MODELLING AND PERFORMANCE ANALYSIS OF HYBRID ELECTRIC VEHICLES: A COMPREHENSIVE STUDY

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ABSTRACT: Internal Combustion Engine (ICE) vehicles will be phased out in favor of Electric Vehicles (EV), which have emerged as an essential component of the automotive industry. Electric vehicles (EVs) are gaining popularity due to technological advancements in a variety of fields. Electric vehicles (EVs) can benefit both the energy and environmental industries. Electric vehicles (EVs) contribute significantly to reducing greenhouse gas emissions from the transportation sector. This essay examines the current situation in India, the ongoing research and improvements in electric car technology, and why electric cars are so vital. This study provides a complete image of the Hybrid Electric Vehicle (HEV) and investigates how well it performs in various stages of operation. This work can be utilized as a starting point for further investigation.

Keywords.: Electric Vehicle (EV), Fuel Cell Electric Vehicle (FCEV), Hybrid Electric Vehicle (HEV)

1. INTRODUCTION

According to the Environmental and Energy Study Institute, it is the third largest source of carbon dioxide emissions. There is a significant increase in the use of gas, oil, and coal. At the United Nations Framework Convention on Climate Change meeting in Madrid, all 190 countries approved the concept of electric transportation as a strategy to reduce fossil fuel emissions. To decrease global warming, the 2015 Paris Agreement requires that carbon dioxide (CO_2) emissions be reduced by half by 2033 and totally eliminated by 2050.

If the global average temperature increases above 2 degrees Celsius, this technique will effectively slow it down. In 2018, air pollution was responsible for 12.5% of all deaths in India. According to a recent study, India is responsible for 25% of global air pollution-related premature deaths and illnesses.

According to the data, pollution contributed to 1.34 million fatalities in 2018. Out of these, 760,000 deaths were associated to particulate pollution from the outside, whereas 370,000 deaths were linked to inside pollution . As a result,

the globe must transition to an environmentally sustainable future by replacing gas-powered vehicles with electric ones. Because stand-alone devices have limitations, it is evident that electric vehicles (EVs) have significant potential in the power industry. This is especially true when they use renewable energy sources such as solar panels and energy storage technology such as lithium-ion batteries.

When Maximum Power Point Tracking (MPPT) technology is applied, solar panels perform better. Coordinated charging, often known as "smart charging," makes it easier to recharge the batteries of electric vehicles that are running short on power. Furthermore, it reduces harmonic content, benefits the system by contributing reactive power, and returns any excess battery power to the grid. The first section of this paper provides a brief overview of why electric vehicles (EVs) are significant and how they may be employed in the future.

The next sections outline India's EV plan and how Kerala is working to encourage electric vehicles. Modeling and analyzing hybrid electric vehicles (HEVs), as well as evaluating the performance of

various operating modes, will aid in the development of prototype designs for electric vehicles. This will be accomplished by replicating real-world driving modes such as acceleration, cruising, and deceleration. Performance analysis is an important step in enhancing the controller's architecture and the components that make it up during the hardware implementation phase. This is particularly significant given the inherent complexity of electric cars. The original system's success can be tested and improved by following the simulation model and outcome analysis.

2. ELECTRIC VEHICLE SCENARIO IN INDIA

As more battery electric automobiles were marketed, India saved ₹3.8 crore in gasoline prices and reduced pollution levels that same year. According to the FAME project, India has approximately 270,000 electric vehicles (EVs), which include electric buses and bicycles. It was able to reduce the price of crude oil by a significant amount, around 120 crore. According to the FAME plan, all vehicles will be electric by 2030.

In 2017, NITI Ayog and the Rocky Mountain Institute of America started investigating whether the concept may work. Furthermore, this will effectively eliminate one gigaton of CO_2 emissions from automobiles. The new tax proposal attempts to encourage people to acquire EVs while discouraging people from driving traditional automobiles by providing incentives for electric vehicles and increasing taxes on regular cars. The Goods and Services Tax (GST) rate is now 28%, with an additional 15% cess. When the Goods and Services Tax (GST) rate hits its peak, it cannot be increased any further. However, the cess can increase.

The additional tax revenue generated by imposing the cess on high-end, pricey vehicles is intended to be utilized to fund electric vehicles. Currently, the government provides subsidies for electric cars (EVs) ranging from ₹7500 to 61 lakhs. EVs have received a total support of ₹305 crore. Kerala, an Indian state, has launched its Electric Vehicle Plan (EVP). The proposal is for 300,000 two-wheelers, 60,000 auto-rickshaws, 5,000 trucks, 10,000 buses, and 200 boats. It is expected that two million electric vehicles will be on the road by 2023.

