Genetic Algorithm for UTS Plug-in Hybrid Electric Vehicle Parameter Optimization

Abdul Rahman SALISA[1,2] Nong ZHANG[1] and Jianguo ZHU[1]
[1]School of Electrical, Mechanical and Mechatronic Systems, University of Technology, Sydney
P.O. Box 123, Broadway, NSW 2007, Sydney, Australia
[2]Deparment of Physical Science, Faculty of Science and Technology
Universiti Malaysia Terengganu, 21030 Kuala Terengganu, Malaysia
Email: Salisa.AbdulRahman@student.uts.edu.au

Abstract

This paper covers modeling, energy management strategy development, genetic algorithm (GA) optimization and simulation results based on the model of the UTS plug-in hybrid electric vehicle (PHEV). The UTS PHEV configuration consists of energy storage system, electric machine (EM), power control unit and internal combustion engine. The difference between the UTS PHEV and the conventional powertrain configurations is that the existing configurations need two EMs to function as the electric generator and motor, respectively, while the UTS PHEV needs only one EM to function as either a generator or electric motor in different time intervals specified by the energy management strategy and therefore, can save space, weight and cost. Extensive research has been conducted on the modeling and comparison of the new and existing powertrain configurations. The objective of this paper is to minimize the fuel consumption and greenhouse gas emissions by optimizing the powertrain parameters. The powertrain was simulated for a standard U.S environmental protection agency drive cycle, the highway drive cycle, and the optimization was performed by using the GA.

Key words: Plug-in hybrid electric vehicle, hybrid electric vehicle, energy management strategy, genetic algorithm, series-parallel

1. Introduction

Fig. 1 shows a block diagram of the proposed UTS plug-in Hybrid Electric Vehicle (PHEV), which consists of an energy storage system (ESS), a power control unit (PCU), an electric machine (EM) and an internal combustion engine (ICE) [1,2]. The EM which functions as either a motor or generator in different time intervals specified by a special energy management strategy (EMS) and an ultracapacitor bank for fast charging and discharging during the regenerative braking and fast acceleration.

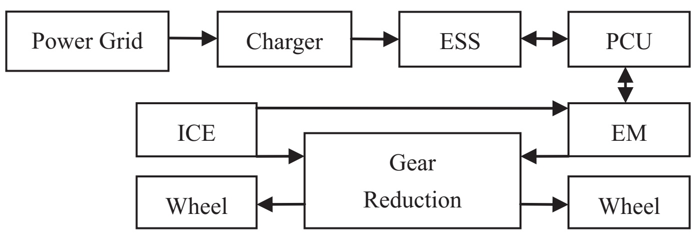

Fig. 1 Block diagram of UTS PHEV configuration

2. UTS PHEV Vehicle Model

The vehicle type selected is an average 5-passenger sedan, which is the majority of vehicles on road. Table 1 lists the typical parameters [3]. In the simulation, the air density is chosen as 1.18 kg/m^3, and the gravitational acceleration 9.81 m/s^2.

Table 1. Parameters of a typical 5-passenger sedan

Name	Value	Units
Aerodynamic drag coefficient	0.29	-
Coefficient of rolling resistance	0.01	-
Frontal area	2.52	m^2
Wheel radius	0.291	m
Vehicle mass	1373	kg

The development of vehicle models begins with the calculations of vehicle energy and power requirements for typical drive conditions based on the parameters and target specifications of the vehicle. The size and capacity of each vehicle component are then determined through a power flow analysis accordingly to meet the requirements. Combining the constitutive equations of all components, we obtain a mathematical model of the vehicle. The vehicle performance for a given EMS and drive cycle is simulated in the MATLAB/SIMULINK environment. Fig. 2 illustrates the MATLAB/SIMULINK model of the UTS PHEV [4-6].

