Energy Management of Parallel Mild Hybrid Electric Vehicle

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***Abstract*—The growing legislation on environmental standards and fuel efficiency improvement has led to development of new energy management system (EMS) in the field of hybrid electric vehicles (HEV). A HEV have two degree of freedom for output power which can be provided by either internal combustion engine or electric motor. The way to split the power during the vehicle driving involves a new control task, which is referred as new energy management controller. In the development of HEV, optimality and real time performance has become the barrier. In this paper the driving modes like electric driving, load point shifting and regeneration have been considered for fuel optimization with battery charge sustainment on two different driving cycles. The rule based control strategy is implemented on the parallel mild HEV model in programming environment of MATLAB/SIMULINK and the model is simulated for New European Driving Cycle (NEDC) and Federal Test Procedure-75 (FTP-75).**

***Index Terms*—Hybrid Electric Vehicle, Energy Management System (EMS), Electric Driving, Rule-Based strategy, State Of Charge (SOC), Torque Split Ratio, Load Point Shifting, Start-Stop.**

I. Introduction

Almost the two third of the fossil fuel around the world are used by passenger cars and heavy vehicles [1]. The rising of fuel prices, their depleting nature, and increase in the pollution level has led to the strict regulations which has made the adaption of the different measures and reduce the fossil fuel dependency. The HEVs are the alternative over the conventional vehicles which can fulfill all the regulations and has the ability to reduce the petroleum consumption and greenhouse gas emission.

HEV have advantages in concern with: 1) downsizing of the engine; 2) recovering of the energy during braking and recharging of the energy storage unit (e.g., battery) and 3) restriction use of the engine operation at speeds and loads where fuel efficiency is low. Moreover, complete electrification is also often challenged by experts given the fact that even though it is emission-free at the area of application of vehicles, it creates emissions at the source of electricity generation. The efficiency of a CE and a power plant is also more or less the same. Considering these challenges, hybridization remains the ideal solution for today.

Compared to conventional CE systems, a hybrid propulsion system can save fuel for the following reasons: a HEV can recover part of the vehicles kinetic energy while braking and use this energy at a later time; an HEV can shut down the CE during idling and low-load phases without compromising the drivability of the vehicle due to the high bandwidth of the electrically generated torque; an HEV can avoid low-efficiency operating points of the CE by first storing excess power in the batteries and later driving the vehicle in an electric-only mode; and, since the electric motor can provide some of the torque during short acceleration phases, the CE in an HEV can be designed with a smaller displacement and, thus, a better average efficiency.

The achievable improvement in fuel economy strongly depends on the vehicle as well as the driving cycle. This potential can only be realized with a sophisticated control system that optimizes energy flow within the vehicle [2]. There have been attempts made to develop controllers in order to better utilize the fuel saving potential of hybrid vehicles. The main aim of developing control strategies for different electric vehicle configurations is to utilize the input signals and calculate output signals which enables to operate the vehicle in a manner which improves its fuel economy and performance coupled with a reduction in emissions [3]. A similar strategy has been proposed in this paper.

II. Architectures of Hybrid Electric Vehicles

A HEV consists of CE, the inverter (IV), battery (BT), and the electric machines like electric motor (EM) and electric generator (EG). Depending on their architecture, HEVs fall into one of the several categories. According to architecture of HEVs are classified in different form below:

A. Series HEV

In Series HEV electric motor is the only source of power to the wheels. The CE drives the electric generator instead of directly driving the wheels. Charging of the battery is done by the generator and it also gives power to the electric motor in order to move the vehicle. It has high energy conversion losses and low complexity.

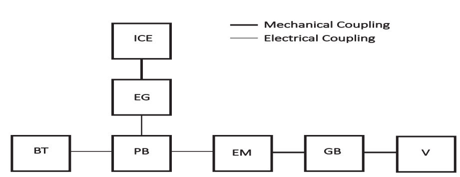

Fig. 1. Series hybrid electric vehicle architecture

B. Parallel HEV

In Parallel HEV, both EM and CE gives power to the wheels at the same time and they both are coupled with torque coupler; which add up the torques of both the CE and EM. Control of CE and EM torques are done independently. Also CE and EM speeds are linked by torque coupler with fix ratio. It has low energy conversion losses and medium complexity.