There are around 13 million cars on the road in the state. Kerala is almost ready to join the four other Indian states that encourage citizens to drive electric vehicles. The purpose of this plan is to foster sustainable growth while also addressing climate change and energy security. Kerala has a high literacy rate, urbanization, and technological know-how, making it an ideal location to pave the way for an e-mobility future. Electric vehicles will gradually replace traditional public transportation vehicles such as autos, buses, and taxis as a complex infrastructure is created.

3. MODELLING OF HYBRID ELECTRIC VEHICLE

Simscape Electrical, Simscape Driveline, and MATLAB Simulink are used to create a model of a Hybrid Electric Vehicle. This can be used to investigate power quality or carry out system-level testing. Alternative models for electrical, battery, and vehicle dynamics can be built using different subsystems. A Simscape-generated battery model is included in the model. Figure 1 depicts a series-parallel arrangement of components from a hybrid electric car that roughly resembles a Nissan.

To reduce environmental contamination and economic losses, the system uses a dual-energy architecture that includes an internal combustion engine (ICE) and an electric motor. This technology combines the advantages of an internal combustion engine (such as dependability and fuel efficiency) with those of an electric motor (including high power and zero emissions at moderate speeds).

This allows for the generation of propulsion force using an internal combustion engine (ICE), a motor, or a hybrid system that combines the two. The Permanent Magnet Synchronous Motor (PMSM) can recharge the battery or drive the

wheels via a gearbox after converting mechanical energy to electrical energy. Regenerative deceleration is an additional option in which the engine is converted into a generator to replenish the battery. Despite this, the control and assembly devices are complex.

Figure 2 depicts the HEV model, which was constructed using the MATLAB Simulink environment. As seen, the input consists of a step signal indicating acceleration. Velocity and torque are measured using speed and torque sensors on the internal combustion engine (ICE), motor, and related components.

The first block represents the power control unit, which is in charge of dispersing the torque and power generated by the engine and internal combustion engine (ICE) in line with the current operating mode. This is accomplished by monitoring torque and speed in response to acceleration, deceleration, and pausing, among other events. In the second block, the battery, generator, converter, and motor are shown. The vehicle mode is determined by the amplitude of the accelerating signal pulse. Following this, the vehicle is driven by either the gearbox or the motor, depending on the mode selected by the control unit—internal combustion engine (ICE) mode or motor mode. The major concerns while developing the vehicle are energy output, rotational force, and velocity. The following section provides a more thorough examination of the units.
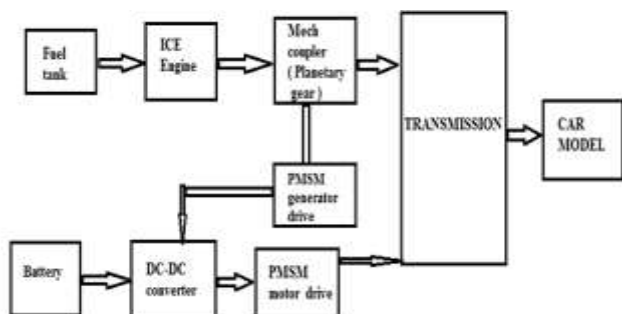

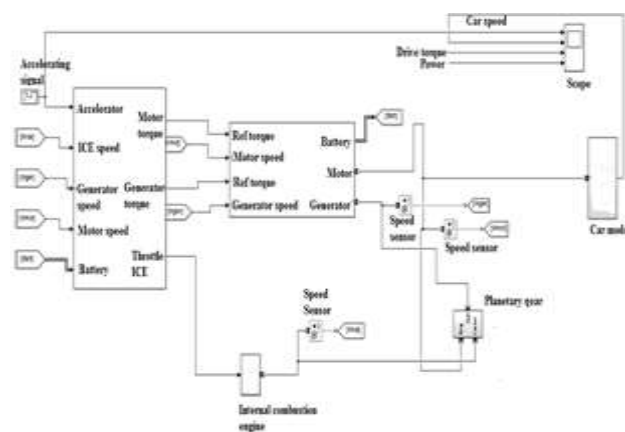Figure 1. Components of a Hybrid Electric Vehicle

Figure 2. HEV model in MATLAB

Figure 3 depicts a planetary gear system that does two things: pair speeds and share power. The speeds of the motor and internal combustion engine (ICE) are calculated by summing up all of the torques. The mechanical link spreads the power generated by the motor and internal combustion engine (ICE). This can be accomplished using either a torque connection or a speed coupling. It distributes and fuses the mechanical driving power from the generator, motor, and internal combustion engine to the wheels.

