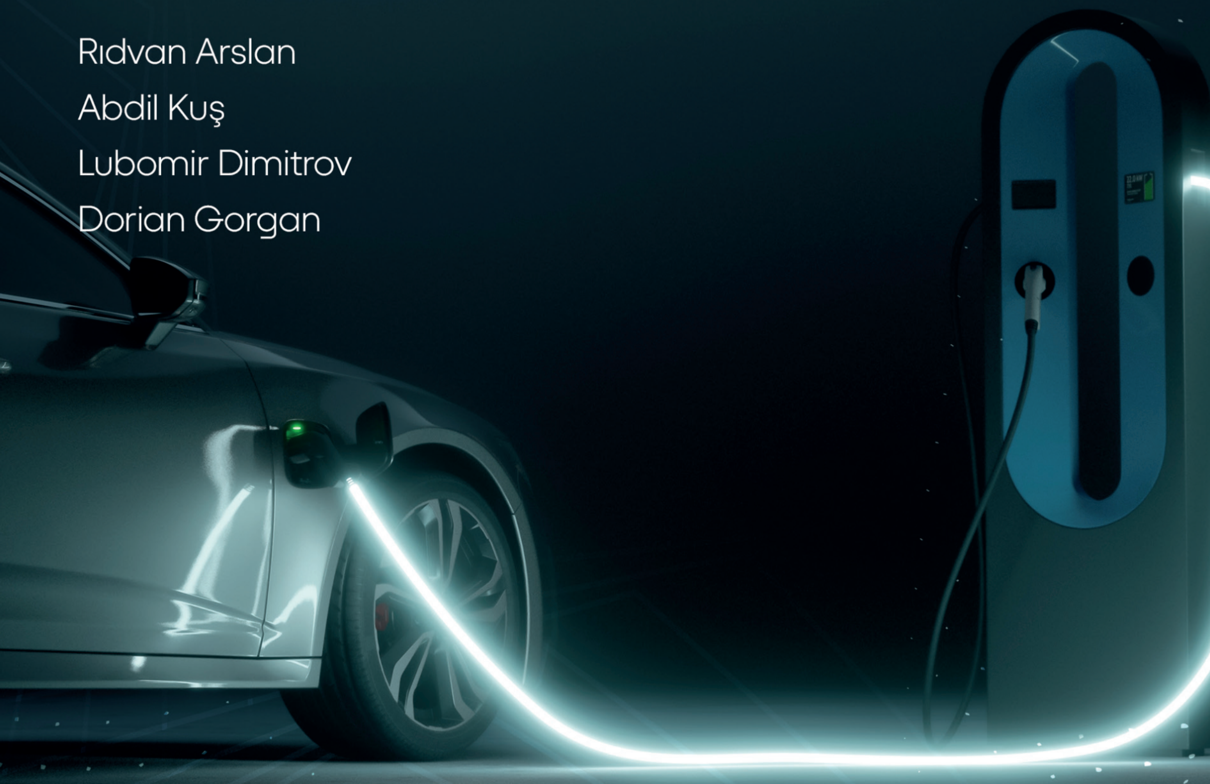
HYBRID & ELECTRIC VEHICLES TECHNOLOGY

Principles, Electronics, Diagnostic

Editors:

Rıdvan Arslan
Abdil Kuş
Lubomir Dimitrov
Dorian Gorgan



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Chapter 1-Automotive Electric and Electronics

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Chapter 2-Introduction to Hybrid and Electric Vehicles

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Chapter 3-Battery and Energy Storage Systems

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Chapter 4-Diagnostics in Hybrid and Electric Vehicles

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CONTENT

CHAPTER 1
Automotive Electric And Electronics

CHAPTER 2
Introduction to Hybrid and Electric Vehicles

CHAPTER 3
Battery and Energy Storage Systems

CHAPTER 4
Diagnostics in Hybrid and Electric Vehicles

ABBREVIATIONS

ABS : Anti-Lock Braking System
ADAS : Advanced Driver Assistance Systems
ADC : Analog-to-Digital Converters,
BEV : Battery electric vehicle
BMS : Battery Management System
BTMS : Battery Thermal Management Systems
CAN : Controller Area Network
CPU : Central Processing Unit
DAC : Digital-to-Analog Converters
DLC : Diagnostic Link Connector
DTC : Diagnostic Trouble Codes
EPS : Electric Power Steering
ESC : Electronic Stability Control
ECU : Electronic Control Unit
EMS : Energy Management Systems
EV : Electric Vehicle
GNNS : Global Navigation Satellite System
HV : High-Voltage
HEV : Hybrid Electric Vehicle
HVAC : Heating, Ventilation and Air Conditioning
ICE : Internal Combustion Engines
TPMS : Tire Pressure Monitoring System
PHEV : Plug-in Hybrid Electric Vehicles
REESS : Rechargeable Electrical Energy Storage System
REEV : Range Extended Electric Vehicle
UDS : Unified Diagnostic Services
OBC : On-Board Charger
OBD : On-Board Diagnostics

PREFACE

Dear Readers,

This book has been prepared to address the increasing demand for specialized training in Hybrid and Electric Vehicles, whose adoption is rapidly growing worldwide. This rapid global transformation has also significantly increased the needs related to the maintenance and repair of these vehicles. As technologies advance and safety, requirements become more complex, professionals in the Hybrid and Electric Vehicle service sector must maintain up-to-date, reliable, and applicable technical knowledge.

To address this increasing training need with targeted content and innovative methods, the project "*Development of Digital Training Materials Supported by Virtual and Augmented Reality for Hybrid and Electric Vehicles*" was launched. This project is supported under the European Union Erasmus+ Program Vocational Education Strategic Partnership Projects, coordinated by Bursa Uludag University. This book serves as a complementary resource to the VR/AR applications developed within the project, parallel to the related project work, to enhance the users' learning experience. These applications can be downloaded from www.vrforev.org. Readers who use the book together with the VR/AR materials will be able to acquire more in-depth and comprehensive knowledge. In this first edition, it is also possible to access animations that can be used with the image-targeted AR application in the first chapter of the book.

Prepared in alignment with the project's content and scenarios, this book is designed not only for students in Vocational High Schools, Engineering Faculties, and Motor Vehicle Service programs but also for professionals working in repair and maintenance shops and individuals interested in automotive technologies.

We sincerely thank all the authors who contributed to the chapters of the book. We hope this publication will meet a significant global vocational training need.

Editors
01.11.2025

CHAPTER 1

Automotive Electric and Electronics

Victor Bacu, Radu Comes, Teodor Stefanut, Adrian Sabou, Constantin Nandra, Raul Alexandru Gorgan, Dragos Andresan, Calin Neamtu, Dorian Gorgan

1. Automotive Electric and Electronics

1.1. Basic Concepts of Electricity and Electronics

Electricity and electronics are at the heart of modern technology, enabling the operation of devices from smartphones and computers to home appliances and industrial machinery. This section will present some of the basic concepts of electricity and electronics, from direct and alternating current to series and parallel electric circuits and even to measurement tools ([1] and [2]).

1.1.1. Direct and Alternating Current Concepts

Alternating Current (AC) flows first in one direction, then reverses to flow in the opposite direction, continuously alternating. In an AC circuit, the voltage constantly shifts between positive (+) and negative (-) values. The speed at which this direction changes represents the frequency of the AC and is measured in hertz (Hz).

Direct Current (DC) flows consistently in one direction, though its level may vary up or down. DC voltage remains either positive or negative, but the magnitude could be different. Electronic circuits typically require a steady DC supply, where the voltage remains constant.

Properties of electrical signals (Figure 1.1):

- *Amplitude* is the maximum voltage reached by the signal and it is measured in volts, V.
- *Peak voltage* is another name for amplitude.
- *Peak-peak voltage* is twice the peak voltage (amplitude). When reading an oscilloscope trace it is usual to measure peak-peak voltage.
- *Time period* is the time taken for the signal to complete one cycle. It is measured in seconds (s).

- *Frequency* is the number of cycles per second. It is measured in hertz (Hz).

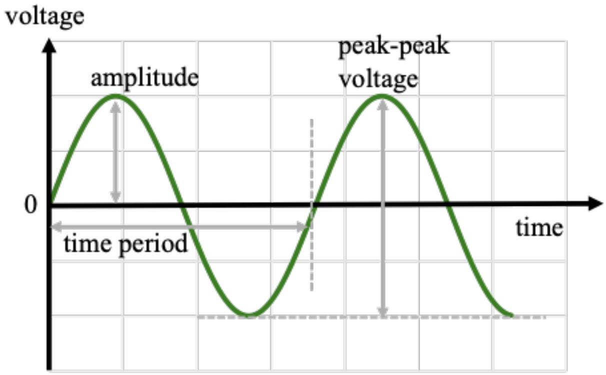


Figure 1.1 Properties of electrical signals

1.1.2 Analog and Digital Signal Concepts

A *signal* is an electromagnetic or electrical current that transfers data from one system or network to another. In electronics, a signal is often a time-varying voltage that functions as an electromagnetic wave carrying information. The signal can be analog and digital (Figure 1.2).

An *analog signal* is a time-varying signal typically confined within a specific range, with an infinite number of possible values within that continuous range. It uses a property of the medium, like the flow of electricity through a wire, to convey information. In an electrical analog signal, characteristics such as voltage, current, or frequency can vary to represent the information being transmitted.

The advantages of using analog signals include:

- Simplicity to process.
- Well-suited for transmitting audio and video.
- Higher density, allowing for more detailed information representation.
- Requiring less bandwidth than digital signals.
- Analog communication systems are generally less sensitive to minor electrical variations.

The disadvantages of using analog signals, include:

- Transmitting data over long distances can result in unwanted signal degradation.
- Suffer from loss during repeated transmission or copying.
- Susceptible to noise and distortion,
- Lower quality than digital signals.

A *digital signal* represents data as a sequence of discrete values. At any given time, a digital signal can only assume one value from a limited set of possible values. The physical property carrying this information can vary and may include:

- Variable electric current or voltage
- Phase or polarization of an electromagnetic field
- Acoustic pressure
- Magnetization of magnetic storage media

The advantages of using digital signals include:

- Minimal noise, distortion, and interference.
- Digital circuits are easy to reproduce in large quantities at relatively low cost.
- Digital signal processing is highly adaptable.
- Digital information is more secure since it can be efficiently encrypted and compressed.
- Reduced error rates due to error detection and correction codes.
- Easily stored on various media, such as magnetic and optical media, using semiconductor technology.
- Long-distance transmission without significant degradation.

The disadvantages of using digital signals include:

- Higher bandwidth than analog transmission for the same data.
- Digital systems and processing are typically more complex to design and implement.

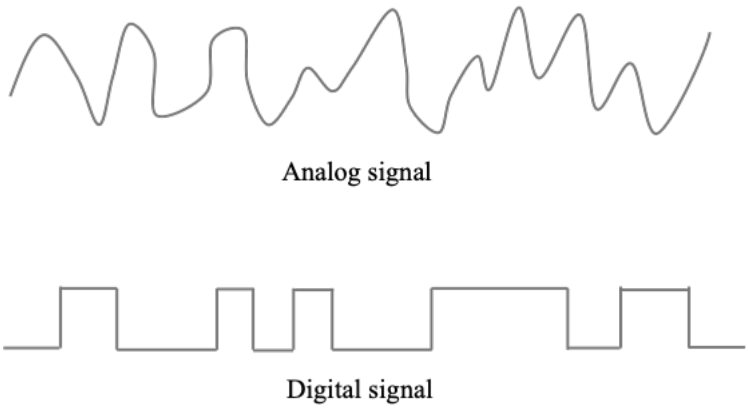


Figure 1.2 Analog vs Digital signals

1.1.3. Conductor, Insulator, and Semiconductor Concepts

Conductors are materials that can transmit various forms of energy (Figure 1.3). The conductivity of metals arises from free electrons which result from the metallic bonding structure. Even with minimal energy, these electrons become sufficiently detached from their atoms, allowing electricity to flow and creating conductivity.

Conductivity is influenced, among other factors, by temperature. As temperature increases, metal atoms vibrate more intensely, restricting the movement of electrons, which leads to an increase in resistance. The best conductors, gold and silver, are seldom used due to their high cost. In semiconductor technology, aluminum and copper are more commonly used for wiring the individual components of microchips as alternatives.

Insulators lack free charge carriers, making them non-conductive. The atomic bond in insulators involves shared electron pairs in nonmetals. Nonmetal elements tend to attract electrons rather than release them, resulting in no free electrons available to act as charge carriers. In the solid state, ions are arranged in a lattice structure where particles are held together by electrical forces. This structure does not provide free charge carriers to support current flow, meaning that substances composed of ions can act as either conductors or insulators, depending on their state and arrangement.

Semiconductors are materials whose conductivity falls between that of conductors and insulators. They form a lattice structure as atoms share electrons to achieve a stable noble gas configuration. Unlike metals, the conductivity of semiconductors increases with rising temperature.

As temperature rises, bonds within the lattice break, releasing free electrons. The absence of an electron at its original location creates a "hole," or defect electron. The flow of electrons and holes determines the conductivity of semiconductors.

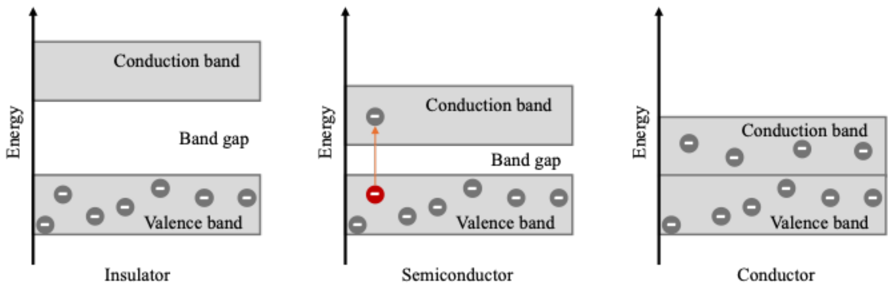


Figure 1.3 Conductors, Insulators and Semiconductors

1.1.4. Magnetic and Electric Field Concepts

Electric Fields are created by electric charges and represent the force that charged particles exert on each other (Figure 1.4). Electric fields are described by Coulomb's law.

Magnetic Fields are generated by moving electric charges (currents) and describe the force magnetic objects exert on each other. They play a key role in inductors, transformers, and electromagnets.

Electric and magnetic fields are interconnected, meaning that a changing electric field generates a magnetic field and vice versa. This relationship is the basis of electromagnetism and electromagnetic waves.

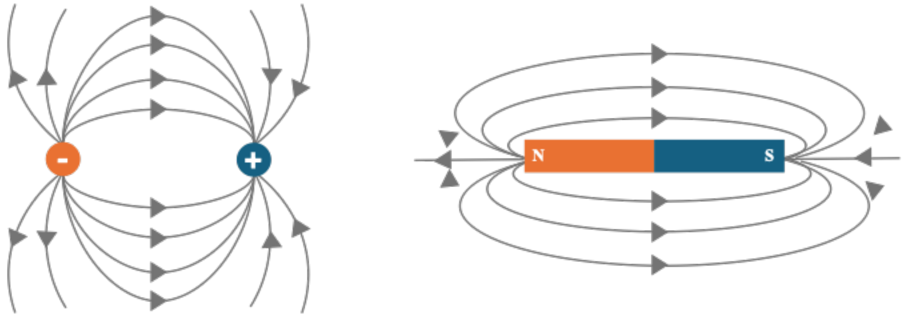


Figure 1.4 Electric field vs Magnetic field

1.1.5 Passive Circuit Elements

Resistors regulate the flow of current (Figure 1.5). Thus, they find wide applications in limiting current, voltage division, and setting up the biasing conditions in various electronic circuits. Basically, resistors oppose the flow of electrical charge or current. This opposition is called resistance, and it is expressed in ohms. The usually used materials for resistors are tungsten, bronze, and constantan on account of their particular resistance qualities.

Capacitators store and release electrical energy, finding wide applications in electronic circuits for decoupling filtering, and energy storage. They allow AC signals to pass while blocking DC signals; hence, they oppose the flow of direct current. A capacitor basically consists of two parallel conducting plates separated by a dielectric material that may comprise a ceramic, mica, glass, waxed paper, or bakelite. The dielectric enables the storage of energy within the capacitor.

Inductors are the components designed to store and release energy in the form of a magnetic field. The most common applications of inductors include filtering, storage of energy, and impedance matching. All inductors are manufactured by winding coiled and insulated wire around a core and on the basis of a principle called electromagnetic induction. Inductors are quite efficient at suppressing electric spikes in electronic circuits.

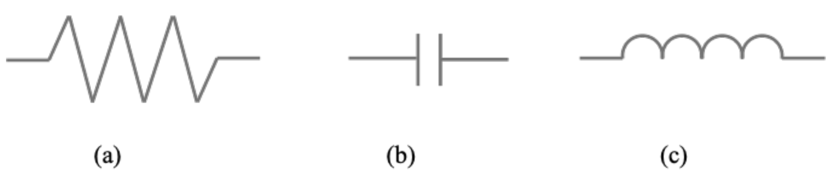


Figure 1.5 Resistors (a), capacitors (b), and inductors (c)

1.1.6. Ohm's Law and Kirchhoff's Law

Ohm's Law is a fundamental principle in electrical engineering that defines the relationship between voltage, current, and resistance in a conductor. Formulated by German physicist Georg Simon Ohm, it states that the current passing through a conductor between two points is directly proportional to the voltage across those points, and inversely proportional to the resistance of the conductor. This relationship is expressed as:

$$V = I \times R$$

where:

V is the voltage (measured in volts, V),

I is the current (measured in amperes, A),

R is the resistance (measured in ohms, Ω).

Ohm's Law is used to calculate the voltage, current, or resistance in simple circuits and is foundational for understanding more complex circuit behavior.

Kirchhoff's Laws, developed by physicist Gustav Kirchhoff, consist of two fundamental principles that apply to current and voltage in electrical circuits: Kirchhoff's Current Law (KCL) and Kirchhoff's Voltage Law (KVL). These laws are essential for analyzing complex circuits, particularly those involving multiple components or branches.

Kirchhoff's Current Law (KCL) states that the sum of all currents entering a node (or junction) in a circuit must equal the sum of all currents leaving that node. This is based on the principle of conservation of charge, which holds that electric charge cannot accumulate at a single point in a circuit.

KCL is used to determine the current in each branch of a complex network, particularly in parallel circuits. In circuit analysis, KCL is fundamental to nodal analysis, a technique that helps solve for unknown voltages at various points in the circuit.

Kirchhoff's Voltage Law (KVL) states that the sum of all electrical voltages around any closed loop or mesh in a circuit is zero. This law is based on the conservation of energy principle, as no net energy should be gained or lost in a closed loop.

KVL is used to find unknown voltages in a loop, especially in circuits with multiple voltage sources or resistive components. KVL forms the basis of mesh analysis, a technique used to solve for currents in complex circuits by defining closed loops and applying KVL to each loop.

1.1.7. Concepts of Power and Energy

Power represents the rate at which energy is transferred, used, or converted from one form to another. In electrical systems, it is used to represent how quickly electrical energy is being consumed or supplied to a device or circuit. It is calculated using the formula:

$$P = V \times I$$

where:

P is power, measured in watts (W),

V is voltage, measured in volts (V),

I is current, measured in amperes (A).

Energy is the total amount of work done or heat generated over a period of time. In electrical terms, it is the cumulative effect of power used over a specified time interval. Electrical energy (E) is calculated by:

$$E = P \times t$$

where:

E is energy, measured in joules (J),

P is power, measured in watts (W),

t is time, measured in seconds (s).

Energy can also be expressed in watt-hours (Wh) or kilowatt-hours (kWh), commonly used for billing electricity consumption. For example, 1 kWh is the energy consumed when 1,000 watts of power is used for one hour.

1.1.8. Series and Parallel Electric Circuits

In a *series circuit*, components are connected end-to-end in a single path, so there is only one path for the current to flow (Figure 1.6). Components in a series circuit have the same current since the current flows continuously from one component to the next. The voltage of a series circuit is divided among its components, with each component's voltage drop proportional to its resistance. From Kirchhoff's voltage law, the sum of voltage drops across each component must be equal to the summed, applied voltage. The total resistance of a series circuit is simply the sum of their individual resistances.

In a *parallel circuit*, components are connected across the same voltage source, forming multiple paths for the current to flow. Each component is directly connected to the power supply, so it sees the full source voltage. Each component in a parallel circuit has the full voltage of the power source across it, no matter how many other components are connected in parallel to it. The current through each parallel path adds together to give the total current in the circuit. The total resistance of a parallel circuit is less than the smallest resistance of the component resistances.

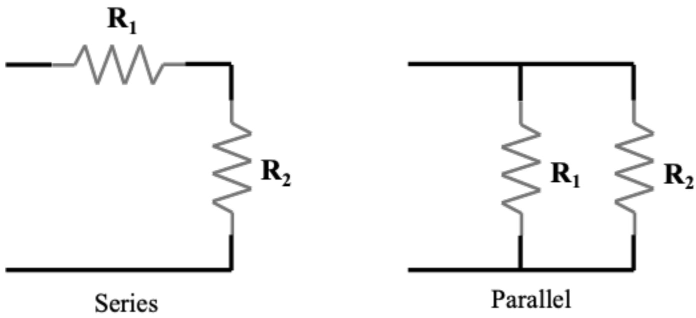


Figure 1.6 Series circuit vs Parallel circuit

1.1.9. Star and Delta Connections

A *star connection* or "Y" is a common connection arrangement in three-phase AC power systems, in which one of the three components or phases is connected to a common central point called neutral (Figure 1.7). In this configuration, three resistances, inductances, or loads are connected in a manner such that one end of each component is connected to this neutral point and forms a shape that gives the outline of the letter "Y".

A *delta connection* is a method in which the three components or phases are interconnected in a close-loop triangular form, and hence, already, in this configuration each component end-to-end connects to the next one, and hence, there can be no central neutral point.

Some of the methods for Star-Delta transformations come in handy in converting a star configuration into its equivalent delta configuration and vice versa. This is quite essential in AC power systems, especially for several needs pertaining to load balancing, impedance matching, and the attainment of certain voltage and current characteristics.

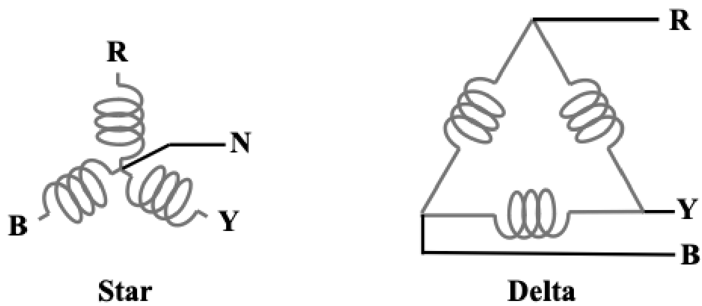


Figure 1.7 Star connection vs Delta connection

1.1.10. Measurement Tools

Multimeter

It is an important versatile tool for the measurement of some key electrical parameters, affording useful voltage by checking the voltage across components and power sources, current to diagnose issues due to overcurrent or faulty connections, and resistance. Modern multimeters are based around an LCD display and a rotary switch to select the various measurement functions. Some of the high-end multimeters are also capable of measuring other quantities such as continuity, frequency, temperature, and in some instances, diode voltage drops. Multimeters can be used for troubleshooting electrical and electronic circuits, verifying connections and component values, and monitoring battery and power supply voltages.

Oscilloscope

The oscilloscope is an excellent tool for observing and analyzing the waveform of electronic signals. Unlike the multimeter that only provides numerical readings, the oscilloscope displays real-time signal variations graphically, with voltage on the vertical axis and time on the horizontal axis. It can be used to analyze frequency, amplitude, phase, and other characteristics and diagnose various issues in quality and stability.

Function Generator

A function generator is an instrument utilized in the generation of waveforms of different types that are required in testing and stimulating electronic circuits, such as sine, square, and triangular. Function generators allow the user to vary parameters like frequency, amplitude, and duty cycle in order to suit different needs for testing. It can be applied to test the frequency response of amplifiers, filters, and audio circuits.

1.1.11. Active Circuit Elements

Transistors

A transistor is a semiconductor device primarily used for amplification and switching applications in electronic circuits. Transistors are fundamental components in both analog and digital electronics, where they control the flow of current by acting as electronic switches or amplifiers. There are Bipolar Junction Transistors which consist of three layers (emitter, base, collector) and Field-Effect Transistors which are voltage-controlled devices, with the voltage applied to the gate controlling the current between the source and drain. Transistors can be used to amplify weak signals, making them essential in audio and radio circuits, where small input signals need to be amplified for further processing. In digital electronics, transistors function as switches that turn on or off based on input signals. This switching capability forms the basis of logic gates and processors.

Operational Amplifiers (Op-Amps)

An operational amplifier (op-amp) is a high-gain voltage amplifier with two inputs, an inverting (-) and a non-inverting (+) input, and a single output. Op-amps are widely used in analog circuits for their versatility and reliability. They can perform a variety of functions, including amplification, filtering, and mathematical operations. They are used to amplify weak signals in audio, sensor, and communication applications. Another use is in active filters, such as low-pass, high-pass, band-pass, and notch filters, to allow or block specific frequency ranges.

Integrated Circuits (ICs)

An integrated circuit (IC) is a compact, self-contained semiconductor device that contains multiple components like transistors, resistors, capacitors, and diodes all fabricated on a single piece of semiconductor material. ICs are designed to perform specific functions, from simple logic gates to complex microprocessors, making them central to modern electronics. There can be digital ICs (capable of handling digital signals) and analog ICs (capable of handling analog signals).

1.1.12. Electromagnetic Interference and Noise Concepts

Electromagnetic interference is an unwanted electromagnetic signal or disturbance induced in an electrical circuit from an external source. It may disturb the normal functioning of an electronic device by altering or degrading signal qualities, which may lead to corrupted data or malfunction. EMI sources include natural sources such as lightning and solar flares, and artificial ones involving other electronic devices, power lines, and motors.

Noise can be defined as random fluctuations or unwanted variations in a signal that may distort the quality of the signal and make accurate interpretation of the signal unrealistic. Noise can result from more than one source, which includes environmental factors, thermal energy within electronic components, and the basic randomness of the electronic systems.

1.2. Sensors

1.2.1. Angular Position and Rotation Sensors

Angular position and rotation sensors measure the rotational position and speed of moving components. For example, in the case of Nissan Leaf, these sensors are essential for monitoring and controlling systems such as the electric motor, steering system, and regenerative braking.

These sensors typically rely on technologies like:

- *Hall effect sensors* - detect magnetic fields generated by a rotating magnet or gear to determine angular position (Figure 1.8a.).
- *Resolver sensors* - measure the angular position by analyzing the electrical signals generated in a rotating electromagnetic field (Figure 1.8b.).
- *Optical encoders* - use light beams and a slotted disk to determine rotational position and speed with high precision (Figure 1.8c.).
- *Potentiometric sensors* - use variable resistance to detect changes in position (less used).

(a) (b) (c)

Figure 1.8 a). Hall Effect sensor [3], b). Resolver sensor [4], c). Optical encoder sensor [5]

The sensor outputs an electrical signal proportional to the angular position or speed, which the vehicle's control unit processes to djust power delivery, engine timing, or steering.

The main applications of these sensors are:

- *Electric motor control sensors* - mounted on the rotor shaft or within the motor housing. Measure the rotor's angular position and speed to ensure precise motor control and efficient acceleration and deceleration. Often implemented using resolver sensors or Hall effect sensors.

- *Steering system (EPS) sensors* - integrated within the steering column. Detect the steering wheel's rotational position and speed to provide better assistance to the driver. Typically employs Hall effect sensors or optical encoders.
- *Regenerative braking system sensors* - coupled to the brake pedal mechanism and calculate braking force to optimize the transition between regenerative and mechanical braking. Commonly uses Hall effect sensors.
- *Transmission control sensors* – located inside or near the gearbox, monitoring the transmission shafts. Track the rotational position and speed of gears to manage gear shifting and efficiency. Often relies on Hall effect sensors or optical encoders.
- *Wheel speed detection sensors* - attached near the wheel hubs. Provide rotational speed data to ABS, ESC and traction control to ensure stability. Typically implemented with Hall effect sensors.
- *Power Electronics (Inverter) synchronization sensors* - integrated in the electric motor or linked to the inverter system. Synchronize the rotor's position with the inverter's power delivery. Often using resolver sensors.
- *Tilt and position in suspension systems sensors* - attached to the suspension arms or struts to provide input for adaptive suspension or height-adjustment systems in advanced HEVs. Potentiometric sensors or Hall effect sensors may be used.

Parameters and metrics:

- *Angle range*: 0° to 360° (full rotation).
- *Resolution*: determines how finely the angle is measured, often in degrees or arcseconds (e.g., 0.1° resolution).
- *Rotational speed*: measured in revolutions per minute (RPM) or radians per second (rad/s).
- *Accuracy*: defines how closely the measurement matches the actual position, typically within ±0.5° to ±1°.
- *Response time*: the time taken to detect position changes, typically in milliseconds.

1.2.2. Temperature Sensors

Temperature sensors monitor critical thermal conditions in hybrid and electric vehicles. In the Nissan Leaf and similar EVs, they ensure the optimal performance and safety of components such as the battery pack, electric motor, inverter and power electronics. By providing real-time thermal feedback, these sensors prevent overheating, support energy-efficient operation and enhance the vehicle's lifespan.

Temperature sensors measure heat levels using a variety of technologies to convert heat into electrical signals for processing by control units:

- *Thermistors (Negative Temperature Coefficient - NTC / Positive Temperature Coefficient - PTC)* - these sensors rely on the relationship between temperature and resistance. NTC thermistors (Figure 1.9a.) decrease resistance as temperature rises, while PTC thermistors increase resistance. They are widely used in battery packs for their accuracy and responsiveness.
- *Thermocouples* - generate a voltage based on the temperature difference between two metals, suitable for high-temperature cases such as the electric motor and inverters (Figure 1.9b.).
- *RTDs (Resistance Temperature Detectors)* - these sensors use a pure metal (e.g., platinum) to measure temperature changes with high precision, ideal for critical components requiring detailed monitoring (Figure 1.9c.).

(a) (b) (c)

Figure 1.9 a). NTC thermistor sensor [6], b). Thermocouple sensor [7], c). SPRT Glass Capsule RTD [8]

The sensors convert thermal data into electrical signals, which are processed by the vehicle's control systems to manage cooling fans, regulate charging rates, or limit power output when necessary.

The main temperature sensors that work together to optimize the vehicle's performance, safety and comfort are:

- *Battery temperature sensors* – integrated into the battery pack and monitor lithium-ion cell temperatures to prevent overheating or freezing. They work with the Battery Management System (BMS) to regulate charging and discharging, minimizing risks like thermal runaway and prolonging battery life.
- *Inverter temperature sensor* - located inside the inverter housing. It measures the temperature of power electronics to ensure optimal operation and prevent overheating during energy conversion.
- *Motor temperature sensor* – embedded in the electric motor and tracks the motor's operating temperature to avoid damage during high load or extended driving conditions.
- *Coolant temperature sensor* – installed in the cooling system and monitors coolant temperatures for the motor, inverter, and battery pack to maintain proper thermal management.
- *Cabin Temperature Sensor* – located near the climate control unit inside the cabin. It regulates the cabin's heating and air conditioning system based on passenger comfort.
- *Ambient temperature sensor* – located near the front bumper or grille. It measures external air temperature for climate control adjustments and vehicle efficiency calculations.
- *Climate control sensors* – located inside the HVAC system. They adjust heating or cooling output based on airflow temperature.
- *Heated steering wheel and seat sensors* - these sensors ensure that heated components maintain comfortable temperatures without overheating.

Parameters and metrics:

- *Measurement range* (typically):
  - Battery pack: -40°C to 85°C.
  - Electric motor and inverter: up to 150°C.
- *Accuracy*: ±1°C to ±2°C for precise battery management.
- *Response time*: in milliseconds, ensuring quick adjustments to thermal conditions.
- *Durability*: designed to withstand automotive-grade environments, including high vibration, moisture and extended temperature ranges.

1.2.3. Pressure Sensors

Pressure sensors monitor fluid or gas pressures in various systems of hybrid and electric vehicles, ensuring safe and efficient operation. In the Nissan Leaf and similar vehicles, these sensors are critical for systems like battery cooling, HVAC (Heating, Ventilation and Air Conditioning), regenerative braking system and tire pressure monitoring.

Pressure sensors measure force per unit area and convert it into an electrical signal. Common technologies include:

- *Piezoelectric sensors* - generate an electrical charge in response to applied pressure (Figure 1.10a.). These are robust and suitable for the high-pressure environments, such as hydraulic systems.
- *Strain gauge sensors* - measure deformation in a material caused by pressure, translating mechanical strain into an electrical signal (Figure 1.10b.).
- *Capacitive sensors* - detect changes in capacitance caused by the movement of a diaphragm under pressure, offering high sensitivity and accuracy (Figure 1.10c.).
- *Differential pressure sensors* - these compact sensors measure the difference between two pressure points (Figure 1.10d.). They are commonly used in applications like air pressure measurement in HVAC systems and pressure drop monitoring across filters.

(a) (b) (c) (d)

Figure 1.10 a). Piezoelectric sensor [9], b). Strain gauge sensor [10] c). Capacitive sensor [11] d). Differential pressure sensor [12]

The main applications of these sensors are:

- *Tire Pressure Monitoring System (TPMS) sensor* – integrated into the valve stems of each tire. It measures tire air pressure and transmits data to the onboard computer.

- *HVAC system sensors* – monitor and regulate pressures to ensure effective air conditioning and cabin temperature control.
- *Battery cooling system sensor* – measures the coolant pressure to maintain proper thermal conditions for the battery pack, enhancing safety and extending battery life.
- *Braking system sensor* – monitors hydraulic pressure in the braking system, ensuring precise coordination between regenerative and conventional braking mechanisms.

Parameters and metrics:

- *Measurement range*:
  - for HVAC systems: 0 to 30 bars (for monitoring).
  - for hydraulic systems: up to 200 bars (in braking system).
  - for tire pressure monitoring systems (TPMS): 0 to 6 bars (for tire safety).
- *Accuracy* (typically): within ±1% of full scale to ensure precise monitoring.
- *Response time*: in microseconds for real-time adjustments in dynamic systems.
- *Operating temperature range*: from -40°C to 125°C.

1.2.4. Flow Sensors

Flow sensors are devices used to measure the rate of fluid or air movement in the vehicle systems. For the Nissan Leaf and similar vehicles, flow sensors are essential in managing the cooling system for the battery pack, electric motor, inverter and HVAC system. Proper flow ensures these components remain within their optimal temperature range, supporting efficient performance and longevity.

Flow sensors operate by detecting changes in a fluid's or gas's velocity, pressure, or thermal properties as it passes through the sensor. Common technologies include:

- *Thermal mass flow sensors* - measure heat transfer between a heated element and the fluid to determine flow rate (Figure 1.11a.). These are used in coolant systems for their precision.
- *Turbine flow sensors* - presents a rotating turbine that spins in proportion to the flow rate and count the rotations to calculate flow (Figure 1.11b.).

- *Ultrasonic flow sensors* - use sound waves to measure the flow velocity (Figure 1.11c.). These non-invasive sensors are used for coolant monitoring.
- *Differential pressure sensors* - calculate flow rate by measuring the pressure drop across a restriction in the flow path.

(a) (b) (c)

Figure 1.11 a). Thermal mass flow sensor [13], b). Turbine flow sensor [14] c). Ultrasonic flow sensors [14]

The main applications of these sensors are:

- *Battery cooling system sensors* - installed in the coolant lines of the battery pack cooling circuit. Monitor the coolant flow rate to ensure efficient heat elimination from the battery cells and to prevent overheating by detecting reduced or blocked coolant flow. Typically employs thermal mass flow sensors or ultrasonic flow sensors.
- *Inverter cooling system sensors* – located along the cooling circuit dedicated to the inverter, often near the inverter housing. Measure the coolant flow rate to maintain the inverter's operating temperature within safe limits. Uses turbine flow sensors or thermal mass flow sensors for accurate flow control.
- *Electric motor cooling system sensors* – located around the motor housing, on the coolant path. Ensure good flow of coolant to eliminate heat from the motor during operation and optimize motor performance. Differential pressure sensors or ultrasonic flow sensors are commonly used for their responsiveness in high-flow applications.
- *HVAC system sensors* - integrated into the refrigerant lines or airflow paths of the HVAC system. Monitor the flow of refrigerant in cabin temperature and detect leaks or blockages in the system that could impact climate control performance. Turbine flow sensors or thermal mass flow sensors are widely used in this application.

- *Battery heating system sensors* – located in the heating circuit connected to the battery pack. Measure the flow of heated air or fluid to ensure uniform heating of battery cells in low temperatures. Support battery performance in cold environments by preventing thermal imbalances. Uses thermal mass flow sensors due to their ability to handle varying fluid temperatures.
- *Charging system cooling sensors* – located near the cooling pathways of the onboard charger or DC fast-charging system. Maintain proper flow of coolant to eliminate heat generated during high-power charging sessions and enhance charging efficiency. Employs ultrasonic flow sensors for non-intrusive monitoring.

Parameters and metrics:

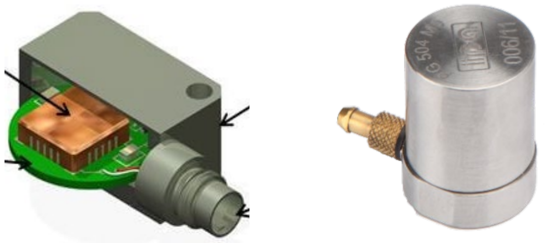
- *Flow rate*: measured in liters per minute (L/min) or cubic meters per hour (m^3/h), depending on the system.
- *Operating temperature range*: -40°C to 125°C.
- *Accuracy*: ±1-3% in critical systems.
- *Response time*: milliseconds.

1.2.5. Acceleration Sensors

Acceleration sensors, commonly known as accelerometers, measure the rate of change in velocity of a vehicle in one or more axes. In hybrid and electric vehicles, these sensors enhance vehicle dynamics by providing data for a range of essential systems and functions including anti-lock braking (ABS), electronic stability control (ESC), advanced driver-assistance systems (ADAS) and airbag deployment. They also contribute to regenerative braking, detecting deceleration to optimize energy recovery.

Acceleration sensors detect changes in motion using principles of inertia. They convert physical acceleration recorded from motion or gravity into a voltage output. Common types include:

- *MEMS Accelerometers (Micro-Electro-Mechanical Systems)* - use tiny structures on a chip that deflect when the vehicle accelerates (Figure 1.12a.). The deflection changes electrical properties, such as capacitance, which is converted into acceleration data.
- *Piezoelectric accelerometers* - generate an electrical charge when subjected to mechanical stress caused by acceleration (Figure 1.12b.).
- *Capacitive accelerometers* - measure changes in capacitance as a proof mass moves within the sensor under acceleration forces.



(a) (b)

Figure 1.12 a). MEMS Accelerometer [15], b). Piezoelectric accelerometer [16]

The main applications of these sensors are:

- *Anti-lock Braking System (ABS) pressure sensor* – mounted near the wheel hubs or suspension system. Detects sudden deceleration or wheel lock during braking and transmits data to the ABS module to modulate braking pressure and prevent wheel lock, improving stability and control.
- *Electronic Stability Control (ESC) sensor* – centralized in the vehicle's control module, often near the center of mass (beneath the driver's seat or in the middle console). Measures lateral acceleration and vehicle yaw rate and helps the ESC system adjust engine power or apply individual brakes to prevent skidding or loss of control during turns or slippery conditions.
- *Advanced Driver Assistance Systems (ADAS) sensors* – mounted within the vehicle's central control system or integrated into specific ADAS modules like adaptive cruise control or collision avoidance systems. Provides data on acceleration and deceleration to support features such as lane-keeping assistance, adaptive cruise control and automatic emergency braking.
- *Airbag deployment and Crash Detection for emergency call sensors* – located inside the airbag control module, typically mounted centrally (under the center console or dashboard). Detects rapid deceleration during a collision and trigger airbag deployment to protect occupants from injury and automatically trigger emergency systems.
- *Regenerative braking system sensors* – located near the vehicle's drivetrain or integrated into the motor control unit. Detect deceleration and changes in velocity and optimize energy recovery by controlling the regenerative braking process, converting kinetic energy back into electrical energy for storage in the battery.

- *Hill Start Assist system sensors* – located near the braking system or within the control module responsible for vehicle dynamics. Detect vehicle inclination and prevent rollback by maintaining braking pressure when the vehicle is stationary on an incline.
- *Electric Power Steering (EPS) sensors* - integrated into the steering column or EPS module. Measure vehicle acceleration to adjust steering assistance for stability and responsiveness.

Parameters and metrics:

- *Acceleration range*: typically measured in meters per second squared (m/s^2) or as a multiple of gravitational acceleration (g), e.g., $\pm 2g$, $\pm 10g$, etc.
- *Sensitivity*: determines how much output voltage corresponds to a given acceleration level, important for accurate readings.
- *Response time*: sub-millisecond response times for critical applications like airbag deployment.
- *Accuracy*: high precision, especially for stability control and ADAS.

1.2.6. Lambda Oxygen Sensors

Lambda oxygen sensors measure the oxygen concentration in the exhaust gases of internal combustion engines (ICE). By generating a voltage that varies with oxygen levels, they provide important feedback to the engine control unit (ECU) to maintain the optimal air-fuel ratio (lambda value) during combustion.

In hybrid electric vehicles (HEVs), these sensors are important for ensuring efficient engine operation and fuel consumption, reducing emissions and protecting the catalytic converter. The ECU uses data from the lambda sensor to adjust fuel injection and ignition timing, optimizing performance and minimizing pollutants.

Although fully electric vehicles like the Nissan Leaf do not use oxygen sensors, HEVs with ICE components rely on them for emissions control and fuel efficiency. Lambda sensors function by comparing the oxygen concentration in exhaust gases to that in ambient air. Common types include zirconia sensors (which generate voltage, presented in Figure 1.13a.) and wideband sensors (which provide precise air-fuel ratio measurements across a broader range, presented in Figure 1.13b.).

(a) (b)

Figure 1.13 a). Zirconia sensor [17], b). Wideband sensor [18]

Parameters and metrics:

- *Voltage output*:
  - Narrowband (zirconia) sensors: typically, 0.1V to 0.9V, indicating lean or rich mixtures, respectively.
  - Wideband sensors: provide a broader signal for finer adjustments.
- *Response time*: milliseconds, critical for real-time adjustments.
- *Operating temperature*: up to 850°C, requiring built-in heaters to reach optimal sensing temperatures quickly.

1.2.7. Current Measurement Sensors

Current measurement sensors are devices that monitor the flow of electrical current within various systems of hybrid and electric vehicles. They are important for ensuring the safe, efficient and reliable operation of the vehicle's electrical components, such as the battery, inverter and electric motor.

In the Nissan Leaf and similar EVs, these sensors are important in monitoring battery charge and discharge rates, motor control and energy management. Accurate current measurement allows the vehicle's control systems to optimize power delivery, extend battery life and maintain safety during operation.

Current measurement sensors use different technologies to detect electrical current flow:

- *Hall Effect sensors* - measure the magnetic field generated by the current in a conductor. They are widely used for non-intrusive current sensing in battery management systems.

- *Shunt resistors* - detect current by measuring the voltage drop across a precision resistor (Figure 1.14a.). They offer high accuracy but require physical connection to the circuit.
- *Rogowski coils* - use a coiled wire to measure the rate of change of current in high-power systems like the motor and inverter (Figure 1.14b.).
- *Fluxgate sensors* - provide highly accurate measurements for high-current applications using magnetic field sensing (Figure 1.14c.).

These sensors convert current levels into electrical signals that are processed by the vehicle's control unit for analysis and action.

(a) (b) (c)

Figure 1.14 a). Shunt resistor [19], b). Rogowski coil [20], c). Fluxgate sensor [21]

The main applications of these sensors are:

- *Battery Management System (BMS) sensors* - integrated within the battery pack or near the main battery terminals. Monitor the charge and discharge currents prevent overcharging or deep discharging. Provide data to calculate the state of charge and state of health of the battery. Commonly uses Hall effect sensors or shunt resistors.
- *Electric motor control sensors* - located near the power lines between the inverter and the electric motor. Measure the current flowing to the motor for precise torque control. Support motor efficiency optimization and safety during operation by avoiding overcurrent scenarios. Typically employs Rogowski coils or fluxgate sensors to handle high-current applications.
- *Inverter system sensors* – located inside or adjacent to the inverter housing, monitoring the DC input from the battery and the AC output to the motor. Ensure efficient energy conversion and regulate power delivery from the battery to the motor. Prevent overcurrent conditions

that can damage the inverter circuit. Often utilizes Hall effect sensors or Rogowski coils for measurement.

- *Charging system sensors* – located at the charging port or within the onboard charger unit. Monitor the incoming current during charging to prevent overloading or overheating and support charging algorithms. Shunt resistors or Hall effect sensors are commonly used for their reliability and precision.
- *Regenerative braking system sensors* - located along the electrical connection between the motor and the battery pack. Measure the current generated by the motor during regenerative braking and optimize energy recovery by adjusting the regenerative braking force based on current feedback. Often employs Hall effect sensors for measurement.
- *Power distribution system sensors* – located near the main distribution box or along critical power lines to auxiliary systems. Monitor current flow to auxiliary systems like HVAC or lighting and prevent overcurrent scenarios that could lead to system failures. Shunt resistors are commonly used for their compact size and accuracy.
- *Cooling system sensors* – located in the circuits powering cooling fans or pumps. Monitor current consumption of the cooling system components to ensure the thermal management system operates efficiently and identify malfunctions like motor stalling. Uses Hall effect sensors.

Parameters and metrics:

- *Measurement range*:
  - Battery Management System: up to ±1000 A.
  - Inverter/Motor control: up to several hundred amperes.
- *Accuracy*: ±1% to ±2%.
- *Response time*: milliseconds.
- *Operating temperature range*: -40°C to 125°C.

1.3. Electronic Control Systems

Conventional vehicles, running on internal combustion engines, started out relying on analogical electro-mechanical control systems, with the new iterations being ever more dependent on computer-controlled systems for all manner of functions, like fuel efficient combustion and transmission [22]. In the case of the newly developed hybrid and electric vehicles (HEVs/EVs), electronic control systems (ECS) represent the backbone rather than simply additions intended to increase their efficiency [23]. This is largely due to the increased complexity of the subsystems found on HEVs/EVs that need to be monitored, controlled, and diagnosed.

At its simplest, a control system can be viewed as a black box that operates on a set of inputs, processing them and producing a set of outputs, which are meant to achieve a certain result. You can think of the electronic control unit (ECU) found inside an EV as an example. It takes the input acceleration (pedal position) from the driver and ensures that the motor delivers the required power output to match the input provided [23].

There are two main categories of control systems:

- *Open-Loop systems* – operate by reacting to input values in a pre-programmed manner, without accounting for the system's state [24].
- *Closed-Loop systems* – operate by continuously monitoring and responding to the system's output, as well as the input values. They can therefore maintain a desired output within specified parameters. [25]

With the significant progress made into areas like chip design and manufacturing over the last decades, the latest ECSs rely on advanced microcontrollers and sensors to implement the loop stages. Rather than a nice feature, these are a requirement for modern HEVs/EVs for which precision is critical [23].

