Modelling and performance analysis of hybrid electric vehicle

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Abstract. Electric Vehicles (EV) have become an integral part of the automotive industry and will soon replace Internal Combustion Engine (ICE) automobiles. The technological trends in the various components of EV have contributed towards extensive use of EVs. EVs can have a positive impact on ecology and power sector. EVs comprehensively decrease the greenhouse gas emissions created by the transport sector. This paper provides a basic understanding of the need for Electric Vehicles, the recent developments in India and the upcoming trends and research in Electric Vehicles. The modelling of Hybrid Electric Vehicle (HEV) and the performance analysis for various operating stages is detailed in this paper. The paper provides a base for additional studies.

Keywords. Electric Vehicle (EV), Fuel Cell Electric Vehicle (FCEV), Hybrid Electric Vehicle (HEV), Modelling, Plug-in Hybrid Electric Vehicle (PHEV), MATLAB Simulink, Simulation

1. Introduction
India is the third-biggest contributor to Carbon Dioxide emissions as per the research conducted by Environmental and Energy Study Institute [1]. There has been considerable increase in coal, oil and gas usage. At the United Nations Framework Convention on Climate Change in Madrid, to combat fossil fuel emissions, all the 190 countries have put forward the solution of electric mobility [1]. Reducing global warming according to the 2015 Paris Agreement would require minimizing CO₂ emissions by 50% by 2033 and eliminate full emission by 2050. This will keep the global temperature rise to below 2°C. Air pollution was a cause of one in eight deaths in India in 2018. The recent analysis show that 25% of worldwide untimely death and disease problem by air pollution happens in India. Statistics reveal that 13.4 lakh deaths in 2018 were owing to pollution, which involves 7.6 lakh deaths owing to external particulate pollution and 3.7 lakh casualties because of domestic pollution [1]. Thus, it becomes all the more important that the world adopts a greener future by resorting to E-mobility by replacing conventional vehicles by Electric Vehicles [2]. EVs have huge scope in power sector by integrating renewables like solar and energy storage technologies like Lithium ion batteries since solo devices will not be able to meet ably the increasing power requirement [3]. Implementing Maximum Power Point Tracking (MPPT) process raises the output of a solar panel [4]. Co-ordinated charging or smart charging supports the Electric Vehicle Charging System for recharging their depleted batteries, provide backing to grid through reactive power, minimizing harmonic content and giving back power to the grid when there is excess power in the battery [5]. The first section of this paper provides a brief overview regarding the need for EVs and its future scope. The next sections
provide the EV policy in India and some of the strategies adopted by Kerala to promote EVs. Modeling and analysis of HEV and performance analysis for different operating modes will enable better design of EV prototypes by mimicking real time operating modes like acceleration, cruising, braking etc. Performance analysis will aid in optimizing the design and selection of the components and controller during actual hardware implementation. This is significant since EVs are largely complex systems. The simulation model and result analysis gives template to construct and check the performance of the original system.

2. Electric Vehicle Scenario in India

India saved ₹ 3.8 crore worth litre fuel owing to increased adoption of battery electric vehicles and also reduced environmental pollution [6]. There are 270000 EVs in India including electric bus and electric scooter according to Faster Adoption and Manufacture of (Hybrid and) Electric Vehicles (FAME) scheme. Large savings to the tune of ₹120 crore in terms of crude oil was realized. FAME proposal target’s to have fully electric vehicles by 2030 [6]. Feasibility study was embarked on by NITI Ayog and Rocky mountain institute of America in 2017. This will also eliminate 1 giga ton CO2 that are emitted by vehicles. There will be new tax scheme to encourage EVs and discourage use of conventional vehicles - subsidy for EV and increased tax for conventional vehicles. Currently GST slab is 28% plus additional cess of 15%. Since GST rate is maximum, it’s not possible to increase it more but cess can be increased. By increasing the cess of large and pricy posh vehicles, the tax thus generated will be given as subsidy for EVs. Currently, Government gives ₹7500 to ₹61 lakhs subsidy for EVs. Till now, EVs have been given central subsidy of ₹ 305 crore [6]. Recently, Kerala – a state in India have charted a roadmap of getting two million electric vehicles by 2023, a convoy of three lakh two-wheelers, 60,000 auto rickshaws, 5,000 trucks, 10,000 buses and 200 ferries as part of the Electric Vehicle Plan (EVP) [7]. Approximately, 13 million automobiles run in the state. Kerala will be fifth state in India to promote e-mobility. This strategy will overcome the problems of energy safety, climate variation and enable sustainable growth. Kerala has the best settings in terms of literacy rate, urbanization and technical knowledge skills to shift to an E-mobility future. There will be a well-planned infrastructure to phase out public modes of transport like buses, autos and taxis and replace them with Electric Vehicles [2].

