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Modeling and Analysis of a Series-Parallel Hybrid Electric Vehicle

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***Abstract*: This research presents an analysis and a methodology for modeling of a Series-Parallel Hybrid Electric Vehicle using MATLAB Simulink. Hybrid Electric Vehicles are well known for their exceptional fuel economy, especially when driven within the city. But at the same time, they are not as cost and fuel-efficient as they should be when driven on highways. Therefore, a predictive control algorithm/strategy has been modeled that prioritizes the working of the Electric motor at high speeds while keeping the Internal Combustion Engine under optimal rpm. The vehicle has been modeled using an internal combustion engine (ICE), along with all the necessary components typically found in a HEV (such as a generator, electric motor, powerful drive train, battery management system, and a logic controller). The logic controller can either be operated by a drive cycle or a direct throttle input and is primarily responsible for the seamless transition and operation of the components. The main focus of this research is to provide valuable insights and research on the modeling of a Hybrid Electric Vehicle power-train, including control strategies and analysis of the statistics based on the real-time simulation along with the results of the vehicle under various drive cycles, including FTP-75, NEDC, HWFET, and JC-08 have been used to determine and verify the working of the effective control strategy. Based on the provided drive cycles, the battery's state of charge (SOC), engine, and Electric Motor's working, torque, and power have been deeply analyzed. As a result, the vehicle provides an overall fuel economy of 54.326 mi/gal and 4.326/100 km (City and Highway, including aerodynamic drag forces), maintaining SOC above 60%.**

***Keywords*: Control Strategy, FTP-75 Drive Cycle, Hybrid Electric Vehicle, Series-Parallel Configuration.**

1. Introduction

One of the rising problems at the moment is global warming caused by gases such as carbon dioxide (CO2), which usually comes from the burning of petroleum products such as Gasoline and Diesel. However, every vehicle has different tailpipe emissions, having a direct relation with its fuel consumption and more combustion will result in more CO2 emissions. The number of HEVs in the US increased by 126 % compared to non-hybrids and EVs [1]. Second, being the dependency on fossil fuels, which act as a primary source for the combustion of automobiles. In a 2006 SAE (Society of Automotive Engineers, 2006) congress, the Department of Energy Secretary stated that the US is "addicted to oil", approximately spending $250 billion the previous year [2]. The Evolution of the automobile industry has always been fascinating, how things changed from a two-wheeler consisting of a single-cylinder engine to a full-scale vehicle with an extremely powerful engine and then the transition to a hybrid vehicle. Over time, consumer demand kept changing, creating an opportunity for the engineers to bring something new to the market. As the industry evolved, people started discovering how gasoline combustion disrupted the natural order, raising a point to make these vehicles environmentally friendly. Gasoline and all types of vehicles have become a daily part of our lives, assisting in public transport, daily commutes, and for various types of business, thanks to the advancement and development in the automobile industry. But if one takes a look at public transport, it is the most widely and commonly used form of transportation around the world, leading to the global petroleum crisis and environmental concerns. Of the total global carbon dioxide (CO2) emissions, the road transportation sector shares 14 % of CO2 emissions [3]. According to the United States Environmental Protection Agency (EPA), a typical vehicle with a petrol engine emits 8,887 grams of CO2 emissions per gallon. Whereas a diesel engine emits about 10,180 grams per gallon, 15 % more than a gasoline engine, contributing to the rising issue of global warming [4]. All these significant factors effectively contributed to the research and development in the field of hybrid electric vehicles (HEVs) and electric vehicles (EVs), which further resulted in an environmentally friendly and fuel-efficient alternative.

HEVs come in a lot of variations, including series, parallel and series-parallel configurations. The main focus of this research is to develop an improved and powerful control strategy, addressing the issues regarding the shifting lag and jerks between ICE and electric motor (causing electric and mechanical power losses) [5]. Having rough low and mid-range idle rpm (revolutions per minute) while cruising and transitioning between mechanical and electrical power trains. Limitations of electric motor when it comes to performing under high rpm and speed. For instance, limiting electric motor by its speed. Usually, HEVs consider speed as their shifting mechanism between components in their control strategies. During low speed, the electric motor operates, and (ICE) becomes operational during high-speed cruising and aggressive driving [6]. Initially, this strategy helps the vehicle while cruising in the city during traffic congestion in terms of fuel economy, but at the same time, it is not cost-effective when

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*Corresponding author: a.wasay988@gmail.com driven on a highway [7]. Therefore, a very powerful power train along with a control strategy has been developed, utilizing state-flows and boolean gates, that is not only dependent on speed but on the acceleration command/throttle signal as well, recovering the battery state of charge (SOC) with effective regenerative braking and ICEs generator, addressing all issues resulting into a better mileage, power delivery and pleasurable driving experience of HEVs. The controlled strategy introduced in this research differs from the control strategy used in conventional Hybrid vehicles, as the main goal of this research and control strategy is to not restrict the operation of an electric motor by its speed, it should be able to operate even at high speeds and not just in the city. This paper focuses on modeling of a series-parallel configuration hybrid electric vehicle, introducing a different set of gear configurations and an improved control strategy for a series-parallel structure. Every configuration has its own modeling structure and power train, along with its advantages and disadvantages, but the series-parallel hybrid architecture highlights the strengths of both series and parallel configurations by putting them together [8]. As series hybrids are more reliable during low speeds, and parallel hybrids are more efficient at high speeds. As a result, series-parallel configuration hands out a very rigid power train, optimizing efficiency and providing better control and power strategy. It allows the vehicle to propel solely on an electric motor as well as on the internal combustion engine or hybrid mode, depending on the dynamics and drive cycle provided to the vehicle. According to the surveys conducted, by 2040, 55% of the automobile production line will consist of HEVs and EVs [9]. Hence, creating more opportunities for automobile companies and engineers to fill the gap between the research, creating something more rigid and reliable.

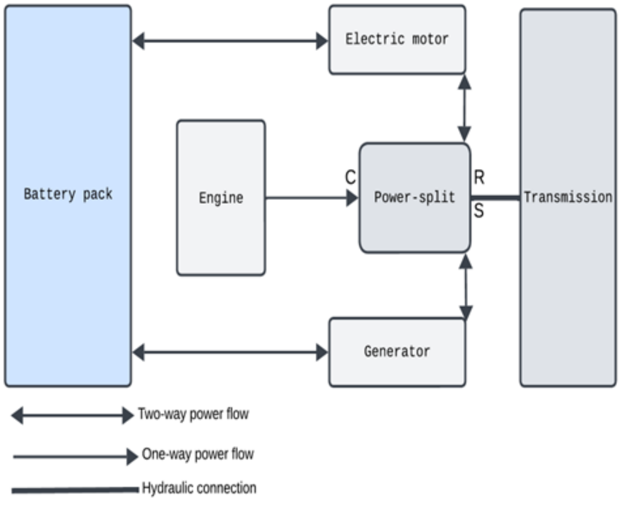

Fig. 1. Hybrid Electric Vehicle (HEV) components/architecture

Generally, a HEV consists of an internal combustion engine (ICE) with a generator and an electric motor, getting power from a powerful battery pack, along with all the necessary components. The way components are utilized and arranged makes them unique and useful. In the series-parallel configuration (ICE), the electric motor and generator are connected with a mechanically coupled device, also known as a planetary gear system through a carrier, ring and sun, respectively. The architecture of a series-parallel HEV can be analyzed by looking at Figure 1, which shows an arrangement of multiple sub-systems incorporated together. The black arrow in the figure represents a two-way power flow from one block to another. The flow of the power depends on the drive cycle factors/driving conditions (such as speed and acceleration), along with the mode of operation of the vehicle (Such as Hybrid mode, Electric mode, or operating on ICE). For instance, during regenerative braking, the power will be provided to the battery and during EV mode or Hybrid mode the battery will provide power to the electric motor. Several drive cycles have been used in this simulation to check the vehicle's response under multiple drastic conditions. Multiple subsections have been modeled accordingly focusing on advanced powertrain optimization and smart logic controllers providing an improved control strategy.

