Chapter 4

Fuzzy Logic Tuned Energy Management Strategy to Improve Fuel Economy in an HEV

A hybrid electric vehicle is powered by the ICE and the battery-powered electric motor. These sources have specific operational characteristics, and it is necessary to match these characteristics for the efficient and smooth functioning of the vehicle. The nonlinearity and uncertainties in HEV model call for an intelligent controller for energy sharing between battery and ICE.

The vehicle performance greatly depends upon torque demand, battery state of charge, and regenerative braking. By considering these, a fuzzy logic-enabled EMS is designed and implemented in this chapter. This EMS allows engine and motor to maneuver in their efficient operating regions. The designed control strategy follow the driver commands and regulations on vehicle performance.

The MATLAB/Simulink is used to carry out simulations, and then the whole system is validated in real-time on hardware in the loop testing platform. This work employs an FPGA based MicroLabBox hardware controller to validate real-time behavior. The proposed scheme results in better fuel economy, faster response, and almost nil mismatch between desired and achieved vehicle speeds. The fuzzy logic-based EMS for HEV has been simulated and validated for various driving cycles.

4.1 Introduction

The key feature in modelling a HEV is its power flow control between available energy sources. The main aim of any good control approach is to satisfy the power demand by minimizing the consumption of liquid fuel, thereby reducing the harmful emissions without degrading vehicle performance.

There are various types of controllers available which can be used to achieve the optimal split of energy between ICE and EM. The conventional algorithm does not guarntee the operation of EM and ICE in the efficient region, and hence optimal use of the sources cannot be achieved. This results in poor efficiency of the vehicle. Therefore intelligent controllers are required to achieve the optimal power split in an HEV.

4.2. Literature review based on fuzzy logic energy management strategy for hybrid vehicles.

In [258], an FLC has been proposed for a parallel HEV, to balance the battery charge, improve the driveability of the vehicle, and decrease the NOx emissions. In [176], the author has developed an intelligent energy management agent (IEMA) and driving condition based FLC, for judicious power split. The simulation was carried out on the UDDS and nine other drive cycles. The results proved that the projected IEMA provides a better solution for parallel HEVs. In [259], [260], the author has presented a new idea of controlling the power of engine and speed in a power-split HEV using FLC for enhanced performance. This approach uses fuzzy gain scheduling to determine appropriate gains for the PI controller based on the operating conditions of the system. In [261], the author has designed an FLC, which considered the input parameters like power demand, the speed of the vehicle, SoC, and optimized the system efficiency. A numerical optimization algorithm has been used to set the engine operating points for getting higher efficiency using fuzzy set theory [262]. In, [263], the objective has been optimized by converting the used motor energy in the form of fuel consumed for a parallel HEV by using fuzzy multi-objective optimization. In, [264], a rule-based algorithm has been presented using FLC for a plug-in parallel HEV to improve efficiency. Lower rates of decline in SoC and fuel consumption was seen using the FLC as compared to traditional rule-based algorithms. In, [265], a predictive EMS using FLC for a parallel HEV based on velocity and reinforcement learning has been presented. In, [266], the author has introduced an intelligent genetic algorithm optimized FLC for a parallel-HEV. The engine target torque, demanded torque and battery SoC serve as inputs to FLC. The torque distribution coefficient between EM and ICE is the output variable. The experimental information and the outcomes demonstrate that the proposed control methodology ensures balanced charging and discharging of the battery, minimizes fuel consumption, avoids the production of the peak torque from the engine, reduces emissions and improves the vehicle performance. In [267], the author has proposed an improved self-tuning fuzzy proportional integral for HEV.

In [268], a new quantity known as BWS (working state of battery) has been used, which is based on battery terminal voltage and SoC. The BWS uses an FL based energy management scheme for a plug-in series HEV to decide on the power split between the battery and the ICE. The results proved their superiority over others in [269] for a series HEV, where fuzzy logic was used as an EMS. In [270], has proposed an FL algorithm to ensure good drivability (comfort) for optimal control of HEV. An FLC has been used to control the clutch transmitting required torque. The simulation in MATLAB/Simulink and HIL tests were carried out [271]. Reza Ghorbani presented the conversion of HEV into PHEV, and FLC was used for a battery energy management system [272]. In [273] & [274] the overall efficiency of a fuel cell/battery hybrid vehicle is maximized by using FLC for power distribution of the vehicle. Simulation results proved that the optimally designed and controlled hybrid vehicle could provide good fuel economy and improve the overall system efficiency.

As per the literature review presented in [169], FLC offers lesser complexity, computational time, and optimal global solution. Therefore, FLC has been used in this work. FLC can obtain the global solution to a constrained problem, making it a very powerful tool in control applications. This chapter aims to develop a Fuzzy logic (FL) based controller (FLC) to get the optimal power split between ICE and EM while fulfilling the driver's speed and torque demands and compelling the engine to work in its efficient region.

FLC can be implemented in real-time easily and effectively, with tracking of every step change. The essential requirement is framing of the proper rules which govern the controller. These rules should take care of vehicle performance governing parameters, like torque requirement, speed, battery SoC, and regenerative braking. Braking is a very important factor which was not considered by other past work in an effective manner.This work accounts for this gap and the brake (regenerative) power has been considered in formulating the FLC rules. The proposed FLC takes Torque, SoC, and brake position as input parameters, aiming to obtain the best fuel economy. The speeds of ICE and EM are chosen for higher efficiency.

From the literature review, the following gaps has been concluded.

1. The series-parallel configuration has not been much explored for the optimization using FLC.
2. Brakes (regenerative energy) is not considered as an input to the FLC.
3. The efficient regions of operation for both the sources (EM and ICE) are not considered as constraints.

Based on these research gaps, this chapter proposes to make the following contributions.

1. Involvement of three crucial & necessary parameters and the constraints as given below to frame the FLC rules

A. State of Charge

It ensures the durability and extension of battery life.

B. Torque

Based on the efficient operating region (Fig. 4.2) and the constraints (Eq. 4.22), the contribution of each source is identified to fulfil the torque demand.

C. Brakes

This parameter has not been explored much for the formulation of fuzzy rules. This is a unique feature of this strategy. Regenerative braking allows recuperation of energy during deceleration of the vehicle which is used to recharge the battery of HEV. It helps in minimizing the energy lost while driving and decreases fuel consumption. The braking energy in urban field may reach up to more than 20% of the total traction energy. In large cities, it may reach up to 50% [275]. The regenerative braking significantly improves the battery energy economy of HEV.

D. Efficient region of operations for both the sources are considered as one of the constraints along with other constraints as in Eq. 4.22.

2. Employment of a series-parallel HEV, which is less explored by researchers.

3. HIL validation of the complete system using MicroLabBox hardware controller.

4. Improved Fuel economy .

4.3. Series-Parallel configuration and its operation

The configuration of the power train greatly impacts the performance of an HEV. In this work, a series-parallel configuration is considered as in Fig. 4.1 and involves the design of ICE, ESS, fuel consumption, and vehicle dynamics.

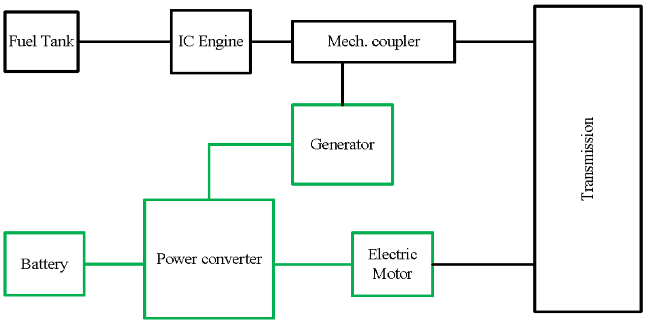


Fig. 4.1 Series-Parallel Configuration of HEV

The series/parallel drive trains combine the advantages and complications of the parallel and series drive trains. The engine can both drive the wheels directly (as in the parallel drivetrain) and can be effectively disconnected, with only the EM providing power (as in the series drivetrain). A popular hybrid drivetrain is the Toyota Prius The series/parallel drivetrain performs better and consumes lesser fuel than either the series or parallel systems alone. The working model of this configuration has been described below through various modes.

4.3.1 EV and regeneration mode

In EV mode, EM is only working, and the rest of the sources are shut off. In an electric drive, the EM operates as a motor and during regeneration, it acts as a generator. This is quite similar to the series mode in HEVs.

4.3.2 Normal driving mode

In this mode, the engine is ON, and it is also known as cruise mode. The power of the engine is split into two parts; one part propels the wheels and other charges the battery.

4.3.3 Battery charging mode

In this mode, the engine is running and only charging the battery to maintain its SoC level. This mode is utilized during an idle stop or when the vehicle is parked.

4.3.4 Power boost mode

This mode is similar to the normal drive mode; the only difference is that the engine alone cannot deliver enough power to accelerate or climb up a hill or to have high acceleration. Therefore the energy from the battery aids to the ICE using EM, i.e. both sources provide power together.