1.3.1. Open Loop Control Systems

The simplest type of control systems are the ones operating on an open loop principle. These are characterized as responding directly to an input, in a cause-and-effect type of behavior. There is no feedback or any monitoring of the output to inform the system's response [24]. This is illustrated in Figure 1.15.

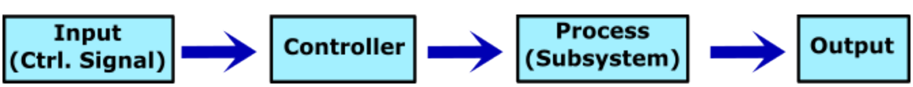


Figure 1.15 Open-Loop Control systems schematic

To exemplify this in the context of a Hybrid/Electric vehicle, think of the simplified system of an accelerating car. The user supplies the input in the form of the amount of torque of the motor based on the position of the acceleration pedal and the system responds by providing a certain speed as the output.

On a level road, the vehicle speed is going to increase predictably based on the amount of torque supplied as an input. The output, speed, is only influenced by the input, or torque (Figure 1.16). However, when driving uphill, a perturbating factor will be influencing the system: gravity. Given the same amounts of torque (input) as before, the vehicle speed (output) is going to behave differently and exhibit lower values because of the pull of gravity that the vehicle must now overcome.

Since an open-loop system does not monitor the output to provide feedback, it cannot react to the changes in its output induced by the perturbating factor [24].

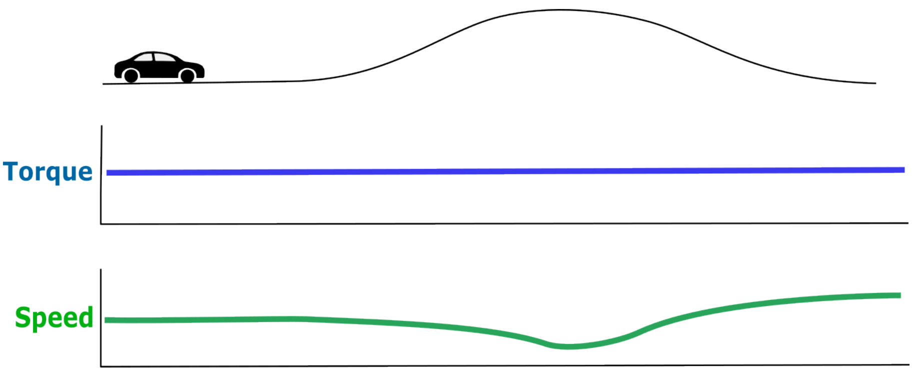


Figure 1.16 – Open Loop Control system example: Constant torque

Main characteristics of Open Loop systems:

- *Lack of Feedback*: the system responds to input values without monitoring its output to adjust for perturbating factors.
- S*implicity*: such systems are easy to design and develop, as well as cheap, since they typically require fewer hardware components.

Common examples include use cases where feedback control is not important, like electrically operated windows, fixed-speed windshield wipers, basic models of vehicle air-conditioning systems.

Advantages of Open Loop systems:

- Cost effective
- Simple to implement
- Increased reliability (fewer components)

Disadvantages of Open Loop systems:

- Inefficient or insufficient in dynamic in environments likely where *perturbating factors* can influence their operation.
- The lack of feedback mechanisms might lead to *errors slowly creeping* into the system over time.

1.3.2. Closed-Loop Control Systems

Systems of this type of work by continuously monitoring their output and adjusting the input in real time to react to various environmental factors that they may be subjected to. In this way, closed loop systems can accommodate the influence of perturbating factors while maintaining the output within a specified range [25]. The basic principle is illustrated in Figure 1.17.

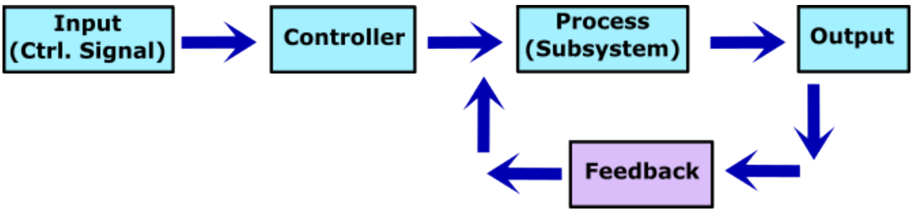


Figure 1.17 Closed-Loop Control systems schematic

Also known as feedback control systems, closed-loop systems are integral to the functioning of advanced HEVs/EVs subsystems. Their feedback mechanisms ensure that any disturbances affecting the system will be compensated for by the input [25]. The term feedback control comes from the fact that the output is fed back to the input, helping the system adjust to maintain a desired behavior.

In keeping up with the previous vehicle driving example, a relevant scenario to explain the functioning of closed loop systems would be the cruise control mode. In this case, the user no longer controls the acceleration but instead provides the system with a desired speed (Figure 1.18). The engine control module manages the torque, analyzes the speed, and makes the necessary corrections to the input torque to maintain the same constant speed, regardless of the road conditions.

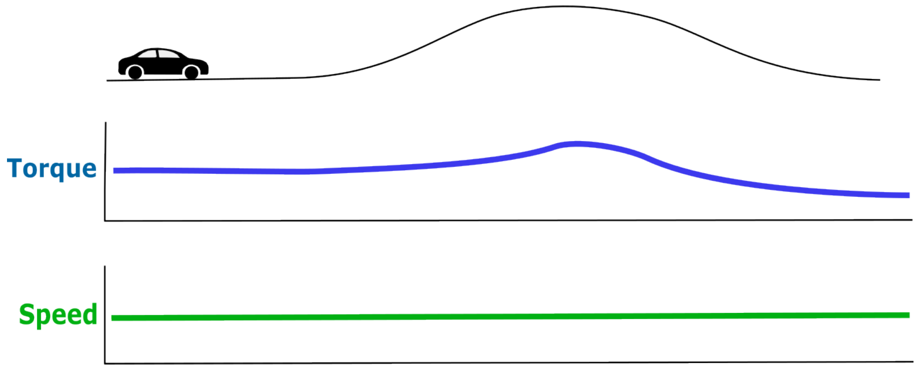


Figure 1.18 Closed Loop Control system example: Cruise control

Main characteristics of Closed Loop systems:

- *Feedback-Driven*: the system continuously monitors its output through sensors and takes action to minimize errors, defined as the difference between the desired and actual value of the output.
- *Dynamic Adjustments:* the system can adapt to changing environmental conditions, ensuring optimal performance.

Advantages of Closed Loop systems:

- High efficiency and precision
- *Adaptability* to perturbation factors
- Self-correcting mechanisms

Disadvantages of Closed Loop systems:

- *Increased complexity* of design and implementation
- *Higher cost* due to a higher number of components and sensors
- Potentially *lower reliability* because of complexity

Closed-loop systems are widely implemented in critical subsystems of HEVs/EVs, such as:

- *Battery Management Systems (BMS)*: Ensures batteries operate within safe temperature and voltage limits.
- *Regenerative Braking*: Recaptures kinetic energy based on the vehicle's speed and braking intensity.
- *Motor Control*: Adjusts torque and speed for efficiency and performance.

1.3.3. Microcontrollers

Microcontrollers are the brains behind most automotive systems, and they provide the means for implementing both open and closed loop electronic control systems, among many others.

At a basic level, microcontrollers are compact computing devices, featuring a processor, memory, and input/output peripherals, all integrated within a single chip. This allows microcontrollers to operate autonomously in resource-constrained environments, performing time-sensitive tasks essential for vehicle control systems [26].

Unlike general purpose processors, microcontrollers are designed and optimized to perform specific tasks for embedded systems.

The typical microcontroller consists of the following (Figure 1.19):

- *Central Processing Unit (CPU)*: Responsible for executing instructions and managing the flow of data.
- *Memory Modules*: Comprising flash memory for storing firmware, RAM for temporary data storage, and EEPROM for non-volatile, reprogrammable storage.
- I/*O Peripherals*: Interfaces like ADC (Analog-to-Digital Converters), DAC (Digital-to-Analog Converters), PWM (Pulse Width Modulation) generators, and GPIO (General Purpose Input/Output) ports that enable communication with sensors, actuators, and other subsystems.
- *Timers and Communication Protocols*: Built-in support for CAN, LIN, UART, SPI, and I2C protocols allows seamless integration with vehicle networks and real-time data handling.

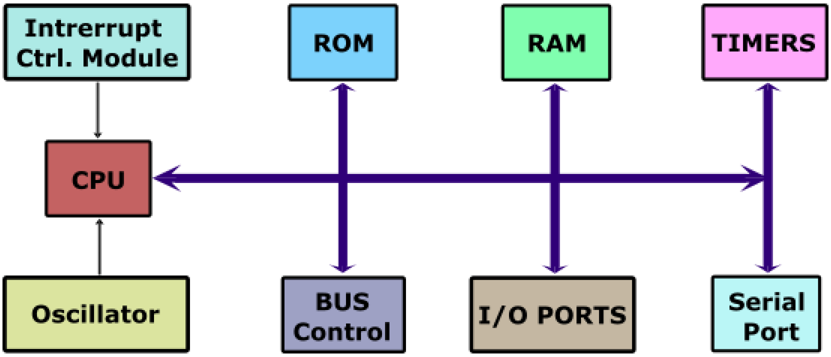


Figure 1.19 Microcontroller architecture

Microcontrollers are aptly described as the “brain” of electronic control systems in HEVs/EVs. They process inputs from a variety of sensors, execute control strategies, and communicate commands to actuators. Their ability to process real-time data ensures precise system performance, efficiency, and safety.

Key applications in HEVs/EVs include:

- *Motor Drive Systems:* Microcontrollers manage electric motors by generating PWM signals for inverters, monitoring torque and speed sensors, and ensuring smooth acceleration and deceleration.
- *Battery Management Systems (BMS):* Microcontrollers monitor battery voltage, temperature, and state of charge (SoC). They implement algorithms to balance cells, predict battery lifespan, and prevent thermal runaway.
- *Power Electronics Control*: They regulate converters and inverters to optimize energy transfer between the battery, motor, and other subsystems.
- *Sensor Integration:* By processing data from temperature, pressure, and current sensors, microcontrollers ensure accurate feedback for closed-loop control systems.

Microcontrollers are integral to executing control system algorithms. In open-loop systems, they perform predefined tasks without feedback, such as controlling simple lighting systems or auxiliary circuits. However, their true potential is realized in closed-loop systems, where they process sensor feedback to adjust actuator outputs dynamically. For example:

- In a closed-loop motor control system, the microcontroller adjusts motor current and voltage in real-time based on speed and torque feedback.
- In adaptive cruise control, it continuously processes data from radar and cameras, ensuring safe following distances by modulating the throttle and brakes.

The microcontroller’s ability to execute these algorithms with high precision and speed is critical for ensuring the stability and efficiency of HEV/EV systems.

1.4. Electric Motors

This chapter delves into the heart of electric vehicle (EV) propulsion: the electric motor. We explore the fundamental principles of electromagnetic induction and torque production, dissecting the key components that make these high-efficiency machines possible. From the role of stator windings and rotor magnets to the intricacies of inverter control, this chapter provides a comprehensive overview of electric motor technology (Figure 1.20).

While AC motors, particularly induction and synchronous motors, have become the dominant choice for EV propulsion due to their high efficiency, power density, and reliability, DC motors also play a significant role, especially in smaller EVs and hybrid vehicles. This chapter will explore both AC and DC motor technologies, examining their operating principles, control strategies, and the factors that influence their performance.

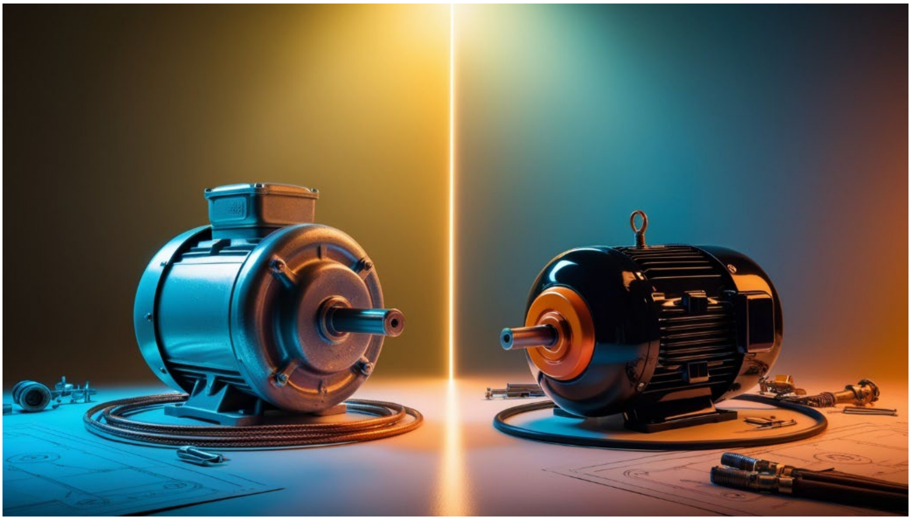


Figure 1.20 AC and DC motor technologies

By understanding the core concepts and the latest advancements, readers will gain insights into the factors that influence motor performance, efficiency, and durability. This knowledge is crucial for engineers, technicians, and enthusiasts alike, as it empowers them to appreciate the complexities of EV propulsion systems and to contribute to the ongoing development of sustainable transportation solutions.

In the following sections, we will delve deeper into the types of electric motors commonly used in EVs, including AC induction motors, permanent magnet synchronous motors, and DC brushed and brushless motors. We will discuss their advantages, disadvantages, and specific applications. Additionally, we will explore the role of power electronics in controlling and optimizing the performance of electric motors, highlighting the importance of inverter technology in achieving efficient and smooth operation.

1.4.1. Types of Electric Motors

Electric vehicles (EVs) are propelled by electric motors, which convert the electrical energy stored in their batteries into mechanical energy. This transformation involves the interaction of magnetic fields and electric currents within the motor.

Two primary types of electric motors are commonly used in EVs:

- *AC (Alternating Current) Motors*: AC motors utilize alternating current to generate a rotating magnetic field, which induces an electric current in the rotor (Figure 1.21 and Figure 1.22). This interaction between the magnetic fields creates the torque necessary to rotate the motor shaft. AC motors are known for their high efficiency, power density, and reliability, making them a popular choice for EV applications.

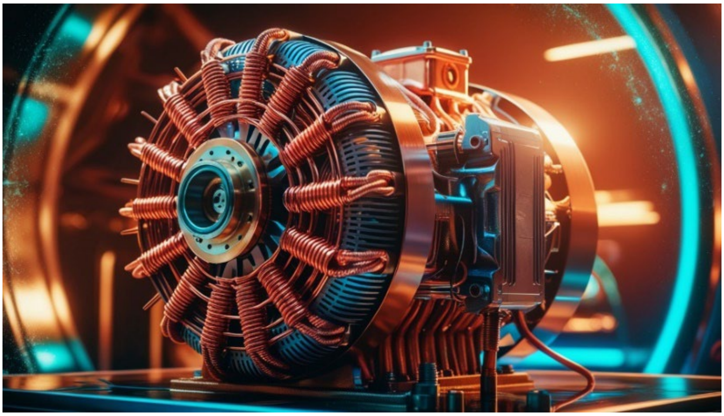


Figure 1.21 AC Motor overview

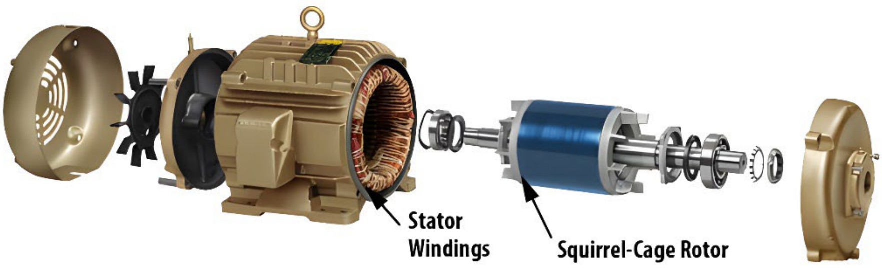


Figure 1.22 AC Motor components [27]

- *DC (Direct Current) Motors*: DC motors operate on direct current, which is supplied to the motor's windings (Figure 1.23 and Figure 1.24). This creates a magnetic field that interacts with a permanent magnet or another magnetic field to generate torque and rotate the motor shaft. While DC motors were more prevalent in earlier EVs, their use has declined due to factors like lower efficiency and maintenance requirements.

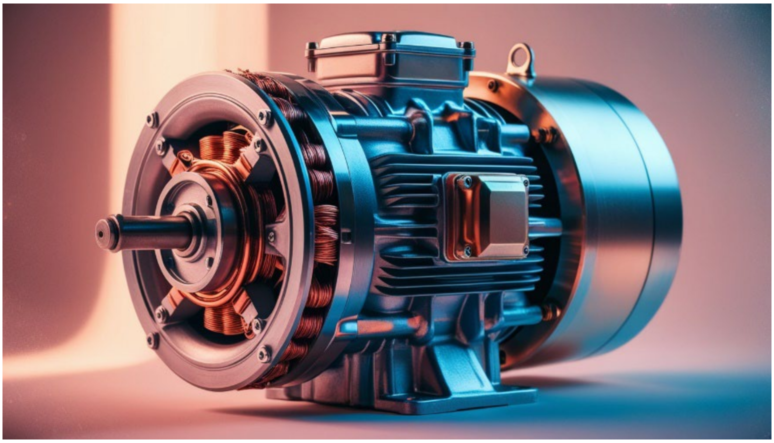


Figure 1.23 DC Motor overview

In recent years, AC motors, particularly synchronous motors, have gained significant popularity due to their superior performance characteristics. However, DC brushless motors continue to find applications in certain niche segments and smaller EVs.

1.4.2. Differences between DC and AC motors

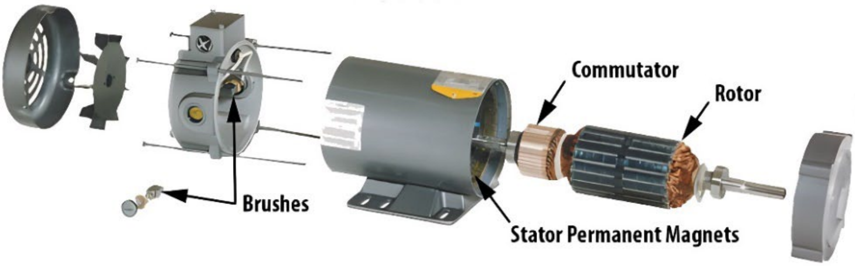


Figure 1.24 DC Motor components [28]

AC Motors

AC motors utilize alternating current to generate a rotating magnetic field (Figure 1.25). This field induces a current in the rotor, creating torque and causing the rotor to rotate. AC motors are renowned for their high efficiency, power density, and reliability. They are categorized into induction motors, which are simple and robust, and synchronous motors, which offer high efficiency and precise control.

DC Motors

DC motors operate on direct current, which is supplied to the armature windings. This creates a magnetic field that interacts with a permanent magnet or another magnetic field, producing torque. While DC motors were more prevalent in earlier EVs, their use has declined due to factors like lower efficiency and maintenance requirements. Modern DC motors, particularly brushless DC motors, offer higher efficiency and better performance, making them suitable for certain niche applications and smaller EVs.

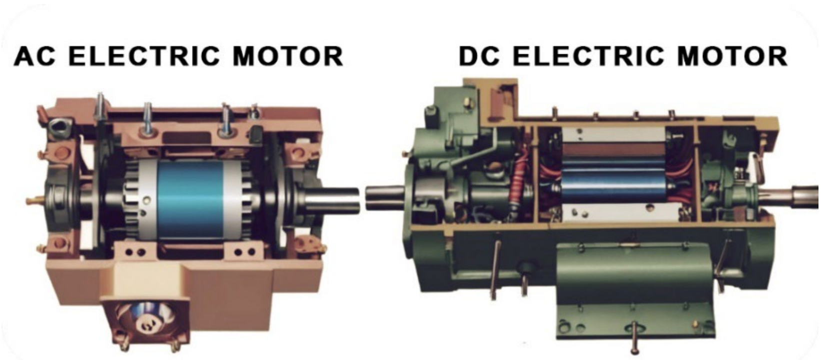


Figure 1.25 AC Electric motor compared to a DC Electric motor

Key Differences

Power Source: AC motors use AC power, while DC motors use DC power.

Commutation: AC motors use electronic commutation, while DC motors can use either mechanical or electronic commutation.

Power Factor: AC motors typically have a lagging power factor, while DC motors have a unity power factor.

Maintenance: AC motors generally require less maintenance compared to brushed DC motors.

Speed Control: AC motors can be controlled by varying the frequency of the AC supply, while DC motors can be controlled by varying the voltage.

Table 1.1 Key differences between AC and DC motors

Feature	AC Motors	DC Motors
Power Source	AC Power Supply	DC Power Supply
Commutation	Electronic commutation	Mechanical commutation (brushed) or electronic commutation (brushless)
Power Factor	Lagging power factor	Unity power factor
Maintenance	Lower maintenance (especially induction motors)	Higher maintenance (especially brushed DC motors)
Speed Control	Variable speed control through frequency variation	Variable speed control through voltage variation

AC Motors

Advantages:

- *High Efficiency*: AC motors, particularly induction and synchronous motors, are known for their high efficiency, which translates to longer driving range and reduced energy consumption.
- *High Power Density*: AC motors can deliver high power output in a compact package, making them suitable for high-performance EVs.
- *Robustness and Reliability*: AC motors are generally more robust and require less maintenance compared to brushed DC motors.
- *Precise Control*: Advanced control systems allow for precise control of speed, torque, and efficiency.

Disadvantages:

- *Complex Control Systems*: AC motors, especially synchronous motors, require more complex control systems compared to DC motors.
- *Higher Initial Cost*: The complex control systems and specialized components can increase the initial cost of AC motor-powered EVs.

DC Motors

Advantages:

- *Simple Control*: DC motors are relatively simple to control, making them suitable for various applications.
- *High Starting Torque*: DC motors, especially brushless DC motors, can provide high starting torque, which is beneficial for accelerating heavy vehicles.

Disadvantages:

- *Lower Efficiency*: DC motors, particularly brushed DC motors, can be less efficient than AC motors, especially at higher speeds.
- *Maintenance Requirements*: Brushed DC motors require regular maintenance, including brush replacement, which can increase operating costs.
- *Lower Power Density*: DC motors generally have lower power density compared to AC motors, limiting their performance in high-power applications.

While both AC and DC motors have their own advantages and disadvantages, AC motors, particularly synchronous motors, have become the dominant choice for electric vehicles due to their high efficiency, power density, and precise control capabilities.

1.4.3. DC Motors

While AC motors have become the dominant choice for electric vehicles (EVs), DC motors still play a role, particularly in smaller EVs and specific applications.

Types of DC Motors Used in EVs

Brushed DC Motors:

- *Simple and inexpensive*: These motors have a simple design and are relatively affordable.
- *Lower efficiency*: Brushed DC motors suffer from mechanical losses due to friction between the brushes and commutator, resulting in lower efficiency.
- *Limited speed range*: Their speed control is limited by the mechanical commutation process.
- *Maintenance requirements*: The brushes wear out over time, requiring periodic replacement.

Brushless DC Motors:

- Higher efficiency: Electronic commutation eliminates mechanical losses, resulting in higher efficiency.
- *Precise control*: Electronic control allows for precise control of speed and torque.

- *Wide speed range*: Brushless DC motors can operate over a wide speed range.
- *Lower maintenance*: No mechanical brushes to replace, reducing maintenance requirements.

Applications of DC Motors in EVs

Powertrain:

- *Small EVs*: In some smaller EVs, DC brushless motors may be used for their simplicity and lower cost.
- *Hybrid Electric Vehicles (HEVs)*: DC motors are often used as starter motors and generators in HEVs.

Auxiliary Systems:

- *Power Steering Pumps*: DC motors can power hydraulic pumps for power steering systems.
- *Water Pumps*: DC motors can be used to circulate coolant in the vehicle's cooling system.
- *Air Conditioning Compressors*: DC motors can power the compressors in air conditioning systems.

Comfort and Convenience Features:

- *Seat Adjusters*: Small DC motors can be used to adjust the position of seats.
- *Window Motors*: DC motors can power window motors for automatic window operation.
- *Sunroof Motors*: DC motors can be used to operate sunroofs.
- *Climate Control Systems*: DC motors can power fans and blowers in climate control systems.

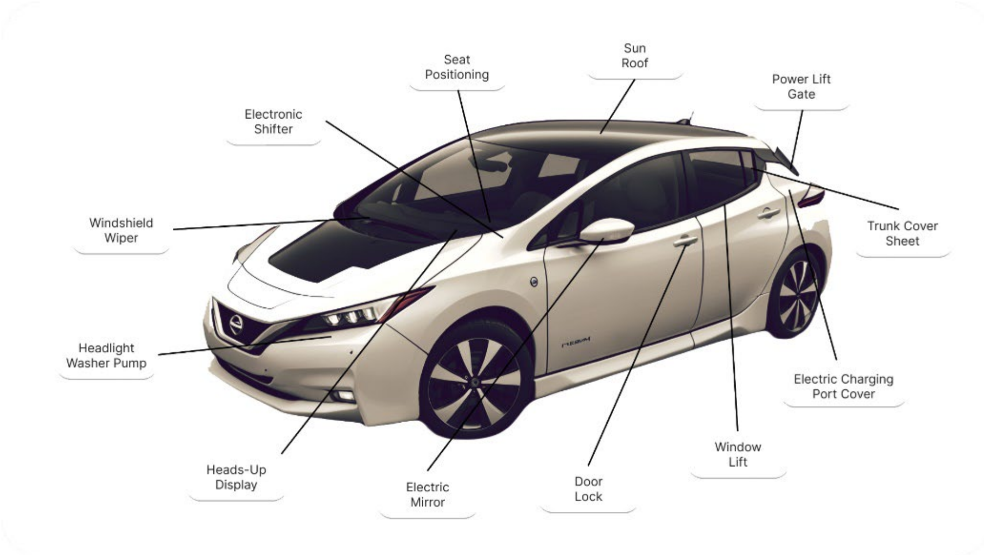


Figure 1.26 Applications of DC Motors in EVs – Nissan Leaf case study

1.4.4. AC Motors

AC motors are the most common type of electric motor used in electric vehicles (EVs) due to their high efficiency, power density, and reliability. They operate on the principle of electromagnetic induction, where a rotating magnetic field is generated in the stator windings, inducing current in the rotor windings. This interaction between the magnetic fields creates torque, causing the rotor to rotate.

Types of AC Motors Used in EVs

Induction Motors:

- *Simple and robust design*: This makes them a popular choice for many EV applications.
- *Wide range of applications*: They are used in various EV applications, from small city cars to larger SUVs.
- *High efficiency and reliability*: They offer excellent performance and durability.
- *Lower power density*: Compared to synchronous motors, they may have slightly lower power density.

Synchronous Motors:

- *High efficiency and precise control*: They offer superior performance and controllability.
- *High power density*: They can deliver high power output in a compact package, making them ideal for high-performance EVs.
- *Permanent magnet synchronous motors (PMSMs)*: Widely used in EVs due to their high efficiency, power density, and precise control.
- *Interior permanent magnet synchronous motors (IPMSMs)*: Offer high torque density and are suitable for a wide range of EV applications.
- *Surface-mounted permanent magnet synchronous motors (SPMSMs)*: Simpler design and lower cost but may have lower power density compared to IPMSMs.

AC motors are employed in various components of electric vehicles to provide efficient and reliable power. Here are some key areas where you can find AC motors:

Powertrain:

- *Drive Motors*: These are the primary motors responsible for propelling the vehicle. They can be induction or synchronous motors, depending on the specific vehicle and its performance requirements.
- *Auxiliary Motors*: Smaller AC motors can be used to power auxiliary systems like power steering pumps, water pumps, and air conditioning compressors.

Chassis and Suspension:

- *Electric Power Steering (EPS) Motors*: These motors assist in steering the vehicle, providing variable steering effort based on vehicle speed and steering angle.
- *Active Suspension Systems*: AC motors can be used to adjust the suspension damping and stiffness in real-time, improving ride comfort and handling.

Comfort and Convenience Features:

- *Seat Adjusters*: Small AC motors can be used to adjust the position of seats, including recline, slide, and height adjustments.

- *Window Motors*: AC motors power the window motors, enabling automatic window opening and closing.
- *Sunroof Motors*: Similar to window motors, AC motors can be used to operate sunroofs.
- *Climate Control Systems*: AC motors power the fans and compressors in the climate control system, regulating temperature and air flow.

1.5. Rectifiers, Converters and Inverters

This chapter provides a foundational understanding of the electrical and electronic components critical to the operation and maintenance of electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs), (Figure 1.27). It is designed to offer practical insights for technicians and engineers involved in servicing these vehicles, focusing on the systems that power, control, and optimize their performance. Emphasis is placed on the interaction of components that enable efficient energy conversion, power management, and control over the electric drive systems.

Figure 1.27 Overview of power converters within EVs and PHEVs (source –AI generated using Leornardo.AI)

This section presents three key power electronics components found in electric and hybrid vehicles: rectifiers, converters, and inverters. These parts work together to control and change electrical energy throughout the vehicle, allowing smooth transitions between different power sources like the battery, motor, and charging system, while making sure the energy is used efficiently (Figure 1.28).

Together, these components enable seamless power flow between the vehicle's various systems, ensuring that energy is converted and distributed optimally for both propulsion and battery charging. The goal of this chapter is to equip readers with a clear understanding of the working principles behind these critical power conversion systems.

1.5.1. AC/DC Rectifiers

Rectifiers are essential in the charging process of electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs). They convert alternating current (AC) from external sources, like public charging stations or home outlets, into direct current (DC), which can be stored in the vehicle's battery. This section explores the operating principles of rectifiers, including how they regulate and stabilize DC output to ensure safe and effective charging, ultimately supporting battery health and performance.

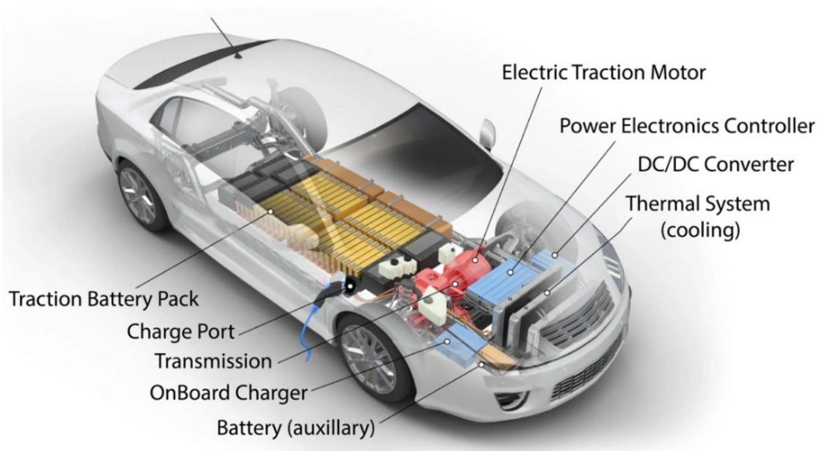


Figure 1.28 Electrical components in the EV and PHEV cars [31]

In EVs and PHEVs, rectifiers are critical components that transform AC, which periodically reverses direction, into DC, a one-directional flow of current. This "rectification" process is achieved through semiconductor devices like diodes or silicon-controlled rectifiers, known for their reliability and efficiency in energy management.

Rectifiers in EVs convert power from the charging source or regenerative braking system into DC to charge the battery. In some cases, the rectified output may need additional smoothing to maintain a consistent DC voltage, crucial for the battery and other systems requiring stable power. This is often done using filters, such as capacitors or inductors. Rectifiers also play a role in managing the charging process, ensuring the battery receives the correct voltage and contributing to the power management system to optimize energy usage.

By contrast, an inverter performs the opposite function, converting DC back into AC to power the motor or other components as needed. This conversion is essential for the operation of many EV motors, which typically run on AC to provide smoother and more efficient power delivery, especially at varying speeds. The inverter also enables regenerative braking, where energy produced during braking is converted back into DC and stored in the battery. This dual functionality makes the inverter crucial for optimizing energy efficiency and extending the driving range of EVs.

Active Front-End (AFE) rectifiers are gaining renewed interest as the demand for high-power Electric Vehicle (EV) charging infrastructure surges. Known for their high efficiency and reliability, AFE rectifiers help minimize disturbances from EV charging operations by reducing harmonic distortion and maintaining operation close to Unity Power Factor (UPF) [29].

1.5.2. DC/DC Converters

DC/DC converters play a vital role in managing voltage levels within electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs). These devices convert the high voltage from the main battery pack, typically ranging from 400V to 800V, down to the lower voltages required to power various vehicle accessories and auxiliary systems, such as lighting, infotainment, power steering, air conditioning, and safety features. Without DC/DC converters, these lower-voltage systems would be unable to operate efficiently from the high-voltage battery in EVs and PHEVs.

The voltage of electric vehicle (EV) battery packs varies depending on the model and manufacturer, with most cars using either 400V or 800V systems. A detailed overview of some of the most popular EVs and their battery voltages is presented within Table 1.2.

Table 1.2 Battery Voltage Systems in Popular Electric Vehicles

Voltage System	Vehicle Model	Battery Voltage	Notes
400V	Nissan Leaf (2nd Generation)	~350-400V	Standard for many mainstream EVs, balancing cost and efficiency for compact/midsize cars.
	Tesla Models (S, 3, X, Y)	~350-400V	Used across Tesla's range for efficient performance and cost management.
	Audi e-Tron, Hyundai Kona Electric, Kia Niro Electric	~350-400V	Common among compact/midsize EVs; efficient for everyday driving.
800V	Porsche Taycan	~800V	First production EV with 800V; allows for faster charging and enhanced performance.
	Audi e-Tron GT	~800V	Shares the Taycan's platform, providing improved charging efficiency.
	Hyundai Ioniq 5, Kia EV6	~800V	Enhances performance and reduces weight, thanks to fewer wiring and cooling needs.

The trend toward 800V systems is growing, mainly due to the faster charging times and potential for greater power output. However, 400V systems remain dominant in the market because they strike a good balance between cost and performance [30]. As charging infrastructure improves, we are likely to see more 800V vehicles on the roads in the near future.

For plug-in hybrid electric vehicles (PHEVs), the high-voltage system is typically higher than in standard HEVs, ranging from 300V to 400V. This allows for longer all-electric driving ranges when the vehicle is plugged in and charged.

The design and functionality of DC/DC converters are critical in ensuring that the electrical systems within the vehicle receive a consistent and stable power supply. In practice, DC/DC converters use semiconductor-based components like transistors, inductors, and capacitors to efficiently step-down voltage levels while minimizing energy loss. The converters must operate with high efficiency to avoid excessive heat generation and power wastage, which can impact overall vehicle performance and energy consumption. Therefore, converter efficiency is one of the most important factors to consider during the design process, especially for EVs, where maximizing range and energy efficiency is crucial.

In addition to providing stable power to low-voltage systems, DC/DC converters in EVs and PHEVs must also be adaptable to a wide range of operating conditions. This includes managing variations in battery voltage as it discharges during vehicle operation, as well as handling input from the regenerative braking system, which can generate varying amounts of energy. Ensuring the converter's ability to handle these fluctuations while maintaining efficiency and reliability is key to optimizing the overall energy management system of the vehicle.

To further enhance the overall energy efficiency, many modern DC/DC converters also feature advanced power management techniques, such as power factor correction, which improves the power quality, and soft-start circuits, which prevent sudden current surges during power-up. These features contribute to reducing energy losses and enhancing the overall lifespan of the vehicle's battery and electrical components.

The integration of DC/DC converters in electric vehicles also helps in reducing the complexity of the vehicle's electrical architecture. By ensuring efficient and stable voltage conversion, converters enable a more compact and streamlined power system, making it easier to manage the diverse power requirements of modern EVs and HEVs. Moreover, as EVs and HEVs continue to evolve, advancements in DC/DC converter technology, such as the use of wide-bandgap semiconductors (like silicon carbide), promise even greater efficiencies, contributing to more sustainable, longer-range vehicles.

In conclusion, DC/DC converters are indispensable for the optimal functioning of electric and hybrid vehicles, ensuring that power is distributed efficiently across the vehicle's systems while conserving energy and improving overall vehicle performance. Their design, efficiency, and adaptability to different voltage levels are central to the success of the vehicle's electrical system, playing a crucial role in maximizing the driving range and supporting the vehicle's long-term sustainability.

1.5.3. DC/AC Inverters

Inverters are a critical component of an EV's drive system, acting as the bridge between the vehicle's DC battery and the AC electric motor. By converting DC power from the battery into the AC power needed by the motor, the inverter enables the efficient operation of the motor and allows the vehicle to perform various driving functions, such as acceleration, deceleration, and regenerative braking.

There are several key functions of inverter technology in EVs and PHEVs cars:

- *DC to AC Conversion with Pulse-Width Modulation (PWM)*

The inverter uses pulse-width modulation (PWM) to create a variable-frequency AC signal from the steady DC power provided by the battery. PWM rapidly switches transistors on and off to create an AC waveform, controlling the frequency and amplitude of the AC power. By adjusting these factors, the inverter can precisely manage motor speed and torque, which enables the EV to accelerate smoothly, coast efficiently, and respond dynamically to driver inputs. PWM also minimizes power loss and heat generation, contributing to overall system efficiency.

• *Motor Control for Enhanced Performance and Efficiency*

The inverter's control over motor speed and torque is central to delivering an optimal driving experience. Advanced inverters use algorithms to regulate the motor's rotation per minute (RPM) in real-time, allowing for smooth acceleration and efficient deceleration. This control extends to regenerative braking, where the motor acts as a generator, converting kinetic energy into electrical energy to recharge the battery. The inverter's role in regenerative braking helps to increase range and improve overall energy efficiency, making it essential for extending EVs' driving capabilities.

• *Thermal Management and Heat Dissipation*

Inverters in EVs operate under high power loads, especially during acceleration or hill climbing, which generates significant heat. To prevent overheating and maintain reliable operation, inverters incorporate thermal management systems. These systems may include liquid cooling channels, heat sinks, or fans to dissipate heat effectively. Some advanced inverters use smart thermal sensors to monitor the inverter's temperature and adjust operation dynamically to avoid thermal overload. Effective thermal management prolongs the inverter's lifespan and ensures consistent performance under various driving conditions.

• *Drive Mode Adaptability and Energy Optimization*

Many EVs feature multiple drive modes—such as economy, sport, or comfort—each tailored to a specific driving style and energy usage profile. The inverter plays a crucial role in these modes by adjusting motor output to match the desired performance characteristics. For example, in economy mode, the inverter may limit power delivery to maximize energy efficiency, while in sport mode, it may deliver maximum power for faster acceleration. This adaptability helps drivers conserve energy or boost performance as needed, enhancing the vehicle's versatility and user experience.

• *Reliability and Fault Management*

High-quality inverters in EVs are designed to detect and manage faults, ensuring safe and reliable operation. If an irregularity, such as a sudden spike in temperature or an electrical short, is detected, the inverter can reduce power output or shut down temporarily to prevent damage to the motor or battery. Advanced inverters may also communicate diagnostic information to the vehicle's onboard computer, allowing technicians to monitor the system's health and address any issues before they impact the vehicle's performance.

- *Bidirectional Power Flow for Vehicle-to-Grid (V2G) and Vehicle-to-Home (V2H) Applications*

Some modern inverters in EVs are equipped for bidirectional power flow, which means they can send power from the battery back to the grid or a home system. This feature, known as vehicle-to-grid (V2G) or vehicle-to-home (V2H), allows EV owners to use their car batteries as energy storage. The inverter's bidirectional capabilities enable this by converting DC battery power back into AC, which can be supplied to power homes during peak hours or returned to the grid to support the broader energy network. This innovative use of inverter technology positions EVs as flexible power assets within smart energy ecosystems.

In summary, inverters are sophisticated and multifunctional devices that are integral to the operation and efficiency of electric vehicles. By managing power conversion, motor control, and energy recovery, they enable smooth and responsive driving, while features like thermal management and bidirectional power flow enhance both reliability and versatility. Understanding inverter technology is essential for EV technicians, as it is key to maintaining vehicle performance and extending battery range in the increasingly diverse landscape of electric mobility.

In electric and plug-in hybrid electric vehicles (EVs and PHEVs), both rectifiers and inverters play crucial roles in the vehicle's power conversion system (Figure 1.29).

1.5.4. Rectifiers and Inverters in EVs and PHEVs

Rectifiers in EVs and PHEVs

Working Principle: A rectifier is used in EVs and PHEVs to convert alternating current (AC) into direct current (DC). This is important because the vehicle's battery, which stores electrical energy, operates on DC.

Applications in EVs and PHEVs:

- *Battery Charging*: When the vehicle is plugged into an AC power source (such as a charging station), the rectifier converts the AC from the grid to DC, which is then used to charge the battery.
- *Motor Drives*: Some EVs use rectifiers in their motor drive systems to ensure that the power delivered to the motors is in the correct form (DC), especially for systems that involve regenerative braking.

Inverters in EVs and PHEVs

Working Principle: An inverter performs the opposite function of a rectifier. It converts DC from the vehicle's battery into AC, which is needed to power the electric motor. Inverters allow for variable frequency control, enabling precise motor speed and torque control.

Applications in EVs and PHEVs:

- *Motor Operation*: The inverter converts the stored DC power from the battery into AC to drive the electric motor. It allows for the regulation of motor speed and direction, a key aspect of electric vehicle propulsion.
- *Regenerative Braking*: During braking, the inverter can also reverse the power flow, converting the AC generated by the motor back into DC to recharge the battery.

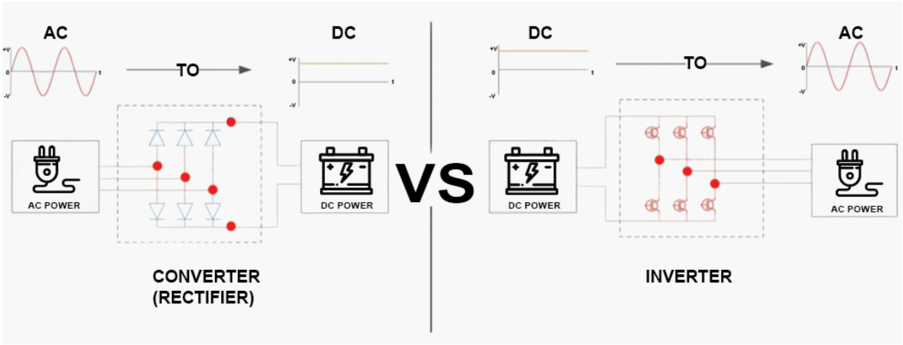


Figure 1.29 Working principles of rectifiers compared to inverters.

Both rectifiers and inverters are critical for the efficient operation of EVs and PHEVs (Table 1.3). Rectifiers ensure the battery is charged from AC power sources, while inverters enable the conversion of stored DC energy to AC for efficient motor control. The coordination of these components allows for smooth and efficient operation, from battery charging to propulsion and regenerative braking.

Table1.3 Power Conversion and Control Methods in EVs/PHEVs

Component	Function	Control Methods
Rectifier	Convert AC to DC for battery charging or supplying DC power to motor control systems.	Controlled mainly by voltage and current control techniques to ensure efficient charging and battery safety.
Inverter	Convert DC from the battery into AC for motor operation, controlling speed, torque, and direction.	Use advanced modulation techniques such as PWM (Pulse Width Modulation), SPWM (Sinusoidal PWM), and SVPWM (Space Vector PWM) to optimize motor performance.

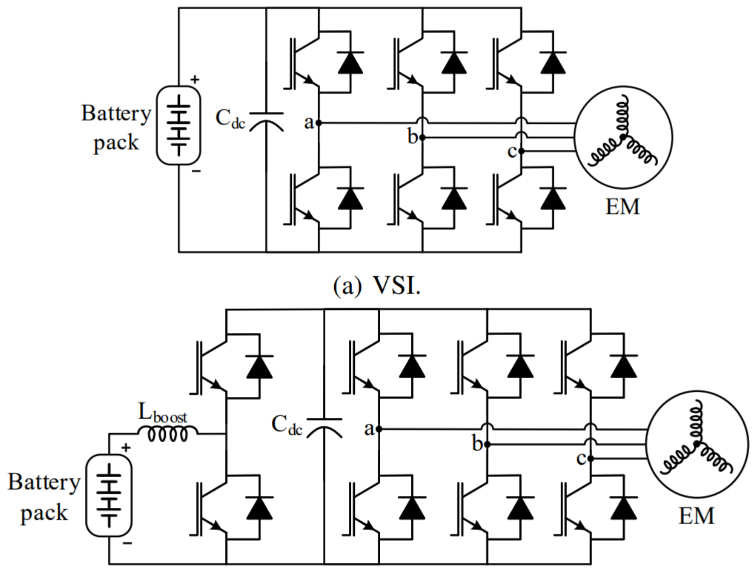
Rectifiers and inverters play essential roles in the energy conversion systems of electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs), as they enable effective management of energy flow between the battery, motor, and external charging sources.

Beyond simply converting AC to DC and vice versa, their functions are highly sophisticated, facilitating efficient propulsion, regenerative braking, and energy storage, all of which are critical for the reliable and smooth operation of EVs and PHEVs such as:

- *Enhanced Energy Efficiency*: Advanced control methods for both rectifiers and inverters optimize power conversion efficiency, which is crucial for extending the driving range. By reducing energy losses in conversion, these components ensure that more power reaches the motor, maximizing mileage per charge.
- *Battery Longevity and Safety*: Efficient rectification techniques are vital for battery health. Voltage and current control methods prevent overcharging or discharging too quickly, which can degrade battery cells. In PHEVs, this protection extends the lifespan of the battery pack, contributing to the long-term reliability of the vehicle.
- *Precise Motor Control*: Inverters are essential for motor management, allowing precise adjustments to torque, speed, and rotational direction, which are key to the driving experience. For instance, modulation techniques such as PWM, SPWM, and SVPWM enable smooth acceleration and deceleration, contributing to the responsive feel expected from modern EVs.
- *Regenerative Braking*: Both rectifiers and inverters contribute to regenerative braking - a process where kinetic energy is converted back to electrical energy and stored in the battery. During regenerative braking, inverters reverse the power flow from the motor back to the battery. This feature is significant for EV and PHEV efficiency as it recaptures energy that would otherwise be lost, extending range and reducing overall energy consumption.
- *Seamless Integration in Hybrid Systems*: In PHEVs, rectifiers and inverters manage energy from both the battery and internal combustion engine systems. This coordination allows for smooth transitions between electric and hybrid modes, improving fuel efficiency and ensuring optimal use of the vehicle's dual power sources.

