OPTIMISATION OF ENERGY MANAGEMENT SYSTEM FOR PARELLEL MILD HYBRID VEHICLES

USING RULE BASED METHOD

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***Abstract*—Since, today there is a change in the automobile sector with a drive towards renewable sources of energy and modern powertrains hybrid vehicle have gained importance. The goal of hybrid vehicles is to maximize the efficiency and range using more than one energy source. The purpose of this paper is to design the controller to reduce the fuel consumption of parallel mild hybrid vehicle when compared to current day's conventional vehicle and to maximize the retention of battery charge by using regeneration and load point shifting techniques. The results obtained were optimal and the fuel consumption of vehicle for NEDC and FTP-75 driving cycle was reduced.**

Keyword—Hybrid Electric Vehicle, State of Charge, Rule based strategy, parallel mild hybrid electric vehicles, charge of battery, energy management, fuel consumption; torque split

I. INTRODUCTION

Hybrid vehicles are the need of the hour with the transition from conventional to newer cleaner powertrains. Hybrid vehicles are vehicles that have at least two different energy converters and two different energy storage systems present on board the vehicle, utilized for vehicle propulsion. Hybrid electric vehicles draw energy from the conventional fuel and an electrical power storage device like battery. Use of two power sources will give HEVs a combined advantage of both ICE vehicles and EV. The list of combined advantages are listed below:

- Engine load point shifting
- Regeneration of Kinetic energy during breaking
- Low cost engine
- Lower pollutant emission
- Electric driving
- Higher flexibility in power source

Electric hybrid vehicle work on energy management systems that decides how to use the primary and secondary energy sources in Hybrid electric vehicle for the maximum efficiency and performance. It is not mandatory that both the energy sources will be operating at all point of the time. Depending upon the conditions the HEVs controller decides the source of energy. For example, when vehicle is at certain defined speed or when it is at temporary halt the vehicle will be in electric drive and the combustion engine will be switched off. The responsibility of power transfer to the driving wheels from the source in a vehicle is taken by drivetrain. In HEVs, the drive trains can be classified in to three types as:

- Series HEV
- Parallel HEV
- Combined HEV

These classifications are based on the arrangement of energy sources and component's architecture. Major components that are considered here are the battery, the electric motor (EM), the combustion engine (CE), a torque coupler and a manual gearbox (MGB).

In Parallel HEVs, the engine and the electric motor are coupled by a torque coupler (TC) and their torque is added together. Therefore, the torques of the engine and the electric motor can be adjusted independently. The engine speed and the electric motor speed are linked by the TC at a fixed ratio, but they cannot be controlled independently.

This paper presents the idea of optimisation of parallel mild hybrid vehicle (PHEV) by using power split energy management strategy. The power split is done using rule based energy management strategy. The basic aim of this paper is to reduce the fuel consumption of HEV by enhancing the performance of control unit. To enhance the performance of control unit a MATLAB/SIMULINK model named 'QSS tool box' is used. QSS tool box has a model of PHEV. In this the controller is designed and programmed to use different operating conditions to optimise the fuel consumption using rule-based strategy. This energy management system is operated on two renowned driving cycles:

1. The EU New European driving cycle (NEDC)
2. EPA federal test procedure (FTP-75)

Information regarding these driving cycles are discussed in section III.

II. Architecture of Parellel Mild Hybrid Vehicle

The mild hybrid concept is the simplest of the hybridization concepts and the architecture for this type of hybrid vehicle involves battery, electric motor, combustion engine, torque coupler and manual gearbox. The torque coupler is a mechanical device that couples the CE, EM and MGB on shaft for singular or combined vehicle propulsion. The equation for torque is:

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

Where T_{CE} is the torque of combustion engine, T_{EM} is the torque of the electric motor and T_{MGB} is the torque of the manual gearbox)

III. Driving Cycles

Driving cycles are standardized defined pattern of driving which considers factors like urban driving, extra-urban driving, and highway driving cycles. By using these cycles fuel consumption and emissions levels are tested and determined. This cycles consists of different speed-time relations of vehicle at different driving modes. Modes like deceleration, acceleration, braking and idling are considered. Basic characteristics of cycles are distance, duration and average speed. For the purpose of this paper we use driving cycles NEDC and FTP-75.

