Control Strategy for Parallel Hybrid Electric Vehicles

Amita Singh, Akshay Trivedi

***Abstract*—Hybrid electric vehicles are gaining significance with depleting non-renewable energy sources. Thus, more research is being done on optimization of hybrid vehicles. This paper deals with equivalent fuel optimization of two driving cycles NEDC and FTP-75. Optimization is based on a deterministic rule-based control strategy. Hybrid electric vehicle comprise an internal combustion engine and an electric motor. Electric motor can work both as a motor and a generator. In this paper vehicle drives on electric motor at low speeds, uses internal combustion engine and motor in generator mode on medium speeds, and uses internal combustion engine and motor in motor mode while cruising.**

***Index Terms*—Energy management, hybrid electric vehicle, rule-based strategy, global optimization**

I. Introduction

Dependence on exhaustible and expensive fuel is one of the major challenges for the automotive industry. As the research for alternative fuel is underway; electric vehicles have come up with a feasible solution. Since battery durability is still an unresolved issue, hybrid vehicles present themselves as the most viable solution so far. Hybrid electric vehicles generally have an internal combustion engine and an electric motor which works in both motor and generator mode [1]. With the use of hybrid electric vehicles not only fuel consumption but also emissions can be reduced to a considerable level. In order to achieve better fuel economy and reduced emissions various architectures of hybrid vehicles have been developed. These architectures can be categorized as follows

A. Series Hybrid Electric Vehicle:

Typically, in series hybrid vehicle CE (combustion engine) is operated at a globally optimal operating point. CE is coupled with a generator which charges the battery. Battery, in turn, with the help of an EM (electric motor) drives the vehicle.

B. Parallel Hybrid Electric Vehicle:

In parallel hybrid vehicle CE cannot be used at a globally optimal operating point. Depending on the driving profile CE can be used alone or it can be coupled with an EM. Here, EM works both as an electric motor and a generator.

Singh A. and Trivedi A. are with University of Kaiserslautern, 67663 Germany email: singh@rhrk.uni-kl.de and trivedi@rhrk.uni-kl.de

C. Combined Hybrid Electric Vehicle:

Combined architecture for electric vehicles is also known as power split. A power split device is used to distribute power depending on the driving profile and state of charge (SoC) of battery. Apart from CE and EM, generator may or may not be used.

Along with appropriate vehicle architecture, energy management strategy also plays a crucial role in achieving optimal fuel efficiency. Energy management strategy can be described as a control strategy which uses a controller for the optimal distribution of power between CE and electric motor [2]. The main objectives of control strategy are to optimize drivetrain efficiency, meet driver's torque request, sustain battery charge and reduce emissions. Some of objectives are contending parameters; therefore a good control strategy is always a trade-off between them [2].Various approaches have been adopted to find an optimal solution. These strategies can be majorly classified as 1) Rule based strategies and 2) Optimization based strategies. Rule based strategies use power flow in drivetrain, efficiency/fuel maps and human expertise to set deterministic rules for the controller. On other hand, optimization based strategies, Dynamic Programming [3] and Equivalent Consumption Minimization Strategy [4], find global optimal solution for the problem for an instantaneous cost function.

This paper focuses on rule based strategies to find optimal solution for mild hybrid electric vehicles and to highlight the future trends of energy management strategy. Rule based strategies are based on load point shifting. Combustion engine is operated close to optimal point of efficiency and fuel consumption at a particular engine speed [2]. However, rule based strategies can also be developed by setting deterministic rules for other operating modes as well. These rules will be discussed under control strategy. Simulink model is used to simulate the results to calculate equivalent fuel consumption for FTP and NEDC driving cycles [5].

II. Hybrid Electric Vehicle Configuration

In this paper, a parallel mild hybrid electric vehicle is considered. The configuration of HEV consists of combustion engine (CE), electric motor (EM), battery (BT), torque coupler (TC) and manual gear box (MGB) as illustrated in figure 1 [6]. In parallel HEVs, both CE and EM can supply required power either standalone or in combination, thus giving an additional degree of freedom in fulfilling the power requirements. The specifications for HEV are as follows:

1) Combustion engine: Maximum Power-60 kW, Maximum Torque-187 Nm
2) Electric motor: Maximum Power-12 kw, Maximum Torque-60 Nm
3) Lithium-ion battery: 16.38 kW
4) Manual gearbox (5-speed)
5) Total vehicle mass: 1115 kg

The vehicle model is based on quasistatic approach in which driving cycle is divided into several small steps of size (h) [7]. Operating points are calculated based on this step size. Fuel consumption is calculated by working backwards through powertrain. In backward model driving cycle is known a priori, thus reversing the physical causality i.e. motion as an input energy and fuel consumption as output energy. The main advantage of using backward model is it has low computational cost and low complexity. However, this cannot be applied in feedback control problems. Hence, it is not applicable for determining the dynamic effects.