As presented by John Reimer et.al, the vast majority of EVs use three-phase voltage source inverters (VSIs) with insulated gate bipolar transistors (IGBTs) due to their high efficiency and low cost (Figure 1.30). The inverter’s

DC input can either be directly connected to the battery pack (Figure 1.30a) or supplied through a DC/DC boost converter to regulate the DC voltage (Figure 1.30b). In both configurations, a large DC-link capacitor Cdc smooths out the ripple in current and voltage caused by switching actions of the active devices. This helps maintain a nearly constant DC-link voltage and reduces high-frequency current harmonics [32].



(a) VSI.

(b) VSI combined with a DC/DC boost converter.

Figure 1.30 The standard inverter topologies used in automotive industry [32]

Within the same research paper, the authors have conducted an independent review of the traction inverter designs from several production vehicles across multiple manufacturers. The components of the Nissan Leaf inverter and the Tesla Model S inverter have been analyzed and presented within the Figure 1.31.

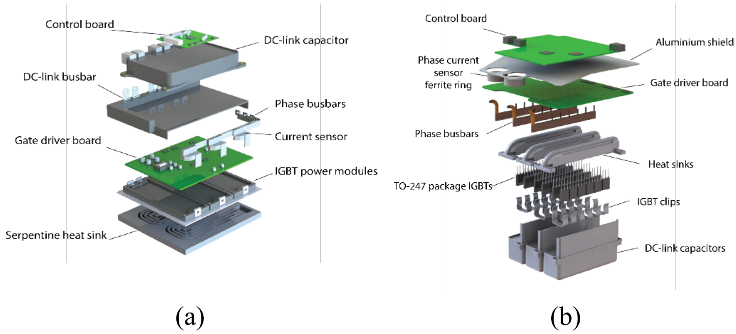


Figure 1.31 (a) Nissan LEAF inverter components b) Tesla Model S inverter components [32]

In summary, rectifiers and inverters are more than simple converters in EVs and PHEVs. They form an advanced control and power management system that underpins core functionalities, from smooth propulsion to energy recovery, making them indispensable to modern EV and PHEV performance and reliability.

1.6. Vehicle Communication Technologies-Data Buses

Modern vehicles are equipped with numerous electronic control units (ECUs) and sensors that manage everything from engine performance and safety systems to in-car entertainment and navigation. To ensure these components work seamlessly together, vehicles use *communication technologies* known as *data buses* (Figure 1.32). In this chapter we will cover some introductory information on data buses and describe diagnostics aspects.

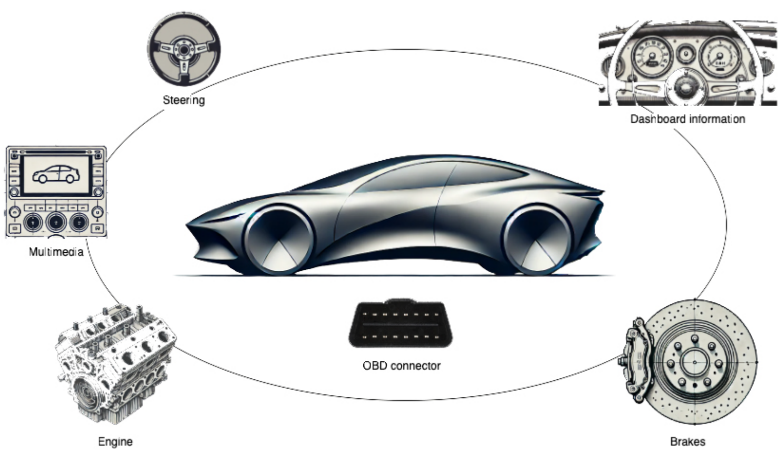


Figure 1.32 A data bus connects all important parts of a car

1.6.1. Data buses

A *data bus* is a communication system that transfers data between components within a vehicle. It acts as a digital highway, enabling ECUs, sensors, and actuators to exchange information efficiently and reliably. The key goal of these systems is to reduce wiring complexity, improve system reliability, and facilitate the integration of advanced vehicle functionalities [33].

Importance of Data Buses

- *Efficient Communication*: they allow real-time data exchange between multiple systems. For some of the systems, like steering, ABS, ESP, it is crucial to ensure that the communication between different components is truly in real-time.
- *Reduced Wiring*: by replacing individual point-to-point connections with a shared bus, data buses minimize the vehicle's wiring harness, saving weight and cost. At the same time, as all the components communicate over the same bus, it is important to prioritize critical elements and ensure that their messages are not delayed by less important ones.
- *Improved Diagnostics*: data buses enable centralized control and diagnostics, making vehicle maintenance easier. By using the OBD connector, service personnel can tap into the system logs and read or delete errors for any of the components connected to the Data Bus.
- *Scalability*: they support the integration of new systems, which is vital for modern vehicles incorporating advanced features like autonomous driving and connectivity.

Diagnostics

As briefly mentioned, the use of Data Buses enables the implementation of complex diagnostics systems that allow service providers to better understand and fix errors on any of the connected components. These systems rely on two major protocols, which will be described in more detail below:

- *Unified Diagnostic Services* – which standardises the communication between the diagnostics tools and the onboard control units of a vehicle.
- *On-Board Diagnostics II* – hardware and software system that standardizes the monitoring of vehicle components and the access to the acquired information.

1.6.2. UDS protocols and services

The Unified Diagnostic Services (UDS) protocol is a standardized communication protocol used in the automotive industry for diagnosing and configuring electronic control units (ECUs) in vehicles. Defined by the ISO 14229 standard, UDS enables consistent and reliable communication between diagnostic tools and a vehicle's onboard systems.

The UDS protocol provides a framework for exchanging diagnostic data between an external device (such as a scan tool) and the vehicle's ECUs. It defines a set of services that support fault detection, system configuration, and reprogramming, ensuring a unified approach across various manufacturers and vehicle types [34].

UDS operates on a request-response communication model, where a diagnostic tester (e.g., a diagnostic tool or software) sends a request to an ECU, which then provides a response. This model facilitates precise control and monitoring of vehicle systems. UDS is implemented over transport layers like CAN (Controller Area Network), FlexRay, or Ethernet, depending on the vehicle's architecture. It adheres to the OSI (Open Systems Interconnection) model, primarily operating at the application layer (Layer 7). Lower layers manage data transfer reliability and network communication.

UDS supports different diagnostic sessions to control the level of ECU functionality available. For example:

- *Default Session*: standard operation mode with limited access to diagnostics.
- *Extended Diagnostic Session*: provides enhanced access for advanced diagnostics.
- *Programming Session*: allows reprogramming and flashing of ECU software.

Importance of UDS

- *Standardization*: UDS ensures compatibility across different diagnostic tools and vehicle manufacturers.
- *Comprehensive Diagnostics*: supports advanced diagnostic and maintenance tasks, including fault reading, system tests, and ECU updates.
- *Efficiency*: enables rapid troubleshooting and software updates, reducing vehicle downtime.

UDS Services Overview

The UDS protocol defines a range of diagnostic services, each identified by a unique service ID (SID). These services are grouped into functional categories, such as data transfer, fault management, and ECU configuration. Key UDS services include [35]:

1. Diagnostic and Communication Management
    - *Diagnostic Session Control* (SID: 0x10) - switches the ECU into different diagnostic sessions, such as default, programming, or extended diagnostic modes.
    - *Tester Present* (SID: 0x3E) - keeps the diagnostic session active by signalling the presence of the tester.
2. Fault Management
    - *Read Diagnostic Trouble Codes* (DTCs) (SID: 0x19) - retrieves fault codes stored in the ECU to identify malfunctions.
    - *Clear Diagnostic Information* (SID: 0x14) - clears stored fault codes and resets the ECU's fault memory.
3. Data Transmission

- *Read Data by Identifier* (SID: 0x22) - reads specific ECU parameters or sensor values.
- *Write Data by Identifier* (SID: 0x2E) - writes or updates certain ECU parameters.

4. Input/Output Control by Identifier (SID: 0x2F) - allows real-time control over an ECU's inputs or outputs for testing purposes (e.g., turning on a fan).

5. Routine Control (SID: 0x31) - executes predefined routines or tests in the ECU, such as system resets or actuator tests.

6. Programming and Configuration

- *Request Download* (SID: 0x34) & *Transfer Data* (SID: 0x36) - used for flashing new software or calibration data onto an ECU.
- *Control DTC Setting* (SID: 0x85) - enables or disables fault detection for specific components during testing.

As vehicles become more connected and autonomous, UDS is expected to evolve, integrating with advanced communication technologies like Ethernet. Enhanced security measures and support for over-the-air updates will further extend its capabilities, ensuring its relevance in modern automotive ecosystems.

In conclusion, UDS is a foundational protocol in the automotive industry, enabling efficient, secure, and standardized diagnostics and maintenance for modern vehicles. Its flexibility and robustness make it indispensable for current and future automotive applications.

1.6.3. OBD II protocols and services

On-Board Diagnostics II (OBD-II) is a standardized automotive diagnostic system that allows for monitoring and diagnosing a vehicle's performance, emissions, and faults. Introduced in 1996 as a requirement in all vehicles sold in the United States, OBD-II has since become a global standard. It provides a universal way to access vehicle data, ensuring compatibility across various makes and models.

OBD-II is both a hardware and software system that monitors a vehicle’s key systems and provides diagnostic information. It uses a standardized Diagnostic Link Connector (DLC), (Figure 1.33), typically located under the dashboard, to allow external diagnostic tools to communicate with the vehicle’s Electronic Control Units (ECUs).

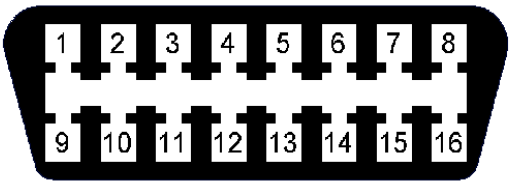


Figure 1.33 Diagnostic Link Connector

The OBD-II system continuously monitors the vehicle's engine and emissions systems during operation. Sensors relay data to the ECU, which evaluates the information to ensure everything is functioning within normal parameters. If a fault is detected, the ECU stores a corresponding Diagnostic Trouble Code (DTC) and may activate the Malfunction Indicator Light (MIL) or "Check Engine Light" on the dashboard [36].

OBD-II data can be accessed through the diagnostic port using a compatible scan tool or software. These tools can retrieve DTCs, view live sensor data, and reset MILs after resolving issues.

Applications of OBD-II

- *Emission Testing* - ensures compliance with regulations by monitoring exhaust emissions.
- *Fault Diagnosis* - helps identify and fix issues, reducing repair time and costs.
- *Vehicle Performance Analysis* - provides real-time data for performance tuning and troubleshooting.

- *Driver Tools* - enables apps and devices to provide fuel efficiency tips and vehicle health monitoring.

OBD-II Components

The OBD-II system consists of several key components that work together to monitor and report vehicle performance and issues:

1. *ECU (Engine Control Unit)* - the central processing unit that controls engine functions, monitors sensors, and adjusts parameters to optimize performance.
2. S*ensors* - devices that measure various aspects of the vehicle's operation, such as oxygen levels, fuel pressure, air intake, and exhaust emissions.
3. *DLC (Diagnostic Link Connector)* - a standardized 16-pin connector located near the driver's seat, used to connect diagnostic tools to the OBD-II system.
4. *Communication Protocols* - OBD-II supports several protocols for communication, including:
   - SAE J1850 PWM (Pulse Width Modulation)
     - Used in Ford vehicles.
     - Operates at 41.6 kbps.
   - SAE J1850 VPW (Variable Pulse Width)
     - Used in General Motors vehicles.
     - Operates at 10.4 kbps.
   - ISO 9141-2
     - Used in Chrysler, European, and Asian vehicles.
     - Similar to the K-line protocol.
   - ISO 14230-4 (KWP2000)
     - Keyword Protocol 2000, common in European and Asian vehicles.
     - Supports more advanced diagnostics than ISO 9141-2
   - ISO 15765-4 (CAN Bus)
     - Controller Area Network (CAN) is the current standard in most modern vehicles.
     - Offers faster communication speeds (up to 1 Mbps)
5. *DTCs (Diagnostic Trouble Codes)* - standardized five-character codes that identify specific issues detected by the system. These codes are

divided into categories such as powertrain (P), body (B), chassis (C), and network (U).

OBD-II Modes of Operation

OBD-II defines ten diagnostic modes, each identified by a unique service ID (Mode $01 to $0A). These modes specify the types of data that can be accessed:

Mode $01: Current Data - provides real-time information on engine performance and sensor values (e.g., engine RPM, coolant temperature, oxygen sensor data).

Mode $02: Freeze Frame Data - captures a snapshot of vehicle conditions at the time a fault is detected.

Mode $03: Diagnostic Trouble Codes (DTCs) - retrieves stored fault codes that indicate malfunctions.

Mode $04: Clear Diagnostic Information - clears stored DTCs and resets emission-related diagnostic data.

Mode $05: Oxygen Sensor Monitoring - provides results of oxygen sensor tests for fuel mixture adjustments.

Mode $06: On-Board Monitoring Tests - reports results of internal tests for emission-related components (e.g., catalytic converters, EGR systems).

Mode $07: Pending DTCs - displays fault codes that are detected but not yet confirmed.

Mode $08: Control of Onboard Systems - allows temporary control of vehicle systems for testing purposes (e.g., turning on fans or actuators).

Mode $09: Vehicle Information - retrieves VIN (Vehicle Identification Number) and other information like ECU software versions.

Mode $0A: Permanent DTCs - displays fault codes that are permanently stored and cannot be erased without resolving the issue.

Standard fault OBD codes

OBD relies on a standardized list of faults, also called DTCs (for Data Trouble Codes), which have been defined so that any diagnostic device can read and decode them. The standard format is presented in Figure 1.34.

P	0	3	0	1

Figure 1.34 Standard format of Data Trouble Codes used in OBD II

Meaning of the first letter of the code:

P: Powertrain, (i.e. engine and gearbox)

C: Chassis

B: Body

U: User network

Meaning of the first digit:

0: Generic fault

1: Manufacturer fault

Note! The standard allows manufacturers to add more codes to this position.

The last 3 digits correspond to an incremental number, with digits ranging from 0 to F (hexadecimal representation).

OBD-II protocols and services are essential for modern automotive diagnostics, providing a universal framework for accessing vehicle data and ensuring efficient maintenance and repair. With its real-time capabilities and standardized approach, OBD-II continues to be a vital tool for technicians, regulators, and vehicle owners alike.

Its integration into modern vehicles ensures compliance with environmental standards, enhances safety, and simplifies maintenance processes. While it has some limitations, its widespread adoption and versatility make OBD-II an indispensable tool in the automotive industry.

1.7. Advanced Driving Support Systems and Autonomous Driving

This chapter offers an overview of Advanced Driver Assistance Systems (ADAS), from basic driver assistance to systems that allow fully autonomous driving. It covers concepts related to the basic structure of ADAS along with the general equipment and technologies required to have them operating, from specific sensors to complex positioning and decision-making systems.

1.7.1. Structure and Equipment

ADAS have been scientifically proven to help reduce the number of road casualties by minimizing human error, reducing risky driver behaviour and even helping with the reduction of traffic jams, carbon emissions and cost of transportation, along with helping enhance driving accessibility for people with disabilities. They use a variety of sensors (Radar, Lidar, Ultrasonic, Cameras, etc.) (Figure 1.35) to detect other cars, obstacles, pedestrians, driving errors and employ interfaces and powerful computing architectures in order to facilitate real-time decision-making and feedback and to enable various levels of autonomous driving.

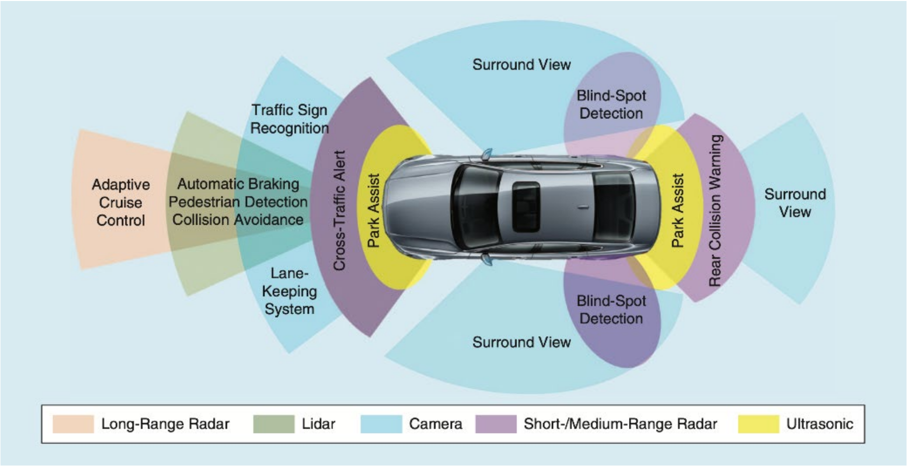


Figure 1.35 ADAS Sensors [38]

1.7.2. Levels

Based on the level of passive/active behaviour and the level of automation, the Society of Automotive Engineers International has defined six autonomy levels for ADAS [39][40] as exemplified in Figure 1.36.

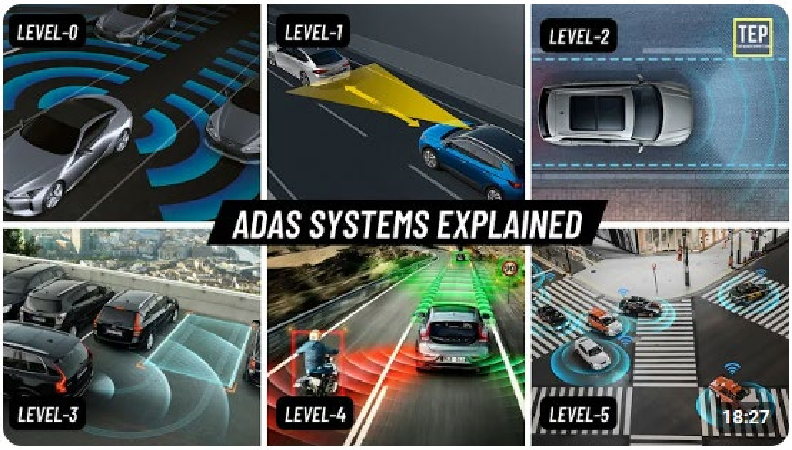


Figure 1.36 ADAS Levels

The six levels of ADAS have the following meaning:

Level 0, No driving automation. At this level, the driver has full control of the vehicle and is not assisted in steering, accelerating or braking by any kind of ADAS. Although, several passive and active safety systems are included in this level, such as anti-lock brakes, Electronic Stability Control or Emergency Brake Assist, Blind Spot Monitoring or Lane Departure Warning.

Level 1, Driver assistance. At this level, the driver is still responsible for all driving activities but can be assisted by ADAS in either steering or accelerating/breaking, but not both simultaneously. This level includes systems such as Adaptative Cruise Control or Lane Keeping Assist.

Level 2, Partial driving automation. At this level, the driver can be assisted by ADAS that simultaneously control the steering and accelerating/breaking but is constantly monitoring the system. This level includes systems such as Traffic Jam Assist, which includes Adaptative Cruise Control and Lane Keeping Assist working together at the same time.

Level 3, Conditional driving automation. At this level, the driver may occasionally engage in activities other than supervising the system but must always be ready to take control if situations occur that the system cannot handle and is prompted to do so. The ADAS can autonomously handle driving decisions, but only for very specific and limited driving scenarios. This level includes systems like Mercedes Drive Pilot or BMW Personal Pilot L3, which have been authorized for scenarios when travelling at up to 60 km/h (37 mph) on German motorways with structurally separated carriageways.

Level 4, High driving automation. At this level the driver is free to engage in activities other than supervising the system and is not required to take over. The ADAS can handle a very wide range of driving tasks (navigate city streets, highways, or other designated areas) but, usually, confined to certain environments or scenarios. This level might include systems such as driverless public transportation on predefined routes or trucks transporting goods within specific geographic boundaries.

Level 5, Full driving automation. At this level the driver is free to engage in activities other than supervising the system and is not required to take over. The ADAS can handle all driving tasks no matter the environment or scenario. Even though it is defined, this level is yet to be achieved.

1.7.3. Sensors

As illustrated in Figure 1.35, several types of sensors are used in ADAS in order to perceive objects outside the vehicle and for its localization in the environment. Due to the fact that each type of sensor has its strengths and weaknesses, when used in the context of ADAS, several types of sensors can be combined for perception. Table 1.4 a comparison of the most used sensors in ADAS. Ultrasonic sensors have been omitted due to their limited sensing scope and range.

Table 1.4 ADAS Sensors Comparison [37]

	RADAR	**LIDAR**	**CAMERAS**
Active/passive sensor	Active	Active	Passive
Spectral components	Millimetre waves	Near-infrared light	Visible light and near-infrared light
Data type	4D point cloud (x, y, z, doppler)	3D point cloud (x, y, z)	2D images
Colour (rgb)	No	No	Yes
Computational burden	Low	Medium	High
Distance capturing	Time of flight	Time of flight	Stereo camera
Velocity capturing	Doppler principle	Track points over time	Optical flow
Strengths	Works well under different light and weather conditions	Very accurate distance measurements	Dense measurements, object classification works well
Weaknesses	Sensible to target reflectivity, bad angular resolution	Sparse measurement, affected by diverse weather conditions	Affected by diverse weather conditions

1.7.4. Sonar, Radar, Lidar, Image Detection

Sonar

Ultrasonic sensors (Sonar) operate by generating high frequency sound waves and measuring their time of flight (reflection return time) in order to estimate the distance to objects around the vehicle. They are typically located on the vehicle's front and back bumper and side corners (Figure 1.37) and are mainly used as backing-up and parking sensors. Their spectral component (sound waves) makes them ideal for low-speed close-range scenarios and their performance can be degraded by an extremely noisy environment. This, coupled with their limited range, makes them mostly unuseful for long-range, high-speed distance detection scenarios such as for automated cruise control or high-speed driving.

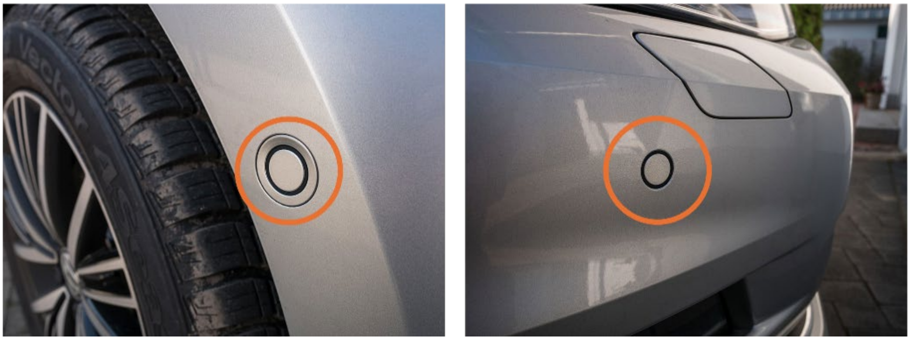


Figure 1.37 Ultrasonic sensors placement

Radar

Radar is one of the sensing technologies incorporated in ADAS. It is mostly used for sensing of the environment around the vehicle using millimetre radio waves. Its limited resolution and accuracy allow it to compute the distance to objects by measuring the time of flight for the emitted radio waves (reflection return time) and, by creating an image from a cloud of points, it can identify object shape and position, but cannot classify the objects (e.g. pedestrian, vehicle, road sign, etc.). Radar is currently used in ADAS based on the category that the sensor falls into (Figure 1.35).

Short-range radar detects objects in the 0.2m-30m range, is usually placed at rear vehicle corners (Figure 1.38 left) and is mostly used for Blind Spot Detection, Rear Collision Warning, Rear Cross Traffic Alert. Medium-range radar detects objects in the 30m-80m range, its placement on the vehicle varies and is mostly used for Front Cross Traffic Assist, Lane Change Assist. Long-range radar detects objects in the 80m-250m range, is usually placed in the front of the car, near the front bumper or behind the grille (Figure 1.38 right) and is mostly used for Automatic Emergency Braking, Adaptive Cruise Control (or Traffic Jam Assist), Forward Collision Warning.

Radar sensors can become misaligned due to different conditions such as light collisions, adjacent repairs of alignment changes. When this occurs, it is imperative that radar sensors are re-calibrated to facilitate their continuous correct operation.

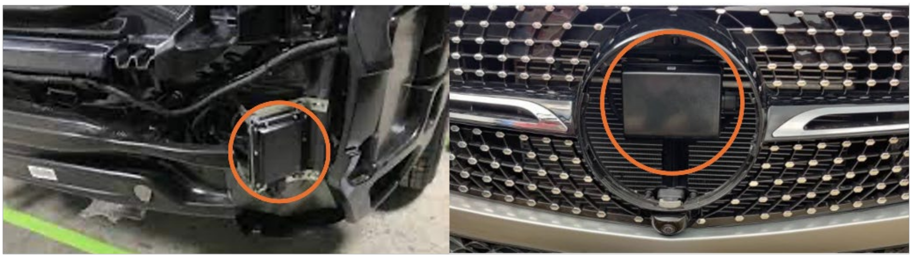


Figure 1.38 Radar sensor placement

Lidar

Lidar works similarly as radar but uses a laser light beam instead of radio waves to sense of the environment around the vehicle. It can compute the distance to objects by measuring the time of flight for the light beam (reflection return time) and, by creating an image from a cloud of points, it can identify object shape and position. Unlike radar, it can even classify some objects (e.g. pedestrian, vehicle, road sign, etc.) due to the enhanced 3D resolution. Mechanical lidar can generate a field of view of a full 360°, but is not very reliable, mostly due to the spinning mechanical parts. Solid-state lidar is more reliable, cheaper and can be used along with other types of sensors to augment environment sensing, but with a much lower field of view. Unlike radar, lidar cannot be placed behind other car elements such as bumpers or grilles. Based on the type of lidar, it is either roof mounted (Mechanical lidar, Figure 1.39 right) or front/back oriented (in the grille, Figure 1.39 left or behind the windshield). Lidar is used in ADAS, along with other types of sensors, for applications such as Automatic Breaking, Pedestrian Detection, Collision Avoidance, Lane Detection, Adaptative Cruise Control.

Figure 1.39 Lidar sensor placement

Image detection

Cameras, along with image detection have become one of the most versatile and important sensors used in ADAS. They are one of the cheapest and readily available sensors and can be used for many sensing tasks, depending on the type of camera ensemble used. Cameras in ADAS are mostly monocular or stereo. Monocular cameras have only one lens, generate a single image at a time and thus have lower image processing requirements than other camera types. However, monocular cameras lack depth information and thus cannot reliably be used for estimating distance. They best serve use cases such as detection of obstacles, pedestrians, lanes, and traffic signs, including traffic lights. Stereo cameras are an ensemble of two or more lenses situated at a fixed distance. Such ensembles are useful at extracting three-dimensional information from captured images and can accurately estimate distance up to a range of 30m. Stereo cameras are usually placed inside the vehicle, behind the rear-view mirror and angled in such a way as to face slightly downwards, towards the road. Monocular cameras can be placed in a large variety of places (front bumper, lateral mirrors, lateral pillars, rear pillars, above the rear license plate, etc.), depending on the task that they are serving.

As proof of the cameras' versatility, Tesla's latest Autopilot is solely based on 8 cameras (Figure 1.40). Three cameras are mounted to the windshield above the rear-view mirror (4), a camera is mounted to each front fender (5), a camera is mounted in each door pillar (3) and a camera is mounted above the rear license plate (1). Powerful image processing and AI techniques use these cameras to take all decisions during driving.

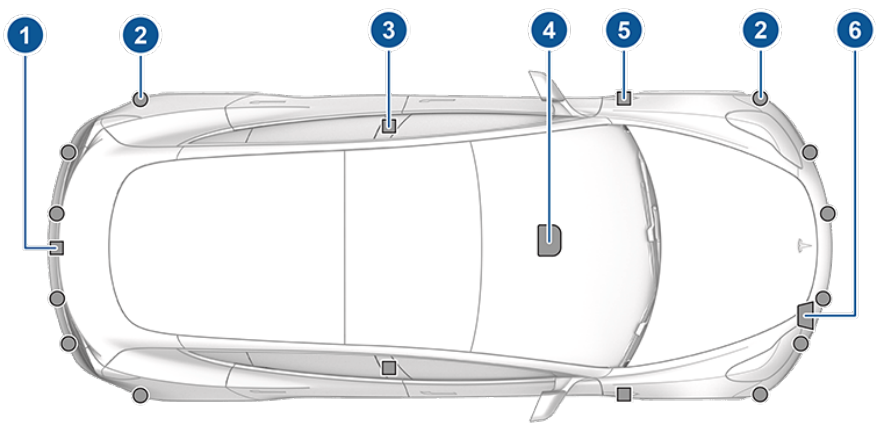


Figure 1.40 Tesla Model 3 camera placement

1.7.5. Positioning Systems

While sensors that enable to accurately perceive the vehicle's environment are a crucial part of ADAS, there is another type of sensorial systems that must be integrated in order to work our way up on the driving autonomy levels: positioning systems [41] (Figure 1.41).

Figure 1.41 Positioning systems

The Global Navigation Satellite System (GNSS) is the term that brings together all global satellite navigation systems and is a system that can offer ADAS precise positioning, navigation, and timing. It uses signals from multiple satellite systems (e.g. GPS, GLONASS, Galileo, BeiDou) to measure distance from at least three satellites to accurately determine the vehicle's position, even in complex urban scenarios and different types of weather, through a process called trilateration. Thus, GNSS plays a crucial role in vehicle positioning systems, but requires additional information for absolute accuracy from other sources, especially at times when GNSS satellite signals are unreachable or not accurate enough (e.g. dense urban scenarios or tunnels).

Inertial Measurement Units (IMUs) are sensor ensembles that incorporate accelerometers and gyroscopes and can estimate and keep movement parameters such as position, velocity and orientation, by integrating acceleration and rotation rate data over time. IMUs can compensate over short intervals of time for satellite signal loss, but they tend to deviate from the real values the longer it runs without updating the frame of reference. However, they can be successfully used for positioning the vehicle for those relatively short time intervals in which, for example, the vehicle is going through a tunnel. Using GNSS as an absolute positioning system and IMUs, along with relative positioning systems comprising the other types of sensors (radar, lidar, cameras), ADAS can accurately position the vehicle. This also allows for geofencing, i.e.

creating virtual boundaries for specific areas or driving scenarios in which particular ADAS functions can be safely enabled, e.g. Mercedes Drive Pilot or BMW Personal Pilot L3 or other level 3 conditional driving automation.

1.7.6. Driving Decision Systems

To make ADAS complete, all sensory information must be processed and based on the results, the systems can take driving decisions. Figure 1.42 shows the flow of operations for visual data in ADAS [38].

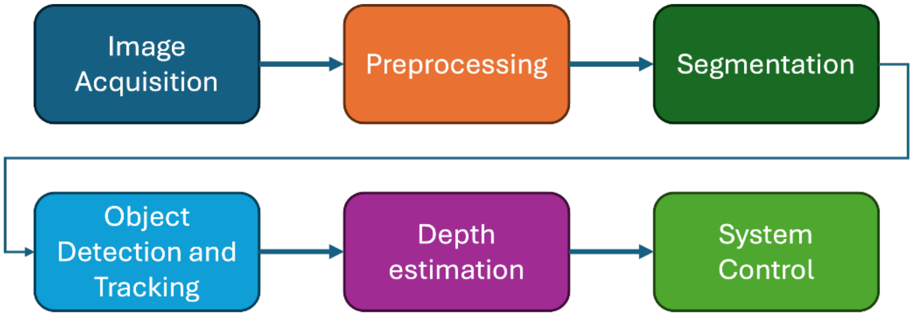


Figure 1.42 Operations flow for visual data in ADAS (Adapted from [38])

Image Acquisition

This stage isolates individual frames from the video stream of one or more cameras. The resulting RGB images (individual pixel colours) are sent along the data flow to the preprocessing stage. Image data acquisition framerate can vary depending on the specific need for detection (e.g. when estimating parameters that are influenced by high speed like distance to other vehicles, a higher frame rate is required, but when detecting traffic signs, a lower frame rate will suffice).

Preprocessing

Raw sensorial data must undergo a process of filtering and preprocessing before detection algorithms car correctly run on them. Most common preprocessing operations include denoising, various image enhancements, colour space conversions and other state-of-the-art filtering operations from the field of image processing.

Segmentation

Segmentation is the process that separates different features from a single image. For instance, segmentation might identify the pixels that belong to road, sky, or objects of interest such as pedestrians, other vehicles, traffic signs, traffic signals, lane stripes etc. This is usually achieved by applying various techniques and thresholds or to exploit known features of the objects (e.g. a stop sign will have red pixels).

Object Detection and Tracking

This stage classifies objects in an image and tracks the identified objects across different frames. This is mostly accomplished with state-of-the-art Machine Learning (ML) techniques that operate on extremely large data sets in order to learn how various objects of interest (e.g. pedestrians, other vehicles, traffic signs, traffic signals, lane stripes, etc.) look like in pictures. Once trained, neural networks are able to express a confidence score with regard to an object that was identified.

Depth Estimation

To estimate the distance from the vehicle to the objects that were detected in the previous stage, most often a stereo camera will be used. Stereo cameras are camera ensembles with two or more lenses that are at a fixed, known, distane. These ensembles can be used to estimate depth by simultaneously processing the images captured by all the cameras. There are also techniques to estimate depth from the image sequence of a single camera, but there usually include very complex computation and require frequent calibration.

System Control

This stage incorporates the results from all previous stages and, based on the confidence score over the type of objects detected, their positions, velocities and other relevant parameters, makes driving decisions and signals the vehicle's controls to take appropriate actions. This stage often incorporates data from multiple types of sensors and bases the decisions on all readings or detections, thus making other stages' accuracy crucial in order to avoid taking decisions based on false positive detections.

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CHAPTER 2

Introduction to Hybrid and Electric Vehicles

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2. Electric and Hybrid Vehicles Technology

2.1. Electro-Mobility Concepts

Electro mobility, also known as e-mobility, is the idea of enabling electric propulsion of automobiles and fleets through the use of interconnected infrastructures, electric powertrain technologies, and in-vehicle information and communication systems. Plug-in hybrids and fully electric vehicles are examples of powertrain technologies. E-Mobility initiatives are driven by market demands for reduced operating costs as well as the need to meet corporate fuel efficiency and emission standards. One important component in lowering CO2 is electro mobility. More than 24% of global CO2 emissions in 2016 came from transportation, so the transition to fully e-mobility cannot be hurried. Achieving a 55 percent reduction in emissions by 2030 and becoming carbon neutral by 2050 are the goals set by the European Union. Passenger cars, which currently account for around 12% of EU CO2 emissions, must quickly decarbonize in order to meet these targets. The solution to these challenges could be the expansion of the vehicles powered by electricity, generally known as electro mobility. Electrical energy can be used to define this term [1-3, 18].

Hybrid Electric (HEV) Vehicles

Hybrid electric vehicles (HEVs) utilize an internal combustion engine alongside one or more electric motors that draw energy from stored batteries. By merging the advantages of impressive fuel efficiency and minimal tailpipe emissions with the capability and distance of traditional vehicles, HEVs offer a compelling option. In these vehicles, the additional power from the electric motor can enable the use of a smaller combustion engine. Furthermore, the battery can supply energy for auxiliary functions and diminish engine idling when the vehicle is stationary. Plug-in hybrids (PHEVs) incorporate a battery-driven electric motor in conjunction with an internal combustion engine [4-8].

Hybrid electric vehicles (HEVs) merge an internal combustion engine with an electric propulsion system. Nonetheless, they surpass conventional internal combustion engines in efficiency by utilizing technologies like regenerative braking [4-8].

Electric (EV) Vehicles

An electric vehicle (EV) operates using electricity as its power source. Battery electric vehicles (BEVs) rely solely on electricity for operation. To power a BEV, you charge its battery with electricity, which in turn energizes the electric motor that drives the vehicle forward. Because the car does not combust any fuel to create motion, it produces no tailpipe emissions. The carbon footprint of a BEV is instead influenced by the method of electricity generation used to charge it. Among the common BEVs included in our program are the Chevrolet Bolt, Nissan LEAF, and Hyundai Kona EV [9, 10].

Differences between PHEV and BEV shown on figure 2.1 are:

- PHEVs are equipped with LPG and therefore:
- have a fuel tank,
- exhaust system (exhausts),
- cooling system for the engine and for this reason
- heating and ventilation in them are done through the conventional method, while in the case of electric cars it is necessary in most cases to use a heat pump to provide heating and air conditioning for the passengers in the passenger compartment and to maintain optimal temperature regimes of the battery.

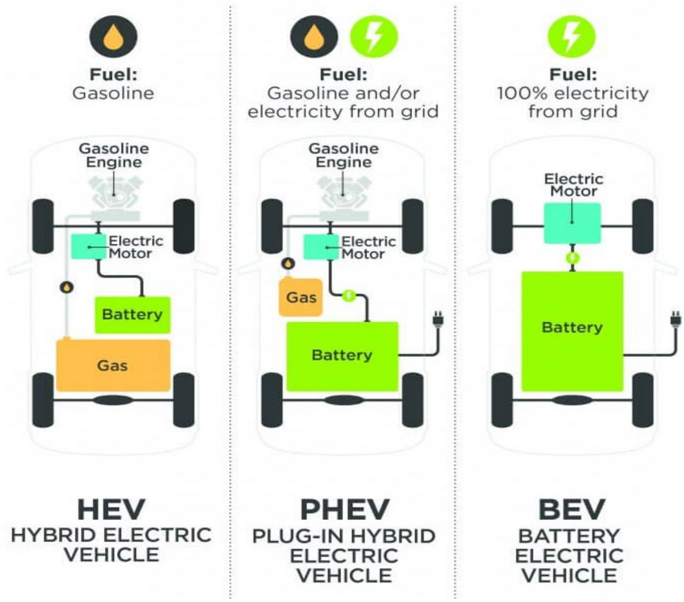


Figure 2.1 Differences between Plug-in Hybrid EV and EV [11]

Similarities between PHEV and BEV:

- Availability of a large battery for storing electrical energy.
- Charging with an external source of electrical energy, and for this reason there is a coupling for charging from a charging station
- Regeneration of electrical energy when stopping
- Electric motors for driving the car
- Device for converting alternating current into direct current when charging from a charging station.

Comparison of Internal Combustion Engine Vehicles and Electric Vehicles

The main types of electric vehicles in comparison with vehicles propelled with ICE are shown in figure 2.2.

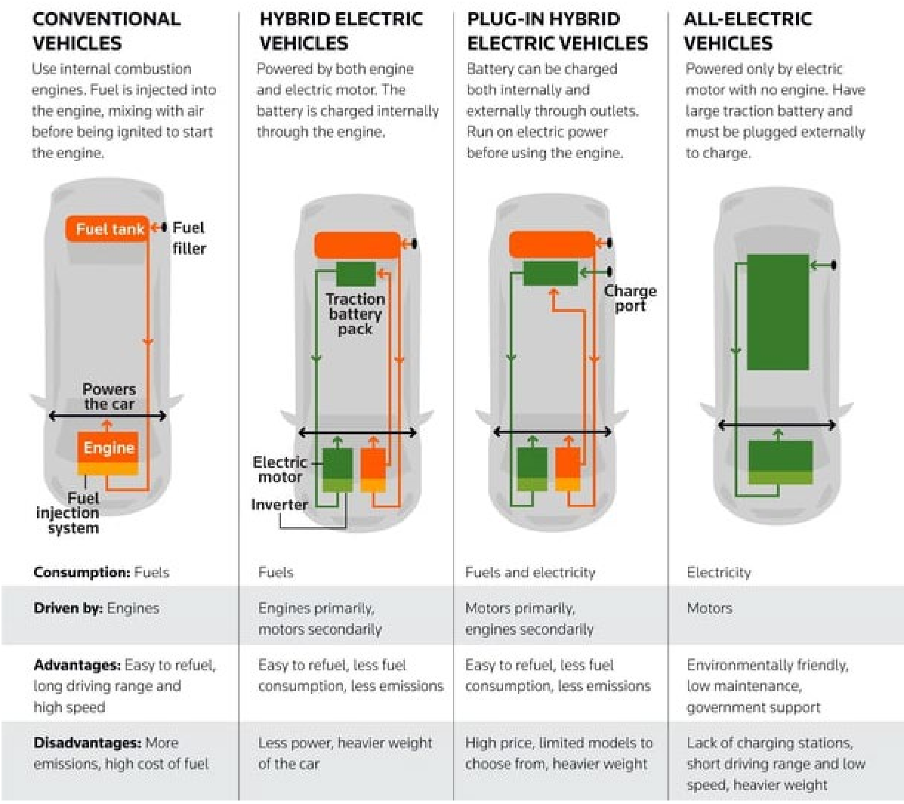


Figure 2.2 Types of electric vehicles and comparison with ICE vehicle [12]

2.2. Hybrid Vehicle Technologies

A Hybrid Electric Vehicle (HEV) is propelled by two or more energy sources, one of which is of electrical origin. The most common powering sources for an HEV are mechanical (ICE) and electrical (from batteries). In the HEV, the addition of an electric motor allows the gasoline engine to be downsized. The gasoline engine in a hybrid is built within the specification of the average power need in driving the vehicle as opposed to the peak power because the electric motor can provide full operation at low speeds plus an acceleration assist when extra energy is needed (high accelerations or climbing steep inclinations). This really combines the fast-refuelling aspect of the ICE with the energy-saving aspect of an EV. The on-board electronics of an HEV can determine whether the gasoline engine, the electric motor, or even both would be the most efficient means of use at any given time [13].

2.2.1. Types and Structural Features

Hybrid Electric Vehicles can be broadly classified into four main categories based on their level of hybridization:

Typically, micro hybrids are powered with a 12V battery and have a maximum electric power capacity of 5 kW. Since their power is low, their capabilities are limited to engine Start-Stop - when braking or idling the engine is turned off and restarted again when needed, thus allowing to save fuel and reduce emission. Although the main drawback of this novelty in the field is limited capacity and capability, this is compensated by the very low price, ease of implementation, and the simplicity of control [14].

Mild hybrids are essentially vehicles with an internal combustion engine plus a slightly enlarged battery and an ancillary electric hybrid motor/generator in a parallel hybrid arrangement. It is not sufficiently large for an electric-only mode of propulsion but does enable the internal combustion engine to be switched off when the vehicle is coasting, braking, or when it has come to a stop. Thereafter, the engine can be started again as soon as power is needed once more. Mild hybrids also usually use regenerative braking and some form of power assistance to the internal combustion engine [15].

In the shape of 48-volt electric systems, mild hybrids do not need to be plugged. The batteries are charged by a mix of power from the gasoline engine and energy recovered when the vehicle brakes; this is also known as regenerative braking.

A full hybrid can operate on the engine, the batteries, or any combination of the two. A big, high-capacity battery allows for operation solely on electricity. These cars have a split-power path, which means it can do more flexible things in the drivetrain by inter-converting mechanical and electrical power. To balance the forces from each portion, the vehicles use a differential style of linkage between the engine and the motor that is connected to the head end of the transmission.

Full hybrid electric vehicles are provided with a battery of not less than 150 V. This has the power of a full hybrid that can energize an electrical powertrain of at least 40 kW. Similar to mild hybrid versions, these vehicles can also be powered solely by electricity to drive the vehicle in short distances. Due to the increase in power rating, these vehicles can store even more kinematic energy during braking, which allows much more fuel saving at the cost of weight as well as price addition. Regarding full hybrid vehicles, there are two main types when it comes to the powertrains: Parallel hybrids and Series hybrids.

The key difference with plug-in hybrids is that these cars can charge their batteries via external chargers as well as internal ones; hence, they usually have greater electric-only ranges than full hybrids. In that respect, Plug-In hybrids essentially serve as something of a half-way point between full hybrid vehicles and fully electric vehicles.

Technically, all-electric vehicles do not fall under the Hybrid category, but some use the little gasoline engine as a backup. After an electric car has run out of power, it takes time to charge before it can become operational again. This range extender hybrid uses its gasoline engine to recharge the battery or drive the electric motor and get you home again rather than leaving you stranded. Depending on how big the 'little' gasoline engine is, this might be a few dozen miles up to hundreds.

2.2.2. Working Principles

In the series hybrid powertrain, illustrated in Figure 2.3, mechanical output from ICE is converted into electrical energy by a generator and the charged electrical energy is used to charge the battery or is fed to an electric traction motor which drives the wheels. The required power electronics components comprise of an AC-DC converter for charging the batteries and a DC-AC inverter for traction motor propulsion. [16].

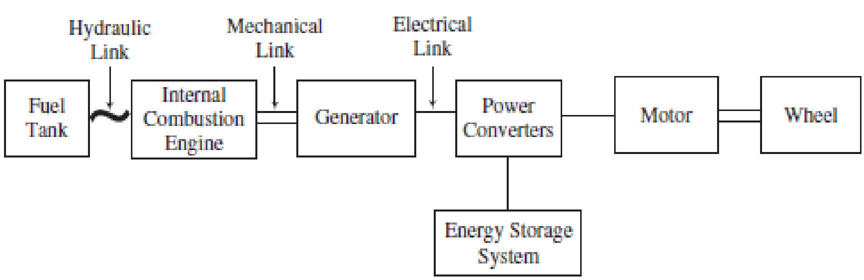


Figure 2.3 Series HEV powertrain

In series configuration (Figure 2.3), the engine is not directly linked to the road load; as a result, the engine does not undergo abrupt changes in operating conditions and will have negligible idling time, which in turn reduces emissions and is more environmentally friendly. Some other advantages of a series hybrid are flexibility in the location of the engine–generator set and simple design. The only disadvantage is that it needs three propulsion components: ICE, generator, and motor. This will result in a longer chain of energy transmission, and, therefore, the efficiency of series hybrids is generally lower than parallel hybrids [16, 18].

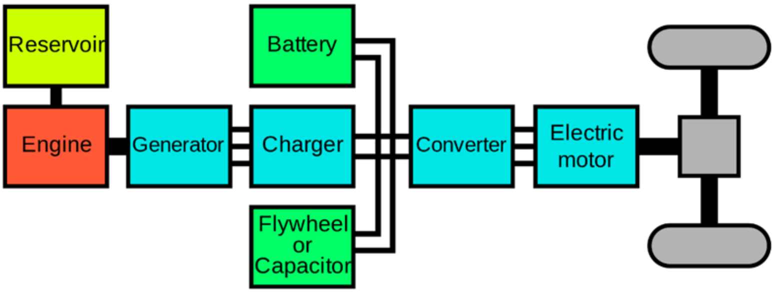


Figure 2.3 Series Hybrid fitted with a super capacitor or a flywheel

In a parallel hybrid powertrain, more than one energy source can provide propulsion power. In this hybrid arrangement, the ICE and the motor are possible to be coupled in many ways; the force needed for propulsion can be supplied either by the ICE or the electric motor or both. The electric motor can function as an electric generator and charge the battery pack during regenerative braking or when the ICE output power is greater than the required power at the wheels.

Choosing a smaller ICE and a smaller motor will be an equivalent in obtaining similar performance of the non-hybrid version. It can be more cost-effective to choose parallel hybrids over series hybrids. However, the disadvantage of the former is that it will require a control system with increased complexity. This is because the propulsion force of a parallel hybrid vehicle can be given both by the ICE and the electric motor. Illustration of a typical powertrain in parallel hybrids is shown in Figure 2.4.

