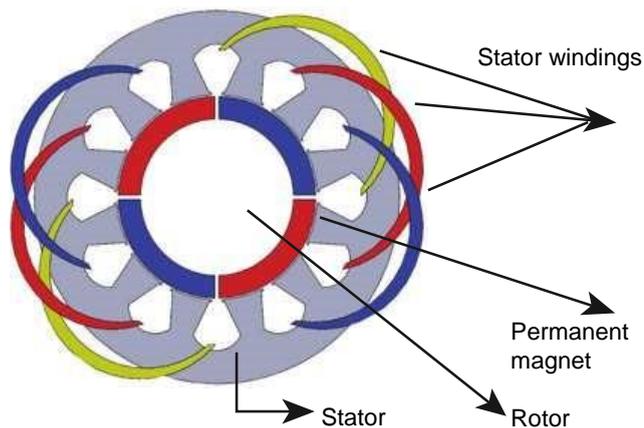


Figure 4.7 shows a distributed type stator winding.

- Distributed type winding
In distributed type windings, one winding coil is in a structure that cuts the other winding coil. For this reason, copper losses are high, output torque is low and costs are high. However, these windings are used in fixed power consumption and high speed back emf limitation applications (Aydın,2014).

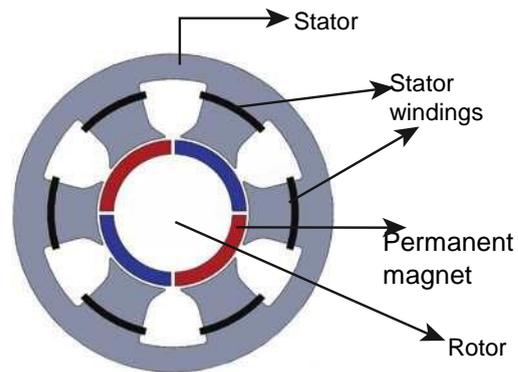


Figure 4.8 shows a distributed type stator winding.

- Lumped type winding
Another winding arrangement used in permanent magnet synchronous motors is the lumped winding type. In motors with this structure, the short stator windings reduce copper losses, so the heat generated in the windings is less than in motors with a distributed type winding structure, and thus the size of the electric motor is smaller. However, this winding arrangement also has some disadvantages. These can be shown as high rotor losses and low reluctance torque value (Aydın, 2014).

4.2.2.2. Permanent Magnet Synchronous Motors According to the Placement of Permanent Magnets Used in the Rotor

The magnet used in rotors, the properties of the material and the way the magnet is placed on the rotor seriously affect the performance of the synchronous motor. For this reason, there are different placement designs of the magnets on the rotor to increase the performance of the synchronous motor. Visual 4.8 shows the placements of the permanent magnets designed so far on the rotor.

Permanent magnets, which provide the formation of the magnetic field in the rotor, are mounted on the rotor in two ways.

These are;

- Placing the magnets on the rotor surface,
- Placing the magnets inside the rotor (embedding). These are also

two types among themselves.

1. Radial placement
2. Circular placement

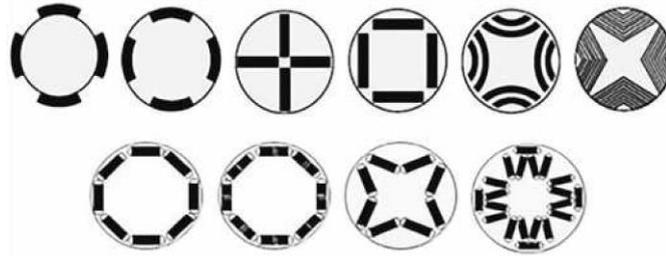


Figure 4.9: Images of permanent magnets settling on the rotor

• Placing magnets on the rotor surface

It is the most widely used motor type among PMSMs. Since the magnets are attached to the rotor surface in these motors, they have the highest air gap flux density. Their production cost and structural strength are low. The magnets are bonded to the rotor surface with special materials. It is preferred in low speed applications due to the possibility of the magnets separating from the rotor surface at high speeds (Aydın, 2014).

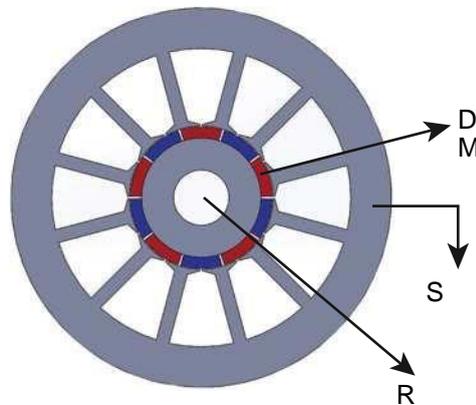


Figure 4.10: Placing permanent magnets on the rotor surface

• Placing magnets inside the rotor (Embedded magnets)

In permanent magnet synchronous motors, since the magnets placed on the rotor surface are exposed to large centrifugal forces when rotating at high speeds, problems such as the magnets breaking off or separating from the rotor surface may occur. For this reason, permanent magnets are placed by gluing them to the holes opened in the rotor. Since the surroundings of the embedded magnet are covered with magnetic material instead of air, the formation of reluctance moment is inevitable. The most important advantage of the embedded type magnet rotor is its mechanical strength. For this reason, it is designed for high speed applications. One

of the remarkable advantages of the synchronous motor with magnets embedded in the rotor is that it has high efficiency. The biggest disadvantage of this design is the high cost of permanent magnets (Özçira, 2007).

