



MOTOR VEHICLE TECHNOLOGY

POWER CONVERTER SYSTEMS MODULE IN ELECTRIC VEHICLES

2023-2-TR01-KA210-VET-000180148

**New Applications in Electric Vehicles
Technology According to 4.0 Standards**



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CONTENTS

1.1. Rectifiers	5
1.2. Working of Rectifiers	6
1.3. Inverters	9
1.4. How Inverters Work.....	10
1.5. DC-DC Converters	15
1.6. Operation of DC-DC Converters	16
2.1. Functions of the Cooling System	22
2.2. Types of Cooling Systems	22
2.2.1. Air Cooled Systems.....	22
2.2.2. Liquid Cooled Systems.....	23
2.3. Parts of the Cooling System	24
2.3.1. Radiator	24
2.3.2. Water Pump.....	25
2.3.3. Cooling Fan	25
2.3.4. Expansion Tank.....	25
2.4. Cooling System Operation	26
REFERENCES	29

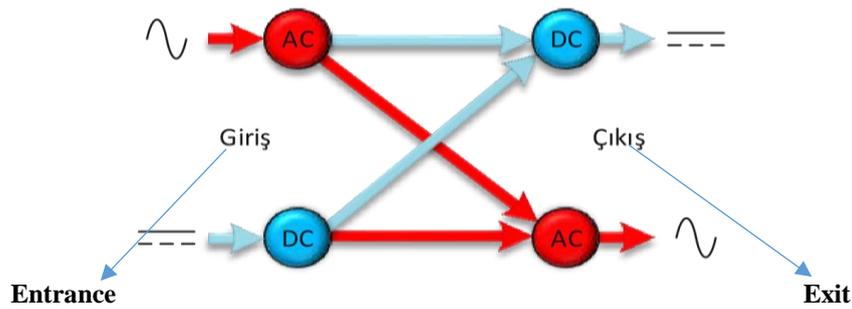
EXPLANATIONS

AREA	Motor Vehicle Technology
PROFESSION	Electric Vehicles
MODULE NAME	Power Converter Systems in Electric Vehicles
MODULE DESCRIPTION	This module is a learning material that provides basic knowledge and skills regarding power converter systems used in electric vehicle technologies, including the structure of converter systems, their working principles and safe intervention practices.
COMPETENCE	Recognize power converter systems, explain their operating principles and apply safe intervention rules.
PURPOSE OF THE MODULE	<p>General Purpose With this module, you will be able to recognize the power converter systems used in electric vehicles, explain their working principles, and safely intervene in these systems.</p> <p>Objectives</p> <ol style="list-style-type: none"> 1. Be able to distinguish the types and functions of power converter systems used in electric vehicles. 2. Be able to explain the structure and working principles of rectifiers, inverters and converters. 3. Be able to understand the placement and function of power converter systems in electric vehicles. 4. Be able to explain the conditions for safe intervention and basic precautions for power converter systems.

1. CONVERTERS

Converters have an important place in the power systems of hybrid and electric vehicles. For example, when a generator driven by an internal combustion engine in a series hybrid vehicle is considered, the alternating current obtained at the generator output must be converted to direct current. Since the electric motors that provide the driving force are generally operated with alternating current, the direct current taken from the vehicle electrical system must be converted to alternating current. In a hybrid or fully electric vehicle, in addition to the high-voltage components in the main power system, there are also low-voltage components as in conventional vehicles. Obtaining the low-level DC voltage (14 V) required for the operation of the receivers in question from the high-voltage DC electrical system of the hybrid or fully electric vehicle is another need. Similarly, in order to operate the air conditioning system motor, the DC system voltage must be converted to AC. Although not all converters in vehicles are limited to these examples, these examples reveal the importance of converters in the electronic systems of hybrid and electric vehicles. Basically, power converters; They are systems that convert direct current to alternating current, alternating current to direct current, direct current to direct current, alternating current to alternating current. Although the power converters used in hybrid and electric vehicles have similar structures to the power converters used outside the automotive sector, the converters used in hybrid and electric vehicles must have physical properties suitable for the working environment. The working conditions in question can be listed as; ambient temperature between -20°C and -50°C , vibration-shaking working environment and electromagnetic compatibility. Power converters are classified according to the type of input and output voltages, as seen in Visual 1.1. The input and output of the converter are direct current (DC) or alternating current (AC):

- DC-DC converter (converter)
- DC-AC converter (inverter)
- AC-DC rectifier
- AC-AC converter



Visual 1.1: Converter types

It is possible to talk about three different converter structures used in hybrid and electric vehicles. The mentioned converters are used in many different areas other than hybrid and electric vehicles. In the converters listed above, AC-AC converters are mostly used outside the automotive sector. Basically, an AC-AC converter contains an AC-DC rectifier and a DC-AC inverter.

There are different numbers of power converters in a hybrid and electric vehicle depending on the power system structure and the hybridization level of the vehicle. An example of an all-electric vehicle block diagram is seen in Visual 1.2. The DC voltage received from the high-voltage battery group as the main energy source of the vehicle is increased to a certain value with the help of a DC/DC converter. In order to operate the vehicle's electric motor, the voltage received from the DC/DC converter output is converted to AC with the help of an inverter. At the same time, a second DC/DC converter is used to obtain the low voltage required to operate the low-voltage electrical receivers in the vehicle.

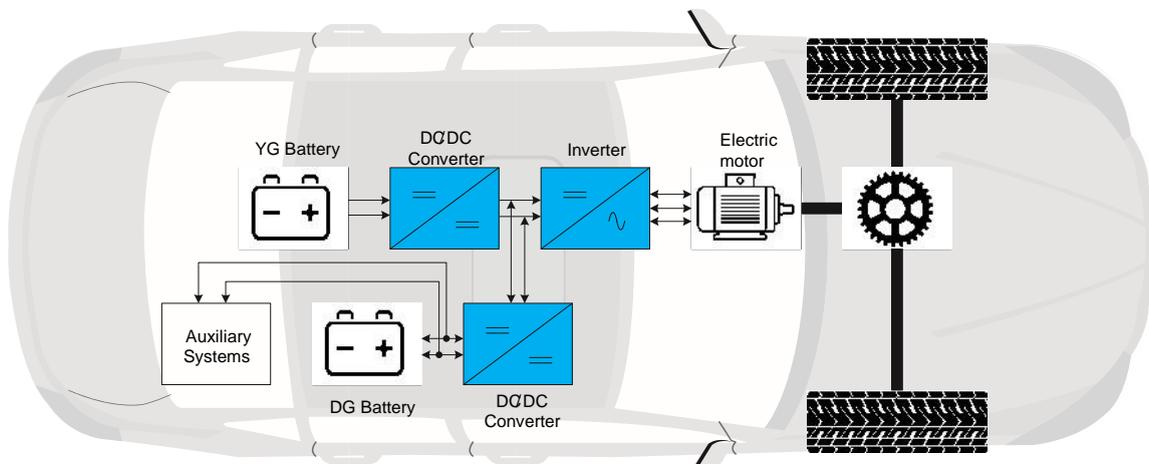


Figure 1.2: Converters in a battery electric vehicle

Similarly, Visual 1.3, Visual 1.4 and Visual 1.5 show sample block diagrams of series hybrid, parallel hybrid and series-parallel hybrid vehicles, respectively. When the block diagrams are examined, it is seen that the number of converter systems used can vary depending on the structure of the vehicles. It should also be noted that there are different applications in the power systems of hybrid and electric vehicles than the sample block diagrams given in these visuals. The visuals are provided to provide an idea about the purposes of use of converters in hybrid and electric vehicles.