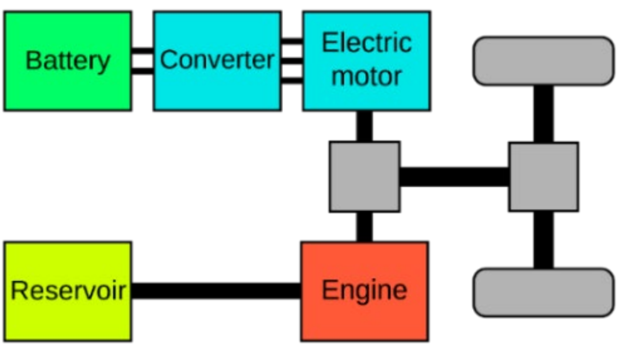


Figure 2.4 Parallel hybrid powertrain

2.2.3. High Voltage Components of Hybrid Vehicles

In a high-voltage hybrid, either the electric motor or the combustion engine can supply drive power to the powertrain, independently of each other or together. In this way, combustion-powered, hybrid, and purely electric propulsion are all possible.

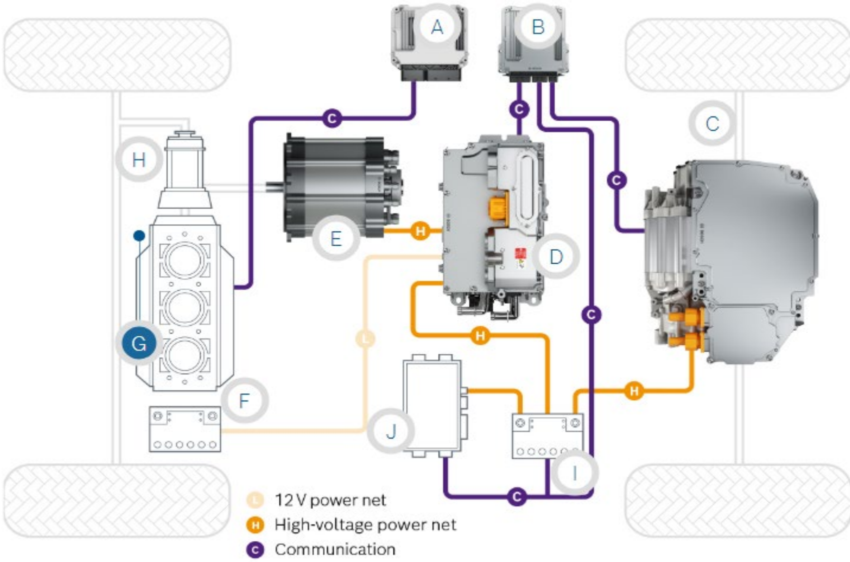


Figure 2.5 Main components and connections between them in PHEV [17]

Figure 2.5 describes the main high voltage components in the PHEV and electrical and communication networks between each other. The main components are:

A- Electronic engine control unit;

B- Vehicle control unit;

C- eAxle;

D- Power electronics, incl. DC-DC converter;

E- Separate motor generator;

F- 12 V battery;

G- ICE (Internal combustion engine);

H- Gearbox;

İ- High-voltage battery (400V and more);

J- On-board charger

The AC/DC charger is a tool that switches the input current voltage from an outside power place into direct current voltage that can be kept in the high-voltage battery pack. Current voltage can't be kept and needs to be “used up,” where direct current voltage is able to be kept and “used up” at a later time. In case a hybrid or electric vehicle has a plug-in design, it takes in AC voltage from an outside power place; however, that voltage has to be changed inside the vehicle and stored as electrical energy for use at a later time [17].

A DC/DC converter takes in high-voltage direct current at the input and changes it to low voltage direct current as output. This output acts as the source of electricity for the low-voltage system and also for the low-voltage battery, just like a generator gives electrical output for the low-voltage electrical systems.

It is meant to convert the DC voltage from the high-voltage battery into AC voltage that can be used to power the electric drive motors. The AC drive motors need AC to create a rotating magnetic field which can then be used to turn the output shaft. The inverter utilizes inside transistors for altering the output voltage. In order to control the speed of the output, the frequency of the current is changed, and to control the power output (which is torque), the inverter changes the amplitude of current.

The motor-generator set designed for hybrid and electric vehicle powertrains works on high-voltage alternating current to create the rotating magnetic field which is used to drive the output shaft and thereby the vehicle. In regenerative braking, the vehicle’s kinetic energy drives the output shaft to act as a generator recharging the high-voltage battery pack.

2.2.4. Hybrid Vehicle Control Systems

The control system is at the heart of an efficient hybrid vehicle both in terms of performance and delivering fuel economy. Its objective is to ensure smooth interaction among the several available power sources—IM, ICE, and energy storage. In addition to optimizing fuel economy and reducing emissions, proper coordination between these entities is essential to derive their maximum benefits. Furthermore, such control systems improve the response of the vehicle as well as driving dynamics. By monitoring a series of real-time parameters, the system can adjust to variations in driving conditions and driver input so that driving becomes more efficient.

A Hybrid Vehicle Control System includes many basic parts which work together to optimize performance and efficiency. These are mainly supported by the Engine Control Unit, Energy Management System, and Electric Motor Control. The Engine Control Unit handles engine tasks to make sure fuel efficiency is good as well as control emissions. Energy Management Systems

(EMS) play a vital role by managing the distribution of electrical energy among the battery, electric motor, and internal combustion engine.

2.2.5. Powertrain Systems

The broad categories of hybrid powertrain systems can be subdivided in various sub-categories based on the relationship between power sources and drive wheels.

Two-clutch parallel-hybrid powertrain is illustrated in Figure 2.6. In the parallel hybrid, powertrain petrol engine and the electric motor can both power the wheels in series or can work simultaneously. In the case of rear-wheel-drive vehicles, one typical hybrid-powertrain configuration employs an electric machine sandwiched between two clutches [18].

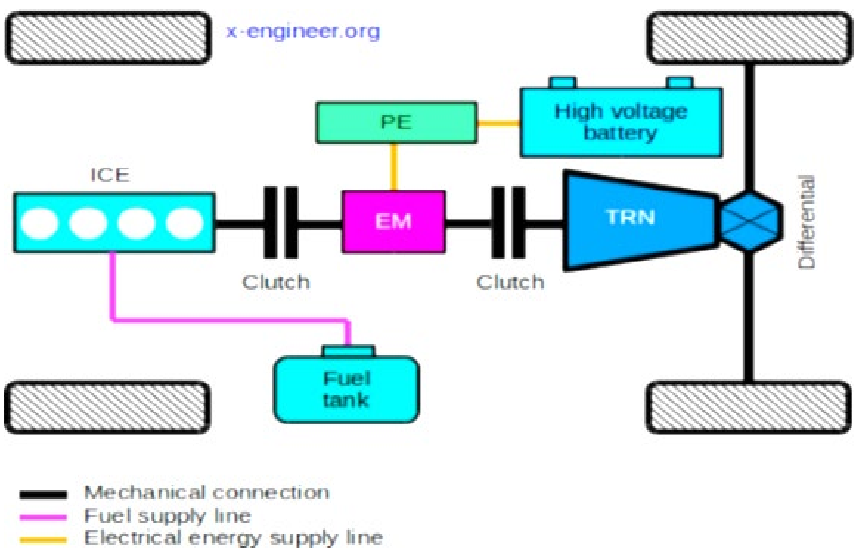


Figure 2.6 Parallel hybrid powertrain with two clutches

The initial clutch, which lies between the engine and electric motor, grants the engine the ability to disconnect from the drivetrain and thus enable itself to drive solely in pure EV mode. The other clutch allows the electric machine to also disconnect from the drivetrain; this is what will enable the vehicle to coast whenever deceleration is called for.

In a series hybrid powertrain (Figure 2.7), the internal combustion engine does not supply torque directly to the drive wheels. It drives an electrical generator. This generator produces all the electrical energy, which the vehicle traction electric motor uses. A series hybrid uses two electric machines: an electric generator connected to the engine and an electric motor connected to the wheels through a single step gearbox and a differential.

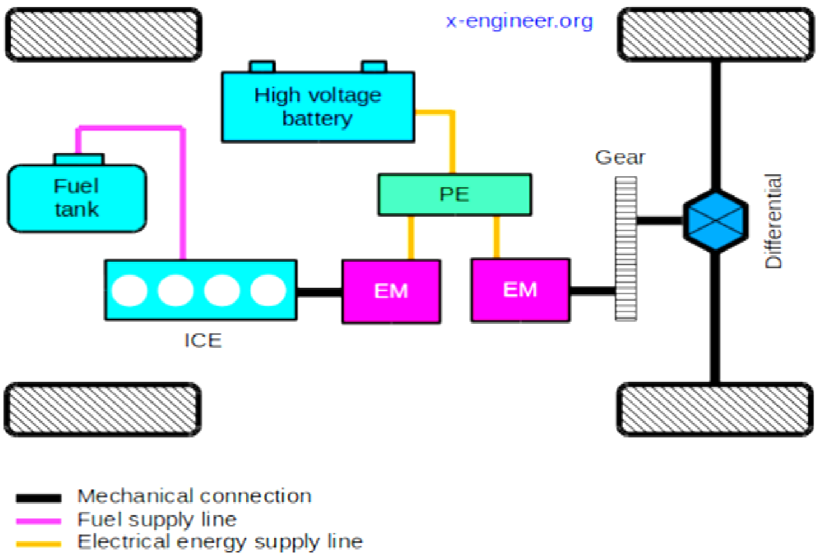


Figure 2.7 Series hybrid powertrain

A series hybrid is inflexible in terms of power output for a wide range of vehicle speeds. Thus, not suitable as hybrid powertrain architecture for road vehicles. However, since it can be fitted with a smaller engine, with a smaller rated power than the traction electric motor, it becomes a Range Extended Electric Vehicle—an REEV.

A series hybrid is converted to a series-parallel hybrid by adding a mechanical connection between the two electric machines. Such architecture has the benefit of low speeds with the clutch open since then the powertrain can behave as a series hybrid and thus run the engine on the most efficient operating point (Figure 2.8). When the vehicle is running fast, the clutch is closed, and the engine is able to transmit torque to the driving wheel; in this case, the powertrain turns into a parallel hybrid.

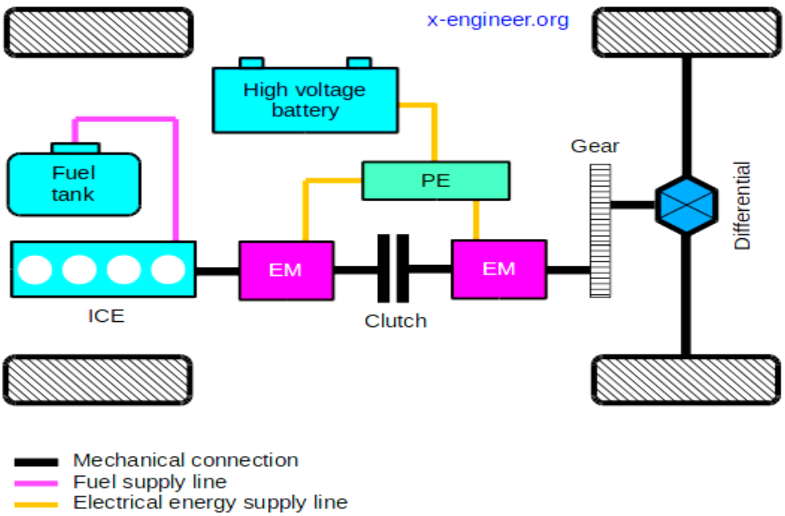


Figure 2.8 Series-parallel hybrid vehicle

Figure 2.9 shows a hybrid vehicle with a power-split architecture, which combines the parallel and series characteristics. A power-split hybrid powertrain mechanically links an internal combustion engine and two electric machines using a power split device (PSD). These two main components of the power-split device are usually a single PSG or multiple PSGs [18].

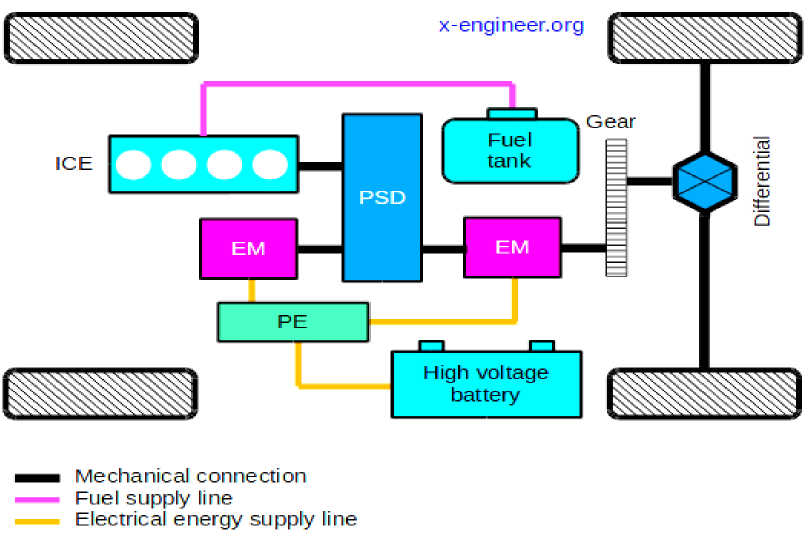


Figure 2.9 Power-split hybrid powertrain

2.2.6. 48V Hybrid Vehicle System

A type of hybrid that has grown more popular in recent years is the 48-volt mild-hybrid system. Its use has broadened the performance and efficiency of vehicles from many automakers and has become an attractive way to get more power from a vehicle without hurting fuel economy.

Mild hybrids, also referred to as 48-volt mild-hybrid systems, represent the least electrified version of hybrid powertrains. These use a small electric motor—sometimes referred to as an integrated starter generator (ISG)—which is bolted to the engine and works in tandem with the internal combustion unit to provide extra power for acceleration. The Volvo ISG is 42 volts, for example. (Figure 2.10) [19].

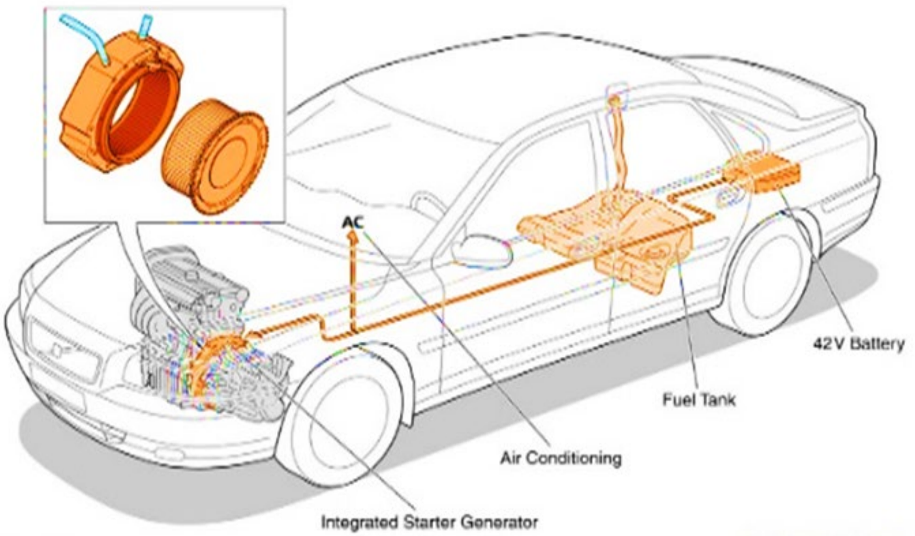


Figure 2.10 The 42-volt Volvo Integrated Starter Generator from 2001[19]

2.3. Electric Vehicle Technologies

An all-electric vehicle (AEV) is a battery electric vehicle (BEV), pure electric vehicle, only-electric vehicle, fully electric vehicle, or all-electric vehicle that uses only the chemical energy stored in rechargeable battery packs and has no secondary source of propulsion, such as a hydrogen fuel cell or internal combustion engine. These electric vehicles drive the wheels by means of electric motors and motor controllers instead of the normally used internal combustion engine (ICE) and do not contain an internal combustion engine, fuel cell, or fuel tank because all power is derived from the battery packs.

An EV is driven by one or more electric motors, supplied with energy by a battery pack. This keeps electricity obtained from the grid by powering up the car with a cable. The battery gets charged using an outside source – a charging plug gets put into the car's charge port. The car's on-board charger changes the plug's electrical current to a type that can charge the battery, whether it's AC (alternating current) – like the sort of power in our home wall outlets – or DC (direct current) – like the type available at public fast charging stations [18].

2.3.1. Types and Structural Features

The main type of EV can operate entirely on electric motion, using just batteries as the energy supply. BEVs send power to the drivetrain only through batteries, depending entirely on stored energy. Thus, range relies on battery capacity. Inside the vehicle, the particular parts of BEVs are shown in Figure 2.11.

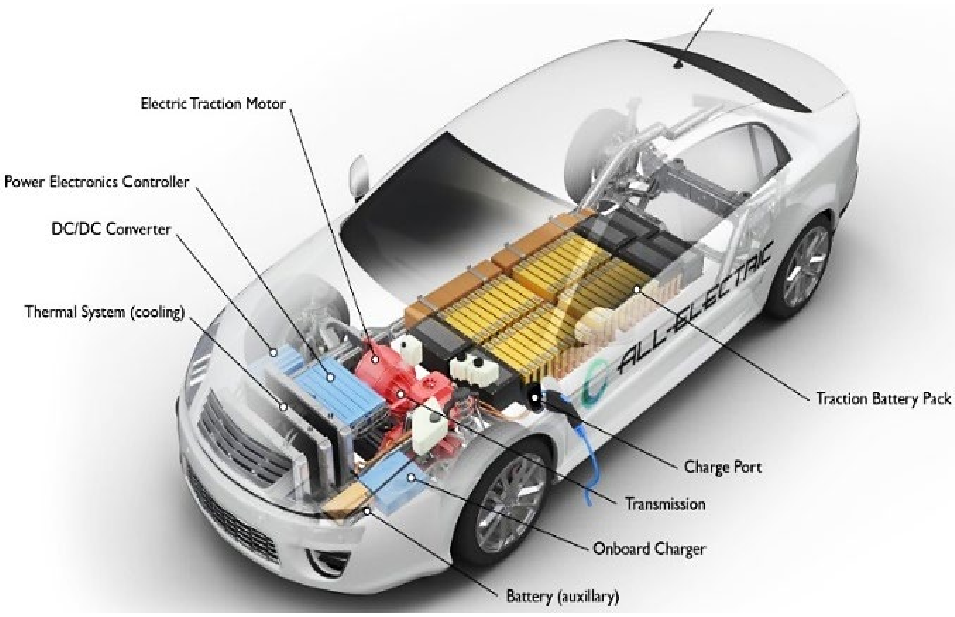


Figure 2.11 Main components of BEVs

2.3.2. Working principles

The working principle of electric vehicles is to convert the electrical energy either stored inside the batteries or generated by other sources into mechanical energy, which will drive the vehicle forward [18]:

- Electric Motor: Instead of internal combustion engines, electric motors are used in EVs — Electric Motors convert electrical energy into mechanical energy. As soon as electricity finds its path through the motor, it creates a magnetic field that causes the motor to spin. This spinning motion is transferred further to the wheels of the vehicle for forward motion.
- Power Electronics: It takes the battery DC and changes it to AC for the motor — then, it also does the job of controlling how fast and how much power the motor has, which for you means your car can speed up and slow down nicely.
- Regenerative Braking: This is one of the most interesting features of most EVs. When the vehicle decelerates, the electric motor operates as a generator; transforming part of the kinetic energy into electric energy, which is later stored in the battery. Such a process helps to enhance the range of the vehicle.
- Charging: Plugging an electric power source into an EV allows you to recharge the battery. A complete charge takes between several hours and a few minutes based on the charger type. Later, we will discuss the different levels of charging an electric car.

2.3.3. Driving Systems

The key parts associated with the drive system of an EV include the electric motor, power electronics, and the battery pack, as well as a controller. Battery pack voltage and capacity largely determine vehicle range and performance. It supplies the electric motor with electricity in the form of direct current. An electric motor carries out the same function in an EV that an internal combustion engine does in a traditional car. It changes the battery's electrical energy into mechanical energy for moving the wheels.

2.3.4. Power Electronics

The power electronics controller is the flow manager of electrical energy delivery from the traction battery and thus controls the speed of the electric traction motor and the torque produced. The main components of power electronics controller are 1. Rectifier, 2. DC-DC converter, 3. Input filter, 4. Inverter as shown in Figure 2.12.

Commands are received by the motor controller from interfaces such as throttle, brake, and forward/reverse control switches. The processing of these commands by the motor controller carries with it very precise control over the speed, torque, and direction, and, hence, the resultant horsepower of a motor in the vehicle.

Divisions of the power electronics control module are within it, each bearing a share of duties. As the home electrical grid charges the vehicle (e.g., 220 V), it turns the alternating current (AC) to direct current (DC), which is then supplied to the high voltage battery. It lowers the high voltage (e.g., 400 V) to the 12 V of the low voltage network.

Figure 2.12 Power electronics controller

The inverter manages the speed and power of the electric machine by changing the flow of electricity from the battery into three different levels, or phases, and then back again. When the vehicle is slowing down and making its own electricity, the inverter does the reverse change, from three-phase AC to DC.

Boost converters or DC/DC, (Figure 2.13) converters link input voltages provided by the battery and output. DC/DC converters are used for cutting or raising the voltage level. The power converter form becomes light, reliable, and small in size, and highly efficient.

Figure 2.13 DC/DC converter

The OBC talks to the vehicle controller and charging station. It finds out the right amount of current/power and the proper charging standard to use. Many charging standards exist all over the world, which includes regional standards for Europe, North America, and China. The OBC can change by itself to the right regional standards, based on info from the EV supply equipment (EVSE) controller or vehicle controller. A view from outside of the OBC is seen in Figure 2.14.

Figure 2.14 On-Board Charger

The onboard charger has an important part in bidirectional charging modes, so it can also change DC power from the high-voltage battery pack to AC power to help AC loads, grid power, and even other EVs.

2.3.5. Electric Motors

Figure 2.15 shows electric traction Motors in EVs. They work by converting electrical energy stored in a battery to the form of mechanical energy. The most critical features for an EV motor are efficiency torque, cost, power to weight ratio, and reliability. The efficiency of an EV motor and the motor controller directly affect the vehicle's weight since the lost power must be compensated for by a bigger battery, which will impact the total weight of the vehicle. Therefore, overall performance and efficiency of an EV are largely determined by the type of motor driver used. Torque-speed characteristics and power-speed characteristics should be compared to select the best traction motor [20].

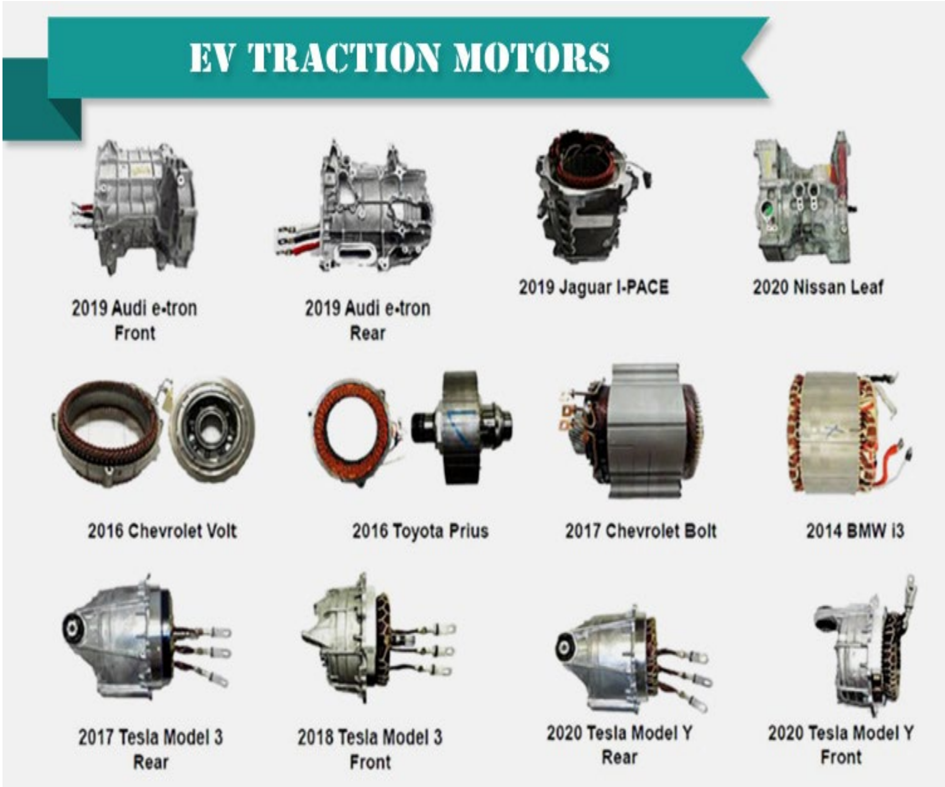


Figure 2.15 Electric vehicle traction motors

Types of the electric vehicle traction motor. Based on the technology used, electric vehicle traction motors are classified as follows [20, 21]:

- AC series traction motors.
- DC series traction motors.
- Three-phase induction motor.
- Linear induction motor.

2.3.6. Batteries

The auxiliary battery does not power the traction motors. It powers the vehicle accessory systems. This includes the headlights, audio system, and computer controls.

Hybrid electric vehicles (HEVs) and electric vehicles (EVs) utilize secondary batteries to charge many accessories. Rather than using the high-voltage (HV) battery to initiate these accessories, it is the secondary battery that allows such systems which require constant voltage supply to remain powered up. This secondary battery helps all 12v electric systems: accessory systems, headlights, audio systems, computer controls. The backups are the air conditioning and heating systems. [23, 26].

An EV battery is also referred to as a traction battery or traction battery pack (Figure 2. 16). Unlike what is called a standard 12-volt starting, lighting and ignition battery, which is meant for an internal combustion engine automobile, an EV high-voltage traction battery is made for the conversion of the chemical energy that is stored inside of it into electricity. This electricity is used to power the electric motors which propel the vehicle. Most EV traction batteries are of the lithium-ion type (Li-ion) [24, 25].

Figure 2.16 Traction Battery pack

2.3.7. Self-Safe Vehicles (ECE-R100)

ECE Regulation No. 100 (or R100) [22] deals with the requirements of safety specifically applicable to the electric power train of road vehicles, including rechargeable battery systems. UN Regulation No. 100 is divided into two parts and scope is as follows:

- Part I: Safety requirements related to the electric power train of road vehicles falling under categories M and N1 with a maximum design speed higher than 25 km/h. These vehicles are not permanently grid-connected.
- Part II: Safety requirements related to the Rechargeable Electrical Energy Storage System (REESS) of road vehicles falling under categories M and N, equipped with electric power train; those excluded here are vehicles that are permanently grid-connected.

High-Voltage Security Systems

High voltage is what people call the big group by ISO 6469-3 voltage class B. They look at low-voltage on board system (from 12-48 volts) and high-voltage (> 60 volts DC and > 30 volts AC) apart, as there are more dangers in the high-voltage range.

Higher voltage range electrical systems are needed to be efficient in any such pursuit towards longer range, faster-charging, higher-performance applications, with risks and impacts being directly proportional to the voltage, current, and energy stored.

There are different systems and mechanisms in an EV that are meant to ensure the safety of both passengers and service personnel, but we should not concentrate only on the systems, but also on human-related factors, awareness and education.

Manual Service Disconnect System – The main purpose of a manual disconnect is to break the circuit inside the battery pack. This is very important, especially when the HV contactors get stuck or accidentally connect after a collision [25, 27]. When this system is activated, there is no voltage across the battery terminals (Figure 2.17).

Figure 2.17 Safety connector

Pilot Line-Interlock

A pilot line is a safety-oriented system that makes a vehicle safe for drivers and mechanics working on or near the vehicle in a workshop area. The purpose of this system is to disconnect the high-voltage battery in the vehicle in the event of incorrect cable disconnection or the appearance of faults. Trainees shall get hands-on familiarity with the pilot line through experimentations based on interactions. HV Interlock System-Function-This system shall work to switch off the HV system in all conditions in which an HV connector is disconnected. It does so by monitoring the loop current within such components as the traction inverter, DC-DC converter, and On-board charger; if an error is found, then this will be the fail-safe mode [27].

Equipotential Circuits

Equipotential bonding among high-voltage components as well as that between any two high-voltage components in an electric vehicle is fundamental for Electric Vehicles. The potential equalization resistance is measured with a milliohm meter. As stated in the above UN ECE R 100, section 5.1, "the equipotential bonding resistance between any two exposed conductive parts must be less than 0.1 ohms."

The high-voltage network is an IT-like network; so both HV+ and HV- are electronically isolated from the vehicle ground and all equipment bodies, as shown in Figure 2.18. If a short circuit should happen in a high-voltage component (no matter if HV+ or HV-), there would be no danger at first because no electrical circuit can be completed due to the electronic isolation. This itself is already a certain level of security [27].

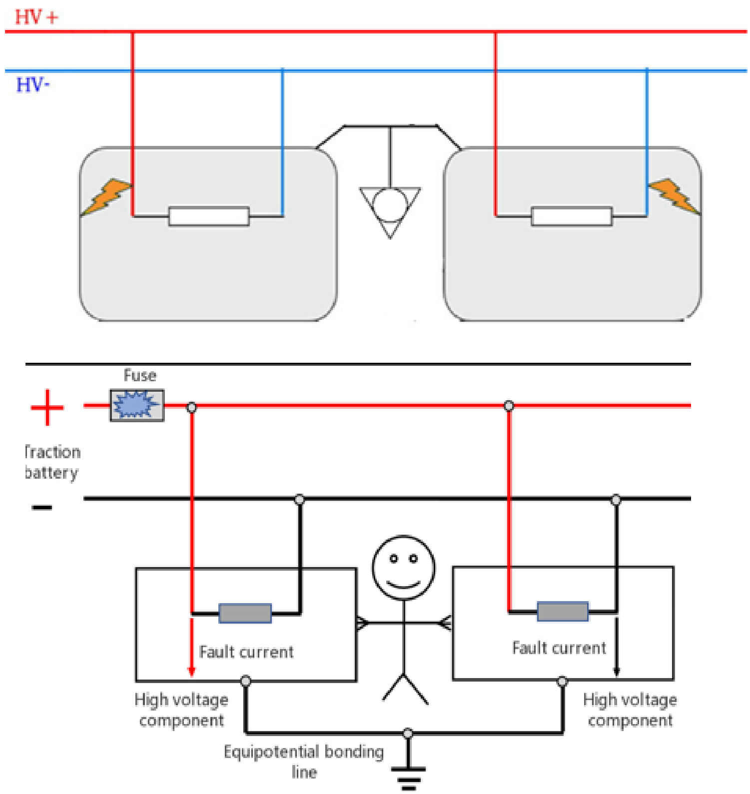


Figure 2.18 Equipotential bonding line

Insulation Resistance and Monitoring Module (IMD)

Isolation resistance is the electrical resistance between two conductive parts in a system, separated typically by an insulating material. In an EV, it is the resistance between HV lines and the vehicle chassis, i.e. DC+ to chassis and DC- to chassis. Isolation monitoring forms an essential part of safety requirements in any HV vehicle system [28].

Collision System

The Battery Monitoring System shall monitor and report the collisions that the batteries of an electric vehicle may undergo, as it provides the data on the damage caused to the battery and alerts drivers or remote operators in advance.

In order to guarantee the safety from the impact, all the countries across the globe have framed the obligatory regulations [22, 28].

(1) Voltage Security: Voltage after the crash test shall not exceed 30V AC or 60V DC.

(2) Power Safety: Total electric energy and capacitor energy after the collision shall not exceed 0.2J.

(3) After the collision, no electrolyte in the crew compartment; a maximum of 5L electrolyte allowed to overflow.

(4) In a crash, the driver area stays still. Parts of the battery box must not go into the inside of the box, and the battery box must not enter the driver area.

(5) After the crash, the battery box must not start a fire or blow up.

Service Plug

Service plug is used to interrupt the Pilot Line (safety interlock circuit), thus disengaging the big high voltage DC relays (contactors) in the high voltage battery. It does not disconnect the high voltage system directly, rather interrupts the pilot line. Service plug is also known as Maintenance plug, Maintenance connector, and Service connector [28].

2.4. Electrical Machines

Electric machines are devices that utilize electrical energy. Typically, the input, output, or both may be related to electricity. It can include transformers, generators, or motors. Such devices convert electricity into mechanical power or vice versa [20].

2.4.1. Torque and Power Characteristics, Motor Efficiencies

A motor torque curve is a graph that shows how much twisting force a motor creates and its spinning speed [rpm]. Torque, measured in units like Newton-meters [Nm] or pound-feet [lb-ft], shows the force of the motor's ability to make turning force, while speed is how quick the motor's output shaft is spinning. The picture shown in Figure 2.19 describes the twisting force and strength curves of an electric motor as functions of spinning speed [24].

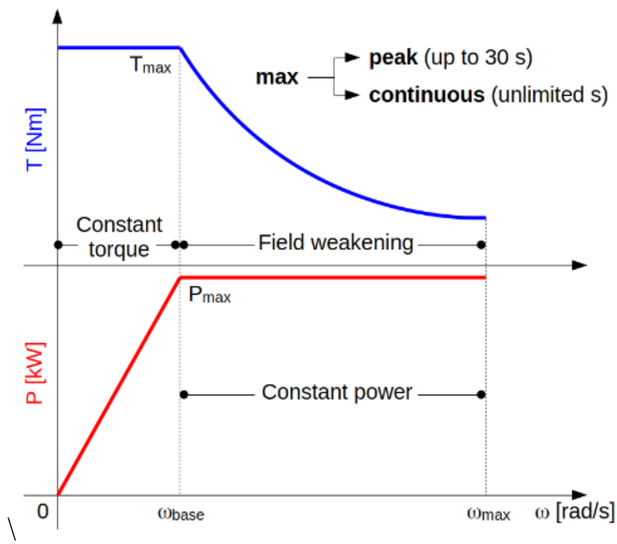


Figure 2.19 Electric Motor Maximum Torque and Power Curves

Motor efficiency speaks for itself, and it is the ratio of mechanical energy produced by the motor to the electrical energy supplied to the motor. In more direct terms, motor efficiency can be expressed as the ratio of output power to input power (see equation 2.1). The efficiency calculated from this ratio is termed direct efficiency. Otherwise, motor efficiency is found indirectly by referencing the losses and input power (see equation 2.2):

$$\eta = \frac{P_{out}}{P_{in}} \tag{2.1}$$

$$\eta = \frac{P_{in}-P_{loss}}{P_{in}} \tag{2.2}$$

where P_{in} and P_{out} are the input and output powers of the motor, respectively, and P_{loss} is the total losses in the motor.

Even though efficiency on 3/4 and 1/2 loads may be provided, motor efficiency is usually given for full rated load. A motor's efficiency is affected by load, rated power, and speed. The efficiency of motors increases with rotation speed generally until peak efficiency is reached; after this point, efficiency starts to decrease with further increases in rotation speed (see Figure 2.20) [24].

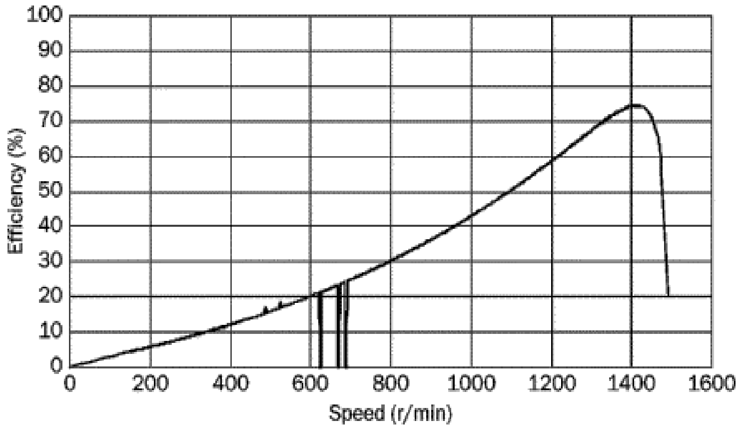


Figure 2.20 Speed vs motor efficiency

The total losses in the motor are of importance because calculating the efficiency is mainly associated with finding the total losses. In this regard, five types of loss in induction motors are defined by IEEE 112 Clause 5 as equation 2.3:

$$P_{loss}=P_{stator}+P_{rotor}+P_{core}+P_{fw}+P_{stray} \qquad (2.3)$$

Where P_{stator} is stator loss, P_{rotor} is rotor loss, P_{core} is core loss, P_{fw} is windage/friction loss, and P_{stray} is stray (also named additional) load loss. The first four loss components are calculated based on the input power, voltage, current measurements, and speed of rotation measured during the testing. The stray load loss is determined by remaining methods under consideration based on the standard used. Essentially stray load losses are those that occur over and above the stator and rotor losses, core losses, and windage and friction losses. They are proportional to the square of the load current and are essentially due to the "leakage" flux produced by the load currents in the laminations and being about 4% to 5% of the total losses. The distribution of the induction motor losses with regard to the load is usually plotted like that shown in Figure 2.21. Core losses and windage and frictional losses are termed as fixed or constant losses because they do not depend on the load. Other losses are considered dependent on load and, therefore, variable with load. The frictional losses (stator, rotor, core, and windage and friction) can be determined directly in the test process [31].

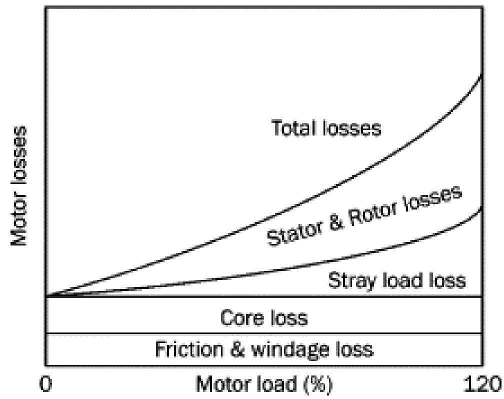


Figure 2.21 Typical distribution of the induction motor losses as a function of the load

2.4.2. Types and Structural Features of Electrical Machines

Electric machines fall into three main categories: transformers, generators, and motors. Transformers are devices that handle electrical power both as input and output. They do this without any appreciably wasted energy and are capable of transferring energy between circuits without establishing any physical connection between them. Electrical Power Input: this belongs to a class of electrical machines called generators. The input to a generator is mechanical power, and the output is considered to be electrical power. Electrical Power Output: this belongs to a class of electrical machines called motors. The input to a motor is taken to be electrical power, and the output is considered to be the mechanical power delivered by the shaft.

Static and dynamic machines are one classification of electrical machines. Transformers represent one example of a static electrical machine, and motors and generators are examples of dynamic electrical machines.

The working principle of a Transformer is Mutual Induction. There is an iron core that supports the windings of a transformer. The flux produced in the core is common to both the primary and secondary winding and this is how voltage gets induced in the windings. The operation principle of the transformer can be such that an alternating voltage is applied across the primary winding. This will be done due to the flow of the magnetizing current in the primary winding. Thereby, the flux will be produced, and it gets concentrated within the closed low-reluctance path of the magnetic core. The flux is common for both the primary and secondary windings. Self-induced voltage will take place in the primary winding which, in turn, causes mutual induction in the secondary winding. As both the primary and secondary windings have the same voltage induced per turn, the number of turns in the winding determines the voltage across the windings.

Transformers are categorized by their voltage levels: the primary classification is by winding arrangement into step-up and step-down types. A step-up transformer increases voltage; a step-down transformer reduces it.

There are two types of generators - DC generators, AC generators, or alternators. In a DC generator, the armature is the rotor, and electromagnetic poles are attached to the stator. When the rotor rotates in the stator, alternating current is induced in the armature and collected through commutator segments attached to the shaft of the motor. The alternating current generated by the armature is enclosed to direct current by commutator.

In an alternator, the armature is fixed at the inner periphery of the stator. It is the electromagnet that will rotate within the stator. The electricity produced in the static armature is fed right to the external circuit. Power is fed from the DC source to the rotor electromagnet through slip rings.

The electric motors can be classified as DC motors or AC motors. DC Motor: these motors are fed by DC supply through commutator segments attached to the shaft of the motor. The motor rotates based on Fleming's left-hand rule. DC motors can be categorized as separately excited DC motors, shunt wound DC motors, series-wound DC motors or compound-wound DC motors.

2.4.3. AC Alternating Current Motors

An AC motor, or an alternating current motor, is comprised of a stationary coil, known as the stator, supplied with alternating current to effect the conversion of electric current into mechanical energy. It is basic to note that the stator represents the stationary part of the motor, and on the other hand, the rotor represents the rotating section of the motor. AC motors can be single-phase or three-phase; three-phase motors are mostly used where there is bulk power conversion. Single-phase AC motors are used where there is small power conversion [20].

The main two classes of AC motors are called synchronous and induction. In a synchronous motor the shaft turns at a speed that is exactly the same as the frequency of the current used. This is done by multi-phase AC electromagnets on the stator which create a rotating magnetic field (Figure 2.22).

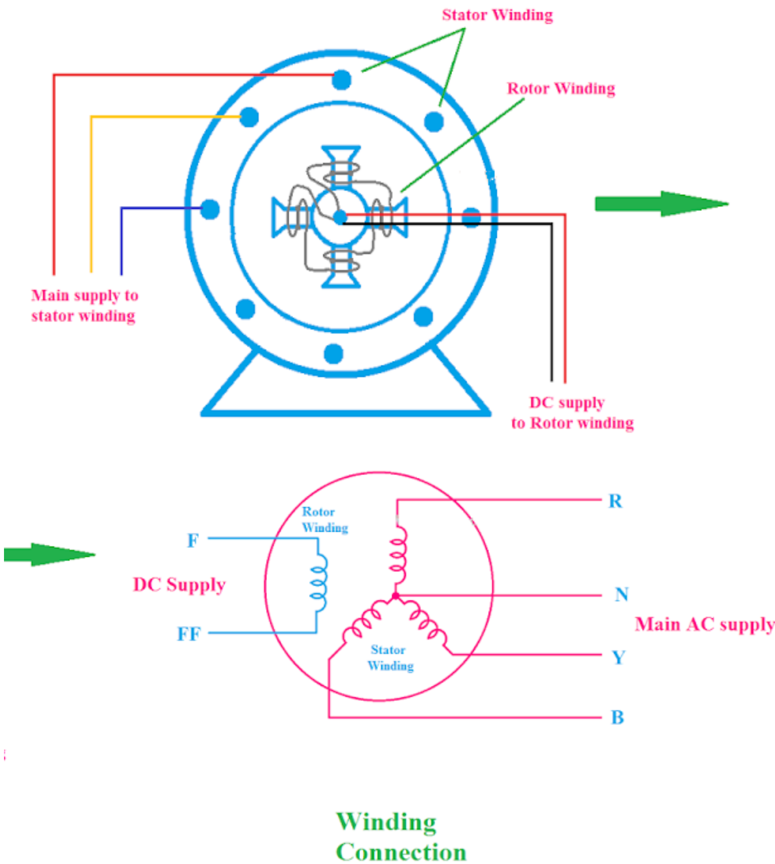


Figure 2.22 Synchronous motor schematic diagram

An induction motor, known also as an asynchronous motor, runs with only the stator excited. The induced current in the rotor's short-circuited coil by the magnetic flux of the stator causes the torque needed to start the rotor (Figure 2.23).

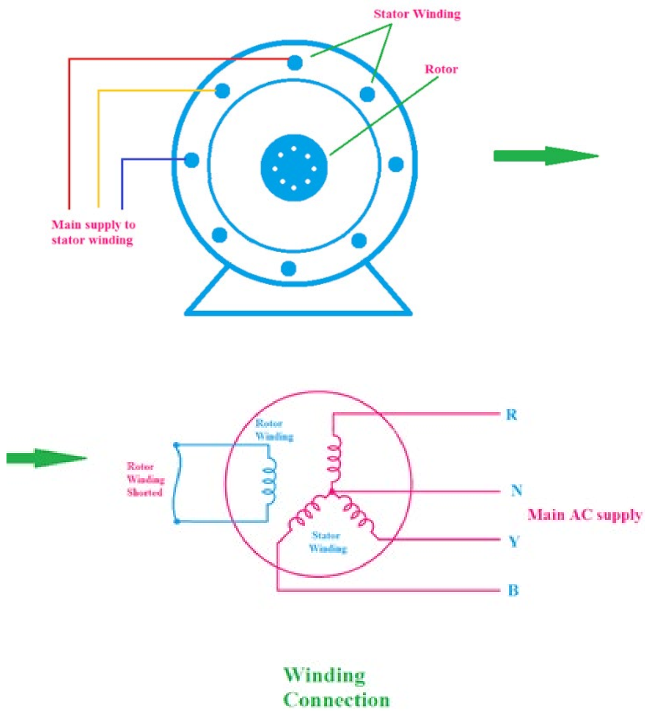


Figure 2.23 Asynchronous (induction) motor schematic diagram

AC motors can serve as a very versatile power source and hence have widespread applications because of their flexibility, efficiency, and quiet operation. They power pumps, water heaters, garden equipment, ovens, and off-road vehicles among a great number of other appliances, tools, and equipment. All this makes them very interesting for many different uses due to their adaptability.

The design of AC motors is relatively simple: A copper-wound stator is part of a system that produces a rotating magnetic field. AC induction motors are designed to meet the top standards of IE3 and IE4; these are benchmarks set internationally for motor efficiency.

The main parts of an AC motor are the stator, which is the outer part that does not move, and the rotor, which is the inner part that moves and is attached to the motor shaft. Both parts create rotating magnetic fields. The one in the stator is made by the alternating current going through its windings.

In an AC motor, typically the winding will act as both the armature as well as the field winding. In other words, when the stator is energized with AC voltage, it will produce a rotating magnetic field that will move at a synchronous speed. Voltages should be induced by this rotating field in both the stator and rotor windings to enable the motor to run.

AC motor is a broad term of different types such as single-phase, three-phase, brake, synchronous, asynchronous, customized, two-speed, and three-speed single-phase motors; their distinctions relate to the applications for which they are intended. The different versions are made for different functions. One type of AC motor is meant for small work; another is designed for more substantial labour. However, the essential distinction among them is the phase of the electrical supply, which seems to vary between uses in homes and industrial uses.

Residential electricity generally uses single-phase or double-phase power; most industrial applications use three-phase power. This fact alone demonstrates the basic distinction between industrial ac motors and their residential counterparts: the different way in which they are supplied with electricity.

Motors are standardized by the National Electrical Manufacturers Association, and the standards, presented in a publication numbered NEMA Standard Publication No. MG 1, are best practice and manufacturing guideline standards for electrical equipment. NEMA does not classify specialized design ac motors; these are called "above NEMA" motors.