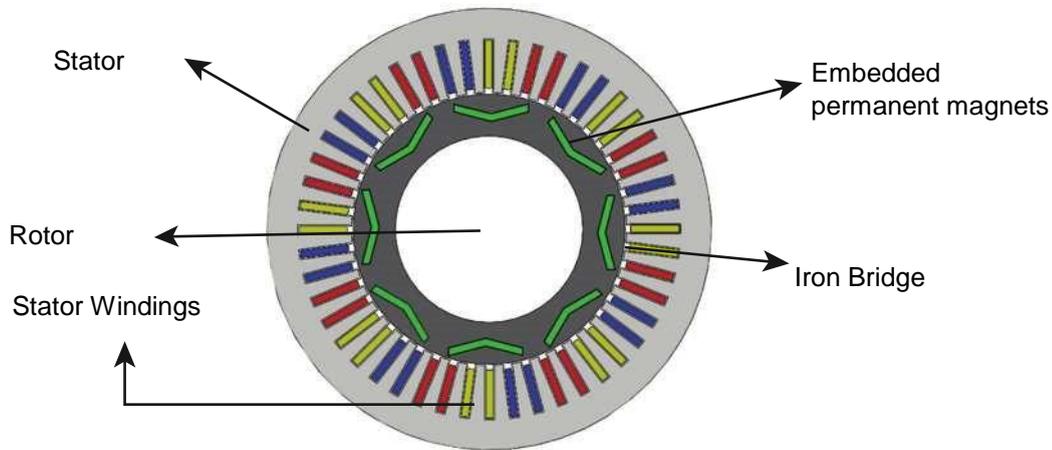
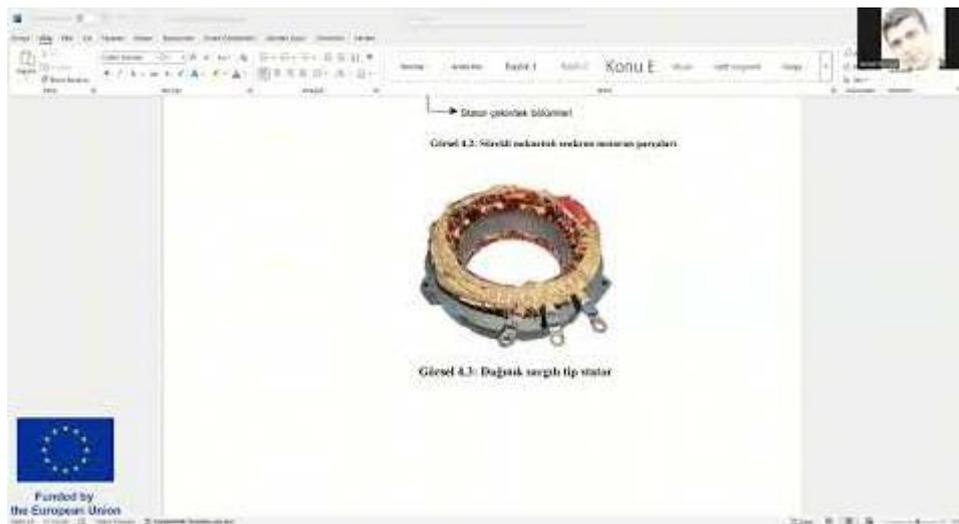


Figure 4.11: Placement of permanent magnets inside the rotor



To play the video, click on the image or click the link below and open it with your browser.

<https://youtu.be/YnhYe3Rfq70>

4.3. Starting Synchronous Motors

The process of reaching the rotor speed from zero to synchronous speed is called starting. Since synchronous motors cannot start on their own, different methods are used to start them. Some of these methods are;

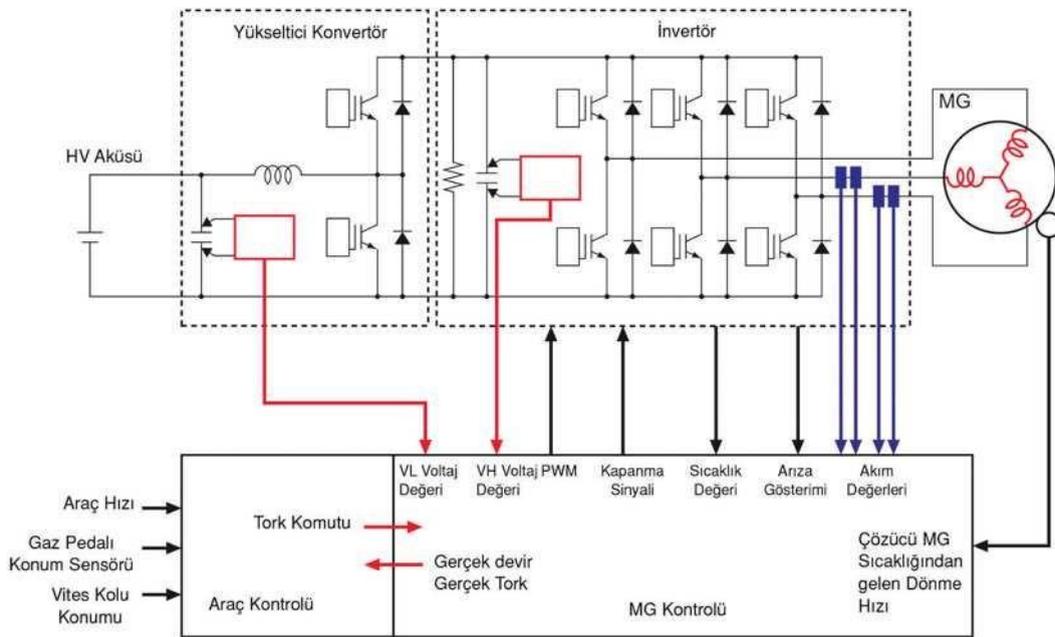
- Using a variable frequency inverter,
- Using shock absorber windings,
- Using a second drive machine,

- Operating as a synchronous generator.

Permanent magnet synchronous motors are used in electric vehicles. A variable frequency inverter is used to start such synchronous motors. Therefore, only the variable frequency starting method will be discussed in this learning unit.