A. EU New European driving cycle (NEDC)

The New European driving cycle in total consist of five sub driving cycles in which, four are urban driving cycle (UDC) and one is extra urban driving cycle (EUDC). NEDC runs for a total length of 11 kilometers for a duration of 1220 seconds. The maximum speed of the cycle is 120 km/h and averaging 33.6 km/h. the driving cycles have intermediate braking torque and accelerates at the high speed at the end of the cycle. Therefore this cycle is mostly relevant to light-duty vehicles.

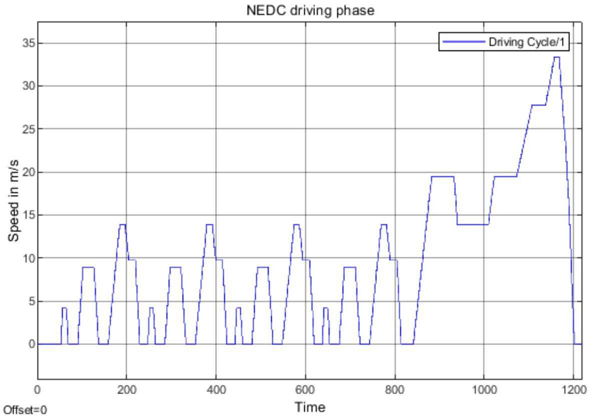

Figure 1: NEDC driving phase

B. EPA federal test procedure (FTP-75)

The American FTP cycle has been defined by US EPA (Environmental Protection Agency). It involve driving condition like city driving, highway driving and aggressive driving with many speed variations and typical on-road driving conditions. FTP-75 runs for a total length of 17.77 kilometers for a duration of 1887 seconds. The maximum speed of the cycle is 91.2 km/h and averaging 34.1 km/h and is relevant to light-duty vehicle.

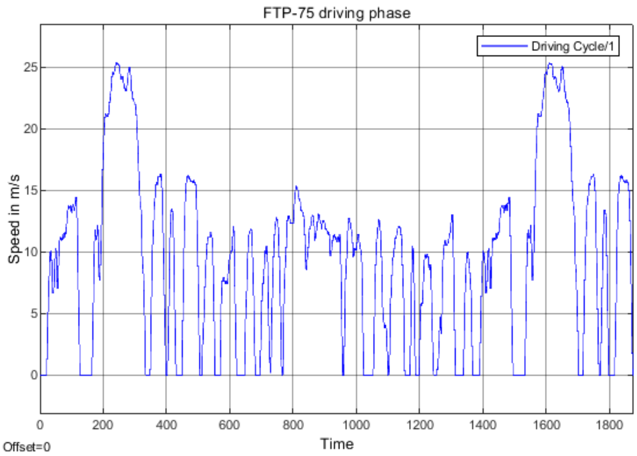

Figure 2: FTP-75 driving phase

IV. Energy Management System

An essential part of that energy management system is the torque split ratio (u) which is defined as a ratio of

Torque of electric motor (T_{EM}) to Torque of manual gear box (T_{MGB}) and is given by expression:

$$u = T_{EM} / T_{MGB}$$

The torque split ratio is a control strategy that chooses the power split between motor and combustion engine. The controller chooses the operating mode depending on the torque conditions that are prescribed in the program to minimise the fuel consumption and also to retain the required battery charge percentage. Depending upon the torque conditions the operating modes are decided. In this paper to optimise the energy management system four operating modes are considered, and these four operating modes are:

1. Load point shifting
2. Regeneration
3. Start stop
4. Electric drive

In the below section the detailed information of these operation modes have been described.

