Rule-based Energy Management System for Hybrid Electric Vehicle

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***Abstract*—The need for eco-friendly hybrid propulsion systems has prompted the creation of sophisticated power management control algorithms that maximize fuel efficiency and reduce pollutant emissions. This paper focuses on control algorithms for hybrid electric vehicles (HEVs) and plug-in HEVs (PHEVs). The discussion covers the development of a rule-based Energy Management System (EMS) strategy. In order to improve the fuel efficiency of a parallel mild HEV, the New European Driving Cycle (NEDC) and Federal Test Procedure (FTP-75) driving cycles used to test the generated EMS are focused on. For both driving cycles, the torque variation compared to a conventional vehicle, torque split ratio, internal combustion engine state, and State of Charge (SoC) of the battery are all examined. The remaining difficulties and prospective areas for future research are also covered.**

***Index Terms*—Hybrid Electric Vehicles, Rule-Based strategy, Energy management system, Sustainability, Optimization**

I. INTRODUCTION

ELECTROMOBILITY has been the key for sustainability as the usage of alternative forms of mobility is becoming challenging because of the rise in pollution and the decline in oil supply. The provision of a reliable mode of transportation and a fuel-efficient vehicle that complies with the most recent emission regulations is one way to help protect the environment. Therefore, this is possible by properly optimizing parallel hybrid electric vehicles (HEVs).

A hybrid electric vehicle is a vehicle that has two or more different energy storage systems and at least two different energy converters installed on it for propulsion [1]. It can be further condensed to a vehicle that uses electrical energy storage mechanisms (such as batteries, capacitors, flywheels, etc.) and consumable fuel to power its mechanical propulsion. There are various HEV architectures, but the three that are most frequently used are series, parallel, and combined. The parallel mild HEV is the primary topic of this paper, and Figure 1's depicts its architecture.

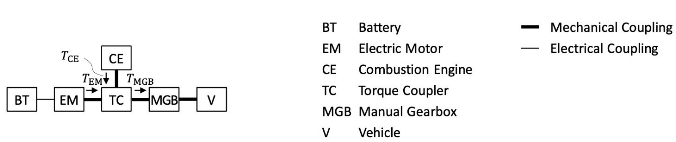

Fig. 1. Architecture of a Hybrid Electric Vehicle

Coordination of the various energy sources, converters, and, in the case of hybrid electric vehicles, power flow control for both the mechanical and electrical paths, present challenges in the design of hybrid vehicles. This necessitates the use of an effective control system or Energy Management System (EMS). A control strategy is implemented in the vehicle central controller and is described as an algorithm that is used to control how the drive train of the vehicle operates [2].

The main goals of the hybrid drive train Energy Management System are to maintain battery charge, provide traction power as needed by the driver, and maximize drive train efficiency in terms of emissions, fuel use, and emissions. To do this, the controller unit receives inputs from the driver, such as torque requests, speed requests, or acceleration requests, and in response, it sends commands to various parts of the vehicle, instructing them to change their behavior or turn ON or OFF.

Different types of strategies are available for optimizing the controller [5], and they are further divided into two categories, which are as follows: a) Heuristic Energy Management Strategies: Rule Based Strategies (RBS) [3], and b) Optimal Energy Management Strategies: Dynamic Programming (DP), Equivalent Consumption Minimization Strategy (ECMS), Pontryagin's Minimum Principle (PMP), Stochastic Dynamic Programming (SDP), and Model Predictive Control (MPC).

An overview of the HEV operating modes and the testing driving cycles is provided in this paper. The MATLAB/Simulink model that was used to demonstrate the Energy Management System is then shown. The structure of the Energy Management System's rule-based state machine is then described, along with the technique for parameter optimization that was employed.

All research findings will be summarized at the end, and a research outlook will be provided.

II. OPERATING MODES OF HYBRID ELECTRIC VEHICLE

There are various modes in which Hybrid electric vehicles can operate. These different operating modes are described below.