2. Methodology/Overall System Design

The main components or subsystems in this simulation include a longitudinal vehicle body, Internal combustion Engine (ICE), Generator, Electric motor, Battery Management System (BMS), Planetary Gear System (Power-Split Device) and Logic Controllers for the systems used. The specifications/key parameters and powertrain of HEV can be seen in Table 1 and Figure 2, respectively.

Table 1
Specifications/Key parameters of HEV

Vehicle body (Mass)	1256 kg
Aerodynamic drag coefficient	0.25
Engine (Power)	57 kW
Engine (Speed at maximum power)	668.8 rad/s
Electric motor (Maximum torque)	400 Nm
Electric motor (Maximum voltage)	600 V
Generator (Maximum voltage)	600 V
Planetary gear (Ring-sun gear ratio)	2.67
Battery (Peak power)	46 kW
Battery capacity (cell-rating)	7.5 Ah
Battery C-rate	2.00
Battery (Initial state of charge)	100 percent
Battery (Initial voltage)	201.6 V

A. Vehicle Body

The Vehicle body serves as a building block of the model. This Simulink block presents the chassis of a vehicle through which vehicle dynamics can be observed after creating a very accurate and realistic vehicle dynamic model. It accounts for the vehicle mass, gravitational forces acting upon the vehicle, inertia, road inclination, torque and other resisting forces acting on the wheels, aerodynamic drag, pitch and weight distribution along the axles. The block is connected with four longitudinal magic tires. The magic tires are longitudinal tires from 'simscape driveline library', which provides a realistic simulation of tire and ground interaction, creating a normal force between the tires and the surface, considering rolling friction, as shown in Figure 3(b). Each tire has its braking system, taking the deceleration command [0-1] as input from the longitudinal driver block. The deceleration command

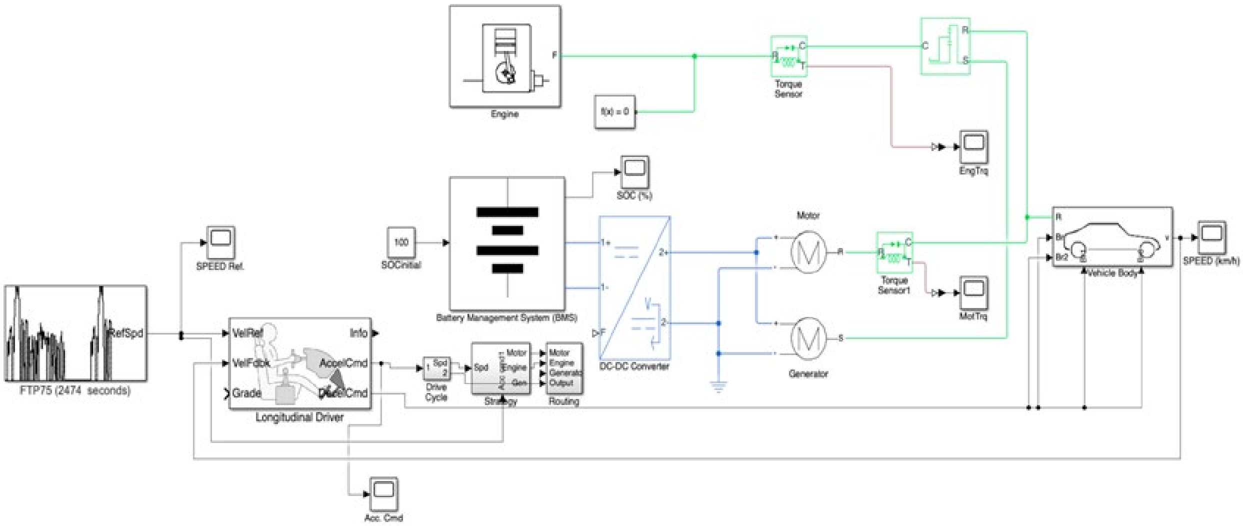

Fig. 2. Overall HEV system modeling

comprises of an input signal from 0 to 1, providing a realistic simulation of the braking system in vehicles as a combination of braking pressure, engine retardation and overall net torque. Every drive cycle has different dynamics, acceleration commands and deceleration commands. These commands/signals are in context with the dynamics of a particular drive cycle. The drive cycle provides a reference speed, which is further fed into a longitudinal driver system block, this block is responsible for generating acceleration and deceleration commands using the data provided by a drive cycle considering all the factors (such as braking pressure, engine retardation with its speed and overall net torque, in result providing a signal from [0-1]). The braking system includes a double-shoe brake with a drum and actuator; the deceleration signal initiates the actuator with pressure, which further results in effective braking. The port H (hub) of the vehicle body is associated with the horizontal motion of the vehicle and is further connected with the H port of the tires, where A serves as an axle of a tire and is connected with another tire as shown in Figure 4. The ports V, Nf, Nr, W and beta are physical ports providing velocity, normal forces acting on the front and the rear end of the axle, headwind velocity and inclination of the vehicle, respectively [10]. Moreover, a transitional position sensor is connected with the hub of the vehicle body to determine the speed and distance traveled. The front axle, along with the wheels, is connected with LSD (Limited Slip Differential), which transmits the torque to the axle, allowing the vehicle to move. LSD is a type of differential that helps to maintain traction on low-grip surfaces while driving on slippery and muddy surfaces, enhancing torque delivery and distribution [11].

As shown in Figure 3(a), the vehicle motion is a result of torque and all other forces acting on it and the vehicle body accounts for all the forces acting on it, for instance, the vehicle inclination (beta), aerodynamic drag and pitch. Where (CG) is the center of gravity and weight acts from the center of gravity. Moreover, an aerodynamic drag of 3 m/s^2 with a drag coefficient of 0.25 is acting on a vehicle, which increases with respect to its velocity. Fd in Figure 3 (a), shows the drag acting on the vehicle, where (Fxf, Fzf) and (fxr, fzr) are the normal forces acting on the vehicle's front and rear wheels, as shown in Figure 3(b). (mg) is the gravitational force acting on a body, which is 9.81 m/s^2.

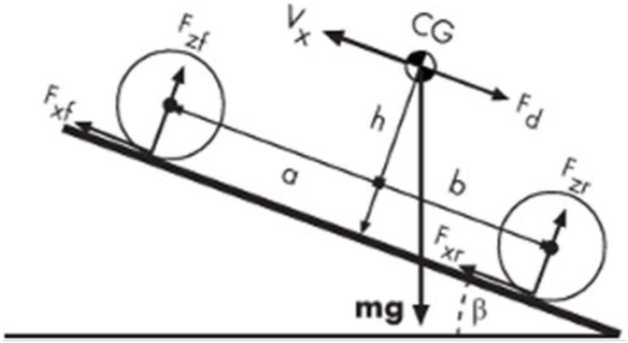

Fig. 3(a). Forces acting on a vehicle body [10]

