Energy Management System for Mild Parallel Hybrid Electric Vehicles

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***Abstract*— Due to the technical advancements in the automotive industry, there is exponential rise in the sales of Hybrid Electric Vehicle as that of conventional vehicles. The depleting number of natural resources and increasing awareness towards green mobility have made the Hybrid Electric Vehicle as one of the tending topics for research. The main advantage of Hybrid Electric Vehicle over conventional vehicle is the reduced fuel consumption and reduced emissions. In parallel architecture of HEV, combustion engine and electric motor both are directly responsible for transmission of power to wheel. Energy management control strategy in Hybrid Vehicles plays an important role for optimizing fuel consumption. In this paper, a rule-based energy management strategy is implemented to reduce equivalent fuel consumption of a mild parallel hybrid electric vehicle. The system is analyzed for NEDC and FTP-75 driving cycle, equivalent fuel consumption was found 3.562 and 3.276 respectively. It was observed that this strategy reduced the fuel consumption by 32.22 %.**

I. Introduction

In today's technology driven world automobiles have become integral part of our life. The emergence of electronically controlled mechanical devices have led to an increment in the efficiency of mechanical devices. From the last two decades we have witnessed tremendous adaptations like transition from conventional vehicle to hybrid electric vehicles. The drivers for these transitions are scarcity of fuel resources, legislations, awareness about climate change, consumer expectations [5]. The vehicle which uses an electrical energy/power storage device along with a consumable fuel for its propulsion is termed as a hybrid electric vehicle (HEV) [1]. As HEVs operate on two different power sources it has attracted attention of researchers [7]. Fuel consumption in HEVs is lesser as compared to conventional internal combustion engine vehicles (ICEV) because: HEVs can recover part of vehicle's kinetic energy while braking and store it later usage, HEVs can shut down engine at idling and low speeds and motor provides power, this gives an opportunity to operate engine in optimal working range, which ultimately results in engine downsizing [6].In order to achieve the perfect combination of lower fuel consumption, lower emissions and best driving performance a control strategy is needed [8].

Zhang et. al. [5] states that, the control strategies for hybrid vehicles are divided into: Online Energy Management Strategy and Offline Energy Management Strategy. In simple terms Online EM's are causal in nature and Offline EM's are non-causal in nature. Rule based strategy is an offline EM's which works on predefined rules. These rules are based on mathematical calculations, knowledge, or intuition. The rule-based strategy is further divided into Deterministic Rule based method and Fuzzy Logic Rule Based Method. Results of Pam et al. [10] states that Rule Based time consumes less computation time and applicable in real time applications as compared to Dynamic Programming.

In this paper by considering the aim to reduce fuel consumption and applicability of the energy management strategy in real time, Rule Based strategy is implemented. Due to the advantages like less computation time, applicability in real time applications Rule Based method is used.

The rest of the paper is organized as follows: Section II gives an overview of the topic. The subsections describe about the classification of electric hybrid vehicles, QSS Toolbox, and the specifications of the vehicle whose energy management system is designed, Section III explains the rule-based energy management strategy used for the purpose. Various operation modes that are considered for reducing the fuel consumption are described in Section IV. Section V shows the simulation results for NEDC and FTP-75 driving cycles. Section VI consists of conclusion obtained from results. Section VII discusses the lacunas in the rule-based method and provides with the future scope.

II. Overview

This section of the paper deals with a general overview of the electric hybrid vehicles. In this section classification of the electric vehicles is briefly discussed. Moreover, a general overview of QSS Toolbox is also provided.

A. Classification of Hybrid Electric Vehicles

HEVs are classified into three main types based on the configurations of the prime movers and power flow.

1) Series Hybrid Electric Vehicles

In series hybrid electric vehicles electric motor (EM) is used to propel the vehicle whereas internal combustion engine (ICE) is coupled to electric generator (EG). Therefore, EG and Battery provide necessary power to electric motor to propel vehicle. As ICE is not directly mechanically coupled to the drivetrain, it can be used in an optimal working point.[1]

2) Parallel Hybrid Electric Vehicles

In parallel hybrid electric vehicles EM and ICE are coupled mechanically using torque converter to provide power for

propulsion of vehicle. In this architecture ICE is coupled mechanically to the drivetrain.[1]
Parallel hybrid vehicles with system voltage in the range 48-150 V, battery energy 0.5 – 2 kWh and motor power 10-15 kW are classified as mild parallel hybrid vehicle. [2]