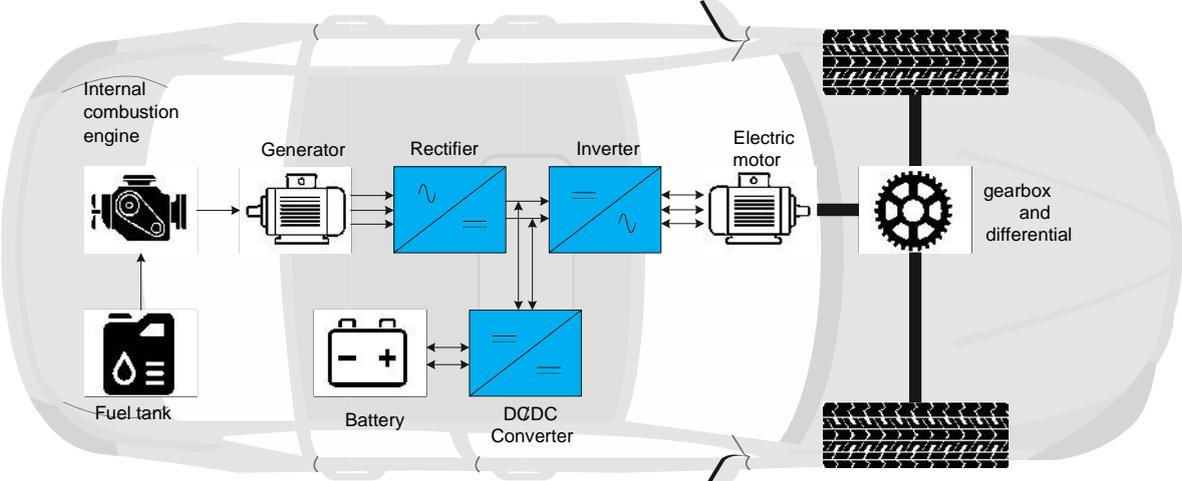


Figure 1.3: Converters in the power system of a series hybrid vehicle

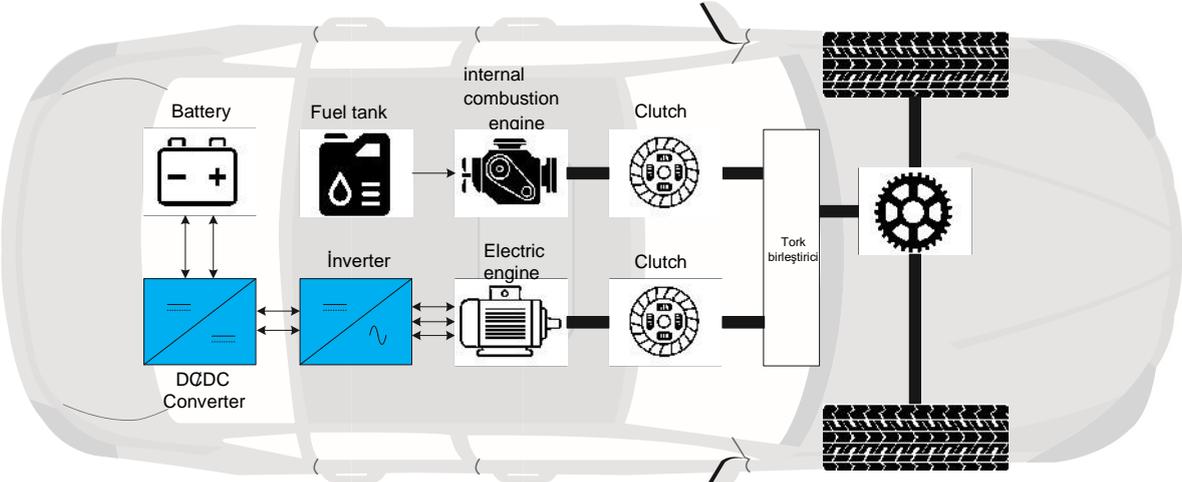


Figure 1.4: Converters in the power system of a parallel hybrid vehicle

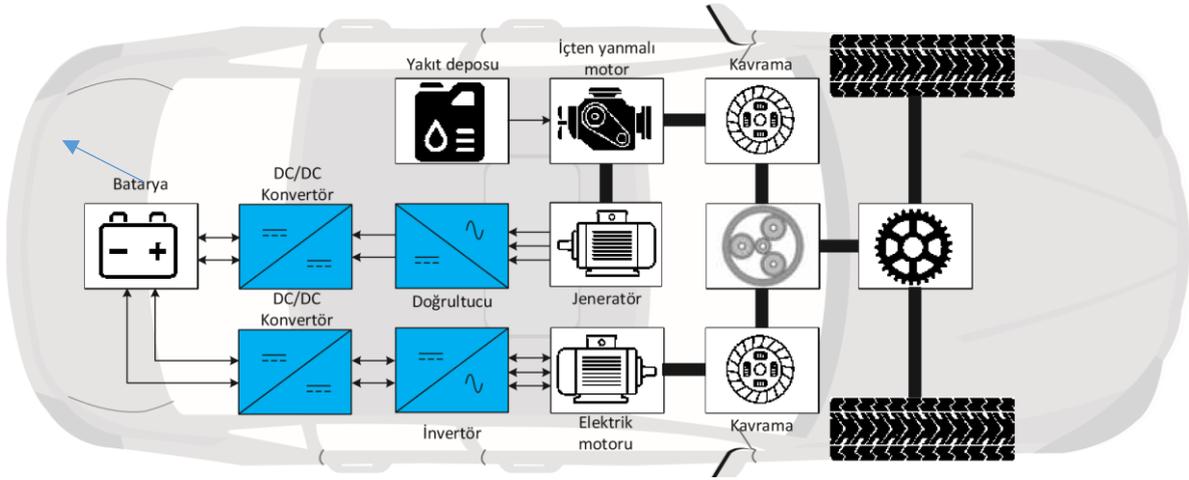
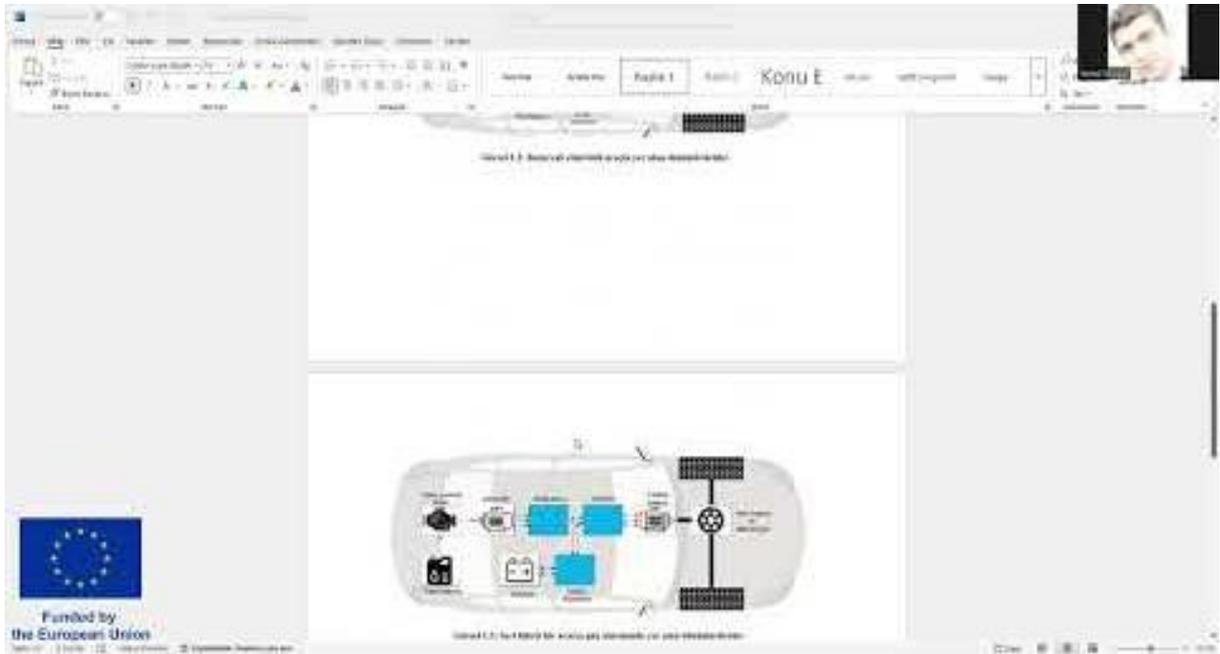
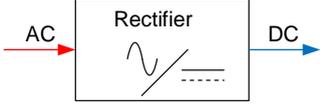
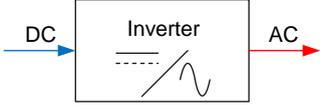
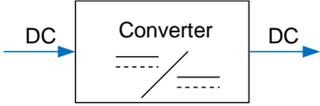


Figure 1.5: Converters in the power system of a series-parallel hybrid vehicle



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<https://youtu.be/zjWw3MNkITo>

Power converters used in hybrid and electric vehicles are basically divided into three groups: rectifiers, inverters and converters.

	<p>Rectifiers are circuits used to convert alternating current to direct current. The input is alternating current, the output is direct current.</p>
	<p>Inverters convert direct current to alternating current. The input is direct current, the output is alternating current.</p>
	<p>Converters enable the conversion of DC voltage at a certain level to DC voltage at a different level. The input and output are direct current.</p>

1.1. Rectifiers

Rectifier circuits enable the conversion of alternating current to direct current. Half-wave and full-wave rectification circuits, the structure of which is explained in the basic electrical and electronic topics, are used in the conversion of alternating current to direct current. Half-wave and full-wave rectification circuits are seen in Visual 1.7 and Visual 1.8. In the circuit in Visual 1.7, the diode switches to conduction in the positive alternation of the input voltage and ensures current flow through the load, and in the negative alternation, it switches to insulation and prevents current flow in the reverse direction through the load. As a result of this study, current flows through the load only in the positive alternations of the input voltage. For this reason, the circuit is called a half-wave rectification circuit.

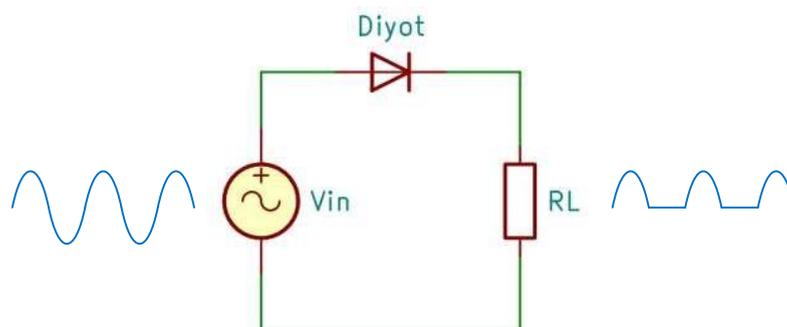
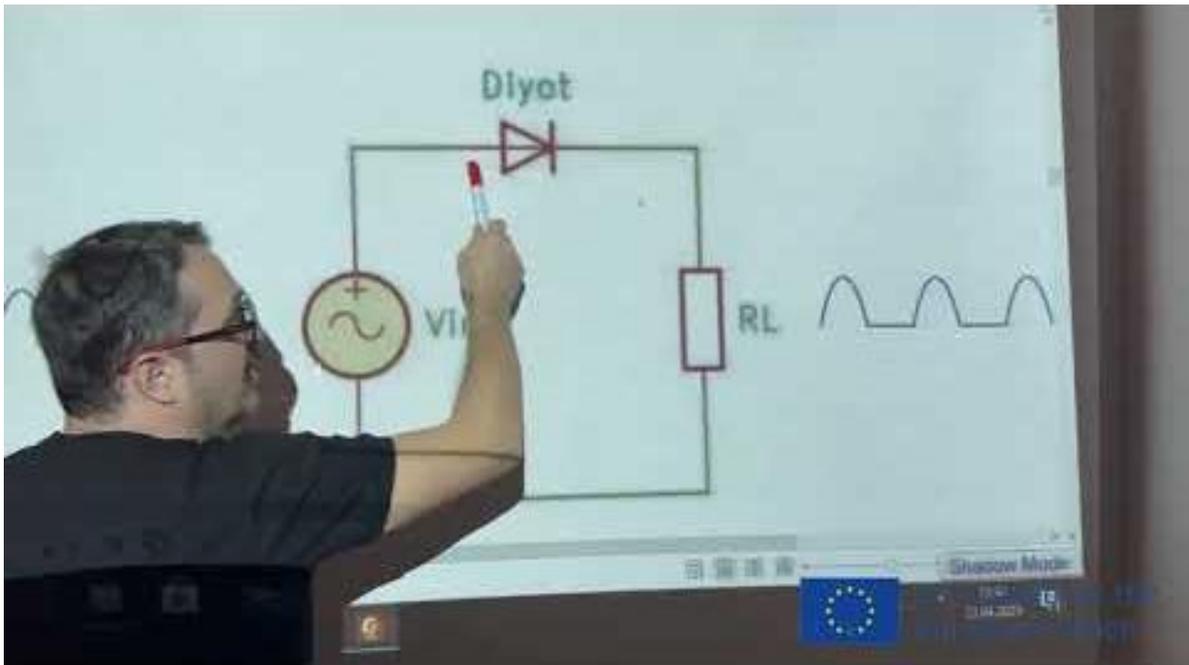


Figure 1.7: Half-wave rectifier circuit



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1.2. Working of Rectifiers

One of the rectifier circuits that will provide rectification of positive and negative alternations of input voltage is the bridge type full wave rectifier circuit. In the positive alternation of input voltage, diodes between points 1-3 and 2-4 are conducting, the current from point 1 passes through the load and reaches point 2. In the negative alternation of input voltage, diodes between points 2-3 and 1-4 are conducting, the current passing through the load is the same as in the positive alternation. As can be seen, both positive and negative alternations of input voltage are rectified in this circuit. For this reason, the circuit is called a full wave rectifier circuit. A capacitor is also connected to the output part in order to reduce the fluctuations in the outputs of the rectifier circuits given in the images.