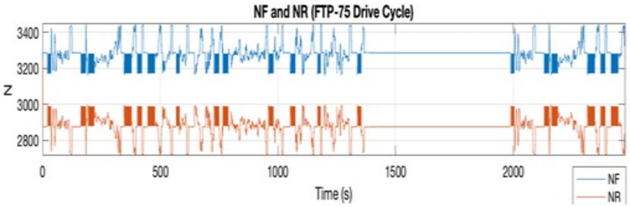

Fig. 3(b). Normal forces acting on the front and rear wheels

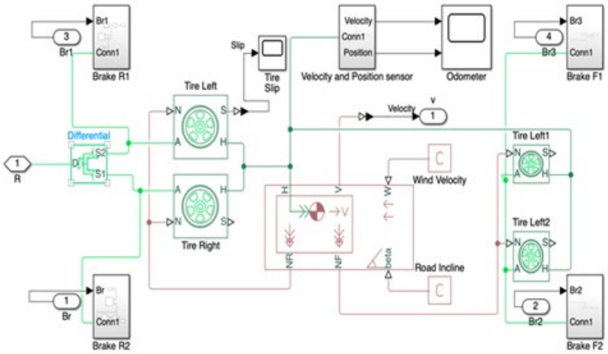

Fig. 4. Vehicle body modeling

B. *Internal Combustion Engine*

A generic petrol engine has been used, connections F and B represent mechanical rotational conserving ports associated with the engine crankshaft and engine block, respectively. As it can be seen in Figure 5, the sub-system consists of ICE with a torque converter along with inertia, mechanically coupled with an automatic variable transmission, with a gear ratio of (3.9), which is further connected with a torque coupling device, also known as a power split device/planetary gear system. Using a Torque converter and transmission with a defined gear ratio in a series-parallel HEV reduces the sudden jerks, lagging and loss of power while transmitting torque or switching between ICE and EM, increasing overall power efficiency and fuel economy [5], [12]. The torque converter is not commonly used in Toyota Prius HEV configuration. However, it has been used by Toyota in other drive-trains, such as the 2018 Toyota Camry UB80E with an automatic transmission [13]. Ports P and FC of ICE serve as physical signal output ports through which engine power and fuel consumption rate are calculated. The block represents a relationship between torque (Nm) and revolution per minute (RPM), which is being modulated by a throttle, as shown in Figure 6.

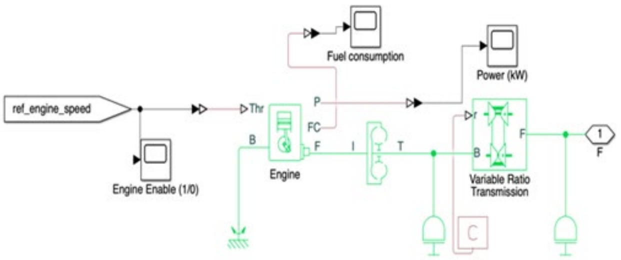

Fig. 5. Internal combustion engine modeling

The internal combustion engine has been modeled by tuning some parameters, including redline control, stall speed and the along with its power. The mentioned parameters have been tuned as 6500 rpm, stall speed as 500 rpm and 57 kW engine (producing approximately 103 Nm torque). Whereas the idle speed controller is tuned to 1000 rpm, allowing the smooth, seamless transition while shifting gears and between power trains, preventing the ICE from stalling immaturely and rough idle. The engine block takes a 'ref engine speed' coming from the controller block as an input, which is further converted in the range of [0,1], which further controls the engine power and acts as a throttle signal, as the model parametrization is set to 'Normalized Throttle'. The engine block uses a programmed relationship between speed and torque. The torque generated is dependent on the power and throttle signal provided to it. The ICE produces the power with respect to the throttle command provided to it, as shown in Equation 1 and Figure 6. It can be analyzed, that when the engine power is increasing, the torque changes with respect to it. Where in equation 1, $g(\varpi)$ represents the function of the engine speed and $P(\varpi,Thr)$ represents the power produced by the engine depending on the engine speed and throttle [14].

$$P(\varpi,Thr) = Thr{\cdot}g(\varpi) \tag{1}$$

Where,
$g(\varpi)$ = function of the speed
Thr = throttle signal

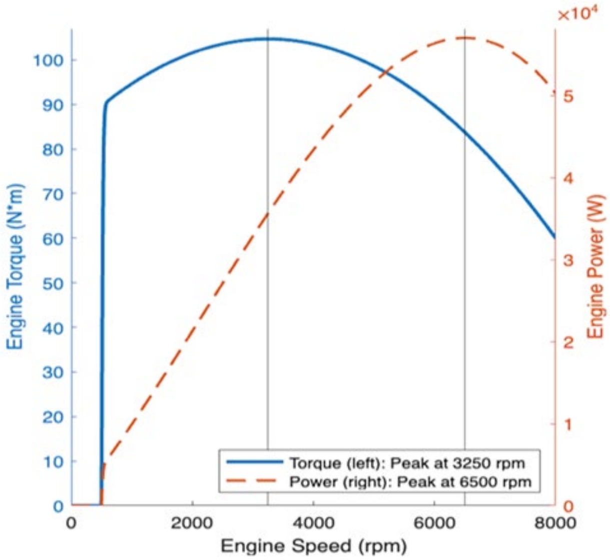

Fig. 6. Internal combustion engine (ICE) Torque vs. Power efficiency plot, with respect to engine rpm

C. *Planetary Gear System*

The series-parallel hybrid electric vehicles (HEVs) consist of a mechanical torque coupling device, allowing higher gear ratios in compact structure, allowing the internal combustion engine (ICE) and electric motors to operate in hybrid, independent and regenerative mode.

The planetary gear system consisting of sun-planet (s, p) and ring-planet (r, p) gears (providing two degrees of freedom) has been modeled using a gear ratio of (2.67). Allowing the smooth transitioning and transmission of the power from the internal combustion engine (ICE) and electric motor, to the final drive shaft distributing the torque with the help of a differential which is further attached to the wheels providing the necessary amount of torque to the wheels, as shown in the figure 7 (b). It has three physical ports, sun, ring and carrier, connected with the generator, motor and drive shaft respectively, as shown in Figure 7 (a). The ring mechanical port finally moves the driveshaft and helps the vehicle to accelerate. The planetary gear system provides geometric and kinematic constraints, as shown in equations 2, 3, 4 and 5. Equation 7 provides the torque transfer equation [15]. Equations 2 and 3, provide a relationship between angular velocities and radius of carrier, sun and planet gears. Overall, equations 2, 3, 4, and 5 represent geometrical constraints for the planetary gear system, playing a vital role in power management and torque distribution. The gear ratio of the planetary gear system has been modeled by using equation 6, it uses the number of teeth on the ring and sun gear along with the radius of the gears, the number of teeth on the ring and sun gear are 32 and 12, respectively. ($gRS\tau S$) in equation 7 is a product of the overall gear ratio of the gear and total torque transfer for sun gear. (τR) provides total torque transfer for the ring gear, as it is responsible for propelling the final driveshaft, as seen in equations 4 and 5. (rR) provides the geometric constraints for the carrier and planet gear, whereas (r_C) accounts for the sun and planet. As a result, equation 7 transfers the total amount of torque through the ring gear. In this simulation, torque transfer losses are considered negligible, whereas the inertia of the gear is (0.001 kg*ms^2).