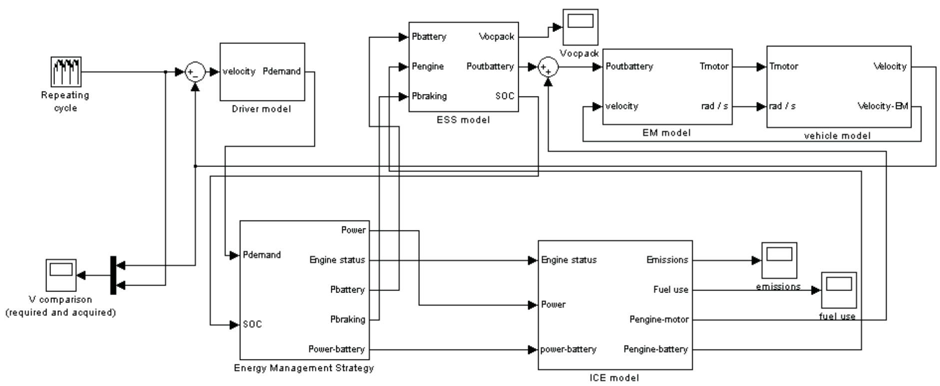

Fig. 2 MATLAB/SIMULINK model of UTS PHEV

3. Development of EMS for UTS PHEV

The EMS is responsible for deciding in which mode that the vehicle is operating. Fig. 3 shows various operating modes of the proposed EMS to control the distribution of power amongst the components, including the mechanical braking, regenerative braking, motor only, engine recharge, engine and motor assist, and engine only mode according to the vehicle power demand in acceleration and deceleration and the state of charge (SOC) level of ESS [7-9].

4. Simulation results

The model presented in Fig.2 is used to simulate the drive performance and fuel consumption of the UTS PHEV for the highway fuel economy test (HWFET) drive cycle shown in Fig. 4. The HWFET drive cycle consists of a mild initial acceleration from zero velocity to the highway velocity in about 100 seconds. Once the highway velocity level is reached, the vehicle velocity varies from 20 m/s to 23 m/s followed by a steep drop to 12 m/s at 300 seconds, and then a rapid increase to nearly 26 m/s. The drive cycle ends as the vehicle slows down to zero velocity at 765 seconds. The power consumption of the vehicle determines the throttle and braking level for a specific drive cycle.

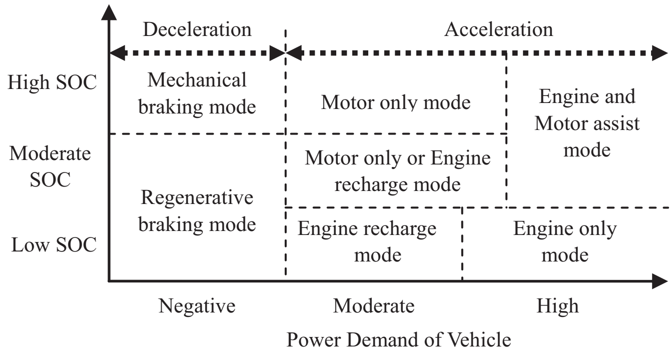

Fig. 3 EMS for the UTS PHEV

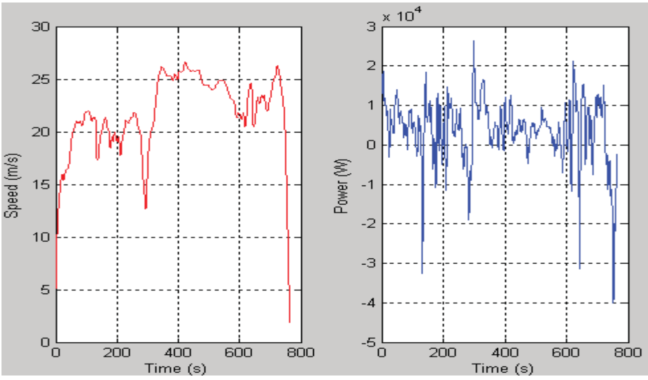

Fig. 4 HWFET drive cycle

Fig. 5 shows the simulated ESS current, voltage and power consumption for the HWFET drive cycle. The peak currents are due to the high power demand to achieve fast vehicle accelerations during respective periods. The negative values on the graph represent the regenerative braking events during the hard braking periods in the cycle. In the ESS voltage graph, the voltage increases during regenerative braking, and decreases during high current discharge when the power demand from EM is at peak.