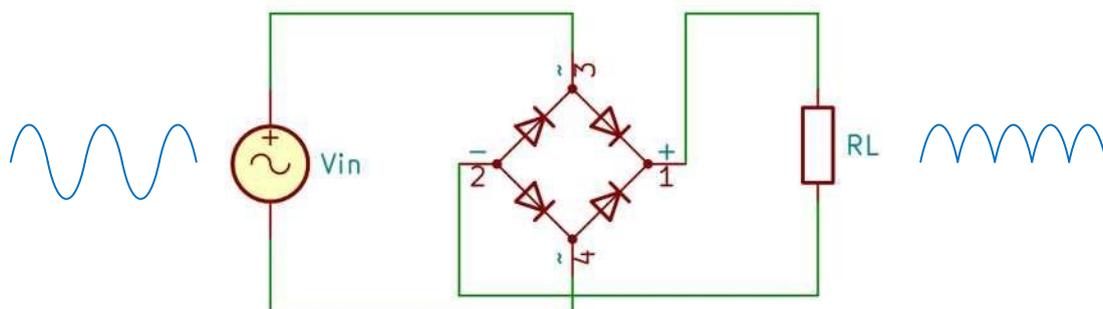
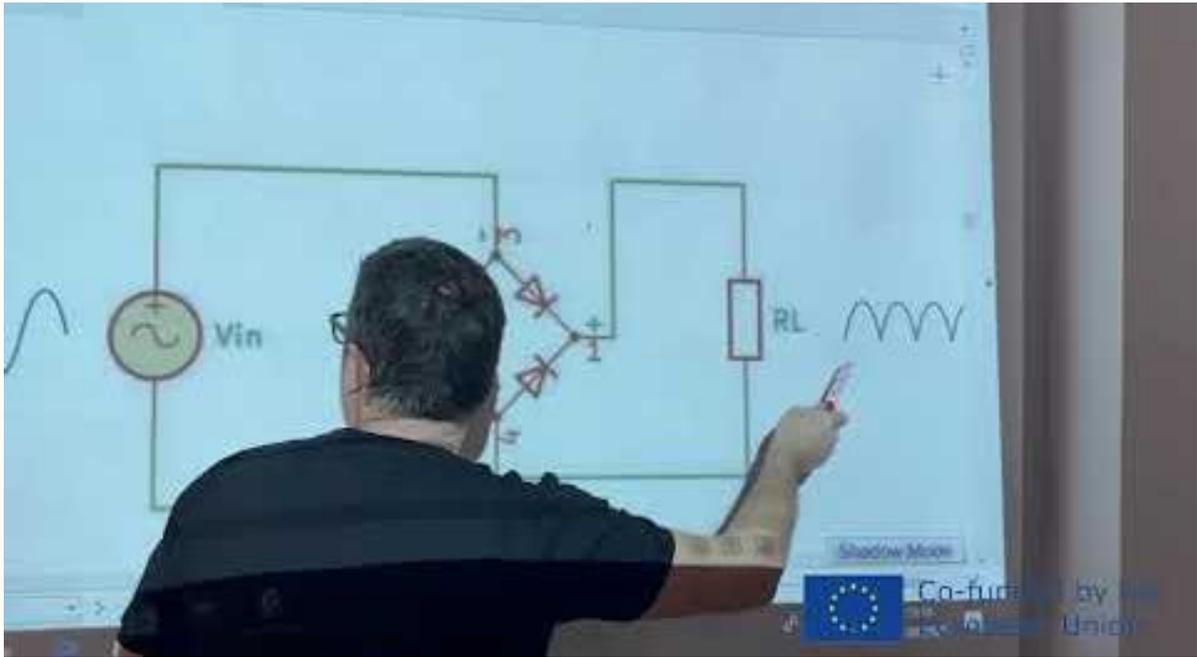


Figure 1.8: Bridge type full wave rectifier circuit



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<https://youtu.be/dCKImFLTKTY>

Rectification of three-phase alternating current is similar to the rectification circuit in the alternator, which is one of the important parts of the electrical system in conventional internal combustion engine vehicles. Full-wave rectification is performed using two diodes for each phase. By rectifying the alternating current produced with a phase difference of 120° in this way, a smoother direct current is obtained. A three-phase full-wave rectification circuit is shown in Figure 1.9. Since the generators used in hybrid and electric vehicles and the output of the electric motor operated as a generator during regenerative braking are three-phase, they are rectified with a rectification circuit similar to the circuit shown in Figure 1.9. The diodes in the switching elements in the inverters, the operation of which will be explained in the following sections, allow the inverter to operate as a three-phase rectifier during regenerative braking.

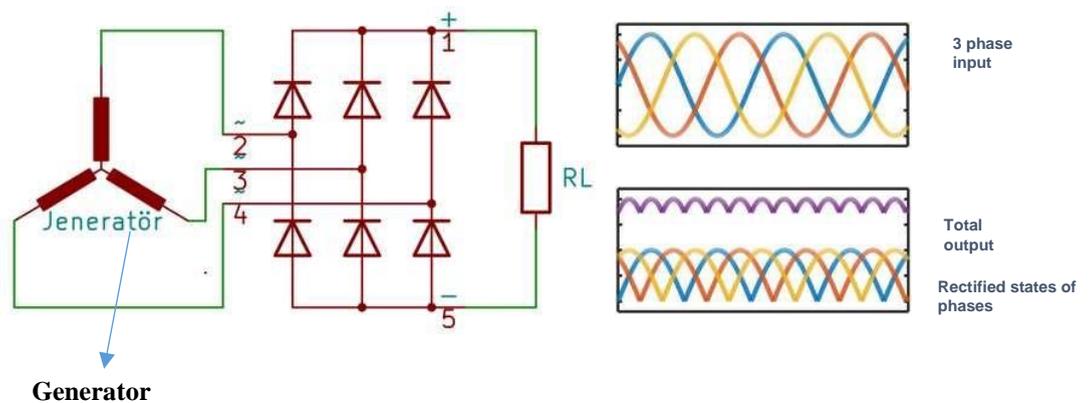
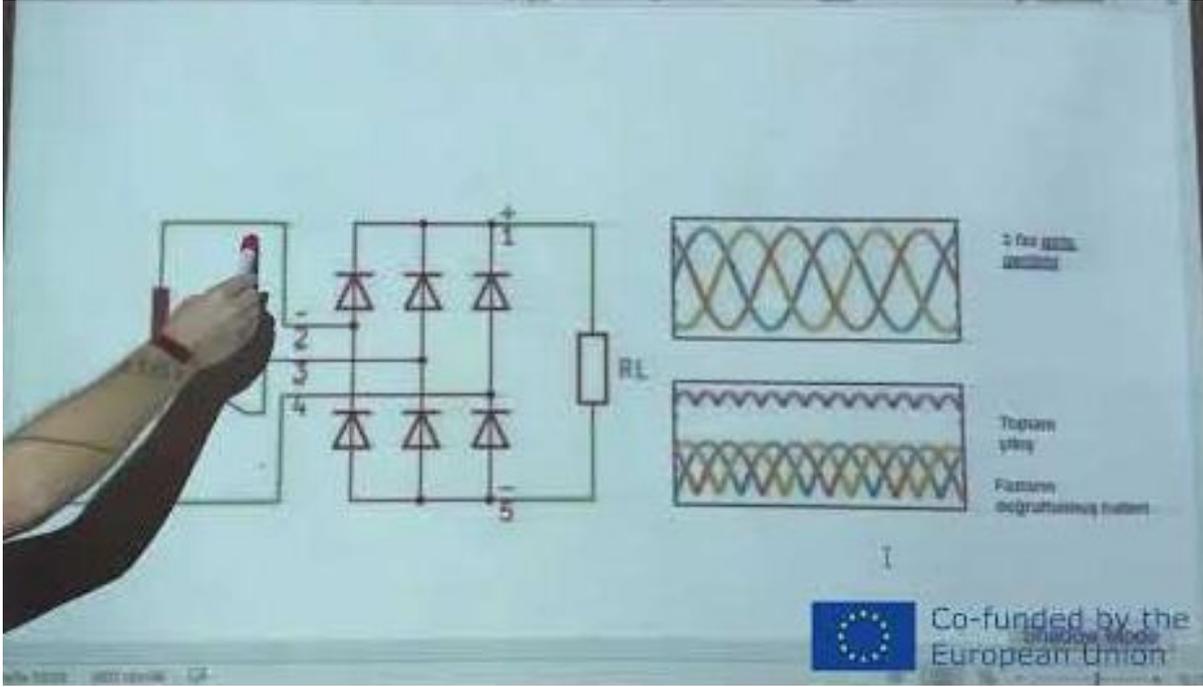
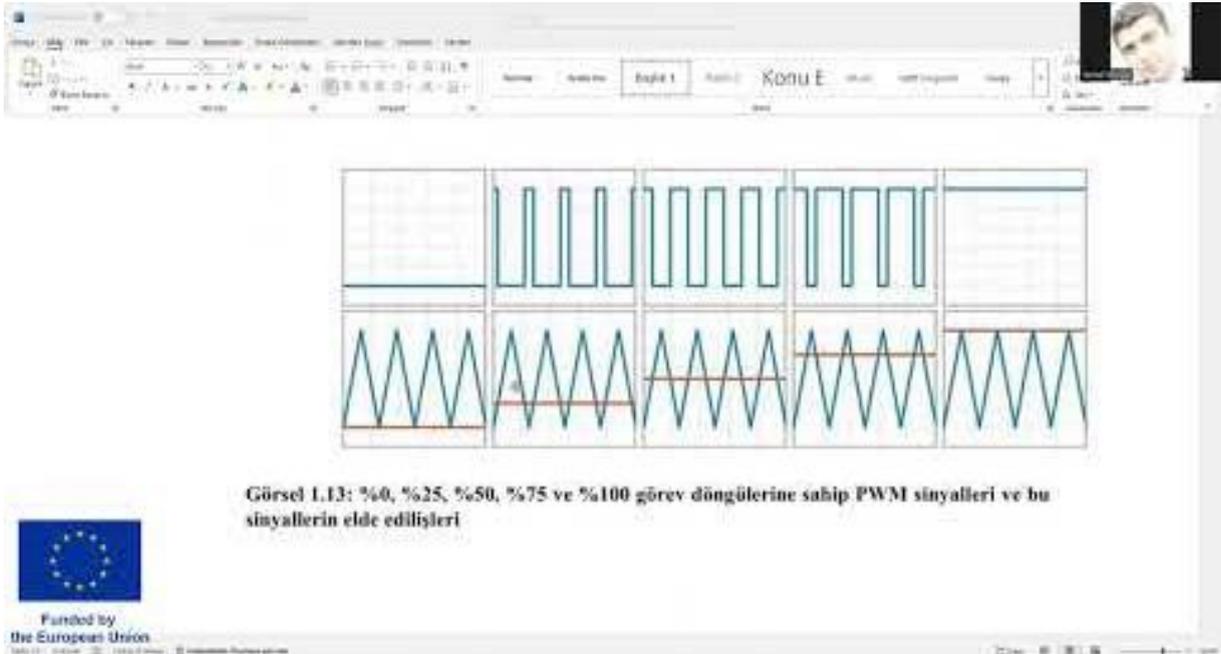


Figure 1.9: Three-phase full wave rectification process



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<https://youtu.be/qfnNbvJvZk4>



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The images below show which diodes are in conduction according to the current directions during 3-phase rectification. In the images, the cases where current occurs between two phases in the generator windings are selected as examples. In cases where current is obtained in three windings, the number of diodes in conduction will be three.