$$r_C\omega_C = r_S\omega_S + r_P\omega_P \tag{2}$$

$$r_R\omega_R = r_C\omega_C + r_P\omega_P \tag{3}$$

$$r_C = r_S + r_P \tag{4}$$

$$r_R = r_C + r_P \tag{5}$$

$$g_{RS} = r_R / r_S = N_R / N_S \tag{6}$$

Where,

r_C = radius of carrier gear
r_S = radius of sun gear
r_P = radius of planet gear
r_R = radius of ring gear
ω_C=angular velocity of carrier gear
ω_P=angular velocity of planet gear
ω_R=angular velocity of ring gear
ω_S=angular velocity of sun gear
g_{RS}=Gear ratio of ring and sun planet gears
N_R =Number of teeth on ring planet gear
N_S =Number of teeth on the sun planet gear

$$g_{RS}\tau_S + \tau_R - \tau_{loss} = 0 \tag{7}$$

Where,

τ_S = total torque transfer for the sun
τ_R = total torque transfer for the ring

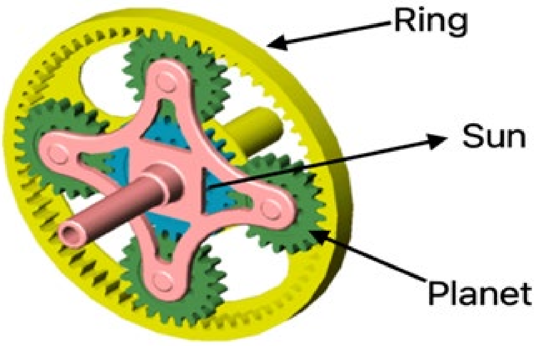

Fig. 7(a). Planetary gear architecture [15]

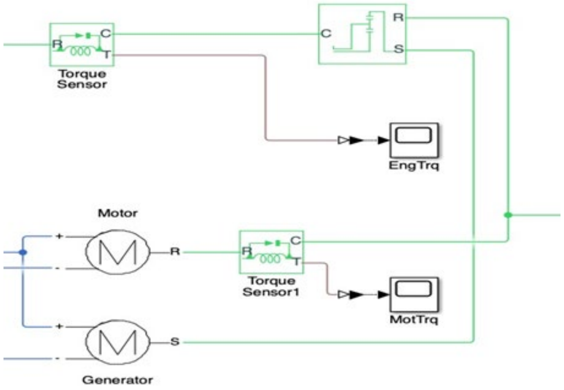

Fig. 7(b). Power-Split device of HEV

D. Electric Motor

A Permanent magnet synchronous motor (PMSM), electric motor has been used in this simulation. This block elaborates working of an electric motor and drive system. The motor is being operated in a torque-controlled mode between the region of [0,400] Nm, depending on the drive cycle and incoming demand of the load from the controller. Many electric motors are available on MATLAB Simulink for modeling but this specific electric motor was chosen for its high efficiency and torque capabilities, it includes a PID control that ensures optimal performance under varying load conditions and allows flexible integration with multiple sub-systems. The rotational shaft (Port R) of the electric motor is connected to the rotational port of the power split device (Port R), which is further connected to the drive shaft. The motor is controlled by a controller logic block, which sends a torque signal and then from the speed controller block, the rpm following the reference torque is calculated, which further gets converted into the torque as an input. The torque signal then goes into a logic block, which is the main decision block of this subsystem, as shown in Figure 8.

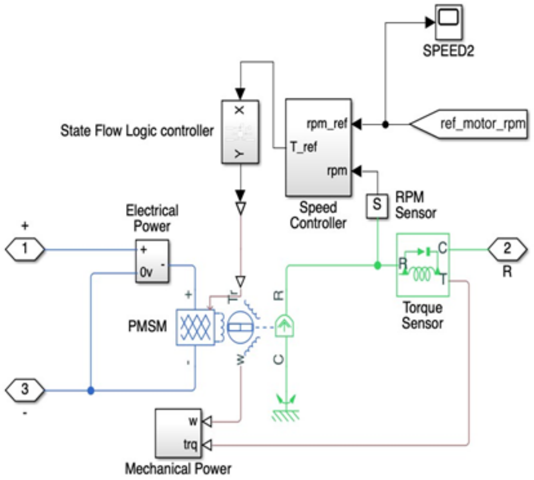

Fig. 8. Electric motor modeling

Multiple power electronics blocks have been modeled to charge the battery; it is responsible for providing the desired voltage to the electric motor from the battery pack and then charging the battery pack again from the regenerative braking when the brakes are applied. To avoid overheating, premature failure and malfunctioning of components, good power quality of the DC network has been considered, allowing the two-way power flow from the battery to an electric motor. Ports 1 and 3, provide connections to the battery from an electric motor.

E. Generator

A synchronous generator model has been used in this simulation which is being operated in a torque-controlled mode. This block serves an important role in charging the batteries of the vehicle when the engine is in motion. The block has two mechanical ports C and R, connected with the vehicle body (Mechanical rotational part) and R which is the rotational part of the generator with the planetary gear system (Port S). Where the plus and minus signs of the generator are connected to the battery pack. The generator acts as a starter for the engine, it keeps the engine under optimal and desired rpm. This block has been modeled using four different subsystems as shown in figure 9. It takes a direct input in the form of torque from the logic controller block, to make sure and correlate the differences in the calculations, an RPM subsystem has been used to ensure the smooth working of the generator. The RPM sensor calculates the RPM of the generator and sends it back to the controller. In addition, some power electronics blocks have been modeled to calculate electrical and mechanical power, as it has to convert the mechanical energy from the engine to electrical energy to charge the battery pack.

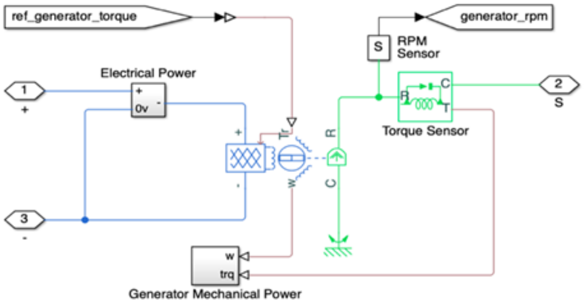

Fig. 9. Generator modeling

F. *Battery Management System (BMS)*

Battery Management System, which is also known as BMS in different lines of fields, is the key and the most important part of any system. It helps to keep a check on the overall battery health, usage of the battery when required and then charging of the battery; it gives a sufficient amount of power and voltage to the system when required. Just like any other system, vehicles also have BMS, which allows the driver to keep track of the charging and discharging of the battery, along with its temperature. This section of the paper presents an analysis and design of the Battery management system. The battery has been designed using equation 8, with characteristics shown in Figure 10(b). The equation derives a relation between the voltage and the remaining charge of the battery, when there is no charge left the battery's voltage will drop to zero [16]. The battery parameters have been modeled using finite battery charge capacity, with a cell rating of 7.5Ah (Ampere per hour) with a C-rate of 2.00. (Vnom) is the Nominal voltage of the battery when there is no load connected. The BMS charges the battery continuously through the generator and regenerative braking but when it drops below 20 percent, the internal combustion engine turns on, to charge the battery and the electric motor does not operate. Since the vehicle is equipped with a regenerative braking system, it allows the vehicle to self-charge, when brakes are applied.

$$V = Vnom*SOC/(1-beta*(1-SOC)) \tag{8}$$

Where,

$Vnom$= Nominal voltage
SOC= state of charge
$beta$= provides a data point, defined by [AH1, V1]