V. OPERATION MODES

Operation modes involves load point shifting, regeneration and start stop. Under load point shifting we have motor mode ($T_{MGB} > 0$ and $0 \leq u < 1$) and generator mode ($T_{MGB} > 0$ and $u < 0$) and electric drive. Regeneration has regenerative mode ($T_{MGB} < 0$ and $u = 1$) and regenerative & friction mode ($T_{MGB} < 0$ and $0 \leq u < 1$).

A. *LOAD POINT SHIFTING*

The efficiency of the engine (η_{CE}) depends highly on the load points ω_{CE} & T_{CE} (where ω_{CE} is the angular velocity of the combustion engine). To improve the efficiency of the engine these load points are shifted by operating the electric motor at desired conditions. In motor mode, the electric motor supplies power to the manual gear box and thus load point can be decreased but it also leads to the discharge of the battery. In generator mode, the electric motor acts as a power generator and charges the battery by this the load point can increased. This can be done keeping in mind that the increase in efficiency should always be greater than the conversion losses. The efficiency can be improved by operating the electric motor in motor mode at low load points and as generator mode in medium load points. Constrains that are involved on the torque coupler ($T_{CE} + T_{EM} = T_{MGB}$), engine ($0 \leq T_{CE} < T_{CE,\,max}(\omega_{CE})$), motor ($T_{EM} < T_{EM,\,max}(\omega_{EM})$) and battery.

The condition for load point shift is given by,

$$T_{MGB} > 27\text{Nm}$$

To achieve optimum fuel efficiency, a minimum torque greater than 27Nm is chosen to operate in LPS mode. In the program, load point shifting happens in four different situations, three of them are in generation mode and one is used for motor mode.

a. Motor mode: The electric motor supplies power to the manual gear box and thus load point can be decreased but it also leads to the discharge of the battery. The condition for motor mode is,

$$T_{MGB} > 100 \text{ and } Q_{BT} >= 9000C$$

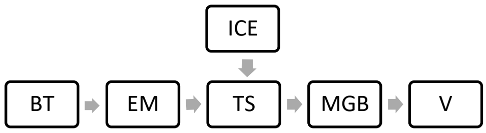

Figure 3: Motor mode

b. Generator mode: The electric motor acts as a power generator and charges the battery by this the load point can increased. The condition for generator modes are,

i) ($T_{MGB} >= 0$) and ($T_{MGB} <= 27\text{Nm}$) and ($Q_{BT} < 3600C$)

ii) ($T_{MGB} > 27\text{Nm}$) && ($T_{MGB} <= 100\text{Nm}$)

iii) ($T_{MGB} > 100$) and ($Q_{BT} < 9000C$)

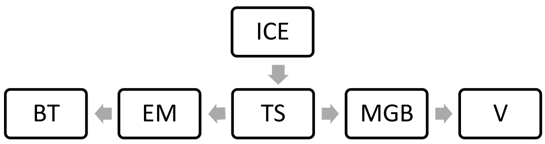

Figure 4: Generator mode

B. *REGENERATION*

When the vehicle undergoes braking there is a dissipation of kinetic energy into friction braking and engine braking. These losses can be redeemed by storing this kinetic energy using regenerative braking. Regeneration helps in gaining significant amount of energy that was previously just losses to the system so it should be maximized. There are constraints involved that should be met for regeneration in torque coupler is,

$$(0 > T_{EM} \geq T_{MGB}) \text{ due to } T_{CE} = 0$$

and optional friction braking), motor ($T_{EM} < T_{EM,\ max}$ (ω_{EM})) and battery.”

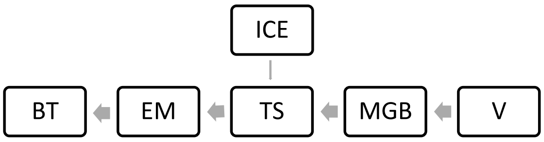

Figure 5: Regeneration mode

C. START STOP

All the previously mentioned operation modes fulfill the requirement when the vehicle is in a state of motion but when the vehicle idles (e.g. traffic signals) the engine idles and energy loss occurs (Combustion engine burns fuel to keep the engine running). To tackle this loss start stop is implemented, it stop the CE when the vehicle is idling to save fuel. It works in combination with either electric drive (T_{MGB} > 0) or regeneration (T_{MGB} < 0) before the vehicle reaches idling condition. The constraints of torque coupler are,

$$(T_{EM} = T_{MGB} \text{ due to } T_{CE} = 0)$$

And for motor,

$$(T_{EM} < T_{EM,\ max}\ (\omega_{EM}))$$

In this paper the start stop function is activated by considering the u values, whenever $u = 1$ the engine will stops running.

