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Supervisory Energy Management Control Strategy for a Series Hybrid Electric Vehicle Based on Stateflow

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Abstract: *Performance of hybrid electric vehicles (HEVs) in terms of fuel economy and emission depends on the energy management strategy (EMS) which is considered a challenging problem; because HEVs have complex structures. To meet this problem, this paper proposes an EMS for a series hybrid electric vehicle based on Stateflow; in order to reduce system complexity regardless of the individual performance of the selected components. Firstly, mathematical models have been established using MATLAB/Simulink environment for both the driver, the traction battery, the electric motor to be used in vehicle traction, and the genset to charge the battery when its state of charge (SOC) falls below a certain value. Secondly, the proposed EMS based on the selected HEV model has been implemented in order to enable and disable the genset, control the genset to be run with a constant speed, and select the appropriate charging current. Finally, the overall system has been evaluated under different standard driving cycles; in order to validate the EMS under different driving conditions.*

Keywords: *- energy management strategy, hybrid electric vehicles, Stateflow, supervisory controller*

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I. Introduction

Traditional vehicles, which use internal combustion engines (ICEs), have problems with air pollution in addition to the dependence on fossil fuels which will run out someday. On the other hand, pure electric vehicles (EVs) have a main problem with the energy shortage (range). So, hybrid electric vehicles (HEVs) are considered one of the promising choices of vehicle industry which can be used to solve these problems.

HEV combines two power sources, an ICE, and an electric motor (EM) with a traction battery. So, an energy management strategy (EMS) is needed to determine the contribution of the two power sources to get the demand power to propel the vehicle. EMS plays an important role in improving fuel consumption and battery lifetime [1].

Several approaches have been proposed to address the problem of energy management control, include dynamic programming (DP) as presented in [2] to prolong the battery lifetime and achieve high efficiency operation of the hybrid energy storage system (HESS), stochastic dynamic program (SDP) as presented in [1] to obtain a near-optimal control strategy only considering the fuel economy, gear-shift, and state of charge (SOC) sustaining. While, model predictive control (MPC) as presented in [3] to improve both energy efficiency and computational speed, an economically-oriented model predictive control (EMPC) approach based on considering the power flows as presented in [4] to improve the control model including efficiencies of the different components as well as improving the control model. Also, Petri nets (PN) approach combined with the GPS as presented in [5] to reduce the HEV's fuel consumption, adaptive fuzzy logic based energy management strategy (AFEMS) strategy as presented in [6] to determine the power split between the battery pack and the ultracapacitor (UC) pack and enhance control performances while it does not need the driving cycle information in advance, proportional integral (PI) controller as presented in [7] to extend the batteries lifetime and presented in [8] to be easily tuned online for better tracking using heuristic method based on particle swarm. As well as frequency approach considering terrain inaccuracy as presented in [9] to improve battery life and overall system efficiency, road grade preview approach as presented in [10] taking into consideration terrain inaccuracy to improve system efficiency and minimize the total cost of the system, including the cost for battery life and energy, online EMS as presented in [11-13] to improve fuel economy and reduce emissions, and other approaches as presented in [14-17].

According to this extensive literature, most papers use complex control strategies, this forms a problem of increasing the complexity of the HEV structure. So, the main target of this paper is to select a simple EMS in order to reduce the complexity of the system.

The remainder of this paper is organized as follows. Section II describes a model for a series HEV contains models for driver, battery, electric motor, genset, respectively. Hence, Stateflow is implemented as an

EMS on the proposed series HEV using MATLAB/Simulink in section III. Then, section IV introduces simulation results. Finally, the conclusion is presented in section V.

II. Models

In this section, mathematical model will be developed in order to represent the main components of a series HEV (driver, battery, electric motor, and genset). This model will be used to design the supervisory controller as shown in figure 1. The block diagram illustrates the relationship between this main component and the proposed supervisory controller to identify inputs and outputs.

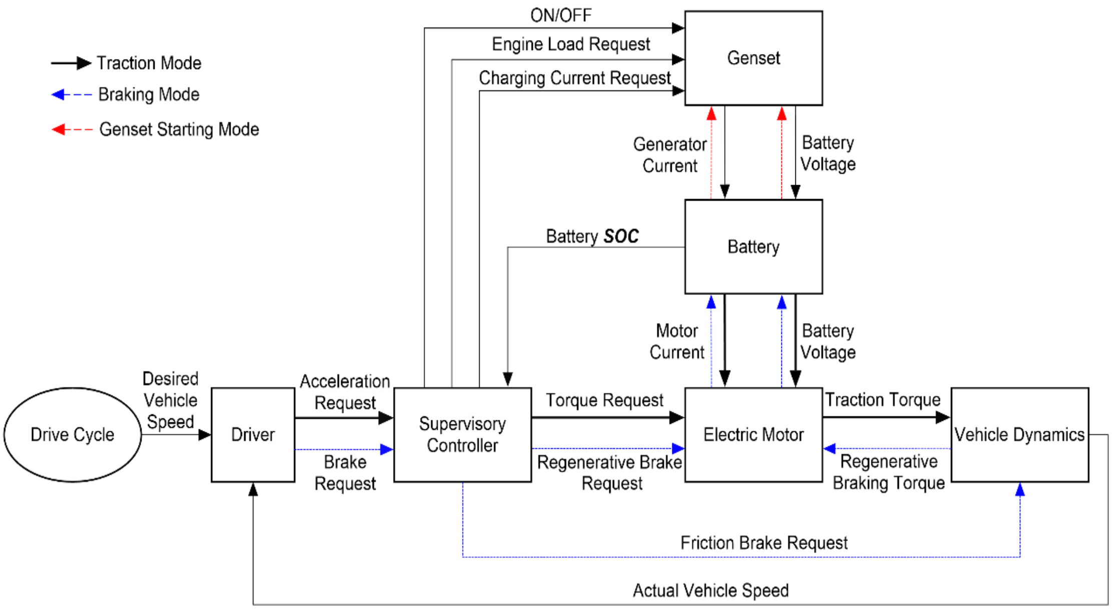

Figure 1: Overall model block diagram

Driver Model:

