Laboratory Manual

For

Hybrid Electric Vehicles Testing Laboratory

(AUPC3205)

Department of Automobile Engineering

PMEC ,Berhampur

Odisha

Course Objectives

1. To provide hands-on experience in testing, analyzing, and evaluating hybrid and electric vehicle components.
2. To familiarize students with testing methods for batteries, inverters, motors, and control systems in EVs and HEVs.
3. To develop skills in real-time data acquisition, drive cycle testing, and diagnostic fault analysis.

Course Outcomes (COs)

On successful completion of this course, students will be able to:

CO1: Identify and understand the functional layout of hybrid and electric vehicle systems.

CO2: Perform performance testing and diagnostics of batteries, motors, and controllers.

CO3: Evaluate drive cycles and regenerative braking using simulation and test benches.

CO4: Analyze communication between vehicle subsystems via CAN Bus and ECUs.

CO5: Conduct real-time data logging, fault detection, and reporting using professional tools.

LIST OF EXPERIMENTS

1. Identification and study of HEV subsystems: electric motor, ICE, battery pack, power electronics, control strategy.
2. Battery testing: Charge-discharge profiling, SoC estimation, cycle life analysis using battery analyzer.
3. Motor controller and inverter testing: Efficiency and thermal behavior under simulated load using dynamometer.
4. Simulation of regenerative braking and energy recovery evaluation on lab rig or using software (e.g., MATLAB/Simulink).
5. Efficiency mapping of BLDC or PMSM motor under varying load and speed conditions.
6. Thermal imaging and analysis of battery and motor during operation to detect hotspots and insulation failures.
7. CAN Bus communication test: Live monitoring of signals from BMS, motor controller, and vehicle ECU using CANalyzer or similar tool.
8. Testing of DC-DC converters: Voltage regulation, input/output current profiling, ripple analysis.
9. Fuel cell testing: Polarization curve, hydrogen consumption, voltage-current characteristics.
10. Drive cycle simulation on chassis dynamometer (WLTP/IDC/FTP-75): power consumption and range estimation.
11. Solar panel-based charging setup: energy yield, peak power output, and integration with HEV battery.
12. Real-time fault detection and logging: DTC readout, freeze frame data interpretation using diagnostic tools and PC interface.

LABORATORY PRECAUTIONS

1. Read the experiment manual carefully before starting the experiment and understand the working principle of the equipment.
2. Ensure proper grounding of all electrical equipment such as battery analyzer, motor controller, dynamometer, inverter, and DC-DC converter to avoid electric shock.
3. Check all connections before powering the system, especially battery terminals, motor wiring, and power electronics connections.
4. Do not touch live terminals or high-voltage components while the system is energized.
5. Wear appropriate safety equipment, such as insulated gloves and safety shoes, when handling batteries and high-power electrical circuits.
6. Follow the correct sequence for switching ON and OFF the equipment (power supply, controller, and load system) as instructed by the lab instructor.
7. Avoid short circuits in battery packs and power electronics modules, as they may cause severe damage or fire hazards.
8. Operate motors and dynamometers within rated limits of voltage, current, torque, and speed to prevent overheating or equipment damage.
9. Monitor temperature during thermal imaging experiments to prevent overheating of batteries, motors, and power electronic devices.
10. Ensure proper ventilation in the laboratory, especially during battery charging, fuel cell testing, or hydrogen-related experiments.
11. Do not disconnect CAN communication cables while the system is operating, as it may lead to communication faults or data loss.
12. Use software tools (MATLAB/Simulink, CANalyzer, diagnostic tools) carefully and verify settings before starting simulations or real-time data acquisition.
13. Keep the work area dry and clean, especially near electrical equipment and batteries.
14. Immediately report abnormal conditions such as unusual noise, overheating, smoke, or unstable readings to the lab instructor.
15. Turn OFF all power supplies and equipment after completing the experiment and disconnect the setup properly.

EXPERIMENT-1

Aim: To identification and study of HEV subsystems: electric motor, ICE, battery pack, power electronics, control strategy.

Apparatus Required:
HEV system model
Electric motor
ICE model
Battery pack
Inverter
Control unit

Theory:

A Hybrid Electric Vehicle (HEV) utilizes two forms of energy storage: electrical energy and fuel energy. Electrical energy is stored in a battery pack, sometimes supported by ultracapacitors, and an electric motor is used as the traction motor to drive the vehicle. Fuel energy, on the other hand, requires a fuel tank and an Internal Combustion Engine (ICE) to produce mechanical power. In some configurations, a fuel cell is used instead of an engine to convert fuel directly into electrical energy. In such systems, the vehicle is driven only by the electric motor. In other configurations, both the engine and the electric motor work together to propel the vehicle.

Electric Motor

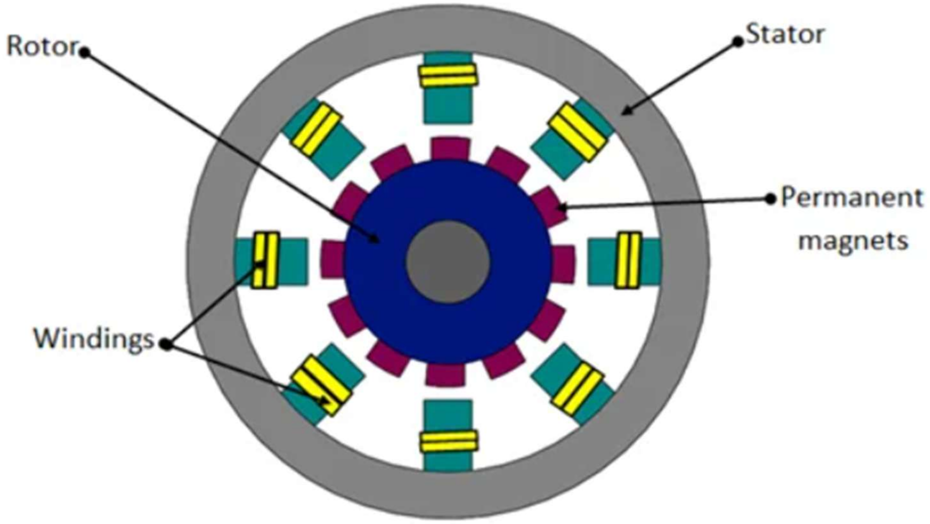
Electric motors serve as the primary driving component in hybrid electric vehicle systems. The traction motor directly drives the wheels and provides several advantages compared to conventional engines. Unlike an internal combustion engine, which must increase its speed before producing maximum torque, an electric motor can deliver maximum torque at very low speeds. Electric motors also operate with high efficiency, low noise, and smooth performance. Additional advantages include excellent acceleration from rest, precise control of vehicle motion, strong reliability, and the ability to operate effectively even with voltage fluctuations.

Several types of electric motors are commonly used in hybrid electric vehicles. The most prominent technologies include Permanent Magnet Synchronous Motors (PMSM), Brushless DC Motors (BLDC), Switched Reluctance Motors (SRM), and AC Induction Motors. These motors are widely preferred because of their high efficiency, reliability, and suitability for automotive traction applications.

A **Permanent Magnet Synchronous Motor (PMSM)** is composed of the following main components:

- **Stator:** Contains three-phase AC windings.
- **Rotor:** Equipped with permanent magnets that are mounted either on the surface or embedded within the rotor.
- **AC Power Source / Inverter:** Supplies the required alternating current to the stator windings.
- **Control Circuit:** Regulates the operation and performance of the motor.

When an AC supply is provided to the stator windings, it produces a rotating magnetic field within the motor. When three-phase AC power is applied, the stator generates a rotating magnetic field (RMF). The permanent magnets present on the rotor interact with this magnetic field and align with it. As a result, the rotor rotates at the same speed as the rotating magnetic field, which is known as the synchronous speed. Continuous rotation occurs because the AC supply keeps changing its direction, maintaining the rotating magnetic field. However, a PMSM is generally not self-starting, and therefore an inverter drive or suitable starting mechanism is typically required to initiate and control its operation.



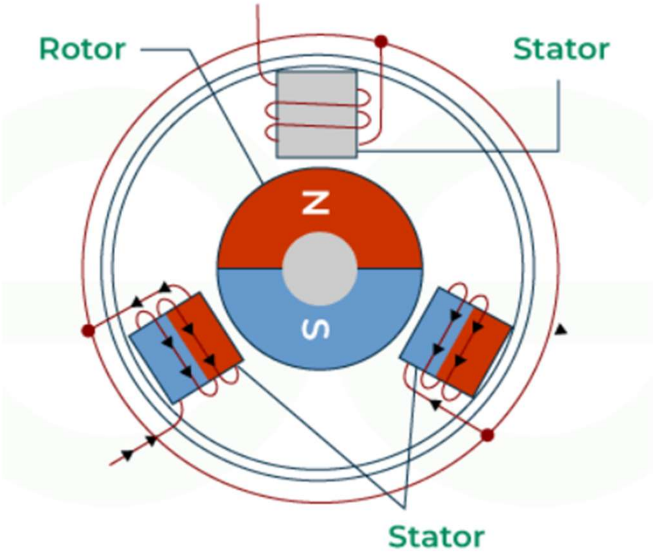
BLDC refers to a Brushless Direct Current Motor. As indicated by its name, this type of motor operates using a DC power supply and does not contain mechanical brushes or commutators. Instead of mechanical commutation, BLDC motors use an electronic commutation system to regulate the current flow through the motor windings.

A BLDC motor mainly consists of the following components:

- **Stator:** The stationary part of the motor that contains the windings.
- **Rotor:** The rotating component that carries permanent magnets.
- **Electronic Controller:** This replaces the conventional brush and commutator arrangement and controls the current supplied to the windings.
- **DC Power Supply:** Provides the electrical energy required for motor operation.

The electronic controller supplies current to the stator windings in a predetermined sequence. As a result, a magnetic field is generated in the stator. The permanent magnets on the rotor interact with this magnetic field, which causes the rotor to rotate.

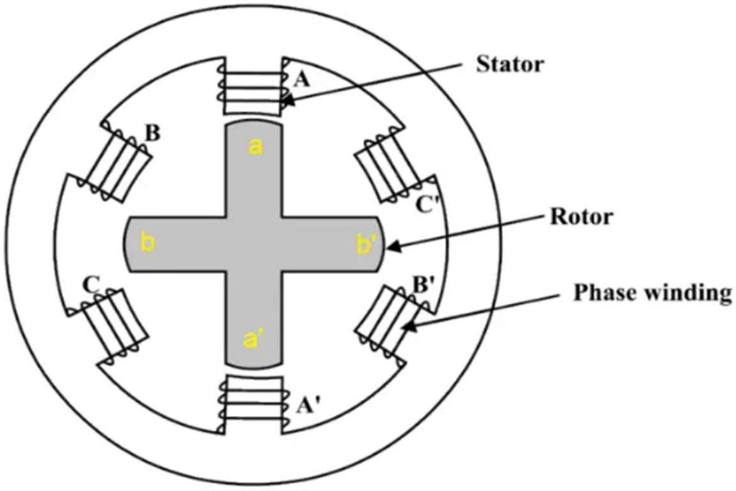
When a DC power supply is applied, current flows through the stator windings and produces a magnetic field. The permanent magnets in the rotor experience attraction and repulsion due to this magnetic field. The electronic controller continuously switches the current between different stator windings, creating a rotating magnetic field. The rotor aligns itself with this rotating field and begins to rotate, thereby generating mechanical motion.



The **Switched Reluctance Motor (SRM)** is an electric motor that works on the principle of magnetic reluctance. In this motor, electrical power is supplied to the stator windings**,** while the rotor has no electrical connections, brushes, or commutators. This makes the mechanical design simple and strong, although it requires an electronic switching system to energize the stator windings sequentially and control torque.

The SRM has a simple and low-cost construction because the rotor does not contain windings or permanent magnets. Instead, the rotor is made of salient poles formed from laminated soft magnetic material**,** while the stator contains field windings similar to those in DC motors. When a stator winding is energized, it produces a magnetic field that pulls the rotor toward the position of minimum magnetic reluctance, causing rotation.

An electronic controller and position sensor are used to switch the stator windings in sequence so that the rotating magnetic field continuously pulls the rotor forward. Unlike induction motors, SRMs operate without slip, allowing accurate control of rotor position and enabling operation at very low speeds or even step-by-step movement.



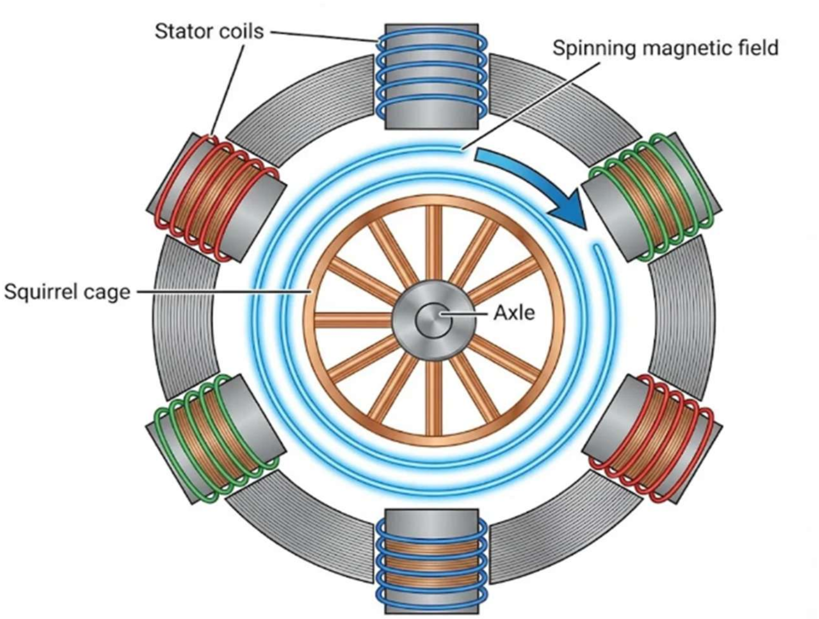
An **AC Induction Motor** is an electric motor that works on the principle of Electromagnetic Induction. When AC supply is given to the stator winding, it produces a rotating magnetic field which induces current in the rotor and creates torque, causing the rotor to rotate.

Main parts:

- Stator – stationary part that produces the magnetic field
- Rotor – rotating part where current is induced

Types:

- Single-Phase Induction Motor
- Three-Phase Induction Motor



ICE model

The **Internal Combustion Engine** provides additional mechanical power and improves the driving range of the vehicle. In a hybrid electric vehicle, the engine performs several important functions. It can drive the wheels directly in a parallel hybrid system, generate electricity to charge the battery, and work together with the electric motor when higher power is required, such as during acceleration or climbing.

The engine used in most hybrid vehicles is usually a gasoline or diesel engine and is generally optimized for better fuel efficiency rather than maximum power output. Many hybrid vehicles use an Atkinson-cycle engine, which helps improve thermal efficiency and reduce fuel consumption.

The internal combustion engine in a hybrid vehicle operates in different modes depending on the driving condition. These modes include engine-only mode, where the vehicle runs only on the engine; hybrid assist mode, where the engine and electric motor work together to provide power; and charging mode, where the engine generates electricity to recharge the battery.

Batter Pack

The battery pack stores electrical energy and supplies power to the electric motor in a hybrid electric vehicle. The most common types of batteries used in hybrid vehicles are Nickel Metal Hydride (NiMH) and Lithium-ion (Li-ion) batteries. The battery pack performs several important functions in the vehicle. It stores electrical energy required for propulsion, supplies power to the electric motor during vehicle operation, and also stores the energy recovered during regenerative braking.

The battery pack is equipped with a Battery Management System (BMS)**,** which monitors important parameters such as the state of charge (SOC), temperature, voltage, and current of the battery. By continuously monitoring these parameters, the BMS ensures the safe operation of the battery and helps maintain a longer battery life.

Power Electronics

Power electronics act as an interface between the battery, the electric motor, and other electrical components in a hybrid electric vehicle. The main components of power electronics include the inverter, DC–DC converter, and the Power Electronics Control Unit (PECU). These components perform several important functions in the vehicle’s electrical system.