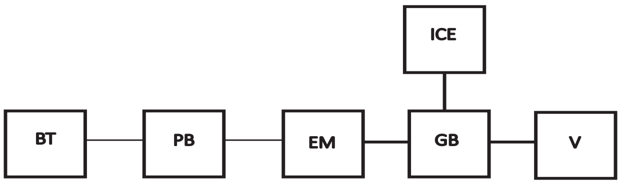

Fig. 2. Parallel hybrid electric vehicle architecture

C. Combined HEV

Combined HEV has features of both Series and Parallel HEV. There is both connection like mechanical and electrical between engine and drive axle. This different power path allows interconnecting between mechanical and electrical power at the same cost. The power supplies to the wheels are either electrical or mechanical or both. It has medium energy conversion losses and high complexity.

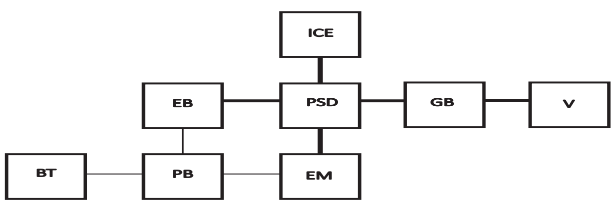

Fig. 3. Combined hybrid electric vehicle architecture

III. Problem Statement

Model of a parallel mild hybrid electric vehicle for MATLAB/Simulink

- Mercedes-Benz A 170 CDI (W168)
- Diesel engine (66 kW / 180 Nm nominal, 60 kW / 187 Nm measured)
- Electric motor (12 kW / 60 Nm)
- Battery (16.38 kW / 0.468 kWh / 48 V)

With following objectives

- Minimizing fuel consumption (for the NEDC used in the EU and the FTP-75 used in the US)
- Ensuring charge sustainment (charge must remain the same on the average)
- Respecting component constraints (maximum torques, maximum currents, etc.)

IV. Parallel mild HEV

In Parallel Mild HEVs, both the CE and EM are used for hybrid and electric driving. The electric motor can be used as generator for regenerative braking and battery charging. The CE and EM both are coupled by torque coupler. The torque coupler is a three-port two degree of freedom mechanical device in general. The torque coupler is a coupling of the CE, EM and MGB on a single shaft in a parallel mild HEV [5].

The torque coupler is characterized by the equation,

$$\omega_{CE} = \omega_{EM} = \omega_{MGB}$$

$$T_{CE} + T_{EM} = T_{MGB}$$

The torque split ratio is defined by the equation,

$$u = \frac{T_{EM}}{T_{MGB}}$$

The torque split ratio characterizes the operation modes.

V. Driving Cycle

The purpose of using the hybrid vehicle depends on the way it is used. The hybrid vehicles have the advantages in recovering back the kinetic and potential energy that might be dissipated during the braking condition and allows the engine to operate in highest efficiency region. The driving cycle takes into consideration the vehicle speed and the road conditions. In all with the vehicle characteristics, this completely defines the road load, i.e., the force that the vehicle needs to exchange with the road during the driving cycle. The road load is the sum of terms which are:

- Inertia, i.e. force needed to accelerate the vehicle
- Grade force, needed to overcome the slope of the road
- Rolling resistance, due to tire/road interaction, bearing losses etc.
- Aerodynamic drag