This model has been developed to represent the driver acceleration and brake requests to control the vehicle and follow drive cycles. It generates a torque request that would normally come from the vehicle's accelerator and brake pedals. A classic feedback system has been used to compare the desired vehicle speed with the actual vehicle speed, and then calculates an error signal as shown in figure 2. According to this error, the driver request signal is determined which is varied gradually over the range from -1 (full braking) to 1 (full acceleration).

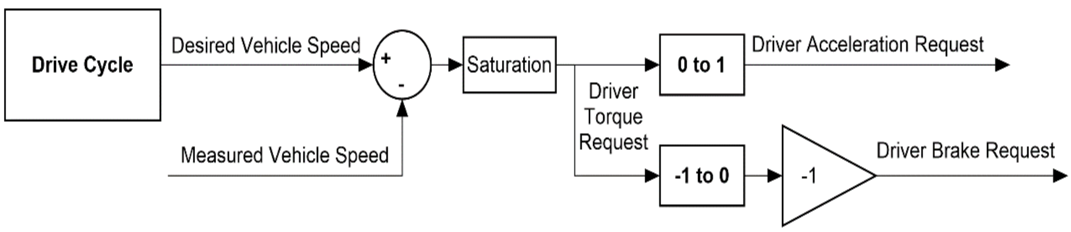

Figure 2: Block diagram of the driver model

Battery Model:

Look-up tables for a typical NiMH battery pack have been used to calculate the battery voltage according to the battery SOC as shown in figure 3. The first look-up table has been used to obtain the battery open-circuit voltage (V_{oc}) while the other two look-up tables have been used to obtain the battery resistance according to the operating mode (charging or discharging) which is determined by the battery current.

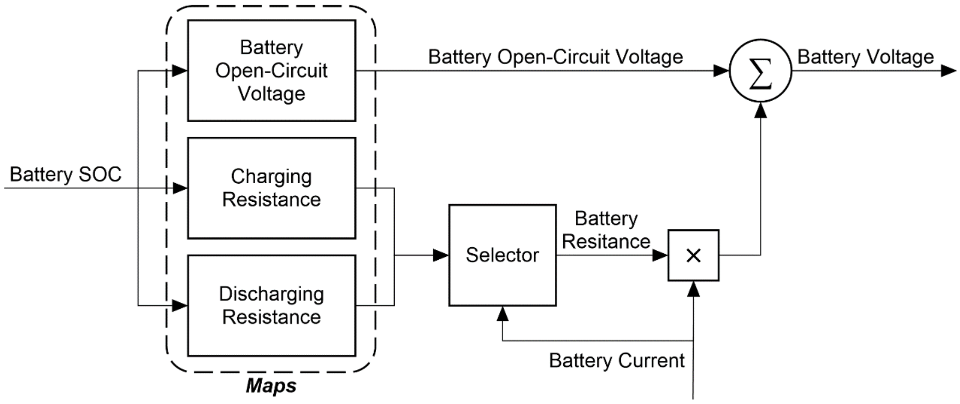

Figure 3: Battery voltage calculation

These values have been used to calculate the battery terminal voltage using ohm's law as shown in equation (1).

$$V_{batt} = V_{oc} + I_{batt} . R_{series} \quad (1)$$

where V_{batt} represents the battery terminal voltage, V_{oc} is the open circuit voltage, I_{batt} indicates the charging or discharging current (positive current charges the battery and increases the battery SOC), and R_{series} is the battery series resistance.

Battery SOC is an expression used to represent the percentage of the present capacity (available battery capacity that can be withdrawn from the battery) of maximum battery capacity [18-20] .It is considered the equivalent of a fuel gauge for the battery pack in electric vehicles (EVs), HEVs. The unit of SOC is percentage points: 0% represents an empty battery, while 100% represents a fully charged battery. SOC is a very important factor that can be used to prevent battery over-discharge or over-charge. Also, it can be used to operate the battery in such a manner that ageing effects are reduced [20].

The most common technique used to calculate the battery SOC is the coulomb counting (CC) method, also known as ampere-hour counting and current integration [21, 22]. The accuracy of this method depends mainly on the precise measurement of the battery current and the accurate estimation of the initial SOC (historic knowledge of SOC_O) [21, 22]. This method uses the charging and discharging battery currents integrated over the operating periods, and then calculates the remaining capacity simply by accumulating the charging or discharging current of the battery to calculate SOC values given by equation (2,3) for both charging and discharging processes respectively:

Charging: $$SOC = SOC_O + \frac{1}{C_{rated}} \int_{t_0}^{t} |i| \, dt \quad (2)$$

Discharging: $$SOC = SOC_O - \frac{1}{C_{rated}} \int_{t_0}^{t} |i| \, dt \quad (3)$$

where SOC_O represents the initial battery SOC, C_{rated} is the pre-known rated (nominal) capacity of the battery which is the total Amp-hours available when the battery is discharged at a certain discharge current from the fully charged state (SOC=100%) to the empty battery state (SOC=0% at the minimum allowable voltage) [19], i is the battery current in amperes (A), and dt is the time interval.