3) *Combined Hybrid Electric Vehicles*

Combined hybrid electric vehicles utilize a complex architecture, where ICE is coupled both mechanically and electrically to the drivetrain providing characteristics of both series architecture and parallel architecture. Power split device (PSD) splits the power generated by ICE into mechanical path and electrical path.[1]

B. *QSS Toolbox*

QuasiStatic Simulation Toolbox (QSS TB) is a toolbox compatible with Matlab/Simulink, which makes the process of powertrain design fast and flexible, as it can also be integrated with other functional toolboxes (e.g., optimization solvers) of Matlab. The main of objective of QSS TB is for calculation of fuel consumptions of powertrains according to desired driving cycles and control algorithms. QSS TB works on the quasistatic approach, in which forces are derived from the speed, gear of the vehicle in discrete intervals of time. The discrete force data calculates the instantaneous angular velocity, torque of engine and thus the fuel consumption. Total fuel consumption is calculated using appropriate numerical method. This approach is totally opposite to traditional analysis of vehicle under dynamic conditions. [1]

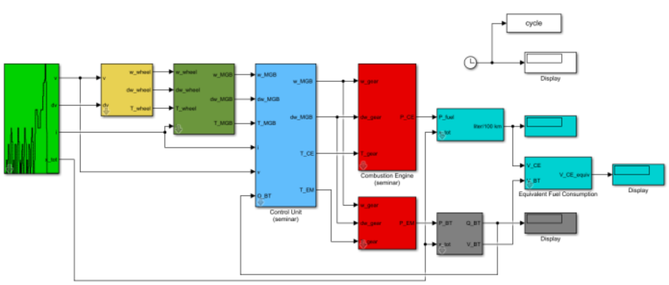

Fig. 1. Model in QSS Toolbox

Two driving cycles are used for simulation:

1) *NEDC (EU New European Driving Cycle):*

This cycle runs for 1220 s and has driving range of 11 km. The maximum speed in this cycle is 120 km/h, whereas average speed is 33.6 km/h. NEDC cycle is based on synthetic driving profile and is relevant for analysis of light duty vehicles. This cycle also provides gear shifting for manual transmissions. There is no consideration of auxiliary systems while calculating fuel consumption from NEDC cycle.[2]

2) *FTP-75 (US EPA Federal Test Procedure):*

This cycle runs for 1877 s and has driving range of 17.77 km. The maximum speed in this cycle is 91.2 km/h, whereas the average speed is 34.1 km/h. FTP-75 cycle is derived from test data measured in Los Angeles in 1975 and is relevant for analysis of light duty vehicles. The determination of fuel consumption is based on EPA 5-cycle method.[2]

C. *Vehicle Specifications*

The specifications of the vehicle are shown in table.

TABLE I. VEHICLE SPECIFICATIONS.[2]

Parameter	Value/Type
Model	Mercedes Benz A170 CDI (W168)
Engine	60 kW, 187 Nm, 4200 RPM, Diesel
Motor	12 kW, 60 Nm, 7639 RPM, PMS
Battery	Li-ion, 16.38 kW, 46.8 V, 0.468 kWh, 13 mΩ
Gearbox	5 Speed Manual
Clutch	Friction Type

The figure shows the architecture of the vehicle used for developing energy management system. It is a mild parallel hybrid vehicle with the motor connected on the gearbox side of the clutch. This architecture resembles P2 architecture [1].

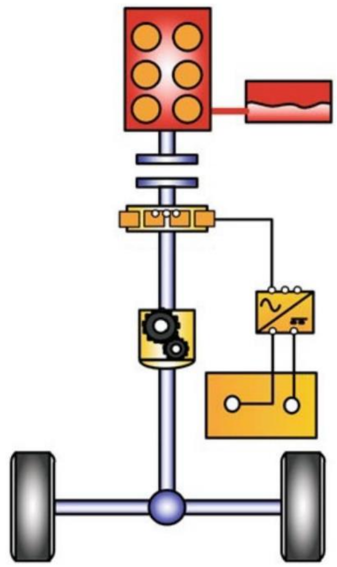

Fig. 2. P2 Architecture

III. RULE BASED STRATEGY

The focus of the study is to implement Rule Based Strategy for Energy Management of a mild parallel hybrid vehicle to reduce fuel consumption. The core of the rule-based method is built on the concept of “load leveling”. The load leveling concept focusses on reducing the difference between the operating ICE condition and the optimal efficiency, fuel economy or emission condition [3]. In the initial stages of the rule-based strategy expected results and expectations are basic parameters for defining set of rules [5].