4.4. The vehicle dynamics, specifications and its components

The power-split HEV configuration has been employed in this work. The reason behind making a choice for this configuration is to exploit the advantage of series and parallel configurations. The configuration of the vehicle has been shown in Fig. 4.1. The driving force (f_t) required for the vehicle can be calculated by

$$f = f_l + f_g + f_{rr} + f_{wind} \tag{4.1}$$

The terms used in the above equation have been explained below:

$$f_l = mV^{\bullet}_{vehicle} \tag{4.2}$$

$$f_g = mg\sin(\alpha) \tag{4.3}$$

$$f_n = mg\cos(\alpha) \tag{4.4}$$

$$\left.\begin{aligned} f_{rr} &= mg\cos(\alpha)\times C_{rr} \\ C_{rr} &= 0.01\times\left(1+\frac{3.6}{100}\times V_{vehicle}\right) \end{aligned}\right\} \tag{4.5}$$

$$f_{wind} = \frac{1}{2}\times P_{air}\times C_d\times A_{ya}\left(V_{vehicle}+V_{wind}\right)^2 \tag{4.6}$$

In the above equations the f_t is the driving force (N) of the vehicle, f_l is the vehicle inertia force (N), f_{rr} is the rolling resistance force (N), f_g is the force of gravity of the vehicle (N), fn is the normal weight force of the vehicle (N), f_{wind} is the wind resistance force (N), α is the road slope (degrees), m is the weight of vehicle (kg), $V_{vehicle}$ is the speed of vehicle (m/s), $\dot{V}_{vehicle}$ the acceleration of the vehicle (m/s^2), g is the gravitational acceleration (m/s^2), p_{air} is the air density (kg/m^3), C_{rr} is the rolling resistance coefficient, C_d is the aerodynamic coefficient, A_{ya} is the surface area of the vehicle (m^2), V_{wind} is the wind speed (m/s). Some of these parameters are defined as fixed vehicle parameters and some of them change dynamically [276], [277].

The torque generated in mechanical systems during the transmission can be calculated by using Eq. (4.7). The Eq. (4.8) is used to calculate the driving power of the vehicle and Eq. (4.9) calculates the wheel torque and the angular speed of the wheel can be calculated using Eq. (4.10).

$$\tau_t = f_t r_w \tag{4.7}$$

$$P_t = f_t V_{vehicle} \tag{4.8}$$

$$\tau_w = \frac{\tau_t}{2} \tag{4.9}$$

$$\omega_w = \frac{V_{vehicle}}{r_w} \tag{4.10}$$

Where $V_{vehicle}$ is the speed of the vehicle (m/s), τ_t is the torque (Nm), τ_w is the wheel moment (Nm), r_w is the wheel radius (m), ω_w is the angular speed of the wheel (rad/s), P_T is the drive power (watt). By calculating the required power for the movement of the vehicle by considering the given equations, the drive system can be designed, and the most suitable drive system can be selected for the vehicle.

The Table. 4.1 represents the parameters of the vehicle considered during simulation

Table 4.1 Vehicle parameters

Components	Values
Tyre radius	0.3m
Wheel inertia	0.1
Vehicle glider mass	918 kg
Aerodynamic drag coefficient	0.2600
Vehicle gear ratio	1.3
Final drive ratio	3.93
Distance from the center of gravity of front axle	1.3500m
Distance from the center of gravity of rear axle	1.3500m
Gasoline density	750*10^{3}gramsmeter^{-3}
Frontal Area	2.160m^2
Transmission gear ratios	1st-3.46, 2nd-1.75, 3rd -1.1, 4th-0.86. 5th-0.71, Final drive-3.21

4.4.1. Motor drive

The BEV and HEV mostly use permanent magnet synchronous motors (PMSM), and the same is employed here. This type of motor may be referred to as a brushless d.c motor because it runs from d.c voltage but does not have brushes. The modeling of the motor is as follows:

Developed Torque is proportional to the armature current (I_A) and is represented in Eq. (4.11) below

$$T_d = K_m \times I_A \tag{4.11}$$

where, K_m (Nm Amp^{-1}), is a motor constant, depends upon the physical construction of the motor.

Back emf (E_b) is proportional to armature speed and given as:

$$E_b = \frac{\omega_m}{K_b} \tag{4.12}$$

Where, ω_m is the speed of the motor in $radsec^{-1}$ and K_b ($Volt(radsec^{-1})^{-1}$) is the back emf constant.

The voltage developed by the motor is given by

$$V_{mot} = I_A \times R_A + L_A \times \frac{dI_A}{dt} + E_b \tag{4.13}$$

where I_A is the Armature current, R_A is the armature resistance and L_A inductance of armature.

Shaft output torque is calculated by subtracting friction loss (B_W) and inertial loss $J \times \frac{d\omega_m}{dt}$ from the total torque developed.

The electro-mechanical power developed is given by

$$P = I_A \times E_b \tag{4.14}$$

Which is equal to the developed mechanical power given by

$$P = T_d \times \omega_m \tag{4.15}$$

The overall efficiency of the motor is given by Eq. (4.16)

$$\eta = \frac{\omega\tau}{\omega\tau + P + K\tau^2 + K\omega^2} \times 100\% \qquad (4.16)$$

Where τ and ω represents the torque and speed at which efficiency is measured. P represents the constant losses, $K\tau^2$ represents the torque-dependent electrical losses and $K\omega^2$ represents the speed-dependent iron losses.

The torque-speed characteristic of the motor is shown below in Fig. 4.2(a), where green colour represents the efficient region.

During vehicle acceleration, the output torque of the motor is calculated based on the desired power determined by the power management control and the shaft speed. The output torque is calculated by the following equation:

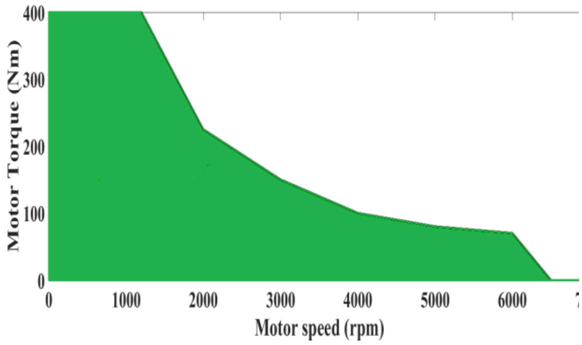
$$T_{mot} = \frac{P_{desired}}{\omega_{engine}} \qquad (4.17)$$

4.4.2. Generator drive

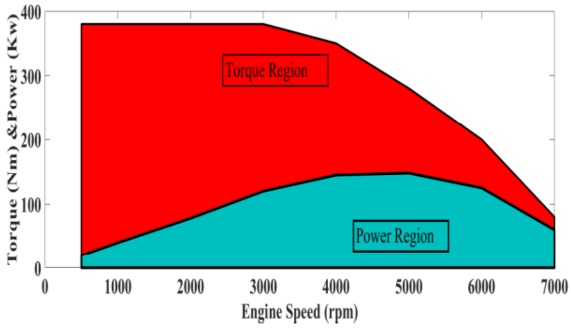
The modeling approach used for the motor can be solely used to model a generator, which is coupled with the ICE to generate electrical power for the battery but the size of the generator may vary according to the application and rating of the vehicle designed. The roles of the EM-generator besides acting as a tractive motor to provide motor torque during acceleration is to perform regenerative braking to trap the lost kinetic energy of the vehicle.

4.4.3. Internal combustion engine (ICE)

As the engine is the primary source of the power in an HEV, therefore, its modeling needs additional attention. Here, throttle percent and ICE speed are considered as inputs to calculate the corresponding output torque and fuel consumption rate. The engine power demand function is given by $P_d(\omega)$, [278]. This function gives the maximum available power for a given engine speed ω. The throttle specifies the engine power. The typical power and torque vs. speed curve of the ICE have been shown in Fig. 4.2(b).



a)



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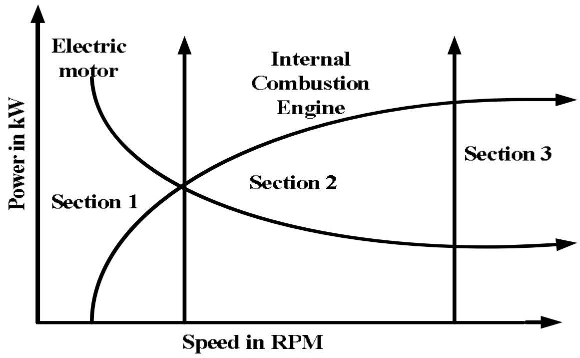


c)

Fig. 4.2. (a) Torque-Speed characteristic of the motor (b) Power and Torque vs. Speed curve for ICE and (c) Generalised Operating regions of EM and ICE

From this graph, it is easy to estimate the efficient working region of ICE which is needed to design a good EMS.

P is the actual power delivered from the engine and is given by :

$$P(\omega,t) = t \times P_d(\omega). \tag{4.18}$$

Where t is the normalized throttle input signal.