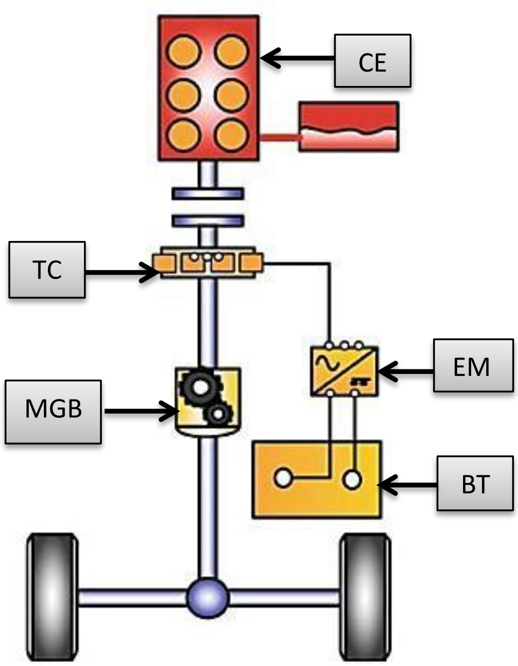

Fig. 1. Architecture of Parallel Hybrid Electric Vehicle

III. Control Strategy

The objective of control strategy is to distribute power between combustion engine (CE) and electric motor (EM) through a controller. The controller splits required power to operate combustion engine at an optimal efficiency curve and thus, minimizing fuel consumption to get optimal efficiency [8]. At times, while fulfilling the torque request battery charge goes to a low value. With an appropriate charge sustenance condition this situation can be avoided. Battery can be recharged by operating the motor in generator mode. The control strategy is based on two core ideas 1) fulfilling the driver's torque request and 2) sustaining the battery charge. In devising control strategy some local constraints, i.e. driver's torque request and integral constraints, i.e. battery charge have to be respected [6]. Deterministic rules of control strategy are thus subject to following constraints:

$$T_{EM} + T_{CE} = T_{MGB} \tag{1}$$
$$|T_{EM}| < T_{EM_{max}}(\omega_{EM}) \tag{2}$$
$$|I_{BT}| < I_{BT_{max}} \tag{3}$$
$$2U_{BT} > U_{OC} \tag{4}$$
$$0 \leq Q_{BT} \leq Q_{BT_0} \tag{5}$$

Where T_{MGB} is the torque of manual gear box, T_{CE} is the torque of combustion engine, T_{EM} is the torque of electric motor, ω_{EM} is the angular velocity of electric motor, I_{BT} is the battery current, U_{BT} is the battery voltage and Q_{BT} is the battery charge. The operating modes on which the control strategy is devised are as follows:

A. Load Point Shifting

The idea behind load point shifting is to operate CE in its optimal range where power can be split in two ways 1) operating the EM in motor mode 2) operating the EM in generator mode [9]. In motor mode, the load on CE is reduced by providing an extra positive torque by electric motor as mentioned in equation (1). The battery is discharged in this mode. Therefore, to sustain battery charge while operating boundary limits are imposed on it. On the other hand, in generator mode a negative torque is supplied to EM. Thus, increasing the load on CE. In generator mode battery can be charged to a limit mentioned in equations (3), (4) and (5). Torque of electric motor is calculated using the following formulae:

$$T_{EM,Motor} = \min(T_{EM_{max}}(\omega_{EM}) - |\theta_{EM} d\omega_{EM}| - \varepsilon_{T_{MGB}}) \tag{6}$$
$$\text{if } T_{MGB} \geq T_{MGB_{th}}$$

$$T_{EM,Gener} = \max(-T_{EM_{max}}(\omega_{EM}) + |\theta_{EM} d\omega_{EM}| + \varepsilon_{T_{MGB}}) \tag{7}$$
$$\text{if } T_{MGB} < T_{MGB_{th}}$$

where ω_{EM} is the angular velocity of electric motor and $|\theta_{EM} d\omega_{EM}|$ gives the inertial torque.

B. Electric Driving

Electric driving means to run the vehicle purely on electric motor (EM). At low torques and low angular velocity, CE does not operate efficiently. Therefore, up to certain values of torque, electric driving is useful in improving CE efficiency as well as reducing the fuel consumption. During electric driving:

$$T_{MGB} = T_{EM} \tag{8}$$

C. Regeneration

Regeneration mode comes into action when brakes are engaged. The brake request by driver splits into regenerative and friction braking torque request [7]. The regenerative braking request is converted into negative torque request within the constraint mentioned in equation (2) which causes EM to operate in generator mode. Thus, the kinetic energy dissipated as heat by friction braking can be used for energy storage in battery by operating EM in generator mode using equation (7). Regenerative energy should be maximized. However, the regeneration can only be maximized between boundary limits of battery charge.