D. ELECTRIC DRIVE

Combustion engine has very low efficiency at low load points (lower speeds with frequent stops). To tackle the lower efficiency, electric drive can be implemented at these lower points and charging can occur at medium load points to increase the efficiency. Also, the electric drive leads to lower pollution and noise levels of the vehicle. The condition where electric drive is implemented is when the increase in efficiency is greater that the charging losses and the constraints for torque coupler is,

$$(T_{EM} = T_{MGB} \text{ due to } T_{CE} = 0),$$

And for motor,

$$(\text{abs}(T_{EM}) < T_{EM,\ max}\ (\omega EM)\ )$$

and for battery

$$(I_{BT} < I_{BT,\ max}, 2U_{BT} > U_{OC}, 0 \leq Q_{BT} \leq Q_{BT0})$$

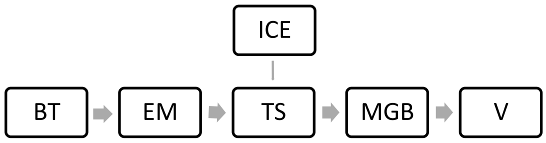

Figure 6: Electric mode

E. Conventional driving

In this mode the vehicle operates as a conventional vehicle, where only engine power is used to run the vehicle. This is applied when there is a need of moderate torque is required with higher angular velocity. The condition for conventional driving is,

$$u = 0$$

VI. CONTROL UNIT

Control unit manages the energy management system and the efficiency and effectiveness can be improved by optimizing the input values. The basic version of control unit is designed for six input variables, in this paper, five input variables such as angular velocity of manual gear box, torque of manual gear box, velocity of manual gear box, acceleration of manual gear box and state of charge are considered. The control unit contains the controller function which determines the torque split ratio based on the torque requirements and other parameters. The unit also contains start stop function which defines the state of engine based on the operating mode.

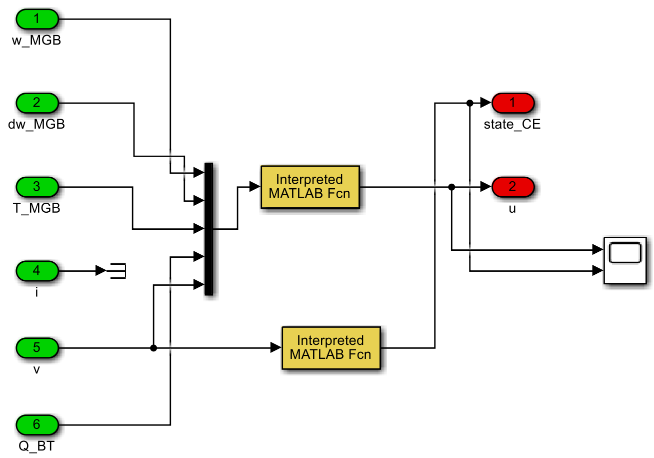

Figure 7: Motor mode

VII. Simulated results

The parallel hybrid vehicle considered for the simulation is Mercedes-Benz A 170 CDI (W168). The vehicle specifications are mentioned in Table 1.

Vehicle	Curb Weight (1115 Kg)
Engine	Fuel: Diesel Maximum Power: 60 KW Maximum Torque: 187 Nm @ 4200 rpm
Motor	Permanent Magnet Maximum Power:12 KW Maximum Torque: 60 Nm @ 7639 rpm
Battery	Lithium-ion Capacity: 10 Ah Maximum Voltage: 54.6V Maximum Power: 16.38 KW
Transmission	Manual 5-speed

Table I: Vehicle specification

QSS tool box was used to implement the changes in the controller. As discussed above, European NEDC and the American FTP-75, were combined in the controller block and condition statements were defined. The behaviour of these two cycles can be better understood in the following figuers.