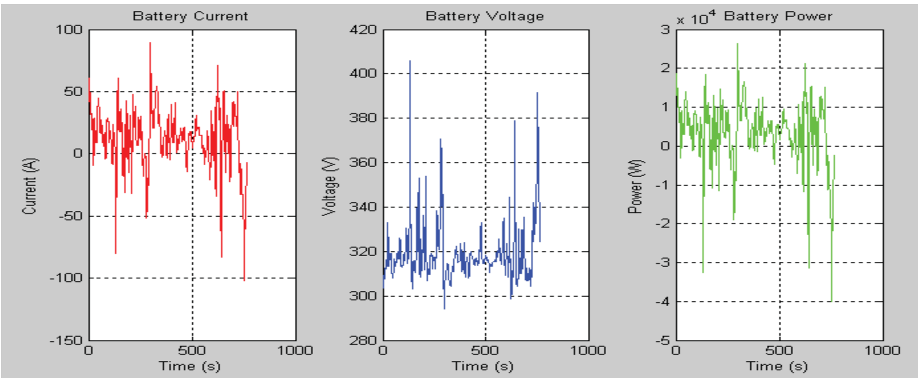

Fig. 5 Simulated ESS current, voltage and power for the HWFET drive cycle

Fig. 6 shows the simulated EM speed, torque and power. As shown in the figure, when the vehicle accelerates, the required EM torque increases quickly, and when the vehicle reaches the relatively stable highway velocity level, a much smaller torque is required to overcome the resistance and air drag to the vehicle. The average power demand from the EM is 8 kW at the highway velocity level and the peak power demand is 24 kW during the acceleration.

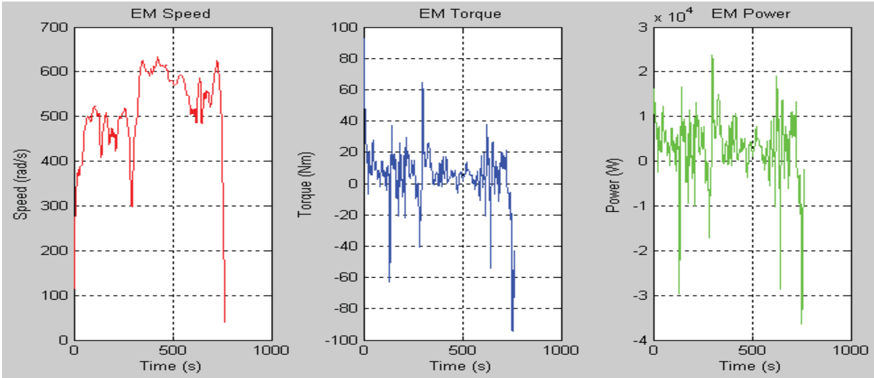

Fig. 6 Simulated EM speed, torque and power for HWFET drive cycle

Fig. 7 plots the simulated wheel speed and torque requirement for the HWFET drive cycle. The maximum wheel torque, 600 Nm, occurs when the vehicle is accelerating from standstill to the highway speed. The required torque then reduces since the HWFET drive cycle only consists of mild accelerations and decelerations.

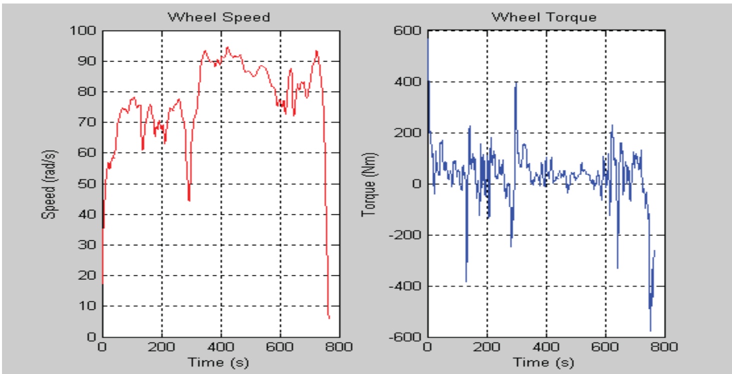

Fig. 7 Simulated wheel speed and torque for HWFET drive cycle

Fig. 8 plots the simulated vehicle speed and the demanded speed for the HWFET drive cycle. As shown, the two curves match very well with a very small error of less than 0.08 m/s between the targeted and acquired speeds. Since this is a typical drive cycle profile for a general driving behavior, it is expected that the UTS PHEV will be able to provide similar highway drive performance as the conventional hybrid vehicle under the actual drive conditions.