A. Load Point Shifting

The idea of this mode is that the load can be varied by operating the electric machine in different modes. The electric machine can be used either as a motor or as a generator [4]. If the power required from the HEV is high, then the electric machine can be used as a motor to help support and accelerate the vehicle. Doing so decreases the load point and this is given by the equation,

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

if, $T_{MGB} < 0$

where,
T_{EM} = Torque of electric motor (Nm)
T_{MGB} = Torque of manual gearbox (Nm)
w_{EM} = Angular speed (rad/s)
θ_{EM} = Energy inertia (kgm^2)
dw_{EM} = Angular acceleration (rad/s^2)
w_{EM}* θ_{EM} = Inertial torque(Nm)
ε = Small arbitrary parameter

If the power required from the HEV is low, the electric machine will be operated in generating mode and the batteries will be charged. This will increase the load shift which means that more energy will be used from the internal combustion engine. However, this will increase the efficiency and will help in running the HEV for longer period. The increase of the load point can be defined by the equation,

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

B. Electric Driving

When running the HEV at low speeds, which is mostly the case inside the cities when there is traffic, the efficiency of the combustion engine is low. To improve the efficiency it's better to run the vehicle in Electric driving mode. The electric motor is better used at these lower speeds when low torques are required. Using this mode will ensure that the fuel consumption will have an overall decrease. Another advantage for using this mode is that it has no pollution emissions.

C. Engine Start/Stop

Normally in vehicles running just with an internal combustion engine the engine keeps running even during idling. This consumes fuel and even emits pollutants. In engine start/stop mode the engine is stopped when the vehicle is braking and is restarted when the brakes are released. This will save fuel and reduce emissions.

D. Regenerative Braking

When the vehicle is decelerating, like in the case of braking, kinetic energy is wasted as heat and energy is dissipated. In regeneration mode the electric machine is used as a generator and the energy dissipated during braking or deceleration can be better stored in batteries as electric energy. There are some limiting factors for regeneration. One limiting factor can be the battery current or battery capacity, in which this mode cant be used when the batteries are already full. The torque split factor of the electric machine in this mode can be by the equation,

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

III. Driving Cycles and Vehicle Model

For simulation on Simulink/Matlab, the QSS toolbox was used. The driving cycle map is used as an input to the vehicle model. The driving cycles output information such as the vehicle speed and acceleration. Also, it outputs the gear ratio and the vehicle's total traveled distance. The vehicle that is modeled in the simulation is the Mercedes-Benz A 170 CDI (W168). The vehicle parameters such as the engine, motor, and battery specifications are also included in their specified blocks in the model. The final output is the equivalent fuel consumption value and that is what should be minimized. The vehicle type/model and specifications are described in Table I.

TABLE I
VEHICLE MODEL AND PARAMETERS

Model	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

From the Simulink model shown in Figure 2, the first green block on the left is the one containing the driving cycle information. The next yellow block will take the vehicle velocity and acceleration as inputs and it will output the wheel speed, acceleration, and torque. These variables will then be sent to the gearbox block, colored in dark green, to apply the gear ratio and adjust the values. The next block, colored in blue, is the control unit block. It is where the energy management code comes into place. This block contains the logic that decides when and how the engine and electric machine operates. After that there are the two red blocks. The upper block is the model of the combustion engine, while the lower one is for the electric machine. Both these blocks will calculate the power required based on the values received from the control unit. The upper red block is then connected to the fuel tank block, colored in blue. This block will calculate the fuel consumption based on the power exerted by the engine. The lower red block is connected to the battery block, colored in gray, and it will calculate the energy consumption from the battery based on the power exerted by the electric machine. The last block calculates the total equivalent fuel consumption from both the energy and the fuel consumption.

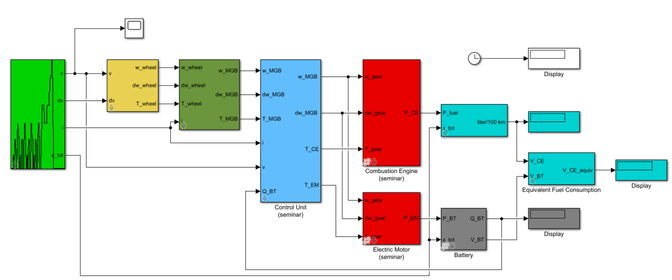

Fig. 2. Vehicle model in QSS

When testing the code on the vehicle model it is important to test the vehicle based on some given driving cycles that are used and well-known worldwide. This will help ensuring that the results can be used in real life and that the model was not just tested with some random inputs that makes no sense when compared to real life scenarios. For that, two driving cycles were used to test the energy management system. These cycles are NEDC and FTP-75.