Induction motors also find classification by electrical design. AC motors come classified by NEMA into five different types that are A, B, C, D, and E, each distinctly enumerating certain measurable characteristics and performance features:

- Classification A:
  - high breakdown torque
  - designed for specific use
  - slip characteristic less than 5%
- Classification B:
  - general-purpose motor
  - slip is 3-5% or less
- Classification C:
  - high starting torque
  - normal starting current
  - low slip

  - little demand for overload
- Classification D:
  - high starting torque
  - high slip of 5 to 13%
  - low full load speed
  - speed fluctuations due to changes in load
- Classification E:
  - high efficiency
  - low starting torque
  - requirements are low

Table 2.1 provides a general description of the various NEMA classifications and their typical uses.

Table 2.1 NEMA Classifications

NEMA Classifications	
Motor A	A motors are commonly used for fans, pumps, and blowers where large starting torques aren't necessary and the motor doesn't need to support a large load.
Motor B	B motors are commonly used for fans, pumps, and blowers where large starting torques aren't necessary and the motor doesn't need to support a large load.
Motor C	C motors are best used in machines that require the motor start under a load such as conveyors, compressors, crushers, stirring motors, agitators, and reciprocating pumps.
Motor D	D motors are used for machinery with high peak loads such as elevators, hoists, oil-well pumping, wire drawing motors, and punch presses.
Motor E	E motors can be used in similar applications to A and B motors like fans, pumps, motor-generator sets, and blowers with low starting torque.

2.4.4. Traction Motors Used in Electric Vehicles

Motors constitute the most crucial part of an Electric Vehicle (EV). They are accountable for taking the chemical energy stored in the cells and expressing it into rotational energy so as to drive the wheels and develop the movement of the vehicle. Therefore, these motors are also widely known as traction motors. The key attributes of a motor for EVs are efficiency, torque, cost, power to weight ratio, and reliability. The efficiency of an EV motor along with the motor controller directly affect the weight of the vehicle since the lost power needs to be compensated for by a larger battery that will have an effect on the total weight of the vehicle.

EVs use various types of motors depending on their propulsion system. Motors can be categorized based on the type of current required, such as DC motors and AC motors. Also, based on the type of their construction or if permanent magnets are present or not. Some of the common types of motors which are applied in EVs are such as BLDC motor, Permanent Magnet Synchronous Motor (PMSM), Induction motor (IM), Switched Reluctance Motor (SRM), Synchronous Reluctance motor, etc.

Asynchronous Motors

The induction motor is sometimes referred to as an asynchronous motor. Two types of induction motors are available on the market: the single-phase induction motor and the three-phase induction motor. Due to their hard starting, low-speed running complexity, and control disadvantages, they tend to have few applications in automobiles. Therefore, only 3 phase IMs are used. There are two types of induction motors based on the rotor of the induction motor. The rotor of the induction motor can be squirrel-cage rotor or wound-type rotor. The synchronous motors work at 100 percent synchronous speed but the induction motors work less than the synchronous speed and therefore they are referred to as asynchronous motors. Induction motors are preferred because of their simple design, high dependence, sturdy nature, easy maintenance, low cost, and competency to toil in a diversity of environmental conditions [22].

Synchronous Motors

As implied by the name, PMSM is an AC machine that contains a permanent magnet; it is somewhat of a cross between a brushless DC machine and an induction machine. Brushless permanent magnet synchronous machines (PMSMs) are highly reliable and efficient. They offer higher torque with lower frame size and no rotor current compared to that of an AC induction machine; these are all advantages over AC induction machines (AICMs). Since there is no stator power share for magnetic field production, its power density is better than that of induction machines of similar ratings. The main advantage of a PMSM is that it can assist you in reducing your design size without any drop in torque because of its wonderful power-to-size ratio. PMSMs are essentially commutated like the BLDC motors, however, the waveforms used must be sinusoidal due to winding construction [22].

DC Direct Current Motors

The DC series motor, known as the brushed DC motor, is the simplest kind of motor. It works when the coils that are inside it are passing an electric current through itself inside a fixed magnetic field (Figure 2.24). This motor is easy to control and has a high capacity for initial torque; thus, it is a fine choice. It uses brushes and commutators for its work. By ensuring the direction of current, the rotation of the motor can be controlled. However, the major drawback is that the brushes wear out fast. It requires periodic maintenance [22].

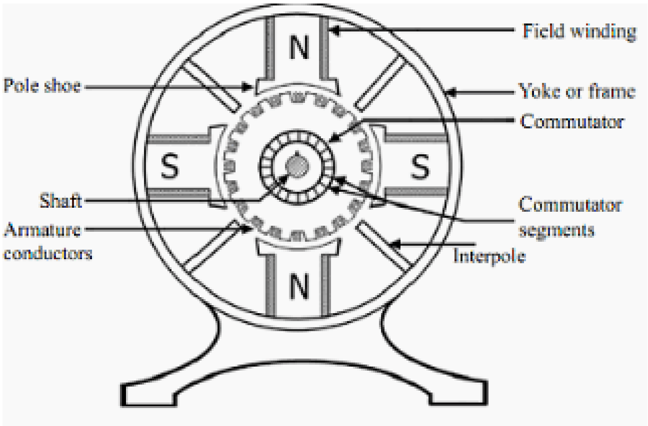


Figure 2.24 Brushed Direct Current motor

Another type of DC motors is Brushless Direct Current Motors (BLDC) which is displayed in Figure 2.25. Brushless Direct Current Motors (BLDC) are also known as electronically commutated motors. These motors are some of the most frequent motors used in the EV industry. BLDC motors do not possess brushes and, therefore, require very minimal maintenance as compared to that of the DC motors. But unlike the brushed DC motor which has simple operation, driving a BLDC motor calls for motor controllers that are complex.

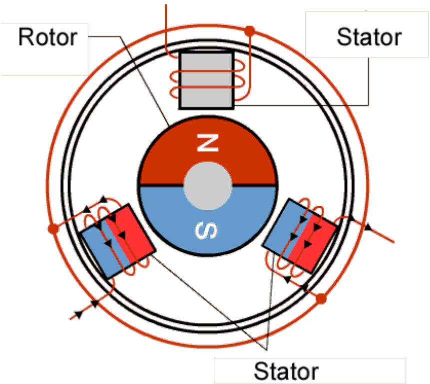


Figure 2.25 Brushless Direct Current Motors (BLDC)

Reluctance Motors

A switched reluctance motor changes torque by changing its magnetic reluctance. A motor has salient poles and windings like a brushless DC motor stator, but the rotor is made of cut salient-pole steel without magnets or windings. Unlike ordinary brushed DC motors power is fed into the stator windings rather than the rotor. This is how an SRM works via the stator. In figure 2.26 only one winding of the phase is drawn for simplification [22].

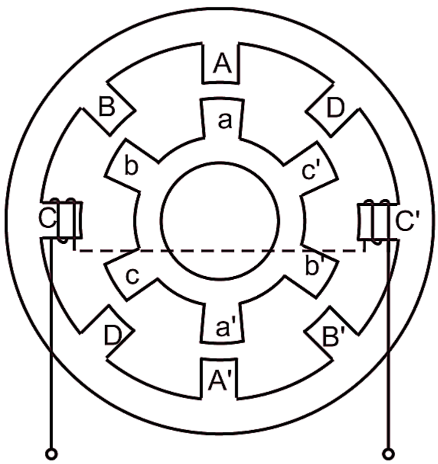


Figure 2.26 Schematic diagram of a 4-phase switched reluctance motor

2.5. Motor Control Systems (EV Power Electronics)

In the intricate network of an EV, many electronic control units (ECUs) have key parts in making sure they run well. One such ECU is the motor control unit (MCU), which works as the brain behind the motor's performance. The motor controller gets orders from interfaces like the throttle, brake, and forward/reverse control switches. The motor controller handles these orders and very carefully manages the speed, torque, direction, and resulting horsepower of a motor in the car.

2.5.1. Structural features and operation of Motor Control systems

The motor control systems have many units, e.g. a control unit acts as the main central control for the motor of the electric vehicle, carrying out a number of key functions to make sure driving is easy and efficient. Its main task is to change the direct current (DC) given by the battery into three-phase alternating current (AC) that runs the motor. A common block diagram of an MCU is shown in Figure 2.27.

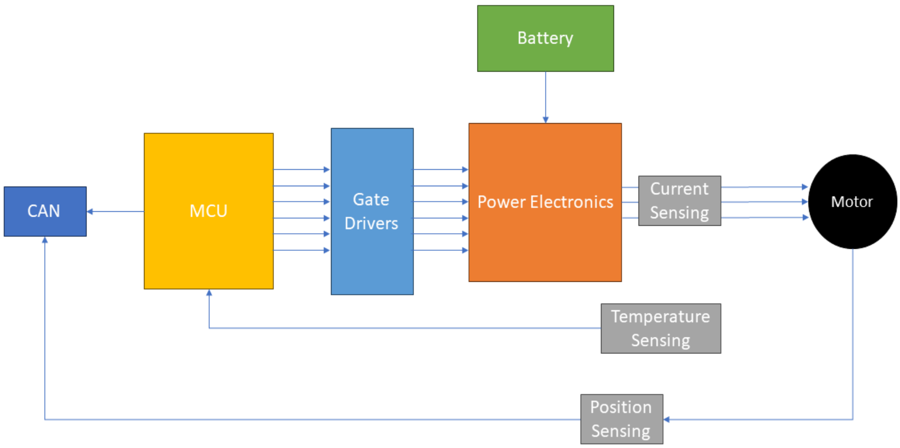


Figure 2.27 Motor Control Unit Block Diagram

Midway between the other parts, the microcontroller manages the hard math of rules and looks after all of the work the motor does. Gate drivers help steer the power switches and get directions from a special helper or PWM channels. The power electronics make the change between DC and AC power.

2.5.2. Power Electronic Systems

Power electronics assume an important function in the motor control unit by converting the energy and giving control over it. Advanced power electronics technologies play their hand in the optimization process for motor control units, sharing their improvements on the general efficiency and performance of electric vehicles. This is the electronics package that runs between the batteries and the motors to control speeds and accelerations of the electric vehicle – similar to a carburettor in a gasoline-powered vehicle.

Inverters

The control required for modern inverters is that of the switches to make them switch on and switch off at the right times to produce the desired AC waveforms. In electronics, there are two broad methods of controlling power flow: one is linear regulation and the other is switching or regulation by Pulse Width Modulation (PWM). Linear regulators work well but are very inefficient since they just "burn off" the difference between the input and the output. Linear regulators are popular even today. A switching regulator or PWM regulator does this by merely switching between fully on and fully off states because that is the most efficient strategy for a switch.

Boost Converters-Buck converters

Boost converters or DC/DC converters are used to link between input voltages presented by the battery and output. DC/DC converters are used for chopping or boosting the level of voltage. A buck-boost converter is used within an electric vehicle to control the voltage of the pack of batteries. Such a converter can step up or step down the voltage as important, which is key to maintaining a stable voltage for the electrical systems of the vehicle. It helps the vehicle to effectively control the flow of power from the battery to the motor and other components. This is key when the voltage of the battery changes during charge and discharge since it helps optimize the performance and efficiency of the power system for an electric vehicle.

2.6. High Voltage Batteries Used in HEV and EV Vehicles

Today's high voltage batteries used in electrical vehicles offer the utmost safety and a long life. Because of all the attention paid to HV Batteries, they are under a big industry standard pressure and regulated by a long list of safety rules of governments all over the world, who invest quite some resources creating standards with which to ensure safety, coordinate research, or investigate recalls, or else any safety-related issues. Most lithium-ion HV Batteries come in an EV today and with the High-Voltage Contactor, of course, capable of switching off the current in a safe and effective way in normal conditions.

2.6.1. Structural features and types of high voltage batteries

A standard battery comprises two or more electrochemical cells that are connected or integrated. The conversion of the chemical energy stored into electric energy results in the working of a battery. A single cell battery comprises a negative and a positive electrode that are connected by the electrolyte, with the electricity produced by the chemical reaction amongst the electrodes and electrolyte. A rechargeable battery has the ability to invert the chemical reaction through the reverse of current, hence the possibility of recharging the battery. The electrodes and electrolyte formation specifies the battery. Various batteries available, or under vigorous developments, are appropriate for EVs. The batteries include:

- Lead/acid

Lead/acid (Pb/A) batteries are the first type of battery used in cars. The battery negative electrodes contain basic lead (Pb) while the positive plates have lead dioxide (PbO2) as active material in charged state. The electrodes are placed in an electrolyte of sulfuric acid (H2SO4). When being discharged the lead of the negative electrodes and the lead dioxide of the positive electrode react with the sulfuric acid. Lead sulphate is formed on the electrodes and the electrolyte loses its dissolved sulfuric acid and becomes water. Energy is released during the chemical reaction and when energy is added the process will reverse.

- Nickel Metal Hydride

There are four types of batteries made with nickel that use nickel in the positive electrode of the battery: nickel iron, nickel zinc, nickel cadmium, and nickel metal hydride. Ni-Zn and Ni-Fe batteries are not considered a choice for EVs their short life cycle and low specific power. Among the cadmium-based batteries, the most mature technology is nickel-cadmium.

- Lithium-ion

The lithium-ion cells are cells that can be recharged; they use lithium as one among the many key components present in the construction of the cell. Li-ion cell comprises four main components, namely the cathode, anode, electrolyte, and separator. The cathode material is what determines Li-ion battery capacity and voltage. The so-called active material has a very important role to play. It plays a very crucial role in the chemical reaction in the battery through which the current is conducted. The capacity of a cell is dependent on the size of the active material at the cathode, i.e., for larger capacity of the cell, the cathodes should be larger. As voltage of the cathode depends on the element used as cathode, the nomenclature of the battery usually depends on the cathode; like a Lithium-ion battery has a cathode made up of Lithium. But since lithium is highly reactive and unstable, making it difficult to contain and use directly, therefore a combination of lithium and oxygen is used as a cathode.

- Solid state battery

Solid-state batteries have not yet found their way into electric vehicles and are only in the developmental stage. Toyota has announced that solid-state batteries will first be commercialized for use in electric vehicles that may hit the roads by 2025. This can be a game changer due to higher energy density in solid-state batteries compared to lithium-ion batteries and better volume efficiency as well since they do not require a lot of space like lithium-ion batteries. As solid-state batteries weigh less, they may actually double the range of electric vehicles as well as the performance.

- **Metal air**

Most metal air batteries cannot be recharged by simply reversing the current as can be done with the other batteries mentioned above. Instead, the electrodes of the battery have to be replaced by new ones. Metal air batteries are mechanically rechargeable batteries and are comparable with fuel cells. A major advantage of the metal air batteries is that the battery only consists of one reactant. The other reactant is oxygen which does not have to be carried in the battery. The metal air battery therefore has a weight advantage over other types of batteries.

- **Sodium nickel chloride**

The sodium nickel chloride (NaNiCl2) or zebra battery is currently under development by the company MES DEA and is to be used in the Think City EV. Zebra originally stood for Zero Emission Battery Research Association but is now associated with the sodium battery being developed by MES DEA.

The positive electrodes of the zebra battery are made from solid nickel chloride while the negative electrodes are made from molten sodium. The central positive electrode is impregnated in a liquid electrolyte of sodium-aluminium chloride. This, in turn, is enclosed by a ceramic electrolyte.

- **Ultra-capacitors**

Between an electrode and an electrolyte, ultra-capacitors (supercapacitors) store energy in a polarized liquid. Energy is stored based on the increase in the surface area of a liquid; the higher the surface area, the more the energy storage capacity. Ultra-capacitors can be used to assist vehicles in recovering energy during braking and then providing additional acceleration and hill climbing power. These devices could be very useful as auxiliary energy storage devices in electric vehicles because they can help level load power from electrochemical batteries.

The common characteristics of chargeable batteries in use are shown in Table 2.2 [32].

Table 2.2 Characteristics of commonly used rechargeable batteries

Specifications	Lead Acid	NiCd	NiMH	Li-ion[1] Cobalt	Manganese	Phosphate
Specific energy (Wh/kg)	30–50	45–80	60–120	150–250	100–150	90–120
Internal resistance	Very Low	Very low	Low	Moderate	Low	Very low
Cycle life[2] (80% DoD)	200–300	1,000[3]	300–500[3]	500–1,000	500–1,000	1,000–2,000
Charge time[4]	8–16h	1–2h	2–4h	2–4h	1–2h	1–2h
Overcharge tolerance	High	Moderate	Low	Low. No trickle charge		
Self-discharge/ month (roomtemp)	5%	20%[5]	30%[5]	<5% Protection circuit consumes 3%/month		
Cell voltage (nominal)	2V	1.2V[6]	1.2V[6]	3.6V[7]	3.7V[7]	3.2–3.3V
Charge cutoff voltage (V/cell)	2.40 Float 2.25	Full charge detection by voltage signature		4.20 typical Some go to higher V		3.60
Discharge cutoff voltage (V/cell, 1C)	1.75V	1.00V		2.50–3.00V		2.50V
Peak load current Best result	5C[8] 0.2C	20C 1C	5C 0.5C	2C <1C	>30C <10C	>30C <10C
Charge temperature	–20 to 50°C (–4 to 122°F)	0 to 45°C (32 to 113°F)		0 to 45°C[9] (32 to 113°F)		
Discharge temperature	–20 to 50°C (–4 to 122°F)	–20 to 65°C (–4 to 149°F)		–20 to 60°C (–4 to 140°F)		
Maintenance requirement	3–6 months[10] (toping chg.)	Full discharge every 90 days when in full use		Maintenance-free		
Safety requirements	Thermally stable	Thermally stable, fuse protection		Protection circuit mandatory[11]		
In use since	Late 1800s	1950	1990	1991	1996	1999
Toxicity	Very high	Very high	Low	Low		
Coulombic efficiency[12]	~90%	~70% slow charge ~90% fast charge		99%		
Cost	Low	Moderate		High[13]		

The numbers are based on middle ratings of business batteries at time of writing. Special batteries with better ratings are not counted.

1. Mixing cobalt, nickel, manganese and aluminium raises power thickness up to 250Wh/kg.
2. Cycle life is based on how deep the discharge is. Shallow DoD makes cycle life longer.
3. Cycle life is based on battery getting regular care to stop memory.

4. Ultra-fast charge batteries are made for a special purpose. (See BU-401a: Fast and Ultra-fast Chargers)
5. The highest self-discharge is experienced immediately after charge. For NiCd, 10% within the first 24 hours is lost; later, it will decrease to 10% every 30 days. High temperature and age raises self-discharge.
6. Traditionally 1.25V; common is 1.20V. (See BU-303: Confusion with Voltages)
7. Higher voltage rating by manufacturers— because of low internal resistance (marketing).
8. Capable of high current pulses; needs time to recuperate.
9. Do not charge Li-ion below freezing (See BU-410: Charging at High and Low Temperatures).
10. This can take the form of equalizing or topping charge to prevent sulfation.
11. Most Li-ion batteries have a protection circuit that cuts off below about 2.20V and above 4.30V; different voltage settings apply for lithium-iron-phosphate batteries.
12. Coulombic efficiency tends to be higher with quicker charge (in part because of the self-discharge error).
13. Li-ion typically has lower cost-per-cycle than lead acid.

Batteries have hundreds, sometimes thousands, of small battery cells. These are connected in either series or parallel connection to get the required voltage and current. Each battery cell has 3-4V. Presently, three types are used: cylindrical, prismatic and pouch – with their own sets of advantages and disadvantages, as indicated in Figure 2.28.

The real battery cells can have varied chemistry, physical shapes, and sizes as liked by different pack makers. Battery packs will always include many separate cells linked in series and parallel to reach the total voltage and current needs of the pack. Battery packs for all electric drive EVs can have several hundred single cells. Each cell has a normal voltage of 3-4 volts, based on its chemical composition. Hybrid and electric vehicles have a high voltage battery pack that includes individual modules and cells organized in series and parallel [33].

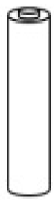
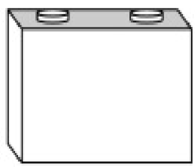
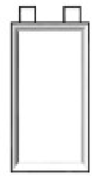
Cylindrical cell	Prismatic cell	Pouch cell
		
• Small size (e.g. 18650 type (ø 18 mm, height 650 mm)) • Hard casing • Low individual cell capacity • Build in safety features • Comparably cheap	• Hard casing • Large size • High individual cell capacity	• Soft casing • Large size • High individual cell capacity • Geometrical deformation during (dis-)charging

Figure 2.28 Types of battery designs

2.6.2. HEV and EV vehicles battery charging connector-charging units

The charging infrastructure industry has agreed upon the Open Charge Point Interface (OCPI) protocol with this hierarchy for charging stations: location, EV charging port, and connector. An EV charging port provides power to charge only one vehicle at a time, even while multiple connectors are attached. Sometimes, the unit housing the EV charging port is called a charging post, which can have one or more EV charging ports. EV charging ports are also sometimes referred to as electric vehicle supply equipment (EVSE) ports. A connector is what is plugged into a vehicle to charge it; though multiple connectors and connector types (such as CHAdeMO and CCS) can be available on one EV charging port, only one vehicle will charge at a time. Connectors are sometimes called plugs. [32].

Level 1 Charging: About 5 miles of range for every 1 hour of charging, assumes 1.9 kW charging power. Alternating Current (AC) Level 1 equipment (often referred to simply as Level 1) gives charging through a 120 volt (V) AC plug. An SAE J1772 standard connector (often referred to simply as J1772, shown in the image in Figure 2.29).

Level 2 AC: Around 25 miles of range for 1 hour of charging (A Level 2 unit can range from 2.9 to 19.2 kW power output). Level 2 AC equipment means charging through 240 V (typical in residential applications) or 208 V (typical in commercial applications) electrical service. Vehicles with a J3400 connector, as shown in Figure 2.29 (only Tesla vehicles at present), can use the connector for all charging levels.

DC Fast Charging: About 100 to 200+ miles of range per half-hour of charging. Direct-current (DC) fast charging apparatus (usually a three-phase AC input) allows quick charging along busy traffic roads at set up stations. Combined Charging System (CCS), CHAdeMO, J1772, and J3400 as indicated in Figure 2.29.

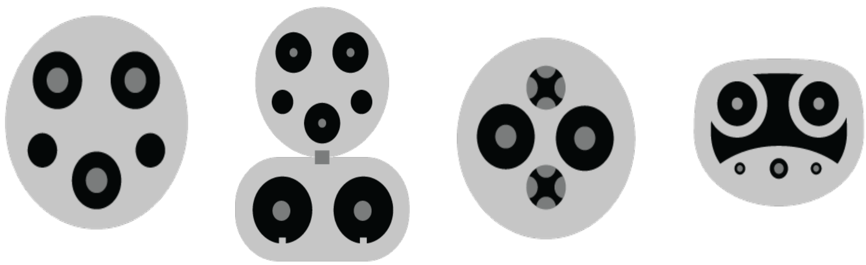


Figure 2.29 J1772, CCS, CHAdeMO and J3400 (NACS) connectors

2.7. Other Systems

2.7.1. Thermal Management Systems

The thermal management keeps the electric motor, power electronics, and the battery at the right temperature while also ensuring passenger comfort in the cabin. Failure of this system leads to demagnetization, aging of insulation materials, reduced efficiency, shorter lifetime, and burnout of the electric motor. A good thermal management system will increase the longevity of the battery cells and is a major safety feature to prevent thermal runaway. The total thermal management system has several thermal circuits that need actuators like electric compressor, coolant pumps & fan motors, valves and flaps, HVAC control modules and electric heaters. Integrated systems are a more common version due to OEMs, and that converges on liquid-based battery cooling strategies.

Battery Thermal Management System

The Battery Thermal Management System of an EV has a significant contribution to extending the life of the Li-Ion battery pack by means of optimizing the operational temperature of the batteries and decreasing the chances of thermal runaway There exist several types of BTMS used in the automotive sector, which include Air-based, Liquid-Based, PCM Thermal

Management-Based, Thermoelectric Element-Based, and Hybrid Systems [34, 35]. The different types of BTMS are represented in Figure 2.30.

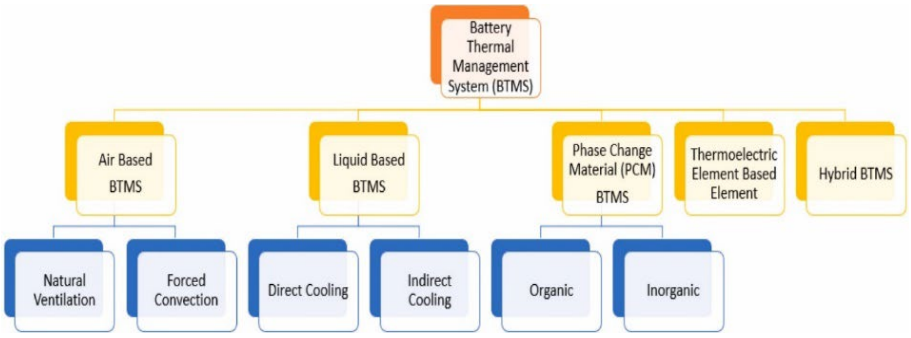


Figure 2.30 Types of Battery Thermal Management System

Inverter-Electric Motor Cooling System

Choose how the electric motor should be cooled based on whether the machine is for general use, its power, and the work environment (see figure 2.31). A common way to cool an electric motor is by air, using the outer part of the motor that has fins; cooling happens on its own by wind or can be made quicker with a fan that turns on the motor's main rod. For places where there's a building, these cooling ways are good enough for most factory jobs. But in cars, the small engine system might not have enough room for fins around the motors. Also, it's best to use motors that are sealed and made water-tight since a vehicle is used outside, and there can be all kinds of weather and no clear temperature and humidity control. The in-wheel motors were developed for military hybrid applications.

A popular method of solving the driving and inverter thermal management issues is by using liquid cooling. The use of liquid coolant to remove waste heat may be more efficient than air because of the increased heat capacity exhibited by most liquid coolants and also the flexibility of controlling the fluid flow to meet the heat removal need. It can be affected by different designs in which the efficiency of heat transfer components, referred to as cold plates or heat sinks, typically determines it [36, 37, 38].

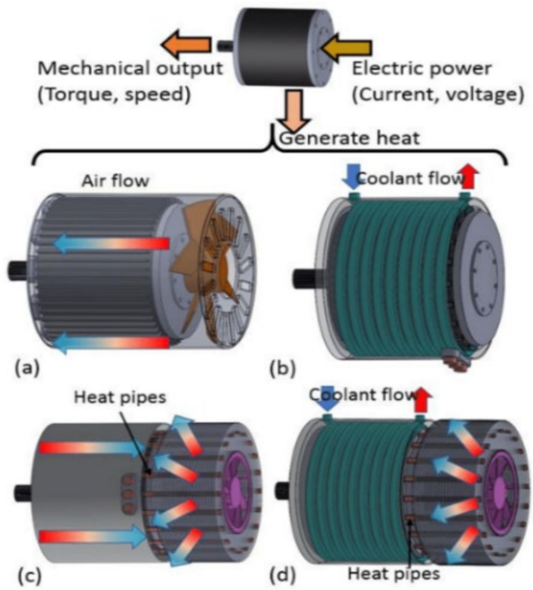


Figure 2.31 Electric motor cooling method

(a) Surface air cooling with a fan coupled to the shaft;

(b) Liquid cooling with coolant jacket;

(c) Heat pipe cooling with attached fins and a centrifugal fan;

(d) Hybrid cooling with heat pipes and liquid.

2.7.2. In-Vehicle Air Conditioning Systems

The electric motor of an automobile does not produce waste heat. However, this does not imply that there is no heating in the car. The operation principles of cooling and heating systems in electric automotives do not differ much from those of combustible engine-driven cars. In electric vehicles, compressors have their own built-in electric motor inverters that convert the direct current drawn from the battery into AC and separators that separate the compressor oil from the refrigerant. One of the nice things about this solution, where the compressor is powered directly from the battery, is that it makes it possible to run the air conditioner when the car is parked, and the engine is off. New electric cars thus also have a heating system based on a heat pump, which is something like the split air conditioners used for heating buildings. Heating and cooling mode operation can be offered by the air-to-air heat pump. In heating, the air that it warms is used directly to the passenger cabin, whereas in cooling, it goes to a condenser and then a dehumidifier before the expansion valve and evaporator. A lithium-ion battery, powered by an inverter, also runs the heat pump.

There are many kinds of heating in electric cars, but the most usual is an electric heater linked to a blower. Even though the power of such heaters is mainly small, as low as 2 to 4 kW, in very cold temperatures they quickly speed up the battery drain. The design of the air conditioning system in BEVs is displayed in Figure 2.32. [39-42].

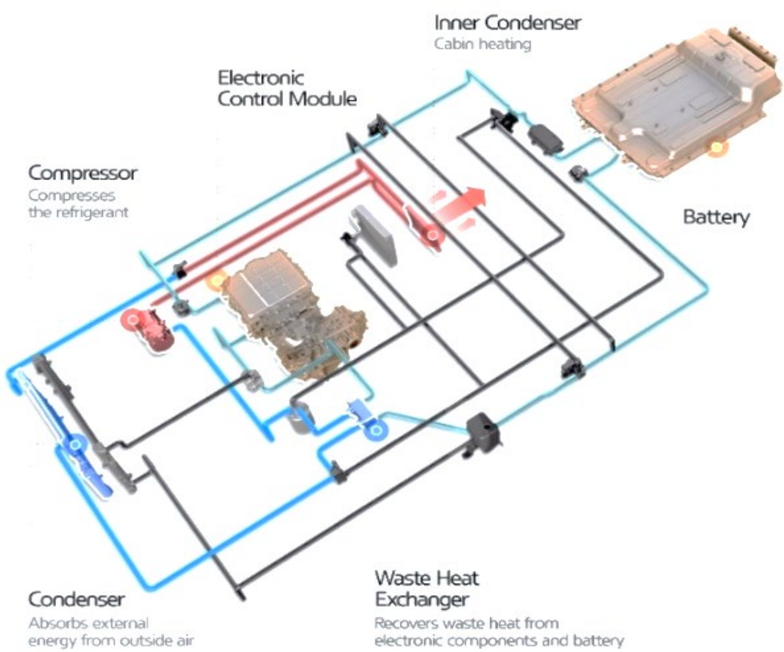


Figure 2.32 In-vehicle air conditioning systems

2.7.3. Steering Systems

This is the intelligent electric motor that controls and helps the steering process. The control unit calculates the optimal steering support based on the steering signal from the torque sensor and then instructs the electric motor with that information so that the electric motor can give the assistance required. (Figure 2.33).

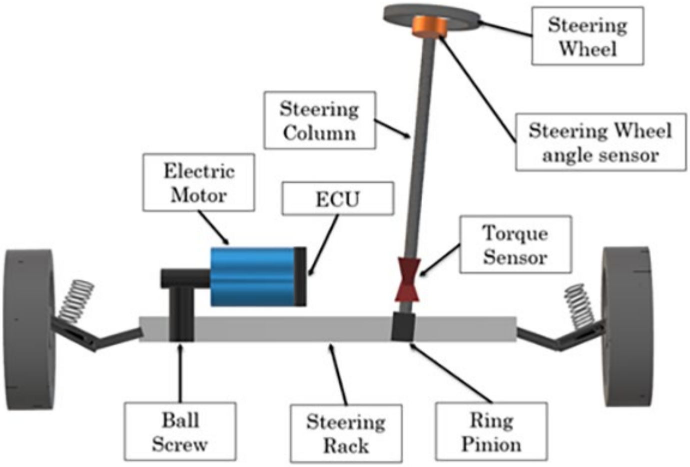


Figure 2.33 components of EPS

The major challenge with any drive-by-wire system is its safety. A mechanical part is far more reliable than a wire which is transmitting some data. Another challenge is to find a proper way to give the driver feedback.

The steer-by-wire system has two main components. The steering rack subsystem and the element operated by the driver, called the steering wheel subsystem. The biggest difference when compared to classic steering systems is that there is no column or a direct link between the wrack and the steering wheel [43].

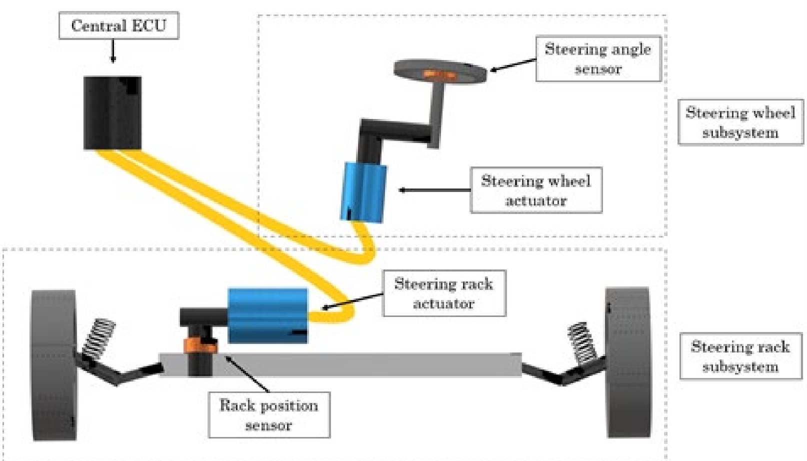


Figure 2.34 Steer-by-wire EPS

2.7.4. Brake Systems

First, it should be noted that the mechanics of how electric vehicle brakes work - as brakes - are largely unchanged. Drivers still apply force to their brake pedal to slow the vehicle.

An electrohydraulic brake is a system that achieves its purpose of operation through a combination of hydraulic and electric systems. The renaissance of this system has been predominantly witnessed in the hybrid and electric vehicles in which the complexity arises due to the regenerative mode associated with the braking system. It involves the use of an electrically motored hydraulic system that generates the force which the pads will exert on the rotor.

Braking Energy regeneration is the conversion of the kinetic energy created when you apply brakes into electric power for your battery. Regenerative brake systems do not recover sufficient energy to keep a vehicle fully charged. The efficiency of regenerative braking depends on the model of the vehicle as well as the driving habits of the operator and not all energy that is being used to power the car is captured by the regenerative braking system, but it is estimated under optimal conditions that about 70% of input kinetic energy from braking can be recaptured. The regenerative braking has a few rather obvious boons. First, it can significantly increase the range of an electric vehicle. And second, regenerative braking can also lengthen the lives of braking pads and rotors in most EV models. This is because most regenerative braking systems also help slow the vehicle down when the driver releases the accelerator pedal. This puts less stress on the brakes themselves when braking. Thus, regenerative brakes are not only more efficient for the vehicle but enhance brake life, which is a saving that benefits the driver even further. Apart from regenerative braking, a couple of other important mechanical contrasts feature in electric vehicles. For instance, EV tires usually tend to be bigger and tougher because EVs are heavier than regular gas cars. And, of course, EV batteries and internal combustion engines differ drastically [44, 45].

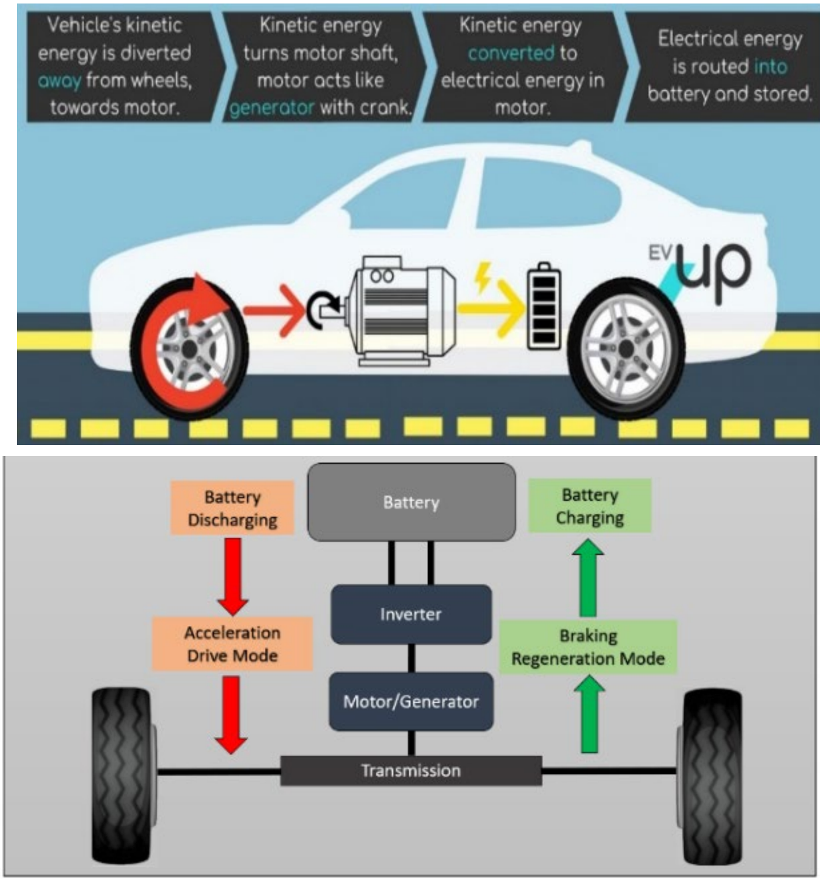


Figure 2.35 Regenerative braking

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CHAPTER 3

Battery and Energy Storage Systems

Fatih Köz, Burak Ün, Abdil Kuş

3. Battery and Energy Storage Systems

3.1. Energy Storage Systems

Energy storage systems are systems that store generated energy using various methods and make it available for use when needed. The disadvantages of petroleum-based fuels, economic crises, and technological advancements have led to the adoption of diverse energy storage methods in the automotive sector. In automotive technology, energy is stored using mechanical methods such as flywheels, hydraulic methods like motor/pump systems, electrical methods like supercapacitors, and chemical methods like batteries. The operating principles of energy storage systems are as follows:

Flywheels are systems that convert energy from internal combustion engines or electric motors into mechanical energy for storage. When needed, the stored mechanical energy is converted back into electrical energy or the desired form of energy. Flywheel storage methods are predominantly used in racing vehicles and heavy-duty vehicles. In the application shown in Figure 3.1, mechanical energy is transferred to the flywheel during braking and then returned to the system at the start of vehicle motion.

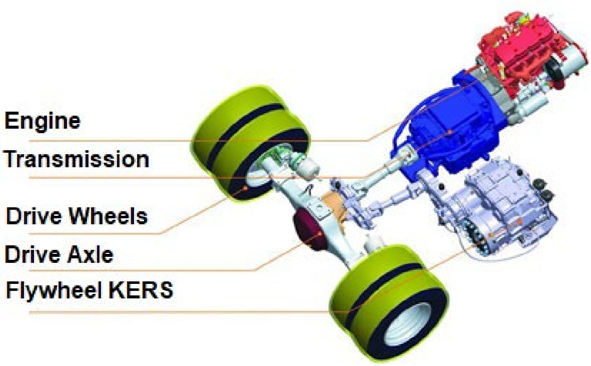

Figure 3.1 Flywheel energy storage system [1]

Hydraulic motor/pump systems involve a pump powered by a mechanical system to pressurize fluid and store it in accumulators or tanks. When needed, the system retrieves mechanical energy from the pressurized fluid via the pump/motor assembly (Figure 3.2).

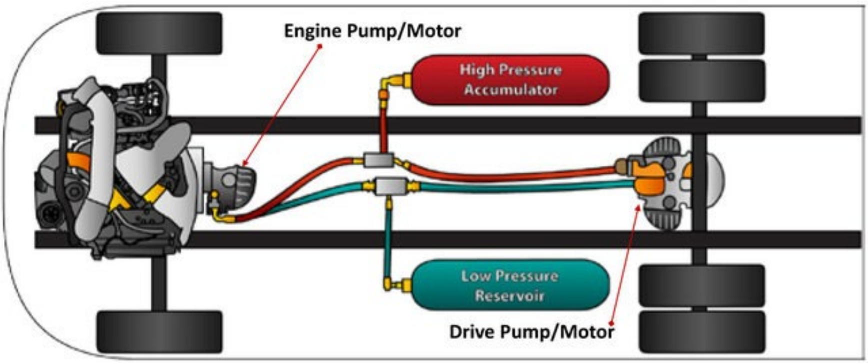

Figure 3.2 Hydraulic energy storage system [2]

Supercapacitors/Ultracapacitors are systems where electrical energy is stored as an electric field (electrostatic) between two electrodes. They offer higher specific power compared to chemical batteries and are known for fast charge/discharge rates and long-life cycles (Figure 3.3). However, supercapacitors have lower energy density than chemical batteries, which is the primary disadvantage preventing their widespread use as battery replacements.

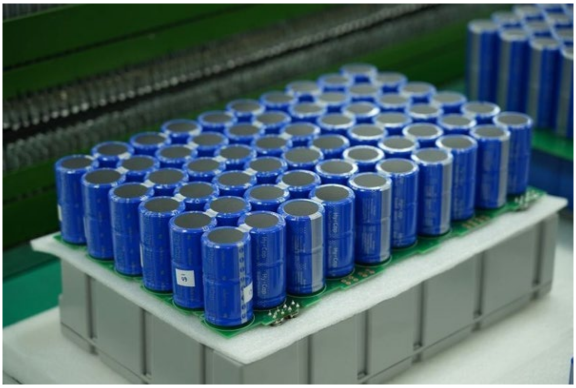

Figure 3.3 Supercapacitor module [3]

Chemical batteries store electrical energy as chemical energy through the chemical materials in their electrodes. A battery consists of two electrodes, the anode and cathode, placed in an electrolyte where chemical reactions occur to store electrical energy. Due to the advancement of electric vehicle (EV) and hybrid electric vehicle (HEV) technologies, chemical batteries are the most widely used energy storage systems today (Figure 3.4).

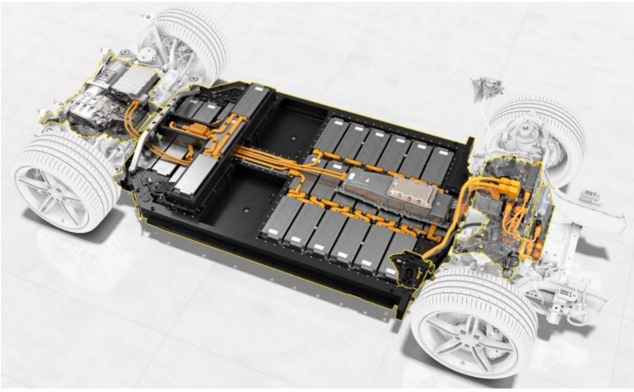

Figure 3.4 High-voltage chemical battery for electric vehicles [4]

3.2. Battery Performance Characteristics

Batteries are composed of specially designed structures utilizing various chemicals. Consequently, different performance characteristics are used to define, classify, and evaluate batteries. Proper evaluation of battery performance characteristics is crucial for selecting batteries for conventional, hybrid, and electric vehicles. The following section explains the performance characteristics of batteries:

Cell Voltage (Nominal Voltage) refers to the specified potential difference between the anode and cathode electrodes. It ranges from 2.1 volts in lead-acid batteries, 1.2–1.4 volts in nickel-based batteries, and 3.4–3.8 volts in lithium-based batteries. The nominal voltage of cells differs from their operating voltage. The operating voltage is 1.8–2.5 volts for lead-acid batteries, 0.9–1.5 volts for nickel-based batteries, and 2.5–4.2 volts for lithium-based batteries.

Capacity (Nominal Capacity) refers to the amount of energy released from chemical reactions within the cell. In other words, it is the specified amount of energy a battery can deliver over a unit of time. It is measured in ampere-hours (Ah) and watt-hours (Wh). In hybrid and electric vehicles with high-capacity batteries, kilowatt-hours (kWh) is the preferred unit. Battery capacity determines the vehicle's range. The capacity rate (C-rate), which represents the usage of capacity over time, is an important concept.

For example, for a 100 Ah battery:

- A 1C rate indicates it can deliver 100 amps (A) for 60 minutes.
- A 2C rate indicates it can deliver 200 A for 30 minutes.
- A C/2 rate means it delivers 50 A over 2 hours, and a C/5 rate delivers 20 A over 5 hours.

For charging, a 2C rate indicates that the battery is charged with 200 A in 30 minutes. A higher C-rate enables fast charging and rapid discharging (Figure 3.5). Fast charging allows the vehicle battery to be charged in a short time, while rapid discharging meets the sudden power demands of the electric motor, enabling quick vehicle acceleration.

Figure 3.5 Capacity (C-rate) [5]

Energy Density refers to the amount of energy available per unit mass or volume of the battery. It is expressed in kilowatt-hours per liter (kWh/L) or kilowatt-hours per kilogram (kWh/kg). Energy density allows for the mass and volumetric comparison of batteries (Figure 3.6). Specific energy is another term for gravimetric energy density.

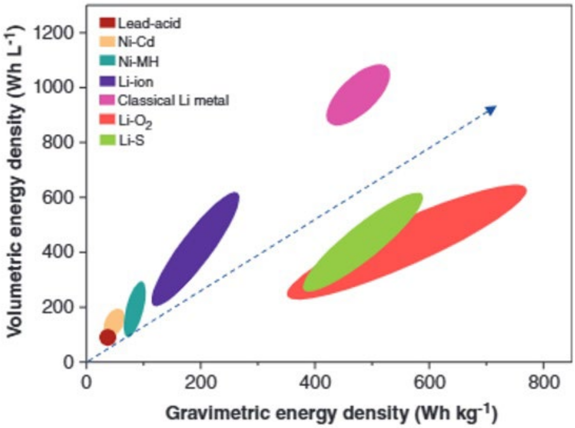

Figure 3.6 Energy density and specific energy graph for chemical batteries [6]

Specific Power is the amount of power a battery can deliver per unit mass and is measured in watt per kilogram (W/kg). For example, in high-performance vhicles, batteries with high specific power are chosen to meet the power demands of high-powered electric motors.

State of Charge (SoC) is the ratio of the energy currently available in the battery to its nominal energy storage capacity. Expressed as a percentage, SoC is displayed on the dashboard to inform the user about the vehicle's range.

Depth of Discharge (DoD) refers to the ratio of the discharged capacity to the total capacity of the battery. It indicates the percentage of the total capacity that can be used for discharge. Subjecting a battery to full or frequent deep discharge negatively affects its lifespan and health. Therefore, DoD is one of the key parameters used to characterize batteries.

State of Health (SoH) is the ratio of the measured capacity of the battery to its nominal capacity. Factors such as aging, deep discharge, overcharging, and temperature reduce the battery's charge-holding capacity over time. SoH, expressed as a percentage, reflects the battery's health relative to its original nominal capacity *[7]*.

Life Cycle refers to the number of charge and discharge cycles a battery can complete without significant performance degradation. A full charge and discharge cycle is considered one cycle. The cycle life determines the battery's lifespan and depends on factors such as temperature, discharge current, state of charge, and depth of discharge. Manufacturers specify the cycle life of cells along with the operating conditions.

Electric vehicles typically use high-voltage systems designed for a 400-volt infrastructure. To achieve faster charging/discharging and higher performance, manufacturers are transitioning to 800-volt systems. Infrastructure preferences influence the chemistry and structure of battery systems. Research on battery chemistry enhances performance characteristics, positively affecting the primary goal of increasing vehicle range.