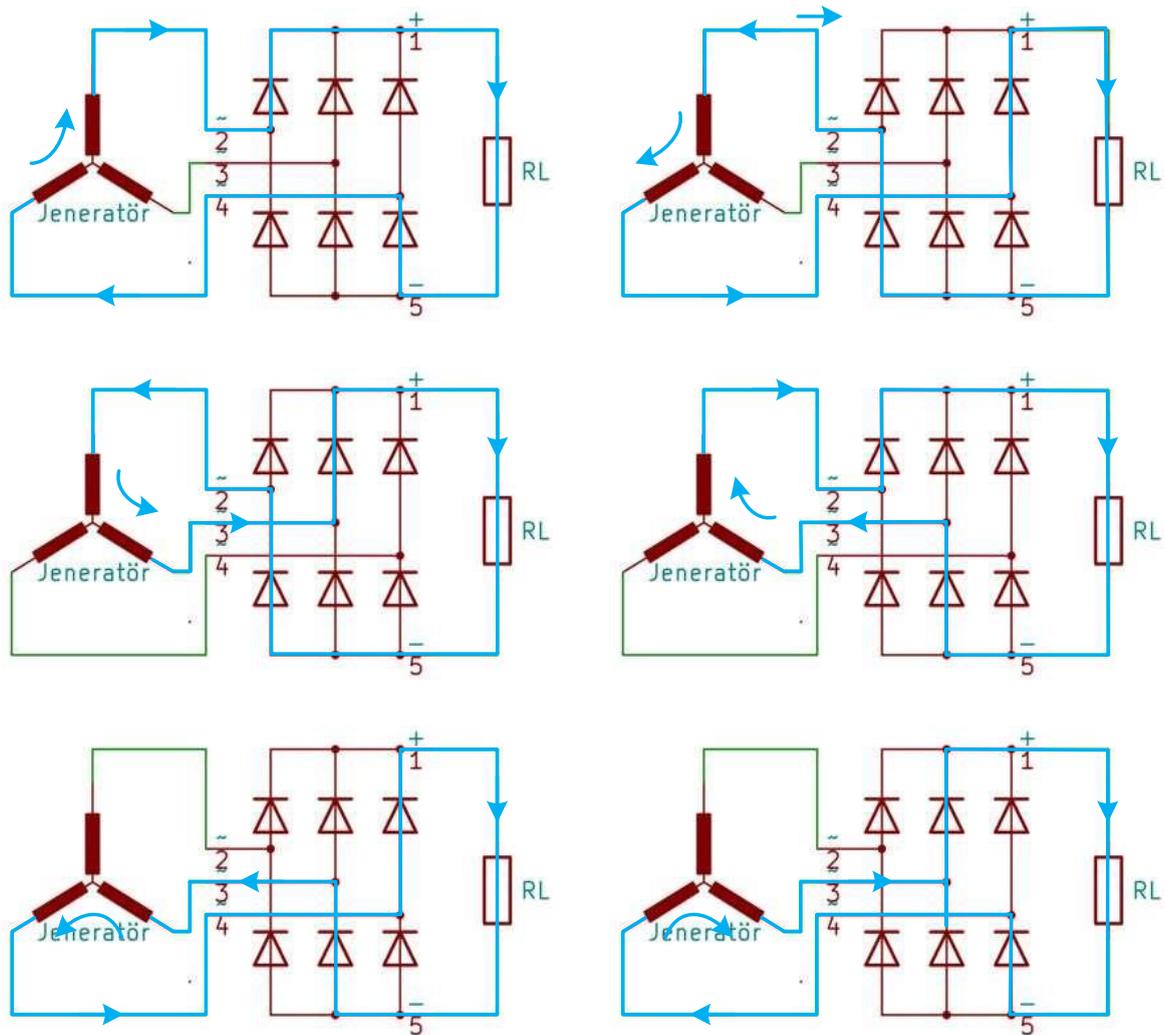


Figure 1.10: Rectification process in a three-phase rectifier circuit

The rectification process performed with the help of diodes is called uncontrolled rectification. In addition to the uncontrolled rectifier circuits explained above, there are also circuits that allow controlled rectification. The controlled rectification process allows rectification to be adjusted according to the load status. In hybrid and electric vehicles, inverters that provide the 3-phase alternating current required to operate the electric motor from direct current can also be operated as rectifiers. Thanks to this feature of the electric motor power converter, the electric motor can be operated as a generator during the braking of the vehicle and the battery pack can be charged with the energy obtained.

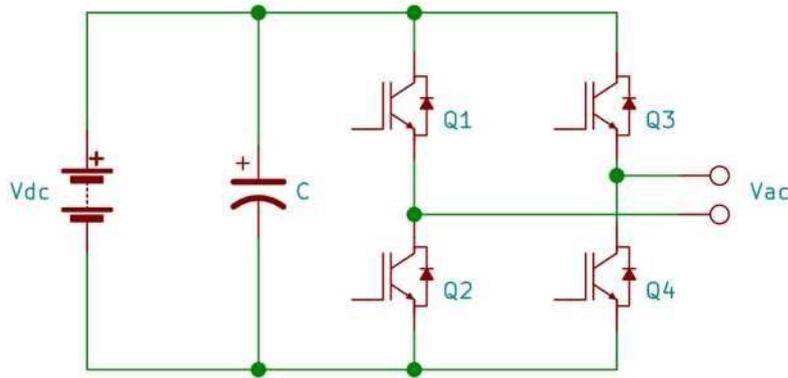
1.3. Inverters

Inverters are circuits that provide conversion from direct current to alternating current. While there is a one-way current flow in direct current circuits, the current changes direction in

alternating current circuits. For this reason, controlled switches are needed to provide current flow in both directions through the load in order to obtain alternating current from a DC source.

1.4. How Inverters Work

In power electronic circuits, MOSFETs or IGBTs (Insulated Gate Bipolar Transistorİnsuleydit Geyt Baypolır Trenzistır) are mostly used as switching elements. Visual 1.11 shows how alternating current is obtained from a DC source. With the help of four IGBTs in the circuit, bidirectional current can be passed through the load connected to the output. For this purpose, alternating current is obtained by alternately switching the IGBTs in the cross position to conduction and isolation. Visual 1.12 shows the order in which the IGBTs are switched to conduction. When the Q1 and Q4 IGBTs are switched to conduction, the direction of the current on the load is to the right. When Q2 and Q3 are switched to conduction, the direction of the current is to the left.



Visual 1.11: Basic inverter structure

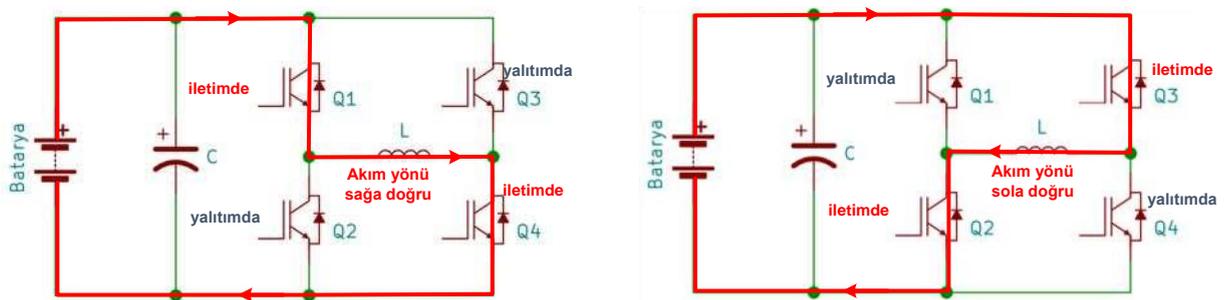


Figure 1.12: Obtaining alternating current in the basic inverter circuit

While explaining the operation of the circuit in Visual 1.11, it was explained above that the Q1-Q4 and Q2-Q3 IGBTs were switched on sequentially. As a result of this process, the current passing through the load will be rectangular. However, in reality, the alternating current is in the form of a sine wave. Therefore, a control is needed that will ensure that the current passing

through the load is in the form of a sine wave. This process is achieved by switching the switching elements to be switched on at high frequencies and variable conduction-isolation ratios. This process is called pulse width modulation. Pulse width modulation is not a control used only in inverters, but is also applied in other areas of power electronics and areas other than power electronics.

• Pulse Width Modulation

Pulse Width Modulation (PWM) is the process of changing the 1 and 0 periods of a square wave signal at a certain frequency according to a certain order. Pulse width modulation is used in power electronics and electronic communication systems. In pulse width modulation, the ratio of the period when the signal is 1 to the total period is expressed as the duty cycle. For example, a 25% duty cycle indicates that the 1 period is one-fourth of the total period, a 50% duty cycle indicates that the 1 and 0 periods are equal, and a 75% duty cycle indicates that three-fourths of the total period is 1. A duty cycle of 0% means that the signal is completely 0, and 100% means that it is completely 1. The sample PWM signals specified are seen in Figure 1.13.

0% Duty Cycle %25 Duty Cycle %50 Duty Cycle %75 Duty Cycle %100 Duty Cycle

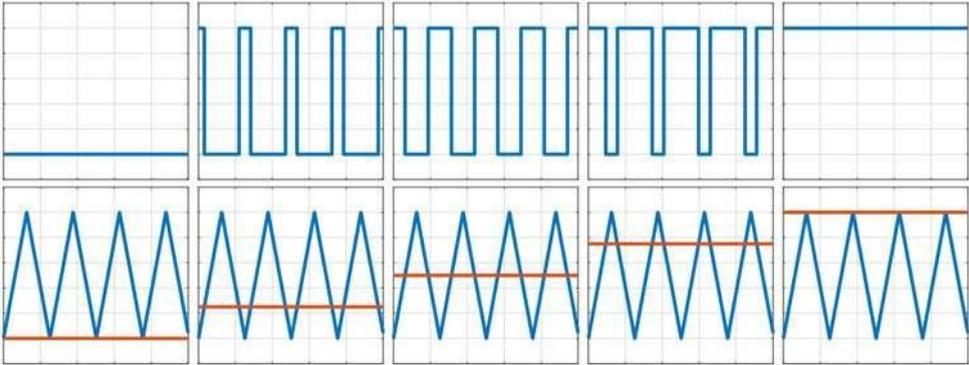


Figure 1.13: PWM signals with duty cycles of 0%, 25%, 50%, 75% and 100% and how these signals are obtained.

In the pulse width modulation control performed to ensure that the current at the output of an inverter is in the form of a sine wave, the duty cycle must be changed by taking into account the amplitude of the sine wave. One of the methods applied to produce pulses with a variable duty cycle in question is to compare the sine wave with a triangle wave signal of a certain frequency. This process is seen in Figure 1.14. The pulse width modulation signal obtained from the reference sine wave is performed by the microcontroller that controls the switching elements in the inverter. If the sine wave amplitude value is greater than the triangle wave amplitude value, the relevant PWM output is made 1 (5 V), otherwise 0. The PWM signals obtained at the output for the positive and negative alternations of the sine wave are shown as

two different levels. In reality, the PWM signals produced are not at two different levels, but are applied to different switching elements. This situation arises from the fact that the switching elements to be PWM controlled in the positive alternation and the switching elements to be controlled in the negative alternation are different. In the circuit given in Visual 1.11, the PWM signal generated for the positive alternation of the signal is applied to the Q1 and Q4 IGBTs, and the PWM signal generated for the negative alternation is applied to the Q2 and Q3 IGBTs.