Electric Motor Model

The electric motor model has been established based on characteristics (torque-speed characteristic curve and efficiency map) of a three-phase AC electric motor. In traction mode, the electric motor is used as the prime mover of the vehicle which converts the electric power drawn from the battery into a mechanical power to generate the required traction torque to move the vehicle as shown as sloid lines in the block diagram in figure 4. In braking mode, the electric motor will act as a generator to decelerate the vehicle by the regenerative braking which converts the kinetic energy from the braking torque into electricity to charge the battery as shown as dash lines in the block diagram in figure 4.

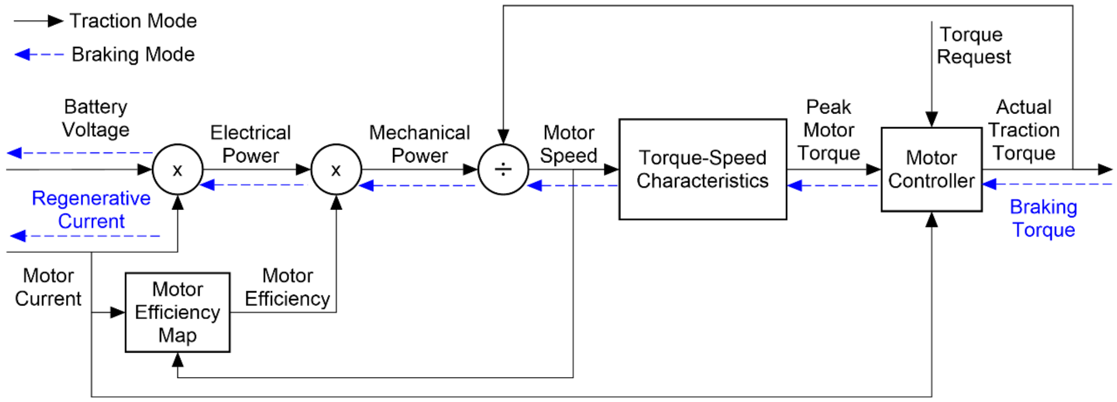

Figure 4: Block diagram of the electric motor

Genset Model

The genset (onboard power generation system) model has been established based on characteristics of a diesel internal combustion engine (ICE) and electric generator to recharge the battery when it reaches a certain SOC. In starting mode, the generator acts as an electric motor, converts the electrical power from the battery to a mechanical power to start the ICE as shown as dash lines in figure 5. In charging mode, the model calculates the charging current from the electric power produced from the generator according to the engine speed which obtained from the engine torque characteristics as shown as sloid lines in figure 5.

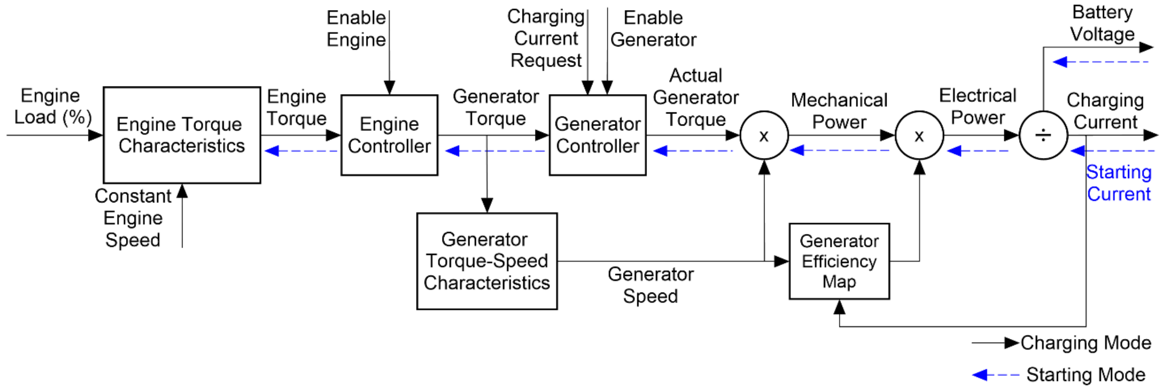

Figure 5: Block diagram of the genset

Vehicle Dynamics Model

This model has been used to calculate the vehicle speed according to the traction or brake torque. The model consists of tire model (from MATLAB/SIMULINK) which calculates the longitudinal force according to the traction force from the motor, the brake torque from the brakes, normal load force and vehicle speed from the longitudinal vehicle dynamics model which have been calculated based on equations (4-6).

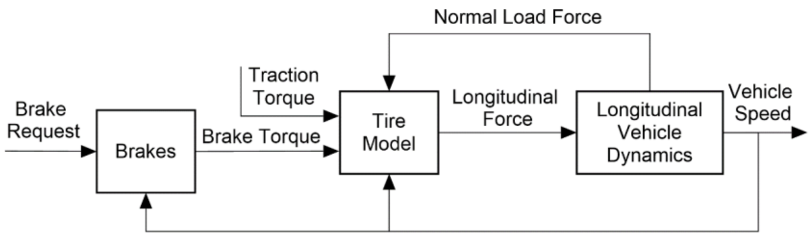

Figure 6: Block diagram of the vehicle dynamics

$$m\dot{V}_x = F_x - W\sin\theta - R_a \quad (4)$$

while m represents the vehicle mass, V_x is the vehicle speed, F_x is the longitudinal force, W is the vehicle weight, θ is the incline angle, and R_a is the Aerodynamic drag force which can be calculates from equation (5)

$$R_a = \frac{1}{2} \rho_a C_d A_f V_r^2 \qquad (5)$$

while ρ_a is the air density, C_d is the aerodynamic drag coefficient, A_f is the frontal vehicle cross-sectional area, and V_r is the relative speed between the vehicle and the wind.

$$F_{zr} = \frac{l_f W \cos\theta + h(m\dot{V}_x + R_a + W \sin\theta)}{L} \qquad (6)$$

while F_{zr} represents the normal load force on the rear axle, l_f is the distance of front axle from the vehicle center of gravity (C.G), h is the height of the C.G above the ground, and L is the wheelbase.