The sun gear, ring gear, and carrier gear connect to the generator, motor, and ICE, in that sequence. Figure 3 shows these gears, marked 1, 2, and 3. The letters r, w, and T represent the torque, speed, and radius of the gears that are coupled. These things can be measured using normal torque and speed equipment. In order to meet traction requirements, the gear alters the relationship between speed and power. The electromagnetic (EM) system powers the ring gear, allowing it to work in a variety of ways. It monitors the speed, horsepower, and torque of all three gears.

This image (Figure 4) depicts the ICE system, which includes a speed sensor and a 60 kW gasoline engine operating at 5000 rpm. It also controls the engine's speed in a roundabout method. Spark-ignition technology is utilized in gasoline engines to achieve the best fuel economy, efficiency, and environmental effect while simultaneously offering the most power at all speeds.

The noise reduction is improved, the economy increases, and the power-to-weight ratio is high. The block has motion, torque, and speed sensors to track power, torque, and speed accurately. This determines how operations will be carried out. The friction coefficient and shaft inertia are two parameters that are clearly defined. The car moves because of the Internal Combustion Engine (ICE), which transmits speed, power, and force to the wheels via the shaft.
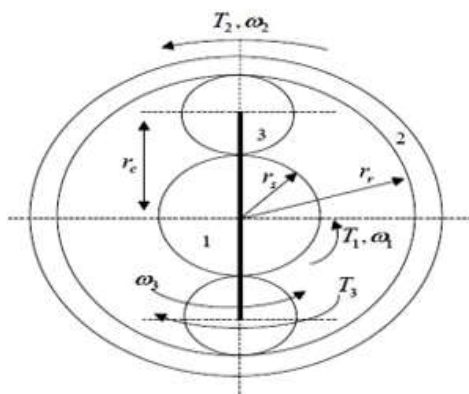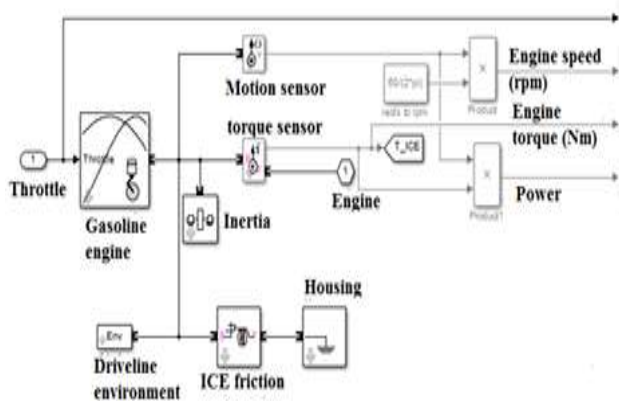

Figure 3. Planetary gear model

Figure 4. Internal Combustion Engine Simulink model

Figure 5 depicts the visible and touchable automobile system components. Newton's second law of motion describes the field of dynamics. Gravity, air resistance, and tire resistance are all forces that the power unit must overcome. Furthermore, it ensures that the entire power capability is utilized. The dynamic forces generated by the tires are what give the road its strength. The car model depicts the forces acting on the vehicle as it moves. Viscosity is a measure of how much physical resistance automotive parts generate. Torque and speed monitors determine

the torque and speed of the vehicle's shaft, making design easier.

There is a gear box attached to the shaft that has the appropriate gears for the load's torque and speed requirements. The gear boosts power while simultaneously slowing the motor. Finally, a different series of gears slows the machine down, and the differential divides the force coming in into two equal halves that power the wheels. Transmission inertia is the resistance created by an object's inertial mass when it moves, which affects how quickly it moves. The tire's drag is caused by its rolling resistance and hysteresis. This causes the road surface to shift form. The numbers were chosen based on the model's baseline values.

The two tires represent how it's shown. Form drag, produced by air resistance, and hydrodynamic drag, generated by the skin effect, are both present. I disagree with the plan. However, this parameter is disregarded because its values are insignificant. There is also no grade resistance because the road has a zero-degree inclination. When something is heading downhill, its own weight acts as a counteracting force, which is known as gradient resistance. In this scenario, the car travels in a straight line. So, the vehicle model depicts the combined forces acting on the car. This can be demonstrated numerically as follows: (1)

$$F_{resistance} = F_r + F_w + F_g + F_a \tag{1}$$

The equation above shows rolling resistance (Fr). Aerodynamic resistance is represented as Rw, grading resistance as Rg, and acceleration resistance as Ra. Equation (2) takes on the following form when the numerical values are changed:

$$F_{resistance} = Mgf_r \, Cos(\alpha) + \frac{1}{2}\rho A_f C_D V^2 + MgSin(\alpha) + M\lambda\frac{dV}{dt} \tag{2}$$