Each term mentioned is a function of both the driving cycle (speed, acceleration, and grade) and the vehicle (mass, frontal area, coefficients of aerodynamic and rolling resistance). Hence for this the fuel consumption need to be specified in reference to the specific driving cycle. Further for the particular driving cycle, the value of the road load and relative magnitude of its component depend on the characteristics of the vehicle. The necessity for a standard method to evaluate fuel consumption of all vehicles on the market, and to provide a reliable basis for their comparison, led to the introduction of a small number of regulatory driving cycles. These driving cycles are generated in such a way that they are the representation of the urban and sub-urban driving conditions and produce the measures of the vehicle speed in the real road conditions. The test procedures are being updated to suit the modern vehicles, following criticism to the previous regulation. In reality, as the acceleration levels are below the capability of the modern cars and no use of the air conditioning, the results obtained for the fuel consumption by testing vehicles according to the previous EPA Standards were much lower than in real-world driving conditions. The situation is somewhat same in the Europe, where the regulatory cycles represent optimistic approximations of the real driving conditions. With the improvements, the regulatory cycles should be considered as a comparison tool rather than the prediction tool. In fact, to predict how the vehicle will be driven is not possible, as each vehicle has different usage pattern and each driver has its own driving style [4].

VI. QSS Toolbox

The Quasi Static Simulation (QSS) toolbox has the flexibility to design the powertrain systems quickly and to calculate the fuel consumption of each system under different strategies. The key idea behind the QSS toolbox is to reverse the usual cause-and-effect relationships of dynamic systems. The toolbox calculates the accelerations and determines the necessary forces, instead of calculating the speeds from given forces (at discrete times).The QSS Toolbox model used is given below,

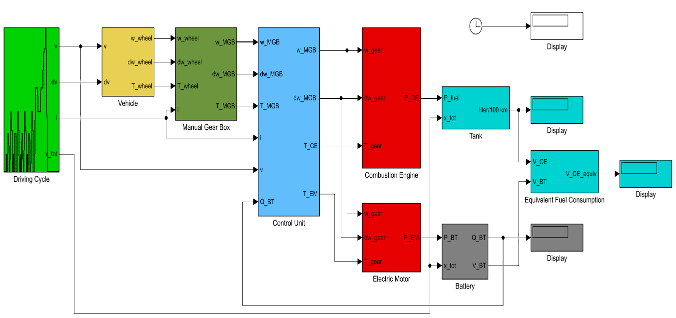

Fig. 4. QSS Toolbox

Here the controller consists of two integrated MATLAB functions. The first function is for implementing start-stop mode and the other function contains logic for switching between the different modes like Electric Driving, Load Point Shifting and Regeneration. The different inputs for the controller block are: W_{MGB}: angular velocity of the manual gearbox D_{MGB}: angular acceleration of the manual gearbox T_{MGB}: torque of the manual gearbox v: velocity of the vehicle Q_{BT}: charge of the battery I: gear ratio

Gear number is also an input but it does not have any contribution of the output. The output of the first MATLAB function gives us Torque Split Ratio (u) while the output of the second MATLAB function gives us the state of combustion, either Start or Stop.

With the aim to retain the charge sustainment and reduce the fuel consumption, we made changes in the algorithm loaded into the controller which detected the cycles input to it. The difference in the properties of both cycles with respect to velocity (v) was used for this differentiation[8].

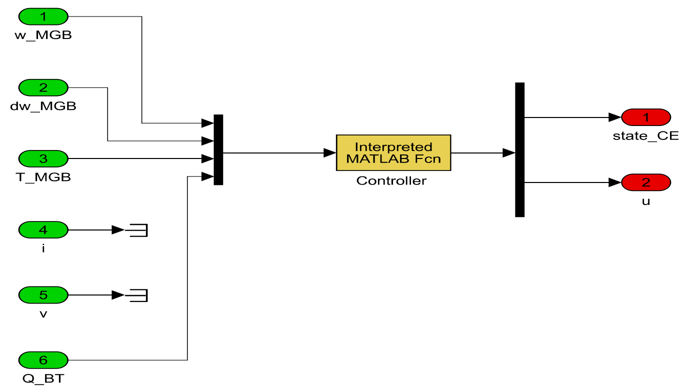

Fig. 5. Controller block

VII. Vehicle operation mode

A. Regeneration

While braking, the negative torque is introduced due to friction and kinetic energy is dissipated as heat. At that time, the motor works as a generator. The generator gain the maximum possible amount of energy which depends on the physical constraint. The remaining energy is absorbed by the friction brakes [1].