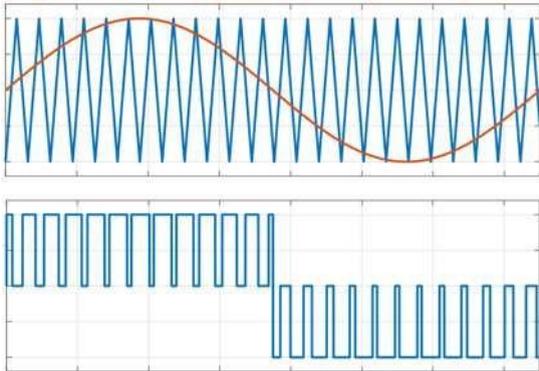


Figure 1.14: Obtaining the PWM control signal suitable for the sine wave

In order to operate a three-phase electric motor using a direct current source, the basic process that needs to be done is to provide current to the phases of the motor at the appropriate timing and in the appropriate direction with the help of switching elements. In hybrid and electric vehicles, inverters used to drive the drive motor are called drive inverters. In hybrid and electric vehicles, the high-voltage battery pack output can be connected directly to the inverter, or it can be connected by fixing the voltage to a certain value with the help of a DC-DC converter. In order to reduce the fluctuations caused by the switches in inverters, a large-capacity capacitor can be connected to the direct current side of the circuit. The basic structure of an inverter consisting of IGBTs for a 3-phase electric motor is shown in Figure 1.15.

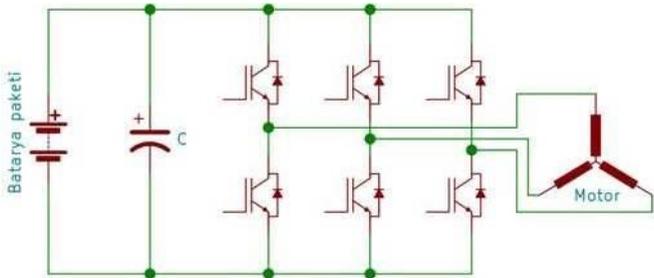


Figure 1.15: Basic structure of a three-phase motor inverter

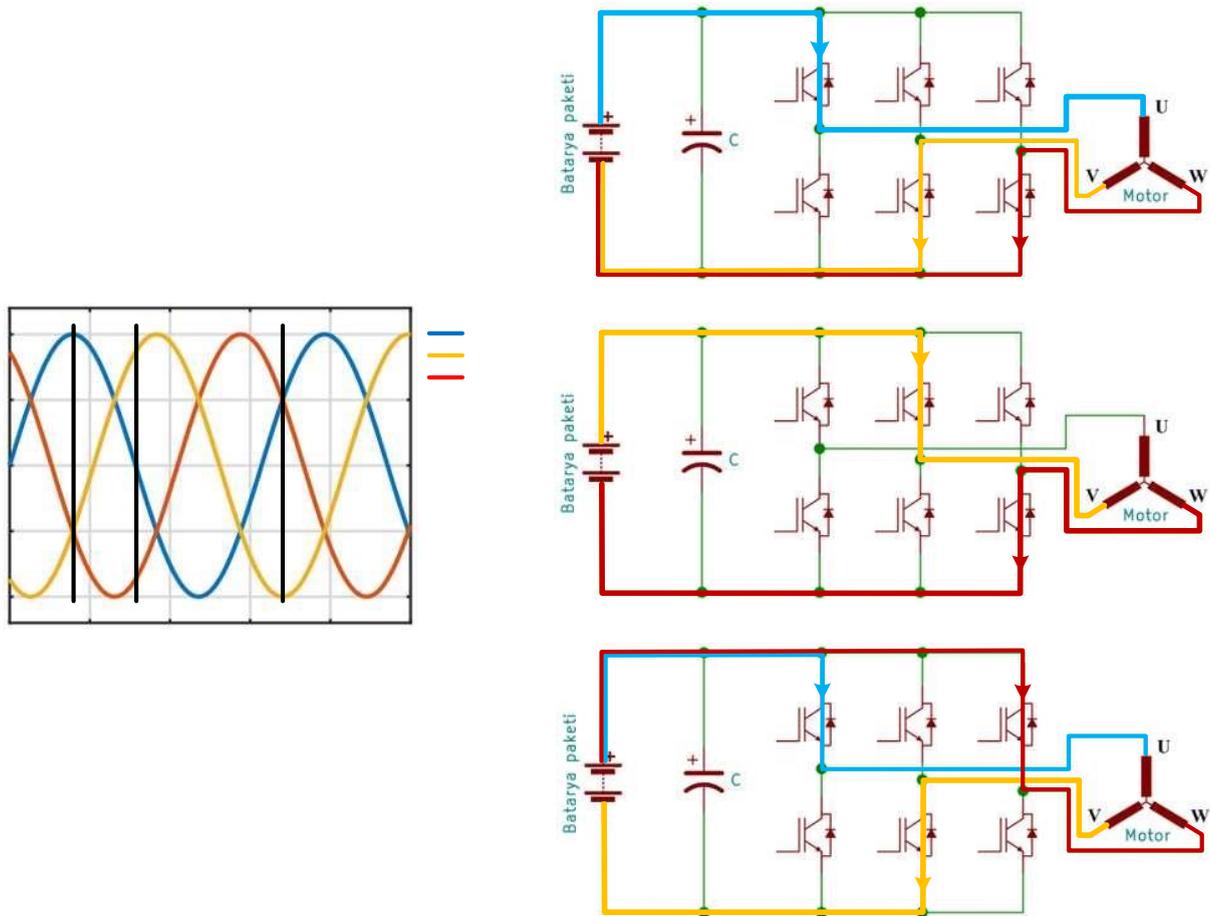


Figure 1.16: Current directions in three-phase motor windings at different moments.

In Visual 1.16, the current directions passing through the three-phase motor windings at the moments indicated by lines a, b and c on the sample signal are shown. At the moment indicated by a, the current passing through the U winding is at a positive maximum value, while the current passing through the V and W windings are equal and negative. At moment b, the current of the V winding is at a positive maximum, the current of the W winding is at a negative maximum, and the current of the U winding is zero. At moment c, the current of the U and W windings is positive and equal, while the current of the V winding is at a negative maximum. The intensity of the currents passing through the windings is provided by PWM control as explained above. When the currents passing through the windings are examined graphically, it is seen that the sum of the incoming current or currents is equal to the sum of the outgoing current or currents. After explaining the basic structures of inverters, visuals of sample inverters used in hybrid and electric vehicles are given in this section. In Visual 1.17, the power control unit used in a 2010 model compact class (C segment) hybrid vehicle is seen.

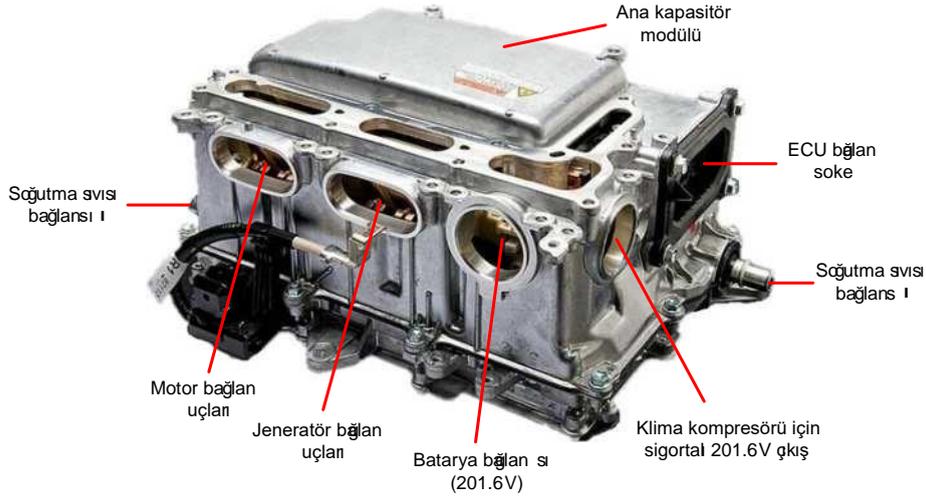
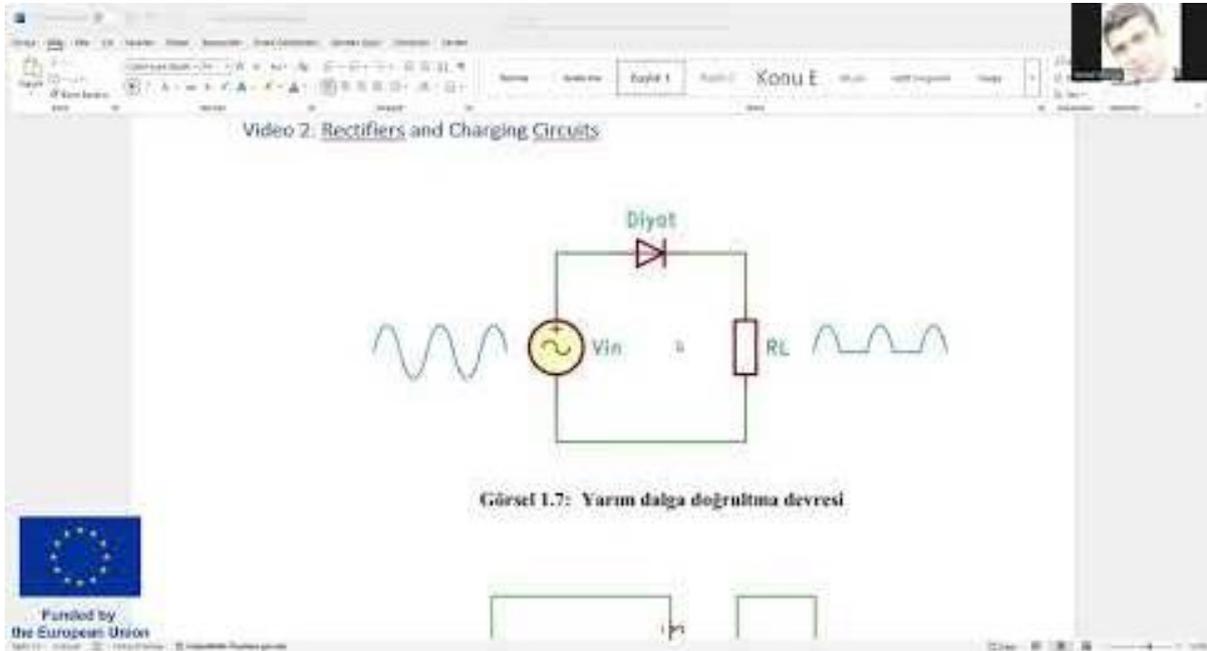


Figure 1.17: Traction inverter used in a hybrid vehicle



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The unit includes an inverter, a booster DC-DC converter, and a step-down DC-DC converter. The inverter converts the direct current provided by the battery into the alternating current required to move the motor/generator.

It also converts the alternating current produced by the motor/generator into direct current. The booster DC-DC converter increases the battery voltage from 201.6 V to 650 V, which is the voltage required for the electric motor/generator. The step-down DC-DC converter provides the required voltage for systems operating with 12 V from 201.6 V.

The electric motors used in hybrid and electric vehicles operate with alternating current and are three-phase. It is also possible to operate the electric motors as a generator when necessary. By operating the electric motors as generators during braking, energy can be stored while the vehicle is slowing down. The electric motor can provide the necessary driving force when desired and operate as a generator when desired by operating the inverter in both directions.