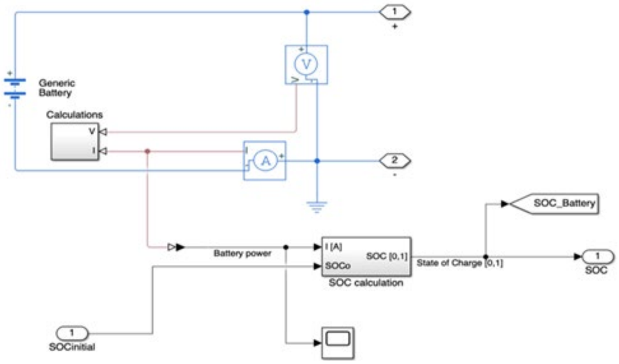

Fig. 10(a). BMS modeling

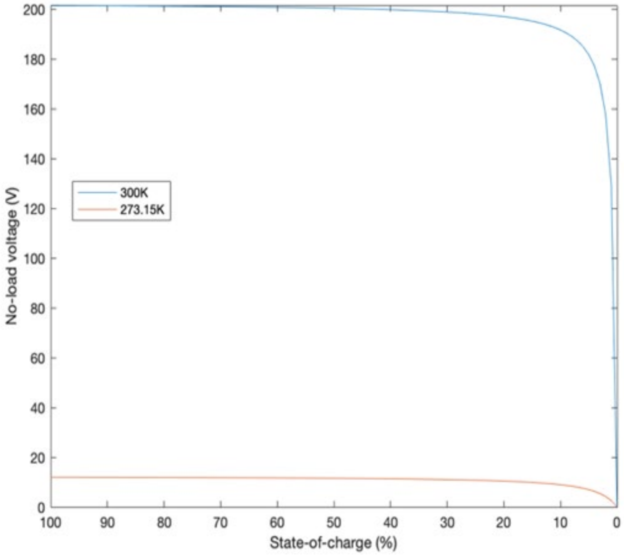

Fig. 10(b). Basic battery characteristics

G. *Logic Controller/Drive Cycles Used*

Several logic controllers have been used in this simulation overall, but the ones responsible for the major decision-making lie in the engine/generator and electric motor. While incorporating multiple subsystems in a simulation it becomes very tricky to manage the operation of multiple components when required [17]. Thus, stateflows and boolean gates have been used to create meaningful logic for these subsystems. Stateflow charts and boolean gates in Simulink are used in energy management systems to handle complex decision-making and control logic of the system (allowing state-based control), providing real-time optimization, along with task scheduling and fault detection in hybrid systems. Moreover, multiple state transitions within a subsystem can be implemented using state flow, providing efficient code while designing algorithms [18]. Whereas Boolean gates help in precision control when it comes to managing complex interactions between ICE and electric motor. MPC (Model predictive control), PID (proportional integral derivative) and machine learning are some other methods through which the logic of the vehicle can be derived but these methods are best used when it comes to the tuning of subsystems. In comparison, Stateflow and Boolean gates combined provide the best results when it comes to interactive decision-making and precision control for hybrid systems. To test the working of all these subsystems, multiple drive cycles have been used. The drive cycle is an input comprising of an acceleration command and a deceleration command with respect to the time. It helps to overlook the overall working of a simulation in various environments [19]. FTP-75, NEDC, HWFET and JC-08 are some of the drive cycles used in this simulation. These drive cycles have been hand-picked to simulate the vehicle in multiple and diverse environments for detailed analysis. Specifications of the drive cycles can be seen in Tables 2, 3, 4 and 5. After simulating them, the performance, efficiency and mileage of the vehicle can be analyzed within the city during peak hours or on a highway.

Table 2
Drive cycle 1

FTP-75	
Total Test Period	2,747 sec (41.5 minutes)
Maximum Speed	91.9 km/h (56.7 mph)
Average Speed	31.67 km/h (19.68 mph)
Total Stops	23
Total Test Length	17.72 km (11 miles)

Table 3
Drive cycle 2

NEDC	
Total Test Period	1,184 sec (19.73 minutes)
Maximum Speed	119.29 km/h (74.56 mph)
Average Speed	33.02 km/h (20.64 mph)
Total Stops	13
Total Test Length	10.86 km (6.79 miles)

Table 4
Drive cycle 3

HWFET	
Total Test Period	765 sec (12.75 minutes)
Maximum Speed	94.4 km/h (59.9 mph)
Average Speed	77.12 km/h (48.20 mph)
Total Stops	1
Total Test Length	16.41 km (10.26 miles)

Table 5
Drive cycle 4

JC-08	
Total Test Period	1,204 sec (20.6 minutes)
Maximum Speed	81.6 km/h (51 mph)
Average Speed	24.4 km/h (15.28 mph)
Total Stops	23
Total Test Length	8.172 km (5.10 miles)

1) *Internal Combustion Engine (ICE)*

Every drive cycle has an acceleration command and deceleration command along with its reference speed (provided through the longitudinal driver block). To model the internal combustion engine (ICE) logic controller, speed, acceleration and battery state of charge (SOC) have been used as input. For instance, if the speed is above 65 km/hr or the acceleration command lies between [0.6-1.00], the engine along with the generator, will begin to operate, However, if the acceleration command lies between [0.8-1.00], the electric motor will also assist, in a scenario where instant torque is required. If the speed is below 65 km/hr only the electric motor will work but if the acceleration command is in between [0.5-1.00] then the engine will be operational, providing the torque and charging the battery. The logic is made considering three constraints: acceleration command, speed of the vehicle and battery health. If the battery is below 20 percent, only the engine will be operational (maintaining a steady 1000 rpm) and will assist in charging the battery. If the vehicle comes to rest after a brief period, the engine comes on to recover the battery's state of charge, thus resulting in an overall improved battery optimization system. A combination of AND, NOT and OR gates has been used to create this logic, as shown in Figure 11., boolean gates are very well known for simplifying logical operations, functions and improving the clarity of codes.

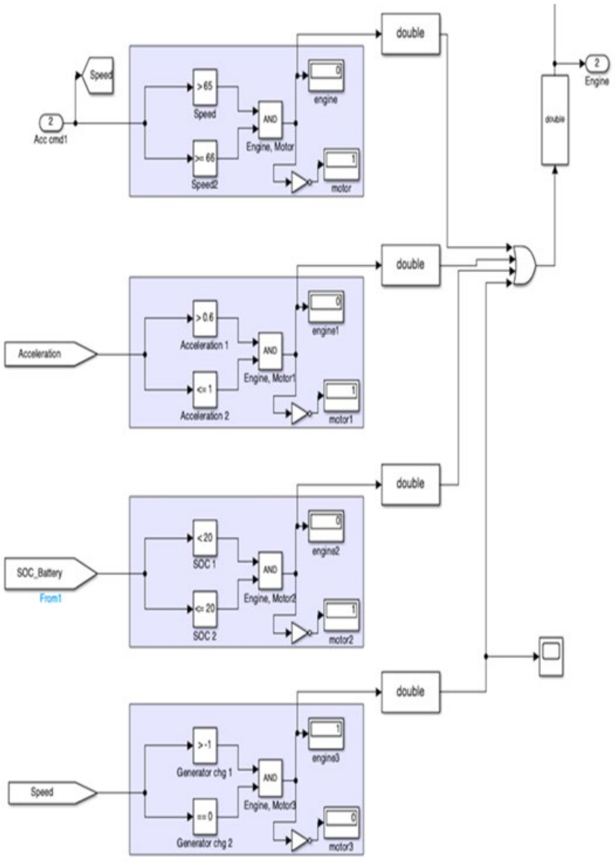

Fig. 11. ICE Logic using Boolean gates

2) *Electric Motor*

Whereas the electric motor has a very intelligent logic controller comprising two blocks, rpm sensor calculation and a state-flow subsystem, with three top priorities. To drive the load solely, the other one is regenerative braking when brakes are applied and assisting the internal combustion engine (ICE) when peak performance is required. The rpm block calculates the rpm and sends it to the controller to maintain a steady rpm. During the start-up mode, the electric motor helps the vehicle to propel; then, it switches between the internal combustion engine (ICE) and electric motor according to the logic provided by the boolean gates and state flow. The state flow block also takes three inputs, defined as acceleration command, speed of the vehicle and state of charge (SOC). If the acceleration command lies between [0.00-0.5] and [0.8-1.00] the motor will be operational in various modes, such as regenerative mode, cruise mode, start-up mode and deceleration mode, as shown in

Figures 8 and 12, respectively. This research introduces an improved control strategy, which does not restrict the vehicle by its speed. The vehicle will still be assisted by an electric motor if it is cruising at 120 km/h and the internal combustion engine (ICE) will be operational, maintaining a low and steady rpm, which helps to recover the battery's state of charge and assists the vehicle. However, if the battery state of charge (SOC) goes below 20 percent, then the electric motor will not operate and the vehicle will only be propelled by the internal combustion engine (ICE). Conventional HEVs consider speed as their switching mechanism between ICE and electric motor, but if it is done through the acceleration/Throttle command (Gas pedal), it results in a higher efficiency and optimal performance, which further eradicates the shifting lag between ICE and electric motor. Figure 8 shows the modeling of the electric motor subsystem, ports 1 and 3 are the positive and negative signs of the electric motor, when the motor drives a load, it takes voltage from the battery, but when brakes are applied or the engine is in the motion, it acts a generator/traction motor to provide regenerative braking and then turns off respectively, so ports 1 and 3 are bidirectional along with the DC-DC converter which allows to charge and discharge battery accordingly.