III. Proposed Control Strategy

In some driving conditions, such as driving the HEV for a long time on a highway at constant speed, the engine ON-OFF control strategy would be appropriate; to avoid the battery from being fully charged, and operate the Genset with its optimum output power. Hence, increase powertrain efficiency.

The main concept of the engine ON-OFF control strategy is shown in figure 7. The Genset operation is completely controlled by the battery SOC to restrict the voltage to avoid over-charging and over-discharging. When the battery is discharged to a specific limit, the battery SOC reaches its preset minimum allowed value (bottom line), the Genset is turned ON to charge the battery; because under this limit battery over-discharging will occur causing a progressive breakdown of the electrode materials. On the other hand, when the battery is charged, the battery SOC reaches its preset maximum allowed value (top line), the Genset is turned OFF, and the HEV is propelled only by the battery; because above this limit battery over-charging will occur, then an excessive current flow causing overheating [23].

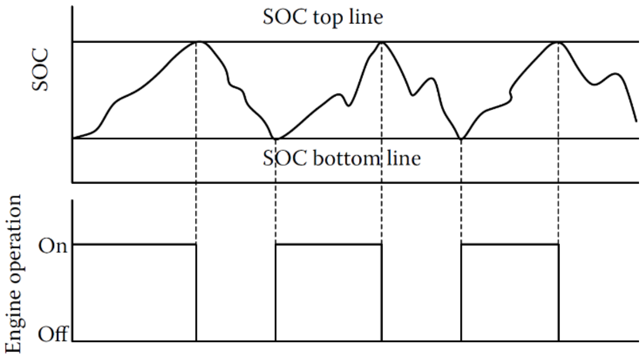

Figure 7: Illustration of the ON-OFF control [24]

Therefore, voltage restrictions are very necessary and should be determined to avoid over-charging and over-discharging. They can be implemented in the control strategy as recommendations for the operating range of the battery SOC according to the battery characteristic curve shown in figure 8.

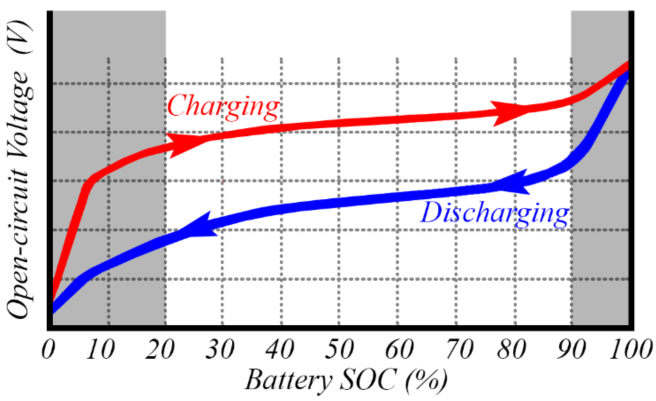

Figure 8: Battery characteristic curve [25, 26]

It is clear that, if the battery SOC exceeds 90% as shown in the right shaded zone in figure 8, the battery will suffer from the high charging stress which reduces battery life in addition to the low discharge efficiency. If the battery SOC falls below 20% as shown in the left shaded zone in figure 8, the battery will suffer from high discharge stress which also reduces battery life. SO, the battery should operate in an appropriate range of battery SOC called ideal SOC working range. Operating outside of these limits will affect battery life.

As can be noticed from the battery characteristic curve shown in figure 9, the cycle life is inversely proportional with the depth of discharge (DOD) which means that deep discharging will shorten the cycle life. Since DOD is considered one of the main factors that affect the battery charge and discharge cycle life [27], it will share the SOC to be the main criterion which has been used to select a safe operating range for the battery.

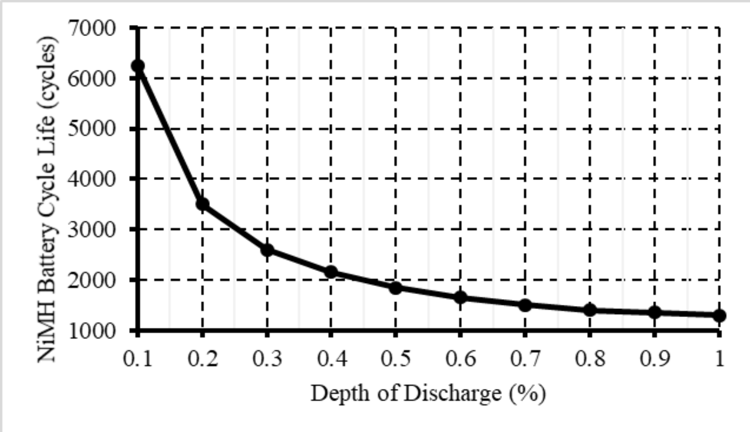

Figure 9: Relationship between DOD and cycle life of the NiMH battery [28]

Therefore, battery management system (BMS) should be used to keep the battery in the safe operating range (60-70%), and ensure a long cycle life in addition to get a good performance. The main function of the BMS is to control the battery SOC precisely for efficient and safe management of the energy flows [29].