3. Modelling of Hybrid Electric Vehicle

A Hybrid Electric Vehicle (HEV) model is assembled using Simscape, Simscape Electrical and Simscape Driveline of MATLAB Simulink. This can be designed for system-level tests or power quality analysis. Model alternatives for the electrical, battery and vehicle dynamics systems can be designed using variant subsystems. A battery model made using Simscape is merged into the model. Figure 1 shows a Hybrid Electric Vehicle with series-parallel configuration, similar to Nissan. It has two energy inputs: an Electric Motor (EM) and an Internal Combustion Engine (ICE), for reducing the losses and environmental pollution. It merges the merits of electric motor (zero pollution and large power during small speed) and an ICE (reliability and efficient operation). This allows either the ICE or the motor or both to provide propulsion power. The mechanical output gets converted to electrical energy using the Permanent Magnet Synchronous Motor (PMSM) which can either replenish the battery or drive the wheels via transmission. There is also an option for regenerative braking by running the motor as generator to recharge the battery. However, the assembly unit and control is complex.

Figure 2 shows the HEV model in MATLAB Simulink environment. An accelerating step signal is the input as indicated. There are speed and torque sensors to measure the speed and torque for the ICE, motor and associated components. The first block represents power control unit which distributes the power and torque from the motor and ICE according to the operating mode. This is accomplished by sensing the speed and torque in accordance with acceleration, deceleration, braking etc. The second block depicts the motor and generator drive along with the battery and converter. The accelerating
signal pulse amplitude indicates the vehicle mode status. The control unit then activates the motor mode or ICE mode to drive the vehicle via the motor or the gear. The main design parameters are car speed, torque and power. The blocks are discussed in detail in the following section.

Figure 1. Components of a Hybrid Electric Vehicle

![Figure 1. Components of a Hybrid Electric Vehicle](image1.png)

The planetary gear system in figure 3 is a speed coupling device which acts as a power split device as shown. Motor and ICE speed are summed together by linking all the torques. The ICE and motor power are allocated using mechanical coupler. This can be done using speed coupling or torque coupling. It transfers the mechanical drive torque from the ICE, motor and the generator by distributing and merging them. It has sun gear, ring gear and carrier gear connected to the generator, motor and ICE respectively. These gears are marked by 1, 2 and 3 in figure 3. The symbols r, w and T indicate the radius, speed and torque of the respective gears. There are usual torque and speed sensors to measure these parameters. The gear changes the speed versus torque profile to suit the traction requirements. The EM provides power to ring gear to facilitate different modes. The corresponding speed, torque and powers for the three gears are measured.

The ICE system represents a 60 kW, 5000 rpm petrol engine and the associated speed controller as in figure 4. It also indirectly regulates the engine speed. The gasoline engine is spark ignition type for optimum performance, economy and environmental impact and to provide maximum power at any
speed. It has high power to weight ratio, high efficiency and less noise. The block has torque, speed and motion sensors to detect the speed, power and torque. This decides the functioning mode. Parameters like the shaft inertia, friction coefficient values etc. are defined. The ICE transmits the torque, speed and power from the shaft to the wheels to drive the vehicle.