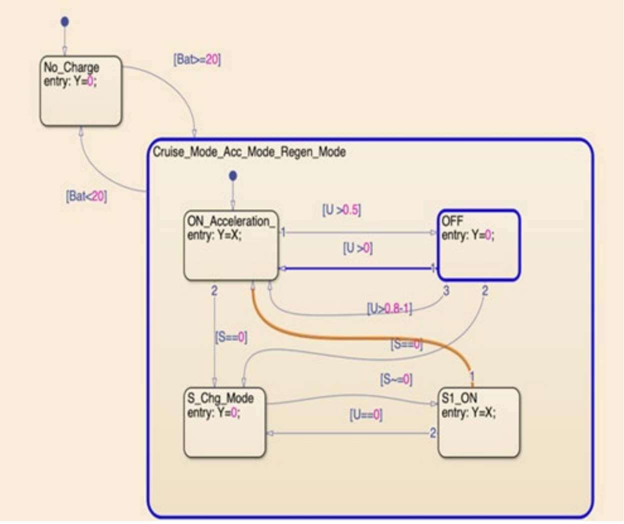

Fig. 12. Electric motors logic using state-flow

3. Results and Discussions

FTP-75 (Federal Test Procedure) simulates urban driving conditions to check the fuel economy of light-duty vehicles with some congestion and frequent stops. The drive cycle has four phases, including the cold-start transient phase, stabilized phase, hot soak phase, and hot-start transient phase, a total consisting of 2,474 seconds, as mentioned in Table 2 [20]. The implementation of the FTP-75 drive cycle yielded some important results. During the cold start, the internal combustion engine (ICE) and electric motor, both in hybrid mode, propel the vehicle, the vehicle achieves a high speed of 91.9 km/h. After analyzing the internal combustion engine (ICE) graph in Figure 13, it can be seen that the internal combustion engine (ICE) is operational, but it maintains a very low rpm, providing 21kW power when the vehicle crosses 65 km/h. During the second and third phases, rapid acceleration and torque are required because of the frequent stops, in response the ICE and electric motor are working, respectively, as can be seen in Figure 13, while charging the battery with the help of a generator and regenerative braking. Between the third and fourth state, for about 808 seconds, the vehicle is completely at rest and at this time, the electric motor is not providing any kind of torque instead, the engine is being used to charge the vehicle battery, maintaining a low and steady rpm. After the fourth phase, there is a Hot-start transient period where the vehicle achieves a maximum speed of 91.9 km/h and then initially comes to rest. While simulating the series-parallel hybrid electric vehicle under FTP-75, it has shown impressive results when it comes to SOC, Engine, Electric Motor power and torque requirement. The whole drive cycle lasted 2,474 seconds (41.5 minutes), and the SOC dropped from 100 percent to 62.28 percent, achieving an average of 15.76 kilometers per liter over the entire cycle, which is quite promising for a series-parallel HEV.

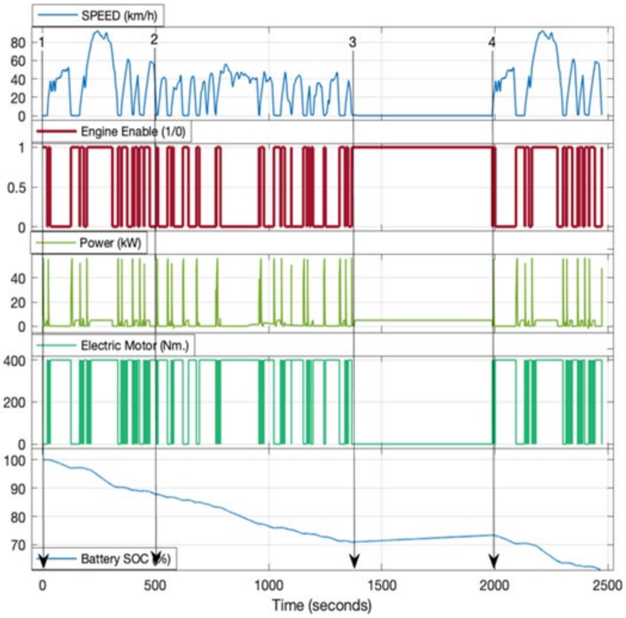

Fig. 13. FTP-75 drive cycle simulation results

NEDC (New European Drive Cycle) is based on aiming at the fuel economy of passenger vehicles used in some parts of Europe, consisting of a total of 1206 seconds. The purpose of using the NEDC drive cycle in this simulation is to check the vehicle's response while driving under 50 km/h within the city and to analyze the response towards aggressive driving. NEDC is a combination of UDC and EUDC, providing an environment of urban and extra-urban driving conditions. NEDC drive cycle can be divided into three phases; the first phase is city driving under 50 km/h with frequent stops consisting of approximately 800 seconds, where the vehicle is being propelled by ICE and mostly electric motor, the electric motor also assists in regenerative braking throughout. The second and third phase provides driving at a higher speed and the vehicle achieves a high speed of 120 km/h, during this phase, the engine and ICE are being used in hybrid mode to propel the vehicle because of the rapid acceleration demand from the controller. The power drawn from the engine during these two phases depends on the throttle/acceleration command, as it is being modulated by the throttle command, which results in a very smooth and low rpm, saving fuel. The cycle demonstrated a smooth acceleration and deceleration along with improved battery management since the SOC dropped from 100 percent to 71.11 percent over the entire cycle, resulting in a better control strategy between ICE and electric motor, as it is also being charged ICE and regenerative braking, as shown in Figure 14.