It consists of several rules for every state of vehicles such that as per the conditions of the variables denoting the states suitable rules are applied [4]. The set of rules which drives the complete model and mode selection is derived from mathematical models, human expertise, or intuition [3]. The shifting between the states is dependent on some rules which are consisting of conditions like power requirement of engine and motor, acceleration and deceleration, vehicle speed and battery soc [5].
In the given vehicle model a set of rules consisting of such variables are defined. The optimization is done by applying

iterative method on the set of variables. Fuel consumption of the vehicle is calculated for every combination of the variables and set of variables denoting minimum fuel consumption are selected.

Firstly, some preliminary values of variables like Load point shifting torque values for motor and generator mode, minimum and maximum battery charge value, maximum torque split ratio value in generator and motor mode are selected. By iterating set of mentioned variables, the optimum combination of variables giving rise to the optimum fuel consumption is determined. The variables and values for NEDC and FTP -75 cycles are mentioned in Tab.2

TABLE II. INPUT VALUES OF VARIABLES.

Parameters	NEDC	FTP-75
Load point shifting torque – Motor Mode (*T_MGB_th*)	58 Nm	50 Nm
Load point shifting torque – Generator Mode (*T*)	29 Nm	32 Nm
Minimum charge in battery (Q_BT_{min})	2500 C	2500 C
Maximum charge in battery (Q_BT_{max})	16000 C	21000 C
Torque Split Ratio – Motor Mode (*u_LPS_mot_max*)	0.2	0.2
Torque Split Ratio – Generator Mode (*u_LPS_gen_max*)	-0.55	-0.35

IV. OPERATION MODES

This paper aims to study the energy management of Mild Parallel Hybrid Vehicle. In parallel hybrid vehicles the two energy sources namely electric motor and combustion engine are mechanically coupled by Torque Coupler. Gearbox torques is therefore given by,

$$T_{MGB} = T_{EM} + T_{CE} \tag{1}$$

where T_{CE} is the torque provided by combustion engine, and T_{EM} is the torque provided by electric motor, T_{MGB} is the flywheel torque. The ratio of torque provided by electric motor to the flywheel torque is known as Torque split ratio. Mathematically it is shown as

$$u = T_{EM}/T_{MGB} \tag{2}$$

Torque split ratio is an important factor for determining the operation mode of vehicle.
Following are the operations considered in this study.

A. Regeneration Mode

In traditional vehicles the braking of vehicle is done by converting the kinetic energy into heat energy with the help of friction. In regeneration, by operating motor in generator mode while braking the kinetic energy can be stored in battery which can be used later [4]. Fig.6. gives the energy flow block diagram of regeneration mode.

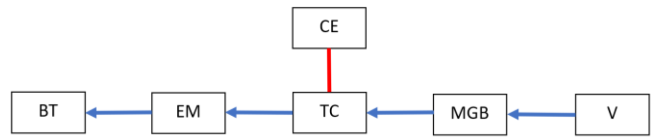

Fig. 3. Regeneration Mode

When $T_{MGB} < 0$ Regeneration mode is activated. To maximize the regeneration following equation is used.

$$u = \min\left(\frac{-T_{EM,max}(\omega_{EM}) - |\theta_{EM} d\omega| + \epsilon}{T_{MGB}}, 1\right) \tag{3}$$

B. Load Shifting Point

In this mode of operation, sharing of the load between engine and motor is done to not only improve engine efficiency but also to lower amount of pollutant emissions. As engine efficiency is strongly dependent upon load, shifting of load point improves engine efficiency. By operating motor in motor mode load point can be decreased on the other hand operating motor in generator mode increases the load point.

1. Load Point Shifting Motor Mode

When engine alone is not able to withstand the load, motor is used in motor mode which causes sharing of the load. As motor works on battery, operating motor in motor mode discharges the battery. Fig.7. gives the energy flow block diagram of regeneration mode.