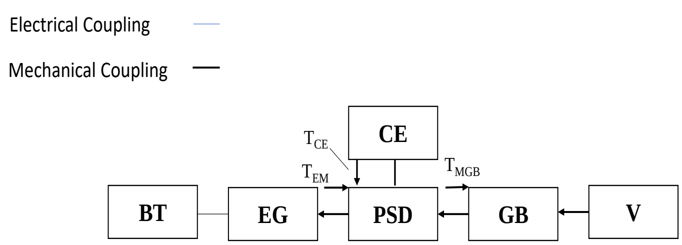

Fig. 6. Regenerative braking

The stored energy can be later used in electric driving mode. For $T_{MGB} < 0$, Torque Split Ratio for regeneration can be found out using the formula below,

$$u = min(\frac{-T_{EM,max}(\omega_{EM}) + |\theta_{EM} d\omega_{EM}| + \epsilon}{T_{MGB}}, 1)$$

Parallel HEVs rely more on regenerative braking and the CE can also act as the generator for supplemental recharging.

B. Electric Drive Mode

Engine efficiency is very low at low speed and high load as well. During this mode, the complete vehicle load is shifted on battery up to defined State of Charge (SoC). Electric drive improves the efficiency of vehicle with the disengaging of the CE. The smooth drive is provided here and so there will be exhaust gases and noise reduction. For attaining an electric drive, the torque split ratio should be one.

$$u = 1 \ and \ T_{MGB} > 0$$

$$T_{EM} = T_{MGB} \ and \ T_{CE} = 0$$

The constraints for achieving this drive mode are:

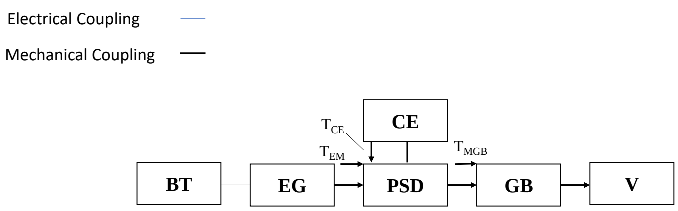

Fig. 7. Electric drive mode

- Flywheel angular acceleration, d_{MGB} = 0
- Velocity, v ≅ 10m/s

C. Load point shifting

Loading condition is different in different driving conditions, based upon which torque-split ratio is defined and power split between CE and EM. Engine efficiency and fuel consumption are largely depend on optimal engine load shifting [6].

1) $T_{MGB} > T_{MGB,th}$: Load will reached its maximum value after threshold torque. At that point, load point can be decreased by operating combined driving mode and discharging the battery. The value of u is defined by,

$$u = min(\frac{-T_{EM,max}(\omega_{EM}) - |\theta_{EM} d\omega_{EM}| - \epsilon}{T_{MGB}}, u_{LPS,max})$$

2) $T_{MGB} < T_{MGB,th}$: Load point can be increased by operating the motor in generator mode and charging the battery.

D. Engine Start-Stop

It is possible that when vehicle running on only the electric mode, the engine is idle in operation. So Start-Stop mode is used for turning of the engine and reduce fuel consumption.

$$State\_CE = 0$$

E. Conventional drive

In conventional drive mode, vehicle runs only on engine. Fuel from the fuel tank is consumed in this drive mode. The Torque split ratio in this mode is,