3.3. High Voltage Battery Technology

With technological advancements, a growing population, and increasing environmental awareness, the demand for electric energy has risen significantly in recent years. Consequently, energy storage systems, one of the most critical components of electric systems, have gained importance. Technological progress has also led to advancements in energy storage systems, as in other fields.

Batteries developed to date are classified based on the type of electrode and/or electrolyte used, including lead-acid, nickel-cadmium, nickel-metal hydride, lithium-ion, and sodium-ion batteries.

3.3.1. Types of Batteries

In 1800, Alessandro Volta invented the voltaic cell, creating the first chemical battery. This invention was a galvanic cell that operated by arranging metal discs in sequence and provided the foundational principles for many modern batteries.

In the mid-19th century, Georges Leclanché invented the zinc-carbon battery, which gained popularity as a durable and economical battery type. It was widely used for portable devices and lighting and became commercially produced.

By the early 20th century, new battery designs, such as Thomas Edison's alkaline storage battery, emerged. During this period, the importance of battery technology grew significantly, particularly for devices like portable radios and the first mobile phones.

In the late 20th century, lithium-ion batteries, known for their high energy density, contributed to the popularity of portable computers, mobile phones, and other mobile devices. Lithium-ion batteries became a preferred power source for electric vehicles due to their lightweight design, high energy capacity, and durability during charge/discharge cycles.

Today, the primary types of batteries used in energy storage systems are lead-acid batteries, nickel-based batteries, lithium-based batteries, and sodium-based batteries.

3.3.2. Lead-Acid Batteries

Lead-acid batteries are divided into two main types: valve-regulated lead-acid (VRLA) batteries and flooded lead-acid batteries. VRLA batteries are also referred to as "sealed" or "maintenance-free," while flooded types are called "vented" or "open type."

Lead-acid batteries are a type of electrochemical cell composed of sulfuric acid as the electrolyte, lead dioxide as the anode, and lead as the cathode. The electrolyte facilitates the chemical reaction between the two electrodes, enabling the storage or release of electrical energy (Figure 3.7).

Figure 3.7 Lead-acid battery [8]

Advantages of Lead-Acid Batteries:

- Low cost.
- High safety performance.
- Long lifespan and low self-discharge rate during use.
- Low maintenance costs.
- Wide operating temperature range.

Disadvantages:

- Limited energy density.
- Low cycle life and irreversible capacity loss.
- Long charging times.
- Thermal instability.
- High weight and environmentally harmful components.

- Rapid self-discharge when not in use for extended periods.
- Prone to sulfation.

3.3.3. Nickel-Based Batteries

Nickel-based batteries come in several types, including Nickel-Cadmium (NiCd-NiCad), Nickel-Metal Hydride (NiMH), Nickel-Iron (NiFe), and Nickel-Zinc (NiZn) [9]. NiCd batteries were widely used in hybrid and electric vehicles until their toxic components led to their prohibition. In hybrid vehicles, NiMH batteries have been widely utilized.

Nickel-Cadmium (NiCd-NiCad) Batteries

The NiCd battery system was first developed in 1899 by Swedish inventor Waldemar Jungner and was commercially produced in Europe and the United States by the 1950s. NiCd batteries were used extensively in portable devices for a long time but were replaced in the market by nickel-metal hydride (NiMH) batteries due to the health and environmental hazards of cadmium.

NiCd batteries have a nominal voltage of 1.2V, with cadmium metal as the anode and nickel hydroxide as the cathode. Electrons released from the positive electrode flow to the negative electrode, reacting with cadmium and hydroxide to form cadmium hydroxide. The electrolyte is potassium hydroxide (KOH). The reaction is reversible, making the battery rechargeable.

Advantages:

- High charge/discharge cycle count.
- Good performance under load; robust structure.
- Long shelf life; can be stored in a fully discharged state and immediately used after a full charge.
- Simple transportation rules; not subject to regulatory controls.
- Operates efficiently across a wide temperature range, including low temperatures.
- Lowest cost per cycle compared to other battery types.
- Available in a variety of sizes and power options.

Disadvantages:

- Lower specific energy compared to newer battery technologies.
- Cadmium is a toxic metal and cannot be disposed of in standard waste facilities.
- High recycling costs.

- Low cell voltage (1.20V) requires multiple cells in series to achieve high voltage.
- High production cost due to the expensive cadmium component.

Nickel-Metal Hydride (NiMH) Batteries

NiMH batteries were considered advanced for their time. They were patented by Stanford R. Ovshinsky and introduced to the market in the 1990s.

NiMH batteries use metal hydrides capable of hydrogen absorption at the anode and nickel hydroxide at the cathode, similar to NiCd batteries. The electrolyte is a potassium solution, and a separator, typically made of polyamide, polypropylene felt, or gauze is placed between the two electrodes. The entire battery is housed in a steel casing.

Advantages:

- High energy density.
- Environmentally friendly as they do not contain pollutants.
- Lightweight construction.
- High resistance to overcharging and over-discharging.

Disadvantages:

- More expensive than NiCd batteries.
- Tendency to cut off current abruptly rather than gradually.
- Prone to self-discharge.
- While a Battery Management System (BMS) is not mandatory, these batteries are among the most challenging to charge correctly without one.
- Poor capacity retention over time.
- Can lose up to 20% of their capacity within 24 hours of the first charge.

3.3.4. Lithium-Based Batteries

Lithium-based batteries can be categorized as follows:

- Lithium-Nickel Manganese Cobalt Oxide (NMC)
- Lithium Iron Phosphate (LFP)
- Lithium Manganese Oxide (LMO)
- Lithium Titanium Oxide (LTO)
- Lithium Cobalt Oxide (LCO)
- Lithium Nickel Cobalt Aluminum (NCA)
- Lithium-Metal (Solid State)

M. Stanley Whittingham is considered the inventor of lithium-ion batteries due to his work on lithium-ion cells in the 1970s. Lithium-ion batteries were first commercially used by Sony in 1991. Their use in electric vehicles (EVs) has transformed perceptions of EVs. Lithium-ion batteries, long used in various applications, have been integrated into EVs due to advancements in cathode materials. NMC and LFP batteries are commonly used in electric vehicles.

Lithium-Nickel Manganese Cobalt Oxide (NMC) Batteries

Also referred to as Li-NMC, LNMC, or simply NMC, these batteries feature a cathode made of nickel, manganese, and cobalt. The nominal cell voltage is 3.6–3.7 volts, with an optimal operating temperature of 25°C. The cobalt in its composition increases costs due to mining challenges. NMC622 and NMC811 chemistries are preferred for EVs, with NMC811 representing 80% nickel, 10% manganese, and 10% cobalt in the cathode composition.

Advantages:

- High energy and power density.
- Good charging performance at low temperatures.
- High resistance to low temperatures.
- Long cycle life.
- Good thermal stability.
- High unit energy density relative to its physical structure.

Disadvantages:

- Susceptible to high-temperature degradation.
- Requires effective thermal management.
- High cost.
- High thermal runaway risk.
- Shorter design life when a high nickel ratio is used to reduce costs.

Lithium Iron Phosphate (LFP) Batteries

LFP batteries use lithium iron phosphate (LiFePO4) as the cathode, graphite carbon with a metallic backing as the anode, and lithium ferrophosphate as the electrolyte. The nominal voltage is 3.2–3.3 volts, with a maximum charge voltage of 4.2 volts. They can operate between -20°C and +70°C. The accessibility and affordability of cathode materials have led manufacturers to favor LFP batteries.

Advantages:

- Utilizes 99% of its capacity.
- High load tolerance.

- Performs well at high temperatures.
- Offers a long cycle life.
- Environmentally friendly.
- Low tendency for thermal runaway.
- Iron and phosphate are abundantly available on Earth.
- Long battery lifespan.
- Short charging times.

Disadvantages:

- Despite being lightweight, achieving the same capacity as NMC batteries requires increasing cell energy density and cell count, leading to a weight disadvantage.
- Poor performance at low temperatures.
- Prone to cell imbalance as it ages.

Lithium-Metal (Solid State) Batteries

Lithium-metal batteries replace the liquid or gel electrolyte found in most lithium-based batteries with a solid electrolyte. Since all battery components are solid, they are referred to as solid-state batteries. The cathode contains the same chemicals as other lithium-based batteries, while ceramic or solid polymer is used as the separator and electrolyte material. Lithium metal is used as the anode material.

Advantages:

- Safer than other lithium-based batteries.
- Higher energy density.
- Long life cycle.
- Supports fast charging.

Disadvantages:

- Susceptible to lithium dendrite formation.
- Issues with electrode interface degradation.
- Challenges in manufacturing.
- Reduced performance at low temperatures.

3.3.5. Sodium-Based Batteries

Sodium, an alkali metal, belongs to the same group as lithium in the periodic table, indicating some physical and chemical similarities. Research on sodium batteries between 1970 and 1990 coincided with studies on lithium-based batteries. Sodium-ion batteries have sodium in the cathode, and the electrolyte is a liquid containing sodium salts. The nominal voltage of a sodium battery is 2.3–2.5 V. These batteries are used as an alternative to lithium-ion batteries in electric vehicles. Due to their cost-effectiveness, they have been adopted for mass production in vehicles (Figure 3.8).

Figure 3.8 Sodium-ion cell [10]

Advantages:

- Low risk of combustion and explosion.
- Easy to recycle.
- Cost-effective.
- Operates efficiently at low temperatures.
- Depth of discharge (DoD) is considered 100%.

Disadvantages:

- Lower energy density compared to lithium-based batteries.
- Limited commercial availability.
- Non-ecological production methods with negative environmental impacts.

3.4. Battery Architecture (Design)

High-voltage (HV) battery packs are among the most critical components of hybrid and electric vehicles. These battery packs determine values such as vehicle range, charging, and discharging conditions. Additionally, they enhance structural features like durability and center of gravity in electric vehicles compared to conventional vehicles. Batteries positioned on the vehicle floor in hybrid and electric vehicles positively contribute to the vehicle's center of gravity and body strength.

High-voltage battery design is a systematic process that includes producing cells from raw materials, manufacturing modules from cells, and assembling modules into packs. HV battery packs consist of various components such as cells, modules, cables/busbars, sensors, thermal system elements, covers, battery management systems, electronics, and sealing elements (Figure 3.9).

Figure 3.9 HV battery pack and components [11]

The building blocks of a battery pack are the cells, which are classified into four types based on their geometric shapes: cylindrical, prismatic, pouch, and blade cells.

Cylindrical Cells

Cylindrical cells are formed by rolling anode, cathode, and separator strips and placing them into a cylindrical can (Figure 3.10). These cells use liquid electrolytes. Their cylindrical shape provides robust mechanical structure and better heat dissipation. The most commonly used cylindrical cells in electric vehicles are 18650, 21700, and 46800. For example, in the 18650 cell, "18" refers to the diameter in mm, "65" indicates the height in mm, and "0" denotes the cylindrical shape. The main disadvantage of cylindrical cells is that fewer cells can be packed into the same volume compared to other cell types, resulting in lower energy density. To increase energy density, more cells are used, which adds weight to the battery pack.

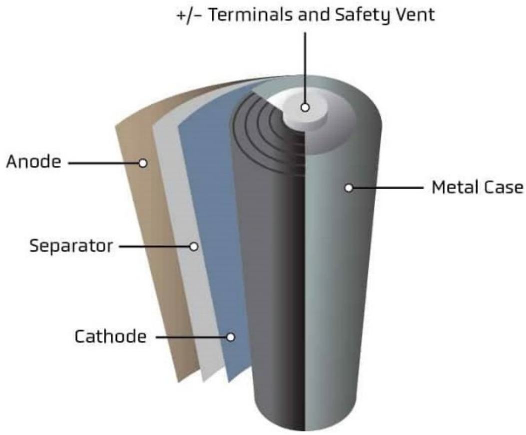

Figure 3.10 Cylindrical cell [12]

Prismatic Cells

Prismatic cells are formed by rolling anode, cathode, and separator strips into a rectangular prism and placing them in a rectangular metal or plastic case. They have a compact structure that optimizes packing density. Prismatic cells are easy to assemble and disassemble using bolted connections, making them popular among manufacturers. However, the casing increases their weight compared to other cell types. Additionally, the corners of the cells are prone to stress, which negatively impacts heat dissipation.

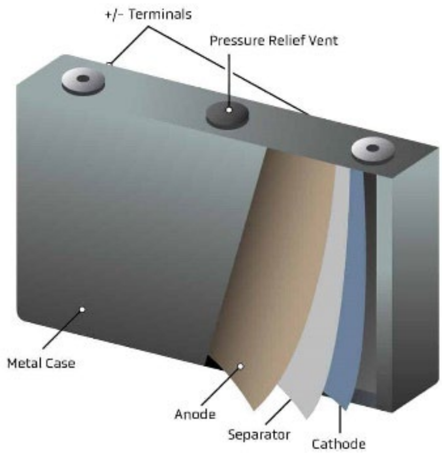

Figure 3.11 Prismatic cell [12]

Pouch Cells

Pouch cells are formed by stacking anode, cathode, and separator strips in a rectangular shape and placing them into a soft aluminum pouch with liquid electrolytes (Figure 3.12). As a newer design, pouch cells are lighter than other cell types of the same capacity and provide higher packing efficiency. However, they have lower mechanical strength and are prone to swelling due to their pouch structure.

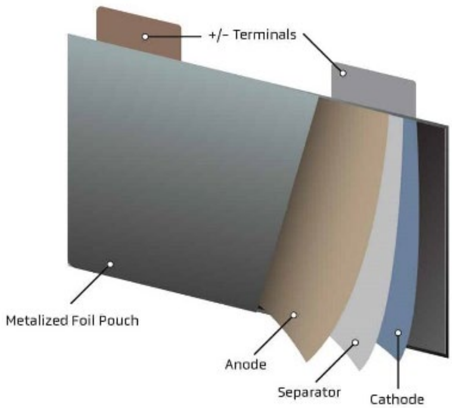

Figure 3.12 Pouch cell [12]

Blade Cells

Blade cells are fundamentally similar to prismatic cells. Anode, cathode, and separator strips are stacked in a rectangular shape and placed in a rectangular metal case. Blade cells differ from prismatic cells in their aspect ratio. Placing positive and negative terminals on the side surfaces reduces battery height, and the cells directly form the battery pack. Their elongated shape increases cell capacity and energy density compared to other cell types with the same chemistry. The longer design also facilitates heat dissipation and transfer. LFP chemistry is commonly used in blade cells.

Figure 3.13 Blade cell [13]

Design Approaches

In traditional designs, cells are assembled into modules, and modules are assembled into battery packs. To reduce vehicle production costs and increase packing efficiency, alternative design approaches are employed, including cell-to-pack, cell-to-body, cell-to-chassis, and module-to-chassis designs (Figure 3.14).

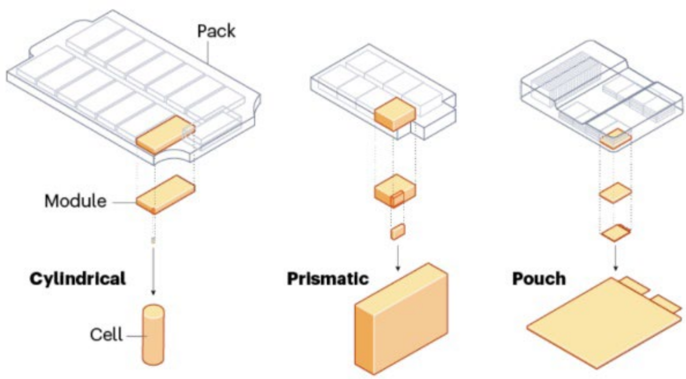

Figure 3.14 Cell-to-module-to-pack formation [14]

3.5. Battery Management Systems (BMS)

Battery packs are formed by connecting numerous cells in series and parallel configurations. Due to the chemical nature of the cells, monitoring their electrical values and thermal states is essential for safe and long-lasting use. Without this monitoring, cells can sustain permanent chemical damage, leading to various hazards. A Battery Management System (BMS) is used to monitor and manage all parameters during the charging and discharging processes of batteries. The BMS consists of hardware and software systems.

3.5.1. Structure and Functions

The BMS performs monitoring, protection, charge-discharge management, fault detection/recording, and communication functions for batteries (Figure 3.15). During monitoring, the BMS tracks module/cell voltage, current, temperature, pressure, insulation, and locking conditions. Based on this data, it estimates the state of charge (SoC), depth of discharge (DoD), available capacity, available energy, and charging time, optimizing battery performance.

For protection, the BMS identifies and validates operating and fault conditions to safeguard the battery. It detects overcharge and over-discharge conditions, insulation faults, and low or high-temperature conditions.

During charge-discharge management, the BMS manages the charging/discharging current, controls switching between the battery and charger, activates the precharge circuit, and performs active or passive balancing.

For fault detection/recording, the BMS identifies and logs conditions like faults, thermal degradation, and fires to maintain overall battery safety. The BMS communicates with the vehicle's main control unit and charger by predicting states based on sensor data.

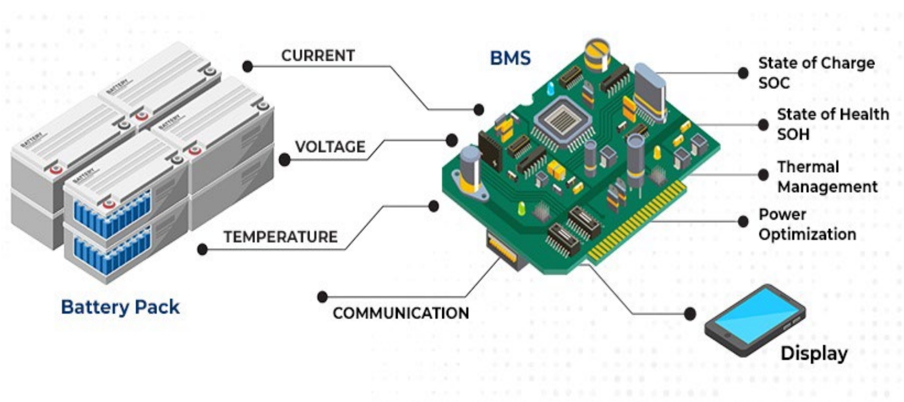

Figure 3.15 BMS Diagram [15]

BMS Topologies

BMS designs vary based on their connections to cells and modules. The general structure consists of a master module communicating with the vehicle's electronic control unit and multiple slave modules connected to cells or modules. There are three main BMS topologies for managing battery packs: centralized, distributed, and modular.

Centralized BMS Topology

This topology uses a single module to manage all cells (Figure 3.16). It has a simple design due to fewer components. However, monitoring and measurement become challenging in batteries with a large number of cells. Connecting all cells to a single module may require more wiring, increasing the risk of signal interference and voltage drop.

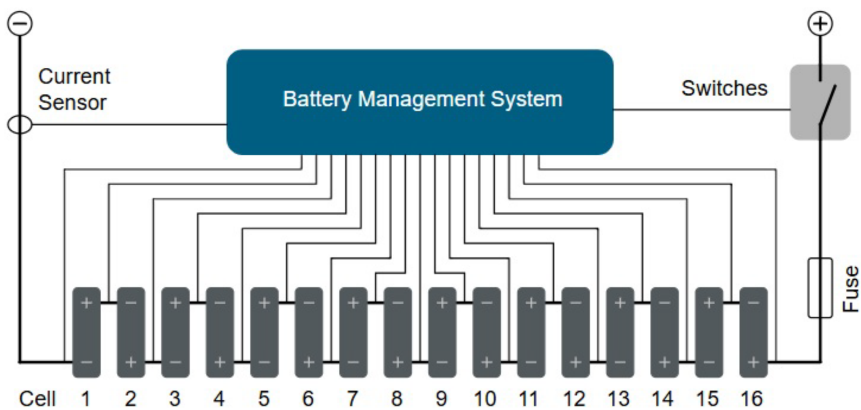

Figure 3.16 Centralized BMS Topology [16]

Distributed BMS Topology

In this topology, each cell is managed by a separate module (Figure 3.17). This allows more efficient cell monitoring and management. However, the increased number of modules results in a more complex structure, leading to higher costs.

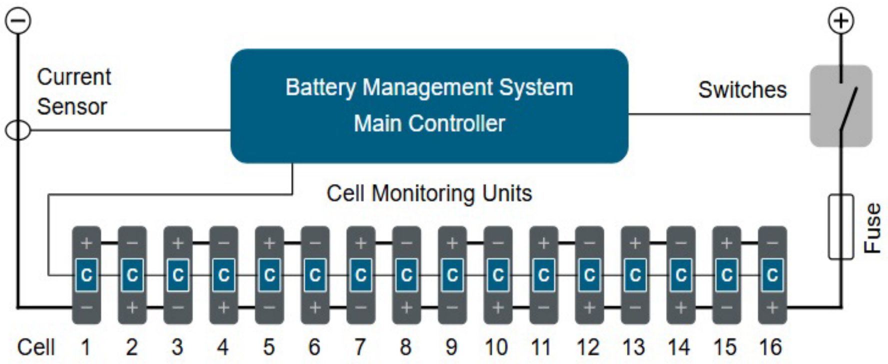

Figure 3.17 Distributed BMS Topology [16]

Modular BMS Topology

This topology involves managing groups of cells divided into modular structures (Figure 3.18). It consists of slave modules that monitor and control cell groups and a master module that acts as a coordinator and communicates with the vehicle's control unit.

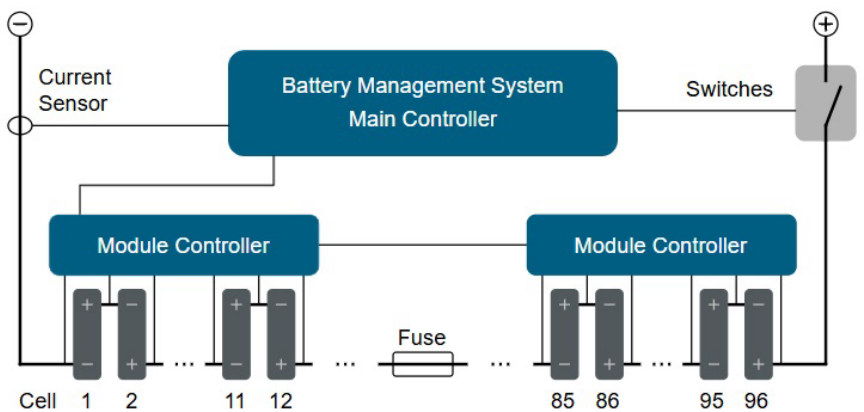

Figure 3.18 Modular BMS Topology [16]

Sensors in BMS

The following sensors are used in the battery pack to execute BMS operations:

- **Voltage Sensor:** Measures cell/module voltages. Voltage monitoring is performed for balancing cells.

- **Current Sensor:** Measures cell/module current. Monitoring the pack's current value is crucial for controlling charging and discharging. Hall-effect current sensors are commonly used.
- **Temperature Sensor:** Measures the temperature of cells, modules, or busbars. It ensures the battery operates within a thermally efficient range.
- **Pressure Sensor:** Measures absolute pressure within the battery pack. It monitors pressure changes caused by thermal degradation or impacts.
- **Gas Detection Sensor:** Detects combustible gases released due to thermal degradation or leakage in the battery. It informs the vehicle control unit of hazardous conditions like fires.
- **Liquid Detection Sensor:** Detects liquid leaks caused by thermal system malfunctions in the battery pack.

3.5.2. Thermal Management Systems

Temperature significantly affects the performance, durability, and lifecycle of chemical cells. At high temperatures, cells begin to degrade and, if not controlled, may experience thermal runaway. Heat generated during charging/discharging processes in batteries must be managed effectively. At low temperatures, cell internal resistance increases, reducing performance. In vehicles used in cold climates, a heating system is necessary to maintain battery temperatures within specific ranges. For example, lithium-ion batteries operate between -20°C and 60°C but achieve optimal performance between 15°C and 35°C. Due to these requirements, Battery Thermal Management Systems (BTMS) are indispensable.

In high-voltage (HV) batteries, manufacturers may implement cooling-only, heating-only, or combined systems. BTMS operates based on data from sensors within the battery pack, such as current, temperature, and pressure.

BTMS can be categorized into three methods: passive, active, and hybrid systems (Figure 3.19). Active systems use refrigerant gases, forced air, or liquids. Refrigerant gases like R1234yf and R774 are commonly used. Liquid-based systems are further divided into direct and indirect types, depending on whether the liquid contacts the module/cell surface. Passive systems rely on natural convection or conduction for cooling without energy input. Phase-changing materials and heat pipes are used in passive systems. Hybrid systems combine elements from passive and active cooling, utilizing different fluids or devices for cooling. The fluids used in cooling systems include air, liquids, and refrigerant gases.

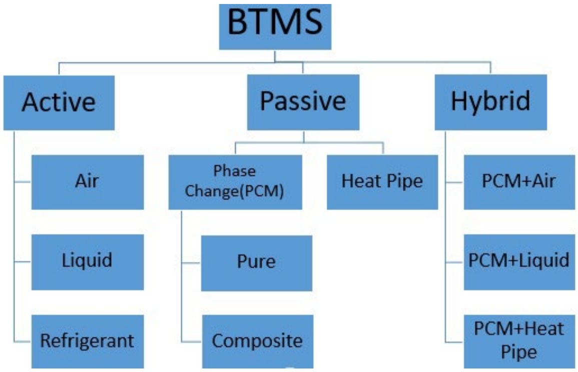

Figure 3.19 BTMS types

When battery chemicals operate at low temperatures, charge/discharge performance and energy capacity decrease. To address this disadvantage, manufacturers may incorporate heating functions into thermal systems. Battery heating systems use the same methods and techniques as cooling systems, with PTC (Positive Temperature Coefficient) heaters being a common choice (Figure 3.20). PTC heaters warm the air or liquid to heat the system. In electric vehicles, thermal management is not limited to batteries; it also involves the cabin, electric motors, and power electronics. An integrated thermal management system is often preferred to manage all these components efficiently, with heat pumps being a popular solution.

Figure 3.20 PTC battery cooling fluid heater [17]

In heat pump systems, refrigerant gas transfers heat indirectly to or from the battery cooling fluid via a heat exchanger (Figure 3.21). If the heat exchanger heats the refrigerant gas, the battery is warmed; if cooled, the battery is chilled. This process is facilitated by electric liquid pumps and electronically controlled directional valves.

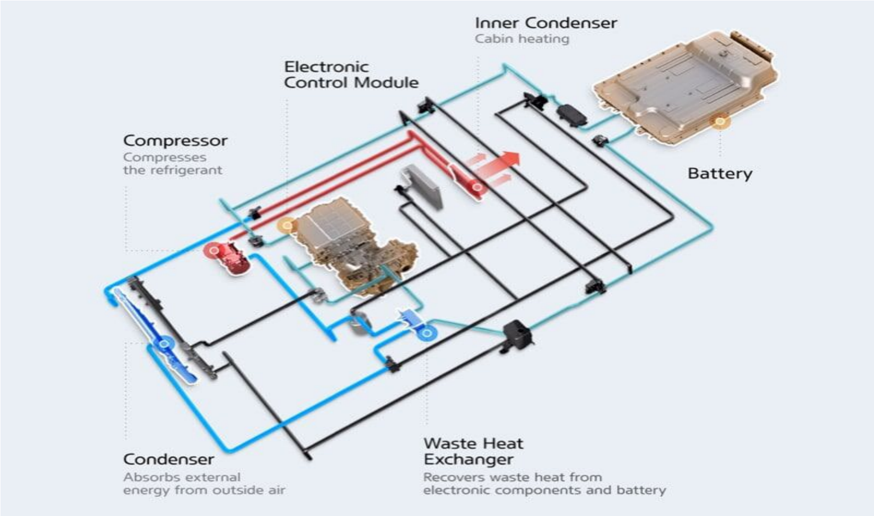

Figure 3.21 Vehicle and battery thermal system[18]

3.5.3. Battery Electronics

High-voltage management in electric vehicles is handled by the Battery Junction Box (BJB) **or** Battery Disconnect Unit (BDU), which contains electrical and electronic circuits (Figure 3.22). These units manage the interface between the vehicle's low-voltage electrical system and the high-voltage system. The components include main contactors, fast-charging contactors, a precharge circuit, fuses, and sensors.

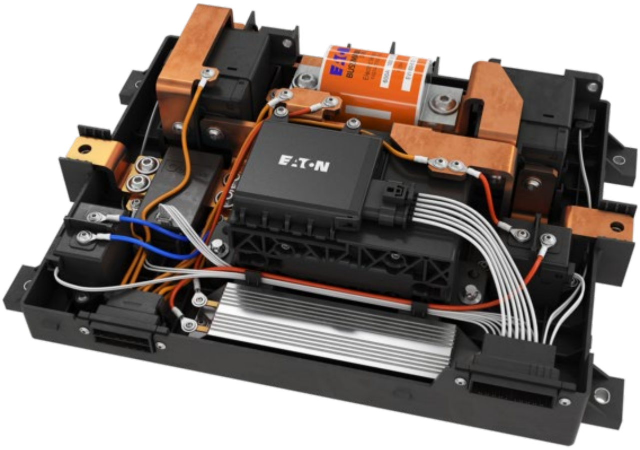

Figure 3.22 Battery Disconnect Unit [19]

The contactors controlled by the BMS are the primary switching elements for high-voltage management. Typically, three contactors positive, negative, and precharge are used for the main battery outputs.

The precharge circuit consists of a contactor, resistor, and capacitor. If high-voltage DC power is delivered directly from the battery to the system, the load components demand high current, which can cause damage to both the battery and the load components. The precharge circuit prevents this issue by gradually introducing current.

The operation of the main contactors and precharge circuit is as follows: When the system requests power, the negative main contactor is engaged first, followed by the precharge contactor. The voltage is then limited via the resistor, allowing the current to stabilize indirectly as the capacitor charges. Once the high voltage is balanced, the positive main contactor is activated, and the BMS permits high-voltage output from the battery (Figure 3.23).

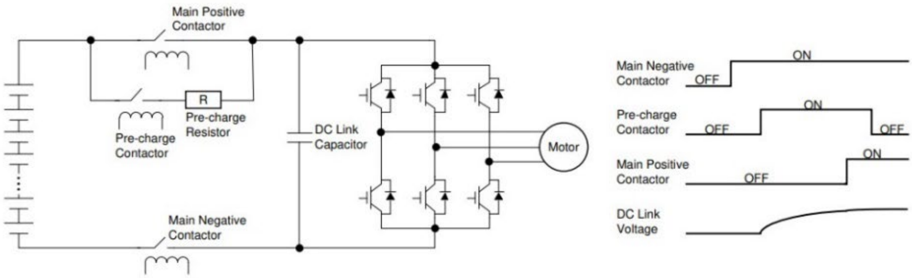

Figure 3.23 Main contactors and precharge circuit [20]

Fuses protect the battery and power electronics from overloads and short circuits. Standard passive fuses, designed to handle high voltage and current, are commonly used in the BDU. Some applications employ pyrotechnic fuses, which include a firing module and piston mechanism like those in airbag modules. During a vehicle collision, if the airbag system is activated, the pyrotechnic fuse receives a signal from the ECU or BMS. The resulting pressure activates the piston, disconnecting the bar in front of it, thereby preventing high-voltage output from the battery.

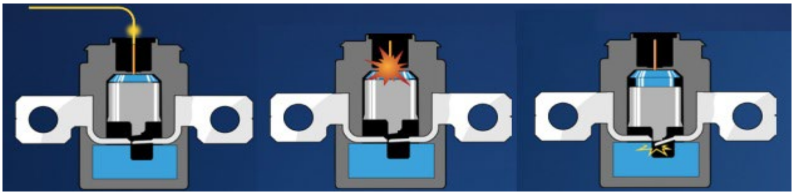

Figure 3.24 Pyrotechnic fuse and its operation [21]

3.6. Battery Transportation and Waste Management

The production of batteries is a systematic process governed by specific norms. The process begins with the extraction of chemicals through mining, followed by refinement and the production of anodes and cathodes. During the production stage, cells are manufactured, which are then assembled into modules and battery packs. In the usage phase, automotive companies install high-voltage (HV) batteries into vehicles and deliver them to users. During their lifecycle, companies provide service operations. After usage, batteries are evaluated based on their state of health (SoH): they are either discarded as waste, recycled, or repurposed for secondary use in energy storage systems. Ultimately, all batteries are subjected to recycling processes. In the recycling phase, cells with good SoH are returned to the production stage, while others are recycled using established methods, returning to the beginning of the process (Figure 3.25).

Figure 3.25 Battery lifecycle stages [22]

Due to the risks associated with battery chemicals, it is essential to monitor the usage and recycling processes of batteries. To facilitate this, the European Union norms plan to make the use of a "digital battery passport" mandatory by 2027. This digital passport aims to track factors such as battery durability, efficiency, and carbon footprint. According to regulations, batteries with a capacity greater than 2 kWh must include a QR code. The QR code links to the digital battery passport, which contains information such as the manufacturer, vehicle category, model and serial number, battery status and chemical composition.

3.6.1. Battery Transportation Processes

Batteries, composed of chemicals capable of releasing flammable and toxic gases, must be transported under strict regulations. Agreements such as ADR (European Agreement concerning the International Carriage of Dangerous Goods by Road) and RID (Regulations concerning the International Carriage of Dangerous Goods by Rail), to which Turkey is a signatory, govern battery transportation. The "Regulation on the Transport of Dangerous Goods by Road" (ADR Regulation) was published by the Ministry of Transport, Maritime Affairs, and Communications in the Official Gazette No. 28801 on October 24, 2013. Guidelines and classification instructions for air and sea transport are also available. These agreements outline directives and labeling requirements to ensure the safe and environmentally sound transportation of hazardous materials.

Regulations must be frequently updated as necessary. According to the United Nations Model Regulations, lithium-based batteries are classified as hazardous materials. Batteries pose both chemical and electrical risks and are categorized under Class 9 in the ADR regulation. Depending on the battery type and whether it is integrated into a device, ADR and RID classifications are specified with different UN codes and labels (Figure 3.26).

UN Code	UN 3091	UN 3090	UN 3481	UN 3480
Explanation	Lithium Metal Batteries With or in the Device	Lithium Metal Batteries	Lithium-Ion Batteries with or in the Device	Lithium-Ion Batteries
Max limit per cell	1 g Lithium	1 g Lithium	20 Wh	20 Wh
All Battery Max Limit	2 g Lithium	2 g Lithium	100 Wh	100 Wh
Weight Max	No Limit	Per Shipment / 30 kg gross	No Limit	Per Shipment / 30 kg gross
Label	 UN 3091	 UN 3090	 UN 3481	 UN 3480

Figure 3.26 Lithium battery transportation standard UN code table [23]

For air transportation, all lithium-ion cells and batteries (classified under UN 3480) must not exceed 30% state of charge (SoC). Proper packaging of batteries is crucial; they must be protected from damage and excessive heat. Specially designed transport boxes are used for battery transportation. Batteries sent for repair or recycling after service operations must be properly packaged and labeled (Figure 3.27).

Figure 3.27 Specialized transport boxes for battery shipment [24][25]

For road transport, these UN 3840 ADR Class 9 P902 and P903 regulation-certified boxes prevent battery damage from falls during transit. Additionally, temperature and shock detection systems can be integrated into these boxes.

Greater care is required when transporting used or defective batteries. Such batteries are subject to Special Provision 376 and must meet certification standards in compliance with ICAO (International Civil Aviation Organization) technical specifications.

3.6.2. Thermal Runaway and Fire

Thermal Runaway

Although battery-related fire incidents in hybrid and electric vehicles (HEVs and EVs) are rare, they pose risks such as high voltage, thermal load, and toxic gas emissions when they occur. Battery fires often spread from cell to cell in a process known as thermal runaway [30]. Lithium-ion batteries operate efficiently at 21–24°C, with operational temperature limits of 15–45°C. Prolonged exposure to temperatures below 15°C causes permanent damage to the battery, while temperatures above 45°C are considered risky. Above 60°C, thermal runaway progresses into a chain reaction (Figure 3.28).

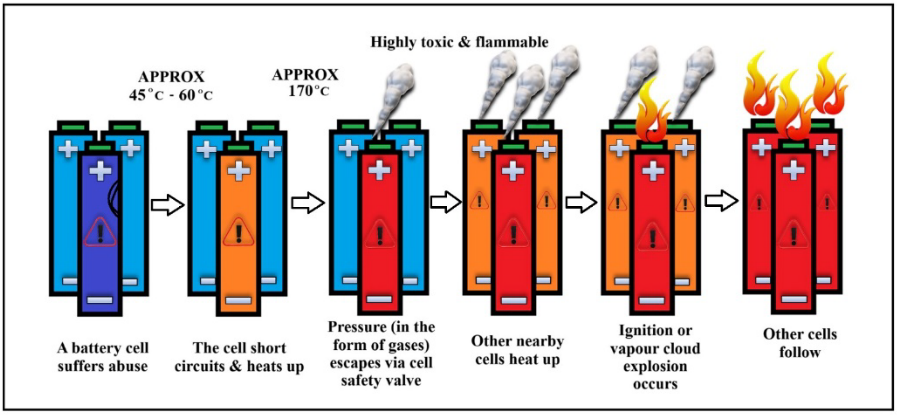

Figure 3.28 Thermal runaway stages

Battery cells are placed close to each other for pack efficiency, which increases the risk of short circuits between electrodes. Heated electrolyte liquids tend to boil. The expanding and boiling liquid is released through a safety valve, potentially triggering thermal runaway in neighboring cells. To mitigate these risks, battery manufacturers use fire-resistant insulated barriers to prevent thermal runaway between cells.

Batteries may sustain mechanical, electrical, and thermal damage:

- **Mechanical Damage:** This occurs due to impacts on the vehicle's battery compartment, damage to the battery casing, compression, crushing, or puncture of cells. These physical damages may deform the separator inside the cell. Damage to the separator between the anode and cathode can cause unwanted electron flow, initiating heat buildup that leads to thermal degradation and ultimately combustion.
- **Electrical Damage:** This includes overcharging or over-discharging of cells, high power output, or internal short circuits within cells. Overcharging causes lithium ions to bind with the anode, while the electrolyte and transition metals decompose. Over-discharge results in dendrite formation inside the cell and the release of gases like carbon dioxide, carbon monoxide, hydrogen, and oxygen. Electrical damage also harms the separator, and any puncture in the separator may cause thermal degradation.
- **Thermal Damage:** Spontaneous high heat generation within the cell or exposure to external heat may initiate uncontrolled reactions, leading

to thermal runaway and fire. High temperatures cause the separator to collapse, failing to insulate the anode and cathode, which results in an internal short circuit and subsequent thermal runaway.

Fire

One of the greatest risks in HEVs and EVs is fire caused by thermal runaway. The rate at which thermal runaway and fire begin varies depending on the battery chemistry. Mechanical, electrical, and thermal damage increases temperature. If abnormal temperature rises are detected, cooling measures should be taken to prevent or delay explosions and ignition. Due to the positioning of batteries under vehicles, lateral flames are often observed. To reduce risks, HEVs and EVs with thermal runaway potential should be parked away from other vehicles.

Battery fires can be extinguished with carbon dioxide or dry chemicals. While these chemicals are effective in controlling and extinguishing fires, they lack cooling properties, increasing the likelihood of re-ignition.

Extinguishing a fire does not necessarily mean toxic gas emissions from the battery have ceased. If electrolyte leakage occurs, the evaporating electrolyte and combustible gases may pose inhalation hazards during intervention. Cooling is the most critical factor. Reducing cell temperature prevents the spread of combustible gases through reaction. In addition to carbon dioxide and dry chemical interventions, methods such as submerging the battery-equipped vehicle in a water tank or covering the battery with fireproof blankets to cut off oxygen can be applied (Figure 3.29).

Figure 3.29 Battery fire extinguishing methods [27][28]

Unlike other fires, battery fires can reignite even days later, even when submerged in a water tank. In some cases, fire crews may wait for the entire battery to burn out under controlled conditions to prevent re-ignition.

In service environments, special fire suppression equipment, the use of thermal cameras, and easily accessible workshop doors to evacuate vehicles and batteries are essential precautions. Additionally, manufacturers are required to publish emergency response guides for HEVs and EVs to assist firefighters and emergency response teams in dealing with potential hazards after incidents.

3.6.3. Waste Management and Recycling

If battery chemicals are not subjected to appropriate recycling processes after reaching the end of their lifecycle, they can harm the environment. Metals commonly found in batteries, such as lead, cadmium, nickel, manganese, cobalt, and lithium, are toxic pollutants for water, soil, and air. As hazardous waste, they must be either disposed of safely or recycled. Another critical aspect of waste management and recycling is the recovery and reuse of valuable metals in batteries, contributing to the economy. Since the reserves of these battery-related metals are limited, recycling processes are essential. Components such as the external casing, cell casing, anode, cathode, separators, plates, and liquid electrolyte in battery packs are recyclable. Each component contains a variety of metals, plastics, and chemicals, making the separation and conversion of batteries a task requiring professional expertise.

High-voltage (HV) battery recycling is carried out under four main stages: preprocessing, stabilization, dismantling, and separation. These main stages employ mechanical (direct recycling), pyrometallurgical, and hydrometallurgical methods. Mechanical separation is used for parts like plastic and metal. Hydrometallurgical processing involves acid precipitation, where rare minerals in the so-called "black mass" are extracted as pure compounds in the form of metal salts. The recovered minerals are then used in new cell production. In pyrometallurgical methods, valuable metals are obtained through various thermal processes (Figure 3.30). Unfortunately, not all components in batteries can be recycled. In such cases, disposal methods are applied within the framework of waste management. Disposal refers to rendering chemicals into a form that does not pollute the environment.

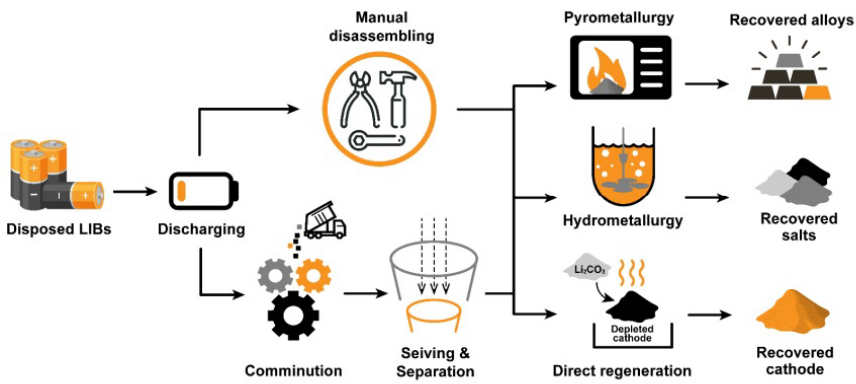

Figure 3.30 Lithium-ion battery recycling methods [29]

3.7. Charging Methods and Systems

igh-voltage (HV) batteries are charged using Electric Vehicle Supply Equipment (EVSE). Charging methods for electric vehicles include wired, wireless, and battery-swapping techniques. Wired charging methods use various connector types for alternating current (AC) and direct current (DC) systems, and charging stations are named based on the type of current they provide. Wireless charging methods do not require cables or connectors; vehicles simply need to be parked over an induction charging unit. In the battery-swapping method, stations store fully charged batteries. The station's technical infrastructure removes the discharged battery and replaces it with a fully charged one in a short time. Advances in battery chemistry have led to significant improvements in charging methods.

3.7.1. Charging Methods

Wired Charging Method

In the wired charging method, there are two approaches based on the type of current:

- **Alternating Current (AC) Charging Method**

This method charges electric vehicles using alternating current only. It operates at 220 volts for single-phase and 400 volts for three-phase systems, with a charging power range of 1.8–22 kW. AC charging is typically done using residential or public charging units. The alternating current from the grid is converted to direct current by the onboard charger in the vehicle and stored in the battery. Compared to the DC charging method, AC charging has higher electrical losses and takes longer to charge.

- **Direct Current (DC) Charging Method**

This method is used exclusively for fast charging electric vehicles with direct current. The alternating current from the grid is converted to direct current by the charging unit. When an electric vehicle connects to a DC charging unit, no further conversion is needed, resulting in lower electrical losses. DC charging is available with portable units starting at 5 kW and goes beyond 400 kW with high-power units.

Wireless Charging Method

As the name suggests, wireless charging, which became popular with mobile phones, is being developed for electric vehicles. This method includes technologies for both stationary and dynamic charging using **Magnetic Resonance Coupling (MRC)**. The charging process occurs through interaction with a charging surface, known as a dock, located beneath the vehicle (Figure 3.31). Dynamic wireless charging prevents time loss by enabling charging while driving, whereas stationary wireless charging is valued for its practicality and ease of use.

Figure 3.31 Wireless charging method [30][31]

Battery-Swapping Charging Method

The varying charging times of electric vehicles have prompted alternative solutions, such as battery-swapping stations (Figure 3.32). For this technology to work, electric vehicles must be technically designed to allow automated battery swapping. Vehicles with depleted batteries enter stations similar to automated car washes. The battery underneath the vehicle is automatically removed and replaced with a fully charged battery without human intervention. The main challenge to widespread adoption of this system is the difficulty of standardizing battery designs across all electric vehicles to integrate with this technology.

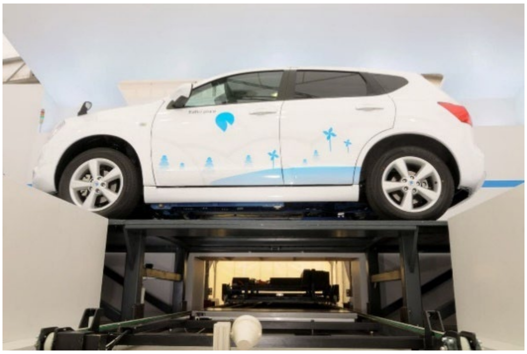

Figure 3.32 Battery-swapping charging method [32]

3.7.2. Charging Modes

There are four charging mode options. Modes 1, 2, and 3 enable charging with alternating current (AC), while Mode 4 supports charging with direct current (DC). In Mode 4, the AC to DC conversion takes place at the station (off-board charger), whereas in the other modes, the conversion is performed by the onboard charger within the vehicle.

Mode 1

Mode 1, also referred to as domestic charging, uses a standard household socket to directly charge the vehicle with AC via its connector (Figure 3.33). Mode 1 supports a current of up to 16 amps with a voltage limit of 250 volts for single-phase and 480 volts for three-phase systems. This is the slowest charging mode. Due to the lack of grounding in some sockets, it poses risks to both the vehicle system and human safety and is therefore banned in Europe.

Figure 3.33 Mode 1 charging process [33]

Mode 2

Similar to Mode 1, Mode 2 uses a household socket for AC charging. The difference lies in the inclusion of a communication and protection device between the vehicle connector and the socket (Figure 3.34). This device, known as the communication adapter, protects systems from sudden electrical surges. It only allows electrical transmission if grounding is available. With this device, the current can reach up to 32 amps.

Figure 3.34 Mode 2 charging process [33]

Mode 3

Known as wall-mounted charging mode, Mode 3 provides up to 63 amps and 44 kW of power (Figure 3.35). The communication adapter is integrated into the charging unit. This AC charging mode is the first to be used in public areas. The capacity depends on the grid supply, and the vehicle's charging power depends on the onboard charger's specifications.