The inverter converts the direct current (DC) power from the battery into alternating current (AC) required for the operation of the electric motor. Power electronics also control the speed and torque of the motor, manage the power flow between the battery and the motor, and regulate the voltage levels within the electrical system. By performing these functions, power electronics ensure efficient energy conversion and proper control of the electric drivetrain in a hybrid electric vehicle.

Control Strategy

The control strategy is considered the brain of a hybrid electric vehicle because it determines how power is shared between the internal combustion engine (ICE) and the electric motor to achieve maximum efficiency. The main objectives of the control strategy are to reduce fuel consumption, maintain the battery state of charge, reduce emissions, and ensure smooth vehicle performance.

The control system selects different operating modes depending on the driving conditions. In electric mode, the vehicle runs only on the electric motor. In engine mode, the vehicle operates only with the internal combustion engine. In hybrid mode, both the electric motor and the engine work together to provide power. During regenerative braking mode, the electric motor acts as a generator and converts braking energy into electrical energy to charge the battery. In battery charging mode, the internal combustion engine generates power to recharge the battery when the state of charge becomes low.

Control strategies can be broadly classified into two main categories:

1. Rule-Based Strategies

Rule-based strategies are further divided into the following subcategories:

i. Fuzzy-Based Control

Fuzzy-based control strategies are of three types: Predictive, Adaptive, Conventional

ii. Deterministic Control

Deterministic controllers are subdivided into: State Machine, Power Follower, Thermostat Control

2. Optimization-Based Strategies

Optimization-based strategies are classified into the following types:

i. Global Optimization

Global optimization methods include: Linear Programming Methods, Dynamic Programming, Stochastic Dynamic Programming, Genetic Algorithms

ii. Real-Time Optimization

Real-time optimization techniques include: EFC Minimization, Robust Control Model, Predictive Control, Decoupling Control

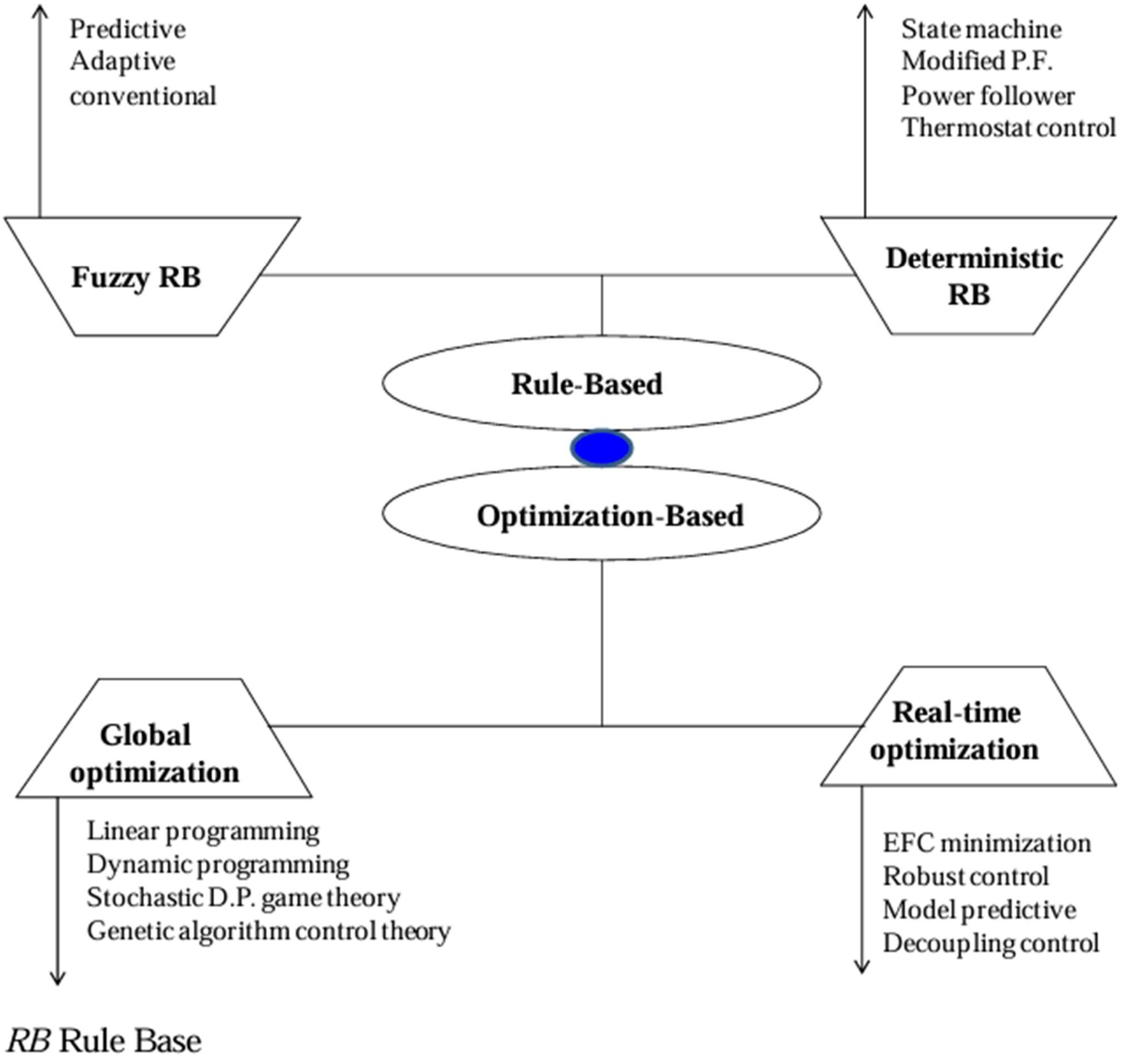


Fig.1.1: Classification of control strategies

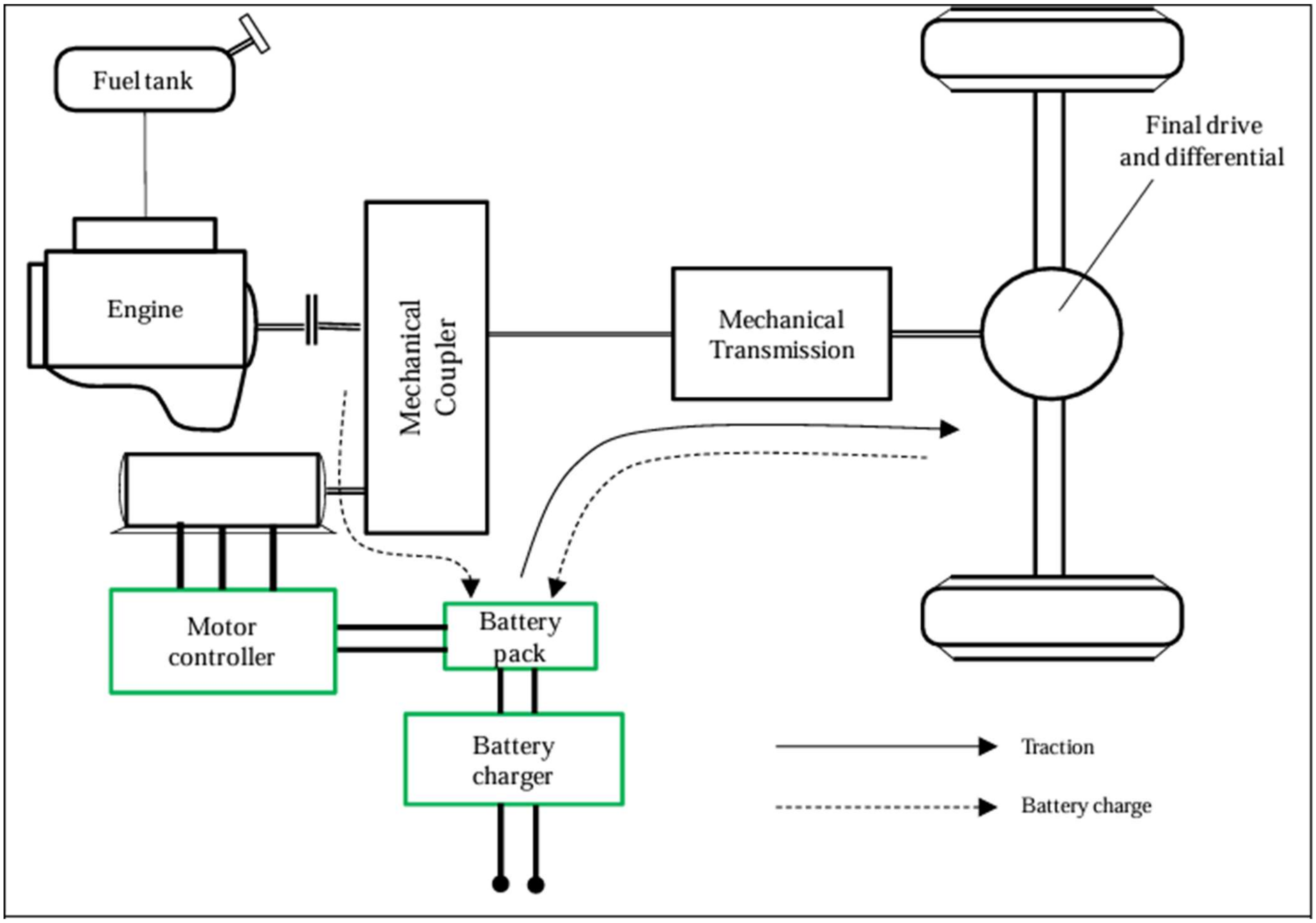


Fig.1.2: Hybrid Drive Train

Procedure:

1. Observe the HEV model or subsystem components.
2. Identify the electric motor, ICE, battery pack and inverter.
3. Study the connection between subsystems.
4. Note the control strategy used to switch between electric and engine modes.

Conclusion:

The major HEV subsystems were identified and their functions were studied in this experiment.

EXPERIMENT-2

Aim: To study the performance characteristics of a rechargeable battery by conducting charge-discharge profiling, estimating the State of Charge (SoC), and analyzing cycle life using a battery analyzer.

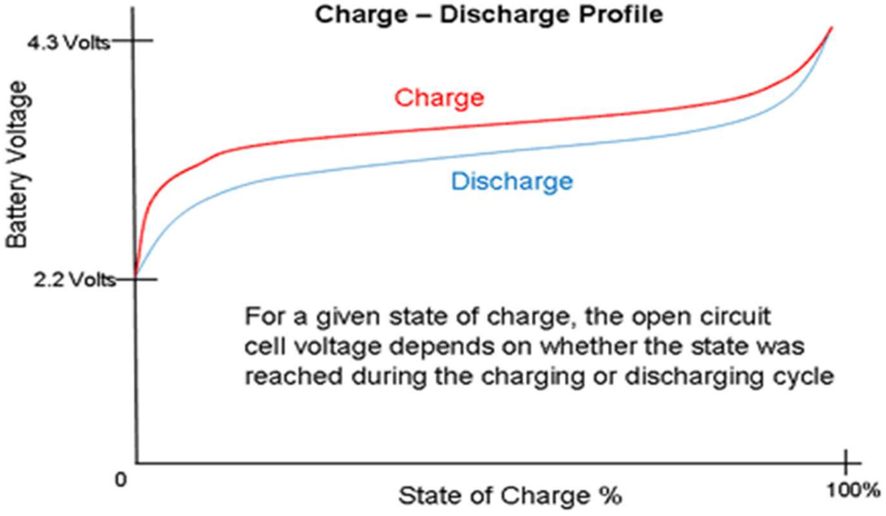
Apparatus:
- Battery analyzer
- Lithium-ion battery pack
- DC power supply
- Multimeter

Theory:

Battery testing is important to evaluate the performance, efficiency, and health of batteries used in applications such as electric vehicles, hybrid vehicles, and energy storage systems. Proper testing helps determine parameters like voltage behaviour, capacity, charging efficiency, and long-term durability. A battery analyzer is commonly used in laboratories to control charging and discharging processes while recording important electrical parameters such as voltage, current, capacity, and energy.

Charge-Discharge Profiling

Charge–discharge profiling is used to study how the battery voltage changes with time during charging and discharging operations. In this method, the battery is first charged to its full capacity and then discharged at a controlled or constant current. During this process, important parameters such as voltage (V), current (A), capacity (Ah), and energy (Wh) are recorded using the battery analyzer. The collected data is then used to plot graphs such as voltage versus time or capacity versus time, which help in understanding the performance characteristics of the battery. These curves provide valuable information about battery efficiency, internal resistance, and operating behaviour under different load conditions.



State Of Charge

The State of Charge (SoC) represents the amount of energy remaining in the battery compared to its maximum capacity. It is usually expressed as a percentage and indicates how much charge is available for use. The SoC can be calculated using the ratio of the remaining capacity to the maximum capacity of the battery multiplied by 100. For example, if a battery with a total capacity of 10 Ah has 6 Ah of charge remaining, the SoC will be 60%. Accurate SoC estimation is important for battery management systems in electric vehicles and energy storage systems. Common methods used for estimating SoC include coulomb counting, which measures the current flowing in and out of the battery, the voltage method, which estimates SoC based on battery voltage levels, and advanced techniques such as Kalman filtering, which combine multiple measurements for more precise estimation. Methods for Estimating Battery State of Charge (SoC)

1. Open-Circuit Voltage (OCV) Method

The Open-Circuit Voltage (OCV) method is commonly used to estimate the State of Charge (SoC) of a battery when it is in a resting state. This method is effective in systems where the battery frequently remains idle.

Implementation:

- The battery is kept idle without charging or discharging for a certain period.
- The terminal voltage of the battery is measured.
- The measured voltage is compared with a standard OCV–SoC reference curve, which depends on the battery chemistry.

Applications:

- Energy Storage Systems (ESS): Large-scale renewable energy storage systems use OCV measurements during standby conditions to determine the battery charge level before supplying power to the grid.
- Uninterruptible Power Supply (UPS): Backup power systems in data centers use OCV estimation to check battery readiness during power outages.

Limitations:

- Requires a long resting period to obtain accurate readings.
- Not suitable for dynamic systems such as electric vehicles or drones.

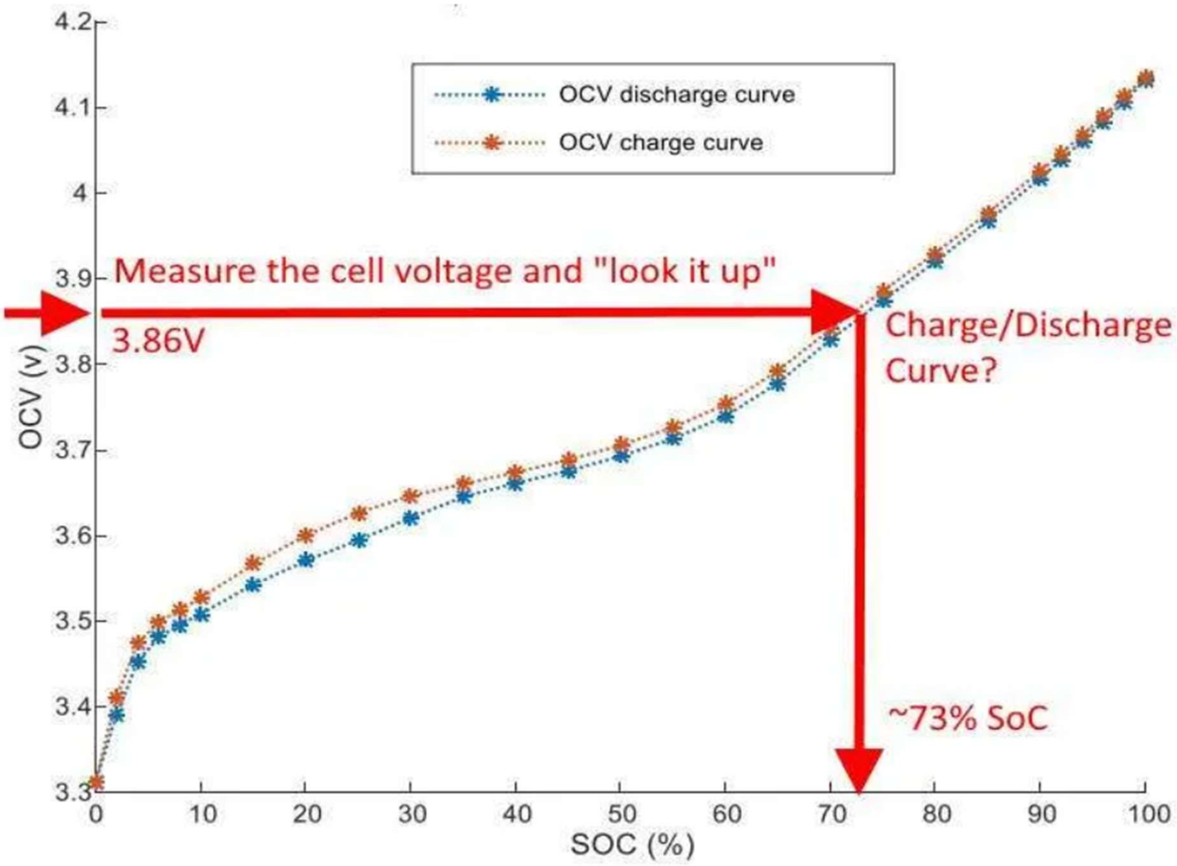
Formula:

$$SOC = f(V_{oc})$$

where

V_{oc} = open-circuit voltage

f = lookup function based on battery chemistry.