A. NEDC driving cycle

From the Fig 8, it can be observed that the torque variations follow the similar pattern till 800 seconds and shows greater variations between 800 to 1220 seconds. This is because the driving cycle consists of four identical urban cycles and one extra urban cycle at the end.

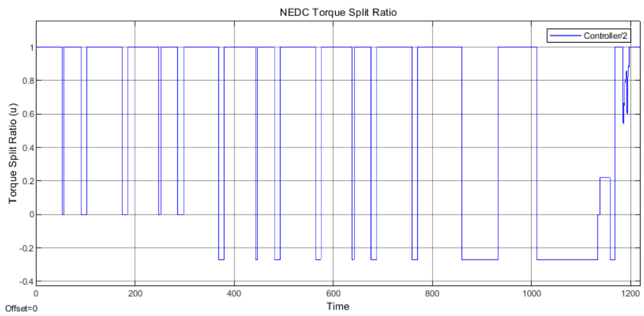

Figure 8: NEDC Torque Split Ratio vs Time

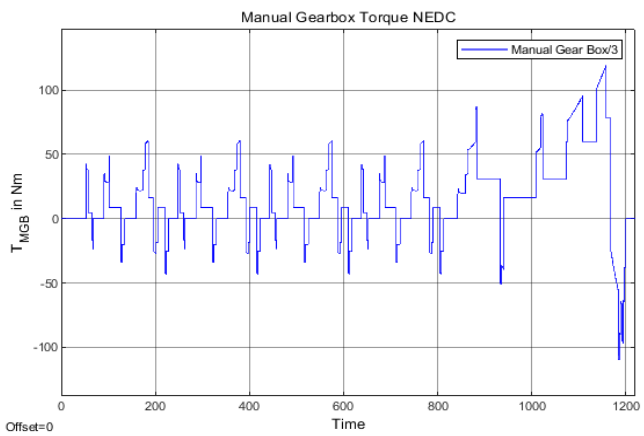

Figure 9: NEDC Manual Gearbox Torque vs Time

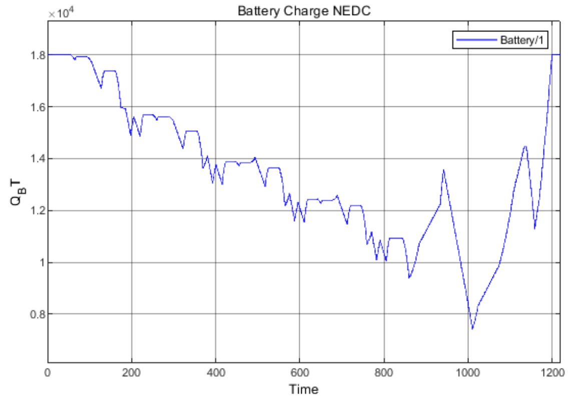

Figure 10: NEDC Battery Charge vs Time

B. FTP-75 Driving cycle

From Fig. 9, it is observed the torque variations are more when compared with NEDC cycles. This is due to driving cycle contains combination of driving patterns with different torque requirements.