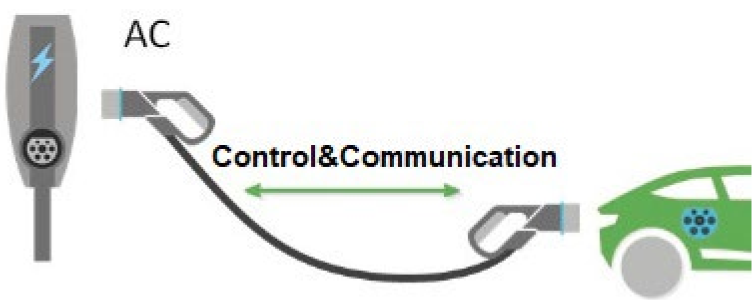

Figure 3.35 Mode 3 charging process [33]

Mode 4

Mode 4 enables DC charging and is categorized as fast or ultra-fast charging, depending on the output power. The AC from the grid is converted to DC by an inverter at the station. The charging device and cable are part of the station, not the vehicle (Figure 3.36). The power capacities of these units are continually increasing, with current capacities reaching 400 amps and 350 kW.

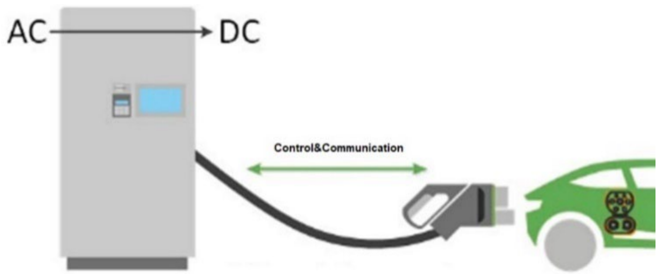

Figure 3.36 Mode 4 charging process [33]

3.7.3. Charging Connectors

Charging connectors, a critical component of EV charging technology, vary depending on power capacity, current type, and country-specific designs. Below are some of the different connector types used globally for electric vehicles (Figure 3.37).

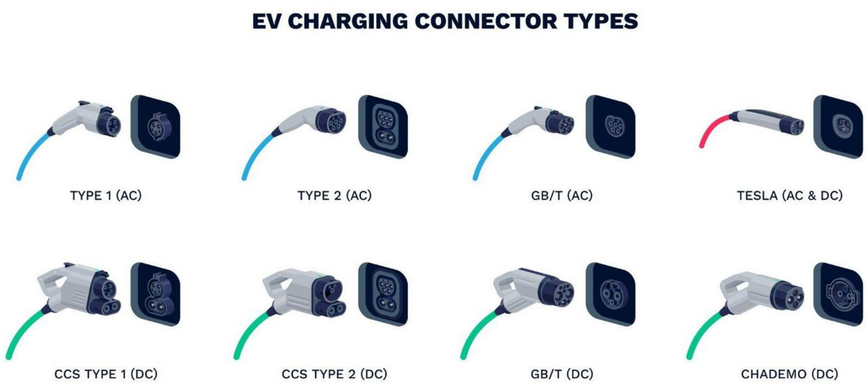

Figure 3.37 Charging connectors [34]

AC Type 1 Connector

Commonly used in North America and Asia, this single-phase socket has a maximum charging capacity of 7.4 kW. Also known as J1772, it is used to charge electric bicycles and light electric vehicles in addition to cars.

Mennekes (AC Type 2) Connector

This connector, standardized in Europe, is water-resistant with an IP rating and features a locking mechanism for safety. It supports up to 22 kW for residential use and 43 kW for public use. It includes three additional cables for three-phase transmission.

GB/T Connector

Developed in China and also used in India, this system supports both AC and DC charging. It can deliver a maximum of 237.5 kW DC power and adapts to different mode levels.

CCS 1 Connector

Known as Combo 1 (Combo Charging System), this connector supports both AC and DC charging with a power output of up to 170 kW. It was the first connector to offer fast charging, dispelling the notion that electric vehicles take too long to charge.

CCS 2 Connector

Known as Combo 2, this connector is similar to CCS 1, offering both AC and DC charging. The main difference is its capability to support up to 500 kW of charging power. Its enhanced cable cross-sections and advanced current-carrying connector pins allow for ultra-fast charging.

CHAdeMO Connector

Developed in Japan in 2009, this proprietary socket supports 400 kW DC charging. It is used in countries like Japan, Europe, and Turkey. Introduced by four major Japanese automakers, CHAdeMO offers a compact design and supports bidirectional charging.

NACS Connector

Tesla developed this proprietary 3-pin connector exclusively for its vehicles, known as NACS in North America. Outside the U.S., Tesla vehicles often use CCS 2 connectors. Tesla’s DC ultra-fast charging stations (Superchargers) provide up to 250 kW DC charging.

3.8. Battery Failures and Maintenance

Due to the chemical structure of batteries, aging and increased internal resistance occur over time with usage. This affects charge/discharge efficiency, reducing battery capacity and consequently the vehicle's range. If failures related to aging and usage are not detected, hazardous situations may arise in the battery and its systems. Maintenance, repair, and fault diagnosis of batteries and their systems are therefore crucial. The Battery Management System (BMS) monitors all battery parameters and facilitates fault diagnosis and detection.

High-voltage (HV) batteries may experience faults in both hardware components and electronic systems. Fault detection is performed electronically using diagnostic devices, and physically through visual inspection, measurement tools, and pressure testing kits. Faults can be categorized as hardware-related or system-related:

- **Hardware-Related Faults:** Include issues in sensors, contactors, connectors, busbars, and similar components.
- **System-Related Faults:** Include overcharging, over-discharging, overheating, overcooling, insulation resistance failures, and software errors in cells or modules.

Maintenance operations involve the measurement and inspection of thermal systems, battery parameters, and battery health (SoH). For HV batteries, fault codes such as P0Axx, P0Bxx, P0Cxx, P0Dxx, and P0Exx are commonly used for fault identification.

3.9. Fuel Cell Technology

A fuel cell is a system that generates electricity through the chemical reaction of hydrogen and oxygen. Vehicles utilizing this technology are known as Fuel Cell Electric Vehicles (FCEVs)**.** These vehicles are expected to become widespread following hybrid and electric vehicles. Unlike electric vehicles, FCEVs have a hydrogen tank, and electricity is generated onboard. They are not dependent on charging units. Hydrogen is stored in the vehicle's tank via a socket at hydrogen refueling stations. The fuel cell generates DC electrical energy, which is stored in the battery. The propulsion is achieved using the electrical energy supplied by the battery to the electric motor(s) (Figure 3.38). The final stage of the chemical reaction releases water vapor, which is expelled from the vehicle.

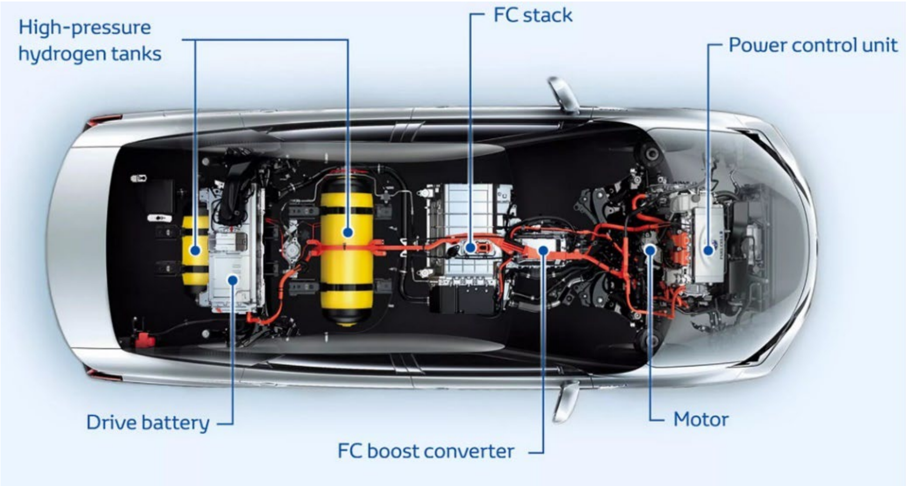

Figure 3.38 Structure of a Fuel Cell Electric Vehicle [35]

3.9.1. Fuel Cell

Research on fuel cells dates back to 1838. The operation of a fuel cell is described as the reverse reaction of electrolysis. It consists of an anode, cathode, an electrolyte membrane (also called a proton exchange membrane), and plates (Figure 3.39). The unit facilitates an electrochemical reaction between hydrogen and oxygen at approximately 80°C. The relatively low reaction temperature is a significant advantage for the system, earning it the term "cold combustion." FCEVs primarily use PEM (Proton Exchange Membrane) fuel cells, which offer the highest energy density among fuel cells.

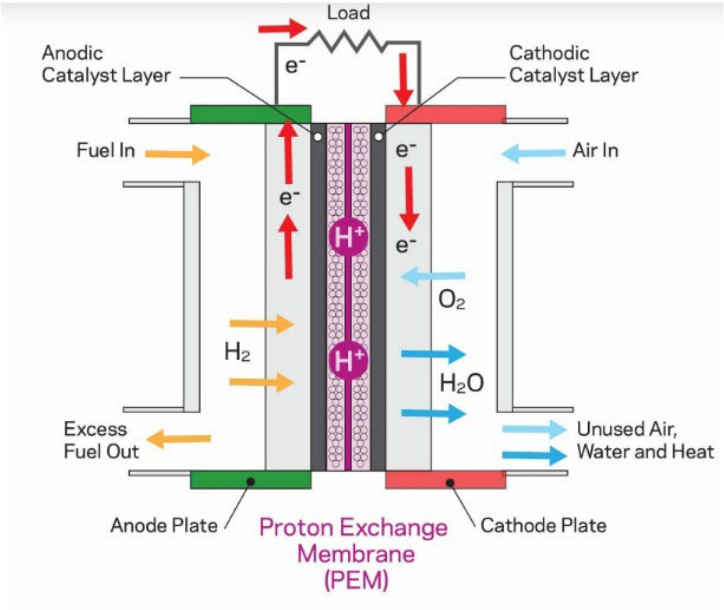

Figure 3.39 PEM Fuel Cell [36]

A single fuel cell is 2 mm thick and generates only 1 volt. Therefore, hundreds of fuel cells are combined to form a **fuel cell stack**. The basic components of a fuel cell are the anode (negative) and cathode (positive) electrodes, which are porous and permeable in structure. At the anode, hydrogen is split into protons and electrons. Electrons flow through the external circuit, generating electricity. Protons pass through the PEM electrolyte to the cathode, where they react with oxygen in an electrochemical reaction. This reaction creates a voltage difference between the anode and cathode, releasing electrons that are stored in the battery. The reaction produces pure water and heat as byproducts, making the system environmentally friendly.

3.9.2. Hydrogen Tanks

Hydrogen tanks store hydrogen received at 350–700 bar pressure from hydrogen refueling stations. These tanks undergo rigorous testing and are designed to withstand up to 225% of their operating pressure. The structure consists of a high-strength carbon fiber shell reinforced with fiberglass layers. The tank is equipped with sensors and a safety valve to prevent leaks.

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CHAPTER 4

Diagnostics in Hybrid and Electric Vehicles

Cafer Kaplan, Barış Erkuş, Ridvan Arslan

4. Diagnostics in Hybrid and Electric Vehicles

4.1. Diagnosis and Servicing

The widespread adoption of electronic control systems in automotive technologies and the production of smart vehicles under the concept of electromobility have significantly transformed fault detection and repair methods. Simple measuring and control tools have been replaced by much more sophisticated diagnostic devices capable of communicating with electronic control units in the system. These devices may be designed specifically to serve a particular brand or model or may be universally applicable without any restrictions.

The term "diagnostics," which refers to fault detection and identification, originally comes from the medical field and describes the methods, devices, and equipment used in the detection, diagnosis, and treatment of diseases. This concept is also commonly encountered in many sectors of the industry, including faultfinding and repair processes. In the automotive sector, the need for diagnostics is increasing both for conventional internal combustion engine vehicles with numerous interconnected electronic control units and for the rapidly growing number of Hybrid and Electric Vehicles (HEVs) enabled by advancing technologies [1]. Globally recognized organizations such as the Society of Automotive Engineers (SAE) and the International Organization for Standardization (ISO) have introduced various standards for diagnostic devices and procedures.

The diagnostic processes applied to hybrid and electric vehicles follow the same general principles. First, it is essential to understand in detail the fault or complaint in the vehicle. Next, the root cause and source of the fault must be identified to carry out the necessary repairs. The most significant difference between hybrid and electric vehicles and conventional internal combustion engine vehicles lies in components such as batteries, electric motors, inverters, and converters. These elements operate at high voltages and currents that pose serious risks to human health. Therefore, additional occupational safety measures must be implemented when performing diagnostics on such vehicles.

4.2. Protective Equipment, Hazard Management and Safe Working Practices

The rules for providing service to hybrid and electric vehicles are outlined in the ECE-R100 Battery Electric Vehicle Regulation, which applies to M-class vehicles equipped with electric drive units but not permanently connected to the power grid and with speeds exceeding 25 km/h, at least four-wheeled passenger motor vehicles, N-class vehicles, and at least four-wheeled cargo trucks. According to this regulation, voltage ranges between 60-1500 Volts DC and 30-1000 Volts AC are classified as high voltage. The regulation also mandates that all the components operating under high voltage must be distinguishable with orange color.

The effects of electrical current on the human body depend on several parameters, including the factors determining the severity of the electrical shock, the intensity and type of the voltage (AC, DC), the duration of exposure to the current, the contact resistance of the voltage (such as skin thickness and moisture), the grounding resistance (such as shoes and clothing), and the path of the current through the body. According to Ohm's Law, the magnitude of the current experienced is largely determined by body resistance and contact resistance. Figure 4.1 presents typical resistance values measured on a human body.

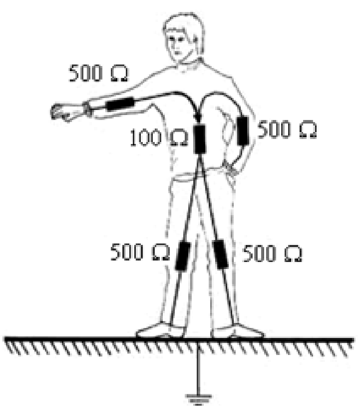


Figure 4.1 Measured resistance values of the human body

Electrical current generally causes three different types of reactions in the human body: thermal effects, chemical effects and muscular tension or paralytic effects. The intensity of electrical current and the burns caused by it are categorized under thermal effects. A large portion of the human body consists of fluids called electrolytes. Prolonged exposure of the human body to electrical current can trigger electrolytic dissociation, leading to poisoning, which is referred to as a chemical effect. Communication between organs and the brain in the human body occurs through the nervous system. When the human body is exposed to high currents, this communication can be disrupted, causing physical phenomena like muscle contractions and cramps, which may result in paralysis. This is referred to as muscular tension or paralytic effects. The maximum permissible voltage levels for human safety are 60 Volts for direct current and 30 Volts for alternating current.

Figure 4.2 presents graphs showing the effects of direct and alternating current on the human body. According to these graphs:

The first region, referred to as the detection threshold, does not cause noticeable effects on the human body.

The second region has limited effects on the human body and generally does not pose a danger. In this region, different effects start to be felt at varying current levels. At 0.5-2.0 mA, the current is perceptible. At 3.0-5.0 mA, initial pain sensations begin to occur. The range of 10.0-20.0 mA is referred to as the release threshold, where it becomes impossible to let go.

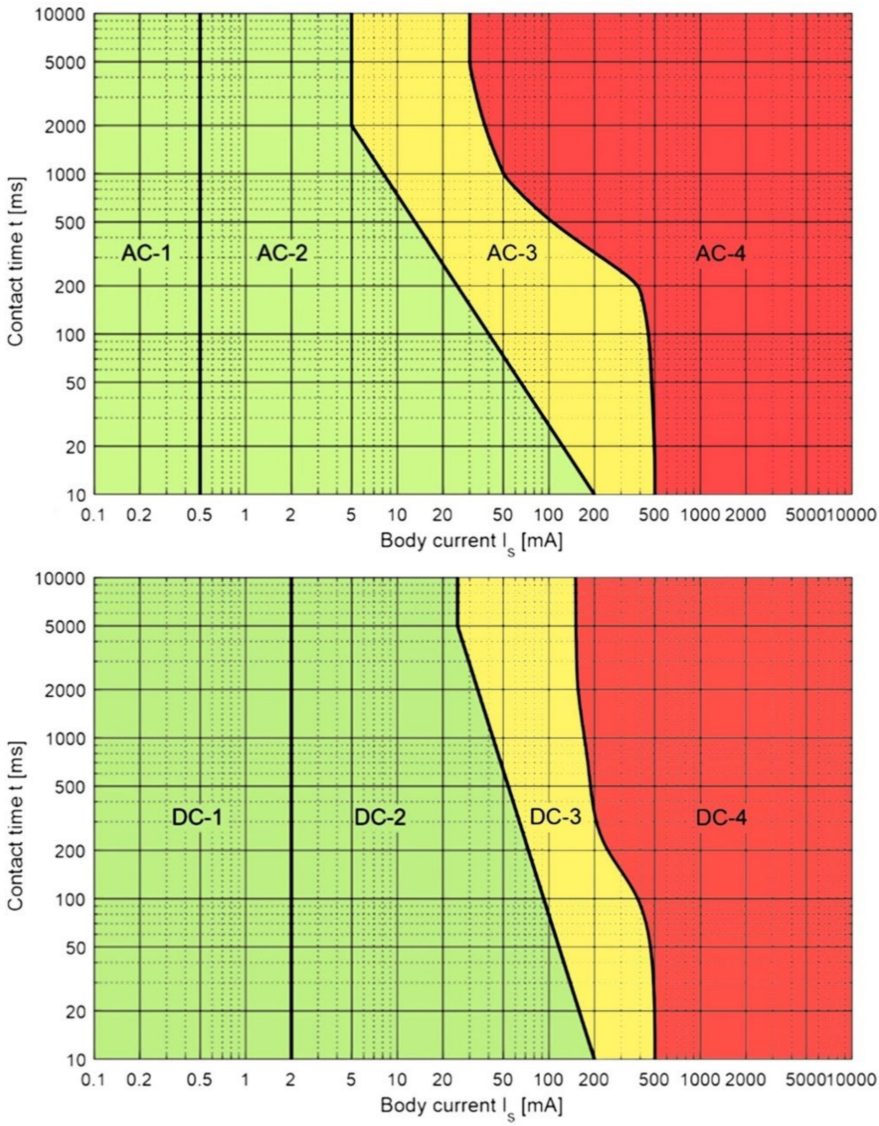


Figure 4.2 Effect of alternating and direct current on the human body [2]

The third region is where the first dangers emerge. In this region, muscle cramps, heart rhythm disturbances, and breathing difficulties may occur.

The fourth region involves severe life-threatening conditions, where complete cessation of the heart and respiration can occur.

4.2.1. Personal Protective Equipment

Individuals working on hybrid and electric vehicles with high-voltage components must wear appropriate personal protective equipment depending on the level of the working environment (Figure 4.3).

Figure 4.3 Personal protective equipment

Face shields/helmets: These protect the face and eyes from arc flashes and sparks caused by electrical discharges. Helmets prevent risks associated with falling objects or accidental contact (Figure 4.4).

Figure 4.4 Face shields

Flame-resistant insulated aprons/work suits: Made of approximately 1 mm thick neoprene material and resistant to 1000 V alternating current (Figure 4.5).

Figure 4.5 Insulated aprons/work suits

Insulated gloves: Protect against electric shocks, arc flashes, and burns or injuries caused by sparks. Gloves should be resistant to 1000 V AC and battery acid (Figure 4.6).

Figure 4.6 Insulated gloves

Leather and cotton gloves: Leather gloves are worn over insulated gloves to provide mechanical protection and facilitate grip. Cotton gloves are worn under insulated gloves to reduce sweating and increase comfort in hot and humid conditions (Figure 4.7).

Figure 4.7 Leather and cotton gloves

Insulated footwear: Free of steel and metal components, these shoes are made of insulating materials. Their soles are made from anti-static material resistant to high voltage. Shoes must be free of dust and dirt before use. The soles should be checked for stones, dents, damage, or nails before use (Figure 4.8) [3].

Figure 4.8 Insulated footwear

4.2.2. Environmental Protective Equipment

When performing maintenance and repair work on hybrid and electric vehicles with high-voltage systems, warning signs appropriate to the vehicle's electrical properties must be used. To indicate the risk of electric shock or high voltage, the symbol specified in the Safety and Health Signs Regulation, shown in Figure 4.9, must be used. This symbol consists of a triangle with a yellow background, a black pictogram, and a black border.

Figure 4.9 High voltage or electric shock hazard warning sign

ECED (Energy Control Tagout and Lockout) is an occupational health and safety procedure like the Lockout/Tagout (LOTO) application ensures the safety of workers by properly shutting down machines or equipment powered by energy. After labeling the hazard, locks suitable for the specific danger are used to complete the lockout process (Figure 4.10). Only the worker responsible for the task can attach the lock, and no other person is allowed to open or modify it.

Figure 4.10 Lockout and tagging system

Environmental Protective Equipment Required for Electric Motor Vehicles:

Insulation mat: Used for individual and collective protection, these mats are made of elastomer rubber with non-slip surfaces on both sides. They can provide insulation between 1500 V and 54,000 V DC. Mats should be visually inspected before each use and cleaned when necessary to remove residues that may impair their functionality (Figure 4.11).

Figure 4.11 Insulation mat

Rescue rod: Used to safely remove an injured person by contacting a safe part of their body during an electrical accident. It is resistant to up to 45 kV and is typically made of fiber material resistant to moisture and heat. It must be at least 1.55 meters long and include a hand guard to prevent slippage (Figure 4.12).

Figure 4.12 Rescue rod

Insulated hand tools: Tools such as screwdrivers, pliers, wrenches, wire cutters, and socket sets must comply with TS EN IEC 50900 standards and provide insulation up to 1500 V DC (Figure 4.13). These tools should always be kept clean. If any damage or arc marks are detected on the metal parts, the tools must undergo an electrical test before use. Tools with visible damage to their double-layered insulation should not be used.

Figure 4.13 Insulated hand tools

Signaling equipment: When working with high-voltage systems in hybrid and electric vehicles, barriers made of red and white plastic chains, PVC plastic poles, or portable panels should be used to prevent unauthorized personnel from entering the work area. Warning signs such as "High Voltage" or "Unauthorized Personnel Prohibited" should be displayed (Figure 4.14) [3].

Figure 4.14 Signaling, identification, and boundary equipment

Service socket locking device and insulated safety lock: The service socket isolates the high-voltage battery from other high-voltage components and separates the battery into electrical sections. This socket, usually located under the rear seat, is orange or green. After removing the socket, a locking device must be used to prevent uncontrolled reinsertion. Then the system can be locked with a padlock to prevent accidental activation of high-voltage systems (Figure 4.15).

Figure 4.15 Service socket locking device and insulated safety lock

4.2.3. Qualifications of HEVs Maintenance Personnel

Since hybrid and electric vehicles operate with high-voltage equipment, personnel conducting maintenance and repair work on these vehicles face life-threatening risks such as electric shock. For this reason, maintenance personnel must be well-versed in safety procedures and implement these rules rigorously.

Despite numerous regulations published in the last 20 years regarding the design, maintenance, and repair of hybrid and electric vehicles, a comprehensive shared literature has not yet been fully established. However, regulations addressing fundamental safety issues when working with high voltage have become globally accepted.

For example: In Austria, the ÖVE-Richtlinie R19:2015 regulation addresses safety concerns for individuals and companies maintaining and inspecting high-voltage systems in vehicles operating at up to 1000 V AC or 1500 V DC.

Germany's DGUV I 209-093:2023.06 regulation outlines minimum requirements for training content and scope to ensure safe operation based on risk assessments of high-voltage vehicles. Finland's SFS 6002: EN regulation emphasizes safety and working conditions for electrical work and the operation of electrical installations. Turkey's TSE K 646:2023 regulation sets rules for authorized service centers for electric vehicles. Additionally, on June 12, 2024, the Vocational Qualification Authority published the Level 4 and 5 National Qualifications for Battery Electric Vehicle Maintenance Technicians and Hybrid Vehicle Maintenance Technicians.

4.2.4. Safe Working Practices Under High Voltage

The high-voltage system components in hybrid and electric vehicles include the high-voltage battery, inverter-converter group, traction motor, air conditioning compressor, and vehicle charging unit (Figure 4.16).

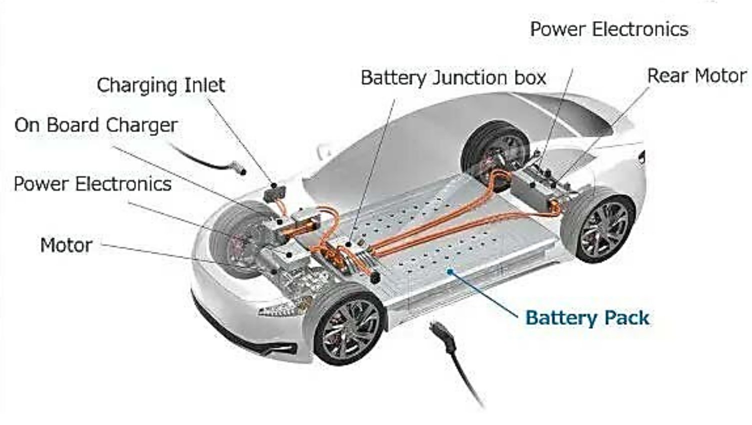


Figure 4.16 Components of an electric vehicle's high-voltage system [4]

Electrical connections between all high-voltage components are made using high-voltage cables with orange insulation. These cables are connected to system components using high-voltage sockets, also marked in orange, and equipped with additional locking mechanisms to prevent accidental disconnection. An example of a high-voltage socket and cable is shown in Figure 4.17.

Figure 4.17 High-voltage socket and cable

Steps for Safe Work on Hybrid and Electric Vehicles

Before beginning work on a hybrid or electric vehicle, the following safety steps must be taken:

- Isolation
- Prevent reconnection
- Verify the absence of voltage

These steps are critical for safe operation. The implementation of these five safety rules for hybrid and electric vehicles can be addressed as follows:

Step 1: Isolation. The following actions should be performed: Turn off the ignition. Remove the service socket or turn off the main battery switch (Figure 4.18). Remove fuses, locking/pilot/monitoring circuit sockets.

Disconnect the vehicle from the power grid by removing the charging plug.

Figure 4.18 Service socket

Step 2: Prevent reconnection (Figure 4.19); Remove the ignition key and prevent unauthorized access. Secure the service contact against unauthorized access. Follow internal company regulations and the manufacturer's instructions.

Figure 4.19 Measures to prevent reconnection

Step 3: Verify the absence of voltage; Even after the high-voltage connection in a hybrid or electric vehicle has been disconnected, residual electrical charges may remain in components storing electrical energy.

When working on high-voltage components, the vehicle must be de-energized. The de-energization process includes the following steps:

- Turn off the vehicle's power button and remove the key to prevent accidental activation.
- Remove any metal accessories or jewelry that could contact components.
- Set up warning signals and barriers around the vehicle with signs like "Caution: High Voltage" and "Unauthorized Personnel Prohibited."
- Disconnect the negative terminal of the 12V battery.
- Inspect and wear insulated gloves.
- Remove the service socket and secure it with a locking device and insulated safety lock to prevent reconnection.
- Wait 5–10 minutes (depending on the vehicle model) for the high-voltage capacitor (inverter) to discharge.
- Use a voltage test device shown in Figure 4.20. to measure the voltage between the inverter's positive and negative terminals, ensuring it reads 0 V.
- Insulate the removed high-voltage sockets and terminals with insulating tape.

Figure 4.20 Checking residual electrical charges in the system

After de-energization, maintenance and repair work can be performed on components other than the high-voltage battery. Once the work is complete, the system must be re-energized. Different manufacturers may have different re-energization procedures. A general example of re-energization steps is as follows:

- Always use appropriate personal protective equipment.
- Unlock the battery service socket.
- Reinstall the battery service socket.
- Reconnect the negative terminal of the 12V battery.
- Turn on the ignition.
- Check warning indicators on the dashboard.
- Use a diagnostic tool to check for faults.
- Remove the signaling equipment.

In hybrid and electric vehicles, high-voltage and low-voltage systems are completely isolated from each other. This insulation is crucial, as any breakdown between these systems will automatically deactivate the vehicle's high-voltage system, effectively de-energizing it.

4.3. Electrical Measuring Instruments

To identify an electrical circuit or a component within the circuit, it is necessary to know one or more electrical parameters, such as voltage, current, resistance, or inductance. Additionally, knowing the reference values of components is crucial for fault diagnosis in circuits.

In hybrid and electric vehicles, besides basic electrical measurements, such as voltage, current, resistance, and inductance, additional measurements like high-voltage measurement, insulation resistance measurement, and equipotential measurement are required, along with new measuring instruments. This section discusses electrical measuring instruments, and the measurement and control methods used in the electrical systems of hybrid and electric vehicles.

4.3.1. Basic Electrical Measuring Instruments

Basic electrical measuring instruments include:

- Voltmeters: Measure the voltage across the terminals of a circuit or component.
- Ammeters: Measure the current drawn by a component in a circuit.
- Ohmmeters: Measure resistance in electrical circuits.

Modern measuring devices, known as multimeters, can perform all these measurements and more (Figure 4.21.a). Some models of multimeters also allow measurements of capacitance, inductance, frequency, and temperature, and they can be used to test the integrity of semiconductor components.

In addition to multimeters, LCR meters, which are designed specifically for measuring inductance, capacitance, and resistance, are frequently used (Figure 4.21.b). Another common instrument is the oscilloscope, which allows observation of signal waveforms over time and provides the frequency spectrum of the signal (Figure 4.21.c) [5].

a) b) c)

Figure 4.21 Electrical measuring instruments

4.3.2. Measuring Voltage, Current and Resistance

Voltage Measurement

Voltmeters are connected in parallel to the circuit for voltage measurements. Digital multimeters are commonly used today. The steps for measuring voltage with a multimeter are as follows:

- Set the multimeter to the voltage measurement mode (Figure 4.22).
- Select the appropriate range on the multimeter if necessary.
- Apply power to the circuit.
- Connect the multimeter probes in parallel to the terminals of the component to complete the measurement.

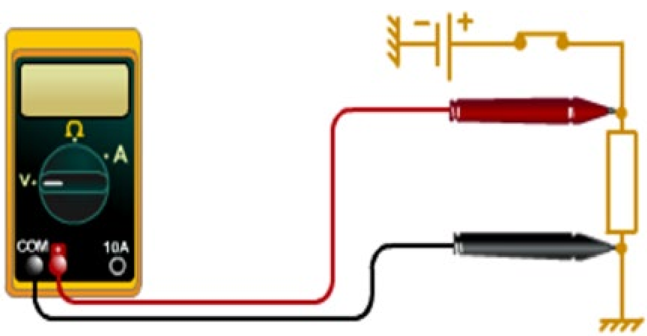


Figure 4.22 Measuring voltage with a multimeter

Current Measurement

To measure the current in an electrical circuit, the ammeter is connected in series with the circuit. Digital multimeters can measure current up to a limited value (typically up to 10 Amperes). Steps for measuring current with a multimeter:

- Set the multimeter to the current (A) measurement mode (Figure 4.23).
- Select the appropriate range on the multimeter.
- Connect the multimeter probes in series with the circuit.
- Apply current to the circuit.

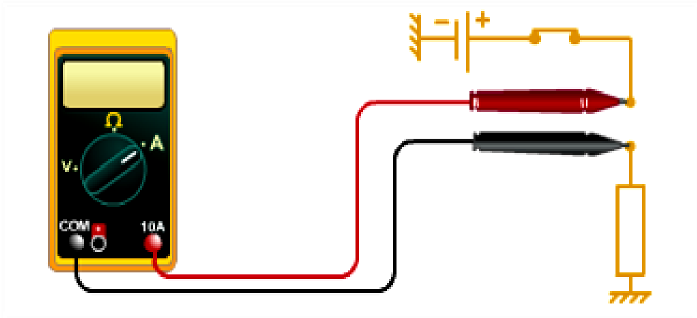


Figure 4.23 Measuring current with a multimeter

Since ammeters are connected in series, they must have very low internal resistance (0–1 Ω) to avoid limiting the current in the circuit. Clamp (cable) ammeters, as shown in Figure 4.24, are used to measure current without disconnecting the circuit.

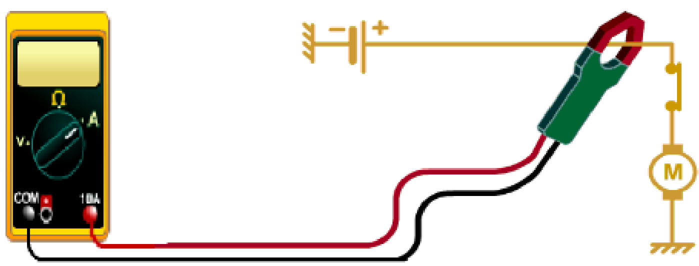


Figure 4.24 Measuring current with a clamp ammeter

Resistance Measurement

Resistance is measured using an instrument called an ohmmeter. Ohmmeters are also commonly used for checking open circuits, short circuits, and continuity in electrical circuits. An energy source is required to use an ohmmeter. Steps for measuring resistance:

- Turn off the power to the circuit.
- Remove the component to be measured from the circuit.
- Set the multimeter to the resistance measurement mode (Figure 4.25).
- Select the appropriate range on the multimeter.

- Connect the multimeter probes to the terminals of the component to complete the measurement.

When using an ohmmeter, avoid holding the probes with your hands during measurement. This can result in the system or circuit resistance being measured along with body resistance, leading to incorrect readings.

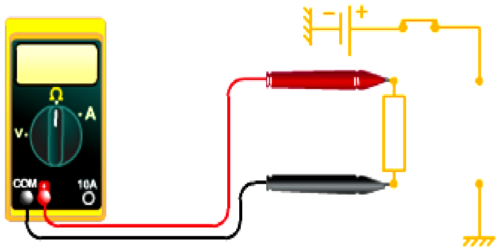


Figure 4.25 Measuring resistance with an ohmmeter **[5]**

4.3.3. Electrical Measurements in HEVs

As discussed in earlier sections, the electrical circuits in hybrid and electric vehicles can be divided into low-voltage and high-voltage circuits. This section provides information on insulation testing, equipotential testing, high-voltage measurement, current measurement, and resistance measurement performed on systems operating under high voltage.

Insulation Testing

Insulation, or dielectric, testing is conducted to verify the safety of high-voltage circuits and components in hybrid and electric vehicles. Insulation test devices are shown in Figure 4.26**.**

Figure 4.26 Insulation test devices

Insulation testers can create a potential difference of up to 1000 V DC at test points to measure insulation resistance in electrical circuits or components, distinguishing them from standard ohmmeters. Figure 4.27 demonstrates the measurement of insulation resistance between the stator windings and the motor housing of an electric motor, and Figure 4.28 shows insulation resistance measurement on a high-voltage cable.

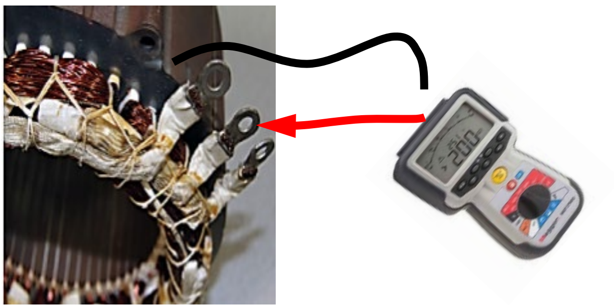


Figure 4.27 Measuring insulation resistance between motor stator windings and housing

Figure 4.28 Measuring insulation resistance in a high-voltage cable

Although values vary among manufacturers, an insulation resistance of 10 MΩ or higher is generally considered acceptable for high-voltage components in hybrid and electric vehicles. Since insulation testers apply high voltage to measurement points, insulated gloves must be worn during testing.

Unlike standard testers, insulation resistance testers must be operated at the voltage levels specified by the manufacturer. Testing at voltages higher than the recommended levels may damage the components. If high voltage is applied to a vehicle's 12V system, there is a risk of damaging electronic devices. The instruction manual of the insulation resistance tester should be carefully read, and safe operating practices must be followed.

Equipotential Testing

The equipotential system ensures the safety functions of high-voltage components. According to the ECE R-100 standard, a test voltage of 5V and a test current of 200 mA are used to ensure that the grounding resistance of all high-voltage components is less than 0.1 Ω. This measurement cannot be performed with conventional ohmmeters. Instead, milliohmmeters, which have highly precise resistance measurement capabilities, are used (Figure 4.29). Figure 4.30 demonstrates the measurement of grounding resistance between the housing of high-voltage equipment and the vehicle chassis using a milliohmmeter.

In systems operating under high voltage, instruments and probes with CAT III insulation levels must be used for current and voltage measurements. Personal protective equipment and environmental protection equipment should also be employed during measurements on high-voltage systems.

Figure 4.29 Milliohmmeters

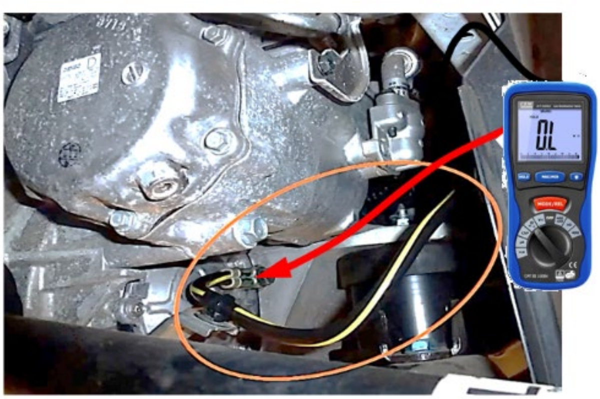


Figure 4.30 Testing with a milliohmmeter

Voltage Measurement

Voltage measurements in hybrid and electric vehicles are conducted using voltage test devices, as shown in Figure 4.31. These devices can measure voltages in the range of 12V–1000V AC/DC.

Figure 4.31 Voltage test device

4.4. Automotive Diagnostic Equipment

Today, mobile diagnostic devices and tablet-compatible diagnostic modules connected to the vehicle's diagnostic socket are widely used (Figure 4.32). These user-friendly devices guide the operator step-by-step during diagnostic procedures, enabling detailed analysis and checks of any unit or specifically targeted faulty components [6]. For instance, if a sensor fails to produce results within the reference value range during analysis, the device may display a warning message. Alternatively, if a sensor provides outputs within the reference range but the data indicates a fault in the system, the operator can use the diagnostic device to perform detailed examinations and observe data variations related to the sensor for further interpretation.

Figure 4.32 MMX diagnostic tool and HGS technical data [7]

The most significant advantage of diagnostic systems is that they allow operators to monitor multiple functions on a single screen. Observing real-time data is as crucial as examining fault codes in a vehicle. Generally, diagnostic procedures start with reading fault codes, followed by analyzing real-time data.

For newer vehicle models, a communication module with a SAE J2534 PassThru interface is required to access manufacturers' online portals. The following examples describe some commonly used diagnostic devices for fault detection and resolution.

Mega macs X (MMX) and HGS Data Diagnostic Devices and Software:

In this section, screenshots of Mega macs X (MMX) and HGS Data diagnostic devices used to find and troubleshoot problems in hybrid and electric vehicles are given as examples.

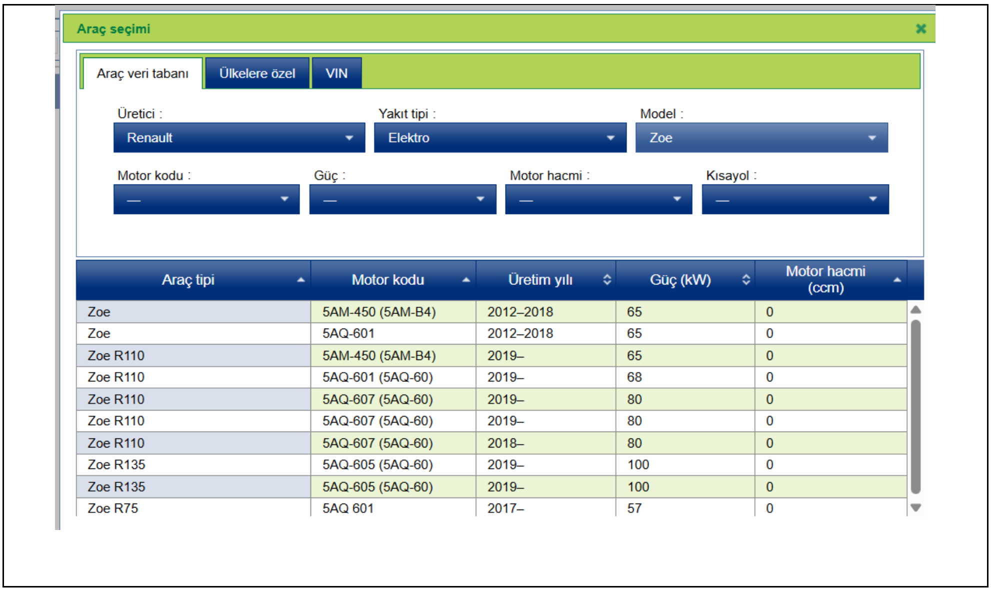


Figure 4.33 System control using MMX diagnostic and HGS technical data [8]

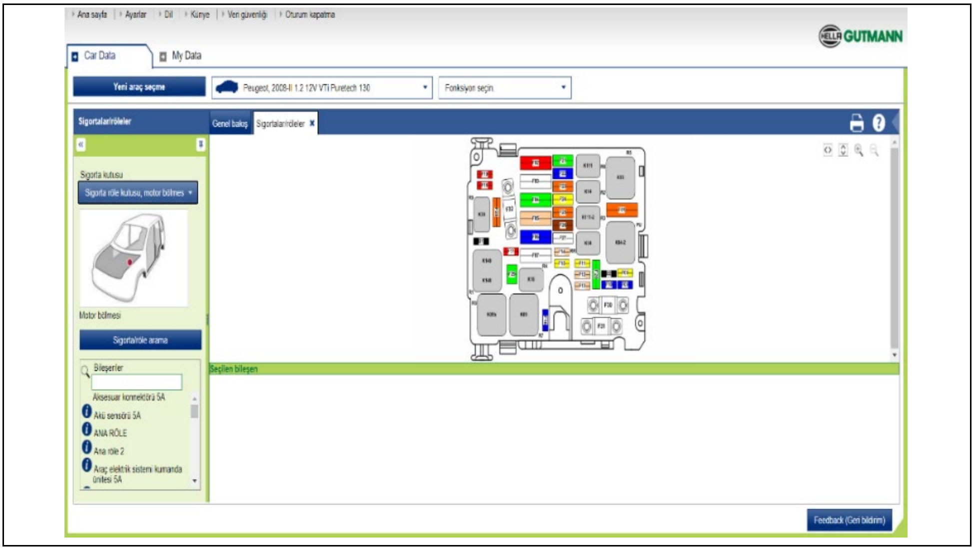


Figure 4.34 Accessing the installation locations of components with MMX and HGS technical data

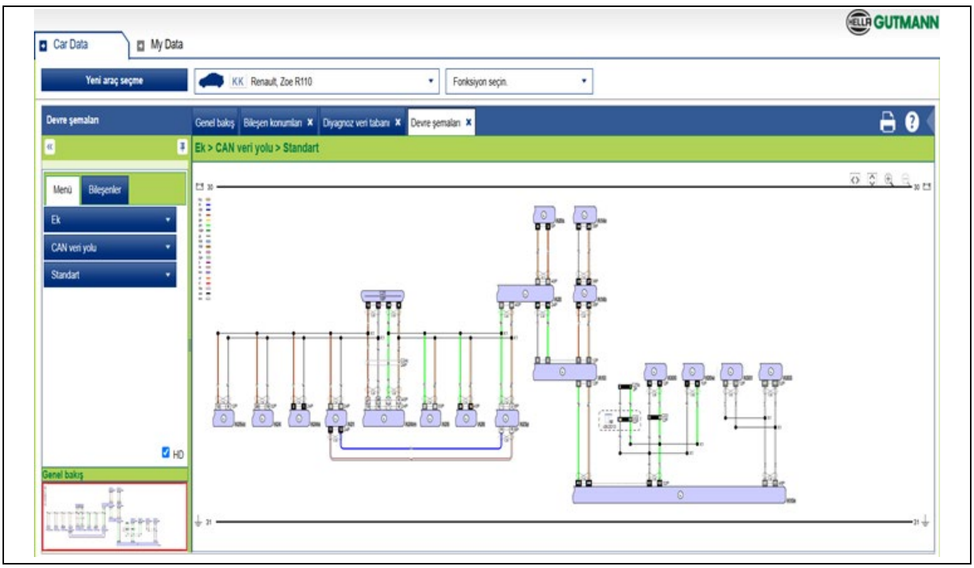


Figure 4.35 Electrical systems overview using MMX diagnostic and HGS technical data

Bosch KTS 590 and ESItronic Software:

In this section, images and screenshots of the Bosch KTS 590 and ESItronic devices, which are used to find and fix faults in hybrid and electric vehicles, are given as examples.

Figure 4.36 Bosch diagnostic devices [9]

The Bosch KTS diagnostic device integrates with the ESItronic software, which offers additional functionality, such as accessing technical documentation for various vehicles. After identifying a vehicle using Bosch ESItronic, it is possible to access details about the electrical and electronic system components, wiring, and locations.