Figure 1.18: Drive inverter in an all-electric vehicle

1.5. DC-DC Converters

DC-DC converters are used to convert a certain level of DC voltage to a different level. In electric or hybrid electric vehicles, DC-DC converters are used for purposes such as increasing the battery voltage to a certain level and providing the necessary voltage for auxiliary units in the vehicle. In some applications, converters that perform bidirectional DC-DC conversion are also used. DC-DC converters can be step-down type, step-up type, or both step-down and step-up type. There are many different topologies in DC-DC converter circuits. Detailed information about DC-DC converter topologies can be obtained from relevant sources. DC-DC converters are generally divided into two groups as insulated and non-insulated. Non-insulated DC-DC converters are generally used in medium and high power applications in vehicles. Among non-insulated DC-DC converters, traditional step-up converters and creeper step-up converters are mostly used in electric or hybrid electric vehicle power systems due to their simple structures, low cost, and easier controllability. Visual 1.19 shows the basic circuit structure of the power control unit used in a Class C hybrid vehicle. The voltage (201.6 V) received from the high-voltage battery pack is increased (500 V) to the inverter by a DC-DC converter. The switching elements (IGBT) in the inverter are operated in a certain order by the control circuit so that the motor can be moved appropriately, as explained above. During regenerative braking, the DC-DC converter reduces the high voltage generated by the motor/generator and converted to DC

by the diodes in the inverter to the appropriate voltage to charge the battery. In this case, it can be said that the DC-DC converter performs bidirectional conversion.



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1.6. Operation of DC-DC Converters

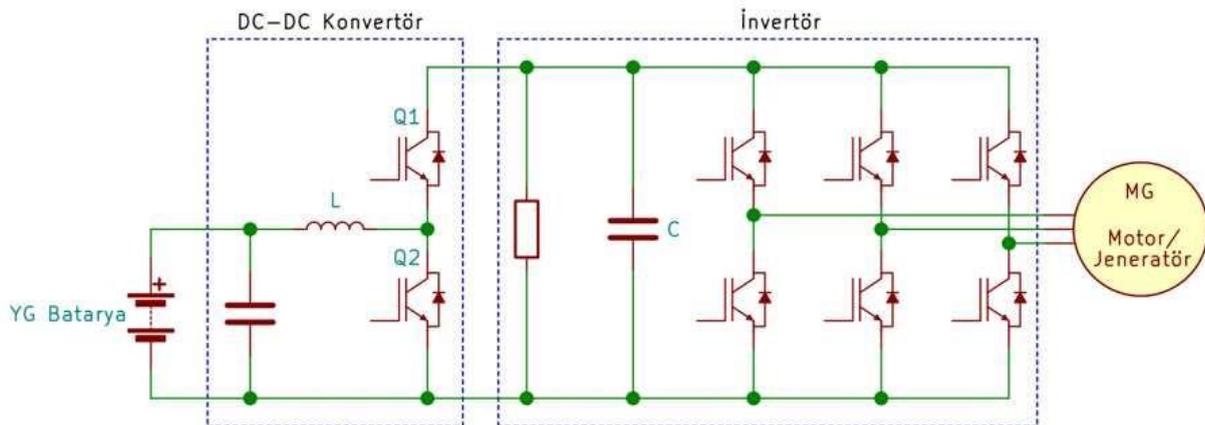


Figure 1.19: Circuit diagram of a bidirectional DC-DC converter

The operation of the DC-DC converter given in Visual 1.19 is explained in the following visuals. The DC-DC converter works as a booster when the battery voltage is increased to the level required for the inverter, and as a reducer when the regenerative braking energy is used to charge the battery. The operation of the booster DC-DC converter is as follows:

- Q2 is switched to conduction and current begins to flow through the L coil.

- In this case, the voltage on the Q2 collector is lower than the HV battery voltage.
- Energy is stored in the L coil while Q2 is conducting.
- By isolating Q2, the sum of the HV battery voltage and the voltage on the L coil is transferred to the converter output via the diode in Q1. Thus, the converter output voltage is ensured to be higher than the input voltage.
- The capacitor (C) in the inverter is also charged at this stage.
- The capacitor meets the voltage requirement during the stage when Q2 is in conduction again.
- During the increase of the battery voltage of Q2, the above-described conduction and isolation process is repeated continuously. This process is carried out at high speeds (for example, 10 kHz in a C segment vehicle).
- The output voltage is adjusted by changing the conduction time of Q2.
- In the booster operation, Q1 is completely disabled.

The operation of the booster DC-DC converter described above is seen in Visual 1.20.

During regenerative braking, the voltage rectified in the inverter must be reduced to a suitable level to charge the battery. For this purpose, the DC-DC converter is operated in the reverse direction. During this operation, the Q2 IGBT is completely disabled. The converter is operated by switching the Q1 IGBT to high-frequency conduction and isolation. The operation of the step-down DC-DC converter is as follows:

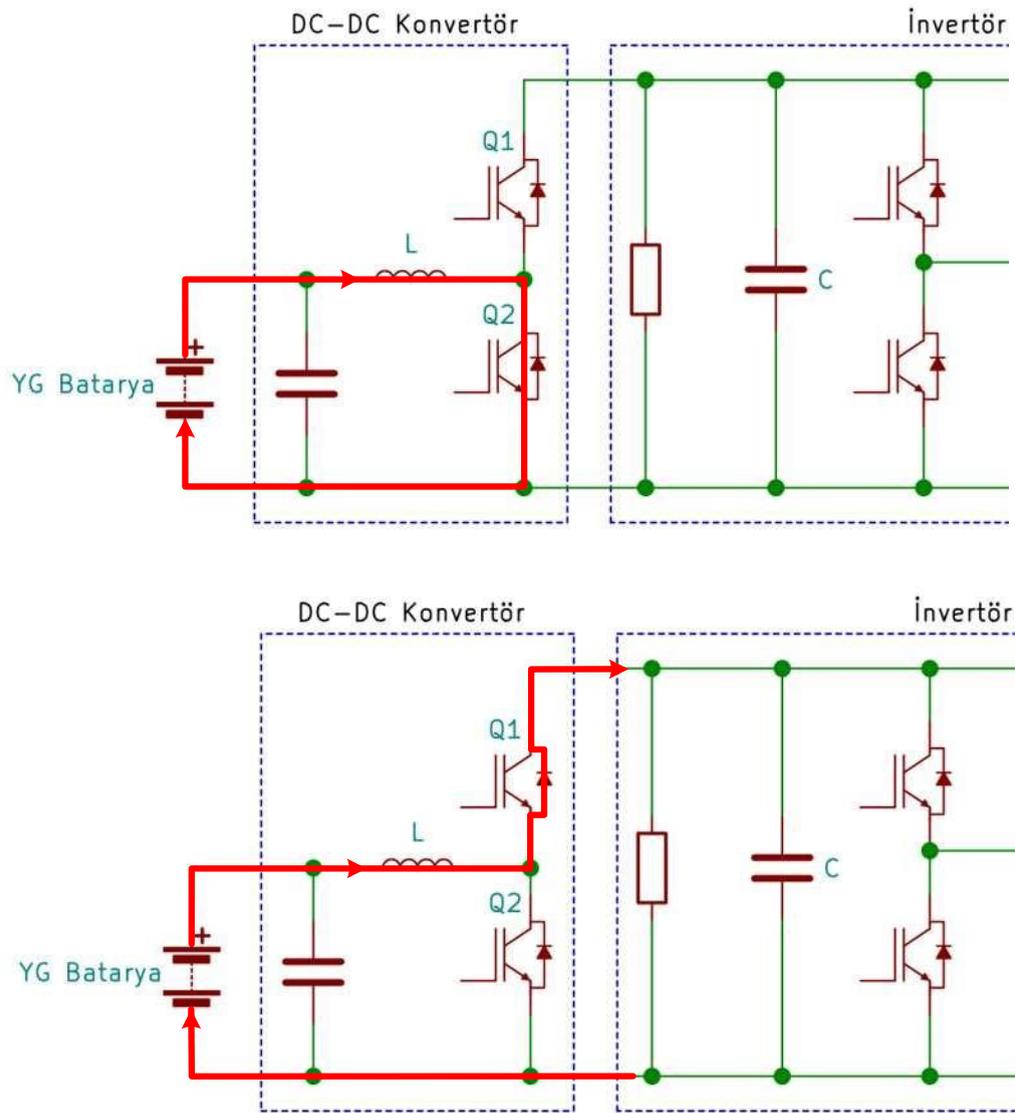
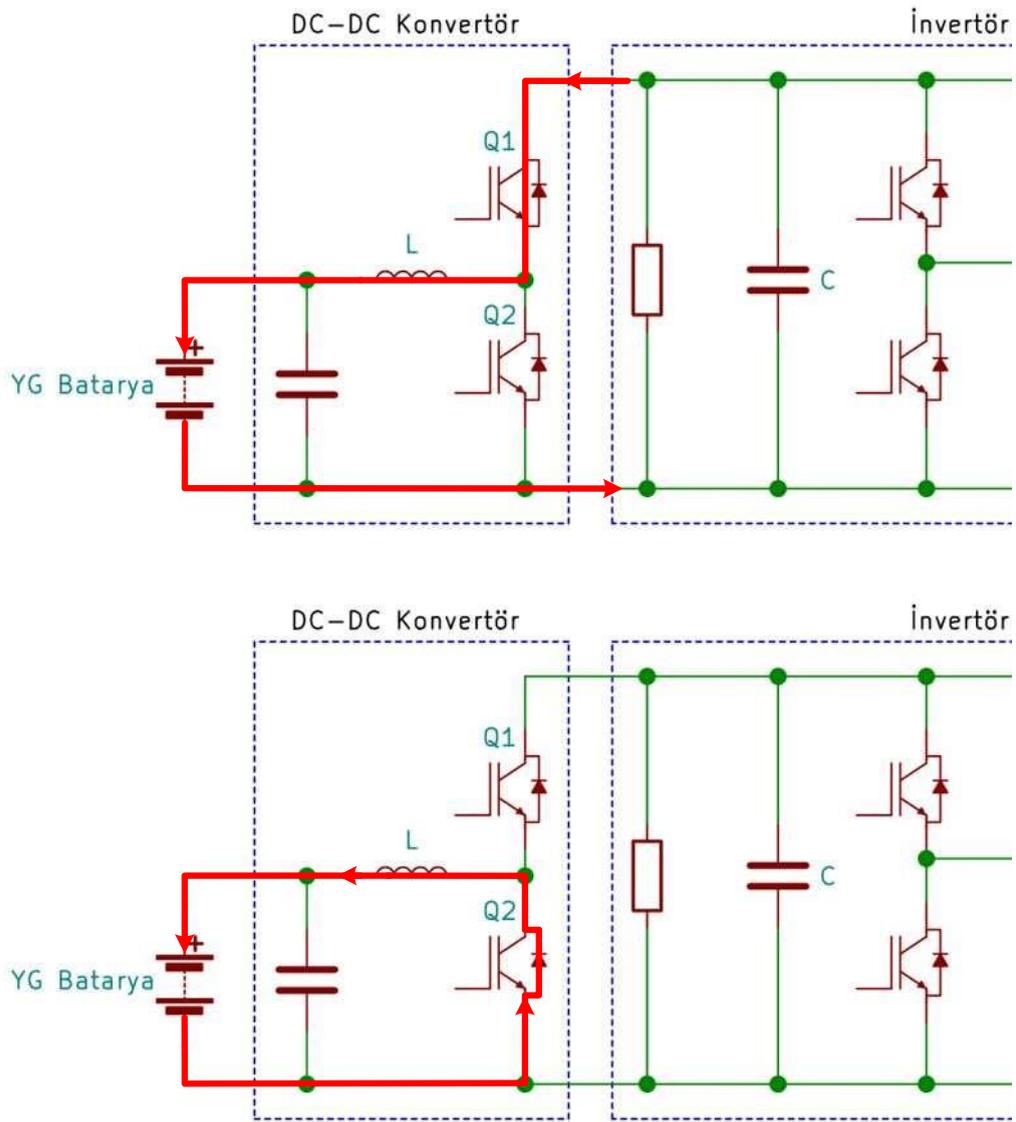