4.3.1. Starting Using Variable Frequency Inverter

When three-phase AC current passes through the stator windings of a synchronous motor, a rotating magnetic field is created in the windings at synchronous speed. Initially, a starting torque cannot be produced in a synchronous motor due to the inertia of the rotor. Since the direction of the torque applied to the rotor changes in the opposite direction with each half-turn of the stator rotating field, the rotor cannot move and rotate in the direction of the stator rotating field. Therefore, since the torque applied to the rotor is zero, the rotor cannot move. However, if the frequency of the voltage applied to the stator is reduced, the speed of the stator rotating field will also decrease, so the rotor starts to rotate in the direction of the rotating field with the help of the torque applied to the rotor. Then, the frequency of the voltage applied to the stator windings is gradually increased, and the rotor speed is increased to synchronous speed. A circuit diagram for starting synchronous motors with variable frequency is shown in Figure 4.12.



Visual 4.12: Starting with variable frequency inverter

4.4. Operation of Permanent Magnet Synchronous Motors

When three-phase AC current passes through the stator windings of permanent magnet synchronous motors, a rotating magnetic field is created. Windings placed at an angle of 120° are required to create a rotating magnetic field. Visual 5.12 shows the U, V and W stator windings. While the same amount of current is applied to two of these three windings, a greater amount of current is applied to the U winding. In this way, the magnetic field forces formed in the W and V windings cancel each other out, while the magnetic field force formed in the U winding (red arrow) is formed in the opposite direction to the current direction given to the winding (blue arrow). In this way, the direction and intensity of the magnetic current formed in the stator windings are determined. In order for the direction and intensity of the magnetic current to change, the direction and intensity of the current sent to the windings are continuously changed by the inverter, and the rotating magnetic field is obtained. Visual 4.13 shows how the rotating magnetic field is formed in the stator windings.

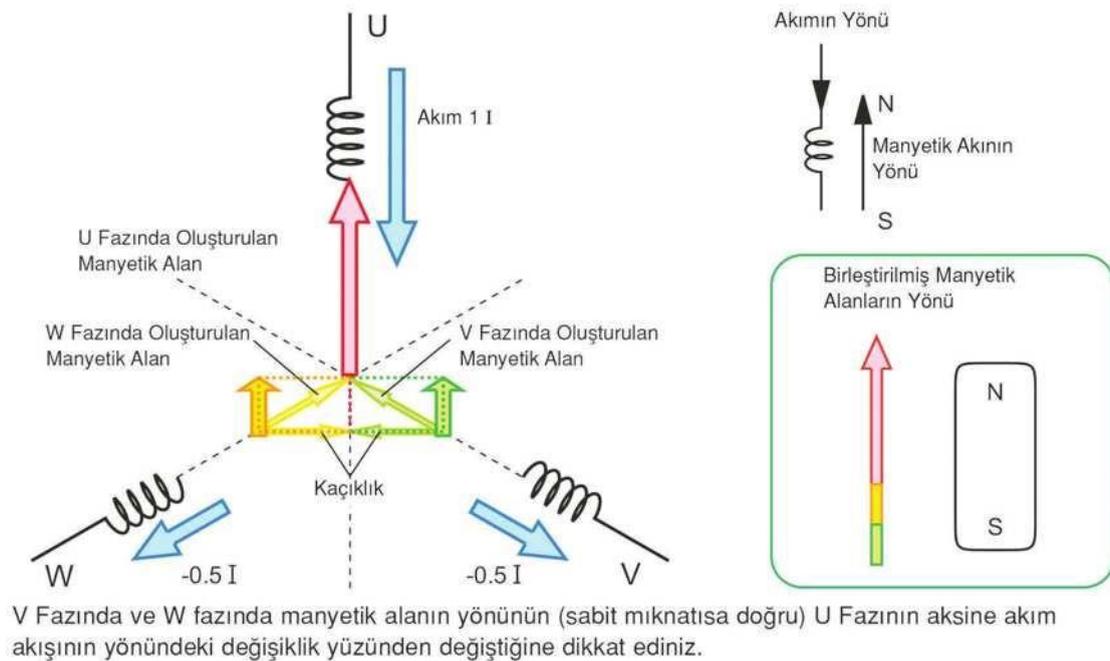


Figure 4.13: Rotating magnetic field formed in the stator windings

When the permanent magnet rotor is inserted into the rotating magnetic field, it will start to rotate with the magnetic field. According to the rotation position and speed of the rotor, this rotating magnetic field is controlled and the permanent magnets in the rotor are attracted by the rotating magnetic field and thus torque is produced. The torque produced is reduced or decreased in proportion to the amount of current. The rotation speed of the rotor is controlled by changing the frequency of the AC current.

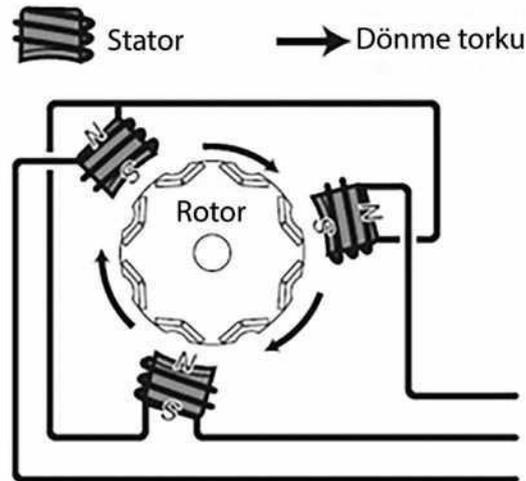


Figure 4.14: Rotation of the rotor in the rotating magnetic field.

4.5. Checks on Permanent Magnet Synchronous Motors

The control operations performed on permanent magnet synchronous motors are divided into two groups. These are;

- Visual controls,
- Electrical controls.

4.5.1. Visual Controls

The following controls are performed during the visual control of permanent magnet synchronous motors:

- Burning control in stator windings
- Deformation control in stator windings
- Noise control in rotor bearings
- Visual control of rotor
- High voltage cable connection control
- Control of rotor balance

4.5.2. Electrical Controls

Since there are no windings on the rotor of permanent magnet synchronous motors, electrical checks are only made on the stator windings. The following electrical checks are made on permanent magnet synchronous motors:

- Resistance check on stator windings
- Continuity check on stator windings
- Leakage check on stator windings to chassis
- Bad contact check on high voltage cable connections

4.6. Advantages and Disadvantages of Permanent Magnet Synchronous Motors

New developments in permanent magnet materials and electric motor drives have enabled PMSM to provide the advantageous features of direct current motors and alternating current motors. When comparing the magnet synchronous motor with other drive motors, the following advantages and disadvantages can be listed (Özçira, 2007).