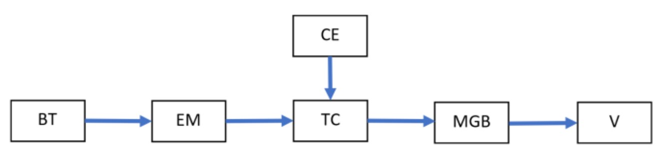

Fig. 4. Motor Mode

The range of torque split ratio for motor mode is $0 \leq u < 1$. For optimizing the fuel consumption under motor mode three conditions $T_{MGB} \geq T_{MGB\_TH}$ and $Q\_BT > Q\_BT_{max}$ and $i = 2$ are used.

$$u = \min\left(\frac{T_{EM,max}(\omega_{EM}) - |\theta_{EM} d\omega| - \epsilon}{T_{MGB}}, u\_LPS\_mot\_max\right) \tag{4}$$

Determination of torque split ratio under motor mode is done with the formula mentioned below.

2. *Load Point Shifting Generator Mode*

In this mode by operating motor in generator mode the power from engine is used to charge the battery. As the power is supplied by engine to run the vehicle as well as to charge the battery, this mode is suitable when the load on vehicle is lower than the power generated by engine. Fig.7. gives the energy flow block diagram of regeneration mode.

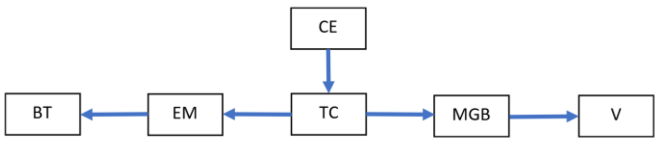

Fig. 5. Generator Mode

The value of torque split ratio for generator mode is $u < 0$. For optimizing the fuel consumption under generator mode three conditions $T_{MGB} > T$ and $T_{MGB} < T_{MGB\_TH}$ and $Q_{BT} < Q\_BT_{max}$ are used. Determination of torque split ratio under generator mode is done with the formula mentioned below.

$$u = \max\left(\frac{-T_{EM,max}(\omega_{EM}) + |\theta_{EM} d\omega| + \epsilon}{T_{MGB}}, u\_LPS\_gen\_max\right) \quad (5)$$

C. *Electric Driving*

In this mode motor is used to drive the vehicle as efficiency of engine is low at low load points. In simple terms in this mode the engine is not working and whole power required to drive the vehicle is supplied by motor [4]. Fig.8. gives the energy flow block diagram of Electric Driving mode.

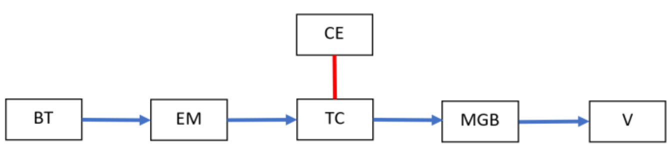

Fig. 6. Electric Driving

The value of torque split ratio for generator mode is $u = 1$. Amount of charge in battery plays an important role as if the charge is above some threshold value, then only electric driving is possible. The conditions for electric driving are $T_{MGB} > 0$ and $T_{MGB} \leq T$ and $Q_{BT} > Q\_BT_{min}$.

C. *Conventional Engine Mode*

In this mode power required to drive the vehicle is supplied by only engine. In case of high torque requirement, the efficacy of this mode is higher. During this mode, the motor is not working and hence the value of torque split factor is $u = 0$. Fig.9. shows the energy flow block diagram of Conventional Engine mode.

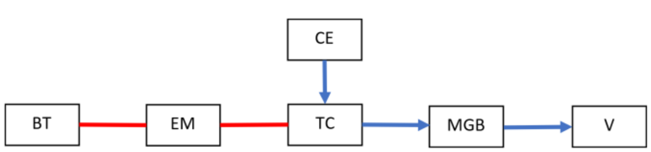

Fig. 7. Conventional Engine Mode

V. SIMULATION RESULTS

QSS Toolbox is a tool by which equivalent fuel consumption for various driving cycles can be determined. In this paper the simulation on NEDC and FTP-75 cycles is performed. The time durations for EDC and FTP-75 are 1220 s and 1877 s respectively. The simulation model is consisting of all parts of vehicle like battery, gearbox, combustion engine, control unit. Out of which controller design is done in the control unit par. By implementing the energy management strategies in MATLAB in the control unit part and running the simulation with the help of Simulink, all possible fuel consumption values are determined. I order to visualize the result variation in the variables like state of charge(soc), Battery charge, Gearbox torque, fuel consumption are plotted with respect to time.