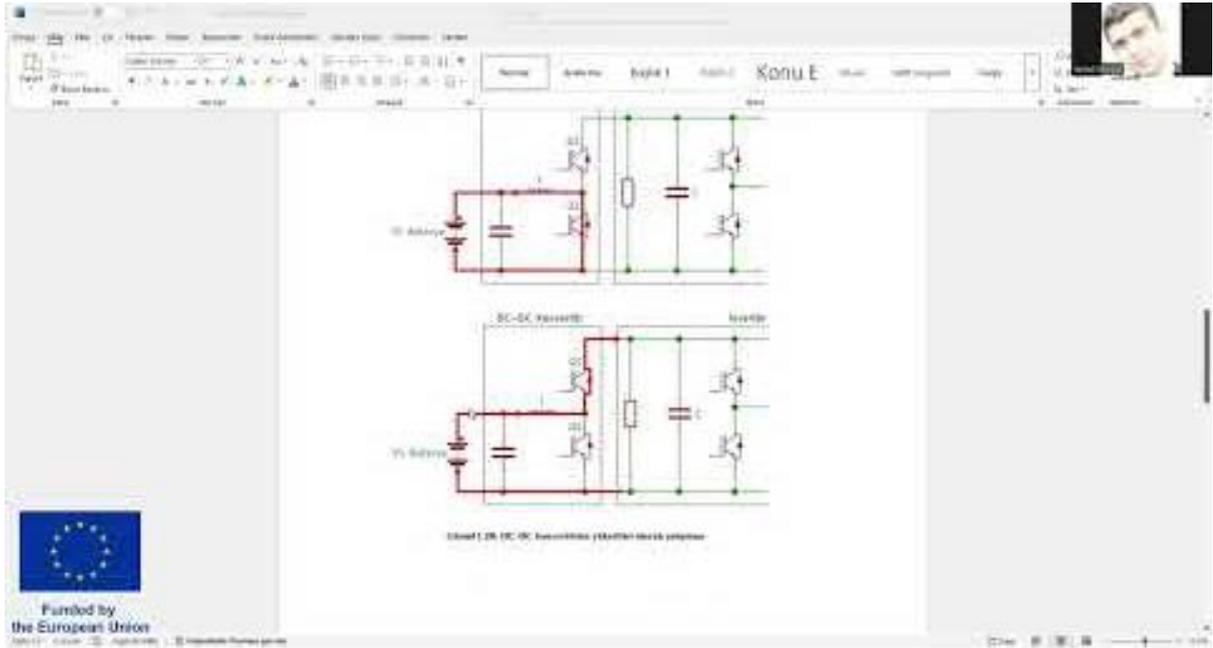
Figure 1.20: DC-DC converter working as a booster

- By completely disabling the Q2 IGBT in the circuit and applying PWM control to the Q1 IGBT, a step-down DC-DC converter is obtained.
- Q1 is switched to conduction and energy is stored in the L coil.
- When Q1 is switched to isolation, the L coil continues its current through the diode in Q2.
- The process of switching Q1 to conduction and isolation is repeated at high speeds.
- In step-down operation, the voltage value applied to the battery from the DC-DC converter is adjusted by changing the duration of Q1 remaining in conduction.

The operation of the step-down DC-DC converter explained above is seen in Visual 1.21.



Visual 1.21: Operation of step-down DC-DC converter



To play the video, [click on the image](#) or [click the link below](#) and open it with your browser.

<https://youtu.be/YAbg13gjPQE>



Figure 1.22: DC-DC converter used in an electric vehicle

Visual 1.22 shows the step-down DC-DC converter that provides the necessary voltage for auxiliary units operating with 12 V in hybrid and electric vehicles. The DC-DC converter in question basically takes on the same function as the alternator in conventional vehicles. The features of the DC-DC converter in Visual 1.22 are as follows:

- Input voltage: 260-420 V DC
- Output voltage: 11-15.5 V DC
- Output current: 135 A
- Output power: 2000 W



Figure 1.23: DC-DC converter used in a high-end all-electric vehicle

Figure 1.23 shows a DC-DC converter used in a high-end all-electric vehicle. Unlike the DC-DC converter seen in Figure 1.22, this converter is cooled with liquid. The features of the DC-DC converter seen in Figure 1.23 are as follows:

- Input voltage and current: 220-430 V, DC 15 A (maximum)
- Output voltage: 9-16 V DC
- Output power: 2500 W

2. COOLING IN ELECTRIC MACHINES

All parts in a machine heat up because they are in contact with each other and work by rubbing against each other. The heat generated needs to be cooled down so that it does not damage the machine over time. For this reason, the cooling system is very important.

2.1. Functions of the Cooling System

The main function of the cooling system is to reduce the high temperature caused by friction in the machine to ideal working conditions and to ensure that the machine reaches ideal working conditions in cold weather conditions.

2.2. Types of Cooling Systems

Cooling systems are generally examined under two headings. These are air-cooled systems and liquid-cooled systems. Liquid-cooled systems are divided into two as water cooling and oil cooling. Cooling systems used in electrical machines are generally water-cooled systems.

2.2.1. Air Cooled Systems

Air-cooled systems are generally used in motorcycle engines, wood saw engines, lawn mowers or machines that require less power, such as generators, because they have lower efficiency than liquid-cooled systems. An air-cooled system is shown in Figure 2.1.

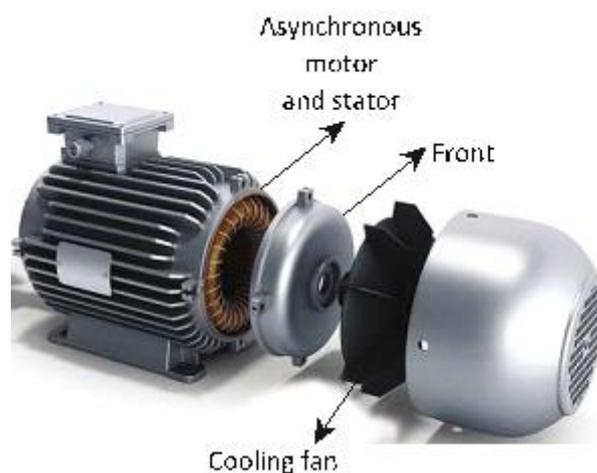


Figure 2.1: Air-cooled system

2.2.2. Liquid Cooled Systems

Liquid-cooled systems are more efficient than air-cooled systems in terms of performance and are the systems used in the vast majority of vehicles today.

2.2.2.1. Oil Cooled Systems

The use of oil in active cooling is not a method commonly used in electric motors. In this method, the oil is adjusted to a certain level of the rotor, circulated through the cooling channels in the body with the help of a pump, and cooling is provided by taking the heat from the windings and transferring it to the outside environment through a radiator. The oil-cooled system is shown in Visual 2.2. Then, the oil cooled in the oil block is pressed into the system again by the oil pump. In the meantime, the parts in the interior that need lubrication are also lubricated, and there is no need for external lubrication.

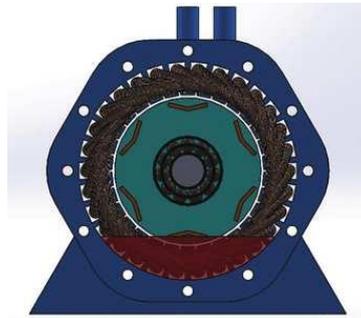


Figure 8.2: Oil cooling system

2.2.2.2. Water Cooled Systems

The most commonly used system today is water-cooled systems. In water-cooled systems, especially in winter months, there is a risk of water freezing, so the freezing temperature of the water placed in the radiator is reduced by using antifreeze or an antifreeze-water mixture. Even when the air temperature drops below zero, it is protected against cold weather and the water does not freeze.

Water is circulated in the channels inside the body where the stators are placed, removing the high heat caused by friction between the rotor and the stator. The water-cooled system is shown in Visual 2.3.

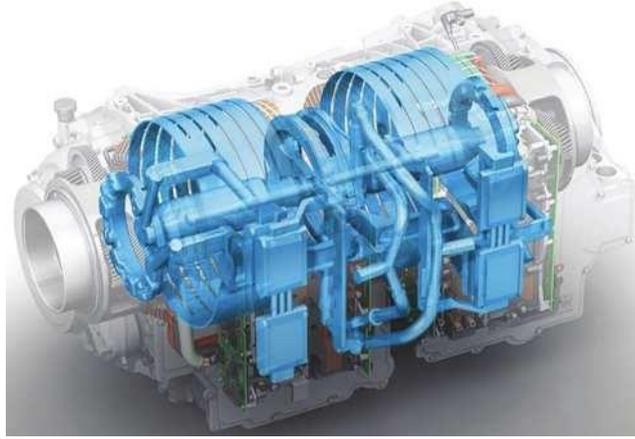


Figure 8.3: Water-cooled system

2.3. Parts of the Cooling System

System components consist of radiator, water pump, cooling fan, expansion tank, cooling water and pipes. Cooling system components are shown in Visual 2.4.

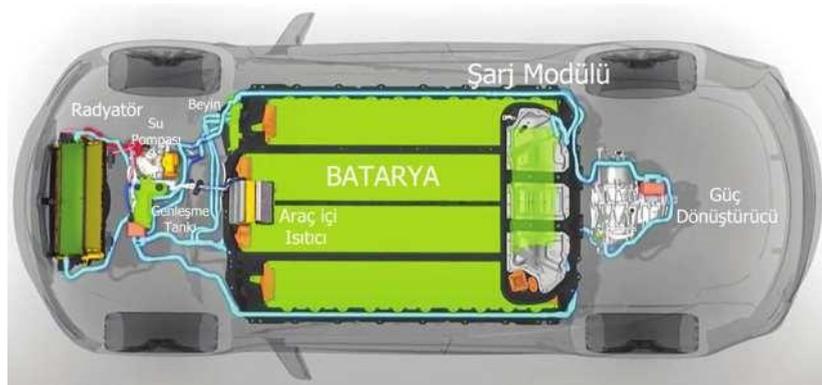


Image 2.4: Cooling system parts

2.3.1. Radiator

The engine cools the water inside by using the vehicle's own kinetic energy and the thin honeycombs made of aluminum on it, by storing the cooling water. The radiator and cooling fan are shown in Figure 2.5.



Image 2.5: Radiator and cooling fan

2.3.2. Water Pump

It is the part that sends the cooled water in the radiator to the system under pressure and ensures that the heated water in the system comes to the radiator to cool. The water pump is shown in Visual 2.6.