A. NEDC (New European driving cycle)

The NEDC can be used to test the fuel consumption and the emission levels in passenger vehicles. This driving cycle was basically designed to test vehicles run with petrol but it can be also used to test vehicles run with diesel. The NEDC can be shown in the Figure 3.

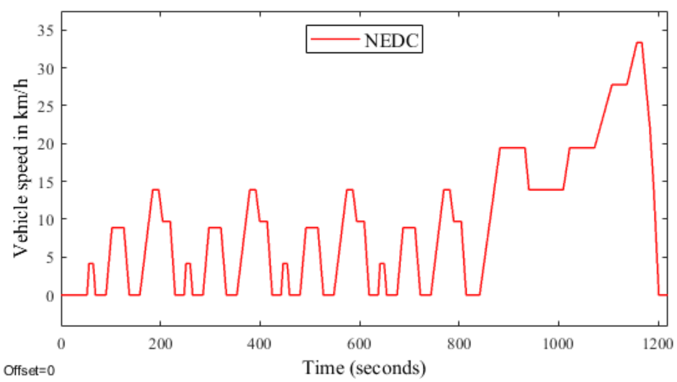

Fig. 3. NEDC (Europe) driving cycle

B. FTP-75 (Federal Test Procedure)

The FTP driving cycle was designed to test the vehicle's fuel consumption and the gas emissions as well in case of driving in cities [6]. It was defined by the US Environmental Protection Agency (EPA) and it doesn't take into consideration the heavy-duty vehicles. So it is used to test passenger vehicles and it considers four driving conditions. These are:

- City driving
- Aggressive driving
- Highway driving
- Optional air conditioning test

The FTP driving cycle can be seen in Figure 4:

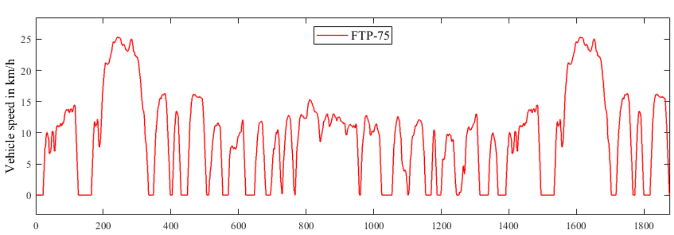

Fig. 4. FTP-75 (USA) driving cycle

IV. Rule-based Strategy

The idea of load point shifting serves as the foundation for rule-based strategy. The goal of the load point shifting technique is to move the actual ICE operating point as close as possible to the position at which it operates efficiently and with the best potential fuel economy. The rule-based Energy Management System for this project was written as an Interpreted MATLAB function. According to Table II, the five modes for switching are: charging (hybrid), regenerative braking, hybrid, electric and conventional.

TABLE II
Rule Base

Rule	Conditions	Result
Rule 1	$T_{MGB} < 0$	Regeneration
Rule 2	$T_{MGB} \geq T_{ED,max}$	LPS(Motor mode)
Rule 3	$T_{ED,th} < T_{MGB} < T_{LPS,gen,th}$	LPS(Gen. mode)
Rule 4	$T_{MGB} < T_{ED,th}$ and $w_{MGB} < w_{MGB,th}$	Electric Driving
Rule 5	default	Engine only (Conventional)

A. Electric

The mode for vehicle will begin by default in this state. Here, the torque split ratio is always $u = 1$, the engine is always OFF, and the clutch is also decoupled. Figure 5 illustrates the two prerequisites for staying on electric. The first is to maintain gearbox torque T_{MGB} between zero and a predetermined maximum torque for electric driving $T_{ED,th}$. State of Charge SoC should be greater than SoC_{min}, the minimum State of Charge. Also another important condition is that $w_{MGB} < w_{MGB,th}$, the upperbound on velocity of the vehicle above which Electric mode should be escaped. When the mode is Electric, it signifies that the vehicle can only be operated in Section II's Electric operating mode. Additionally, the change from Hybrid to Electric and vice versa simulates the Start/Stop operating mode by itself.