A. *Vehicle Velocity (v m/s)*

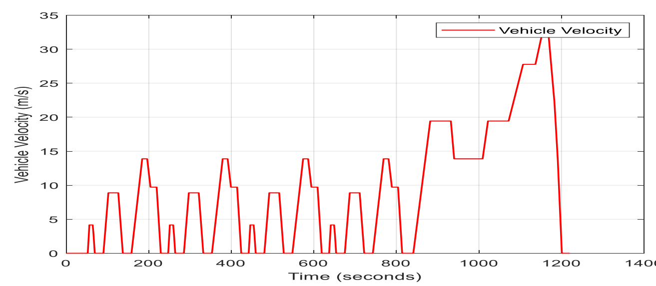

Fig. 8. Vehicle Velocity Variation (NEDC)

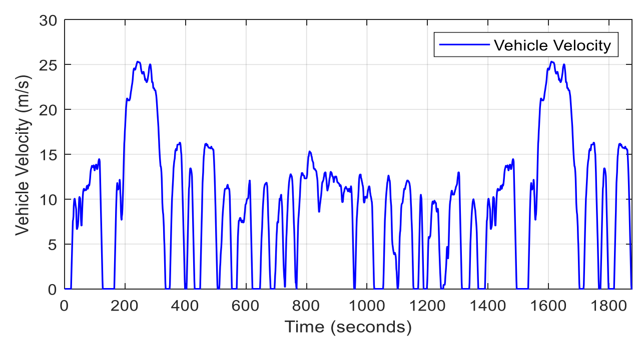

Fig. 9. Vehicle Velocity Variation (FTP-75)

B. *Angular Velocity (ω_{EM} rad/s)*

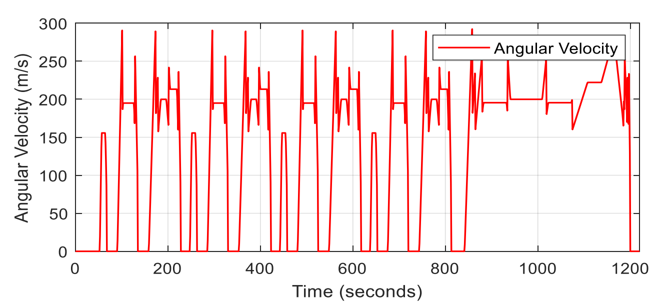

Fig. 10. Angular Velocity Variation (NEDC)

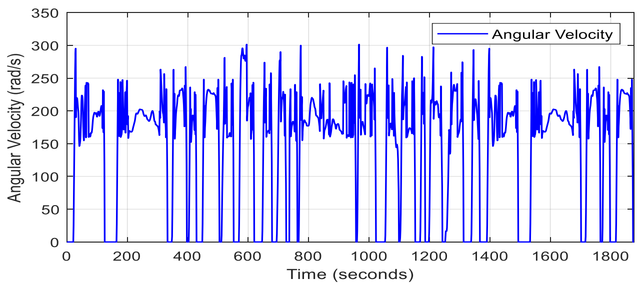

Fig. 11. Angular Velocity Variation (FTP-75)

C. *Gearbox Torque (T_{MGB} Nm)*

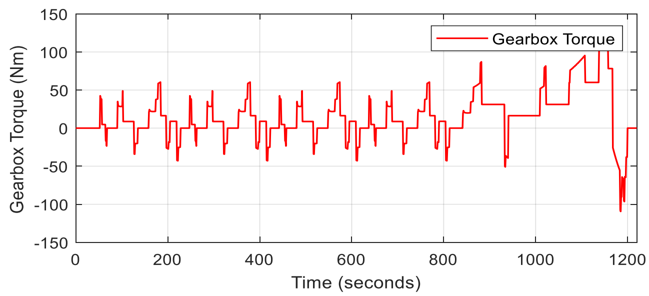

Fig. 12. Gearbox Torque Variation (NEDC)