The torque of the engine is given by $T_{engine} = \frac{P}{\omega_{engine}}$ (4.19)

The ICE, EM and generator parameters have been summarized below in Table 4.2.

Table 4.2 ICE, EM and Generator parameters

Parameters	Specifications
Motor Power (PMSM)	50kW@500v d.c volts
ICE Power	57 kW @5000 rpm
ICE Torque	115 Nm @ 4200 rpm
ICE Min Speed	1000 rpm
ICE Max Speed	4500 rpm
The heating value of gasoline	42600 J/g
Generator	30 kW

4.4.4. The battery system and SoC estimation:

The NiMH type battery is used in this work. The following equations govern the battery SoC, [11].

$$SoC^{*} = \frac{OCV - \sqrt{OCV^{2}} - 4 \times R \times P_{bat}}{2 \times R \times Q} \tag{4.20}$$

$$SoC = \omega SoC_{v} + (1-\omega)(SoC_{i} - \eta) \tag{4.21}$$

Where SoC^{*} is the rate of change of SoC, OCV is open circuit voltage, η is the correction factor, P_b is the battery power, R is the resistance offered by the battery cell.

The battery parameters used in this work are provided in Table 4.3.

Table 4.3 Battery parameters

Nominal voltage	217V
Initial SoC	0.9 (mapped as 90)
Series resistance	0.02 ohm
Rated capacity	3100Ah
Battery capacity	45 kW

4.5. Fuzzy logic-based energy management for an HEV

To accomplish the power split efficiently between ICE and EM, drivers' logic, energy management logic, constraints which a vehicle has to follow and the technique by which the strategy is to be implemented, play a vital role. These components/logics are explained below.

4.5.1. Driver logic

The goal of the driver controller is to create a module that parodists the response of a real-life driver. On the road, the driver tries to achieve the desired vehicle by controlling the throttle and the brakes accordingly. The driver will press on the accelerator pedal as hard or as light, as per the desired acceleration. Similarly, one will push the brake pedal according to how quickly or slowly one likes to decelerate. To model such behaviour, the driver controller monitors the differences between the desired and the actual vehicle speeds, and the error value is fed into a proportional controller. Hence two proportional controllers are used to generate the percent throttle and the percent braking.

It should be noted that during vehicle braking, the desired speed will be lower than the actual vehicle speed, and therefore it is necessary to negate the error signal to generate a positive braking percent. Percent throttle is then used by the engine to output engine torque, and by the power management controller to activate motor assist mode. Similarly, the percent braking is fed to the mechanical brake controller to activate the mechanical brakes, and to the power management controller to activate the regenerative braking mode. The benefit of modeling the driver controller logic as a separate module is that if desired, the HIL interface can replace the proportional controller which allows the user to control the throttle and brake directly in real-time. In the proposed work, this logic is tested in HIL.

4.5.2. The energy management logic

The driver inputs the acceleration and brake to the controller. The controller also takes the SoC from the battery management system and torque demand from ICE, EM, and generator. It also considers certain constraints as the boundary condition explained in 4.5.3. Based on these inputs, fuzzy rules are formulated. The controller produces the output in terms of torque request from the motor, generator and the throttle in case of ICE. The PGS is basically a power splitting device and is responsible for dividing the power between the generator and ICE, based on the speed parameter. The detailed block diagram of the system model has been provided in Fig. 4.3.

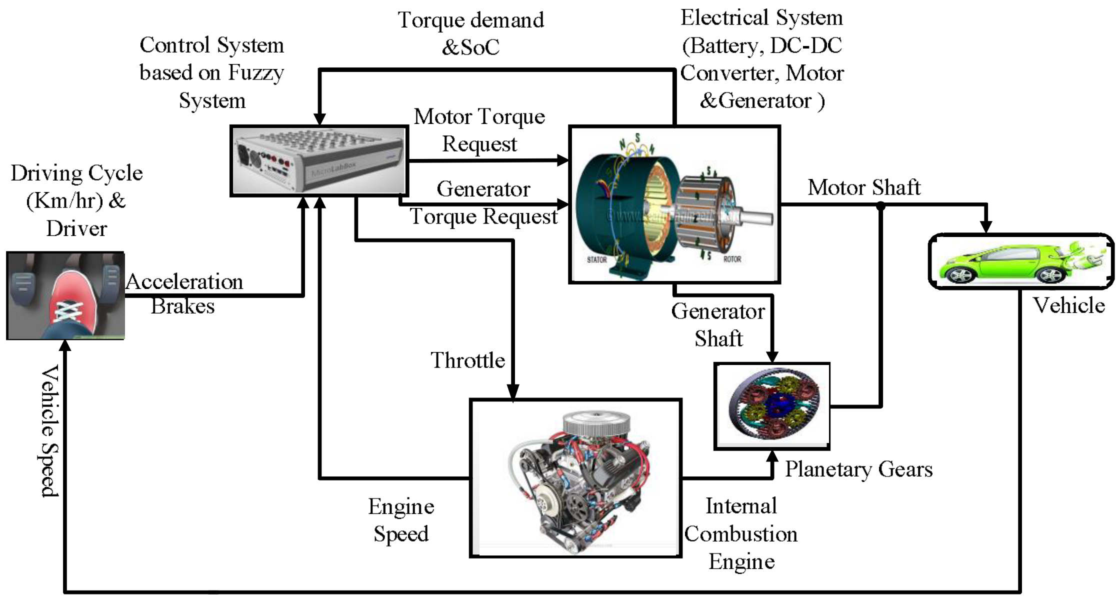


Fig. 4.3 Block diagram of the simulation with input & output parameters

The goal of energy management is to control the energy in such a way that the desired vehicle speed is achieved. The desired power equals the maximum power available multiplied by the percent throttle, where the maximum power available is assumed to be the sum of the maximum power available from the ICE and the EM.

4.5.3 Constraints

There are some constraints which are essentially to be obeyed in all circumstances. A sound control logic takes care of these constraints and never violates them. These constraints have been illustrated below:

$$\left\{\begin{array}{l}\omega_{e,\min} \le \omega_e \le \omega_{e,\max} \\ \omega_{mg,\min} \le \omega_{mg} \le \omega_{mg,\max} \\ T_{e,\min} \le T_e \le T_{e,\max} \\ T_{mg,\min} \le T_{mg} \le T_{mg,\max} \\ SOC_{\min} \le SOC \le SOC_{\max}\end{array}\right\} \tag{4.22}$$

Where, $\omega_{e,\min}$, $\omega_{e,\max}$, $\omega_{mg,\min}$, $\omega_{mg,\max}$, $T_{e,\min}$, $T_{e,\max}$, $T_{mg,\max}$, $T_{mg,\min}$, $SoC_{\min}$ and $SoC_{\max}$ are the minimum and maximum values of speed and torque considered as constraints range of the engine, motor and generator set, and SoC, respectively. Keeping these constraints in mind, an FLC has been developed to meet the power demand of the vehicle.

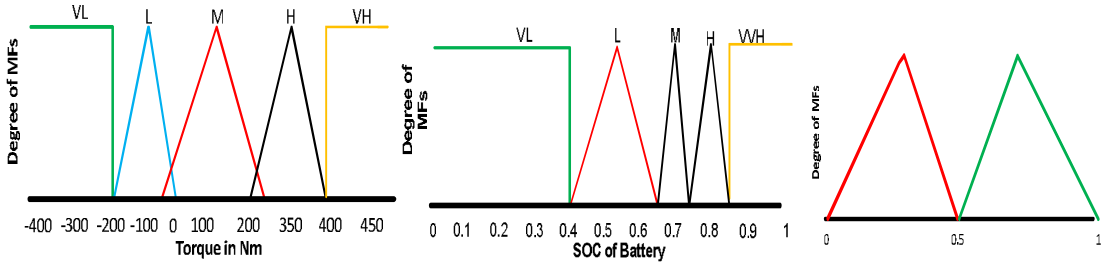
4.5.4. The Fuzzy logic controller (FLC)

FLC is adopted here for implementing energy management in an HEV. The various parameters of HEV like, Torque demand, SoC and brakes are applied to the FLC controller as input variables. The two inputs namely, demanded Torque and SoC are divided into five membership function (MF), i.e., very low, low, medium, high, and very high and the third input, brake, is divided into two MFs, high and low. Therefore, there are 50 (5*5*2) rules formed which will decide the switching ON/OFF of the sources. These MFs are shown below in Fig. 4.4. The controller will provide three outputs with each in the form of 1 and 0 which represents the on/off state respectively. These outputs will enable/disable (turn ON/OFF) the ICE, EM and generator.

When the generator is in ON condition, it means that the battery is getting charged using ICE. If ICE is OFF and the battery is still getting charged, it can happen due to braking energy where the motor acts as a generator to charge the battery. The brake position is mapped from 0 to 1 in two steps. First, when the brake is below 0.5, it is considered as low and would not charge the battery. Second, if the brake position is from 0.5 to 1, it is considered as high, and the braking energy will be utilized to charge the battery. The power versus speed characteristics of EM and ICE is required to identify the efficient regions of operation and the same is given in Fig. 4.2 (c). The motor should be used during the starting condition when the vehicle is in gear position 1 and 2 as its efficiency is quite high in that region.