2. Coulomb Counting Method

The Coulomb Counting method estimates the battery SoC by measuring the current flowing into and out of the battery over time.

Implementation:

- A current sensor measures the charge (in ampere-hours) flowing in and out of the battery.
- The accumulated charge is added to or subtracted from the previously known SoC value.
- Periodic calibration is required to correct accumulated errors.

Applications:

- Smartphones and Laptops: Devices manufactured by companies such as Apple Inc. use coulomb counting along with voltage references to display battery percentage.
- Medical Devices: Portable medical devices such as pacemakers and insulin pumps rely on coulomb counting for accurate battery life estimation.

Limitations:

- Small sensor errors accumulate over time, causing drift in the SoC estimation.
- The method depends heavily on an accurate initial SoC value.

Formula:

$$SoC(t) = SoC(t-1) + \frac{I(t)}{Q_n}\Delta t$$

where:

SoC(t) = estimated State of Charge at time, t
SoC(t-1) = previous State of Charge at time t-1
I(t) = charging or discharging current at time, t
Q_n = battery cell capacity
Δt = time step between t-1 and t

3. Kalman Filter Method

The Kalman Filter is an advanced model-based technique used to estimate the battery SoC by continuously updating predictions based on real-time measurements of voltage, current, and temperature.

Types of Kalman Filters:

- Extended Kalman Filter (EKF): Suitable for non-linear battery models.
- Unscented Kalman Filter (UKF): Provides better accuracy for highly non-linear battery systems.
- Adaptive Kalman Filter: Adjusts parameters automatically as the battery ages.

Implementation:

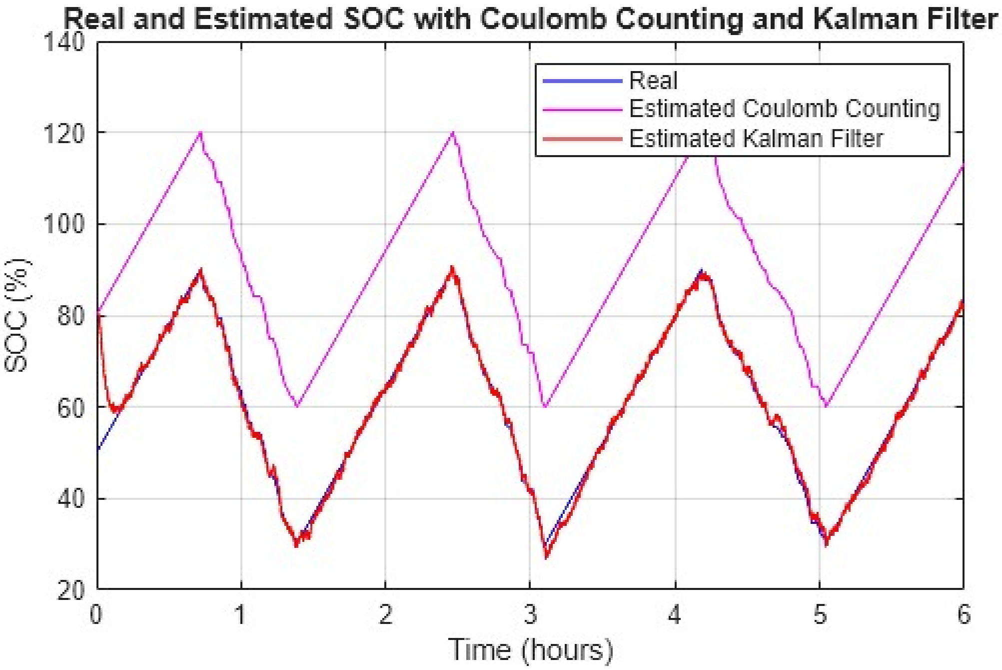
- The algorithm begins with an initial estimate of SoC.
- Real-time measurements are obtained from sensors.
- A mathematical model processes these measurements.
- The filter continuously updates and corrects the SoC estimation based on feedback.

Applications:

- Electric Vehicles: Companies such as Tesla, Inc. use Kalman filter–based algorithms in their battery management systems for accurate SoC prediction and driving range estimation.
- Electric Buses and Fleet Vehicles: Manufacturers like BYD Company use UKF-based SoC estimation to optimize battery performance under varying load conditions.

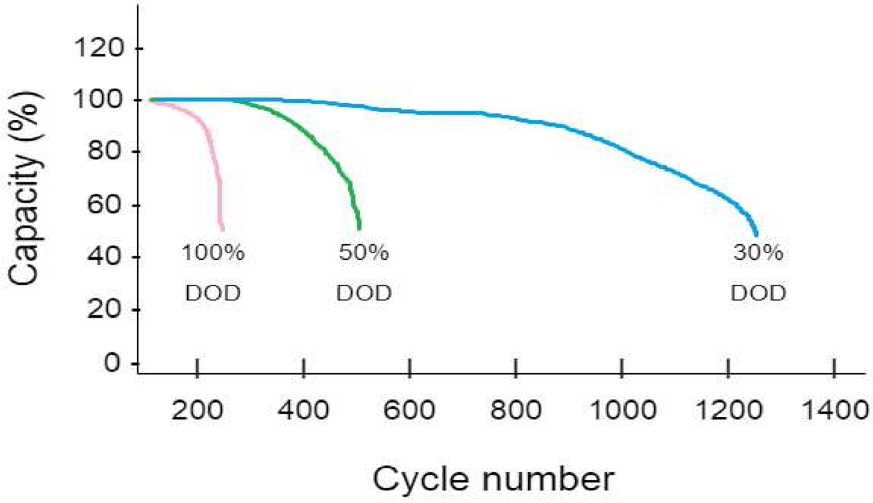
Limitations:

- Computationally complex and requires higher processing power.
- Not suitable for low-cost battery systems with limited computing capability.



Cycle Life Analysis

Battery life cycle analysis evaluates both the performance degradation and environmental impacts of batteries from production to disposal, using modeling, predictive tools, and life cycle assessment methodologies.Cycle life refers to the number of complete charge and discharge cycles a battery can undergo before its capacity reduces to a specified level, usually about 80% of its original capacity. For example, if a battery initially provides 100% capacity, it is considered degraded when its usable capacity decreases to around 80%. Cycle life testing is performed by repeatedly charging and discharging the battery while measuring its capacity after each cycle. This analysis helps determine the durability, degradation rate, and long-term performance of the battery. Understanding cycle life is important for predicting battery lifespan and ensuring reliable operation in practical applications such as electric vehicles and renewable energy storage systems.



Relationship between battery capacity, Depth of discharge and cycle life of shallow-cycle battery

Procedure:

1. Connect the battery terminals to the battery analyzer and ensure that the polarity is correct.
2. Set the required charging current in the analyzer software and start charging the battery until the maximum voltage limit is reached, while recording the voltage and capacity values.
3. Set the discharge current in the analyzer and start the discharging process until the cut-off voltage is reached, and record the voltage versus time data.
4. Determine the remaining capacity of the battery and calculate the State of Charge (SoC) using the appropriate formula.
5. Repeat the charge–discharge cycles several times, record the capacity for each cycle, and observe the degradation of the battery to analyze its cycle life.

Observation Table:

Table 1: Charge Profiling Data

Time(min)	Voltage(V)	Current(A)	Capacity(Ah)

Table 2: Discharge Profiling Data

Time(min)	Voltage(V)	Current(A)	Capacity(Ah)

Table 3: SoC Estimation

Cycle Number	Maximum Capacity(Ah)	Remaining Capacity(Ah)	SoC%

Table 4: Cycle Life Analysis

Cycle Number	Measured Capacity(Ah)	Capacity Retention(%)

Graphs to be Plotted

1. Voltage vs Time (Charging Curve)
2. Voltage vs Time (Discharging Curve)
3. Capacity vs Cycle Number

Conclusion:

The battery was successfully tested using a battery analyzer, and the charge–discharge characteristics, state of charge, and cycle life performance of the battery were analyzed.

EXPERIMENT-3

Aim: To analyze the efficiency and thermal behavior of a motor controller and inverter under different load conditions using a dynamometer test setup.

Apparatus:

Electric Motor
Motor Controller
Inverter
Dynamometer (Load simulator)
Battery Pack
Temperature Sensors or Thermal Camera

Theory:

1. Motor Controller

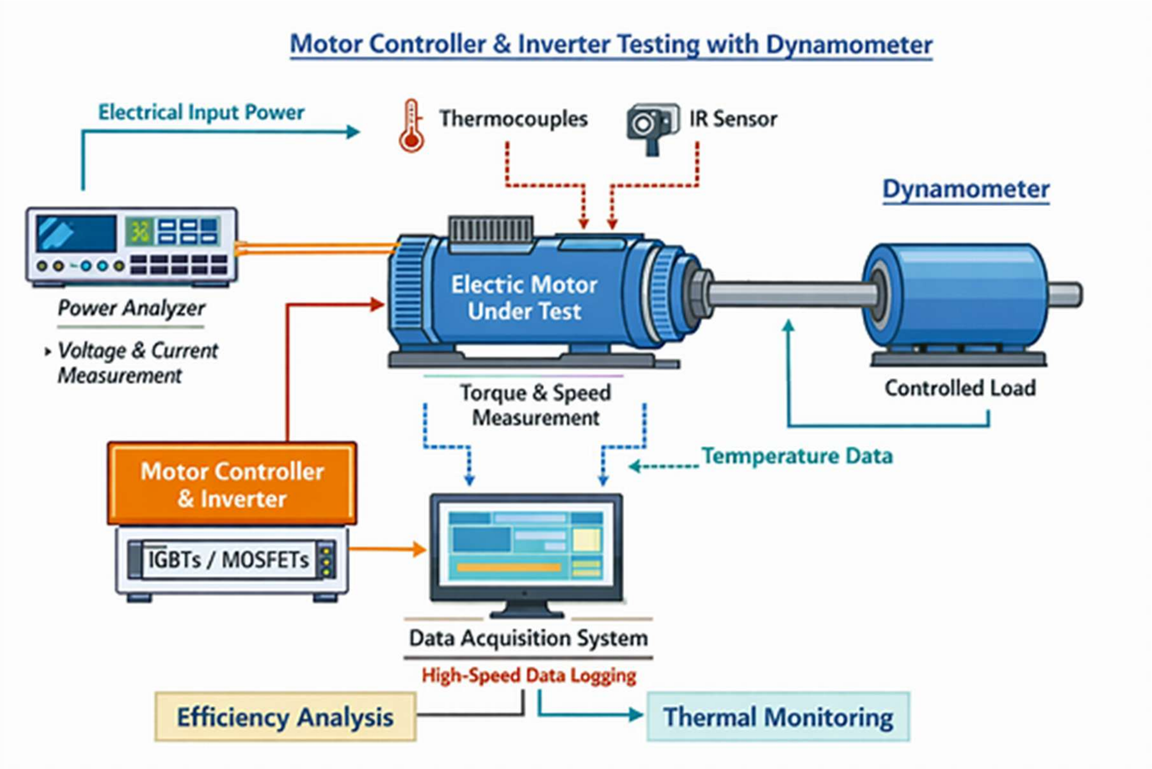
A motor controller is an electronic device used to regulate the operation of an electric motor. It controls important parameters such as motor speed, torque, and direction of rotation by adjusting the electrical power supplied to the motor. In electric drive systems, the motor controller receives commands from the control unit and processes signals from sensors to maintain the desired motor performance. It also provides protection functions such as overcurrent, overvoltage, and thermal protection to ensure safe operation. In a thermal testing system, the motor controller helps simulate different operating conditions so that the temperature rise and thermal behaviour of the motor and related components can be studied.

2. Inverter

An inverter is a power electronic device that converts direct current (DC) into alternating current (AC) to drive AC motors. In electric vehicle and motor testing systems, the inverter converts the DC power from a battery or power supply into controlled AC voltage and frequency. By adjusting the switching of semiconductor devices, the inverter controls the speed and torque of the motor. During thermal testing, the inverter supplies variable power to the motor under different load conditions, allowing researchers to observe heat generation and thermal characteristics of the motor and power electronics.

3. Dynamometer

A dynamometer is a testing device used to measure the performance of a motor or engine by applying a controlled load. It measures parameters such as torque, speed, and power output. In motor testing laboratories, a dynamometer is connected to the motor shaft to simulate real operating conditions. During thermal testing, the dynamometer applies different load levels to the motor while measuring its performance. This allows engineers to analyze how temperature changes affect efficiency, power output, and overall system performance under various load conditions.



Efficiency is defined as the ratio of output mechanical power to input electrical power. High efficiency indicates better energy utilization and reduced losses.

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

Where:

Pout = Output mechanical power of the motor

Pin = Input electrical power from the inverter

Procedure:

1. Connect the power supply, inverter, motor controller, motor, and dynamometer according to the setup diagram.
2. Ensure proper electrical connections and safety precautions.
3. Start the motor using the motor controller interface.
4. Apply different load conditions using the dynamometer.
5. Measure and record input voltage, current, torque, speed, and temperature.
6. Calculate input power, output power, and efficiency for each load condition.
7. Observe the temperature rise of the inverter and controller during operation.
8. Repeat the test for multiple load levels and record the results

Observation Table:

Table 1: Electrical Input Parameters

Voltage(V)	Current(A)	Input Power(W)

Table 2: Motor Output Parameters

Speed(RPM)	Torque(Nm)	Output Power(W)

Table 3: Efficiency Calculation

Input Power(W)	Output Power(W)	Efficiency (%)

Table 4: Thermal Behavior

Time(min)	Controller Temperature (°C)	Inverter Temperature (°C)

Conclusion:

The motor controller and inverter were tested under simulated load conditions using a dynamometer, and their efficiency and thermal behavior were analyzed successfully.

EXPERIMENT-4

Aim: To simulate the regenerative braking system of an electric vehicle and evaluate the energy recovery during braking using MATLAB/Simulink software.

Apparatus:	Computer with MATLAB Simulink Electric motor model (BLDC / DC motor) Battery model

Theory:

A Regenerative Braking system is a type of braking system that converts the kinetic energy of a moving vehicle into electrical energy during braking. The generated electrical energy is stored in the battery and can be reused to drive the motor. This improves overall energy efficiency and reduces energy loss in electric and hybrid vehicles.

Principle

The regenerative braking system works on the principle of Conservation of Energy, which states that energy cannot be destroyed but can be converted from one form to another.

In a conventional friction braking system, the kinetic energy of the moving wheels is converted into heat energy due to friction between the brake components, and this energy is lost to the surroundings. However, in a regenerative braking system, the kinetic energy of the wheels is converted into electrical energy instead of heat. This electrical energy is then stored in the battery for later use. This system is mainly used in electric and hybrid vehicles where an electric motor is used to drive the vehicle.

Construction

A regenerative braking system mainly consists of the following components:

1. Motor/Generator
The motor performs two functions in this system. During normal operation, it acts as a motor and converts electrical energy from the battery into mechanical energy to rotate the wheels. During braking, the same motor operates as a generator and converts the kinetic energy of the wheels into electrical energy.