B. Hybrid

In this condition, the engine is continually running and the torque split ratio u can vary. If $u > 0$, the motor is operating in motor mode and the operating mode is load point shifting. If $u < 0$, the motor is operating in generator mode and the operating mode is load point shifting. Finally, if $u = 0$, the car only has a combustion engine running. Figure II illustrates two requirements to continue using a hybrid vehicle: the first is that the torque be $T_{MGB} > T_{ED,max}$ and the second is that the level of charge be $SoC > SoC_{min}$.

C. Charging

The split ratio is $u < 0$ and the engine is always on in this condition. This implies that the electric device constantly charges the battery while operating in generator mode. Figure II illustrates that the mode is achieved when $T_{LPS,gen,th} < T_{MGB} < T_{ED,th}$. The vehicle stops charging in just two circumstances: when the state of charge is higher than the state of charge ready state, or when braking $T_{MGB} < 0$.

D. Regenerative Braking

The engine is always off in this mode, emulating the decoupling of the clutch and the torque split of $0 < u < 1$. Figure II illustrates that there is only one condition to continue using regenerative braking, and that is torque $T_{MGB} < 0$. This indicates that the Energy Management System switches to regenerative braking as soon as the torque falls below zero.

E. Conventional

The engine switches to purely conventional mode or ”only engine” mode when none of the rules follow, making this a default rule. All of the torque to the wheels comes from the engine.

V. Optimization of Parameters

A response optimizer tool from MATLAB was first used to define the best settings for the various thresholds utilized in the rule-base machine. To achieve this, the values of the parameters that were to be optimized were started in a separate .m file. Now that these values have been imported into the Simulink model from the workspace, a set of optimized parameters is constructed for the minimization of a pre-specified branch from the Simulink model and also based on the constraints provided to the response optimizer. Because in this instance, the minimization function is not convex, values of threshold parameters for a local minimum were provided by the response optimizer [7]. The threshold values for the Interpreted MATLAB function were manually changed after depending on these local minimum values in order to manually converge the optimization parameters. This procedure was conducted twice, once for the FTP-75 test and once for the NEDC driving cycle. The comparable fuel consumption and battery *SoC* were recorded after each repetition. The values of optimal parameters are shown in Table III.

TABLE III
Optimal Parameters

	Notation	Optimal value
Torque threshold for LPS in motor mode	$T_{ED,max}$	33 Nm
Torque threshold for LPS in gen.r mode	$T_{LPS,gen,th}$	34 Nm
Torque threshold for Electric mode	$T_{ED,th}$	29 Nm
Velocity threshold for Electric mode	$w_{MGB,th}$	300 rad/s
Maximum torque-split factor for LPS	$u_{LPS,max}$	0.01

VI. Results and Conclusion

Here is a description of the fuel consumption improvement that was achieved after threshold optimization. Table II shows that for conventional vehicles with combustion engines exclusively, the fuel consumption is 4.897 *l/100km* for NEDC and for FTP-75, 4.675 *l/100km*. However, under the proposed hybrid method, the corresponding fuel consumption for NEDC and FTP-75 was 3.019 and 3.111 *l/100km*, respectively. The equivalent fuel consumption is 3.564 and 3.339 *l/100km* for NEDC and FTP-75 respectively. Using the conventional vehicle as a baseline, the improvement percentage for NEDC is 38.35% and for FTP-75, it is 33.45%.