Image 8.6: Water pump

2.3.3. Cooling Fan

It is the fan that creates air circulation to cool the heated water inside the radiator. The radiator and cooling fan are shown in Visual 2.5.

2.3.4. Expansion Tank

As the temperature of the cooling water in the system increases, the volume of the heated water also increases. The expansion vessel is placed in the system because a container is needed where this water will expand to a certain height and contract again during cooling. The expansion vessel is shown in Figure 2.7.



Figure 2.7: Expansion vessel

2.4. Cooling System Operation

The refrigerant cycle within the system circulates (completely circulates) as shown in Figure 2.8.

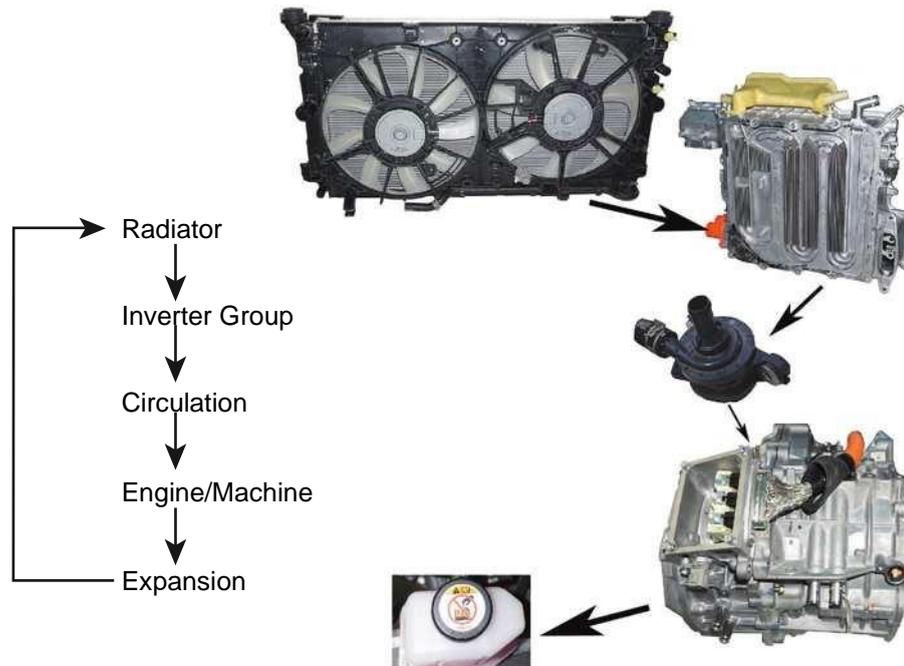
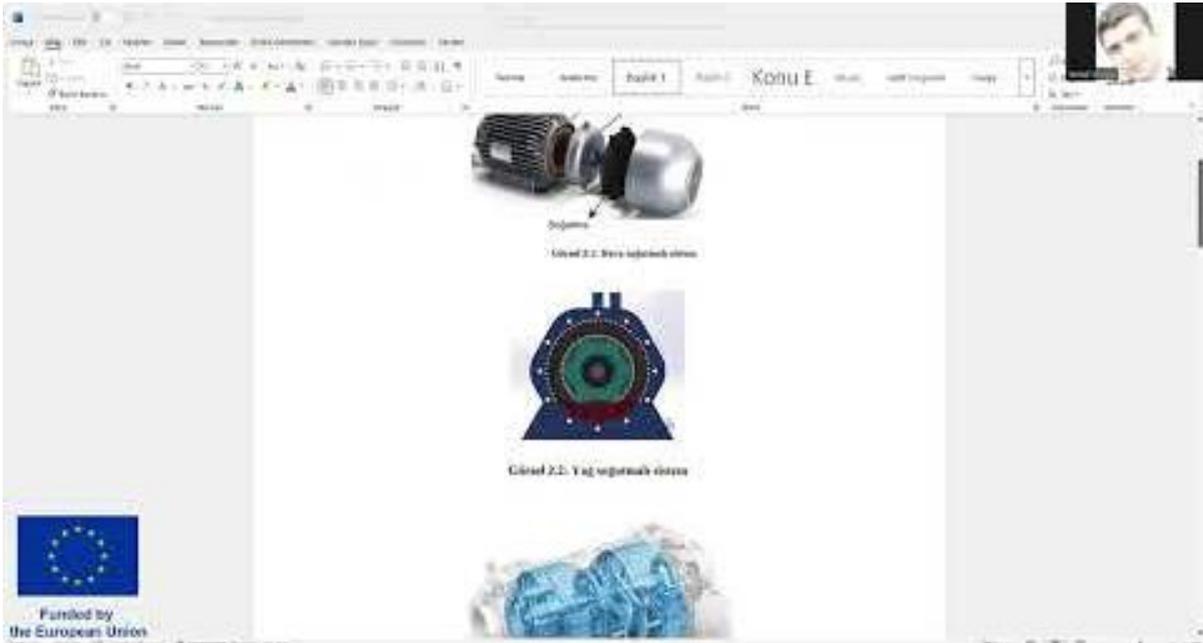
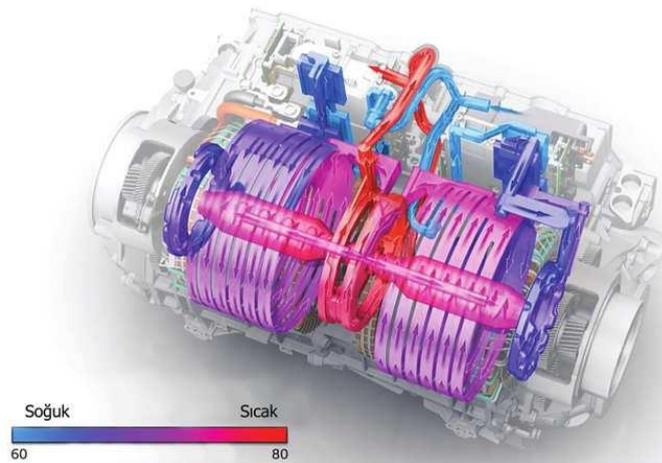


Figure 2.8: Refrigerant cycle



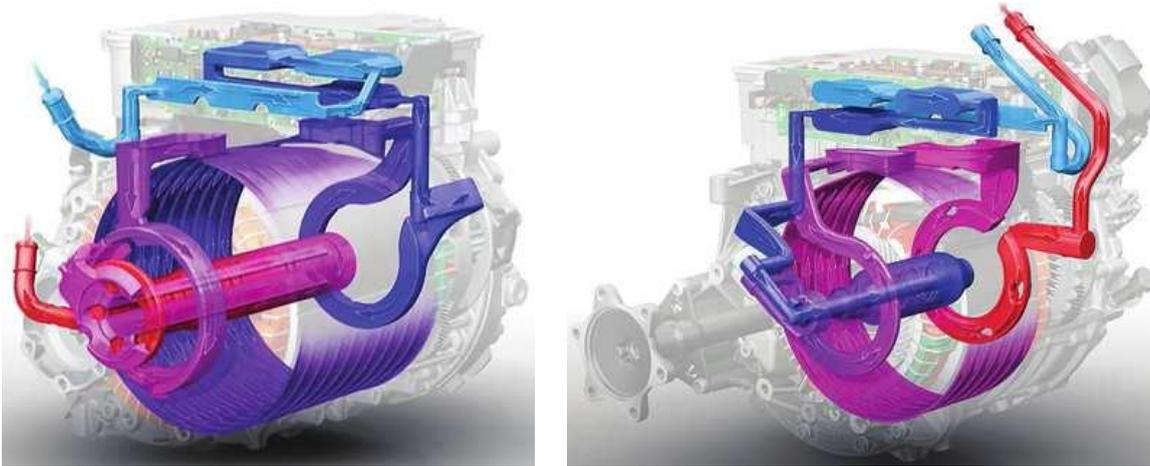
To play the video, click on the image or click the link below and open it with your browser.
https://youtu.be/9j_IMIR2ooA

Water enters from the top of the radiator and is cooled by the cooling fan as it flows down between the aluminum plates. The cooled water exits from the bottom of the radiator through pipes, is drawn by the water pump and is pumped back into the system through the pipes. Water circulation in the water-cooled system is shown in Visual 2.9.



Visual 2.9: Water circulation in water-cooled system

Water first circulates through the aluminum cooling fins of the inverter-converter group and moves towards the cooling channels around the stator in the body of the motor. Water circulations in water-cooled systems are shown in Visual 2.10 and Visual 2.11.



Visual 2.10 – Visual 2.11: Water circulation in water-cooled system

The inner part of the rotor shaft is equipped with water channels, and the rotor is aimed to cool down faster. Visual 2.12 shows the water flow inside the rotor of the water-cooled system. The high heat generated in the rotor and stator is transferred to the water, thus cooling the rotor and stator. In the meantime, the water heats up, and after the heated water leaves the channels around the stator, it enters the radiator from the top of the radiator through the pipes and is cooled again.

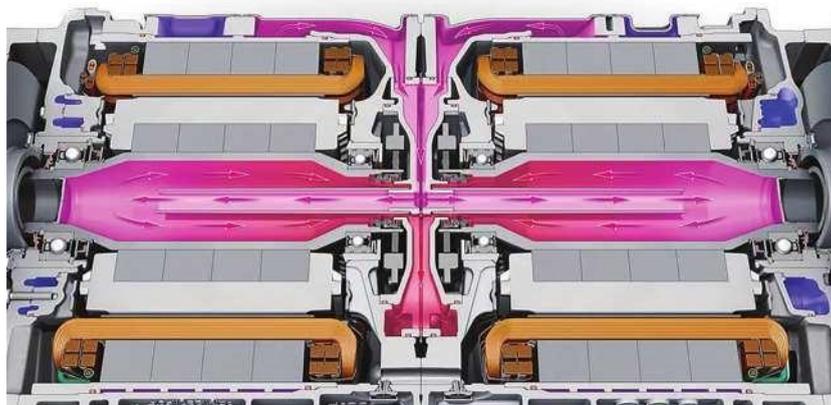


Figure 2.12: Water flow inside the rotor of the water-cooled system

REFERENCES

Agamloh, E., von Jouanne, A., & Yokochi, A. (2020). An overview of electric machine trends in modern electric vehicles. *Machines*, 8(2), 20.

Aydın, E. (2014). Minimization of torque ripples of buried permanent magnet synchronous motors (Master's thesis). Gazi University, Institute of Science, Ankara.

Başer, E. (2016). Development of a motor selection algorithm suitable for road conditions in electric vehicles (Master's thesis). Duzce University, Institute of Science, Düzce.

Chakraborty, S., Vu, H. N., Hasan, M. M., Tran, D. D., Baghdadi, M., & Hegazy, O. (2019). DC–DC converter topologies for electric vehicles, plug-in hybrid electric vehicles and fast charging stations: State of the art and future trends. *Energies*, 12(8).

Chan, C. C. (2007). The state of the art of electric, hybrid, and fuel cell vehicles. *Proceedings of the IEEE*, 95(4).

Çanakoğlu, A. İ., Ünsal, A., & Tunaboğlu, N. S. (2012). *Electric machines*. Anadolu University Publications.

Demirci, Y. (2010). Electric motor control in hybrid vehicles (Master's thesis). Istanbul Technical University, Institute of Science, Istanbul.