2. Battery
The battery stores electrical energy and supplies it to the motor to run the vehicle. During braking, the electrical energy generated by the motor (acting as a generator) is stored in the battery.

3. Motor Controller
The motor controller regulates the flow of electrical energy between the battery and the motor. During normal operation, it supplies electrical energy from the battery to the motor. When the brake is applied, it stops the power supply to the motor and allows the generated electrical energy to be sent back to the battery for charging.

Working

Running Condition:

When the vehicle is running, the motor controller supplies electrical energy from the battery to the motor. The motor converts this electrical energy into mechanical energy, which rotates the wheels and moves the vehicle.

Braking Condition:

When the driver applies the brake, the motor controller disconnects the power supply from the battery to the motor. However, the wheels continue to rotate due to their kinetic energy. This rotation causes the motor to act as a generator, producing electrical energy. The generated electrical energy is then sent to the battery through the controller, thereby charging the battery. The generation of back electromotive force also helps slow down the rotation of the wheels.

Applications

Regenerative braking systems are commonly used in the following applications:

- Electric vehicles
- Hybrid electric vehicles
- Electric trains

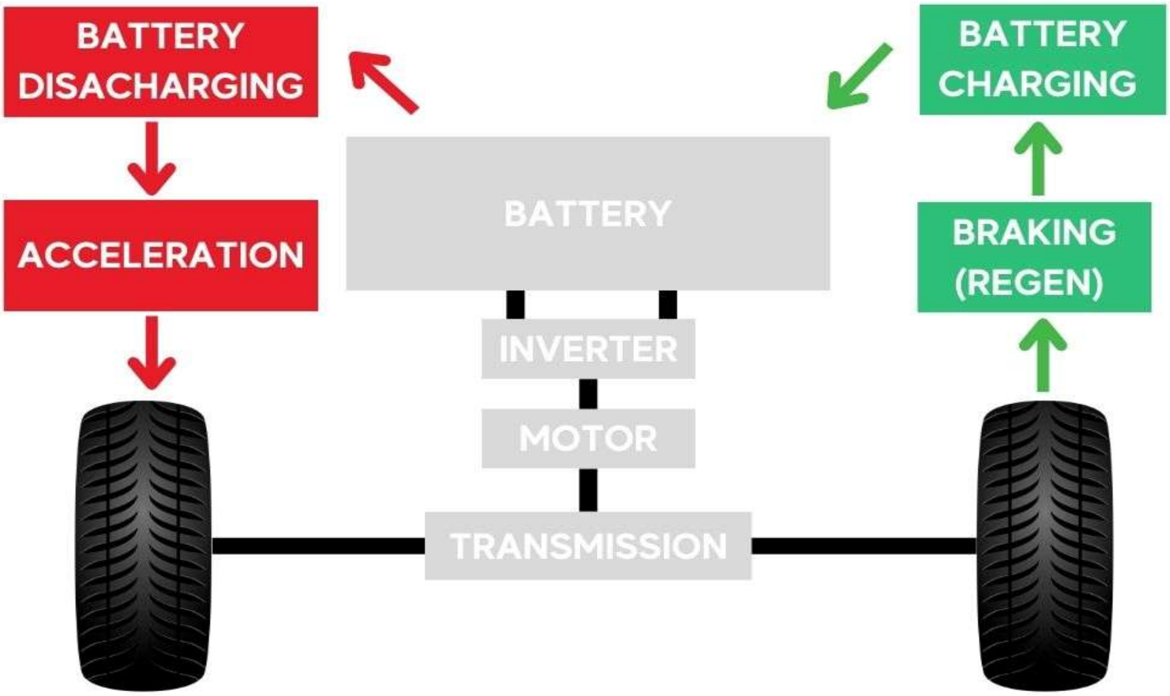


Fig. 4.1: Regenerative Braking System

This recovered electrical energy is then stored in the battery or energy storage system, which increases the overall efficiency of the vehicle and extends its driving range.

The kinetic energy of the moving vehicle can be expressed as:

$$E_k = \frac{1}{2}mv^2$$

Where

- m = Mass of the vehicle
- v = Velocity of the vehicle

During regenerative braking, a portion of this kinetic energy is converted into electrical energy and stored in the battery.

Energy recovery efficiency can be calculated as:

$$\eta = \frac{Recovered\ Energy}{Total\ Kinetic\ Energy} \times 100$$

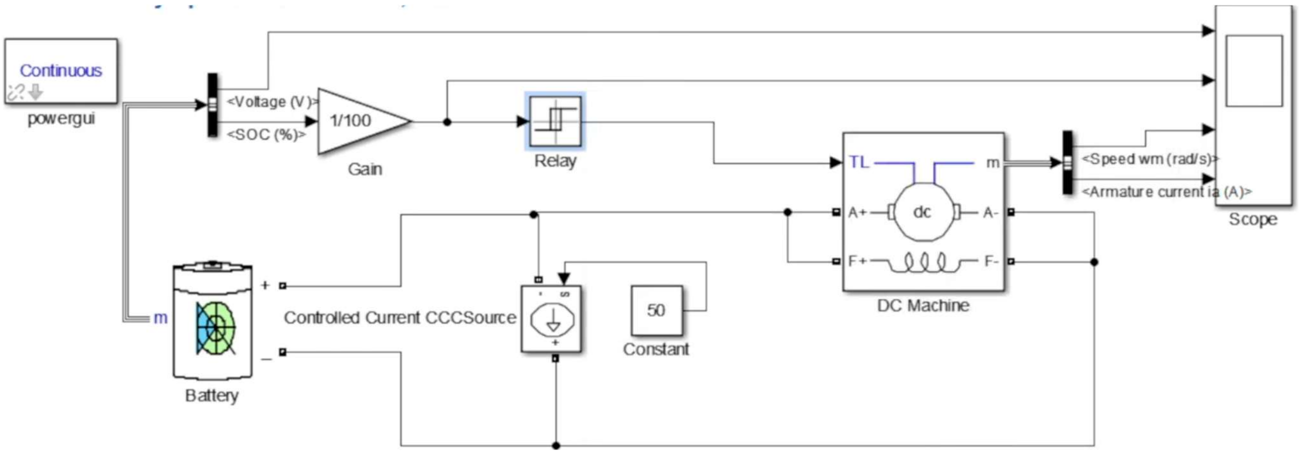


Fig. 4.2: Regenerative Braking Simulation with MATLAB/Simulink software

Procedure:

1. Open MATLAB/Simulink and create a new simulation model.
2. Add blocks representing the electric motor, battery, power converter, and braking control system.
3. Define the vehicle parameters such as mass, speed, and braking torque.
4. Apply a braking input signal to simulate vehicle deceleration.
5. Run the simulation and observe the motor operating in generator mode.
6. Record the recovered electrical energy stored in the battery.
7. Calculate the energy recovery efficiency.
8. Plot graphs of vehicle speed vs time and recovered energy vs time.

Observation Table:

Table 1: Vehicle Parameters

Parameters	Value
Vehicle Mass (kg)	
Initial Speed (m/s)	
Braking Torque (Nm)	

Table 2: Energy Recovery Data

Time (s)	Vehicle Speed (m/s)	Recovered Energy (J)	Battery Voltage (V)

Table 3: Efficiency Calculation

Total Kinetic Energy (J)	Recovered Energy (J)	Efficiency (%)

Conclusion:

The regenerative braking system was successfully simulated using MATLAB/Simulink, and the energy recovered during braking was analyzed and evaluated.

EXPERIMENT-5

Aim: To determine and analyze the efficiency characteristics of a PMSM motor under different load and speed conditions.

Apparatus:

PMSM motor test setup
Motor controller or inverter
Dynamometer or mechanical loading system
DC power supply
Torque sensor
Tachometer
Digital voltmeter and ammeter

Theory:

A Permanent Magnet Synchronous Motor (PMSM) is a type of AC synchronous motor in which the rotor contains permanent magnets that produce a constant magnetic field. The stator windings are supplied with three-phase AC power, creating a rotating magnetic field. The rotor locks with this rotating magnetic field and rotates at the same speed as the stator field, which is why it is called a synchronous motor. Because there is no rotor current and no slip, PMSM motors generally have high efficiency, high power density, and better performance compared with many other motors.

In many applications such as electric vehicles, robotics, and industrial drives, the motor does not operate at a single speed or load. Instead, it operates over a wide range of operating conditions. Therefore, it is important to study how the efficiency of the motor changes with different speeds and loads. This process is known as efficiency mapping.

During the experiment, the Permanent Magnet Synchronous Motor is operated at various speed levels and load conditions with the help of a motor controller and a loading device such as a dynamometer. At each operating point, important parameters including voltage, current, rotational speed, and torque are recorded. These measured values are then used to calculate the electrical input power, mechanical output power, and overall efficiency of the motor.

By evaluating the efficiency at different combinations of speed and load, an efficiency map of the motor can be created. This map clearly shows the operating region where the motor achieves the highest efficiency. Studying this efficiency distribution is essential for the design and optimization of electric drive systems, particularly in electric vehicles, where improving motor efficiency plays a significant role in increasing the vehicle’s energy utilization and driving range.

Procedure:

1. Connect the PMSM motor with the controller, power supply, and dynamometer according to the circuit diagram.
2. Ensure all measuring instruments are properly calibrated.
3. Start the motor at no-load condition.
4. Measure and record input voltage, input current, and motor speed.
5. Apply load gradually using the dynamometer.
6. For each load condition, record: Voltage(V), Current(A), Speed(RPM) and Torque(Nm).
7. Repeat the experiment for different speed levels.
8. Calculate input power, output power, and efficiency for each reading.
9. Plot efficiency vs load or efficiency vs speed graph.

Calculation:

1. **Input Power**

$$P_{in} = V \times I$$

2. **Output Power**

$$P_{out} = \frac{2\pi NT}{60}$$

3. **Efficiency**

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

Observation Table:

Sl. No.	Voltage(V)	Current(A)	Speed(RPM)	Torque(Nm)	Input Power(W)	Output Power(W)	Efficiency(%)

Conclusion:

The efficiency of the PMSM motor was determined under different load and speed conditions, and the efficiency characteristics were analyzed.

EXPERIMENT-6

Aim: To study the temperature distribution of an electric motor and battery during operation using thermal imaging and to identify hotspots and possible insulation failures.

Apparatus:

Electric motor (BLDC / PMSM / Induction Motor)
Battery pack (Li-ion battery)
Motor controller
Dynamometer
Infrared camera

Theory:

In electric vehicle and electric drive systems, electrical and mechanical losses produce heat in the motor and battery. The major sources of heat include copper losses in windings, iron losses in the motor core, friction losses, and internal resistance losses in the battery cells.

Excessive temperature rise can cause several problems such as:

- Reduction in motor efficiency
- Battery degradation
- Insulation failure of windings
- Safety hazards in battery packs

Thermal imaging is a non-contact temperature measurement technique that uses an infrared camera to detect heat radiation emitted from surfaces. The camera converts infrared radiation into a visual thermal image showing temperature distribution.

By analyzing thermal images during motor and battery operation, hotspots such as overheated windings, connectors, terminals, or battery cells can be identified. Early detection of such abnormal temperature regions helps prevent component failure and improves system reliability.

The experimental setup consists of a battery pack connected to an electric motor through a motor controller. The motor is coupled with a mechanical load such as a dynamometer. A thermal imaging camera is used to capture temperature distribution of the motor surface, battery pack, and electrical connections while the system operates under different load conditions.

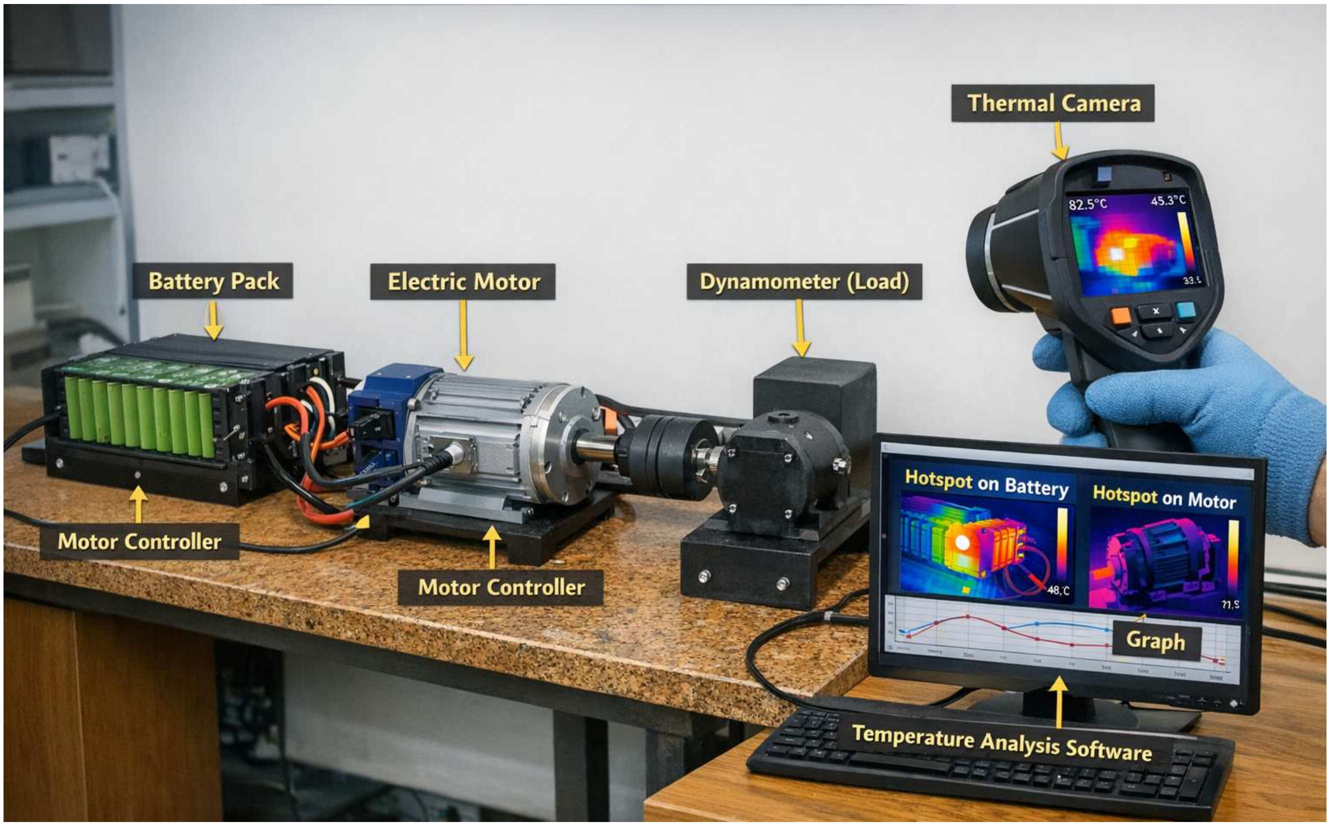


Fig. 6.1: Thermal Imaging of Battery and Motor

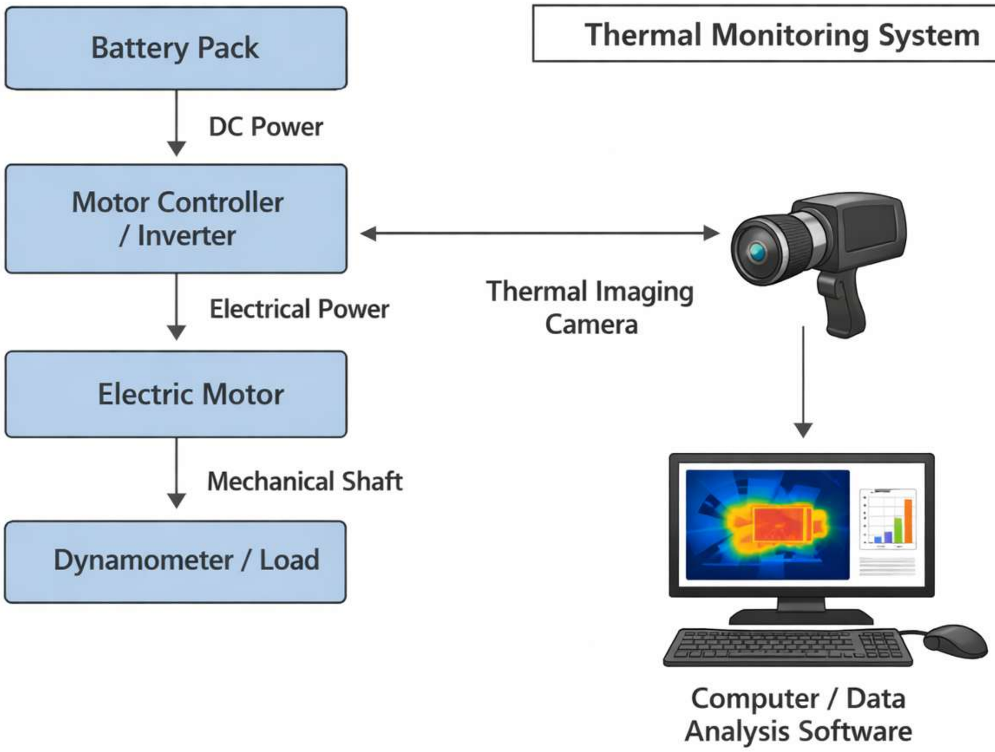


Fig. 6.2: Line Diagram of Thermal Monitoring System of Battery and Motor

Procedure:

1. Connect the battery pack to the motor controller and electric motor properly.
2. Ensure all electrical connections are tight and insulated.
3. Start the motor and allow it to run at a selected speed with no load.
4. Use the thermal imaging camera to capture thermal images of the motor casing and battery pack.
5. Gradually apply load to the motor using the dynamometer or load device.
6. Capture thermal images at different load conditions.
7. Record the temperature distribution and identify any abnormal heating areas.
8. Note the maximum and minimum temperatures observed in the motor and battery.
9. Save the thermal images for analysis.
10. Stop the system after completing the measurements.