A logic to switch between charging and no charging states is required; in order to operate the engine within its optimal efficiency region and the battery SOC within its optimal range without over-charging and over-discharging. So, Stateflow has been used to implement the engine ON-OFF control strategy by designing a logic for the supervisory control of a series HEV model considering the different simulation scenarios.

The concept of the implemented Stateflow chart is shown in figure 10. The main control parameters are driver request and battery SOC. In discharging mode, when the battery SOC reaches 60% (which is selected to represent $SOC_{charge\ ON}$ signal), the supervisory control sends a signal to start the ICE, a signal to enable the generator, an engine load request to control fuel supply to the ICE responding to the load changes to keep running the ICE at a constant speed (1800 rpm); in order to produce a constant frequency as well as improve the genset efficiency, and then set a charging current from the generator to charge the battery. In charging mode, the battery SOC reaches 70% (which is selected to represent $SOC_{charge\ OFF}$ signal), the supervisory control sends a signal to shutdown the genset.

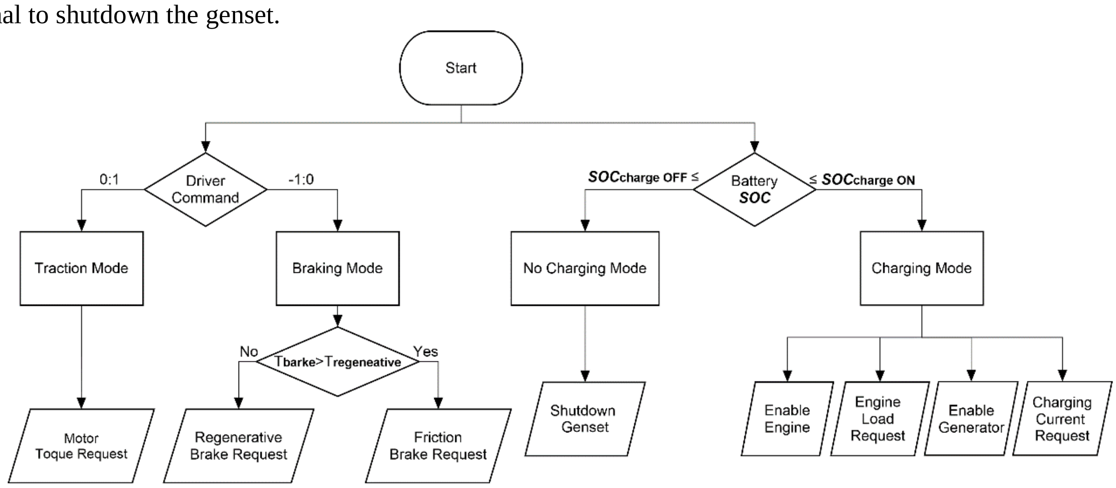

Figure 10: Stateflow Chart

IV. Simulation Results

The proposed model was established and simulated using MATLAB/Simulink; in order to verify the validity of the proposed EMS and test the robustness of the controller under different driving conditions using different standard diving cycles [30, 31]. The selected driving cycles are New European Driving Cycle (NEDC), Federal Test Procedure (FTP-75), US06 Supplemental FTP, Highway Fuel Economy Test (HWFET), Urban Dynamometer Driving Schedule (UDDS), and Worldwide Harmonised Light Vehicle Test Procedure (WLTP).
The values of the parameters which have been used in the model are assumed logically; because the main target of this paper is to check the controller performance regardless of the details of the selected component.

Firstly, simulation has been done under the standard driving cycle NEDC as sown in figure 11 as a vehicle speed in (km/h) vs. time in (s), and the corresponding battery voltage, engine speed, battery SOC, and generator current. This driving cycle has been used in order to simulate driving in downtown crowded areas. It is composed of two main sections, the first section consists of an urban driving cycle, repeated 4 times, is plotted from 0s to 780s. The second section is the extra-urban driving cycle, plotted from 780s to 1180s. This allows to better represent actual on-road driving by combining modern city and freeway driving.