4.6.1. Advantages

- Since there is a permanent magnet in the rotor winding, there is no need for excitation flux. Therefore, there is no external excitation source. Since there are no excitation losses, the motor efficiency is higher.
- Brush and collector arrangement is used in DC and some AC motors. Since this arrangement is not required in SMSM, maintenance costs are reduced and efficiency is increased since there are no losses in brushes and collectors.
- Not using a collector causes the rotor to become shorter, and the absence of windings in the rotor causes its weight to decrease. Therefore, the moment of inertia is low and its dynamic performance is good.
- Since the air gap induction increases, fewer stator windings can be used and thus it can be manufactured in a smaller volume and weight compared to direct current and asynchronous motors of the same power.
- Since there are no windings in the rotor, SMSM is easier to cool.
- The power factor is higher compared to asynchronous motors. In systems fed by the inverter, having a high power factor is important in terms of efficiently utilizing the power of the inverter.

4.6.2. Disadvantages

- When inverter control systems are not used, there is no change in speed. The application areas are also where constant speed is required.
- In order to provide synchronization between the permanent magnet and the stator rotating field, the rotor position must be known. The rotor position can be determined with sensors, but this increases the cost.
- Since there is no excitation current in the generator operating state, voltage adjustment cannot be made.
- Since the magnetization power of permanent magnet materials may decrease at high temperatures, the reliability of the system decreases.
- Due to the high prices and production costs of high-energy magnets, magnetic synchronous motors are more expensive than direct current and asynchronous motors.

- In the types of permanent magnets mounted on the rotor surface, there is a risk of the magnets breaking off the rotor surface at high speeds.
- There is a situation of axial displacement when the rotor is removed from the stator during maintenance.



Figure 4.15: Rotation of the rotor in the rotating magnetic field



<https://www.youtube.com/watch?v=r9oHidfhs>

Scan the QR code or click the link below to watch the video.

5. IN-WHEEL MOTORS

5.1. Structure of In-Wheel Motors

Electric motors that are placed inside the vehicle wheels and do not use any transmission organ to turn the wheels are called in-wheel motors. This motor, which is very efficient due to its technology and design, has started to be widely used in the electric car industry in recent years. Electric motors have been considered as a system instead of internal combustion engines or as a support system since the introduction of electric vehicles. Different types of motors have been used in electric vehicles. While systems where electric motors were mostly used in the first productions of electric vehicles and power was transferred to the wheels with gears were used, today there has been a transition to systems where a separate electric motor is used for each wheel and the driving force is directly connected to the wheel. At the same time, these motors are also called wheel (hub) motors due to their direct connection to the wheel (Akıncı, Ekren, Hüner 2008).



Image 5.1: In-wheel engine

5.1.1. History of In-Wheel Motors

While in-wheel motors are just starting to be used in today's electric vehicle drive systems, the first production and patent processes date back to the 1900s. The foundations of in-wheel motor technology were laid by an American inventor named Wellington Adams on June 24, 1884, and this motor was documented with patent number 300, 827. The patent, which was used in many studies between 1884 and 1897, was evaluated by Ferdinand Porsche.

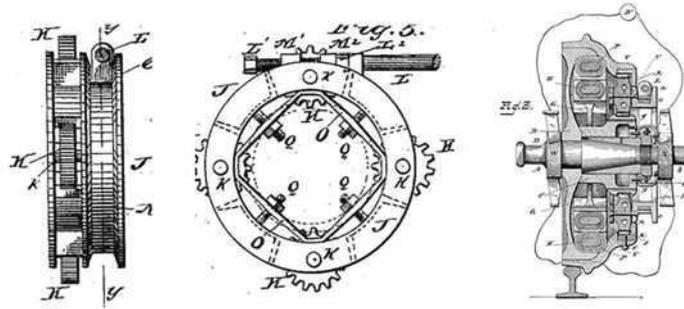


Figure 5.2: Wellington Adams' patent received in 1884

In 1897, Ferdinand Porsche produced the world's first prototype hybrid vehicle. This hybrid vehicle had in-wheel motors that powered the front wheels. The power of these in-wheel electric motors was around 3.5 kW. This hybrid vehicle was called the Lohner-Porsche. While the first prototypes had in-wheel motors only in the front wheels, later models used in-wheel motors in all four wheels. This car caused a sensation at the World Exhibition in Paris in 1900. In the following years, 300 Lohner-Porsches were produced and they had wealthy buyers. The world's first hybrid vehicle is shown in Figure 5.3.



Figure 5.3: The renewed Lohner-Porsche, the world's first gasoline-electric hybrid car

5.1.2. Parts of the In-Wheel Motor

In-wheel motors are electric motors, so they contain many parts used in other electric motors. In-wheel motors, which have a brushless DC motor structure, there is one rotor and one stator

element. In traditional direct current motors, rotors are generally located inside the stator, while in-wheel motors they are outside. Stator windings are located inside the rotor. There is also a microprocessor that provides voltage and current control and an inverter group that converts DC current to AC current. A cooling system is also used to reduce the heat generated due to high current usage. The rotor of the in-wheel motor is directly connected to the rim. When the rotor rotates, the wheel moves. There are also elements of the brake system that allow the vehicle to stop on the wheel motor. The in-wheel motor is also connected to the vehicle's suspension system. In-wheel motors generally consist of the following parts:

- Stator
- Rotor
- Inverter
- Cooling system
- Brake system



Figure 5.4: Parts of the in-wheel engine

5.1.2.1. Stator of In-Wheel Motor

The stator of the in-wheel motor is located in the center of the motor, unlike other direct current motors. The structural condition of the stator is the same as the stators in other electric motors. The stator of the in-wheel motor is seen in Figure 5.5.