Figure 6 shows the electric motor, generator, battery, and boost circuit. They form the electrical system. The initial component of the system is a battery with a capacity of 5 ampere-hours (Ah), a voltage of 200 volts (V), and a power output of 18

kilowatts. The boost converter uses voltage mode control. The low power from the battery is increased to 500V so that the AC motor can operate. The motor and drive system are powered by an Interior Permanent Magnet Synchronous Motor (IPMSM) with a power output of 40 kW and an energy supply of 500 V. There are several types of motors, including brushless DC motors (BLDC), induction motors (IM), and switching reluctance motors (SRM).

The permanent magnet synchronous motor (PMSM) has advantages in terms of cost, power density, dependability, efficiency, and controllability [8]. There are sensors that can detect the motor's speed and power. The engine has eight poles and an unusual rotating form. The vector regime allows for a high spinning speed of 6000 revolutions per minute (rpm), which weakens the magnetic field. The generator is a permanent magnet synchronous motor (PMSM) with two poles and 20 kW of power, as is the accompanying drive system.

With the same degree of control as before, you can attain a peak speed of 12,000 rpm. The rotor current, torque, speed, and stator current are some of the variables that can be adjusted. Depending on the mode of operation selected, the generator and motor supply the energy required to propel the vehicle. Because of how torque and speed interact, the torque regulator prevents the motor from overheating. When the motor voltage approaches the inverter voltage, saturation may occur because the motor current drops. This configuration adjusts the reference torque dependent on the motor speed to prevent it from becoming too high.
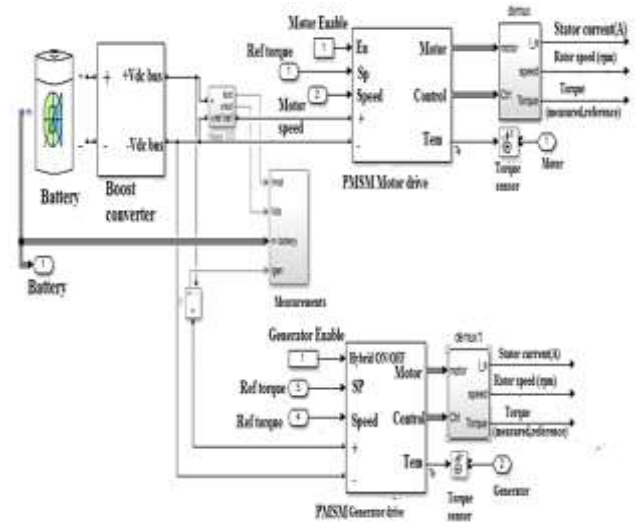

Figure 5. Vehicle dynamics model

Figure 6. Electrical system in HEV model

Figure 7 depicts the energy control system, which provides the drives and internal combustion engine (ICE) with the essential patterns required to ensure proper and efficient power distribution. The first block of the BMS maintains the State of Charge (SoC) between 50% and 90%. It prevents the voltage from falling and accurately calculates how much power the battery requires. The amount of torque required varies with the rate of acceleration (deceleration, acceleration, or maintaining the same speed).

Depending on the mode, the car is powered by a motor, an internal combustion engine (ICE), or a combination of the two. The torque and speed readings from the sensors are utilized to calculate the power. The ICE, engine, and motor speeds are all recorded and monitored to ensure that they do not exceed the speed limits.

The reference signals are calculated based on the hybrid electric vehicle's (HEV) speed and the quantity of accelerating signals. The controller calculates how much power the motor requires by dividing it by the generator's and battery's power capabilities. To generate the necessary electricity, the engine's rotational speed and force can be adjusted.
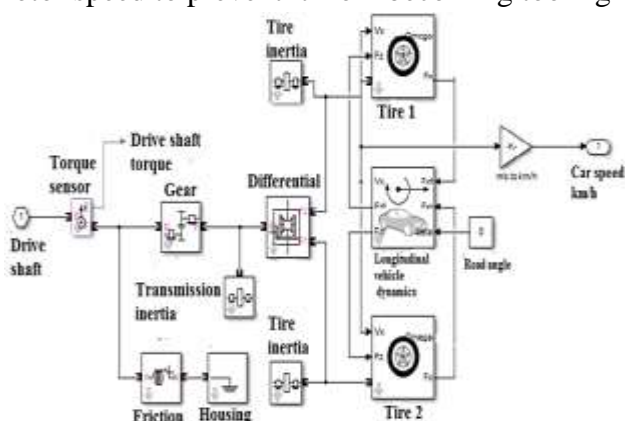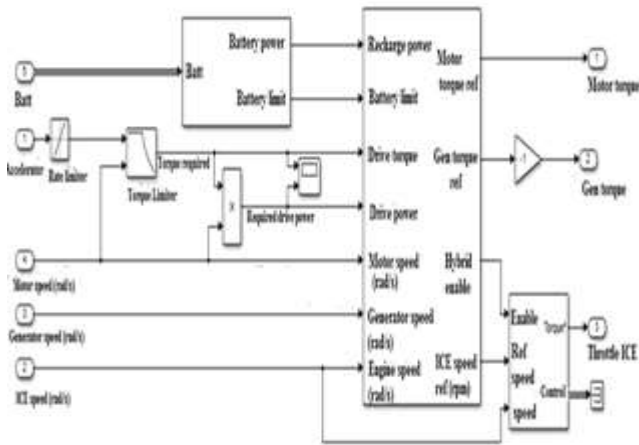
Figure 7. Energy control system