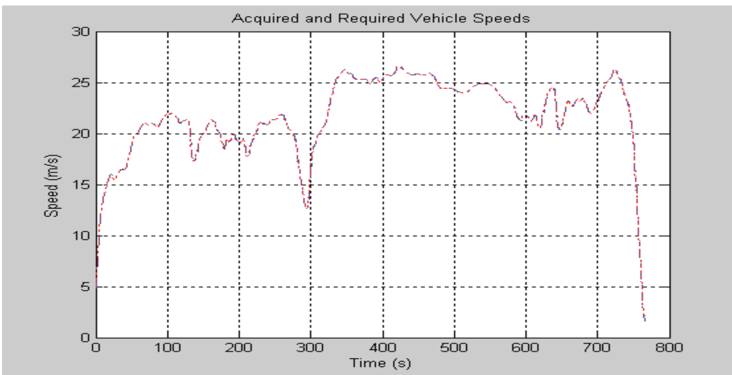

Fig. 8 Simulation results of acquired and required speeds for HWFET drive cycle

5. Optimization

Optimization is a process of exploring the minimum and maximum limits of an objective function while at the same time satisfying certain constraints on the design variables and also selecting the best combination in every iteration. We used the model-in-the-loop approach in our design optimization process [10 – 12]. Initially, the UTS PHEV model simulation utilizes initial values of the design variables or default values, and from there we get the numerical values of the objective function. In our case, values are the fuel consumptions and emissions reduction, which are reflected by four parameters including fuel usage, hydro-carbon (HC), carbon monoxides (CO) and nitrogen oxides (NO_x) level. In the meantime, the constraint function, which is the vehicle performance, is evaluated continuously.

The genetic algorithm (GA) is used in the model-based design optimization. It can be summarized briefly as illustrated in the flowchart of Fig. 9. Table 2 shows a set of parameters used in this research [13,14]. The objective is to minimize the fuel consumption and emissions, such as HC, CO and NO_x, of the vehicle for the HWFET drive cycle.