ICE should generally be used in section 2. There is some condition in which power through EM and ICE simultaneously is considered efficient than individual acting source as in section 3 of the graph in Fig. 4.2 (c). Based on these characteristics, an efficient region in terms of torque is identified which will help in deciding the turning ON/OFF of the ICE/EM. The MFs for various input variables are shown in Fig. 4.4.

Input variables



(a) MF of Input variable (Torque demand)

(b) MF of Input variable (SoC)

(c) MF of Input variable (Brakes)

Fig. 4.4 Input and Output variables with their membership function

Output variables:

The output will be either 1 or 0 which represent the ON/OFF condition of the ICE, EM and generator respectively. The FLC has been modeled on the basis of the arguments given below, which illustrates the various modes of working of the sources available in HEV. Because the engine and the EM have different efficient working regions, HEVs should have a variety of different operating modes to take full advantage of the series-parallel hybrid drive system. Hybrid car's working modes can be divided into the following four types:

1) When the vehicle is started and is at low speed: to prevent the engine from working in a higher fuel consumption region, the vehicle is driven by the EM alone.

2) When the vehicle is running at a constant speed: the engine alone drives the vehicle and determines whether to charge the battery or not based on the SoC of the battery pack.

3) Under the condition of acceleration or hill climbing and other large loads: the engine and motor drive the hybrid vehicle at the same time.

4) When decelerating or braking: the engine does not work, the motor recovers regenerative braking energy as much as possible, and the mechanical brake consumes the remaining portion. The starting 3 modes are governed by the torque equation as given below:

$$T_{req}=T_{eng}+T_{mot} \tag{4.23}$$

where, T_{req} is the required torque determined by the vehicle accelerator pedal signal, the current vehicle speed, and the transmission gears. T_{eng} and T_{mot} are the engines and the motor torque respectively. Positive or negative torque offered by the motor can adjust the operating points of the engine based on its efficiency curve. An EMS should be designed based on the required torque and SoC of the battery. The engine and the motor met this torque based on their efficient region of operation thereby improving the fuel economy of the vehicle. The control rule table of EMS based on FLC is given in Table 4.4.

BRAKES LOW **BRAKE HIGH**

Table 4.4 The control rule table of EMS based on FLC

		TORQUE				
		VL	**L**	**M**	**H**	**VH**
SoC	**VL**	G+E / G+E	G+E / G+E	G+E / G+E	G+E / G+E	E / G+E
	L	M / G+M	G+E / G+E	M+G+E / M+G+E	M+G+E / M+G+E	M+E / G+M+E
	M	M / G+M	M / G+M	M / G+M	M+G+E / M+G+E	M+E / G+M+E
	H	M / G+M	M / G+M	M / G+M	M+G / M+G	M+E / G+M+E
	VH	M / G+ M	M / G+M	M / G+M	M / G+M	M+E / G+M+E

Legends: VH – Very high, **M**-Medium, **H**-High, **L**-Low, **VL**-Very low, **M**-Motor, **G**-Generator, **E**-ICE. G+E means, generator and ICE are ON at a time.

The upper portion in a box shows the rules for high brakes, and the lower portion shows the rules for low brakes.

4.6. Simulations and hardware results

This work involves a feed-forward approach which includes a driver model, which decides the required speed and the present speed to develop proper throttle and brake commands (by the use of PI controller). The throttle command is converted into a torque demanded by the engine (and/or motor). The propulsion power, requested by the driver, gives acceleration and speed. The torque supplied by the internal combustion engine is input to the transmission model, which adjust the torque according to the transmission's efficiency and gear ratio. The computed torque is forwarded through the drivetrain, in the direction of power flow, until it results in a tractive force at the tire/road interface. The vehicle driver model uses vehicle velocity feedback from the vehicle dynamics and a commanded vehicle velocity to generate braking or accelerating command. The feed-forward approach is particularly desirable for hardware development and detailed control simulation. Because feed-forward models deal in quantities measurable in a physical drivetrain such as control signals and true torques, vehicle controllers can be developed and tested effectively in simulations. Also, dynamic models can be included naturally in a feed-forward vehicle model. Finally, the forward-facing approach is well-suited to the calculation of maximum effort accelerations, as they are essentially wide-open throttle events. The feed-forward model is illustrated in Fig. 4.3.

The driver that is, a PI block puts a requirement of acceleration and braking which is fed to the controller. Based on logic, intelligence and constraints, the controller meets the torque requirement in such a way that the optimal condition of the vehicle is achieved with its smooth operation. The sources available are the ICE, EM, and generator and they are to be operated in their efficient region. The proposed system is developed in MATLAB/Simulink and then validated in real-time on HIL testing platform using FPGA based MicroLabBox. MicroLabBox controller helps in realizing the complex control concepts into reality. It provides a high computation power with very low I/O latencies, which leads to significant real-time performance. The HIL laboratory setup for the validation of the simulated results is shown in Fig. 4.5.
The result obtained through simulation and real-time HIL are provided with the explanatory inference below in Fig. 4.6 to Fig. 4.8.

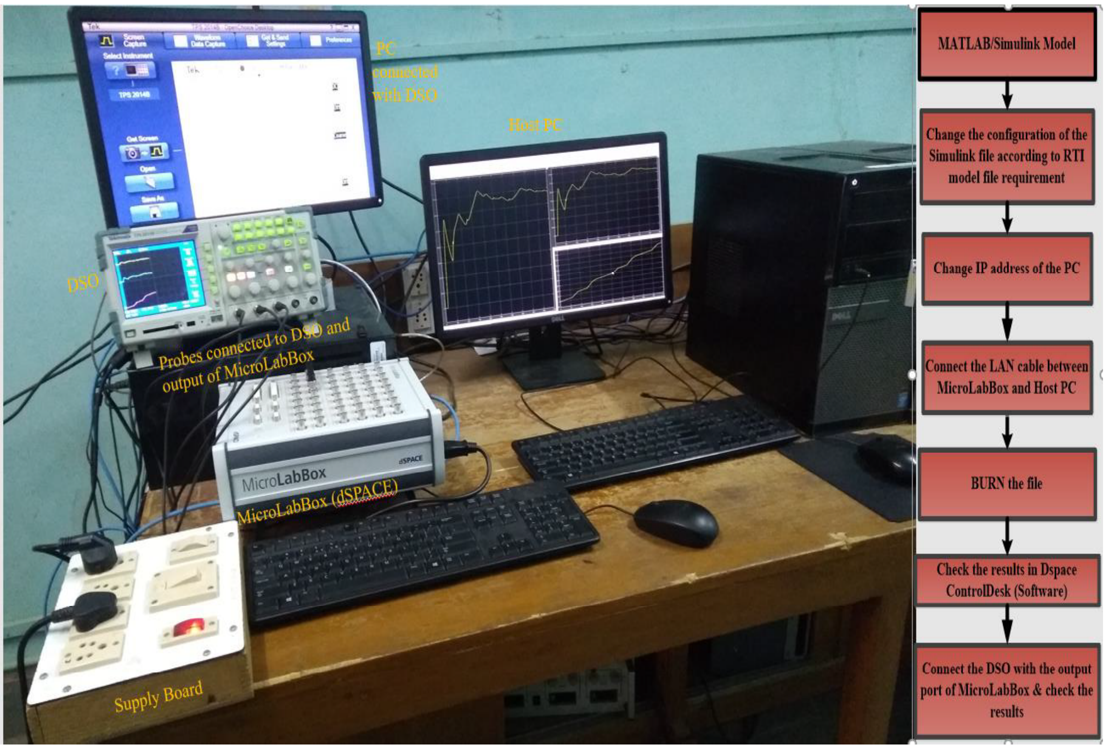


Fig. 4.5. HIL Setup of the System.

In Fig. 4.6 to Fig. 4.8, **S** and **H** represent the simulation and the HIL results respectively for the same setup. The real-time results are similar to the simulation results, which proves the design of the proposed system.

The simulation model has been tested for various driving cycles, but here results are given for only New European driving cycle (NEDC). Figs 4.6 (S1) and 4.6 (H1) represent the vehicle speed. Based on the speed, the required torque will be supplied from the available source as per the controller logic. The vehicle functioning on NEDC is explained below.

At the starting of the vehicle, EM provides the power for propulsion. If SoC is low, the generator also remains in ON condition. Fig. 4.6 (S2) and Fig. 4.6 (H2) depict the SoC variation with respect to vehicle speed. When vehicle catches up a certain speed and crosses a threshold value, then the ICE gets turn ON and also charge the battery through generator if SoC is in the low or medium range. Concerning the chosen driving cycle, the following can be observed easily:

At 0s to 10s: vehicle speed is zero, and hence all sources are set to OFF condition as shown in Figs. 4.6 (S1) to 4.6 (S5) and 4.6 (H1) to 4.6 (H5).