4. PERFORMANCE ANALYSIS AND DISCUSSION

The video shows the car running through all of its stages of operation, including cruising, acceleration, and charging its batteries while traveling at high speeds. Figure 8 illustrates how an acceleration pulse signal is used to initiate the exercise. When in accelerator mode, the game lasts approximately 60 seconds. To control the operation, an acceleration signal of 0.6 must be maintained for the first four seconds and then reduced to 0.1 for the next four seconds. This is like to pressing down on the gas pedal in a real car. The last value of the pulse is set to -0.6, indicating that it will halt until the simulation time is up. Following that, the heart rate is increased even further, to 0.7, and held there for five seconds. Figure 9 shows how the DC bus voltage for the traction drive system is managed and maintained at a constant 500 V while it operates.

Figure 10 shows how a DC-DC converter can be utilized to increase the power output from the battery from 200V to 500V. The duty cycle of the IGBT switches is altered to control the operation of the DC-DC converter.

The 500 V voltage will activate the Permanent Magnet Synchronous Motor (PMSM), which will propel the vehicle forward. Voltage mode control is required to maintain a constant voltage across the entire cycle. In a closed-loop system, the deviation is fixed by a proportional-integral (PI)

controller that compares the output voltage to a 500V reference.

Following this, as illustrated in Figure 9, the 500 V direct current (DC) bus voltage remains constant. Figure 11 depicts a planetary gear that maintains a power relationship, with zero power added to the sun gear, ring gear, and carrier gear. Figure 12 demonstrates that the car's speed increases from zero to 70 km/h after 12 seconds of standing still, then returns to 60 km/h in 15 seconds. In the following section, the virtual time instant is denoted as tS.
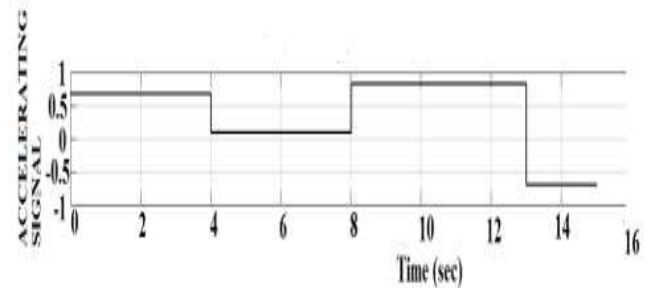

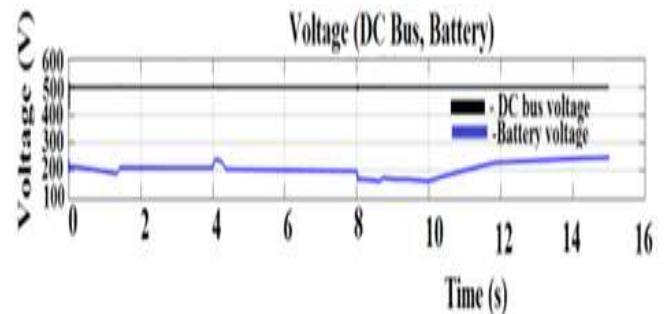Figure 8. Accelerating simulation pulse

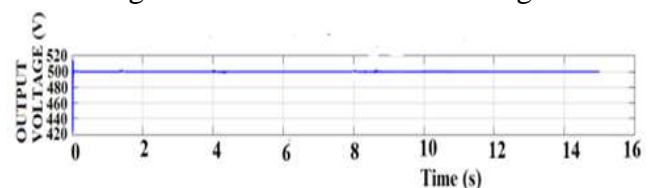Figure 9. Constant DC bus voltage
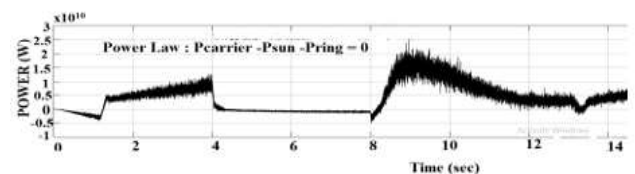