$$u = 0$$

VIII. Rule Based strategy

The achievable change in mileage depends emphatically on the vehicle and on the driving cycle. Rule-Based Strategy provides the rules that emphases the set of condition which provides the efficient compromise between conventional driving and the electrical driving. Start-Stop condition of the engine depends upon the state of charge of battery, power requested, needed torque and speed of the vehicle. This potential can be acknowledged by controlling the engine and motor power supply just inside the vehicle. Early energy management control was based on experimental considerations inspired by the expected behavior of the propulsion systems. As engine gives less torque at the starting of the vehicle compare to motor at low speed. Hence, a typical control system is to run the powertrain in an absolutely electric mode from a stop to a picked vehicle speed.
If the state of charge of battery goes below lower limit of battery then the power supply switches to the CE. At this time, CE supplies the power to the wheels and it also charges the battery by regeneration. Then, if the vehicle needs more power under certain load condition than the addition power is given by the EM to achieve certain speed. When state of charge of the battery is higher than the lower limit; in such cases the vehicle is run on EM and CE goes switch off to achieve higher fuel efficiency. The strategy used here is based on splitting the power requirement between the engine and the motor such that the vehicle operates at high efficiency. Rule based control strategies are used to achieve the best fuel economy, efficiency, performance, and emission for a specific driving cycle.
The idea of rule based strategy is based on the concept of load levelling and state of charge. The load levelling strategy is to shift the CE operating point as close as possible to optimal point of efficiency, fuel economy, or emission at particular speed.
Generally, the best fuel economy for this system is found at lower torque and lower engine speed than the best point of efficiency. This means that better fuel economy will be attained by having smaller accelerator commands. In this study CE is the primary source of power and EM is the secondary source of power. Both the sources are used as per the different requirement of power, torque and efficiency [7].

IX. Simulation Strategies

QSS toolbox works on different driving cycles which can be selected manually from driving cycle block. In this paper, we considered NEDC cycle which is running for 1220 seconds and FTP-75 cycle for 1877 seconds.
The simulated results for the respective cycles are given below,

TABLE I
List of variables

Name	Unit	Notation	NEDC	FTP-75
Max Torque Split Ratio	-	$u_{LPS,max}$	0.1	0.1
Min Torque Split Ratio	-	$u_{LPS,min}$	-0.576	-0.212
Threshold torque for electric mode	$N \cdot m$	$T_{MGB,th}$	29	32
Threshold torque LPS mode	$N \cdot m$	T	60	100
Min SOC for electric mode	-	SOC	0.35	0.35
Min SOC for LPS mode	-	SOC	0.8	0.8

A. Manual gearbox torque

When $0 < T_{MGB} < T$ vehicle run on electric mode. For, $T < T_{MGB} < T_{MGB,th}$ the vehicle operates in load point shifting generator mode.

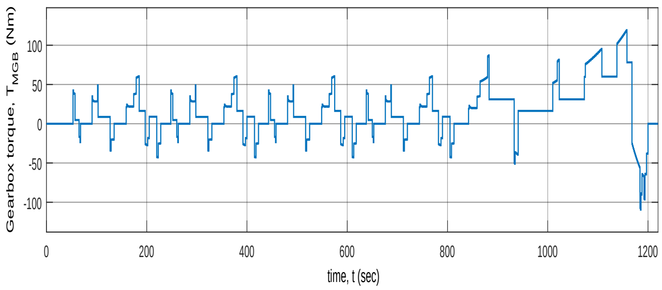

Fig. 8. Manual gearbox torque for NEDC

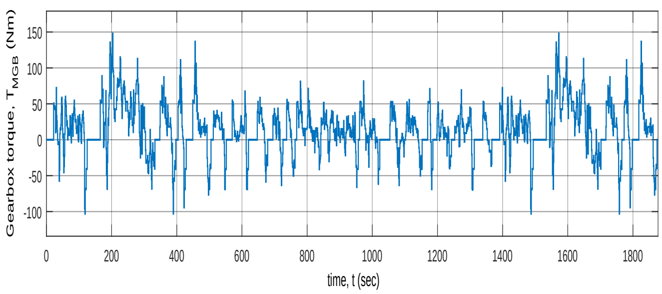

Fig. 9. Manual gearbox torque for FTP-75

B. Battery charge

When $SOC > 0.35$ vehicle run on electric mode. For, $SOC > 0.8$ the vehicle operates in load point shifting motor mode. Otherwise, vehicle run in load point shifting generator mode.