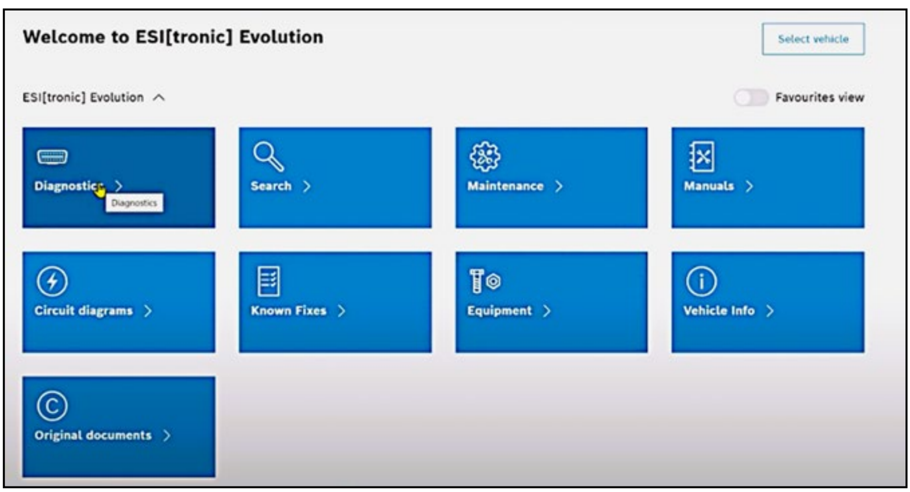


Figure 4.37 ESItronic software interface [10]

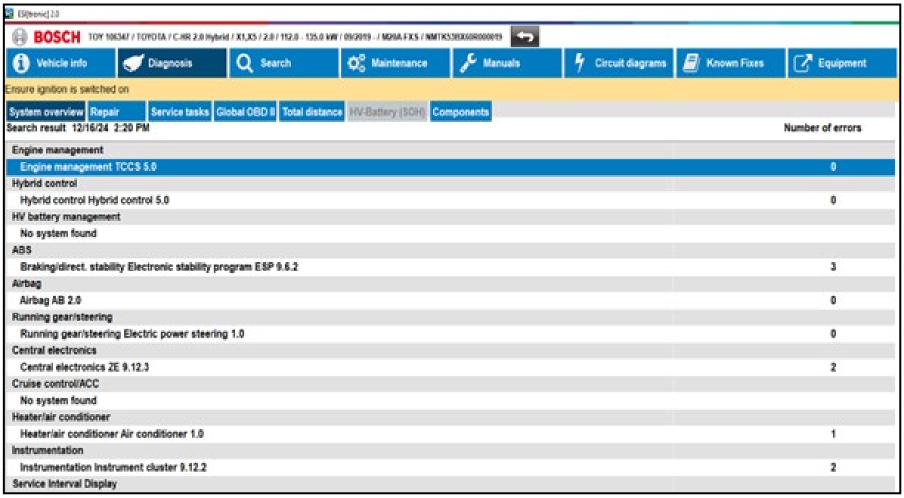


Figure 4.38 System scan screen

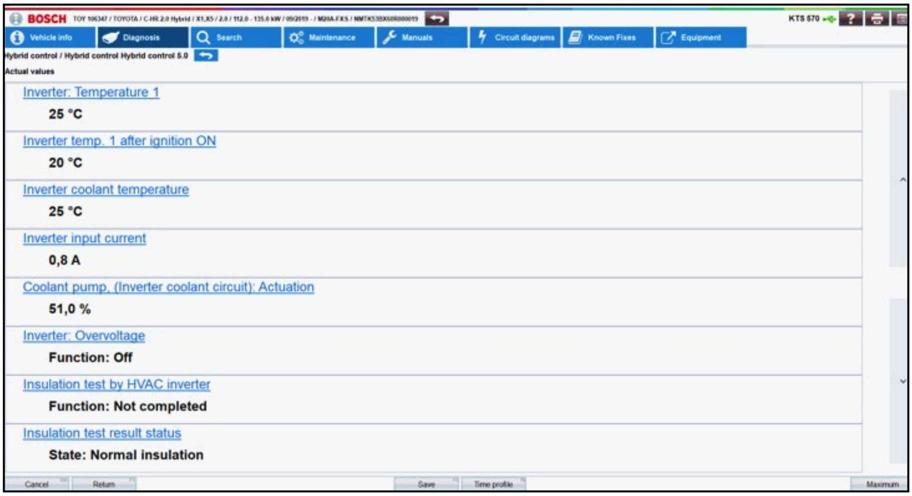


Figure 4.39 Hybrid control unit inverter/converter real-time data menu, showing 8 different real-time data parameters

Another feature of Bosch ESItronic software, which also work integrated with the KTS diagnostic device, is that it provides access to technical documents belonging to different vehicles. After the vehicle identification process with Bosch ESItronic software, it is possible to access the parts, installations and locations of the electrical - electronic system related to this vehicle.

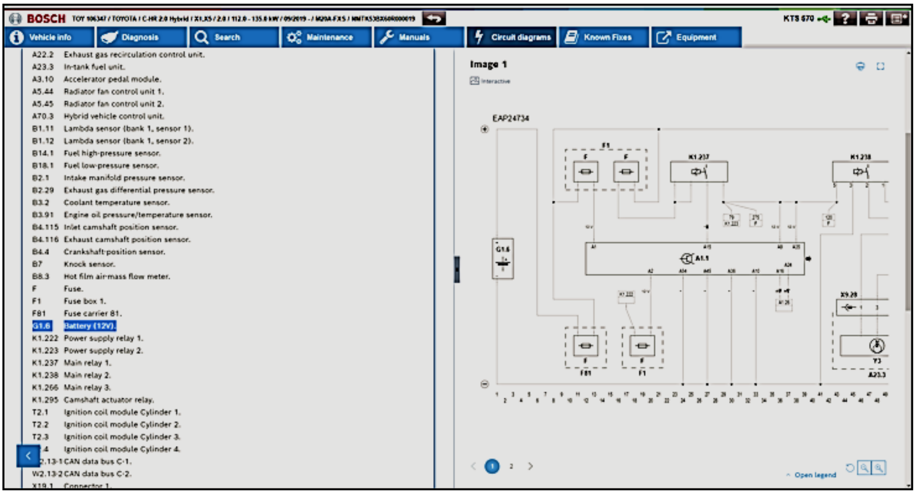


Figure 4.40 Accessing circuit diagrams using Bosch ESItronic software

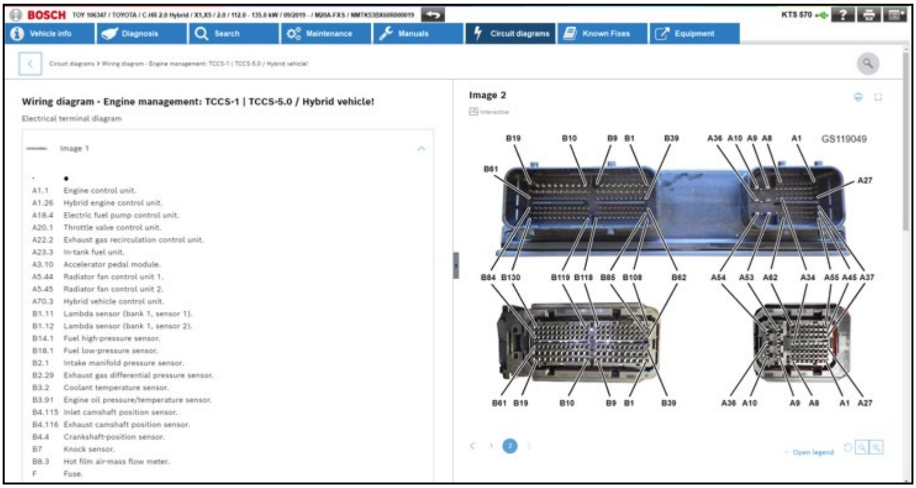


Figure 4.41 Accessing pin connections for the internal combustion engine electronic control unit using Bosch ESItronic software

4.5. Common Faults and Solutions in HEVs

This section presents examples of faults, and their solutions observed in a sample vehicle [11-12].

P3302 Overvoltage Fault in Cell Module No. 1 of Battery Pack

Fault Description: The possible causes of the P3302 fault code are:

- Traction motor inverter/VCM failure
- Cell module failure
- BMS (Battery Management System) failure
- Data bus failure
- Faults caused by cable harnesses or sockets

This section discusses a fault arising from the voltage of Cell Module No. 1 exceeding the allowable operating range and provides a solution.

Fault Detection Steps:

1. Put the vehicle in the READY (Ready On) position and wait for at least 10 seconds.
2. Use the fault code reading menu to detect the "P3302 Overvoltage Fault in Cell Module No. 1 of Battery Pack" error with the diagnostic tool.
3. Clear the fault codes.

Solution: The solution is presented using a sample vehicle as a reference. The Cell Module No. 1 in the battery pack must be replaced.

Steps to Replace the Battery Cell Module:

1. De-energize the vehicle.
2. Remove the battery pack from the vehicle.
3. Dismantle the upper housing of the battery pack.
4. Disconnect the battery voltage sensing terminal and BMS wiring harness socket and test the continuity between the relevant pin in the BMS socket (A) and the relevant busbar (B) using the short-circuit method. No open circuit connections should be observed during this test.

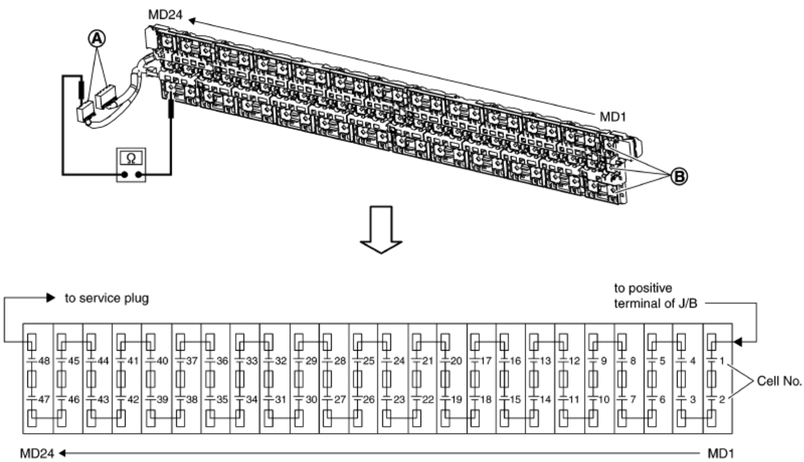


Figure 4.42 High-voltage battery busbar terminal structure

5. Check the voltage of the respective module. The voltage between terminals (A) and (B) of each module should read between 8.5 and 5 volts. If these voltage values are not observed, the module must be replaced.

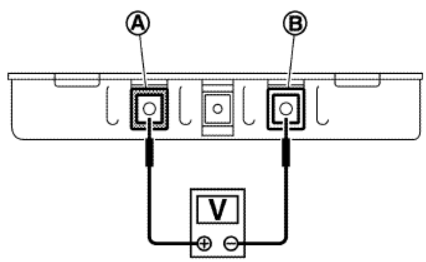


Figure 4.43 Measuring module terminal voltages

6. Reassemble the battery module and reinstall it in the vehicle.
7. Perform a Leakage test to ensure proper sealing.
8. Conduct an Equipotential Test to verify electrical safety.

P3061 Battery Cell Voltage Fault

Fault Description: The P3061 fault code occurs because of a fault in the open-circuit detection circuit of the BMS (Battery Management System) module.

Fault Detection Steps:

1. Put the vehicle in the READY (Ready On) position and wait for at least 10 seconds.
2. Use the fault code reading menu to detect the P3061 "Battery Cell Voltage Fault" error with the diagnostic tool.
3. Clear the fault codes.

Solution: The solution is presented based on a sample vehicle. The *BMS module* must be replaced.

Steps to Replace the BMS Module:

1. Remove the upper cover of the battery pack.
2. Disconnect the low-voltage cable socket (A) of the BMS module.

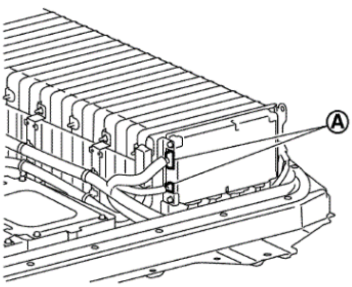


Figure 4.44 High-voltage battery and BMS

3. Remove the mounting nuts (A) and then the mounting bolts (B) of the BMS module.

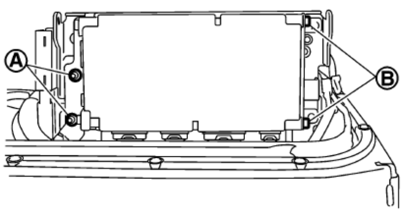


Figure 4.45 BMS

4. Disconnect the high-voltage wiring harness socket (A) and remove the BMS module.

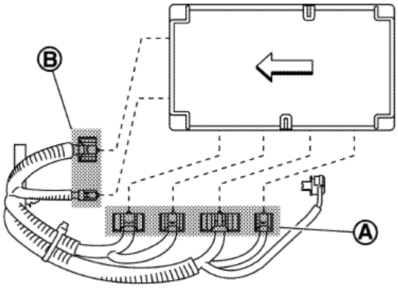


Figure 4.46 BMS and cable connections

5. Install the new BMS module. The BMS module has two cable harness sockets: one for high voltage and one for low voltage.

Important: If the high-voltage socket is connected to the low-voltage point, it may cause smoke and component damage. Ensure that the sockets are connected to the correct points.

Make sure the high voltage wiring harness clips are reinstalled in their original positions. If any clip is damaged, replace it with a new one before installation.

6. Reinstall the upper cover of the battery pack.
7. Perform a Leakage test to ensure proper sealing.
8. Conduct an Equipotential Test to verify electrical safety.

P0A2F Traction Motor Overtemperature Fault

Fault Description: The P0A2F error occurs when the traction motor temperature exceeds the operating temperature for 2 seconds or longer.

Possible causes for the P0A2F fault code include:

- Leakage in the cooling system.
- Low coolant level.
- Blockage or bending in cooling hoses.
- Traction motor temperature sensor failure.
- Cable harness or socket-related faults.
- Traction motor stator winding failure.

This section addresses a fault caused by an issue in the traction motor stator winding and provides a solution.

Fault Detection Steps:

1. Place the vehicle in the READY (Ready On) position and wait for at least 10 seconds.
2. Drive the vehicle for 20 minutes to allow it to warm up.
3. Perform 10 consecutive full accelerations from 0 km/h (0 MPH) to 60 km/h (37 MPH).
4. Stop the vehicle.
5. Use the fault code reading menu to detect the P0A2F "Traction Motor Overtemperature" error using the diagnostic tool.
6. Clear the fault codes.

Solution: The solution is provided based on a sample vehicle.

1. Check for leaks in the cooling system. If a leak is found, identify the location and repair it.
2. Check the coolant level. If the level is low, refill as necessary.
3. Inspect the cooling hoses for blockages or bends. If any issues are found, resolve them.
4. Place the vehicle in the READY (Ready On) position and wait for at least 10 seconds.
5. Drive the vehicle for 20 minutes to allow it to warm up.
6. Perform 10 consecutive full accelerations from 0 km/h (0 MPH) to 60 km/h (37 MPH).
7. Stop the vehicle and check for fault codes using the diagnostic tool.

If no fault codes are present, the issue is resolved.

If the P0A2F fault code is still detected, proceed with the following steps.

Traction Motor Diagnostics and Replacement

1. De-energize the vehicle.
2. Lift the vehicle and remove the bottom cover of the battery pack.
3. Disconnect the high voltage wiring harness socket and the PTC heater wiring harness socket from the battery pack.
4. Measure the voltage between the terminals of the high voltage wiring harness socket and the PTC heater wiring harness socket.

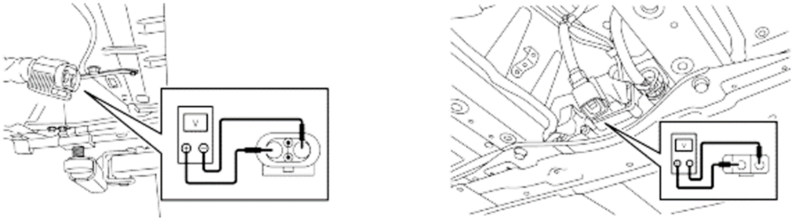


Figure 4.47 Measuring voltage across high-voltage and PTC heater sockets

5. Ensure the measured voltage between the terminals of the high voltage wiring harness and the PTC heater wiring harness is zero volts.
6. Conduct an insulation resistance test on the traction motor.

Steps for insulation resistance testing:

- Remove the traction motor from the vehicle.
- Set the insulation resistance tester to 500V and hold this setting for 30 seconds until the value stabilizes.
- Access the stator winding terminals (U, V, and W phases). Since the phases are interconnected, measuring one phase's insulation resistance is sufficient.
- Place one probe of the tester on the motor housing and the other on the selected phase terminal.
- If the insulation resistance reading is 10 MΩ or greater, the insulation is in good condition.

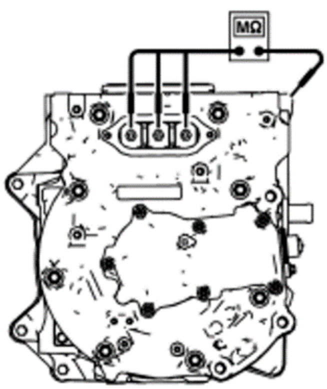


Figure 4.48 Measuring insulation resistance of motor stator windings

7. Inspect the traction motor temperature sensor.

- The sensor transmits its data through two pins on the motor cable socket. In the sample vehicle, these are pins 44 and 45.
- Perform a resistance measurement between these pins. The resistance value should correlate with the ambient temperature.
- If the measured resistance matches the expected value for the given temperature, the sensor is functioning correctly.
- If the resistance does not correlate with the ambient temperature, replace the sensor.

8. If the sensor is functioning correctly, proceed to check the stator winding resistance of the traction motor.

- Measure the phase-to-phase resistance of the stator windings using a milliohmmeter.
- Since the resistance is temperature-dependent, wait for the service-specified cooling period before testing (e.g., 8 hours for the sample vehicle).
- For the sample vehicle, the stator winding resistance should be 14.1–17.9 mΩ at 20°C. If the measured resistance is outside this range (e.g., 10 mΩ), it indicates a fault in the stator winding.

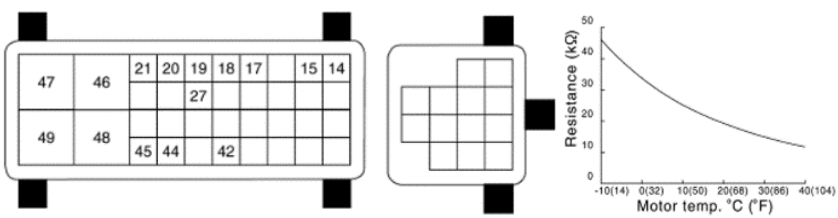


Figure 4.49 Pins on the motor cable socket and temperature sensor characteristic curve

9. Replace the traction motor as the final resolution if stator winding damage is confirmed.

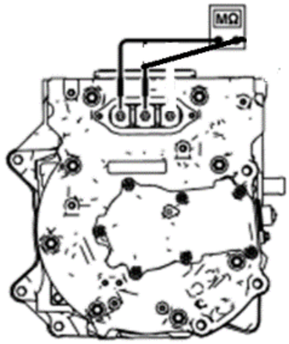


Figure 4.50 Measuring phase-to-phase resistance of traction motor stator windings using a milliohmmeter

P0A3F Drive Motor Position Sensor (Resolver) Fault

Fault Description: The P0A3F fault occurs when there is an anomaly in the resolver circuit, which detects the speed and position of the traction motor.

Possible causes for the P0A3F fault code include:

- Faults in the inverter cable harness or sockets.
- Faults in the resolver cable harness or sockets.
- Faults in the resolver windings.

This section addresses a fault caused by an issue in the resolver windings and provides a solution.

Fault Detection Steps:

1. Place the vehicle in the READY (Ready On) position and wait for at least 10 seconds.
2. Use the fault code reading menu to detect the P0A3F "Drive Motor Position Sensor (Resolver)" fault using the diagnostic tool.
3. Clear the fault codes.

Solution: The solution is presented based on a sample vehicle.

With the power switch in the OFF position:

4. Inspect the inverter cable harness and sockets for physical damage or faults.
5. Inspect the resolver cable harness and sockets for physical damage or faults.

6. Disconnect the F13 connector (on the inverter side) of the cable between the inverter and traction motor, and measure the resistance between pins 17, 18, 19, 20, 21, and 27 and the ground. The resistance values should be 100 kΩ or greater.
7. Check for short circuits between the pins of the F13 connector (inverter side) and the corresponding pins on the F14 connector (motor side).

The following pin pairs should be shorted:

- F13_17 to F14_6
- F13_18 to F14_7
- F13_19 to F14_5
- F13_20 to F14_1
- F13_21 to F14_8
- F13_27 to F14_2

Measure the resistance for these pin pairs; it should be 1Ω or less.

2. Measure the resistance between the following pin pairs on the F13 connector**:**

- Pins 17-18, 19-27, and 20-21
- The resistance values should be 100 kΩ or greater**.**

3. Inspect the resolver winding resistances**.**

On the F14 connector**,** measure the resistance:

- Between pins 1-8: 20–35 Ω
- Between pins 2-5: 8–15 Ω
- Between pins 6-7: 20–35 Ω

If the measured values do not match these ranges, the resolver is faulty and must be replaced to resolve the issue.

Battery Leakage Test Procedure

Whenever the high-voltage battery module of a hybrid or electric vehicle is removed and reinstalled, a battery leak test must be performed. The following steps outline the procedure for a sample vehicle:

1. Remove the service socket and attach the air leak test device adapter (Figure 4.63).

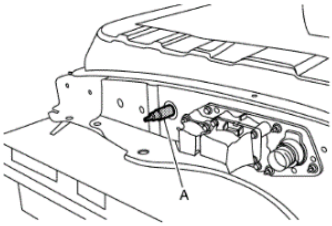


Figure 4.51 Air leak test device adapter connection

2. Attach the air leak test device gauge (Figure 4.64).

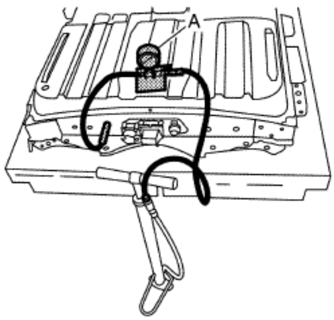


Figure 4.52 Air leak test device

3. Reinstall the service socket.
4. Use vinyl tape or a similar tool to seal the PTC wiring harness socket (Figure 4.65).
   - o Use tape wide enough to cover the entire PTC wiring harness socket with a single strip.
   - o Apply the tape carefully to avoid wrinkles.

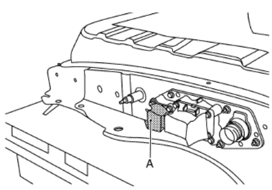


Figure 4.53 Preventing air leaks from the PTC wiring harness socket

5. Seal the vent hole using vinyl tape or a similar tool (Figure 4.66).
   - Use tape wide enough to cover the entire vent hole with a single strip.

- Apply the tape carefully to avoid wrinkles.

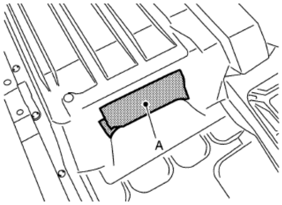


Figure 4.54 Preventing air leaks from the vent hole

6. Follow these steps to check the battery pack pressure:
    - Open the valve on the air leak test device (Figure 4.67).
    - Caution: Do not operate the pump before opening the valve.
    - Slowly operate the air pump to apply the specified test pressure to the battery pack.

If the gauge pressure does not increase or fluctuates, identify the source of the air leak. Do not exceed a pressure of 2.0 kPa (0.0204 kg/cm^2) on the battery pack or air leak test device.

- Close the valve and wait for 1 minute.
- Check whether the air leak test device reading remains within the limit.
- If the pressure falls below the limit, locate the air leaks. Listen for air escaping to identify any leaks during pressure application.

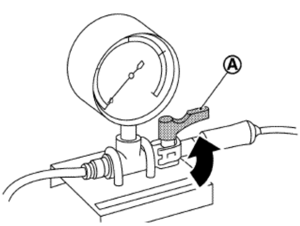


Figure 4.55 Opening the valve on the air leak test device

4.6. Road Assistance

When providing road assistance to hybrid and electric vehicles, it is crucial to adhere to safety measures and apply equipment and procedures suitable for the vehicle's sensitive systems. Proper interventions by professional and trained teams ensure the safety of both the vehicle and the environment. The following considerations should be taken into account during the process:

1. Safety Measures

• *High-Voltage System Awareness:* Hybrid and electric vehicles have high-voltage systems, and improper handling of these systems can lead to severe accidents. Orange-colored cables in the system indicate high voltage and should never be touched with bare hands.

• *Use of Insulated Equipment:* Personnel must use insulated gloves and equipment to mitigate the risk of electric shock.

• *Fire Suppression Measures:* Electric vehicles pose a risk of battery fires. Therefore, fire suppression equipment, especially those suitable for **Class D fires**, should be readily available.

2. Transportation and Towing

• *Flatbed Transport:* Hybrid and electric vehicles should be transported using flatbed tow trucks to avoid damage to the motor and battery systems.

• *Prevent Wheel Rotation:* The battery system can generate energy through wheel movement, potentially damaging the battery even when the vehicle is turned off. Therefore, wheel movement must be prevented during transportation.

• *Secure Tie-Down Points:* Use manufacturer-specified tie-down points when towing or securing the vehicle.

3. Vehicle Condition Check

• *Check Vehicle Mode:* Ensure the vehicle is not in "Ready" mode.

• *Battery Condition:* Check battery temperature levels and charge status. Particularly in accident scenarios, inspect for any battery leaks.

• *Diagnostic Check for Faults:* During transportation or road assistance, use a professional diagnostic tool to read fault codes and perform appropriate interventions.

4. Special Procedures for Accidents

• *Battery Damage Assessment:* After an accident, if there is evidence of battery leakage, swelling, or smoke, professional teams should handle the situation.

• *Fire or Smoke:* If there is a risk of a battery fire, trained personnel should monitor the situation, and fire suppression should be carried out by professional teams if necessary.

5. Trained and Authorized Personnel

Road assistance personnel for electric and hybrid vehicles must have specialized training in the structure and features of these vehicles. A lack of proper knowledge can lead to incorrect interventions and more significant damage.

6. Information and Communication

• *Customer Communication:* Inform the customer about the safe transportation process before proceeding.

• *Contact with the Manufacturer:* For specific faults, technical support or assistance from the manufacturer may be necessary.

7. Environmental Factors

• *Water and Moisture Conditions:* Exposure to water can cause severe damage to electric vehicle batteries. Ensure all systems are fully deactivated before transporting vehicles affected by flooding.

• *Extreme Temperatures:* Take special precautions to ensure battery safety in extreme heat or cold conditions.

8. Proper Equipment Usage

Specialized equipment designed for electric vehicles, such as tow trucks, tie-down apparatus, and diagnostic tools, must be used. Standard equipment may damage the sensitive systems of these vehicles.

Figures 4.56, 4.57, 4.58 and 4.59 provide examples from the roadside assistance guide for the Renault ZOE model as examples of roadside assistance in electric vehicles.

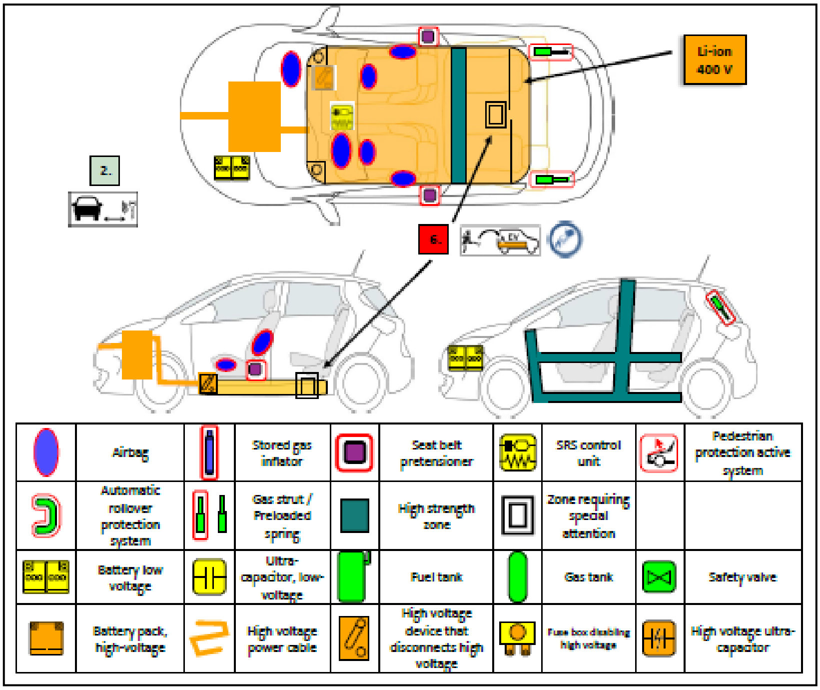


Figure 4.56 Locations of high-voltage components in the vehicle [13]

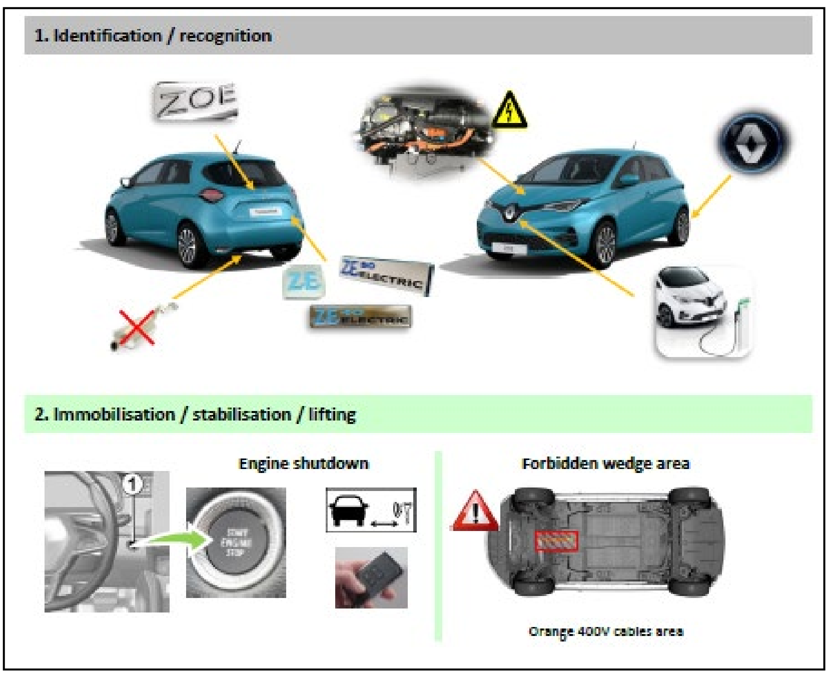
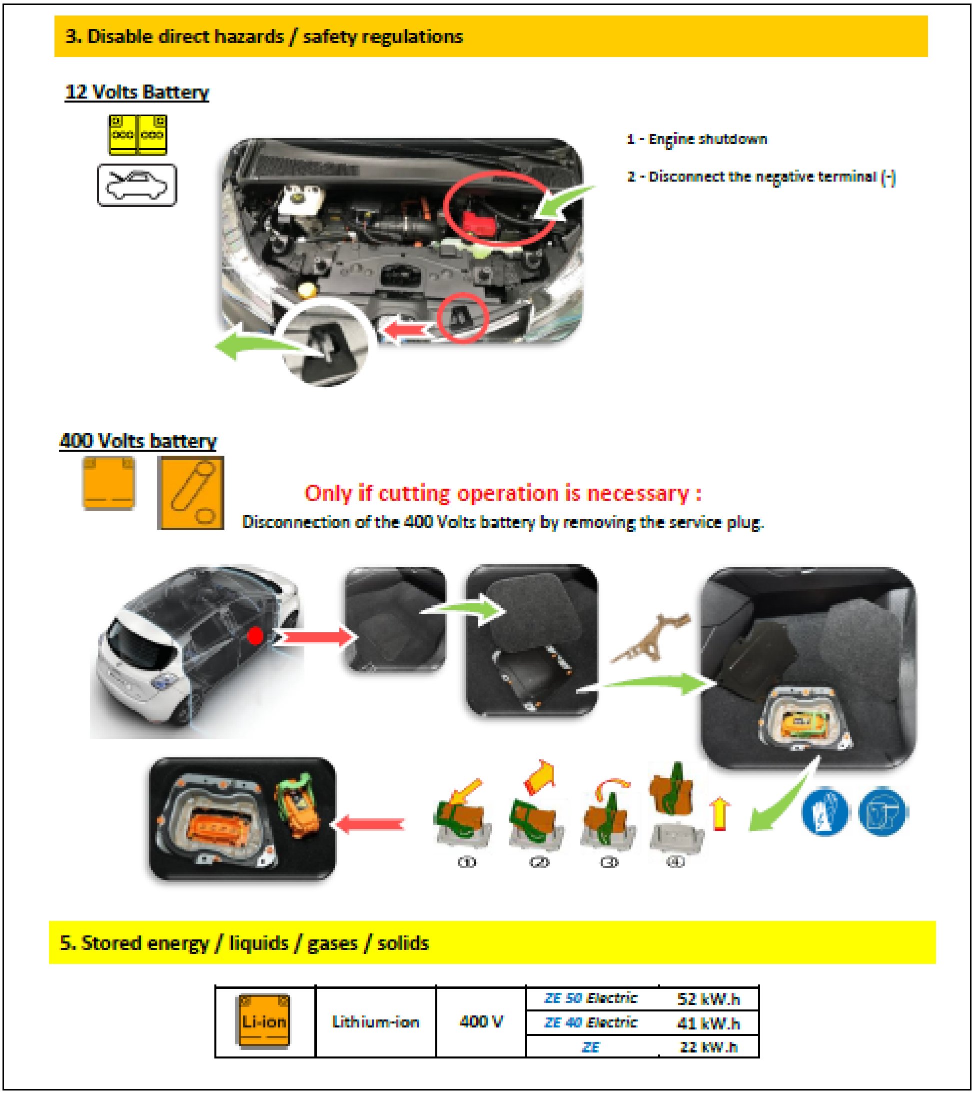
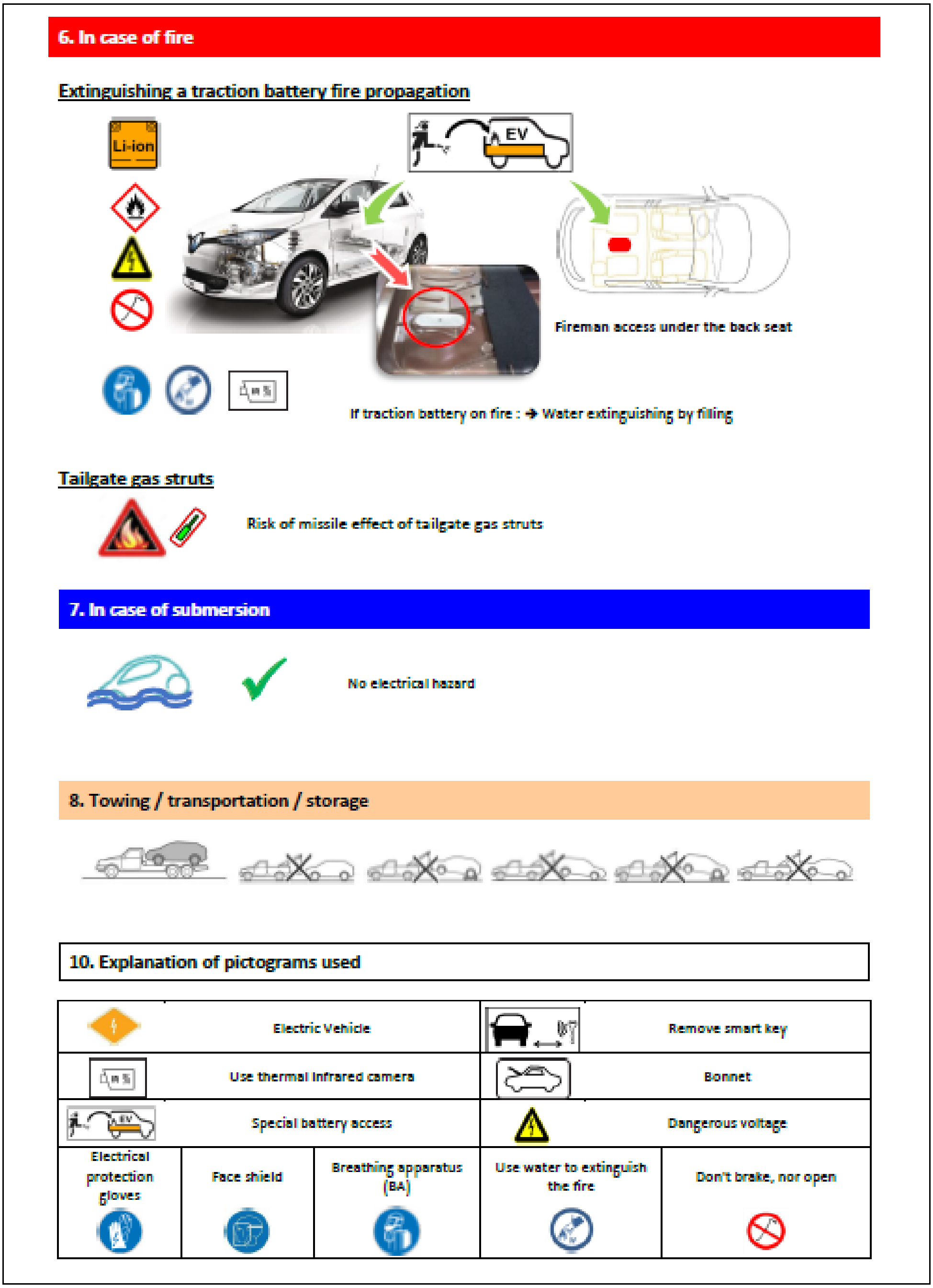


Figure 4.57 Precautions when lifting the vehicle with a lift



Li-ion	Lithium-ion	400 V	ZE 50 Electric	52 kW.h
			ZE 40 Electric	41 kW.h
			ZE	22 kW.h

Figure 4.58 Battery locations



6. In case of fire

Extinguishing a traction battery fire propagation

Li-ion

EV

Fireman access under the back seat

If traction battery on fire : → Water extinguishing by filling

Tailgate gas struts

Risk of missile effect of tailgate gas struts

7. In case of submersion

No electrical hazard

8. Towing / transportation / storage

10. Explanation of pictograms used

	Electric Vehicle			Remove smart key
	Use thermal Infrared camera			Bonnet
	Special battery access			Dangerous voltage
Electrical protection gloves	Face shield	Breathing apparatus (BA)	Use water to extinguish the fire	Don't brake, nor open

Figure 4.59 Risks associated with fire or submersion in water and related explanations

4.7. Advanced Driver Assistance Systems and Autonomous Driving

This section provides a brief overview of advanced driver assistance systems and autonomous driving, followed by a discussion on sensor calibrations. ADAS systems are considered to be a precursor to autonomous driving and are fundamental for a safer and more efficient transportation future. Both technologies aim to reduce significantly traffic accidents, to improve fuel efficiency, to enhance environmental sustainability, to reduce traffic congestion, and to make transportation more accessible for individuals with disabilities. However, legal regulations and ethical decision-making processes surrounding these vehicles remain areas of debate.

4.7.1. Advanced Driver Assistance Systems (ADAS)

ADAS are electronic systems designed to enhance driver safety, improve driving comfort, and minimize accident risks. These systems are equipped with technologies such as sensors, cameras, radars, and artificial intelligence algorithms. The main features of ADAS systems are as follows:

- *Adaptive Cruise Control:* Automatically adjusts speed to maintain a safe distance from the vehicle ahead.
- *Lane Keeping and Departure Warning:* Warns the driver or automatically keeps the vehicle in its lane when it begins to drift.
- *Automatic Emergency Braking:* Warns the driver of a collision risk and, if necessary, automatically stops the vehicle.
- *Blind Spot Monitoring: Alerts* the driver audibly or visually if a vehicle is in the blind spot.
- *Traffic Sign Recognition:* Detects traffic signs and informs the driver (e.g., speed limits).
- *Parking Assistance Systems:* Facilitates parking with automatic parking, parking space detection, and rearview cameras.
- *Driver Fatigue Detection System:* Detects if the driver is fatigued or distracted and recommends taking a break.

4.7.2. Autonomous Driving

Autonomous driving refers to vehicles managing themselves without human intervention. This technology is powered by sensors, mapping systems, artificial intelligence, and machine learning algorithms. Autonomous driving is classified into five levels by the Society of Automotive Engineers (SAE):

• Level 0 (Manual Control): The driver is fully responsible, with only basic warning systems.

• Level 1 (Assisted Driving): A single task is automated (e.g., cruise control).

• Level 2 (Partial Automation): Multiple tasks, such as steering and speed control, are automated, but the driver maintains constant control.

• Level 3 (Conditional Automation): The vehicle assumes full control in specific situations, but the driver must intervene when required.

• Level 4 (High Automation): The vehicle is fully autonomous in most driving conditions but may operate in limited areas.

• Level 5 (Full Automation): The vehicle operates entirely independently under all conditions, requiring no driver intervention.

Advanced technologies used in autonomous driving include:

• Sensors and Cameras: Detect nearby vehicles, pedestrians, road signs, and other obstacles.

• Lidar and Radar: Measure distances and detect speeds (Figure 4.60).

• Mapping and Positioning Systems: Navigate using detailed maps and GPS data.

• Artificial Intelligence and Machine Learning: Analyze environmental data and improve decision-making capabilities.

• Onboard Computing: Process large volumes of data quickly to make real-time decisions.

Figure 4.60 Autonomous vehicle systems [14]

4.7.3. Sensor Calibrations in ADAS

Calibration ensures that a system or component functions accurately within predefined references. To minimize accident risks, the radar and camera-based ADAS equipment in vehicles must be periodically checked to ensure their accuracy as defined by manufacturers. If any issues are detected, necessary repairs should be made, and the components should be recalibrated to align with the manufacturer's specifications.

Sensor calibration in ADAS must be performed under the following conditions:

- After accident-related repairs.
- After minor bodywork repairs.
- After front-end geometry adjustments.
- In case of system sensor faults.
- After mechanical maintenance.
- After vehicle modifications.
- After sensor replacements.
- After painting processes (e.g., hood painting).

Vehicle manufacturers specify two types of front radar calibration for ADAS: Dynamic Self-Calibration and Static Calibration.

- *Dynamic Self-Calibration:* Performed on the road without requiring calibration equipment. This type does not involve user guidance by the diagnostic tool.
- *Static Calibration:* Conducted in a workshop environment using calibration and diagnostic tools (Figure 4.61).

Figure 4.61 Static calibration [15]

4.7.4. Common Fault Codes in Hybrid and Electric Vehicles

Table 4.1 provides examples of some standardized fault codes encountered in hybrid and electric vehicles for informational purposes [16], [17], [18]. It should be noted that these fault codes are not exhaustive and are continuously expanded and updated in response to technological needs.

Table 4.1 Some of the Standardized Fault Codes in HEVs

P0A38	Generator Temperature Sensor Circuit Low
P0A39	Generator Temperature Sensor Circuit High
POA3A	Generator Temperature Sensor Circuit Intermittent
P0A3B	Generator Over Temperature
P0A3C	Drive Motor "A" Inverter Over Temperature
P0A3D	Drive Motor "B" Inverter Over Temperature
POA3E	Generator Inverter Over Temperature
P0A3F	Drive Motor "A" Position Sensor Circuit
P0A40	Drive Motor "A" Position Sensor Circuit Range/Performance
P0A41	Drive Motor "A" Position Sensor Circuit Low
P0A42	Drive Motor "A" Position Sensor Circuit High
P0A43	Drive Motor "A" Position Sensor Circuit Intermittent
P0A44	Drive Motor "A" Position Sensor Circuit Overspeed
P0A45	Drive Motor "B" Position Sensor Circuit
P0A46	Drive Motor "B" Position Sensor Circuit Range/Performance
P0A47	Drive Motor "B" Position Sensor Circuit Low
P0A48	Drive Motor "B" Position Sensor Circuit High
P0A49	Drive Motor "B" Position Sensor Circuit Intermittent
P0A4A	Drive Motor "B" Position Sensor Circuit Overspeed
P0A4B	Generator Position Sensor Circuit
P0A4C	Generator Position Sensor Circuit Range/Performance
P0A4D	Generator Position Sensor Circuit Low
P0A4E	Generator Position Sensor Circuit High
P0A4F	Generator Position Sensor Circuit Intermittent
P0A50	Generator Position Sensor Circuit Overspeed
P0A51	Drive Motor "A" Current Sensor Circuit
P0A52	Drive Motor "A" Current Sensor Circuit Range/Performance
P0A53	Drive Motor "A" Current Sensor Circuit Low
P0A54	Drive Motor "A" Current Sensor Circuit High
P0A55	Drive Motor "B" Current Sensor Circuit
P0A56	Drive Motor "B" Current Sensor Circuit Range/Performance
P0A38	Generator Temperature Sensor Circuit Low
P0A39	Generator Temperature Sensor Circuit High
POA3A	Generator Temperature Sensor Circuit Intermittent
P0A3B	Generator Over Temperature
P0A3C	Drive Motor "A" Inverter Over Temperature
P0A3D	Drive Motor "B" Inverter Over Temperature
POA3E	Generator Inverter Over Temperature
P0A3F	Drive Motor "A" Position Sensor Circuit
P0A40	Drive Motor "A" Position Sensor Circuit Range/Performance
P0A41	Drive Motor "A" Position Sensor Circuit Low

P0A42	Drive Motor "A" Position Sensor Circuit High
P0A43	Drive Motor "A" Position Sensor Circuit Intermittent
P0A44	Drive Motor "A" Position Sensor Circuit Overspeed
P0A45	Drive Motor "B" Position Sensor Circuit
P0A46	Drive Motor "B" Position Sensor Circuit Range/Performance
P0A47	Drive Motor "B" Position Sensor Circuit Low
P0A48	Drive Motor "B" Position Sensor Circuit High
P0A49	Drive Motor "B" Position Sensor Circuit Intermittent
P0A4A	Drive Motor "B" Position Sensor Circuit Overspeed
P0A4B	Generator Position Sensor Circuit
P0A4C	Generator Position Sensor Circuit Range/Performance
P0A4D	Generator Position Sensor Circuit Low
P0A4E	Generator Position Sensor Circuit High
P0A4F	Generator Position Sensor Circuit Intermittent
P0A50	Generator Position Sensor Circuit Overspeed
P0A51	Drive Motor "A" Current Sensor Circuit
P0A52	Drive Motor "A" Current Sensor Circuit Range/Performance
P0A53	Drive Motor "A" Current Sensor Circuit Low
P0A54	Drive Motor "A" Current Sensor Circuit High
P0A55	Drive Motor "B" Current Sensor Circuit
P0A56	Drive Motor "B" Current Sensor Circuit Range/Performance
P0A57	Drive Motor "B" Current Sensor Circuit Low
P0A58	Drive Motor "B" Current Sensor Circuit High
P0A59	Generator Current Sensor Circuit
P0A5A	Generator Current Sensor Circuit Range/Performance
P0A5B	Generator Current Sensor Circuit Low
P0A5C	Generator Current Sensor Circuit High
P0A5D	Drive Motor "A" Phase U Current
P0A5E	Drive Motor "A" Phase U Current Low
P0A5F	Drive Motor "A" Phase U Current High
P0A60	Drive Motor "A" Phase V Current
P0A61	Drive Motor "A" Phase V Current Low
P0A62	Drive Motor "A" Phase V Current High
P0A63	Drive Motor "A" Phase W Current
P0A64	Drive Motor "A" Phase W Current Low
P0A65	Drive Motor "A" Phase W Current High
P0A66	Drive Motor "B" Phase U Current
P0A67	Drive Motor "B" Phase U Current Low
P0A68	Drive Motor "B" Phase U Current High
P0A69	Drive Motor "B" Phase V Current
P0A6A	Drive Motor "B" Phase V Current Low
P0A6B	Drive Motor "B" Phase V Current High
P0A6C	Drive Motor "B" Phase W Current
P0A6D	Drive Motor "B" Phase W Current Low
P0A6E	Drive Motor "B" Phase W Current High
P0A6F	Generator Phase U Current
P0A70	Generator Phase U Current Low
P0A71	Generator Phase U Current High

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INDEX

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