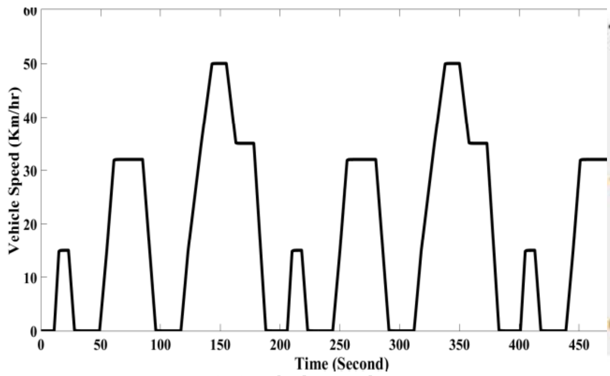
At 10s to 30s: suddenly vehicle speed increases and the motor provide power for propulsion and ICE remains OFF condition. Therefore, SoC which was initially at 90 (representing 0.9) starts to decrease. These can be analyzed from Figs. 4.6 (S2), 4.6 (S3) and 4.6 (S5). The corresponding real-time results are given in Figs. 4.6 (H2), 4.6 (H3) and 4.6 (H5).

At 50s to 100s: as the power demand is high so, motor and ICE both act during this period but motor acts as a secondary power source and provides power for a few seconds (50s to 75s). Depending on the amount of SoC, the generator remains in ON/OFF condition. This brings the battery in charge sustaining mode. This can be analyzed from Figs. 4.6 (S2), 4.6 (S3), and 4.6 (S5), generator with SoC. Figs. 4.6 (H2), 4.6 (H3) and 4.6 (H5) are captured for real-time operation and yield similar information.

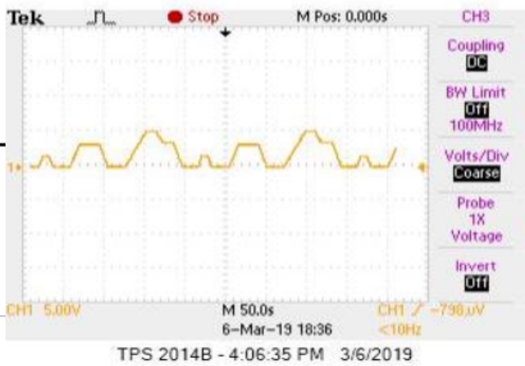
At the 60s the generator is in ON condition, and it charges the battery. Therefore, SoC starts increasing till 90s. From the 90s it starts decreasing for a short period of time as the generator becomes OFF. This can be seen in Fig. 4.6 (S4)

At 120s to 180s: since the power demand is very high; therefore, EM and ICE are in ON condition. Battery SoC is depleting till 150s, and then it goes to its minimum level hence needs to be charged after 150s by means of ICE and generator. This can be analyzed from Figs.4.6 (S2), 4.6 (H2), 4.6 (S3), 4.6 (H3), 4.6 (S4), 4.6 (H4), 4.6 (S5) and 4.6 (H5).

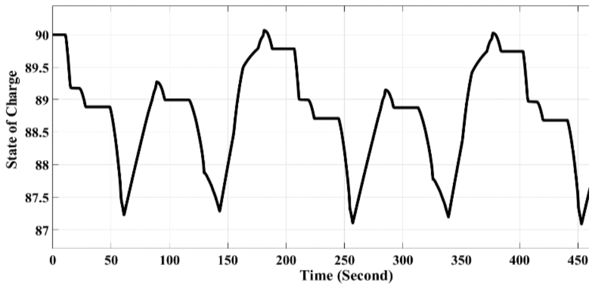
The executed algorithm instantly addresses the speed and power demand by turning ON the single or multiple sources according to logic and constraints fed in the controller, which is evident from the resultant graphs provided here.



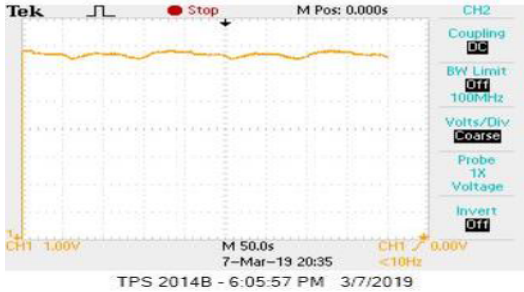
(S1) Vehicle Speed



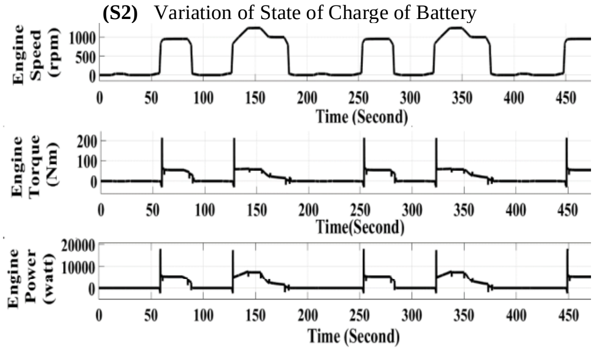
(H1) Vehicle Speed



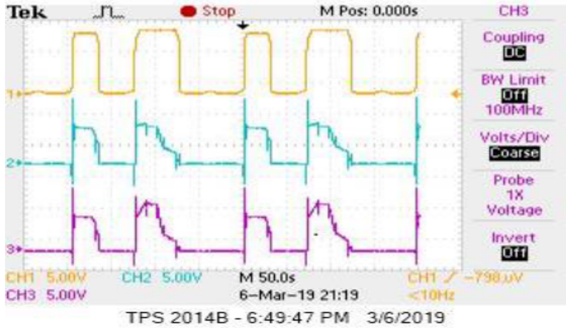
(S2) Variation of State of Charge of Battery



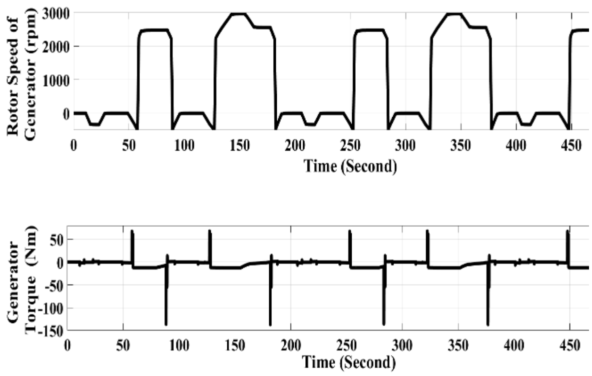
(H2) State of charge of Battery



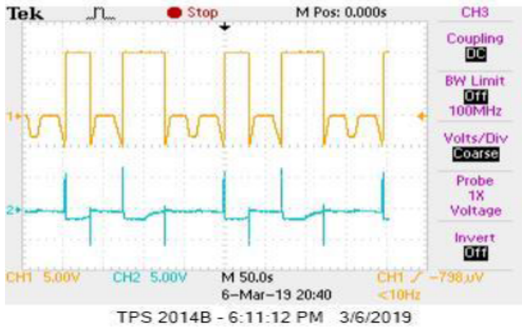
(S3) (a) Engine speed, (b) Engine torque, and (c) Engine power



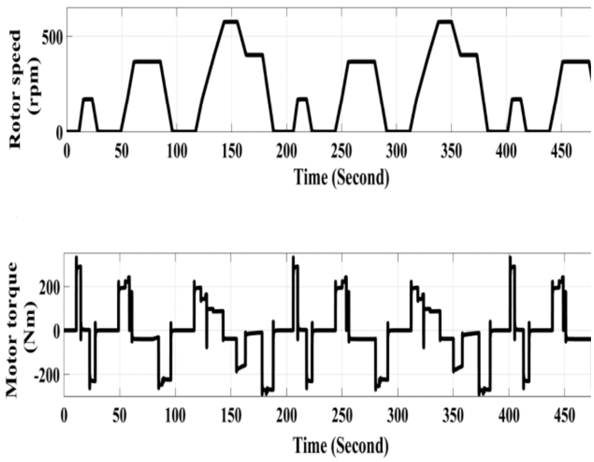
(H3) (a) Engine speed, (b) Engine torque, and (c) Engine power



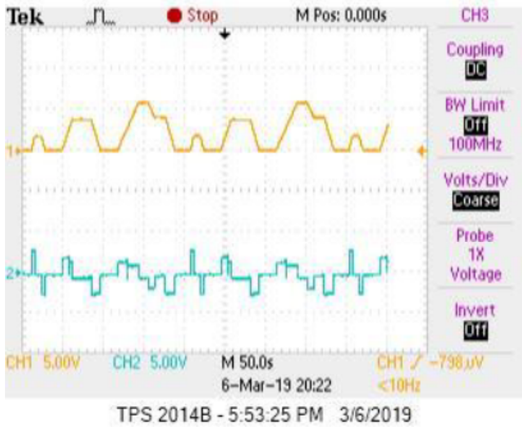
(S4) Generator : (a) Speed and (b)Torque