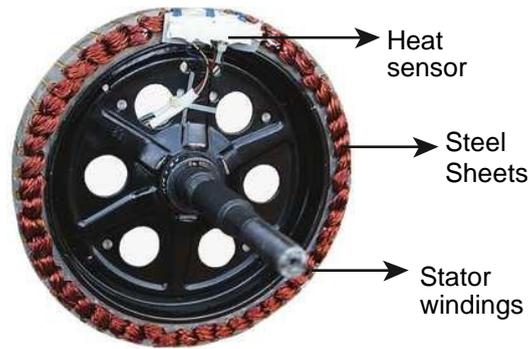


Figure 5.5: In-wheel motor stator

5.1.2.2. In-wheel Motor Rotor

In-wheel motors have external rotors. Permanent magnets are glued onto the rotor. In-wheel motor rotors, rare earth element permanent magnets such as Samarium-Cobalt ($\text{Sm}_2\text{Co}_{17}$) or Neodymium-Iron-Boron (Nd-Fe-B) are preferred. The rotor is the moving part of the motor and is connected to the wheel rim. The rotor starts to rotate with the effect of the magnetic fields in the stator and rotor and transmits this movement to the wheel. The in-wheel motor rotor, which is integral with the wheel, is seen in Figure 5.6.

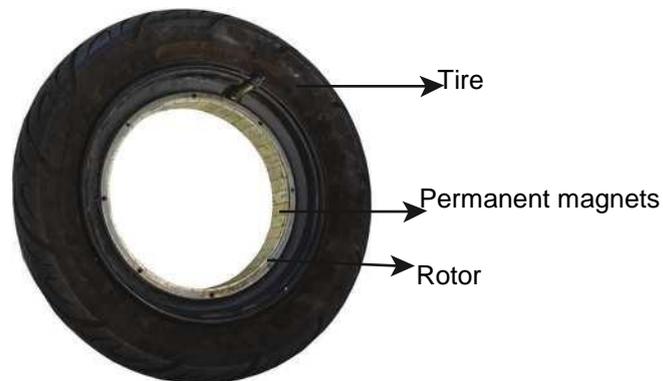


Figure 5.6: In-wheel motor rotor

5.1.2.3. In-wheel Motor Inverter

Three-phase alternating current is used in the stator windings of the in-wheel motor. Therefore, the direct current in the battery of the electric vehicle must be converted to alternating current. The part that performs this conversion is the inverter. There may be differences in the location of the in-wheel motor inverters on the vehicle. In some electric vehicles, the inverter is the vehicle body, while in some vehicles it is in a compact structure with the in-wheel motor. The inverters on the wheel motor are half the size of other inverters. There are some benefits to having the inverter on the wheel motor. When the inverter is mounted somewhere on the

vehicle, the number of cables that need to go to the wheel motor increases. This also increases the cost. Visual 5.7 shows the inverter group in a compact structure with the in-wheel motor.

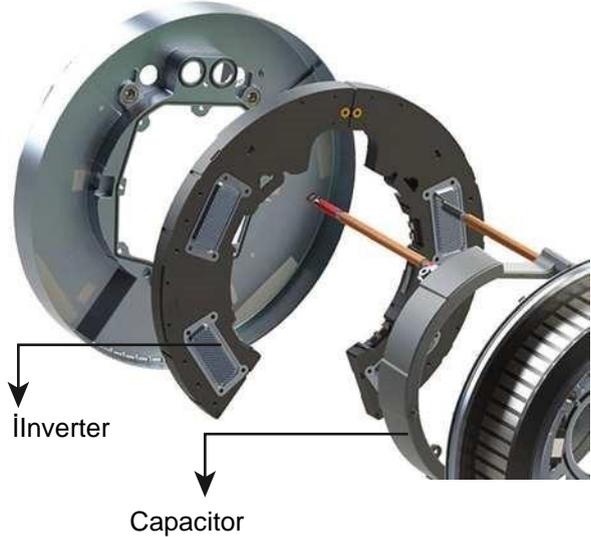


Figure 5.7: In-wheel motor and microinverter

5.1.3. Features of an In-Wheel Motor

The technical specifications of the sample in-wheel motor used in a concept car are shown in the table below.

Variables	The value	Unit
Nominal supply voltage	370	DC V
Maximum torque	1200	Nm
Sustainable torque	650	Nm
Maximum speed	1500	rpm
Maximum output power	110	kW
Engine efficiency	94	%
Cooling system	Liquid cooled	L/dk.
Engine weight	33	Kg
Power control electronics	Integrated inverter	

Table 5.1: In-wheel Motor Specifications

5.1.4. Areas of Use of In-Wheel Motors

Today, in-wheel motors are used in motorcycles, bicycles, scooters, cars, buses, off-road vehicles, trucks, etc. In-wheel motors are used extensively in bicycles, motorcycles and

scooters. They have also started to be used in buses and trucks. However, they are currently generally used as a concept in cars. Some concept cars that use in-wheel motors are listed below. An electric bus using in-wheel motors is seen in Visual 5.8. • General Motors Sequel 2005

- Protean Electric's Mini QED in 2006, Ford F-150 pickup truck in 2008 and other cars using its Hi-PaDrive
- Mitsubishi MIEV concept model 2005
- Chebela (2010), a small urban EV prototype using 2 direct-drive in-wheel motors at the rear
- Citroën C-Métisse, a wheeled electric motor vehicle developed by TM4
- Heuliez will use Michel's Active Wheel (including motorized active suspension) in 2008.
- ZAP-X, in 2007, uses high-tech electric hub motors to all four wheels, delivering 644 horsepower to the ground on a lithium-ion battery pack.
- Peugeot BB1, designed in 2009, uses in-wheel motors for the rear wheel motors.
- Toyota subsidiary HinoMotors showed a concept 6x6 truck chassis called “FlatFormer” at the 2019 Tokyo Motor Show.



Figure 5.8: An electric bus using an in-wheel motor

5.2. Types of In-Wheel Motors

Since in-wheel motors are mostly used in concept electric vehicles, they have not been fully diversified in the literature. However, according to academic studies written on this subject, the types of in-wheel motors are given below.