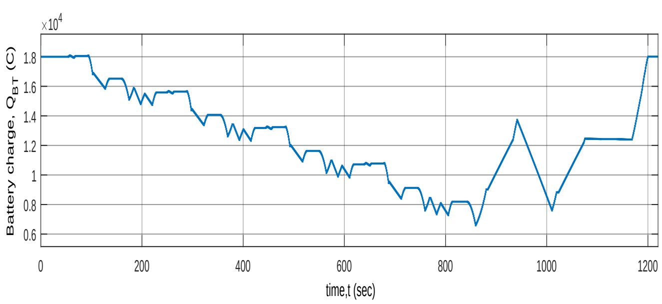

Fig. 10. Battery charge for NEDC

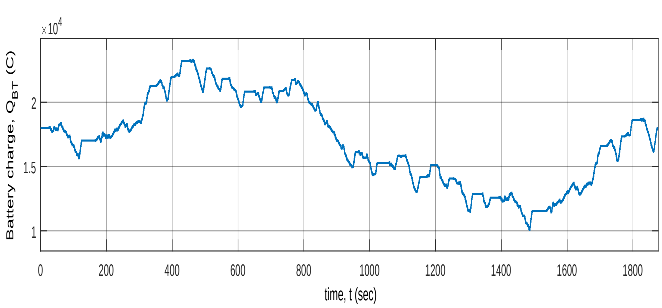

Fig. 11. Battery charge for FTP-75

C. Threshold torque

When torque of manual gearbox exceed threshold torque T, vehicle switch power between EM and CE. for NEDC, it is $60N \cdot m$ and for FTP, it is $100N \cdot m$.

D. Vehicle velocity

In this stretagy, vehicle velocity is not considered for the power split. But, for lower velocity vehicle run on electric mode and for medium velocity it run on CE would be benificial.

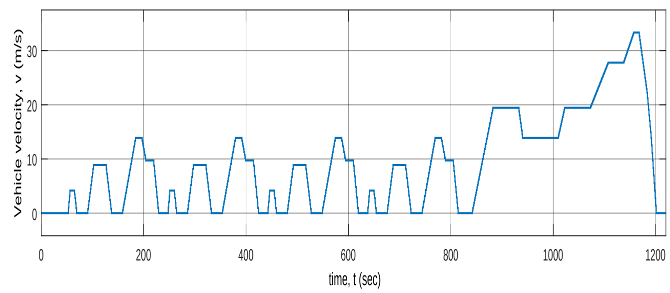

Fig. 12. Vehicle velocity for NEDC

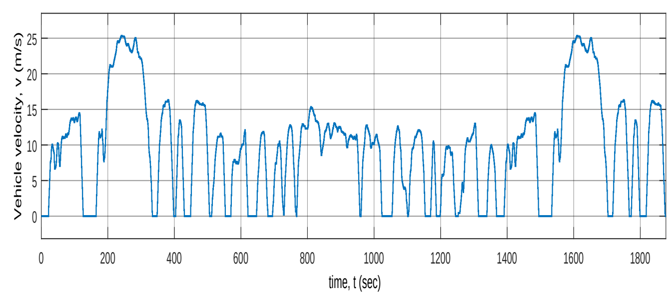

Fig. 13. Vehicle velocity for FTP-75

E. Torque split ratio

If the vehicle is not running under electric or regeneration mode then the engine must be turned ON.

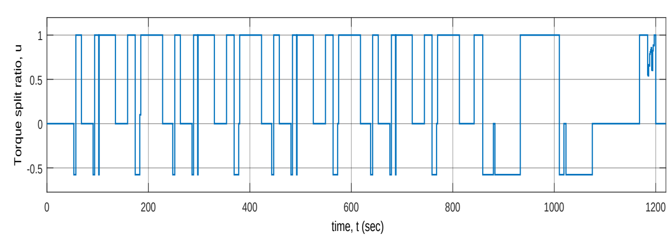

Fig. 14. Torque split ratio NEDC

X. Outcomes

The aim of the fuel reduction and efficiency improvement are fulfilled by switching the modes of the vehicle at the right time. When the vehicle starts there is low torque requirement

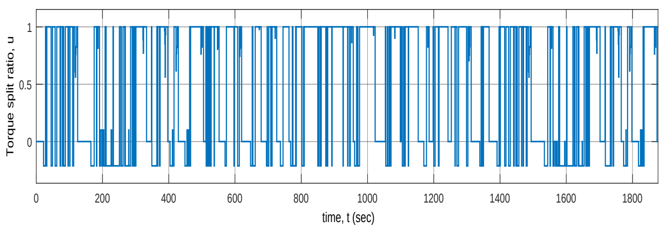

Fig. 15. Torque split ratio FTP-75

due to which more fuel is consumed by CE so here in the initial stage the vehicle is powered with the battery.