D. Power Assist

In power assist mode, means both CE and EM operate simultaneously. In this mode EM can assist the motor in low torque conditions so that the vehicle reaches a required torque value where, CE can be used alone in its optimal range of operation [10]. Power assist can be considered as a variant of load point shifting and is obtained using equation 6.

E. Start-Stop

Start-Stop system is used in hybrid electric vehicles to automatically shut down and restart combustion engine to minimize idling [**?**]. Vehicle is operated using equations (6) and (8) either only on electric drive at low speeds or when vehicle is to be started and stopped frequently. Thus, reducing fuel consumption and emissions.

IV. Implementation of Control Strategy

The implementation of control strategy is done on the controller using MATLAB. Controller has four input variables 1) Driver's torque request i.e. flywheel torque (T_{MGB}) 2) flywheel angular velocity (ω) 3) flywheel angular acceleration ($d\omega$) and 4) battery charge (Q_{BT}). The output variable torque split factor u is then calculated by setting various rules based on input variables. The torque split factor (u) is the ratio of electric motor torque (T_{EM}) to the flywheel torque (T_{MGB}). Based on different operating modes and torque split factor (u), torque is distributed among the electric motor and combustion engine. The rules consist of if-else statements i.e. if a condition holds true execute a set of rules otherwise either move to next condition or execute different set of rules. The if-else conditions are defined as combination of rules or individual condition, using logical operators (AND or OR). The rules can be summarized as follows:

1) If torque request is low operate the vehicle in power assist mode ($0 < u < 1$), using more power from electric motor. However, battery charge should fulfill boundary conditions mentioned in equations(3), (4) and (5) at all times.
2) If torque request is less than desirable torque for CE, operate the vehicle in full electric mode (u = 1 described by equation (8)).
3) If vehicle is operating at its full efficiency, a part of load can be used by electric motor to reduce fuel consumption and discharging the battery ($0 < u < 1$; motor mode described by equation (6)).
4) If vehicle is operating under threshold value, CE can be driven for high loads and a negative torque is provided to electric motor to charge the battery ($0 < u < 1$; generator mode described by equation (7)).
5) During braking driver's torque request is less than zero, electric motor is operated in generator mode (described by equation (7)).
6) When torque request is negative and angular velocity is low, operate the electric motor in generator mode within the constraint mentioned in equation (2) to charge the battery and stop the engine from idling (Stop mode with regeneration).
7) When battery is charged and engine is operating at optimum load and efficiency, only combustion engine should run ($u = 0$; conventional driving).

One of the guiding principle for determining rules is that combustion engine should be used for relatively high efficiency; while for less efficient regions, preference should be given to electric motor. It is also possible to shut off the engine. The second guiding principle reflects the charge sustenance criterion i.e. the charging and discharging of battery should be controlled so that battery charge remains within predefined boundary limits.

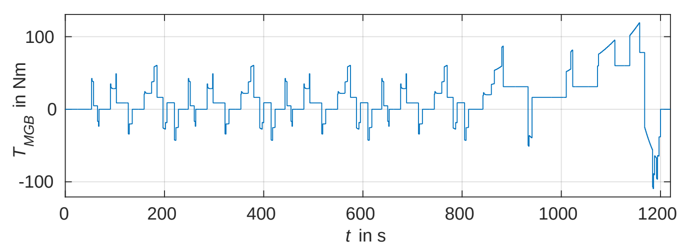

Fig. 2. Torque of manual gearbox T_{MGB} for NEDC.

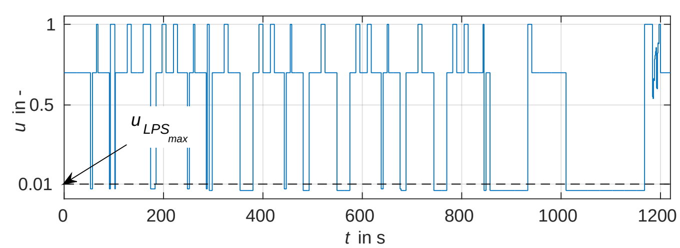

Fig. 3. Torque-split ratio u for NEDC.

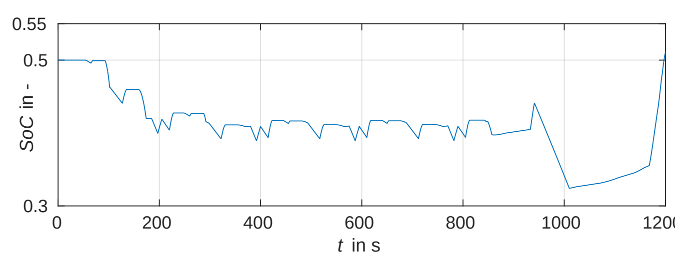

Fig. 4. State of battery charge SoC for NEDC.