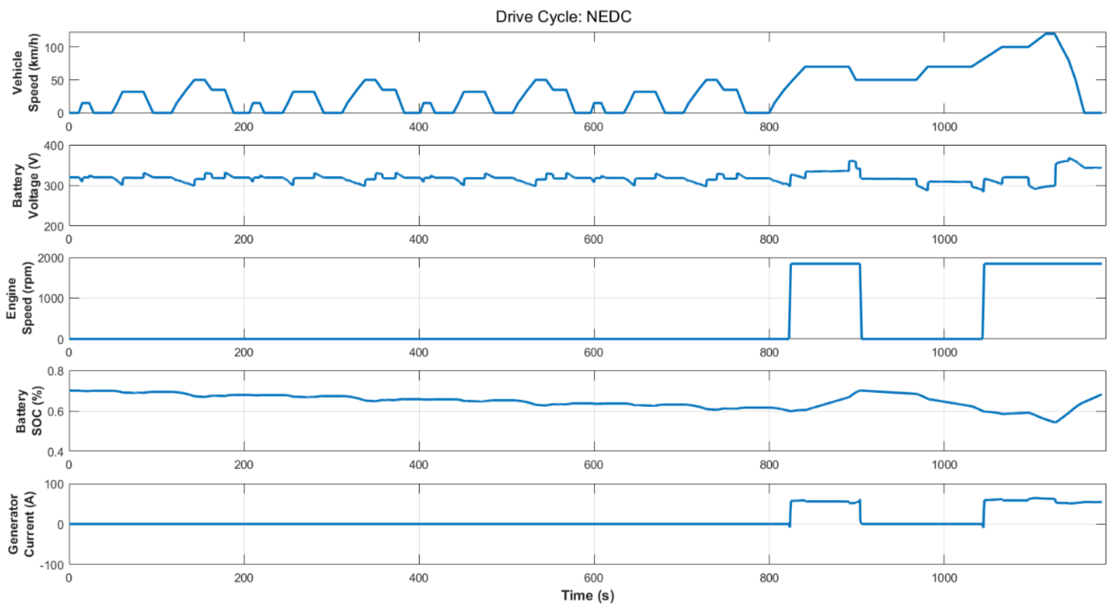

Figure 11: Simulation results under the NEDC driving cycle

Simulation results in figure 11 shows that the genset is not operated in the first section which contains the urban driving cycle; because the electric motor does not require to draw a high current from the battery. So that, the battery SOC does not reach 60%. In the second section which represents the extra-urban driving cycle, the electric motor requires a high current from the battery, so that the battery SOC falls to 60% at 824s and the genset is operated to charge the battery until the battery SOC reaches 70% at 904s, and then the genset will shutdown. Finally, the motor draws a high current again from the battery, so the battery SOC will falls to 60% again at 1045s, and the genset will operate again to the end of the driving cycle. It can be noticed that the battery SOC falls to 59% at1043:1195s, and starts to decrease below 60% gradually from 1095s to reach 56% at 1128s, and then increases to reach 60% at 1145s.

Secondly, simulation has been done under the FTP driving cycle, shown in figure 12, which has been created by EPA (Environmental Protection Agency). This driving cycle represents a travelling cycle, consists of an urban driving section including frequent stops and a highway driving section.

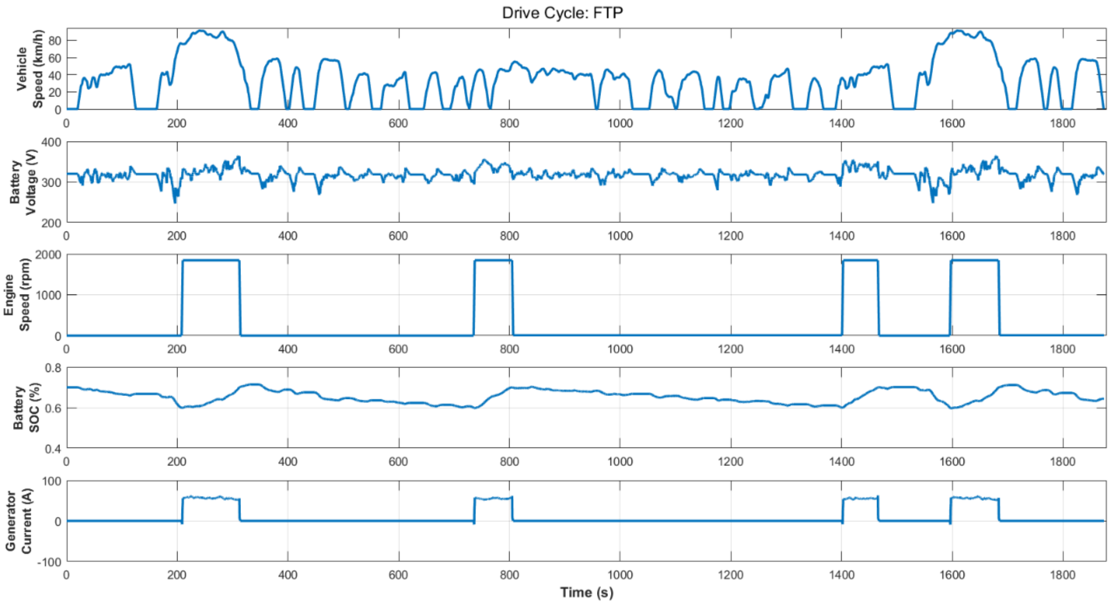

Figure 12: Simulation results under the FTP driving cycle

Simulation results in figure 12 shows that the genset is operated twice in the highway driving sections (at 210:312s and 1597:1864s); because the electric motor draws a high current from the battery. While in most of the urban driving sections, the genset is not operated except two times (at 736:805s and 1402:1465s); because despite the motor draws a small current, it consumes this current for a long time causing battery drainage. This long time varies according to the aggressive frequent stops.

Thirdly, the simulation has been done using the US06 Supplemental FTP driving cycle, shown in figure 13, which was developed to complement the shortcomings in the FTP-75 driving cycle in the representation of aggressive, high speed and/or high acceleration driving behavior, rapid speed fluctuations, and driving behavior following startup. This driving cycle has a higher top speed of 130 km/h and some higher acceleration which represents a much more aggressive driving behaviour.