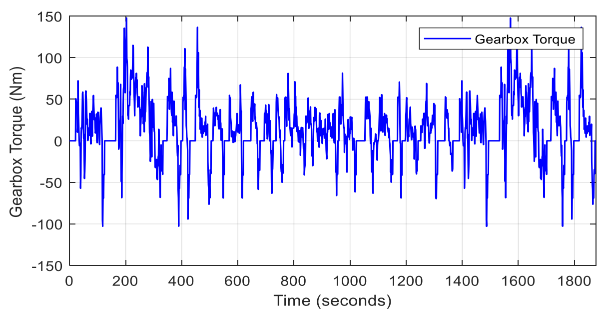

Fig. 13. Gearbox Torque Variation (FTP-75)

D. *Torque Split Ratio (u)*

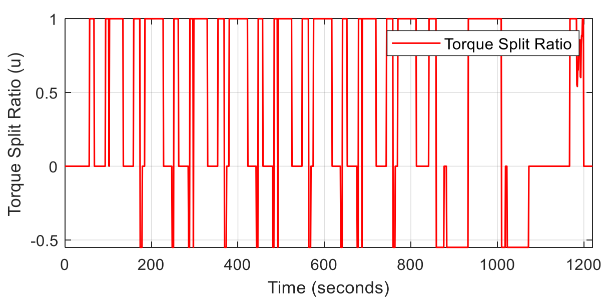

Fig. 14. Torque Split Ratio Variation (NEDC)

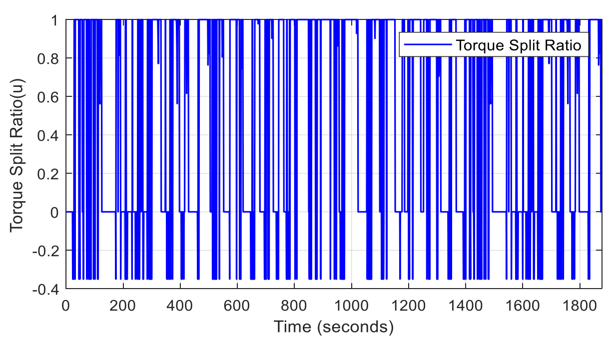

Fig. 15. Torque Split Ratio Variation (FTP-75)

E. *Battery Charge (Q_BT C)*

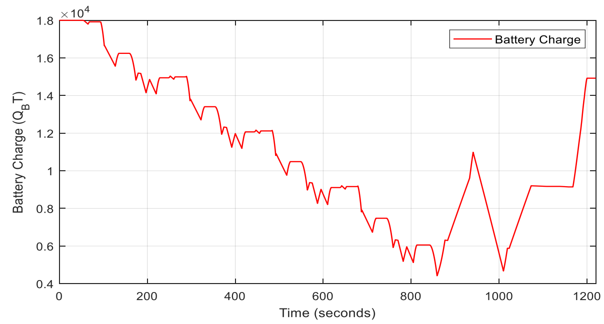

Fig. 16. Battery Charge Variation (NEDC)

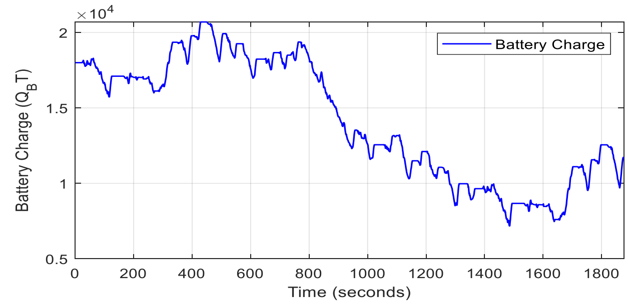

Fig. 17. Battery Charge Variation (NEDC)

F. *State of Charge (q_BT)*

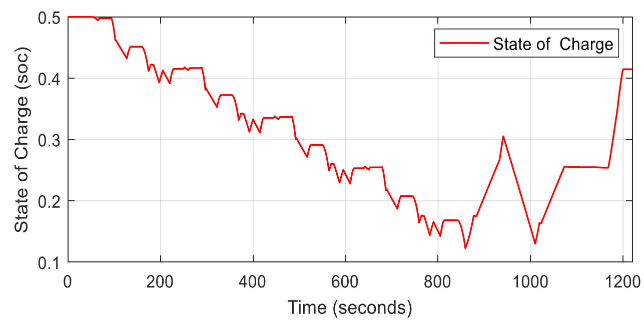

Fig. 18. State of Charge Variation (NEDC)