Wheel motors used in electric vehicles are divided into three according to their flux. These are; axial, radial, and transverse flux. The most suitable type for use in electric vehicles is the axial

flux in-wheel motors. Axial flux motors are divided into two as permanent magnet and induction. Axial flux asynchronous motors are divided into two as wheel axial flux and two-rotor axial flux. Axial flux permanent magnet synchronous motors are divided into two as axial flux slotless permanent magnet and axial flux slotted type synchronous motor (Akıncı, Ekren, Hüner 2008).

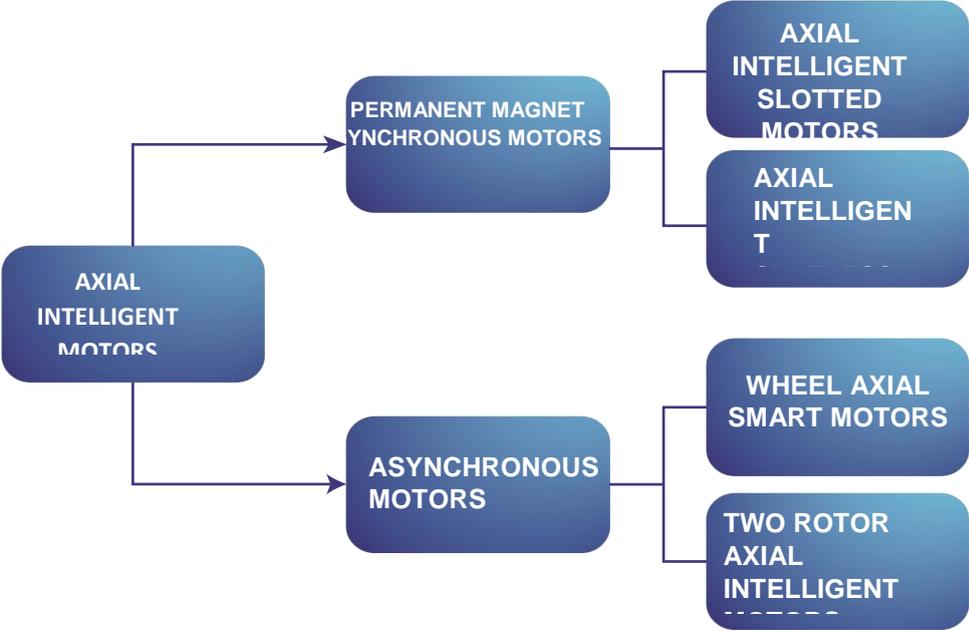
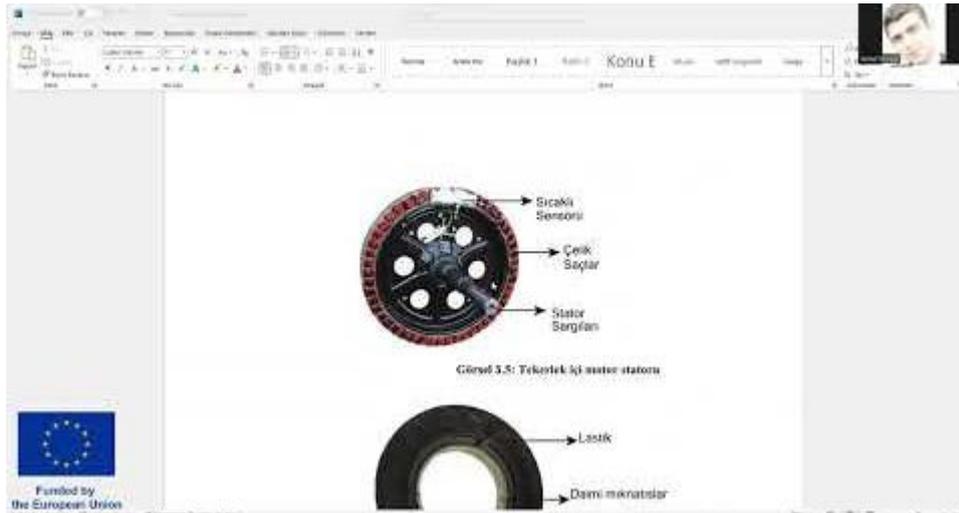


Image 5.9: Types of in-wheel motors

When examined in terms of structure, in-wheel motors used in electric vehicles may show differences. Some automotive companies that have conducted R&D studies on this subject and tested their products in concept electric vehicles have designed different in-wheel motors. While some of these companies use a powerful in-wheel electric motor in the center, some companies have used a gear system that increases torque with gears driven by a small electric motor. In addition to these studies, another company has designed a more complex structure by placing the suspension system inside the wheel and increased the usage area in the vehicle even more.



Figure 5.10: Structure of the different in-wheel motor



To play the video, click on the image or click the link below and open it with your browser.

<https://youtu.be/PlcujPiL3fM>

5.3. Operation of In-Wheel Motors

The working principle of in-wheel motors is similar to other electric motors. The main difference between in-wheel motors and other motors is that the rotor is not inside the stator windings but outside. The DC current from the battery is converted to AC current by the inverter and sent to the stator windings. The rotating magnetic field formed in the stator creates a pole effect and interacts with the magnetic field of the natural and strong magnets of the rotor arranged around the stator windings, creating a pushing or pulling force in the rotor and causing the rotor to rotate. Since the rotating rotor is attached to the wheel, the wheel rotates and the vehicle moves.

5.4. Advantages and Disadvantages of In-Wheel Motors

In-wheel motors are used in many electric vehicles today. In-wheel motors have advantages and disadvantages like every system.