Figure 10. Constant DC/DC converter output

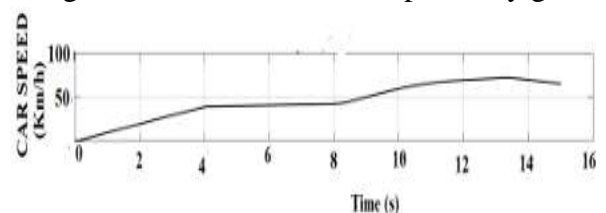Figure 11. Power balance in planetary gear

Figure 12. Variation of car speed with acceleration pulse

When the game starts and time is 0, the car remains stationary. Figure 8 demonstrates that the car gradually accelerates until it achieves 60% of its maximum speed. When the required power falls below 13 kW, the hybrid electric car can only move when the motor powered by the battery is employed. The generator and ICE are not producing any power right now. When the car first starts, the battery provides all of the power; the internal combustion engine (ICE) is shut off.

When tS reaches 1.2 seconds, the hybrid mode activates since more than 13 kilowatts of power are required. The internal combustion engine (ICE) and battery combine to operate the motor and generate energy for the hybrid electric vehicle (HEV). The permanent magnet synchronous motor (PMSM) is powered by both an engine and a battery. A planetary gear device is a crucial component. A sun gear will link to the generator, a ring gear to the motor and gearbox, and an ICE to the carrier gear. Because the engine burns fuel, it generates the same amount of electricity for both the ring gear and the solar gear. At this level of operation, the Internal Combustion Engine (ICE) and Electric Motor (EM) work together to deliver the power required for maximum movement.

At time tS = 4 s, the acceleration pulse shifts to 10%, indicating that the car remains at the same speed. The engine's slow reaction time implies that it can only progressively reduce power right away. When batteries are depleted, they reduce the torque required and utilize the power produced. This occurs while moving properly.

There is a dramatic decline in power to the generator, and it stops working after 4.6 seconds, denoted as tS. The battery is solely used to generate the necessary electricity to operate the vehicle.

The pulse speed increases by 70% in 8 seconds, denoted as tS. The Internal Combustion Engine (ICE) restarts to give the additional power required. Because of the ICE assembly's significant dynamic response time, the engine and battery's combined power output is insufficient to meet power demands. As a result, the estimated drive power does not satisfy the requirements.

When the simulation period reaches tS = 8.5 s, the computed torque will approach the reference value. In addition, the engine produces a lot of power.

When the time since start (tS) reaches 10 seconds, the state of charge (SOC) falls below 38%. Before the simulation, it was at 42%. As a result, the battery must be recharged, lowering its power level. When the hybrid electric vehicle (HEV) accelerates, it uses the engine's power to charge both the battery and the motor separately. To ensure that the charging process runs properly, the motor will utilize less power, which means it will be unable to provide enough force. This is analogous to the motor switching to generator mode while the car is going so that the battery can be charged.

At time tS = 12 seconds, the indication for speeding up switches to -60%, indicating that regenerative braking has commenced. The machine is switched off, and its power will eventually deplete. When the wheels power the motor, it runs in generator mode. This makes it easier to convert the physical energy required for movement into electrical energy to recharge the battery. This refers to the regular braking or slowing movement.

At tS = 13 seconds, the engine abruptly stops producing power. When the acceleration signal reaches 0.6, which corresponds to the location of the accelerator illustrated in Figure 8, the car enters start-up mode and progressively accelerates, as shown in Figure 12. When the car is in cruise control, a signal with an amplitude of 0.1 keeps the speed constant. When there is additional power, the speed increases to 70 km/h and then remains at 60 km/h. Figure 13 shows the observed and reference waveforms for the simulated drive torque. When the car starts for the first time, it requires more power. The motor takes four seconds to generate a powerful torque of 250 Nm. The observed torque is the same as the reference torque, indicating that more power is

required during startup. During driving, torque and power decrease, causing the waveform magnitude to drop to 50Nm over the next 4 seconds. After 13-15 seconds of charging, the torque felt during regenerative braking has dropped to -250 Nm.