(H4) Generator: (a) Speed and (b)Torque



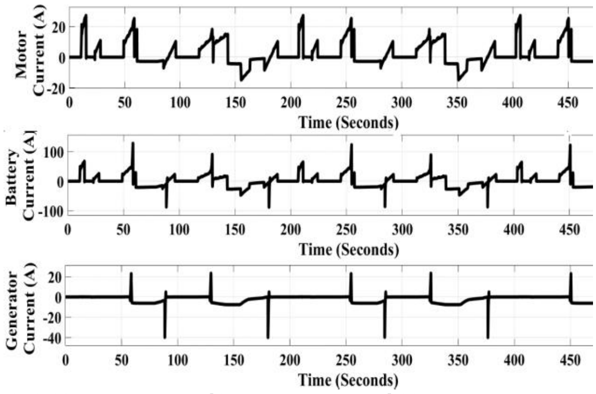
(S5) Motor: (a) Speed and (b)Torque



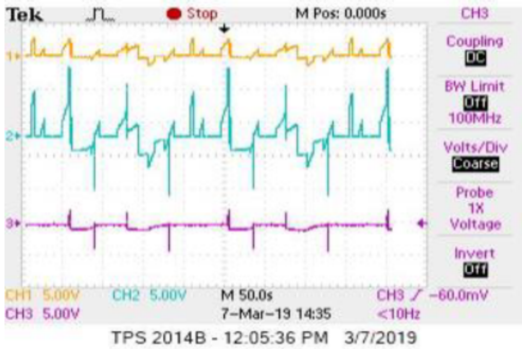
(H5) Motor: (a) Speed and (b)Torque

Fig. 4.6 The simulated and HIL results of vehicle speed, SoC, engine speed, engine torque, engine power, generator speed, generator torque, motor speed, and motor torque. S represents MATLAB simulation results and H represents HIL results for similar conditions.

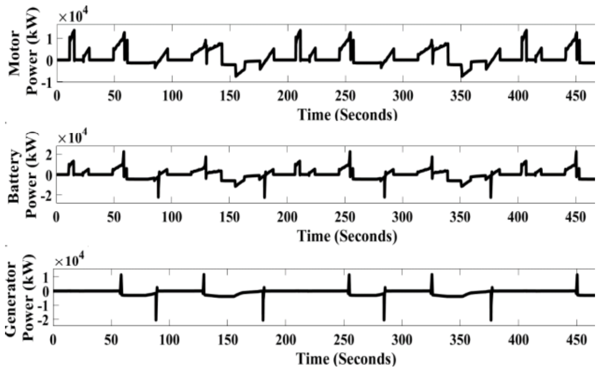
Fig. 4.7 shows the variation in the currents of motor, battery, and generator with respect to the power drawn by these sources. Fig. 4.7 (S1) represents the current and Fig. 4.7 (S2) represents the power of motor, battery, and generator respectively. The results given below demonstrate the effect of variation in any parameter on other parameters. The analysis proves that the proposed algorithm is working as per the user requirement in an efficient way.



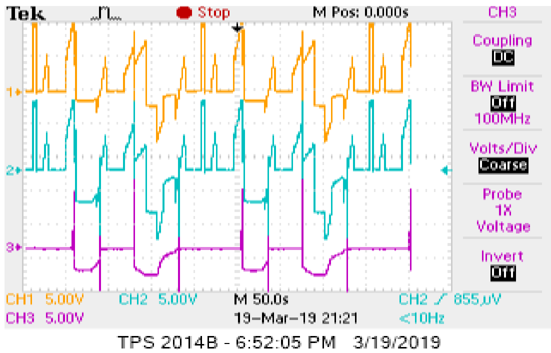
(S1) (a) Motor current, (b) Battery current and (c) Generator current



(H1) (a) Motor current, (b) Battery current and (c) Generator current



(S2) (a) Motor power, (b) Battery Power and (c) Generator Power



(H2) (a) Motor power, (b) Battery Power and (c) Generator Power

Fig. 4.7 The simulated and HIL results of motor current, battery current, generator current, motor power battery power, and generator power

The PGS plays a vital role in power split among the available sources (ICE, EM, and Generator). The PGS has three output ports, out of which sun, ring and carrier gears are connected to the generator, motor and ICE respectively. Figs. 4.8 (S1) and 4.8 (S2) present the variation in speed of these gears with respect to variation in torque at these gears. The PGS is responsible for the production of various gear ratio based on the vehicle speed. Figs. 4.8 (H1) and 4.8 (H2) represents the similar results obtained on HIL testing platform.

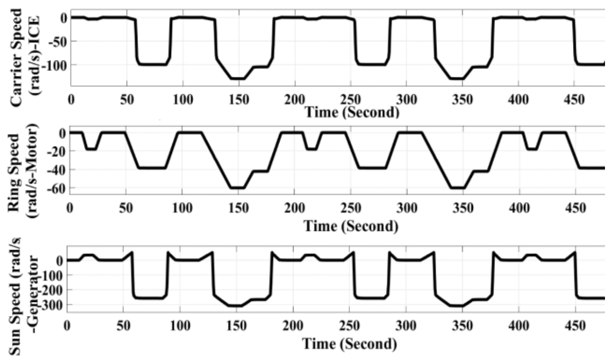
The fuel economy of the vehicle is a very important indicator of its performance. A good HEV should have high fuel economy which can be achieved by using mainly EM with an order that it operates in its efficient region. This leads to higher battery utilization and hence a decrease in SoC level. The fuel consumption in the simulation has been calculated in terms of Mileage (Km/L), Miles per gallon (MPG) and amount of the gasoline consumed in terms of Litre.

The fuel flow can be calculated by the Eq. (4.23).

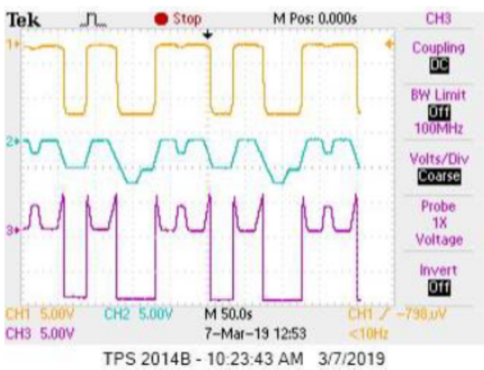
$$Injection\ amount\ =\ \frac{Fuel\ flow}{\frac{Engine\ speed}{60}\times\frac{Cylinder\ count}{Revolution\ per\ stroke}} \tag{4.23}$$

The results of the fuel economy have been shown in Fig. 4.8. Where Fig. 4.8 (S3) and Fig. 4.8 (S4) demonstrate the fuel economy using a conventional controller (without FLC) and with FLC. It is very clear that a better fuel economy is obtained after employing FLC. Fig 4.8 (H3) and 4.8 (H4) show corresponding fuel economy results in real-time using FPGA based MicoLabBox hardware controller.

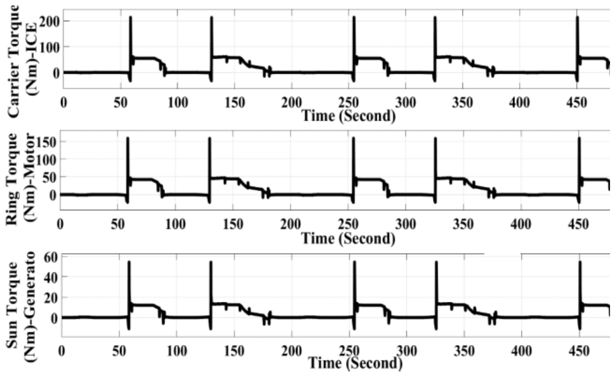
Vehicle speed needs to meet the expectation of the driving cycle (desired sped). When the speed of the vehicle is matched to the driving cycle, and if it coincides and leaves no trace after overlapping, then it is called as an ideal condition, but it is up to the EMS, how good an algorithm is designed, so that the vehicle speed can catch up to the driving cycle. A good control algorithm ensures that the desired speed is met. The Fig. 4.8 (S5) represents the desired and achieved speed graphs for conventional controllers. It is seen that there is a mismatch (i.e. trace missing) in these speeds. The Fig. 4.8 (S6) represents the desired and achieved speed graphs using proposed FLC controllers. These speed graphs get almost coincide i.e. no trace missing. This further proves that the proposed method offers better drivability of the vehicle. Fig 4.8 (H5) and 4.8 (H6) display the HIL results for desired and achieved speeds without and with FLC.