5.4.1. Advantages

- They can be used to power rear- or front-wheel drive vehicles as well as all-wheel drive versions.
- With no drivetrain, automotive engineers can add more cargo room, create crumple zones around the passenger compartment for a safer car, or design a smaller, lighter, more efficient car.
- In-wheel motors eliminate the need for a drivetrain with a transmission, differential, and axle. This reduces mechanical losses in every component between the engine and the wheel, and makes the vehicle run quieter.
- In-wheel motors act as generators to brake. The spinning wheels are forced to work against electromagnetic fields to produce electricity, slowing them down. This regenerative braking also allows the vehicle to produce electricity that can then be stored and reused, extending the life of the brake pads.
- Thanks to advances in electronic motor control, engineers can now control the torque, speed, and even direction of rotation of each in-wheel motor. This means features like anti-lock brakes, traction control, and even cruise control can be handled by a single master controller.

5.4.2. Disadvantages

- Electric energy is required to power in-wheel motors. In order to use this energy, vehicles must be equipped with rechargeable batteries. However, these batteries add weight to the vehicle and introduce potentially hazardous substances into the waste stream. They also put an additional burden on the country's energy grid and increase the need for new power plants.
- The biggest challenge facing in-wheel motors is the weight problem of unsprung mass. Unsprung weight is the mass of all components of a car that are not supported by the suspension. Unsprung weight in a vehicle includes the wheels, tires, and brakes. Too much unsprung mass will cause the vehicle to ride uncomfortable.
- Due to the proximity of the in-wheel motor to the wheels, they are not protected against road shock and heat caused by braking at the desired level.
- In-wheel motors are expensive because they contain many new technologies and are therefore very expensive.

5.5. Checks on In-Wheel Motors

The control procedures performed on in-wheel motors are divided into two groups. These are;

- Visual controls,

- Electrical controls.

5.5.1. Visual Controls

The following controls are performed during the visual control of the in-wheel motor.

- Burning control in stator windings
- Deformation control in stator windings
- Noise control in stator bearings
- Visual control of the rotor
- High voltage cable connections control
- Rotor balance control
- Leakage control in cooling system

5.5.2. Electrical Controls

Since there is no winding on the rotor of in-wheel motors, only electrical controls are performed on the stator windings. The following electrical controls are performed on in-wheel motors.

- Resistance control in stator windings
- Continuity control in stator windings
- Leakage control to chassis in stator windings
- Bad contact control in high voltage cable connections
- Inverter controls
- Temperature sensor control

6. SYNCHRONOUS GENERATORS

GENERATORS

One of the important types of energy used in cars today is electrical energy. Electrical energy can be produced in many ways. In this learning unit, synchronous generators, which are a type of AC generators used in electric vehicles and are basically divided into two groups as DC (Direct Current) and AC (Alternating Current), will be examined. The definition, structure, types, operation, measurement and control of synchronous generators will be discussed.

6.1. Definition of Synchronous Generator

Everything is known by its opposite. In order to understand synchronous machines, it is necessary to talk about asynchronous machines. In the light of asynchronous motors and synchronous motors topics covered in previous learning units, the meanings of the words “asynchronous” and “synchronous” were examined, and an expression that is the opposite of each other was created by adding the letter “a” to the beginning of the common word synchronous.

The literal meaning of synchronous is that there must be at least two parameters, these two parameters must be compared and work together.

When three-phase voltage is applied to a synchronous or asynchronous electric motor, two values occur on the motor. One of these is the value formed (calculated) on the windings and this is called synchronous speed.

The other is the value measured on the rotor shaft, this is called rotor speed.

Calculation of synchronous speed per minute	
$n_s = 120 \times f/p$	Synchronous speed = $120 \times$ frequency/number of pole pairs

If the two speed values expressed above are equal, this motor is called a synchronous motor. If the calculated value is higher than the measured value, this type of motor is called an asynchronous motor. The biggest reason for the difference between synchronous speed and rotor speed is the losses that occur between the rotor and the stator. Therefore, the synchronous speed value can never be lower than the rotor speed value. The status of synchronous and rotor speed is given in Visual 6.1.

Synchronous (Calculated) Speed	Rotor Measured Speed	Engine Type
High	Low	Asynchronous Motor
Equal	Equal	Synchronous motor
Low	High	-----

6.2. Structure of Synchronous Generator

Synchronous motor and synchronous generator are structurally identical. If electrical energy is applied to the input of a synchronous machine and mechanical energy is obtained from its output, it is called a synchronous motor; if kinetic energy is applied to the input of a synchronous machine and electrical energy is obtained from its output, it is called a synchronous generator. A permanent magnet synchronous generator is shown in Figure 6.2. The part of a generator that carries alternating current windings is called an armature, and the part that carries direct current windings is called an inductor. The stator (armature) winding is connected to the alternating current output, and the rotor (inductor) winding is connected to the direct current source. Therefore, it is included in the group of double-excited machines.

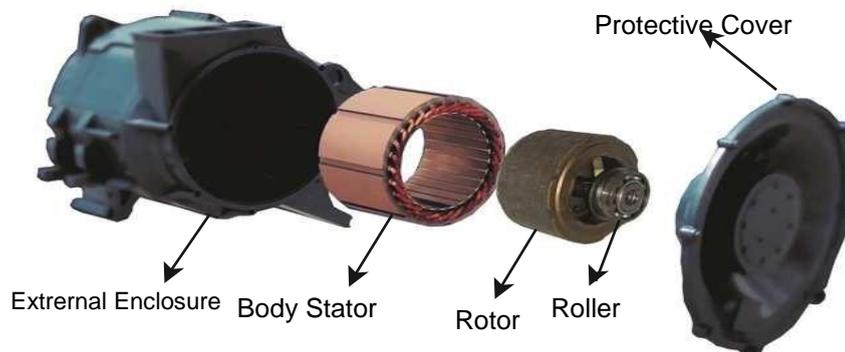


Figure 6.2: Permanent magnet synchronous generator

The stator is the part where the alternating current windings are wound. It is formed by packaging the silica sheets and winding them on. The stator and windings are shown in Visual 6.3. The rotor is the part where the pole windings are located and where direct current is applied. Since the rotors in the generators used in vehicles are usually permanent magnet rotors, there are no pole windings. The rotor is shown in Visual 6.4.