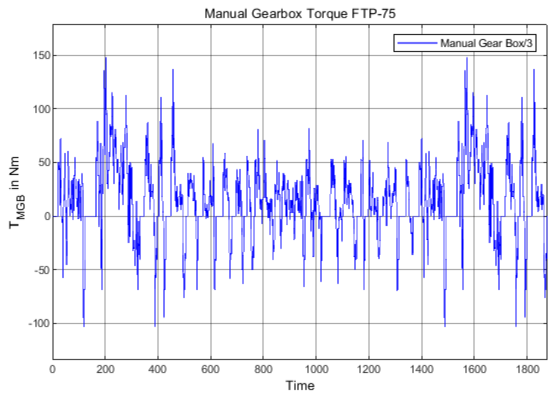

Figure 11: FTP-75 Manual Gearbox Torque vs Time

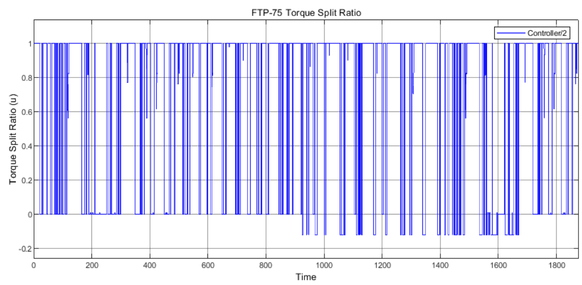

Figure 12: FTP-75 Torque Split Ratio vs Time

From Fig. 10 and Fig. 13, it is observed that the battery has been utilised for a significant amount of time during these cycles and at the end of the cycle, state of charge has been retained.

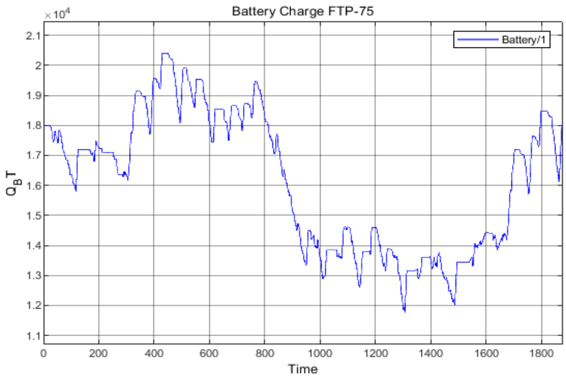

Figure 13: FTP-75 Battery Charge vs Time

The Simulink model was simulated for both the driving cycles NEDC and FTP-74 for the runtime 1220 seconds and 1875 seconds respectively. In Table II, the results of the simulation for fuel consumption of both the driving cycles are presented,

Driving Cycle	CE $V_{CE,eq}$ [l/100kms]	HEV $V_{CE,eq}$ [l/100kms]	%Reduction
NEDC	4.897	3.660	25.26
FTP-75	4.675	3.353	28.27
Average	4.786	3.506	26.74

Table II: Fuel Consumption

From the above comparision, it can be observed that there is a drastic reduction of fuel consumption in both the driving cycles in Parallel HEVs.

In Table III, the results of the state of charge during initial and final conditions can be observed,

Driving cycles	Initial SoC $\times 10^4$ [C]	Final SoC $\times 10^4$ [C]
NEDC	1.8	1.8
FTP-75	1.8	1.801

Table III: State of charge (SoC)

VIII. CONCLUSION

An energy management system has been constructed in MATLAB/Simulink for a parallel mild hybrid vehicle by designing a controller which is a part of the QSS Toolbox. A rule based strategy was implemented through which the fuel consumption for the NEDC and FTP-75 driving cycles were 3.660 liters/100km and 3.353 liters/100km respectively. The average fuel consumption of the two driving cycles is 3.506 liters/100km which is a 26.74% reduction as compared to a conventional vehicle. The battery charge of the vehicle is maintained at 50% for both the driving cycles.

IX. FUTURE WORK

The simple rule based methodology which is implemented in this paper has been shown to reduce the fuel consumption significantly as compared to a conventional vehicle. However, there is a scope for further improvement in charge retention and fuel consumption. Dynamic Programming (DP) and real-time energy control system could be realized which could further improve the results. These methods could also be combined with a machine learning approach to realize the optimum balance between performance and economy.

X. APPENDIX

BT	BATTERY
ICE	INTERNAL COMBUSTION ENGINE
EG	ELECTRIC GENERATOR
EM	ELECTRIC MOTOR
V	VEHICLE
U	TORQUE SPLIT RATIO
V	FUEL CONSUMPTION [L/KM]
T	TORQUE [NM]
Ω	SPEED OF THE WHEEL [RAD]
DΩ	ACCELERATION OF THE WHEEL [RAD/S2]

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