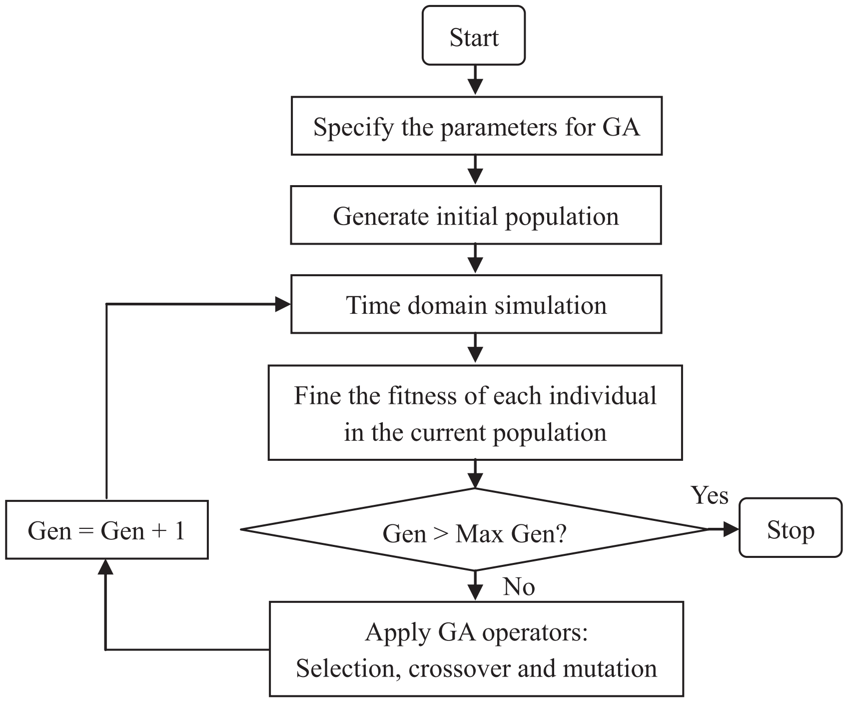

Fig. 9 Flowchart of the GA

Table 2. Parameters used in GA

Parameters	Value
Population size	20
Crossover probability	70%
Mutation probability	1.75%
Maximum generation counted	300

The default UTS PHEV model with the initial values of design variables given in Table 3 is simulated. Table 4 shows the tenth design variables used in this study. Each design variable is also restricted within a lower and an upper bound.

The fuel consumption and emissions were observed for three HWFET drive cycles due to huge processing time. A comparison of the fuel economy and emissions before and after the optimization is given in Table 5. A significant improvement in the fuel used and emissions is achieved by optimization.

Table 3. Initial design variables

Design variable	Initial value
ICE power rating	43kW
EM power rating	75kW
Vehicle mass	1373kg
Battery number of modules	25
Minimum Battery SOC allowed	0.4
Maximum Battery SOC allowed	0.8
Ultracapacitor number of modules	50
Minimum Ultracapacitor SOC allowed	0.9
Maximum Ultracapacitor SOC allowed	0.3
Final drive ratio	6.7

Table 4. Upper and lower bound design variables

Description	Lower Bound	Upper Bound
ICE power rating, ICE	30000	60000
EM power rating, EM	40000	100000
Vehicle mass, Mass	1100	1500
Battery number of modules, B_{mod}	10	40
Minimum Battery SOC allowed, HiSOCB	0.5	0.9
Maximum Battery SOC allowed, LoSOCB	0.1	0.4
Ultracapacitor number of modules, UC_{mod}	40	60
Minimum Ultracapacitor SOC allowed, HiSOCUC	0.7	1.0
Maximum Ultracapacitor SOC allowed, LoSOCUC	0.1	0.3
Final drive ratio	4	8

Table 5. Fuel used and emissions comparison

Description	Before optimization	After optimization
Fuel used (g)	468.839	448.4709
HC (g)	19.5771	19.3136
CO (g)	30.6298	29.305
NO_x (g)	3.7114	3.1094
PM (g)	0	0

Table 6. Final design variable values

Description	Unit	GA
ICE power rating, ICE	kW	39
EM power rating, EM	kW	60
Vehicle mass, Mass	kg	1305
Battery number of modules, B_{mod}	Module	28
Minimum Battery SOC allowed, HiSOCB	-	0.82
Maximum Battery SOC allowed, LoSOCB	-	0.26
Ultracapacitor number of modules, UC_{mod}	Module	46
Minimum Ultracapacitor SOC allowed, HiSOCUC	-	0.89
Maximum Ultracapacitor SOC allowed, LoSOCUC	-	0.12
Final drive ratio	-	6.5

Table 6 shows the final values of the tenth design variables after optimization. It is shown that the rating of the EM is greatly reduced, implying that down-sizing of the EM has been achieved. On the other hand, the ICE is down-sized to a lesser extent. The mass of the vehicle varies as the design variables change because the mass of the vehicle depends directly on some of the design variables.

6. Conclusion

The results of the vehicle subsystems in terms of ESS current, voltage and output power, and EM speed, torque and power, are within reasonable and expected range of actual typical behavior of these subsystems. The components of the vehicle subsystems are correctly sized as the vehicle is capable of achieving performance to a target velocity. It can be concluded that results of the UTS PHEV model are correct.

Based on the optimization results, the following observations can be made. The fuel used of the UTS PHEV is decreased and the emissions of HC, CO and NO_x are decreased as well with the GA optimization. The power rating of the ICE and EM are reduced significantly.

Acknowledgements

This research is part of the work performed by the Centre for Intelligent Mechatronic Systems, University of Technology, Sydney.

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