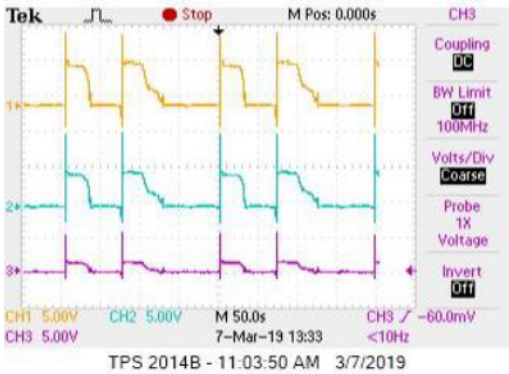
(S1) PGS: (a) Sun speed (Generator), (b)Ring speed (Motor) and (c) carrier speed (ICE)



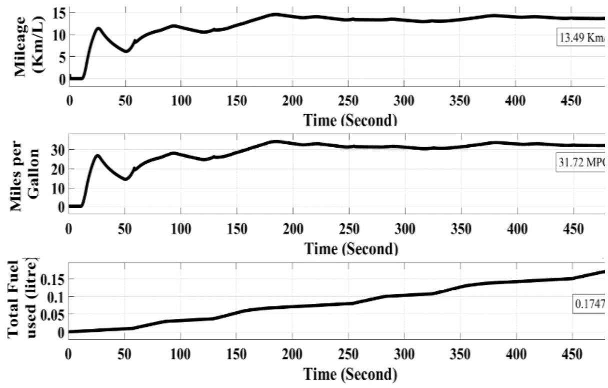
(H1) PGS : (a) Sun speed (Generator), (b)Ring speed (Motor) and (c) carrier speed (ICE)



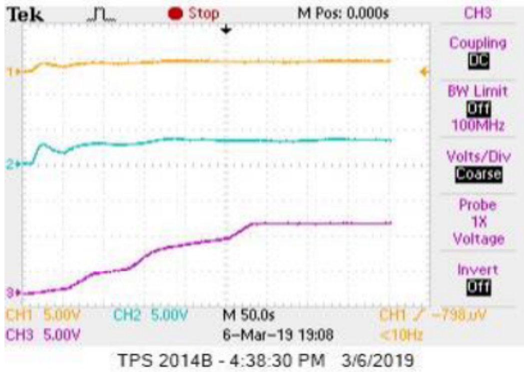
(S2) PGS: (a) Sun Torque (Generator), (b) Ring Torque (Motor) and (c) Carrier Torque (ICE)



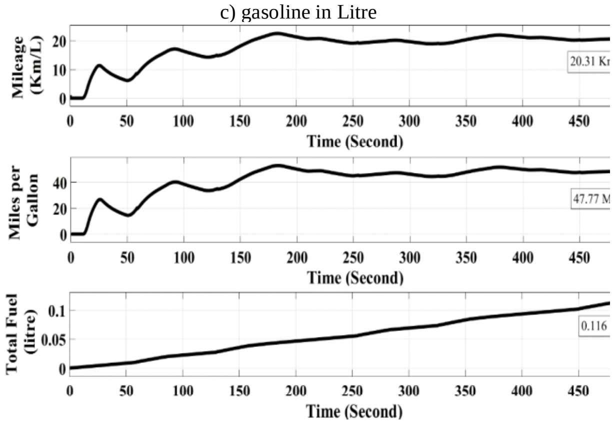
(H2) PGS: (a) Sun Torque (Generator), (b) Ring Torque (Motor) and (c) Carrier Torque (ICE)



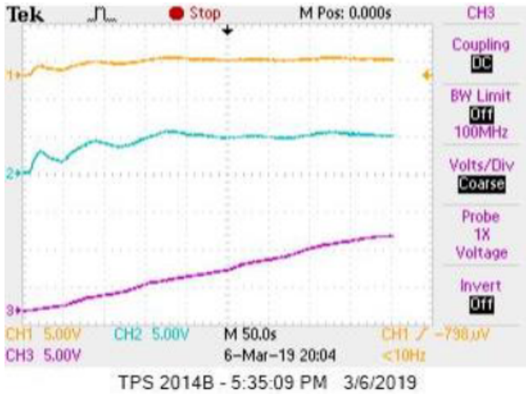
(S3) Fuel economy without FLC: (a) Mileage in Km/L, (b) MPG, and c) gasoline in Litre



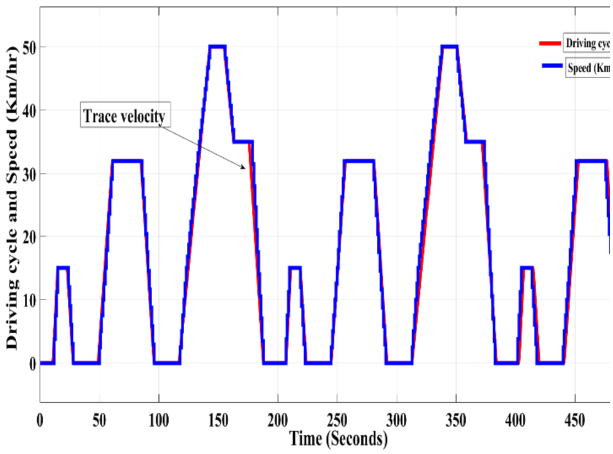
(H3) Fuel economy without FLC: (a) Mileage in Km/L, (b) MPG, and (c) gasoline in Litre

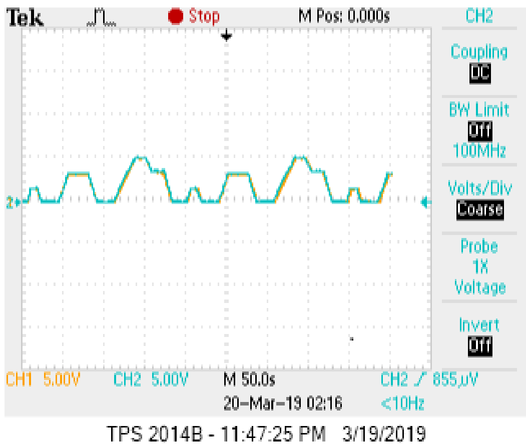


(S4) Improved Fuel Economy with FLC:a) Mileage in Km/L, b) MPG, and c) gasoline in Litre



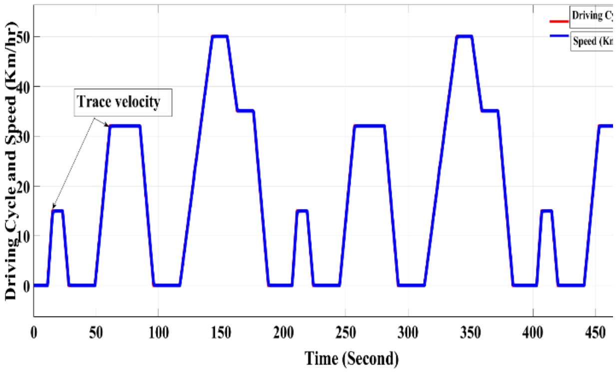
(H4) Improved Fuel Economy with FLC: a) Mileage in Km/L, b) MPG, and c) gasoline in Litre

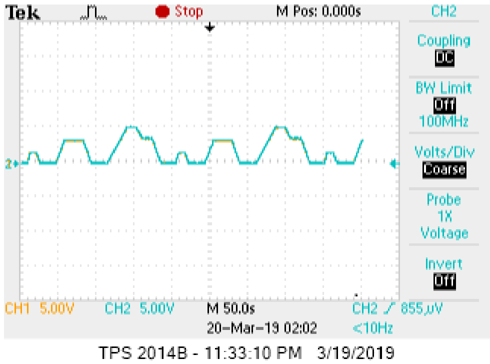




(S5) Desired and achieved speeds of the vehicle using a conventional controller

(H5) Desired and achieved speeds of the vehicle using a conventional controller





(S6) Desired and achieved speeds of the vehicle using FLC

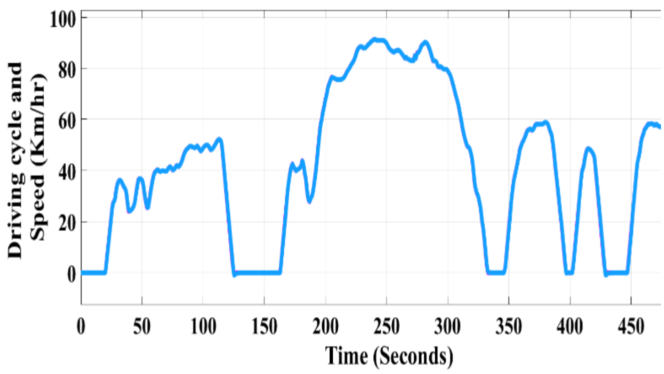
(H6) Desired and achieved speeds of the vehicle using FLC

Fig. 4.8. The simulation and HIL results of: PGS- Sun speed (Generator), Ring speed (Motor), carrier speed (ICE) , Sun Torque (Generator), Ring Torque (Motor) carrier Torque (ICE), Fuel Economy without FLC- Mileage in Km/L, MPG, gasoline in Littre, Improved Fuel Economy with FLC- Mileage in Km/L, MPG, and gasoline in Litre, desired speed and achieved speed of the vehicle- without and with FLC.