Observation Table:

Sl. No.	Motor Speed (RPM)	Load Condition	Battery Temperature (°C)	Motor Surface Temperature (°C)	Hotspot Location

Conclusion:

Thermal imaging is an effective method for monitoring the temperature behaviour of motors and batteries. It helps detect overheating, poor electrical connections, and insulation failures, thereby improving the reliability and safety of electric drive systems.

EXPERIMENT-7

Aim: To study Controller Area Network (CAN) bus communication and perform live monitoring of signals from Battery Management System (BMS), Motor Controller, and Vehicle ECU using CAN alyzer or similar CAN monitoring tool.

Apparatus:

Electric Vehicle control system
Battery Management System (BMS)
Motor Controller
Vehicle ECU (Electronic Control Unit)
CAN interface module (USB-CAN or CAN adapter)
CAN monitoring software
CAN cables and connectors
Power supply

Theory:

CAN

The Controller Area Network (CAN) bus is a communication system widely used in automobiles to allow different Electronic Control Units (ECUs) to exchange information without the need for a central computer. It operates on a decentralized architecture, where multiple nodes can be connected or removed without affecting the overall communication, making it flexible and easy to expand.

The CAN bus is designed to function reliably even in environments with high electromagnetic interference. It uses a peer-to-peer communication method, where all ECUs have equal priority to transmit data. Message transmission is managed through an arbitration process, in which the message with the highest priority (lowest identifier) is sent first without causing data collision. Due to its strong resistance to electrical noise and disturbances, the CAN bus is highly dependable and well-suited for safety-critical applications in modern vehicles.

Battery Management System(BMS)

Battery Management System (BMS) theory focuses on converting raw electrochemical data from batteries into meaningful electronic decisions for practical use. It applies theoretical concepts of battery control to ensure reliable and efficient operation in applications such as Electric Vehicles (EVs) and Energy Storage Systems (ESS).The BMS plays a vital role in maintaining safety, improving efficiency, and extending battery life by continuously managing key parameters. It uses advanced algorithms to estimate important indicators like State of Charge (SOC), State of Health (SOH), and Remaining Useful Life (RUL).To ensure safe operation, the BMS constantly monitors battery voltage, current, and temperature. This helps prevent issues such as overvoltage, undervoltage, excessive current, and thermal runaway. Additionally, it enhances performance through techniques like cell balancing. The system also sets and enforces safe operating limits by protecting the battery from overcharging, deep discharging, overheating, and overcurrent conditions. In critical situations, the BMS can disconnect the battery from the system to avoid damage or hazards.

Motor Controller

The motor controller in a Hybrid Electric Vehicle (HEV) system plays a key role in managing the coordination between the internal combustion engine and the electric motors in a power-split configuration. It ensures smooth and efficient operation by regulating motor speed and torque according to driving conditions. The controller helps improve fuel efficiency while maintaining overall vehicle performance by intelligently distributing power between the engine and electric motor. It also integrates multiple subsystems, including the motor driver, power electronics, and battery management system, to achieve effective control and reliable operation.

Electronic Control Unit(ECU)

The Electronic Control Unit (ECU) acts as the main controller in a hybrid vehicle, responsible for managing energy flow, controlling torque, and coordinating the operation of the motor, battery pack, and conventional engine system. It plays a central role in ensuring smooth and efficient vehicle performance.

The ECU receives inputs from the driver, such as accelerator pedal position and vehicle speed, and processes these signals to make real-time decisions. Based on this information, it regulates energy usage, commands the required torque, and synchronizes the functioning of all major subsystems, ensuring proper drivability and overall system efficiency.

CANalyzer

CANalyzer is a powerful and user-friendly software tool used for analyzing and simulating network communication in the automotive sector and related fields. It provides an intuitive interface that supports both basic and advanced operations.

This tool allows users to monitor and verify the type of communication taking place within a network. It can be used to transmit, receive, and record data, as well as perform interactive diagnostics of Electronic Control Units (ECUs). CANalyzer offers essential features suitable for beginners, along with advanced capabilities for detailed analysis by experienced users.

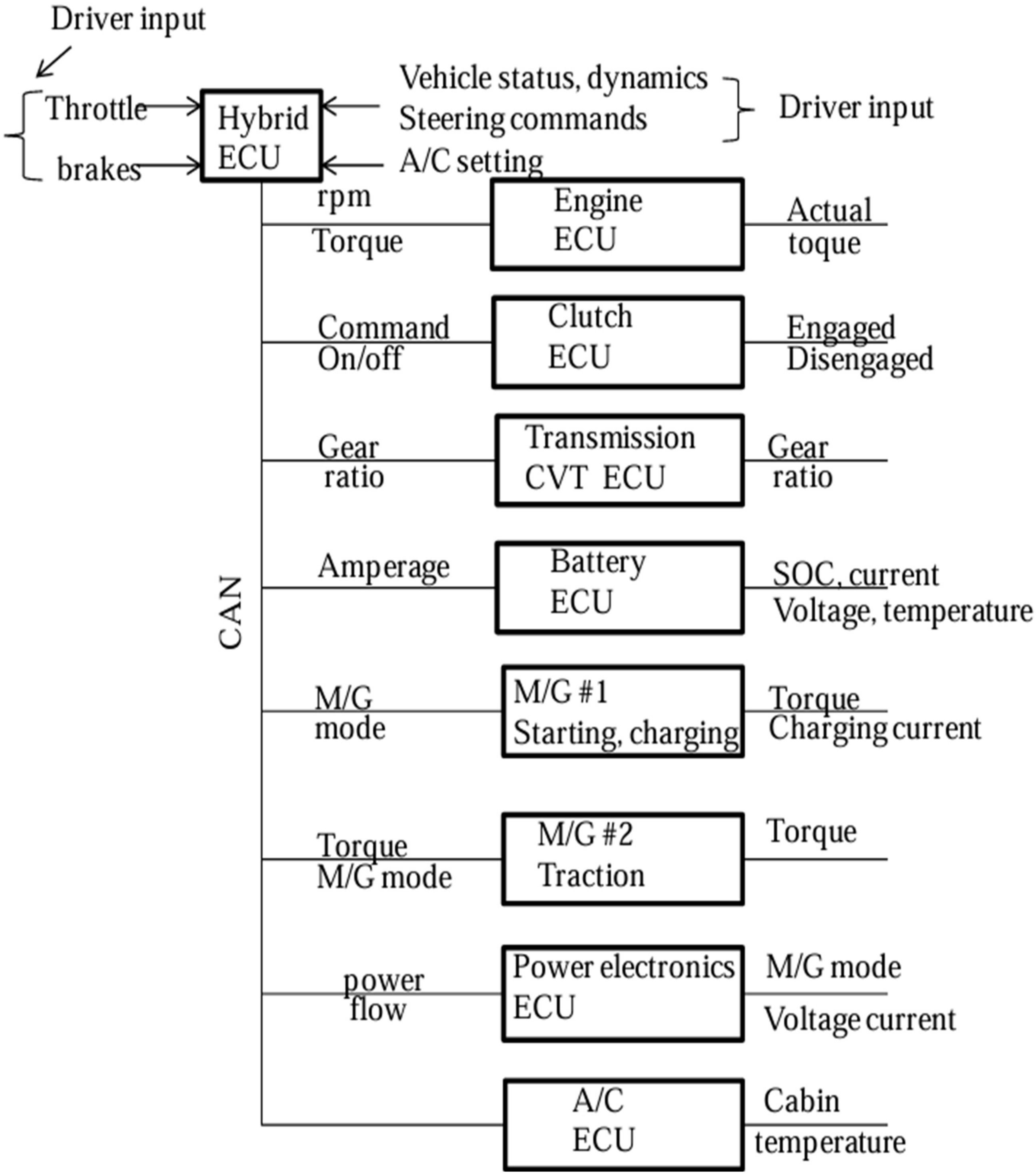


Fig. 7.1: Typical CAN For HEV

Procedure:

1. Connect the USB-CAN interface to the computer.
2. Connect BMS, Motor Controller, and ECU to the CAN bus using proper wiring (CAN_H and CAN_L).
3. Provide power supply to all devices.
4. Open CANalyzer software.
5. Configure CAN settings: Select channel ,Set baud rate (e.g., 500 kbps) ,Load DBC file
6. Start the measurement.
7. Observe CAN messages in the trace window.
8. Identify and monitor signals such as: BMS → Voltage, SOC, Temperature
   Motor Controller → Speed, Torque
   ECU → Status signals
9. Record observations in the table.
10. Stop measurement after completion.

Observation Table:

Message ID	Signal Name	Value	Source ECU

Conclusion:

CAN bus communication was successfully studied, and real-time signals from BMS, Motor Controller, and ECU were monitored using CANalyzer.

EXPERIMENT-8

Aim: To study the performance of a DC-DC converter by analyzing voltage regulation, input/output current characteristics, and ripple voltage under different load conditions.

Apparatus:

DC-DC Converter module (Buck/Boost Converter)
Variable DC Power Supply
Digital Multimeter
Oscilloscope
Resistive Load / Electronic Load

Theory:

The performance of DC–DC converters plays a vital role in achieving efficient power conversion and ensuring the stable operation of electrical systems. Important performance parameters include voltage regulation accuracy, transient response, and output ripple voltage. These factors are largely affected by the converter design, control method, and the operating load conditions. The types of DC–DC Converters are

1. Buck Converters

Buck converters are used to step down the input voltage while increasing the output current. They are commonly applied in situations where a higher supply voltage needs to be reduced to a lower level, such as in USB ports and processor power supplies.

2. Boost Converters

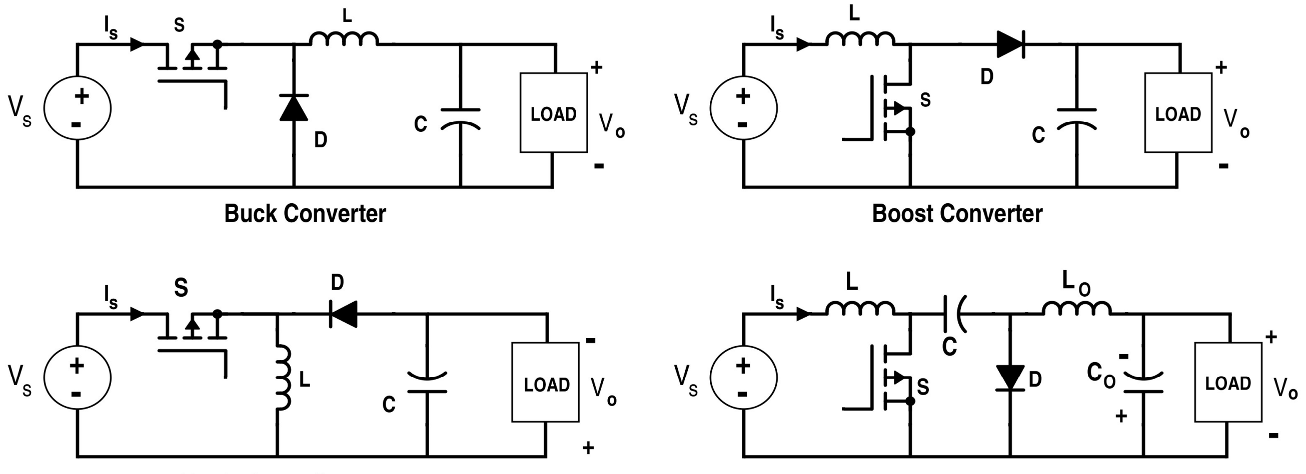
Boost converters perform the opposite function by increasing the input voltage while reducing the output current. These are suitable for applications that require a higher voltage than the available input source.

3. Buck–Boost Converters

Buck–boost converters combine the functions of both buck and boost converters. They provide the ability to either increase or decrease the voltage, offering greater flexibility in controlling both voltage and current.

4. Ćuk Converters

Ćuk converters are a specialized form of buck–boost converters capable of managing both voltage and current variations efficiently. They are widely used in power management applications due to their improved performance characteristics.



Buck Converter

Boost Converter

Buck-Boost Converter

Cuk Converter

Fig. 8.1: Line diagram of types of DC-DC converter

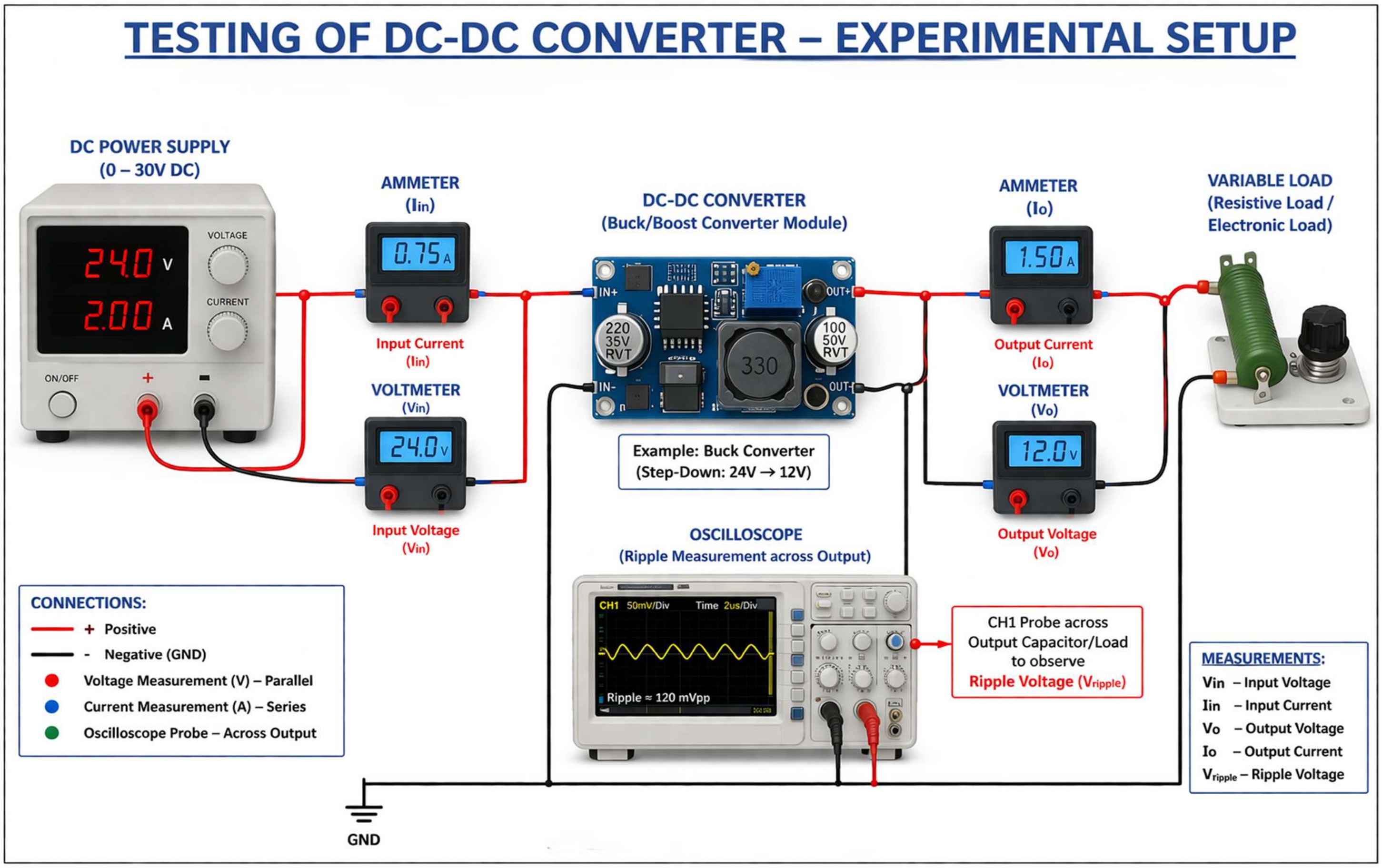


Fig.8.2: DC-DC Converter Test Setup

To effectively evaluate the performance of a DC–DC converter, the following aspects should be considered:

1. Voltage Regulation-This refers to the converter's ability to maintain a constant output voltage even when there are changes in input voltage or load current.
2. Input and Output Current Characteristics-This involves studying the relationship between input and output currents to assess the converter's efficiency and its capability to handle power.
3. Ripple Voltage-Ripple voltage indicates the fluctuations present in the output voltage over time, which can influence both the performance and lifespan of the converter.