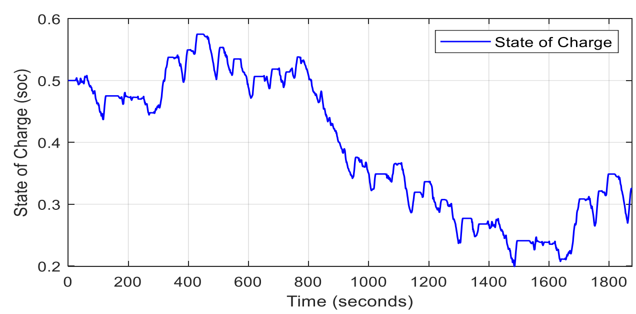

Fig. 19. State of Charge Variation (NEDC)

G. Equivalent Fuel Consumption (V_{CE} (l/100 km)

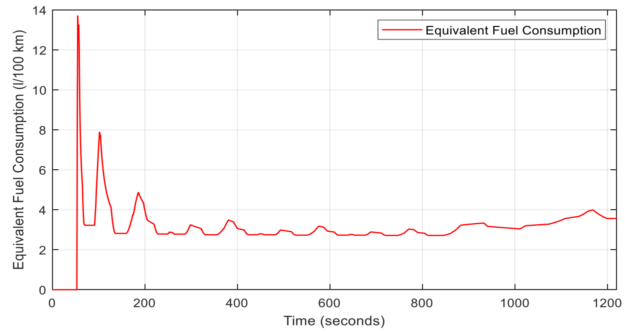

Fig. 20. Equivalent Fuel Consumption Variation (NEDC)

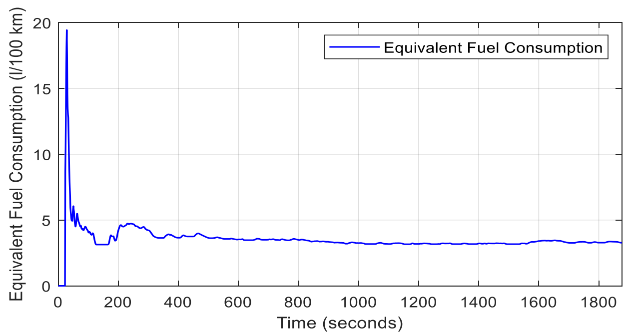

Fig. 21. Equivalent Fuel Consumption Variation (FTP-75)

The quantitative result of the simulation is shown in Table 3.

TABLE III. RESULTS

Parameters	NEDC	FTP-75
V_{CE} (l/100 km) for conventional vehicle	4.897	4.675
V_{CE} (l/100 km) for Mild Parallel Hybrid Vehicle	3.562	3.276
Reduction in fuel consumption (%)	27.2%	29.9%
Average Fuel consumption for (NEDC+FTP-75)	3.419	
Initial Charge in the battery Q_{BT} initial (C)	18000	
Final Charge in the battery Q_{BT} final (C)	14924	11717

VI. Conclusion

To reduce the fuel consumption of a mild parallel hybrid electric vehicle, an efficient energy management system is required. Although there exist various types of energy management systems, a rule-based energy management strategy is employed because of it is easily implementable. The rules are consisting of set of variables like load point shifting torque for motor and generator mode, minimum and maximum value of state of charge. The method employed needs fine tuning of parameters. The method is based on set of rules which are derived from mathematical models, experience, intuition. From the simulation results it can be concluded that 23.80 % and 33.10% fuel consumption reduction is observed compared to conventional vehicle in NEDC and FTP-75 cycle respectively.

VII. Future Work

Although rule-based method is easy to understand and requires less computation time, the rules need to be defined separately for varying driving conditions. Numerical values of some parameters have not affected our results, but it is paramount to consider the precise and realistic values of such parameters. The disadvantage of this method is that it does not give global optimum values. Further optimization of the results from rule-based strategy can be done with an optimization algorithm like Model Predictive Control (MPC), Dynamic Programming (DP). MPC works based on calculating the system input trajectory and then optimizing the future system output. As QSS Toolbox can map the exhaust emissions of the engine according to engine load in similar fashion with fuel consumption, an energy management strategy can be designed which takes consideration of both exhaust emissions and fuel consumption giving a environment friendly system.

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