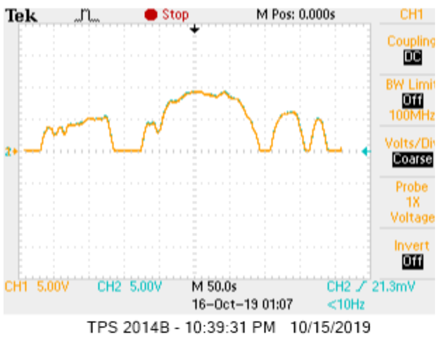
4.7. Verification of proposed EMS on different other driving cycles

The verification of the EMS based on FLC for two widely used driving cycle i.e. FTP-75 and WLTP driving cycle has been provided in Fig. 4.9 and Fig. 4.10 respectively. The results prove that the proposed FLC-based EMS holds valid for other driving cycles as well and it results in no trace missing.

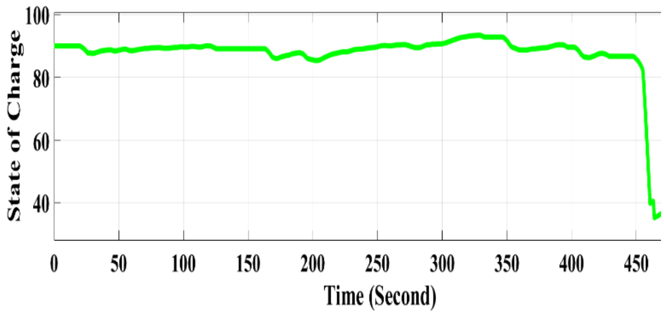
1. Fuel Economy and SoC under FTP-75 driving cycle



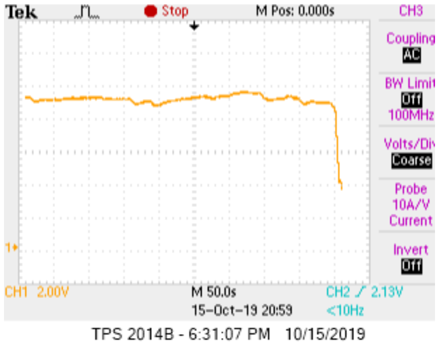
(S1) Driving cycle and Vehicle speed based on FLC



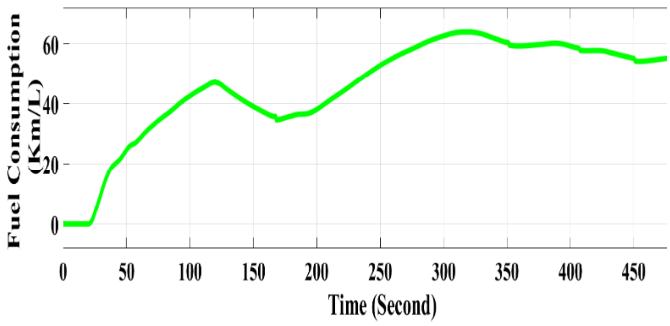
(H1) Driving cycle and Vehicle speed based on FLC



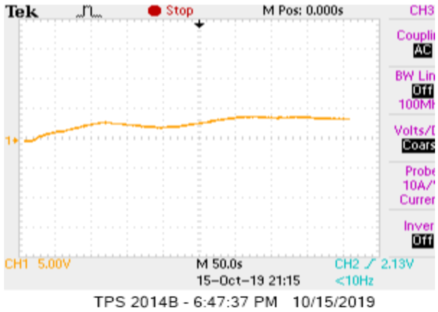
(S2) Variation of State of charge with FLC based EMS



(H2) Variation of State of charge with FLC based EMS



(S3) Fuel consumption with FLC (Km/L)



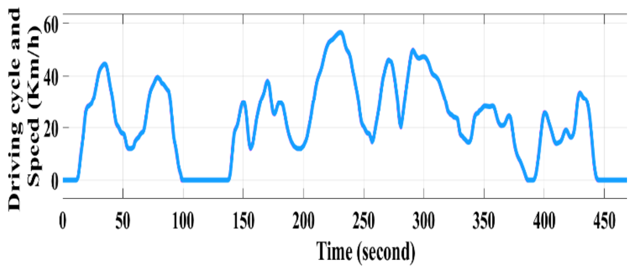
(H3) Fuel consumption with FLC (Km/L)

Fig. 4.9 The simulation and HIL results of driving cycle & vehicle speed, SoC and Fuel consumption (Km/L) with FLC for FTP-75

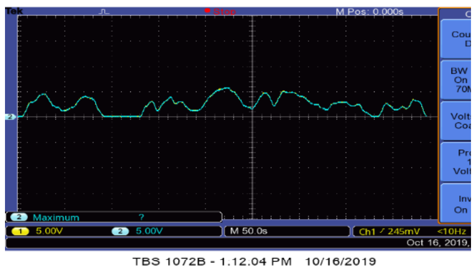
Table 4.5 The fuel economy of the FTP-75 driving cycle

Fuel Consumption (FC)	Km/L	MPG	L/100Km
FC without FLC	35.79	84.18	2.794
FC with FLC	56.13	132	1.782

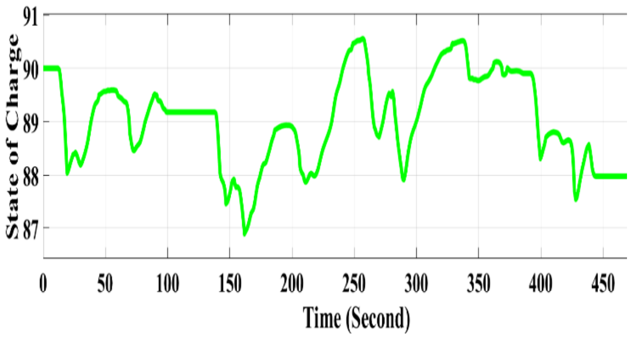
2. Fuel Economy and SoC under WLTP driving cycle



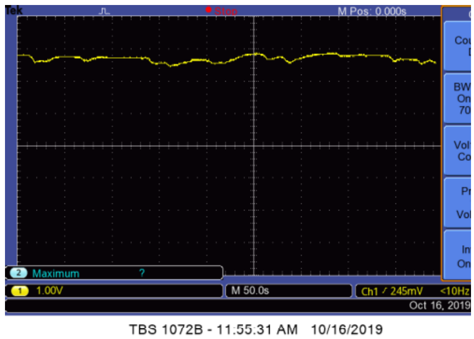
(S1) Driving cycle and Vehicle speed based on FLC



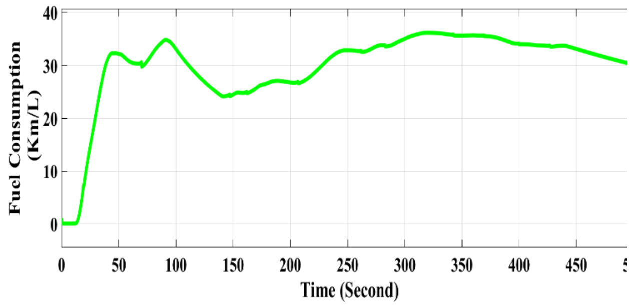
(H1) Driving cycle and Vehicle speed based on FLC



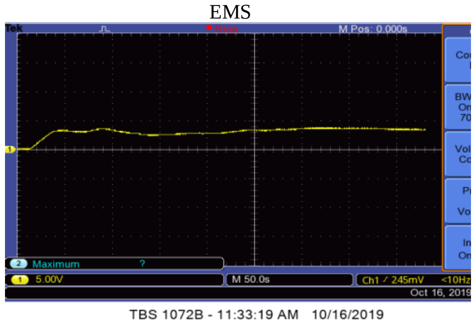
(S2) Variation of State of charge with FLC based EMS



(H2) Variation of State of charge with FLC based EMS



(S3) Fuel consumption with FLC (Km/L)



(H3) Fuel consumption with FLC (Km/L)

Fig. 4.10 The simulation and HIL results of driving cycle & vehicle speed, SoC and fuel consumption (Km/L) with FLC for WLTP driving cycle.

Table 4.6 The fuel economy of the WLTP driving cycle

Fuel Consumption	Km/L	MPG	L/100Km
FC without FLC	21.34	50.2	4.6
FC with FLC	30.17	70.95	3.315

4.8. Summary

The chapter presents the design, modeling and FLC tuned EMS for an HEV. The whole system is modeled mathematically in detail and then simulated in MATLAB/Simulink environment. After that, the model is validated in real-time on HIL platform using FPGA based MicroLabBox hardware controller. The FLC managages the energy sharing between the available sources. The proposed FLC based EMS considers the torque demand, SoC of the battery and brakes (regenerative braking) as primary inputs and follows several constraints imposed, including the efficient region of operation for ICE and EM. It has been observed that for FTP-75 and WLTP driving cycle there is an improvement of 84.7 to 132 MPG and 50.2 to 70.95 MPG respectively.

Based on these inputs and constraints, the FLC controller turns ON/OFF the available power sources. This strategy regulates the torque in such a way that the engine and motor maneuver in their efficient operating regions. The proposed EMS offers better fuel economy and faster response and minimizes the trace missing between desired and achieved speed as compared to conventional EMS.