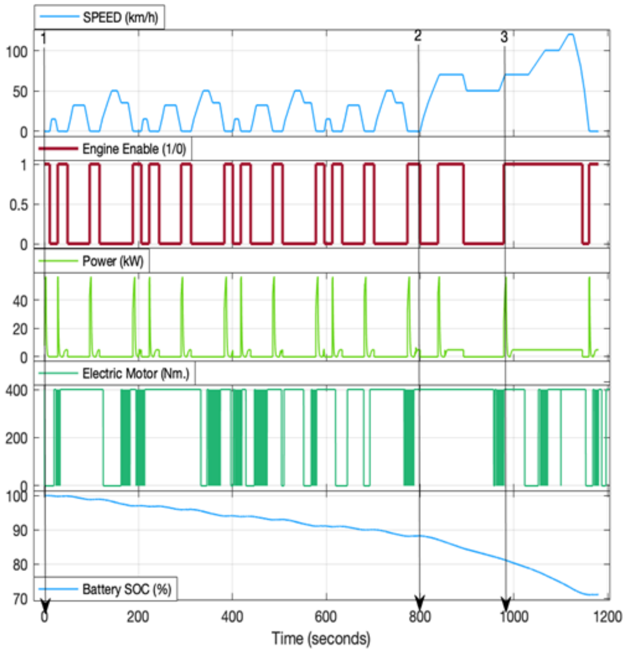

Fig. 14. NEDC drive cycle simulation results

HWFET provides a drive cycle of 765 seconds, approximately 12.75 minutes, on a highway without any stops. It is a combination of cruising at a high speed and rapid acceleration. The cycle can be divided into three parts. The first part is rapid acceleration from 0 to 300 seconds. Initially, the vehicle is being propelled by the motor and engine in response to the rapid acceleration through the gas pedal. During the second part, the vehicle is cruising and is mostly propelled by the electric motor, even though the vehicle has a speed ranging between (70 km/h-94.4 km/h). During the last period, the vehicle comes to rest after 165 seconds and the motor acts as a generator to charge the batteries along with the engine. The power-train control strategy introduced in this research allows the vehicle to run on an electric motor solely, even when it is cruising at a high speed, resulting in a better fuel economy. One of the main objectives of this research was to save fuel, improve the battery's state of charge (SOC) and develop an improved control strategy that only enables the engine when it is required. In case high acceleration and instant torque is required, then the motor and ICE will work together in hybrid mode to attain the desired results and optimal driving experience. The whole drive cycle lasted 1108 seconds (12.7 minutes), and the SOC dropped from 100 percent to 84 percent under high rpm and speed, as shown in Figure 15.

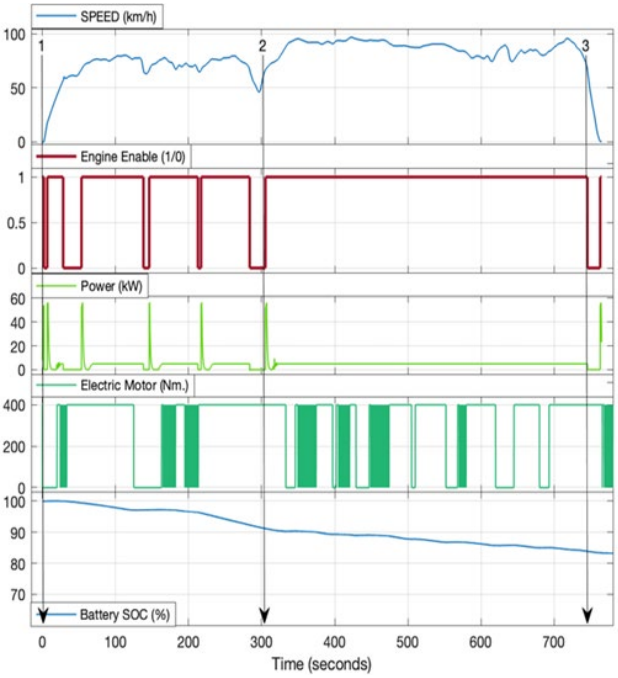

Fig. 15. HWFET drive cycle simulation results

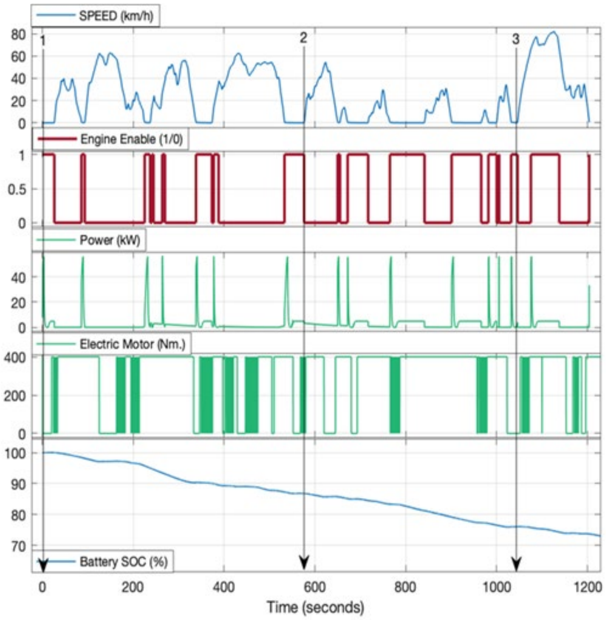

Fig. 16. JC-08 drive cycle simulation results

Japanese JC-08 provides a drive cycle for light-duty vehicles/passenger cars and represents driving conditions in a city during peak hours and congestion, along with rapid acceleration and deceleration. JC-08 drive cycle plays an important role in determining the vehicle response while idling, regenerative braking, battery health, power distribution between ICE and the electric motor, rapid acceleration and deceleration. The vehicle speed result graph can be divided into three parts respectively, the first part lasts from (0-580 seconds), including multiple stops and rapid acceleration. During the first part, the vehicle is being propelled by the electric motor and the ICE is assisting, when there is a demand of rapid acceleration. The second part also shares the same characteristics as the first part. The frequent stops in the drive cycle result in frequent braking enabling regenerative braking to effectively recapture the battery's health and maintain it over the entire cycle. The rising peaks shown in Figure 16, (SOC Graph) represent regenerative braking. During the last part, the vehicle attains a high speed of 81.6 km/h and then eventually comes to rest. The power-train control strategy introduced in this research has worked effectively to maintain power distribution between ICE and the electric motor in order to optimize the fuel economy of the vehicle which further maintains the battery charge level, as it only dropped from 100 percent to 75.98 percent over the entire cycle.

Figure 17(a) depicts the power losses of HEV's electric motor being operated under the FTP-75 drive cycle. The losses have been observed while switching between power trains (mechanical and electrical), the losses are usually copper losses due to the resistance in the motor windings because of operating under high rpm and drawing a significant amount of current, as shown in Figure 19. The simulation results show that the power losses varied with the driving conditions, as it can be observed during the 3-4 period in Figure 14, the vehicle speed is zero and is at rest, so the power losses are also zero, as the electric motor is not operational, as shown in Figure 17(a). The power losses of the electric motor have some implications on the whole HEV power-train, as more power is being withdrawn from the battery, affecting the overall battery health and fuel efficiency of the vehicle.

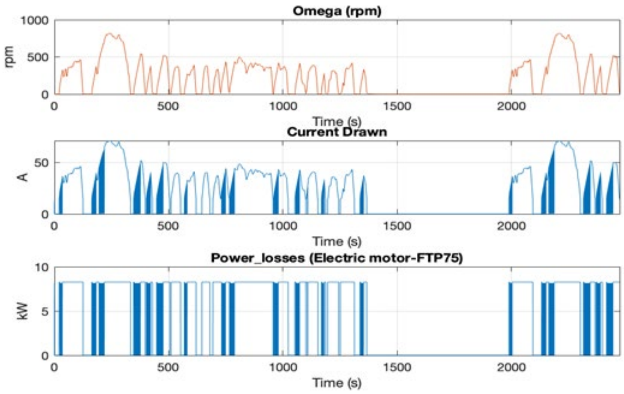

Fig. 17(a). RPM, current drawn and power losses (kW) of electric motor under FTP-75

Figure 17(b) depicts an electric motor efficiency plot, it holds a lot of significance in evaluating the performance of an electric motor in a series-parallel hybrid architecture, providing an analysis of the efficiency of an electric motor with respect to rpm and torque. The efficiency is represented by a color bar on the right side, which is dependent on the rpm of the motor, it shows where the motor can be operated most efficiently. The motor achieves the highest efficiency at the intersection of the green, yellow, and blue zones, under 1000 rpm. In this simulation, the motor is being operated under 1000 rpm to achieve the best and optimal performance, as shown in Figure 17(a).