TABLE IV
Fuel Consumption Improvement

	Combustion Engine	EMS on EHV	Improvement
NEDC	5.572 l/100km	3.019 l/100km	45.81 %
FTP-75	5.319 l/100km	3.111 l/100km	41.51 %

TABLE V
Equivalent Fuel Consumption

	Equivalent Fuel consumption
NEDC	3.564 l/100km
FTP-75	3.339 l/100km

Figure 5 and 6 depicts the *SoC*’s and the operating modes’ simulated behavior during the NEDC driving cycle. When driving an electric hybrid vehicle, it can be seen that the *SoC* gradually drops until it approaches the minimum *SoC* allowed (SoC_{min}) at about time t = 900s. After that, the state machine moves into the charging mode and gradually increases the *SoC*. The vehicle speed is simply shown in Figure 7 for reference.

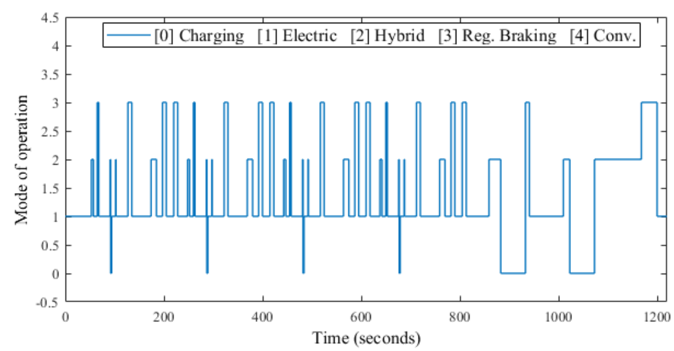

Fig. 5. Operating modes of NEDC

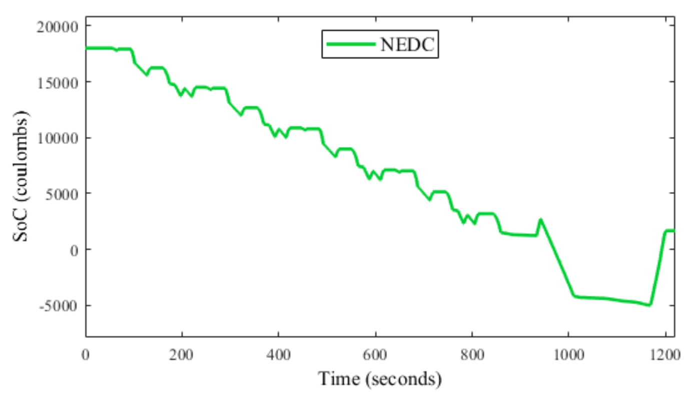

Fig. 6. SoC of NEDC

Figure 7 and 8 depicts the *SoC*’s and the operating modes’ simulated behavior during the FTP-75 driving cycle. It can be seen that the *SoC* first rises gradually as a result of frequent stopping intervals and a greater proportion of hybrid driving than electric driving. The amount of time spent driving on electricity increases about t = 500s, steadily draining the battery but never reaching the bare minimum SoC_{min} permitted. Due to driving cycle demand, it begins to run largely on hybrid once more starting at t = 1500s and on, slightly recharging the battery without entering the Charging state. The vehicle speed is shown in Figure 4 for reference.