Figure 3. Planetary gear model

Figure 4. Internal Combustion Engine Simulink model

Figure 5 depicts the physical components of the vehicle system. The dynamics is defined by Newton’s second law of motion. The propulsion unit should overcome the forces of gravity, air and tire resistance. It also ensures that the power potential is fully utilized. Tire dynamic forces characterize the retarding force on the road. The car model represents the impact of forces when the car is in motion. Viscosity represents the losses due to the vehicle parts. There are torque and speed sensors to detect the vehicle shaft torque and speed for design purpose. The shaft is connected to a gear box which utilizes suitable gears to match the load torque-speed requirements. The gear decreases the motor speed and reinforces the torque. There is a concluding drive of gears that reduce speed and the differential divides incoming torque into 2 equivalent torques that act on the wheels for motion. There is acceleration inertia or resistance due to inertial mass that occurs during motion which is represented by transmission inertia. The tire inertia is due to the rolling resistance and hysteresis of tire component. This causes deformation of the road surface. These values are chosen based on standard values available in the model. It is represented for the two tires. There is also aerodynamic drag due to the skin effect and shape drag owing to air resistance. This opposes the motion. However, this parameter is neglected due to low values. Further, the road angle is zero implying the grading resistance is zero. Grading resistance is the opposing force produced due to the weight of the vehicle.
when it travels on a slope. In this case, car is driven on a straight road. Hence, the vehicle model represents all the forces that act’s on the vehicle and in equation form, it can be written as in equation (1):

\[ F_{\text{resistance}} = F_r + F_w + F_g + F_a \]  

(1)

In the above equation, \( F_r \) is the rolling resistance \( F_w \) is the aerodynamic resistance, \( F_g \) is the grading resistance and \( F_a \) is the acceleration resistance. Substituting the values, we get equation (2) as:

\[ F_{\text{resistance}} = M g f_r \cos(\alpha) + \frac{1}{2} \rho A_f C_D V^2 + M g \sin(\alpha) + M \lambda \frac{dV}{dt} \]  

(2)

In the vehicle dynamic equation (2), \( M \) is mass of the vehicle in kg, \( g \) is the acceleration constant \((m/s^2)\) and \( \alpha \) is the road angle in radians. \( \rho \) is the density of air in kg/m\(^3\), \( A_f \) is the vehicle frontal area in m\(^2\) and \( V \) is the vehicle speed in m/s. \( C_D \) is the drag coefficient and \( \lambda \) is the rotational inertia constant.

The electrical system in figure 6 has four portions: electric motor, generator, battery and the boost circuit. The first component is a battery of 5 Ah, 200 V, 18 kW Lithium ion module. The Boost converter uses voltage mode control. It boosts the small battery voltage into 500V for driving the AC motor. Electrical motor is a 500 V, 40 kW Interior Permanent Magnet Synchronous Motor (IPMSM) along with its drive. The PMSM is a notch above other motors like Brushless DC Motor (BLDC), Induction Motor (IM) and Switched Reluctance Motor (SRM) when compared with parameters like power density, dependability, efficiency, controllability and overall expense [8]. There are torque and speed sensors to detect the torque and speed of the motor. The motor has 8 poles and is salient rotor style. Flux weakening vector regime helps in acquiring high speed of 6000 rpm. There is also a 500 V, 2 pole, 20 kW PMSM generator and related drive. The same aforementioned control provides a high acceleration of 12000 rpm. The parameters controlled are the stator current, torque, speed and rotor current. Depending on the operating mode, the motor and the generator provides power the drive the vehicle. The torque limiter limits saturation due to torque-speed characteristic. As the motor generated voltage becomes closer to inverter voltage, there is a risk of saturation due to less motor current. This arrangement limits the reference torque with respect to the motor speed to prevent saturation.

![Figure 5. Vehicle dynamics model](attachment://figure5.png)
Figure 6. Electrical system in HEV model

The energy control system in figure 7 provides the connecting base waveforms for the two drives and the ICE for accurate distribution of the power. Initial block of Battery Management System (BMS) keeps State of Charge (SoC) amid 50% and 90%. It averts voltage failure and estimates the power necessary from battery. Depending on the acceleration rate (cruising, speeding or braking), the torque required and hence the power varies. The power required is calculated using the torque and speed detected using the sensors and depending on the mode, either the motor or ICE or both of them are used in propelling the vehicle. The speed of ICE, motor and generator are detected for this purpose and are kept within the reference speed limits. The process of determining the reference signals involve employing the accelerating signal value and the measured HEV speed. The controller also estimates the power for the motor by breaking up the required power in terms of power capability of the battery and generator. Requisite generator power can be obtained by varying the torque and the engine speed.