Figure 6.3: Stator and windings

The rings ensure that the direct current supply to the rotor is taken from the external circuit if the synchronous machine is operating as a generator. The brushes ensure that the voltage is applied to the rotor from the external circuit. The brushes are made of carbon or carbon alloy. Since the rings and brushes are generator parts used in power plants, they are given here for informational purposes. Since the generator rotors used in automobiles are usually permanent magnets, there are no parts such as rings and brushes. The bearings and other parts are the parts that allow the rotor to rotate easily around an axis and protect the rotor from external effects. The bearings consist of parts such as shaft, propeller, terminal box, covers.



Figure 6.4: Rotor and shaft

5.3. Synchronous Generator Types

- Round rotor synchronous generator (Generally used in cogeneration plants.)
- Turbo rotor synchronous generator (Generally used in cogeneration plants.)
- Salient pole synchronous generator (Generally used in hydroelectric plants.)
- Permanent magnet synchronous generator (Used in light industry and automobiles.)

Note: Cogeneration is a technology that enables the production of electricity and heat energy together in order to use energy more efficiently.

6.4. Working of Synchronous Generator

In synchronous generators, the pole windings are usually located in the moving part of the machine, namely the rotor. Instead of pole windings, permanent magnets are used in the rotor. In the pole windings, a direct magnetic field that does not change with time and whose amplitude is constant is formed in the air gap by being fed with direct current, or it is in a state of permanent magnetization. The synchronous generator rotor and stator are shown in Visual 6.5.

This magnetic field passes through the three-phase winding planes placed in the stator at different angles as a result of the rotor being rotated by an external drive machine. Thus, a three-phase voltage is induced in the stator windings of the generator with the rotating magnetic field. This voltage is variable with time, that is, it is an alternating voltage.



Figure 6.5: Synchronous generator rotor and stator

The R-S-T phases are derived from their English names. First of all, a reference phase is needed to evaluate the three phases relative to each other. In other words, the reference phase is called the second phase, and finally the third phase is called the third phase. The representation of the R-S-T signals in the form of a sine wave is given in Figure 6.6.

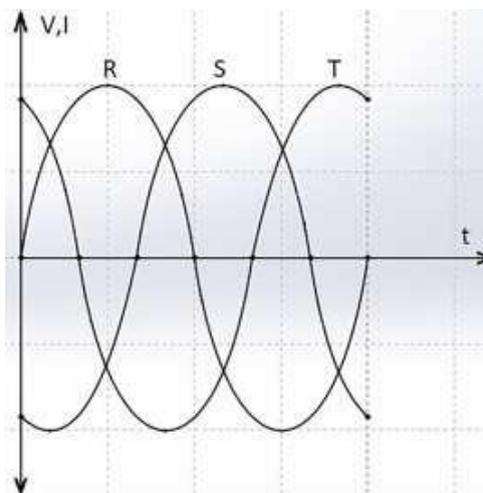


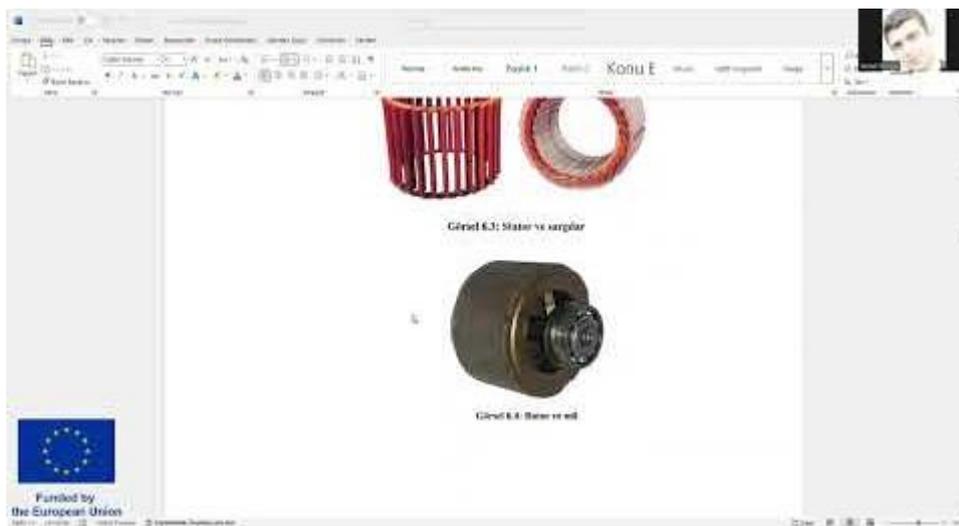
Figure 6.6: R-S-T signals are sine waves

6.5. Working Principle of Regenerative Braking System

It is a system used to charge the battery by converting the kinetic energy in the vehicle into thermal energy and discharging the heat, instead of converting the kinetic energy into electrical energy with the help of a synchronous generator. In electric vehicles, when the gas pedal is released, this system is automatically activated and the vehicle is slowly braked.



Figure 6.7: Regenerative braking



To play the video, click on the image or click the link below and open it with your browser.

<https://youtu.be/PQB0MIRoJS4>

Regenerative Braking System Activation

When the vehicle is moving at a certain speed and the gas pedal is not pressed, the kinetic energy on the vehicle, that is, the rotational energy of the wheels, starts to turn the rotor of the synchronous motor through the gears. Regenerative braking is shown in Figure 6.7.

The necessary condition for operating the synchronous motor as a synchronous generator is that the rotor's rotational speed is higher than the magnetic field's rotational speed. At this time, the inverter-converter group comes into play. The inverter-converter group adjusts the frequency entering the synchronous motor and keeps the rotating magnetic field speed below

the rotor speed. Thus, a current much higher than the current coming from the converter is generated in the stator windings. The current generated is alternating current. With the help of the ACDC rectifier, the current is converted to direct current and the battery is charged. A magnetic field force in the opposite direction to the movement of the wheels is applied to the rotor at this time, and the vehicle's deceleration process is also performed. Therefore, the vehicle's speed can be adjusted precisely using a single pedal (gas pedal). In addition, the brake pedal is used for a full stop.

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