Procedure:

1. Connect the DC power supply to the input of the DC-DC converter.
2. Connect a resistive load to the output terminals.
3. Measure the input voltage and current using a multimeter.
4. Measure the output voltage and current at different load levels.
5. Observe the output voltage waveform using an oscilloscope.
6. Measure the ripple voltage from the oscilloscope waveform.
7. Repeat the readings for different loads.
8. Calculate voltage regulation and analyze the ripple content.

Calculation:

The input power supplied to the converter is calculated as:

$$P_{in} = V_{in} \times I_{in}$$

The output power delivered to the load is:

$$P_{out} = V_o \times I_o$$

Converter Efficiency:

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

Voltage Regulation:

$$\text{Voltage Regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100$$

Ripple Voltage:

$$V_{ripple} = V_{max} - V_{min}$$

Ripple Percentage:

$$\text{Ripple \%} = \frac{V_{ripple}}{V_o} \times 100$$

Observation Table:

Load (Ω)	**Vin (V)**	**Iin (A)**	**Vo (V)**	**Io (A)**	**Ripple Voltage(mV)**	**Ripple Percentage(%)**

Conclusion:

The DC-DC converter performance was analyzed by measuring voltage regulation, current characteristics, and ripple voltage under different load conditions. The results show the converter maintains a nearly constant output voltage with acceptable ripple levels.

EXPERIMENT-9

Aim: To study the performance of a fuel cell by plotting the polarization curve, analyzing voltage–current characteristics, and measuring hydrogen consumption under different load conditions.

Apparatus:

Proton Exchange Membrane Fuel Cell (PEM Fuel Cell Stack)
Hydrogen gas cylinder / hydrogen supply system
Fuel cell test station
Electronic load / variable resistive load
Digital voltmeter
Digital ammeter
Hydrogen flow meter

Theory:

To study the voltage–current (V–I) characteristics of a fuel cell, different V–I models can be used to simulate how the fuel cell behaves under various operating conditions. These models help in understanding the internal processes occurring inside the fuel cell and assist in detecting any unusual or degraded performance. The effectiveness of these models can be assessed by comparing how accurately they simulate the fuel cell behaviour and how well they explain performance degradation over time.For analyzing hydrogen consumption, it is important to measure the amount of hydrogen used by the fuel cell when operating under different load conditions. This is typically done by gradually changing the load connected to the fuel cell and observing the corresponding hydrogen flow rate. Monitoring hydrogen usage helps in evaluating the efficiency and overall performance of the fuel cell system.

Evaluating fuel cell performance by plotting the polarization curve, studying the voltage–current characteristics, and measuring hydrogen consumption at various load levels is essential for improving the efficiency, reliability, and practical applications of fuel cells. When the load connected to the fuel cell changes, the current increases and voltage decreases, producing a polarization curve. Typical losses in fuel cells include: Activation losses, Ohmic losses, Concentration losses

Activation losses: These losses occur because of the slow rate of electrochemical reactions at the electrodes. They affect the ability of the fuel cell to initiate and sustain the flow of electric current, especially at low current densities.

Ohmic losses: These losses arise due to resistance to the flow of ions through the electrolyte and electrons through the electrodes and external circuit. The magnitude of ohmic losses increases proportionally with the current flowing through the cell.

Concentration losses: These losses occur when there is a limitation in the supply or transport of reactant gases, such as hydrogen and oxygen, from the flow channels to the catalyst layer. This mass transport limitation results in a reduction of the cell voltage at higher current levels.

Together, these losses influence the overall efficiency and operational performance of the fuel cell system.

➢ Fuel Cell Characteristics Curve

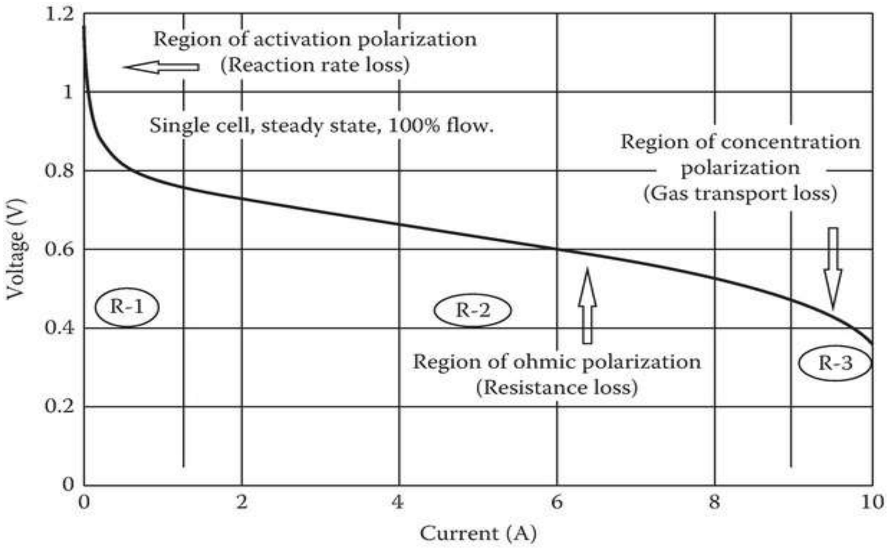


Fig.9.1: Typical fuel cell V–I characteristic curve

A typical voltage–current (V–I) characteristic of a fuel cell shows that the output voltage gradually decreases as the current drawn from the fuel cell increases. The fuel cell I–V characteristic curve is generally divided into three operating regions: R-1, R-2, and R-3. The point located between regions R-2 and R-3 is called the maximum power density point (MPP), also known as the knee point or optimum operating point. If the fuel cell is loaded beyond the current corresponding to the maximum power point, the operating point shifts into region R-3, which lies to the right of the optimum point. In this region, the fuel cell voltage decreases rapidly and may eventually drop close to zero. As a result, the fuel cell is unable to deliver useful power. Operating the fuel cell for a long time in region R-3 can also lead to damage or degradation of the cell. Therefore, fuel cells are usually operated within region R-2, where the performance is stable and efficient.

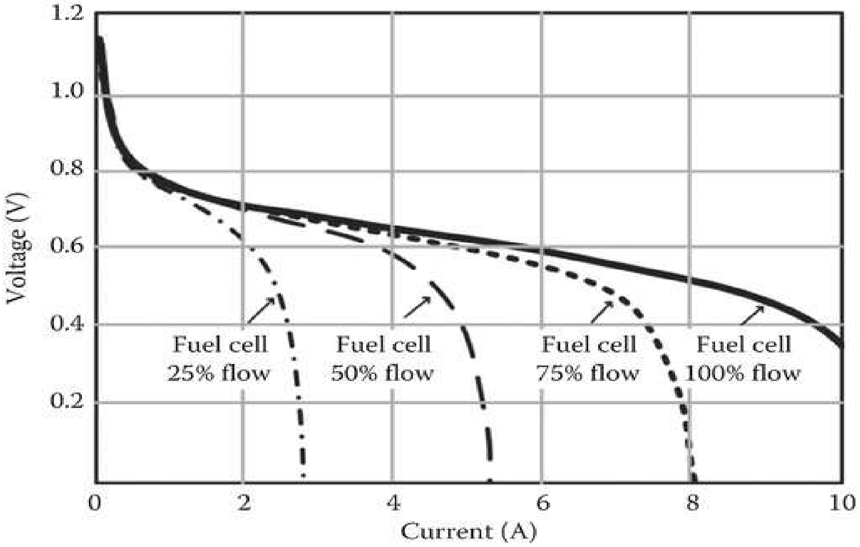


Fig.9.2: Variation of fuel cell output and MPP with fuel flow.

The flow rates of both the fuel and the oxidant are carefully regulated so that the stoichiometric ratio stays within the required design limits. Maintaining this ratio helps achieve a proper balance between reactant supply, heat generation, water management, and pressure drop within the fuel cell system.

Fuel cells generally respond slowly to rapid changes in electrical load because the electrochemical reactions and mechanical processes inside the cell take time to adjust. Due to these slower internal dynamics, fuel cells cannot immediately supply power during sudden load variations. Rapid load changes may create conditions where the amount of reactants inside the fuel cell becomes insufficient. This low-reactant condition can negatively affect the performance of the fuel cell and may reduce its operational lifespan. Because the response time of a fuel cell is slower compared to the electrical load demand, an energy storage device is often used along with the fuel cell. A secondary energy source, such as a battery or an ultracapacitor, helps support the system during transient conditions. It performs three important functions:

1. It compensates for the slow dynamic response of the fuel cell.
2. It quickly responds to sudden changes in electrical load.
3. It supplies power to the load until the fuel cell output stabilizes and reaches the new steady-state operating condition.

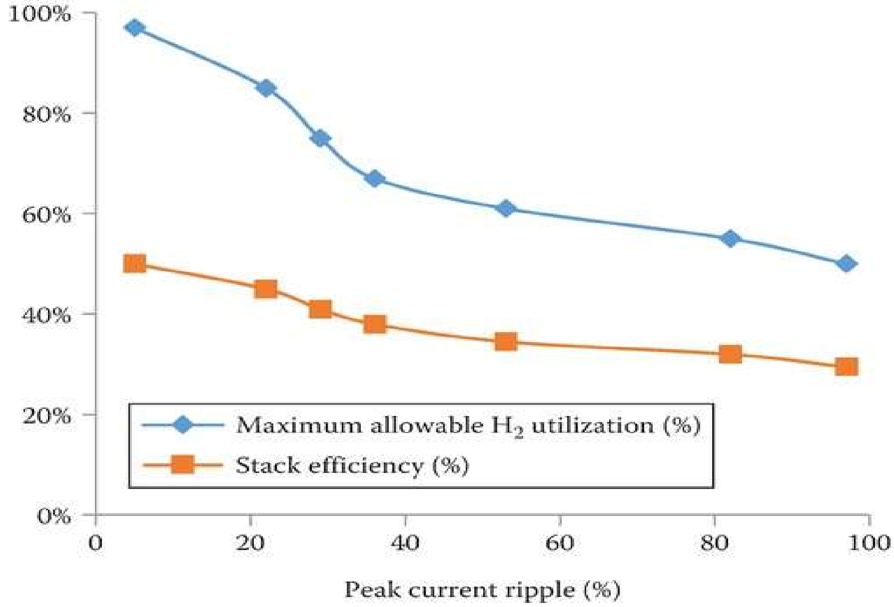


Fig.9.3: Effect of current ripple on fuel utilization in fuel cells.

Fuel cells are highly sensitive to low-frequency ripple currents. When a fuel cell–based power plant supplies alternating current to a utility grid or an AC load, a second harmonic component of the line current may appear in the fuel cell stack. This can disturb the normal operation of the fuel cell system and may even cause the power unit to shut down. Therefore, it is necessary to minimize or absorb this low-frequency ripple current.

Due to the presence of ripple current, the fuel supply often needs to be regulated according to the peak current value rather than the average current. As a result, more fuel may be supplied than actually required. This leads to fuel wastage, increased energy cost, and reduced efficiency and fuel utilization of the fuel cell system.

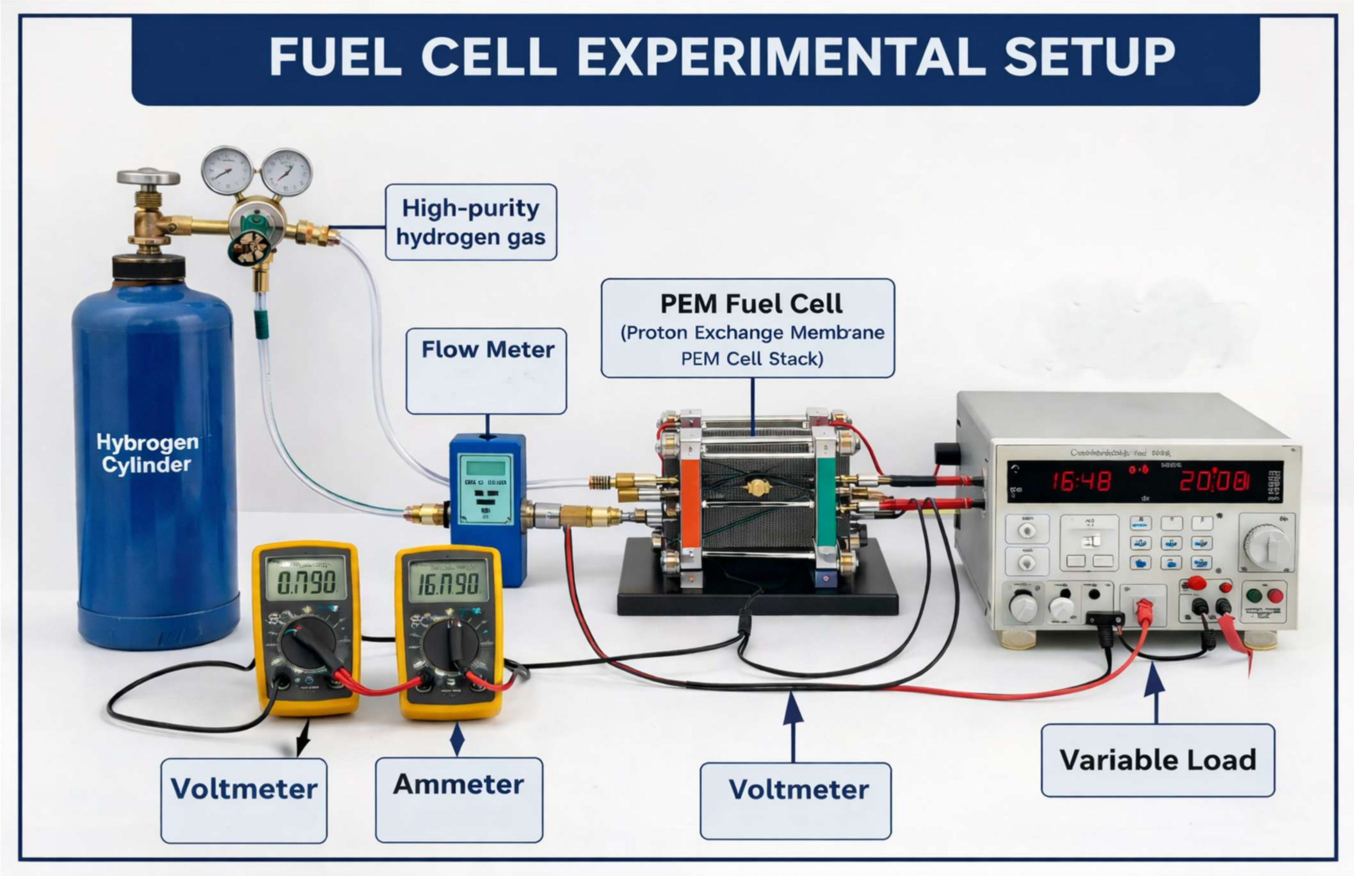


Fig.9.4: Fuel Cell Experimental Setup

Procedure:

1. Connect the fuel cell stack to the test station.
2. Supply hydrogen gas to the anode side of the fuel cell.
3. Supply air/oxygen to the cathode side.
4. Switch on the fuel cell system and allow it to stabilize.
5. Connect the variable load to the fuel cell output.
6. Gradually increase the load current.
7. Measure and record the voltage and current for each load condition.
8. Note the hydrogen consumption using the flow meter.
9. Plot Voltage vs Current (Polarization Curve).
10. Analyze the performance characteristics.