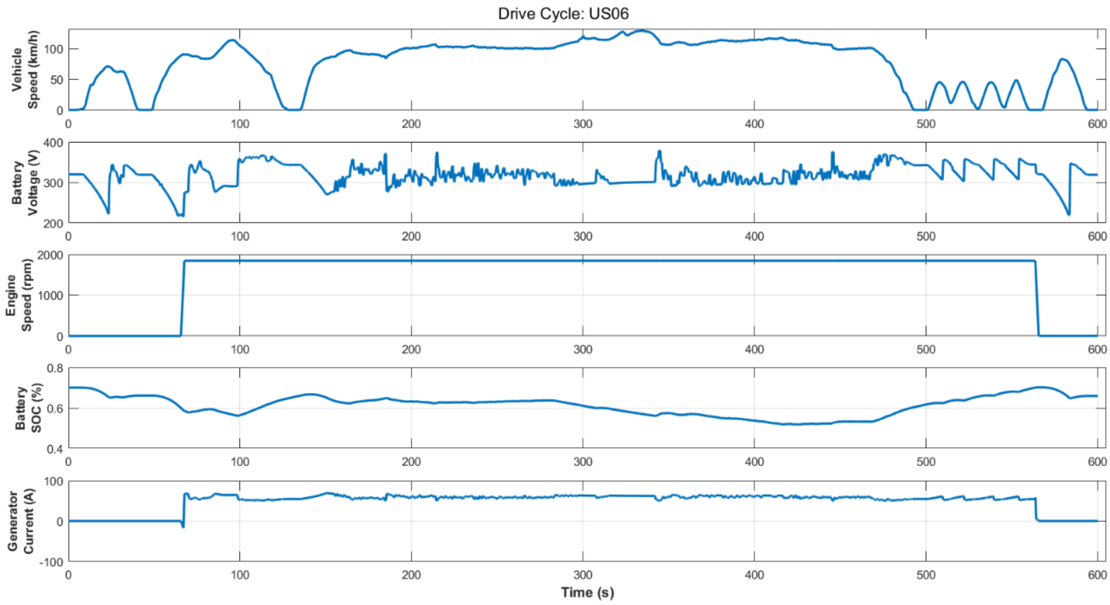

Figure 13: Simulation results under the US06 driving cycle

Simulation results in figure 13 shows that the genset is operated in the most of the driving cycle (from 67s to 564s); because the electric motor draws a continues high current for a long time due to the higher speed and the more aggressive driving behaviour. It can be noticed that the battery SOC starts to decrease below 60% at 66s to be 56% at 98s, and then increases to be 60% at 112s. Also, it starts to decrease below 60% again at 310s to be 52% at 415s, and then increases to be 60% at 490s.

Fourthly, the simulation has been done using the HWFET driving cycle, shown in figure 14, which is a chassis dynamometer driving schedule developed by the EPA to represent a highway driving cycle.

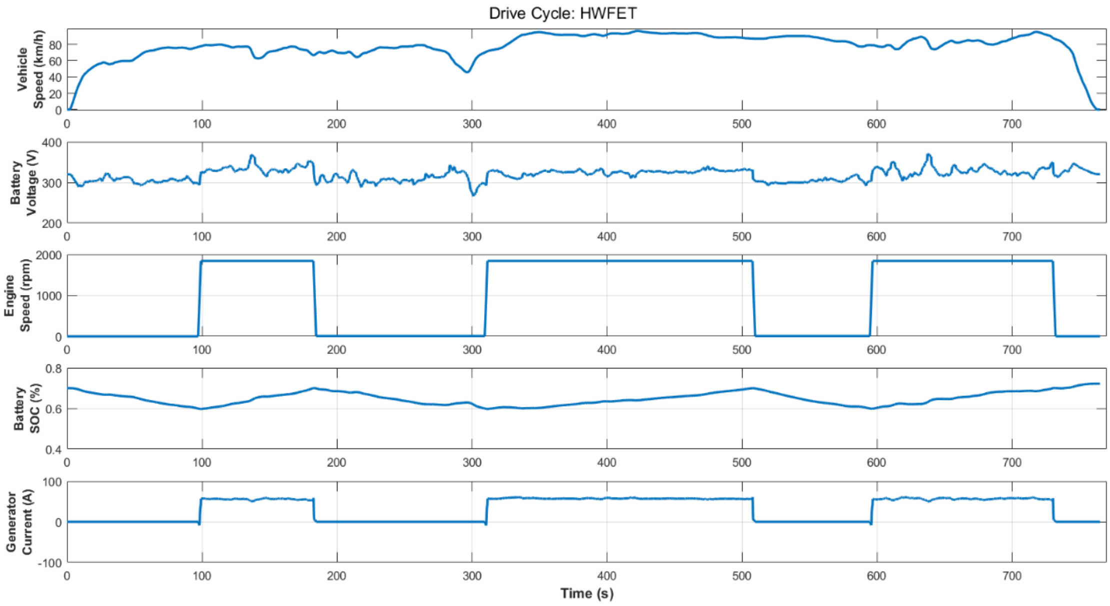

Figure 14: Simulation results under the HWFET driving cycle

Simulation results in figure 14 shows that the genset is operated three times (at 98:182s, 311:508s, and 596:730s) and the battery SOC does not falls below 60%; because there are no stops in this driving cycle which leads to smooth driving behaviour.

Fifthly, the simulation has been done using the UDDS driving cycle, shown in figure (15), also called US FTP-72 cycle or LA-4 cycle. This cycle has been used to simulate an urban route with frequent stops.