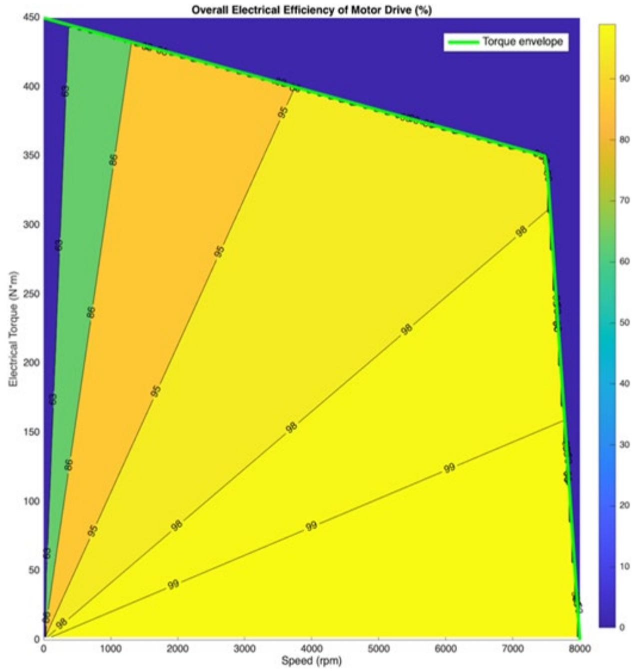

Fig. 17(b). Electric motor efficiency map (%) with respect to torque (Nm.) and speed (rpm)

Figure 18 shows the battery power losses of HEV under the FTP-75 drive cycle. The losses are mainly Internal resistance, self-discharge and thermal losses. Since the power train is hybrid and requires switching more often between power trains, the power losses are generally greater when it comes to the battery, as it is charging and discharging at the same time. Thermal losses are mainly due to the high power demand when the electric motor is operational. Whereas internal resistance losses are caused by the high current draw.

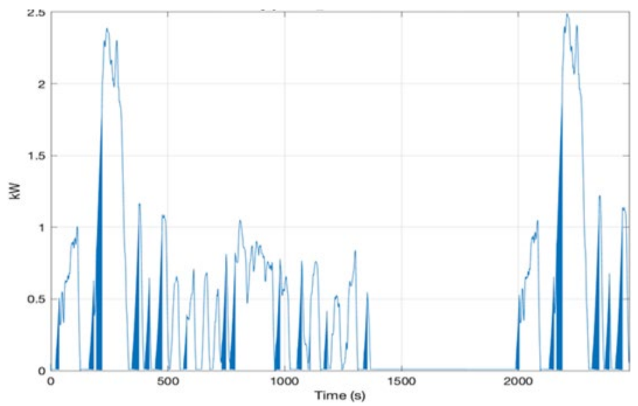

Fig. 18. HEV Battery power losses (kW) over FTP-75

Figure 19 depicts the amount of fuel consumed in kg/s over the drive cycles, with an average of 0.0004544, 0.0004170, 0.0005819, and 0.0003894 kg/s, respectively, providing an overall fuel average of 54.369 mi/gal and 23.115 km/l after conversion from kg/s to respective units, utilizing the fuel used and distance covered according to the drive cycles provided, as shown in Table 6. Upon results analysis (Figures 13, 14, 15 and 16), it can be observed that the vehicle is being propelled by an electric motor most of the time and in hybrid mode. The battery is being charged by ICE and regenerative braking. Moreover, lab testing conducted on a third-generation Toyota Prius by the US Department of Energy's Advanced Vehicle Testing Activity (AVTA) states that it has a mileage of 50 mi/gal (combined city and highway) [21]. Whereas the fourth generation 2023 Toyota Prius (LE FWD model) has a mileage of 57 mi/gal (Highway and city), according to EPA [22].

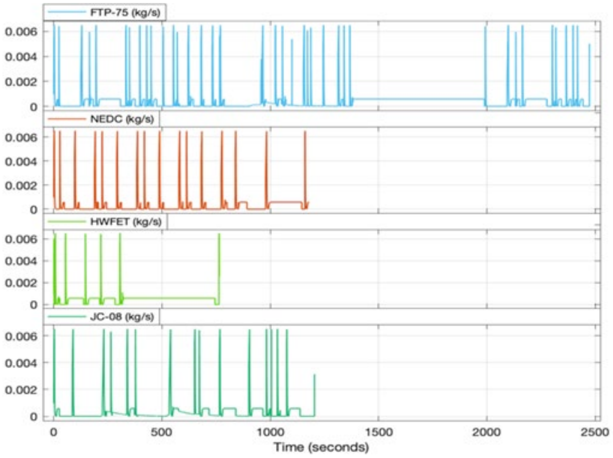

Fig. 19. Fuel consumption results using FTP-75, NEDC, HWFET and JC-08, respectively

Table 6
Fuel consumption (km/l, l/100km and mi/gal)

Drive Cycle/Calculations	Overall Fuel Consumption
FTP-75 (17.72 km)	1.124 liters, 15.76 km/l
NEDC (10.86 km)	0.492 liters, 22.07 km/l
HWFET (16.41 km)	0.445 liters, 36.87 km/l
JC-08 (8.17 km)	0.460 liters, 17.76 km/l
Overall average (km/l)	23.115 (Highway and city)
Overall average (l/100km)	4.326 (Highway and city)
Overall average (mi/gal)	54.369 (Highway and city)

4. Conclusion

The paper presented an effective control strategy for modeling series-parallel HEVs using MATLAB Simulink software. The research focused on an improved control strategy used in HEVs and how it restricts the vehicle to use an electric motor at high speeds. The methods introduced in this research eradicate the shifting lag and provide better control optimization over ICE and electric motor, improving the overall battery management system, energy, and power distribution channel. A new set of architecture has been introduced using a torque converter and automatic variable transmission while modeling the ICE sub-system. The architecture eradicates the jerks while switching between the electrical and mechanical drive-trains, minimizing power losses and delivering a sufficient amount of torque when required, without any lag. The primary objective of this research was to bring out a control strategy that effectively works under dynamic environments, maintaining the best standards of fuel efficiency. To test the proposed control strategy, multiple drive cycles, including FTP-75, NEDC, HWFET and JC-08, have been simulated to test the power-train capability and rigidness under various driving conditions provided by the drive cycle. Overall, the vehicle has maintained its SOC above 60 percent under every drive cycle, providing an impressive average mileage of 54.369 mpg over the provided drive cycles (City + Highway). Ultimately, the method introduced in the control strategy and logic differs from the one used in conventional HEVS, making it unique, as speed is not the only thing it uses for the shifting. The control strategy/algorithm includes a shifting mechanism between ICE and the electric motor that is based on the vehicle acceleration/throttle command, speed and SOC. As a result, it proves to be fuel-efficient within the city and on the highways as well, as it also allows the vehicle to propel on an electric motor most of the time.

Overall, the paper underlines the significance of introducing new methods in the automobile industry and highlights the role of advanced control strategies in the optimization of a Series-Parallel Hybrid Electric Vehicle (HEV) by using capabilities of State flow charts and MATLAB Simulink in depth. The detailed modeling validates a clear picture of the efficacy of control strategy and working of a Hybrid system within the city and on the highway under various drive cycles, along with the analysis of how the mileage of hybrid vehicles on highways can be improved. The research not only deepens the understanding of Hybrid systems but also lays the groundwork for future innovations in predictive control algorithm strategy. As this field progresses, it is anticipated that the development of an even more precise control strategy and modeling of Hybrid Electric Vehicles will foster the analysis and its applications in sustainable automotive technologies.

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