Observation Table:

Load Condition	Voltage	Current (A)	Current Density (A/cm²)	Hydrogen Flow Rate (Ltr/min)

Conclusion:

The voltage–current characteristics and polarization curve of the fuel cell were obtained, and the relationship between load current, voltage drop, and hydrogen consumption was analyzed.

EXPERIMENT-10

Aim: To simulate standard vehicle drive cycles on a chassis dynamometer(WLTP/IDC/FTP-75) and evaluate the power consumption, energy usage, and driving range of an electric vehicle (EV).

Apparatus:

Electric vehicle or EV powertrain test setup
Chassis dynamometer
Computer with drive cycle simulation software
Data acquisition system
Battery management system (BMS) interface
Speed and torque sensors
Power analyze

Theory:

Drive cycle simulations carried out on chassis dynamometers are important for assessing vehicle performance, particularly in terms of fuel efficiency and emission levels. Standardized driving cycles such as the Worldwide Harmonized Light Vehicle Test Procedure (WLTP), the Indian Driving Cycle (IDC), and the Federal Test Procedure (FTP-75) are commonly used for this purpose.

1. WLTP Drive Cycle

The Worldwide Harmonised Light Vehicles Test Procedure (WLTP) is an internationally accepted standard used to evaluate fuel consumption, carbon dioxide emissions, and pollutant outputs of conventional, hybrid, and electric vehicles. It was introduced to replace the older New European Driving Cycle (NEDC), which no longer accurately represented modern driving conditions. Developed using real-world driving data collected from various regions, WLTP aims to better reflect everyday driving behaviour. The WLTP drive cycle, also known as the Worldwide Harmonized Light-duty Vehicles Test Cycle (WLTC), is structured to simulate a wide range of driving environments, including urban, suburban, rural, and highway conditions.

The cycle lasts approximately 30 minutes, which is longer than the 20-minute NEDC, and covers a distance of 23.25 km, more than double that of its predecessor. It has an average speed of 46.5 km/h and a maximum speed of 131.3 km/h. The cycle is divided into four distinct phases like Low, Medium, High, and Extra-High, each representing different driving scenarios. The Low phase corresponds to city driving with frequent stops and low speeds, the Medium phase reflects suburban conditions, the High phase represents rural roads, and the Extra-High phase simulates highway driving. Compared to NEDC, WLTP incorporates more dynamic driving behaviour, including faster acceleration, shorter braking periods, and more realistic stopping patterns.

During testing, each vehicle is evaluated in both its lightest and heaviest configurations, taking into account optional equipment, cargo, and passengers. WLTP applies to all new passenger cars and light commercial vehicles, which are categorized based on their power-to-weight ratio to determine the appropriate test cycle class. For electric vehicles, WLTP is used to estimate driving range by measuring energy consumption across all four phases, while city range is calculated using only the Low and Medium phases.

Overall, WLTP offers several advantages over the NEDC, including more realistic estimates of fuel consumption and CO_2 emissions, improved representation of real-world driving conditions, and model-specific data available at the point of sale. It also promotes global standardization, enabling better comparison of vehicle performance across different markets. Although WLTP provides more accurate laboratory results, actual on-road performance may still vary depending on factors such as driving habits, traffic conditions, and weather.

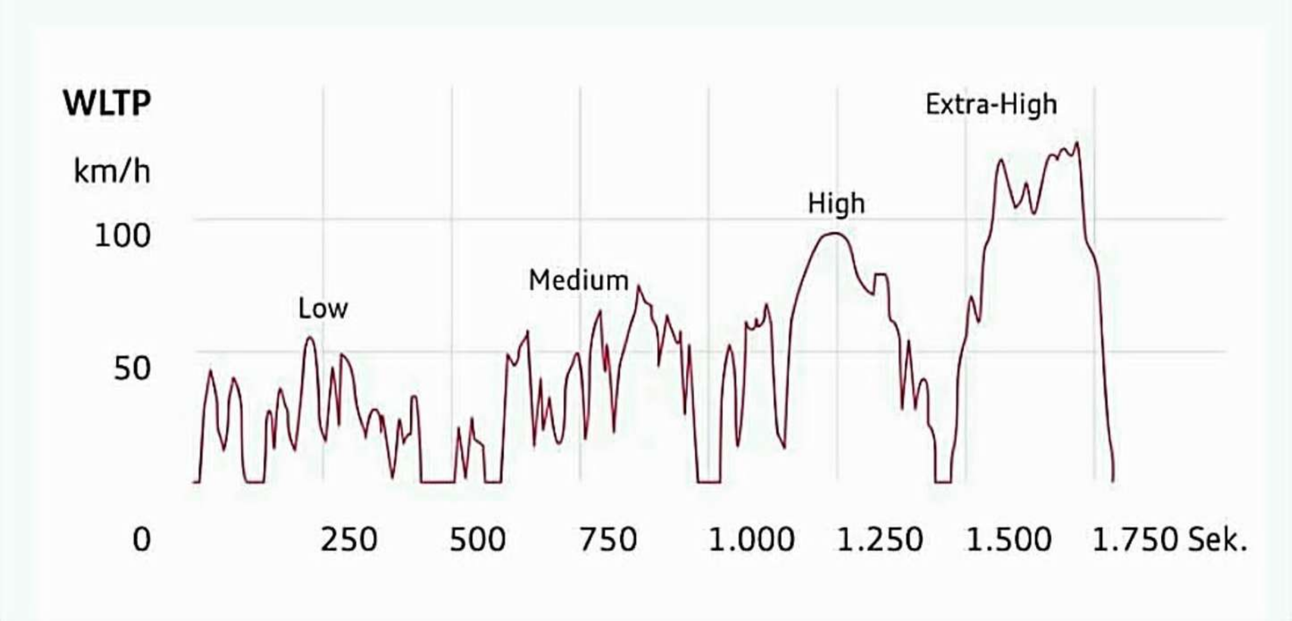


Fig.10.1: Speed - Time Profile in WLTP

2. IDC Drive Cycle

The Indian Driving Cycle (IDC) is a standardized test cycle used in India to evaluate vehicle emissions and performance. It was the first driving cycle introduced in the country for vehicle certification, mainly focusing on emissions and safety assessment. The IDC has a total duration of 108 seconds and covers a distance of approximately 3.94 km, with an average speed of about 21.9 km/h. It consists of six different driving modes and is characterized by gentle acceleration levels, typically below 0.65 m/s^2, along with relatively low engine loads. While it is designed to represent urban driving conditions, it does not fully capture the complexity of real Indian roads, such as heavy traffic congestion or rural highway scenarios.

The cycle includes various vehicle operating states such as acceleration, deceleration, constant speed, and idling. Additionally, a preconditioning idling period of 40 seconds is allowed before testing begins, except in the case of diesel vehicles. IDC is widely applied to assess parameters such as traction force, energy consumption, and emission levels for different types of vehicles, including two-wheelers, three-wheelers, and electric vehicles. It serves as a baseline for comparing vehicle performance under controlled laboratory conditions, and has been used in studies to evaluate factors like traction torque, power requirements, and energy efficiency, which can vary depending on vehicle characteristics such as mass and aerodynamic profile.

Despite its usefulness, the IDC has certain limitations as it does not accurately reflect real-world driving conditions in India. To overcome these shortcomings, the Modified Indian Driving Cycle

(MIDC) was developed. MIDC introduces improvements such as a higher speed range of up to 90 km/h, more realistic patterns of acceleration and idling, and closer alignment with international standards like the New European Driving Cycle (NEDC). However, even with these enhancements, MIDC may still fall short in representing the full variability of real-world driving, including differences in traffic density, road conditions, and high-power acceleration requirements.

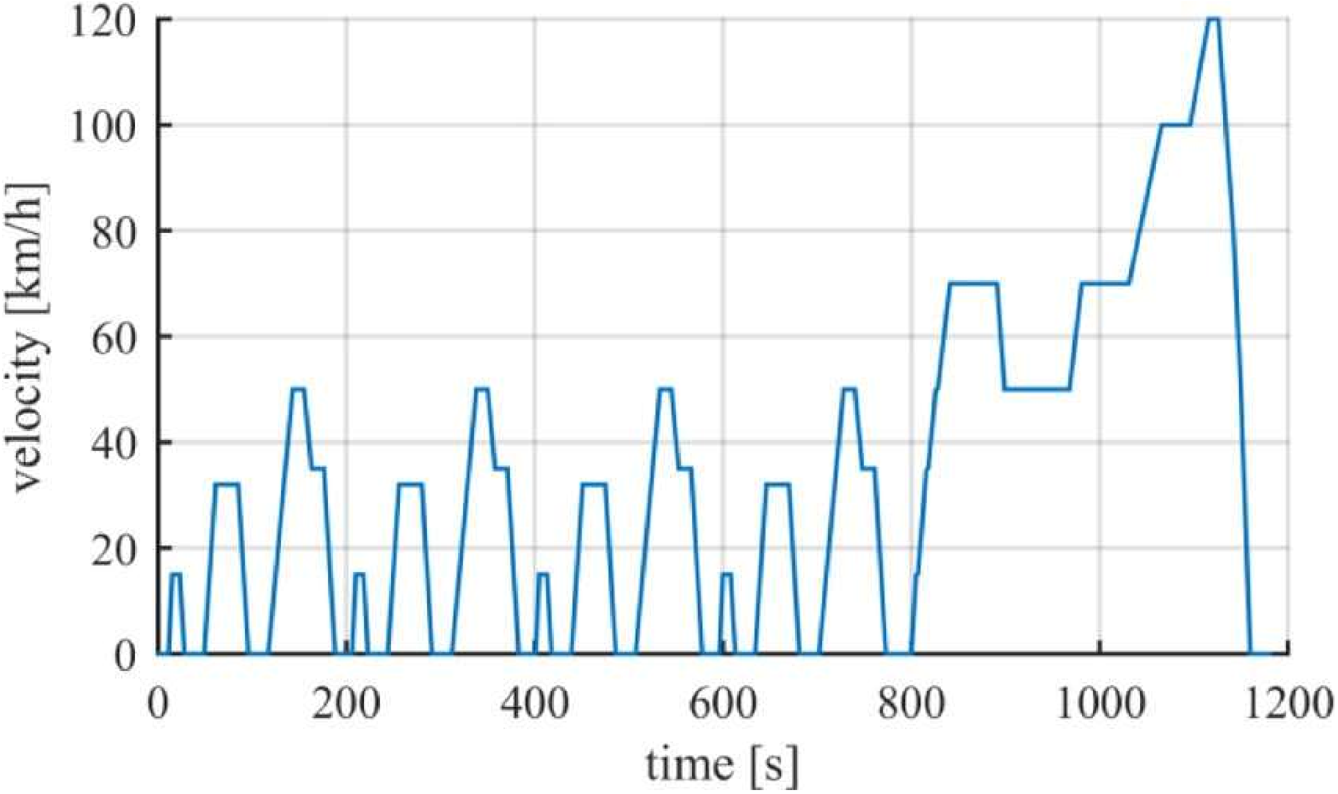


Fig.10.2: Velocity - Time Profile in IDC

3. FTP-75 Drive Cycle

The FTP-75 (Federal Test Procedure 1975) is a standardized driving cycle developed by the United States Environmental Protection Agency (EPA) to simulate urban driving conditions for evaluating vehicle emissions and fuel economy. It is primarily used for light-duty passenger cars and trucks and is based on the earlier Urban Dynamometer Driving Schedule (UDDS), also known as the LA4 or city test, which was introduced in 1972. The FTP-75 cycle was later refined in 1975 by repeating the initial portion of the UDDS and applying weighting factors to better represent typical city driving behaviour.

The FTP-75 cycle is divided into three main phases. The first phase, known as the cold start phase, begins with the engine at ambient temperature and lasts for 505 seconds, capturing emissions during the critical engine warm-up period. The second phase is the stabilized driving phase, which continues under the UDDS pattern for 867 seconds and reflects normal stop-and-go city traffic conditions. The third phase, called the hot start phase, occurs after a 10-minute engine-off period (hot soak), during which the first 505 seconds of the UDDS are repeated to simulate a warm engine restart. In total, the FTP-75 cycle runs for approximately 1,874 seconds (around 31 minutes), covering a distance of 11.04 miles (17.77 km) at an average speed of about 21.2 mph (34.1 km/h). Emissions from each phase are measured and combined using weighting factors, with greater emphasis placed on the hot start phase.

The FTP-75 is widely used to measure tailpipe emissions of pollutants such as hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx). It also plays a crucial role in determining fuel economy ratings for vehicles, forming the basis for the "city" miles-per-gallon (MPG) values published by the EPA. Additionally, it supports regulatory compliance under frameworks such as the Clean Air Act and Corporate Average Fuel Economy (CAFE) standards. Beyond conventional vehicles, the FTP-75 is also applied in electric vehicle testing to estimate energy consumption and driving range under simulated urban conditions.

Despite its importance, the FTP-75 has certain limitations. It does not fully account for aggressive driving behavior, high-speed conditions, or additional loads such as air conditioning usage. As a result, laboratory results based on this cycle have historically overestimated real-world fuel economy by approximately 20–30%. To address these shortcomings, supplemental test cycles such as the US06 (for high-speed and aggressive driving) and SC03 (for air conditioning effects) are used alongside FTP-75.

The FTP-75 remains a fundamental tool for assessing vehicle emissions and fuel efficiency under city driving conditions. Its structured phases, inclusion of both cold and hot start conditions, and standardized methodology make it essential for regulatory testing and performance evaluation of both conventional and electric vehicles.