When a point comes where the torque exceeds its threshold limit and higher load condition at high speed, the degree of hybridization is maximized and load is shifted between EM and CE. However, when the vehicle is to be driven in the normal or city driving conditions the difficulties come into consideration that which strategy is to be considered. For optimization, the vehicle is switched to the conventional driving mode as the the CE can be used to its best efficiency, the speed as well as load requirements can be meet with charging of the battery which can be further used during the higher load conditions.

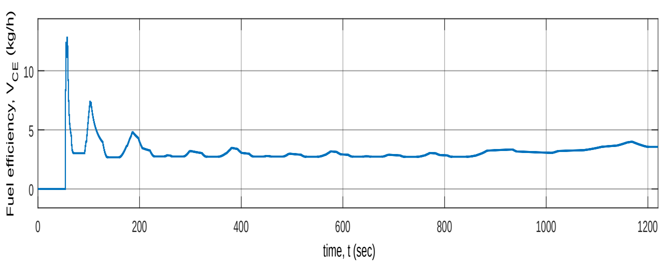

Fig. 16. Fuel consumption NEDC

TABLE II
FUEL CONSUMPTION IN CONVENTIONAL VEHICLE

Fuel Consumption For CV	
NEDC	4.897
FTP-75	4.675

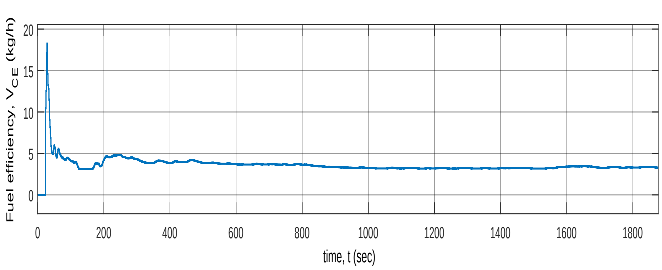

Fig. 17. Fuel consumption FTP-75

In this paper, the results for the NEDC driving cycle and FTP-75 driving cycle are calculated by optimized use of CE and EM at different stage of cycle. The outcomes are in terms of the minimizing the fuel consumption by ensuring equivalent the charge sustainment as of start.

TABLE III
FUEL CONSUMPTION IN HYBRID ELECTRIC VEHICLE

Fuel Consumption For HEV	
NEDC	3.56
FTP-75	3.283

The Rule Based Strategy was implemented on the system, which resulted for the fuel consumption of 3.56 litre/100km for NEDC driving cycle and 3.283 litre/100 km for FTP-75 driving cycle. The equivalent fuel consumption of both cycle is 3.4215 litre/100km.

$$v_{CE,equiv} = \frac{v_{CE,equiv,NEDC} + v_{CE,equiv,FTP-75}}{2} = 3.4215$$

XI. FUTURE WORK

In the future, there can be additional challenges would arise due the need in order to supply optimal energy to the HEV system such as plug-in HEVs [2]. This paper focused on the rule based strategy to obtain the results of particular driving cycles. Nevertheless, it gives good results, but there is still a room of improvement in the near future. Some alternatives are available such as Dynamic Programming (DP), Equivalent Consumption Minimization Strategy (ECMS), and Model Predictive Control (MPC) with which more effecient result could be obtained. [2].

The issues like durability and sustainability of the energy sources, reduction in the components in the vehicle to reduce its weight, development of new power split technologies and control strategies, reduction in gas pollutants and vibration in vehicle have to be addressed in the coming time[9].

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