Figure 7. Energy control system
4. Performance Analysis and Discussion
The simulation depicts various functioning stages of the vehicle for a full sequence: acceleration, cruising and battery charging during speeding. An acceleration pulse signal is given to start the simulation as shown in figure 8. The simulation will run for around one minute using the accelerator mode. Operation is controlled by keeping the accelerating signal constant at 0.6 during initial 4 s and 0.1 within next 4 s where the signal is reduced (equivalent to releasing the pedal in a real vehicle). The accelerating pulse is subsequently increased to 0.7 for the next 5 s and the final value of the pulse is set to -0.6 (equivalent to braking) till the simulating time ends. For the complete running time, DC bus voltage for the traction drive system is controlled and kept constant at 500 V as shown in figure 9.

Since the battery output voltage is 200V, this voltage is boosted to 500V using DC-DC converter as in Figure 10. The operation of DC-DC converter is controlled by adjusting the duty cycle of the IGBT switches. This 500 V output will be used to drive the PMSM motor to propel the vehicle. This voltage should be maintained constant throughout the cycle using voltage mode control. The output voltage is compared with the reference voltage of 500V and the error is corrected using a PI controller in the closed loop. Thus, the DC bus voltage is maintained regulated at 500 V as shown in figure 9. The power relation is maintained in the planetary gear in figure 11 where the equivalent sum of powers of sun gear, ring gear and carrier gear equals zero. As per figure 12, the vehicle initially at rest touches 70km/h at 12 s and eventually falls to 60 km/h at 15 s. In the following section, t_s represents the simulation time instant.

![Accelerating simulation pulse](image)

**Figure 8.** Accelerating simulation pulse

![Constant DC bus voltage](image)

**Figure 9.** Constant DC bus voltage

![Constant DC/DC converter output](image)

**Figure 10.** Constant DC/DC converter output
1. Initially when simulation time is zero, the vehicle is stationary. The car slowly accelerates to 60% as indicated in figure 8. If the requisite power becomes lesser than 13 kW, the HEV starts its motion utilizing just the motor power provided by battery. Generator and ICE produce zero power in this stage. At start up, battery acts as the sole source of propulsion power and ICE remains off.

2. When $t_S$ becomes 1.2 s, requisite power is higher than 13 kW prompting activation of hybrid mode. Here, the HEV traction power is delivered by ICE and battery (via motor). Battery and generator drives the PMSM. Planetary gear is another important component. The ICE will be connected to carrier gear, generator will be mechanically coupled with the sun gear and ring gear will be coupled to the motor and associated transmission. The ICE splits its power between the sun gear and ring gear. This operating stage relates to full throttle acceleration where both ICE and EM share the required power.

3. When time becomes $t_S = 4$ s, accelerating pulse is altered to 10% (i.e., vehicle cruises). Due to sluggish response of the engine, it can only slowly reduce its power instantly. Hence, battery consumes the generated power and minimizes the torque necessary. This is during the normal driving mode.

4. During $t_S$ of 4.6 s, generator power becomes zero and is fully stopped. The necessary propulsion power is generated singly utilizing the battery.

5. During $t_S$ of 8 s, accelerating pulse gets increased to 70%. The ICE restarts to generate additional requisite power. The sum of power produced by generator and battery falls short of the necessary power due to the slow dynamic responding time of generator-ICE assemblage. Therefore, estimated drive torque cannot reach the reference value.

6. When simulation time reaches $t_S = 8.5$ s, actual estimated torque touches the reference value. The generator also offers high power output.

7. When $t_S$ becomes 10 s, SOC reduces below 38% (initial value was 42% before simulating). Hence, the battery should be recharged and thus battery power becomes negative. The generator divides its output power amongst battery and motor and battery is recharged using this when HEV accelerates. Motor will reduce its power demand to facilitate charging and hence requisite torque cannot be met. This corresponds to charging during driving where the motor changes to generator mode.

8. When $t_S = 12$ s, accelerating signal becomes -60% (implying regenerative braking). Hence, generator is switched off (its power takes some time to settle to zero). Motor works in generator mode, driven by the wheels thus facilitating the conversion of kinetic energy during driving into electrical energy which replenishes the battery. This relates to deceleration or normal braking.

9. When time, $t_S = 13$s, generator power becomes fully zero.
Corresponding to the accelerator position in figure 8, when the acceleration signal is 0.6, vehicle is in start-up and speed increases gradually as in figure 12. During cruising mode when amplitude of signal is 0.1, car speed remains steady and on further acceleration, speed increases to 70 km/h and then settles to 60 km/h. Figure 13 represents the simulated waveforms of drive torque (reference and measured). Initially, the torque required is higher during starting of the vehicle. This high torque of 250 Nm is provided by the motor till 4s and measured torque equals the reference torque to meet the demand for additional power during starting. During cruising in the next 4s, the torque and the equivalent power required are lesser and hence the waveform magnitude reduces to 50Nm. Finally, during regenerative braking, the torque becomes -250 Nm when the battery is charged during 13-15s.