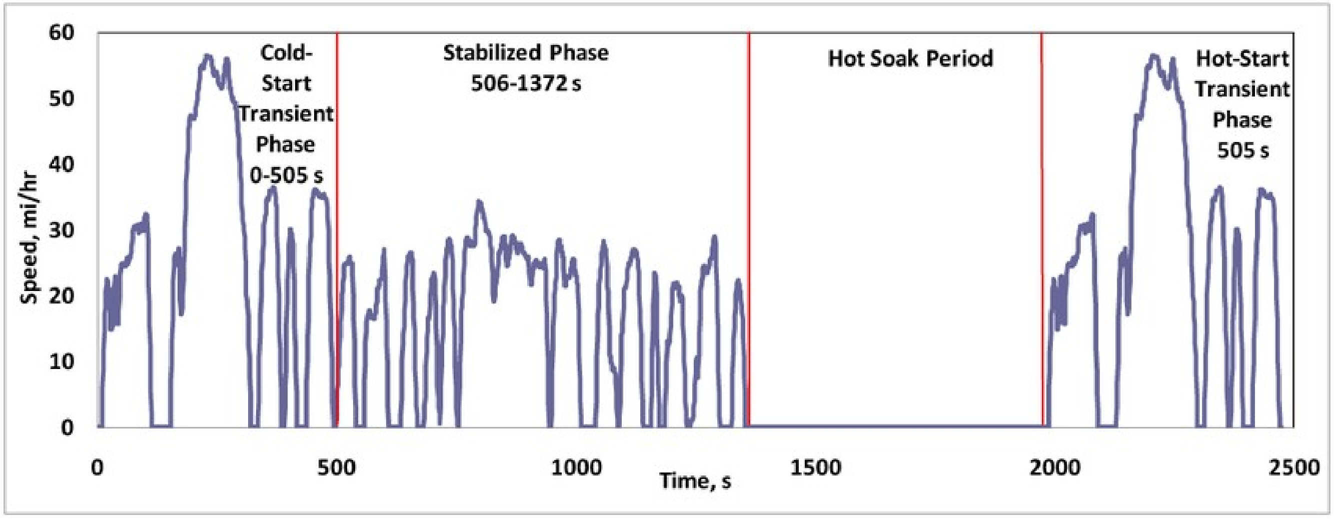


Fig.10.3: Speed-Time Profile in FTP-75

These driving cycles are specifically developed to replicate different real-world driving conditions in a controlled environment. By using these standardized methods, it becomes possible to consistently evaluate and compare the performance of various vehicles with accuracy and reliability.

In this experiment, the vehicle is placed on a chassis dynamometer, which simulates road load by applying controlled resistance to the wheels. The vehicle follows a predefined speed vs time drive cycle programmed into the dynamometer control system.

Procedure:

1. Place the electric vehicle on the chassis dynamometer rollers and secure it properly.
2. Connect the data acquisition system to measure voltage, current, and speed.
3. Select a drive cycle such as WLTP / IDC / FTP-75 in the dynamometer software.
4. Start the simulation and allow the vehicle to follow the speed-time profile automatically.
5. Record the following data during the test: Battery voltage
   Battery current
   Vehicle speed
6. Power consumption
7. Repeat the test for different drive cycles if required.
8. Calculate total energy consumption and estimate the driving range

Calculation:

1. **Power Consumption**

$$P = V \times I$$

2. **Total Energy Consumed**

$$E = \int P\,dt$$

3. **Energy Consumption per km**

$$Energy/km = \frac{Total\ Energy}{Distance}$$

4. **Range Estimation**

$$Range = \frac{Battery\ Capacity}{Energy/km}$$

Observation Table:

Time(sec)	Speed(km/hr)	Voltage(V)	Current(A)	Power(P)

Conclusion:

The vehicle power consumption and energy usage were analyzed under selected drive cycles. The estimated driving range was calculated based on the measured energy consumption.

EXPERIMENT - 11

Aim: To test a solar panel-based charging system, measure the energy yield and peak power output of the solar array, and demonstrate integration with a Hybrid Electric Vehicle (HEV) battery through proper power electronics.

Apparatus Required:

Solar PV panel(s)

Solar charge controller (MPPT)

DC-DC boost/buck converter

HEV Battery / Battery bank

Load (resistive/HEV motor simulator)

Multimeter

Data logger

Connecting cables

Theory:

Solar Panels

A solar photovoltaic (PV) panel is composed of multiple solar cells connected in series or parallel to produce a usable DC voltage. When sunlight falls on these cells, the photons in the solar radiation excite electrons in the semiconductor material, generating electrical current. The performance of a PV panel is characterized by key parameters. The open-circuit voltage (Voc) represents the voltage across the terminals when no external load is connected, while the short-circuit current (Isc) is the current flowing when the output is shorted. The maximum power point (Pmpp**)** refers to the combination of voltage and current at which the panel delivers its maximum power output, calculated as $P = V \times I$. This maximum power point is critical for energy harvesting because the electrical output of the panel depends on environmental factors such as solar irradiance and temperature. Operating a solar panel close to its P_MPP ensures optimal conversion efficiency and maximizes the energy yield over time.

Charge Controller (MPPT)

To extract the maximum possible energy from a solar panel, a Maximum Power Point Tracking (MPPT) charge controller is employed between the PV array and the battery. The MPPT controller continuously monitors the voltage and current output of the solar panel and adjusts the electrical operating point to maintain the panel at its maximum power point, regardless of changes in sunlight intensity or temperature. This dynamic adjustment is essential because the raw PV output fluctuates with environmental conditions, and directly connecting the panel to a battery could result in suboptimal charging or energy loss. The MPPT controller ensures that the energy delivered to the battery is maximized, improving overall system efficiency and reducing charging time.

DC-DC Converter and Battery Integration

Solar panels produce DC power whose voltage varies depending on solar irradiance and temperature. However, a Hybrid Electric Vehicle (HEV) battery requires a fixed voltage for safe and efficient charging. To bridge this gap, a DC-DC converter either a boost or buck converter is used to regulate the panel output to match the battery's voltage and current requirements. This allows the battery to be charged safely without over-voltage or over-current conditions. In addition, the battery is protected by a Battery Management System (BMS), which prevents overcharging, deep discharge, and thermal issues. By integrating the PV panel, MPPT controller, DC-DC converter, and BMS, solar energy can be efficiently harvested and stored in the HEV battery, ensuring reliable performance and longevity of the battery system.

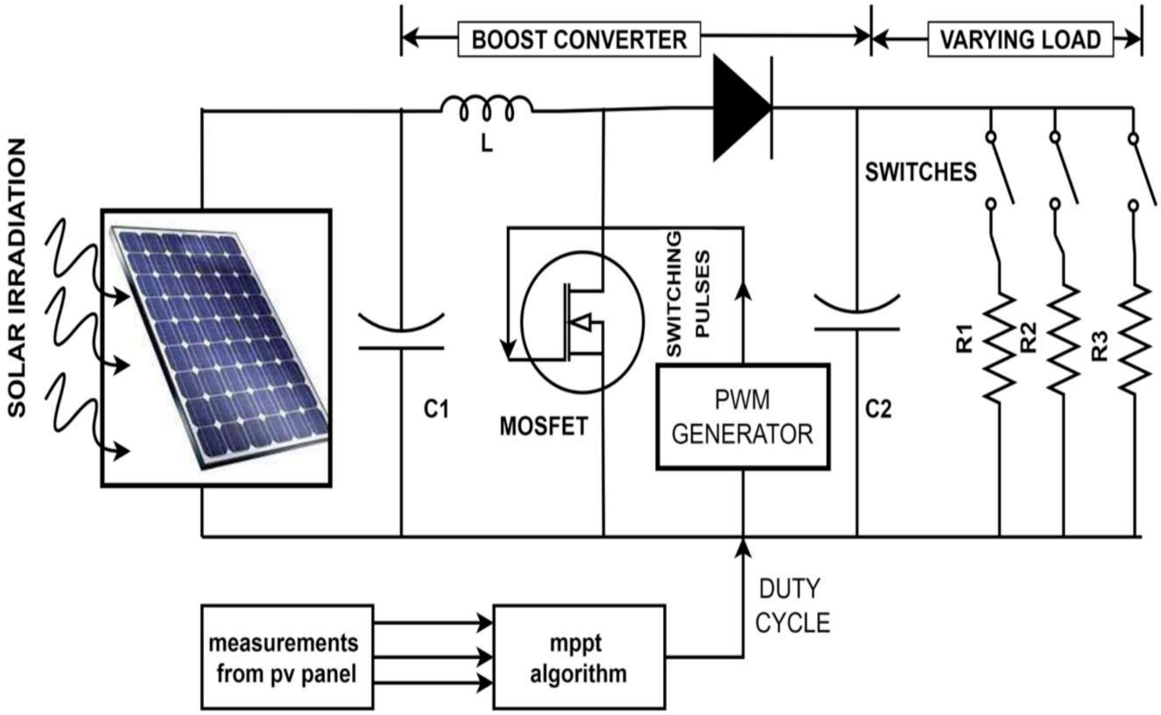


Fig.11.1: Circuit Diagram of Solar panel based charging system

Procedure:

1. Connect the solar panel to the charge controller.
2. Connect the charge controller to the HEV battery.
3. Attach measuring instruments (voltmeter, ammeter, wattmeter) appropriately.
4. Place the solar panel under sunlight or a solar simulator.
5. Measure and record: Output voltage (V), Output current (I), Solar irradiance
6. Calculate instantaneous power using: $P=V\times I$
7. Repeat readings at different times of the day to observe variation.
8. Determine peak power output from recorded values.
9. Calculate total energy yield: $E=\sum(P\times\Delta t)$
10. Observe battery charging behavior and note charging time and efficiency.

Observations Table:

Time (sec)	Voltage (V)	Current (A)	Power (W)	Battery Voltage (V)	Battery Current (A)	Energy Logged (Wh)

Conclusion:

In this experiment, we successfully examined a solar panel-based charging setup and measured its energy yield and peak power output. The MPPT charge controller optimized power extraction, while the DC-DC converter regulated output for safe battery charging. The HEV battery was charged effectively using solar energy, demonstrating renewable energy integration with electric vehicles. Overall, this lab helped us understand PV power generation, power electronics for energy conversion, and practical challenges in real-time energy harvesting and storage.

EXPERIMENT - 12

Aim: To perform real-time fault detection in a vehicle using an OBD-II diagnostic tool, read and analyze Diagnostic Trouble Codes (DTCs), and interpret freeze frame data through a PC interface for effective fault diagnosis and performance monitoring.

Apparatus required:

OBD-II compliant vehicle / engine test rig

OBD-II scan tool (ELM327 / Bosch scanner)

Laptop/PC with diagnostic software

USB/Bluetooth interface module

Connecting cables

Power supply

Theory:

On-Board Diagnostics (OBD-II)

OBD-II is a standardized system used in vehicles to monitor engine performance and emissions. It stores faults as Diagnostic Trouble Codes (DTCs) and provides real-time data through sensors.

On-Board Diagnostics II (OBD-II) is a standardized automotive diagnostic system used in modern vehicles to monitor engine performance, emission systems, and other critical components. It was introduced to reduce harmful emissions, improve fuel efficiency, and provide a universal system for fault detection across different vehicle manufacturers. The OBD-II system continuously collects data from various sensors and sends it to the Electronic Control Unit (ECU) for analysis.

The working of the OBD-II system is based on continuous monitoring and comparison of sensor data with predefined values. Sensors such as oxygen sensors, mass air flow sensors, throttle position sensors, and coolant temperature sensors measure engine parameters and send signals to the ECU. The ECU processes this data and compares it with stored reference values. If any parameter deviates beyond acceptable limits, the ECU detects a fault, stores a Diagnostic Trouble Code (DTC), captures freeze frame data, and activates the Malfunction Indicator Lamp (MIL) to alert the driver.

Freeze frame data is a snapshot of engine operating conditions at the moment a fault occurs. It includes parameters such as engine speed, vehicle speed, coolant temperature, engine load, and fuel trim values. This data is extremely useful for diagnosing faults because it shows the exact conditions under which the problem occurred. It helps technicians understand the root cause and reduces guesswork.

OBD-II includes both continuous and non-continuous monitoring systems. Continuous monitoring systems, such as misfire detection and fuel system monitoring, operate at all times while the engine is running. Non-continuous monitoring systems, such as catalytic converter efficiency and evaporative emission control, operate only under specific conditions. Additionally, readiness monitors indicate whether a particular test has been completed, which is important for emission testing.

Diagnostic trouble codes (DTCs):

Diagnostic Trouble Codes (DTCs) are standardized error codes stored in the Electronic Control Unit (ECU) of a vehicle whenever a fault or abnormal condition is detected in any of its systems. These codes form a core part of the On-Board Diagnostics (OBD-II) system and help in identifying issues related to the engine, transmission, emission control, and other subsystems. When a fault occurs, the ECU continuously monitors sensor data, and if the values exceed predefined limits, it records a DTC and may also activate the Malfunction Indicator Lamp (MIL) to alert the driver. Thus, DTCs act as a bridge between the vehicle and the technician for effective fault diagnosis.

Diagnostic Trouble Codes follow a standardized five-character alphanumeric format, typically written as P0XXX. Each character in the code has a specific meaning that helps in identifying the nature and location of the fault. The first character is a letter that indicates the system in which the fault has occurred. For example, “P” stands for Powertrain, “B” stands for Body, “C” represents Chassis, and “U” indicates Network or communication-related faults. The second character is a numeric digit that defines whether the code is generic (0) or manufacturer-specific (1). The remaining three digits provide detailed information about the specific fault within that system. This structured format ensures uniformity and makes it easier for technicians to interpret faults across different vehicles.

DTCs are broadly classified based on the system in which the fault occurs. Powertrain codes (P-codes) relate to engine and transmission issues, including fuel system, ignition, and emission control. Body codes (B-codes) are associated with components such as airbags, seat belts, and climate control systems. Chassis codes (C-codes) deal with systems like braking, steering, and suspension. Network codes (U-codes) refer to communication errors between different control modules within the vehicle. This classification helps in narrowing down the fault area quickly during diagnosis.

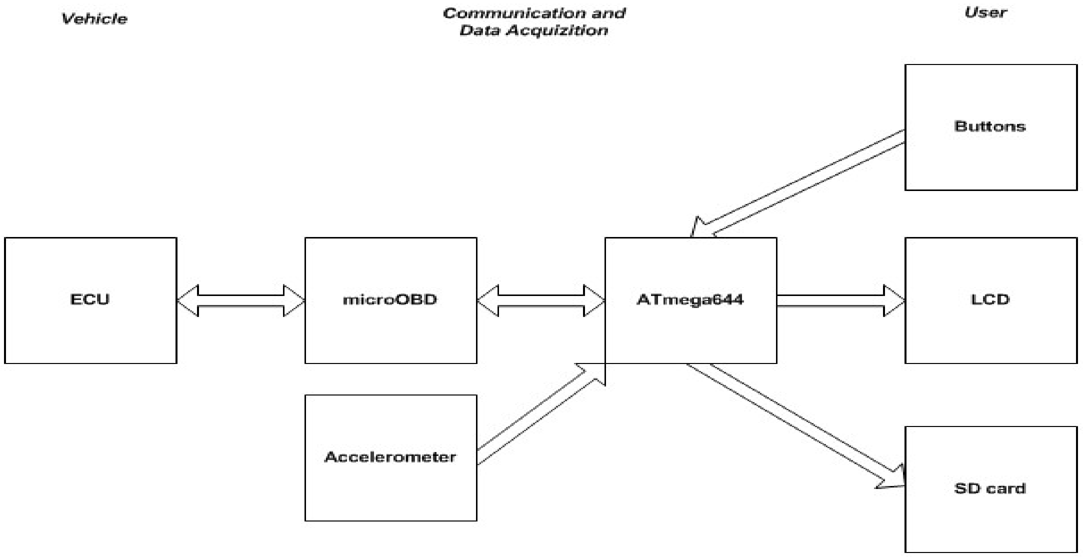


Fig.12.1: Block Diagram of OBD-II

Procedure:

1. Locate the OBD-II port in the vehicle (usually under the dashboard).
2. Connect the OBD-II scanner or interface to the port.
3. Connect the scanner to the PC via USB or Bluetooth.
4. Launch the diagnostic software on the PC.
5. Turn the vehicle ignition to ON (engine may be OFF or running as required).
6. Establish communication between the software and the vehicle ECU.
7. Select the option to read Diagnostic Trouble Codes (DTCs).
8. Record the displayed DTCs.
9. Access freeze frame data corresponding to each DTC.
10. Note key parameters such as: Engine RPM, Vehicle speed, Engine load, Coolant temperature
11. Clear the DTCs (if required) and observe system response.
12. Enable real-time data logging and monitor live parameters.
13. Save the logged data for further analysis.

Observations Table:

Sl. No.	DTC Code	Description of Fault	Status (Stored / Pending / Permanent)	Freeze Frame Data	Real-Time Parameter Observed

Conclusion:

In this experiment, we used an OBD-II scanner and a PC to check for vehicle faults. We were able to read error codes (DTCs), see the freeze frame data showing engine conditions at the time of the fault, and monitor live parameters like RPM, speed, and temperature. This helped us understand how faults occur and how to diagnose them quickly. The experiment showed that OBD-II makes vehicle troubleshooting easier and more accurate.