During the starting procedure, the motor has essentially no power because the battery juice is only needed to provide a powerful initial push that propels the vehicle forward. Figure 14 provides an example of this. During this time, the generator and motor provide the necessary electricity. When regenerative braking is activated, as illustrated in Figure 14, the motor acts as a generator, and its power is displayed as a negative number. Figure 15 illustrates that the shapes of the power and current flow waveforms are identical. The currents of both the motor and generator climb throughout the first phase of the start-up and acceleration process. This is because the battery is supplying electricity. Figure 15 depicts the fluctuations in current clearly. The DC-DC converter increases the battery's output voltage from 200V to 500V. The duty cycle of the IGBT switches is adjusted to control how the DC-DC converter operates. The Permanent Magnet Synchronous Motor (PMSM) will use the 500 V electricity to propel the vehicle forward. Voltage mode control is required to maintain a constant voltage across the entire cycle. In a closed-loop system, a proportional-integral (PI) controller is utilized to compensate for any voltage difference between the output and a 500V reference. Figure 10 illustrates that the DC bus voltage reains constant at 500 V.
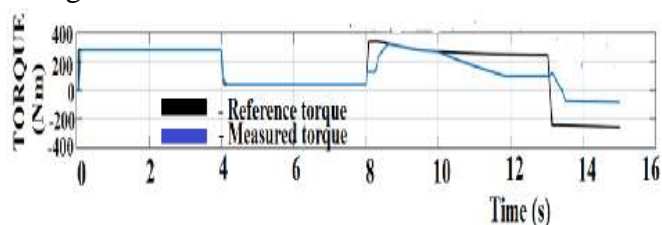

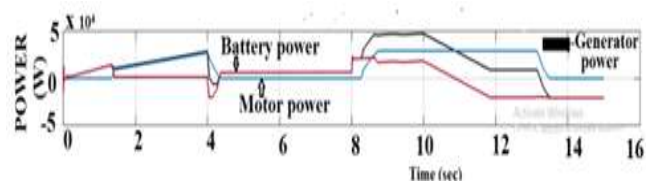Figure 13. Torque demand during operating stages

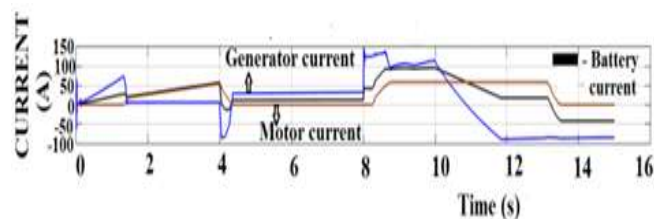Figure 14. Power allocation waveforms of the drive

Figure 15. Current flow in battery, generator and motor

Figure 16 depicts how the battery's State of Charge (SoC) fluctuates as the car moves between operational modes. It depicts the battery's current capacity as a proportion of its total capacity. When you first receive the device, the battery is around 42% charged. The battery's charge gradually declines as it provides power for movement during the early stages of acceleration. As a result, power reduces to 38% when speeding up and must be restored. With regenerative stopping, the motor can function as a generator, converting mechanical energy into electrical energy to charge the battery. This is demonstrated by the pattern, in which the State of Charge (SoC) increases in the final section.
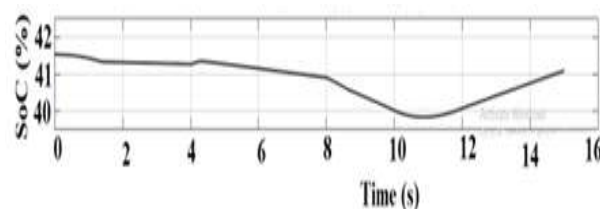

Figure 16. Variation of SoC for different modes

Figure 17 illustrates that the stator current of the Permanent Magnet Synchronous Motor (PMSM) decreases when the motor is not moving and increases during the first four seconds of acceleration, as predicted in typical operating modes. Figure 16 shows how the current drawn by the stator source changes depending on the mode. Figure 18 depicts how the motor speed varies over time. The battery powers the motor at initially, which gradually increases its speed until it reaches 1500 rpm.

To manage the speed, a vector driver is employed to correct any errors discovered while comparing the real and reference speeds. Following that, during typical driving, the speed remains constant

for 4 to 8 seconds before increasing as the car accelerates and decreasing as it slows. Figure 19 depicts the electromagnetic torque produced by the PMSM to propel the vehicle forward in various driving conditions. At low speeds, PMSM delivers a lot of torque or power at first, allowing for a smooth start-up in two seconds.