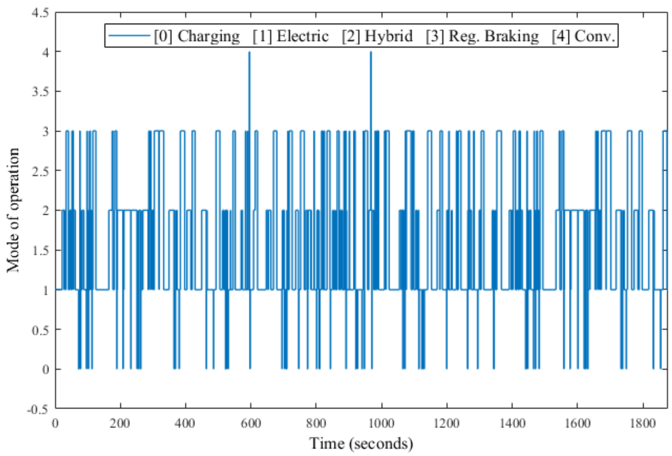

Fig. 7. Operating modes of FTP-75

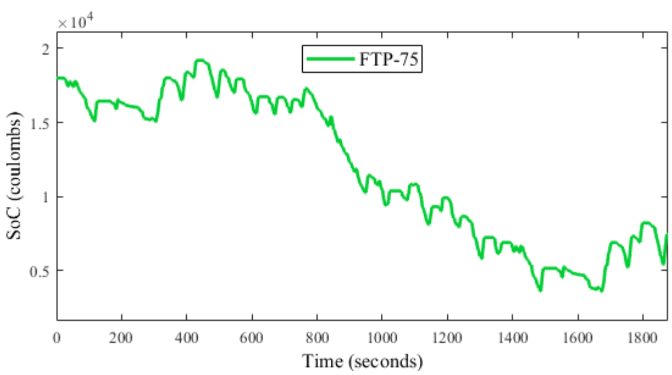

Fig. 8. SoC of FTP-75

The final comparison is between the behavior of the Engine torque T_{MGB} in a parallel hybrid with the proposed Energy Management System and a conventional vehicle (combustion engine only) in Figure 9 and 10. In general, $T_{MGB,conventional}$ is significantly greater than $T_{MGB,hybrid}$ for low torques. When $\mathrm{T}_{\mathrm{MGB,hybrid}} = 0$, but $T_{MGB,conventional} > 0$, the hybrid electric vehicle is traveling entirely on electricity with the combustion engine turned off during certain times. In contrast, it can be shown that $T_{MGB,conventional}$ performs worse than $T_{MGB,hybrid}$ for medium loads since the electric motor is operating in generator mode, increasing the load on the engine and simultaneously recharging the battery.

According to the findings, the improvement in the equivalent fuel consumption for the NEDC driving cycle is greater than the improvement in FTP-75. This is primarily due to the fact that hybrid vehicles have a greater influence on fuel consumption when driving in cities. The FTP-75 driving cycle frequently involves stop-and-go driving and low torque driving. The NEDC driving cycle, in contrast, involves longer stretches of higher-speed highway driving. NEDC driving

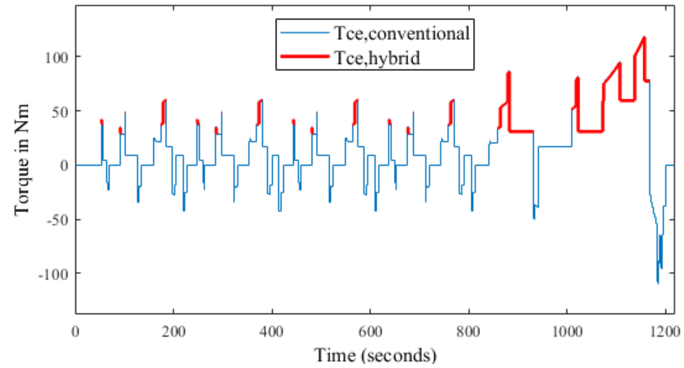

Fig. 9. Engine torque comparison for conventional and hybrid mode for NEDC

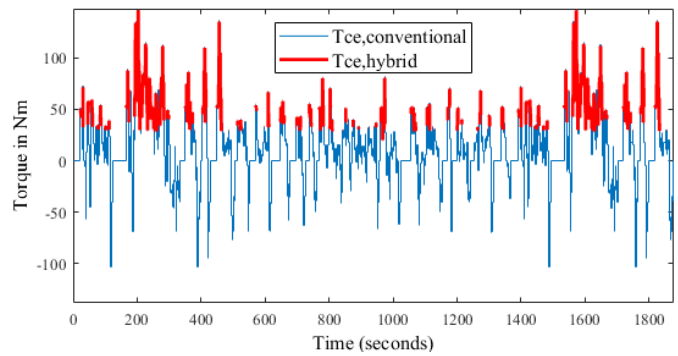

Fig. 10. Engine torque comparison for conventional and hybrid mode for FTP-75

cycle definitely had a greater influence on the decision-making process for parameter tuning.

VII. Future work

The future prospects would be to focus on optimisation methods such as Dynamic Programming or Model Predictive Control for implementing the strategy and finding all optimal parameters at once.

Acknowledgments

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