V. Simulation And Results

Simulation of controller has been implemented in QSS Tool Box using MATLAB/Simulink for two driving cycles 1) NEDC 2) FTP-75 [5]. Figures 2 and 5 represent the variation of driver's torque requests depending upon the driving cycle. Torque-split ratio u illustrated in figures 6 and 3 is calculated for given boundary conditions for battery charge. It is recommended to operate battery such that charge is sustained over time. In the implementation, battery charge as illustrated in figures 4 and 7 increased by 9% in the overall driving cycles.

The overall equivalent fuel consumption is calculated by averaging the respective fuel consumption obtained from the two driving cycles

$$\begin{aligned}\vec{V}_{CE_{equiv}} &= \frac{1}{2}(V_{CE_{equiv,NEDC}} + V_{CE_{equiv,FTP-75}}) \\ &= \frac{1}{2}(3.511 + 3.439) \\ &= 3.475\end{aligned}$$

where $V_{CE_{equiv,NEDC}}$ and $V_{CE_{equiv,FTP-75}}$ are the equivalent fuel consumptions for NEDC and FTP-75

Battery charge for NEDC $(Q_{BT,NEDC})$ is 2.05+e4 and battery charge for FTP-75 $(Q_{BT,FTP-75})$ is 1.89+e4.

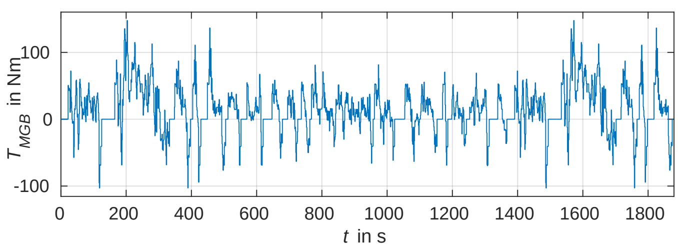

Fig. 5. Torque of manual gearbox T_{MGB} for FTP.

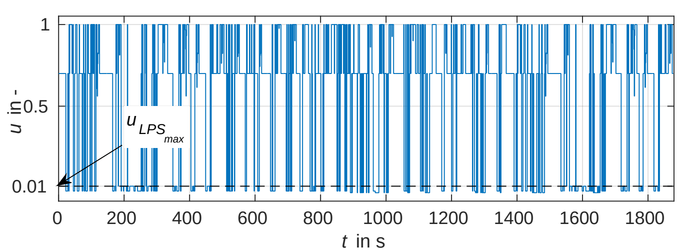

Fig. 6. Torque-split ratio u for FTP.

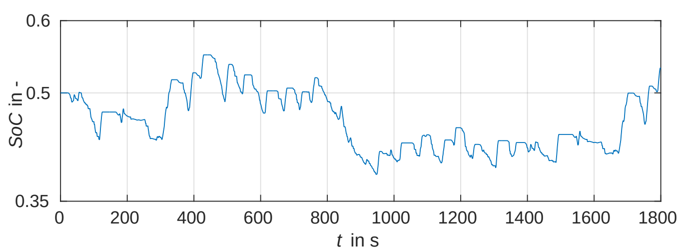

Fig. 7. State of battery charge SoC for FTP.

VI. Conclusion

Supervisory control strategy for hybrid electric vehicle has been devised in the paper using deterministic rule-based approach. A controller has been developed which gives optimal equivalent fuel consumption for both NEDC and FTP-75 driving cycles. It can be inferred from the results that electric and hybrid drives are more beneficial than conventional drive for urban settings. Figures 4 and 7 depict that the battery charge is increased by 9% in the overall driving cycles. This control strategy sets a benchmark for optimal fuel consumption and battery charge sustenance rather than finding a global optimal solution. The controller is robust and can be tuned to different parameters and expert knowledge. However,various aspects like transmission losses and emission reduction are not considered. Rule based strategy does not give optimal solution for all driving profiles due to the increased number of variables like road slope, temperature, etc. With the increasing number of variables and Boolean operations, it is difficult for the controller to provide an optimal solution. Therefore, it cannot be used for complex architecture.

In future, the robustness can be increased by using adaptive fuzzy logic and devising a control strategy which can provide global optimal solution. This can be achieved by Dynamic Programming and ECMS which minimizes the instantaneous cost function for a given problem [1]. Moreover, emissions can be reduced and fuel economy can be improved using real time data with GPS and driving profiles. Therefore, the results thus obtained would be better and customized for a given environment.

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