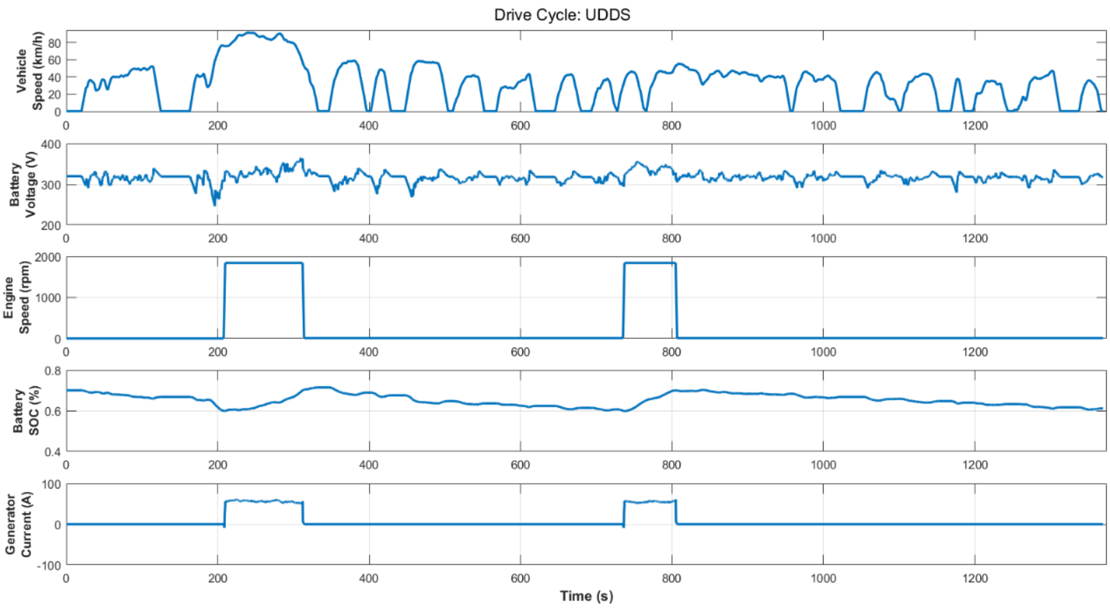

Figure 15: Simulation results under the UDDS driving cycle

Simulation results in figure 15 shows that the genset is operated twice, the first at 209:312s due to the high vehicle speed in this phase, and the second at 736:804s due to the long time consuming the current. It can be noticed that the battery SOC does not falls below 60%.

Finally, the simulation has been done using the WLTP driving cycle for Class 3b vehicles (maximum speed ≥ 120 km/h), shown in figure (16) is a chassis dynamometer test. This driving cycle consists of four sections to represent the actual different speed conditions as following: the low-speed section to represent the urban driving, the medium-speed section to represent the suburban driving, the high-speed section to represent the extra-urban driving, and the extra high-speed section to represent the highway driving respectively.

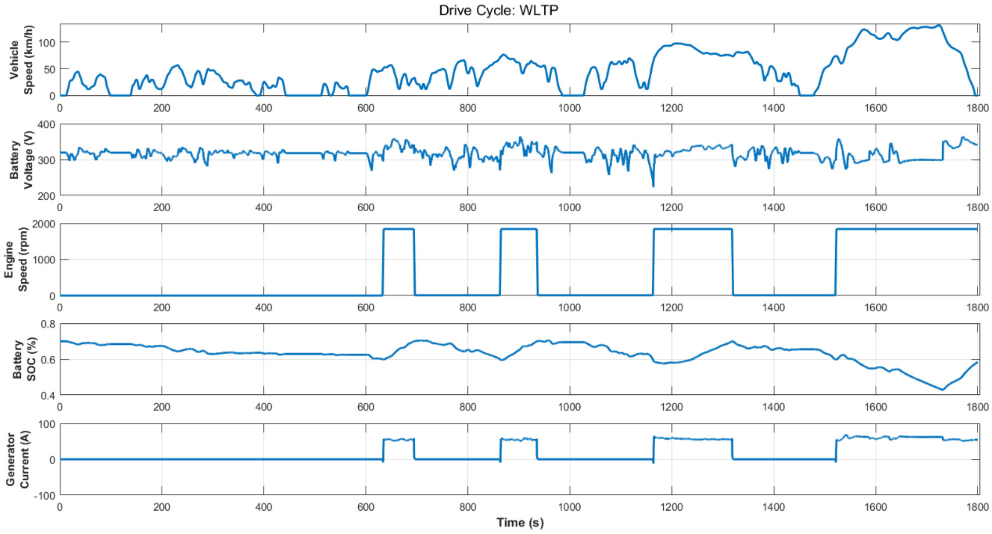

Figure 16: Simulation results under the WLTP driving cycle

Simulation results in figure 16 shows that: in the low-speed section, the genset is not operated, in the medium-speed section, the genset is operated twice (at 634:694s and 864:935s). While in the high-speed section, the genset is operated once at 1164:1318s. Finally, in the extra high-speed section, the genset is operated once at 1522s to the end of the driving cycle. It can be noticed that the battery SOC starts to decrease below 60% in the high-speed section at 1162s and reaches 58% at 1184s, and then increases to reach 60% at 1235s. Also, it starts to decrease below 60% in the extra high-speed section at 1552s and reaches 45% at 1732s, and then increases to reach 60% at 1800s.

V. Conclusion

`This paper proposed an energy management strategy (engine on-off control strategy) using Stateflow as the supervisory control. Firstly, the model for a series HEV has been established, then the proposed strategy has been implemented using MATLAB/Simulink. Finally, verification for the validity of the proposed energy management strategy has been done under different driving conditions using different standard driving cycles.
Simulation results during FTP, HWFET, and UDDS driving cycles show that the proposed energy management strategy meets the selected criteria perfectly, without any deviation in the battery SOC which has been kept within the selected range (60:70%) during whole the driving cycle duration. While the battery SOC falls below 60% to form a small deviation during NEDC, US06 Supplemental FTP driving cycles, and a relatively high deviation during WLTP driving cycle. This deviation can be eliminated by increasing the output current from the generator.

Simulation results show that the proposed control strategy is appropriate to use Stateflow as a supervisory controller for HEVs; because its simplicity reduces system complexity, and it is verified effectively.

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