As soon as the car resumes regular driving, the motor power gradually drops over the next 4 to 8 seconds. When regenerative braking is applied, the vehicle's torque acts in the opposite direction, giving the value a negative sign. Vector control is one method for managing torque and speed. To achieve flux lowering control, the flux and speed must be adjusted. Torque and flux numbers are used to compare motor currents to their respective base values. The PWM output for the three-phase inverter of the PMSM motor is generated by a current controller.

Figure 20 depicts the ICE waveforms, which show the engine's torque, power, and speed under various operating conditions. When the power signal is received, the car can be driven by either the engine or a motor. When the throttle signal is strong, ICE mode is activated. When the throttle signal is weak, the ICE mode is switched off.

There is no throttle during the initial phase because the motor is the only mechanism in use. As a result, the internal combustion engine (ICE) is shut off for 1.2 seconds at the start. There is no torque, power, or speed in the thing. The Internal Combustion Engine (ICE) provides the additional power required for the car to accelerate. Figure 20 depicts how the power and torque progressively increased over a few seconds. These figures decrease to zero both when the car slows down and when it is going normally.
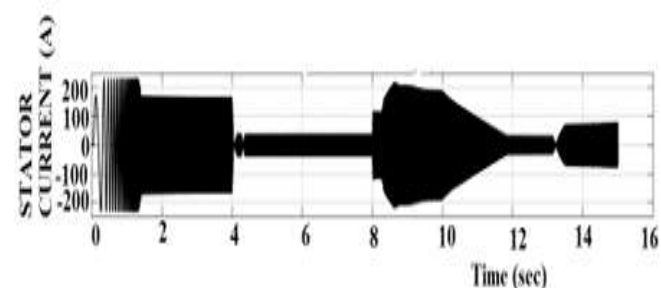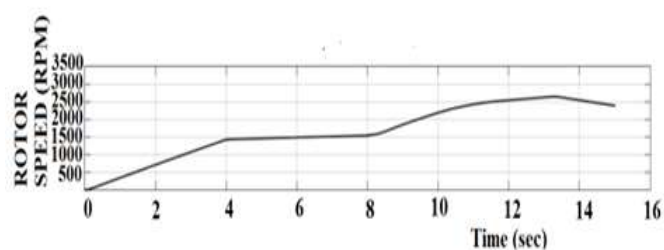

Figure 17. PMSM stator current
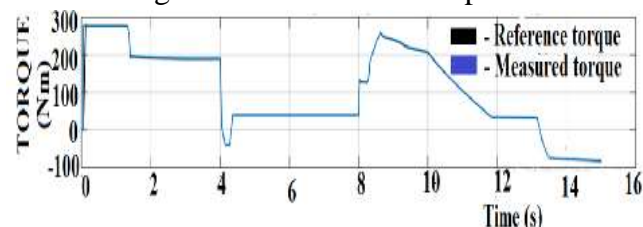

Figure 18. PMSM motor speed
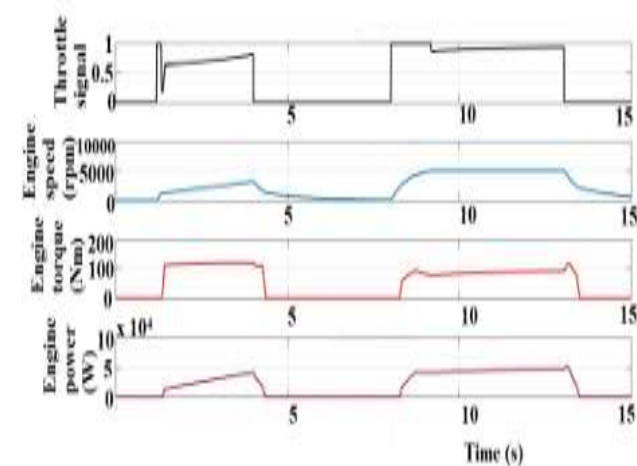

Figure 19. Torque produced by PMSM motor

Figure 20. Engine speed, torque and power

5. CONCLUSION

Electric vehicles (EVs) are an important solution to address the issues produced by fossil fuels while also reducing pollution in the existing market. The study employs MATLAB Simulink to simulate an electric vehicle (EV) and its components in order to investigate how energy is distributed, how dependable the EV is, how design variables influence the EV, and how the EV responds to various operating conditions. Important findings were discovered for voltages, currents, speed, power, and other factors originating from the battery, motor, converter, and engine. It is critical to employ HEV models and simulation in future studies and car design since more study is being conducted on the most efficient motor, battery, drive arrangement, and part size. Electric vehicle research and

development will expand in the future as more green energy sources are used and smart grids are connected to them. This will enable environmentally responsible success and long-term prosperity.

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