During starting, the motor power is zero since the battery power is used to give high starting torque to run the vehicle. This is depicted in figure 14. During acceleration mode, both generator and motor provide the requisite power. The motor functions as a generator during regenerative braking and power is negative as seen in figure 14. The current flow waveforms also follow the same pattern as the power waveforms as given in figure 15. The battery current increases while delivering power during initial start-up and during acceleration mode, both generator and motor current increases. The variation of current is clearly shown in figure 15. Since the battery output voltage is 200V, this voltage is boosted to 500V using DC-DC converter. The operation of DC-DC converter is controlled by adjusting the duty cycle of the IGBT switches. This 500 V output will be used to drive the PMSM motor to propel the vehicle. This voltage should be maintained constant throughout the cycle using voltage mode control. The output voltage is compared with the reference voltage of 500V and the error is corrected using a PI controller in the closed loop. Thus, the DC bus voltage is maintained regulated at 500 V as shown in figure 10.

![Figure 13. Torque demand during operating stages](image1)

![Figure 14. Power allocation waveforms of the drive](image2)
State of Charge (SoC) of the battery varies in figure 16 as the vehicle traverses different operating modes. It is a measure of the current battery capacity expressed as a percentage of its maximum capacity. Initially, the battery charge is close to 42%. This charge gradually reduces as the battery provides propulsion power during starting and acceleration. Hence, charge reduces to 38% during acceleration and needs to be replenished. This is accomplished during regenerative braking where the motor works as a generator and mechanical energy is transformed to electrical to recharge the battery. This can be seen in the waveform where the value of SoC increases in the last portion.

Corresponding to the operating modes, the stator current of the PMSM in figure 17 increases when the motor delivers propulsion power during the first 4s during acceleration and the current reduces during normal driving. Depending on the mode, the current drawn by the stator supply reduces as shown clearly in figure 16. The variation of motor speed is shown in figure 18. Initially, during starting, battery provides power via motor and hence the motor speed gradually increases to 1500 rpm. The speed is regulated using vector control by comparing actual speed with a reference speed and error correction using vector controller. This speed remains steady during normal driving between 4 - 8s and then increases during acceleration and finally reduces during deceleration. Figure 19 illustrates the electromagnetic torque produced by the PMSM to propel the car during different running conditions. Initially, PMSM provides high torque or power at low speed to enable smooth starting till 2s. Then, the motor torque reduces once the car resumes normal driving between 4 - 8 s. The torque is negative during braking for recharging the battery. Both speed and torque are regulated by vector control where the flux along with speed produces flux weakening control. The motor currents are compared with their reference values based on the flux and torque values. This produces the PWM signal for the three phase inverter of the PMSM motor using current controller.

The ICE waveforms in figure 20 illustrate the engine torque, power and speed during various functioning modes. The throttle signal activates the hybrid operating mode where the engine alone or engine in tandem with the motor drives the car. When the throttle signal is high, ICE mode is activated and when its magnitude is low, ICE is turned off. Initially during starting, only the motor is used and hence the throttle signal is zero. Hence, ICE is turned off during initial 1.2 s. Thus, its power, torque and speed are zero. When the vehicle accelerates, the additional power is provided by the ICE. The increase in torque and power can be seen in the figure 20 during the next few seconds. These values drop to zero during normal driving as well as during braking.
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
EVs are of great significance in the present market to negate the detrimental effects of fossil fuels and reduce pollution. In the paper, a HEV and corresponding machineries are modelled using MATLAB Simulink to examine the energy flow, reliability, design factors and the response of the EV to different operating conditions. Substantial outputs for voltages, currents, speed, torque etc. of battery, motor, converter and engine was obtained. With the increasing studies for finding the best motor, battery, drive configuration and component sizing, this modelling and simulation of HEV will be vital for future researches and automotive designers. The scope of research and development in EVs will increase in subsequent years paving way for sustainable development and green environment further pioneered by wide adaption of renewables and alliance with smart grids.

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