PARALLEL AND SERIES ELECTRIC HYBRID VEHICLE SIMULATION

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LIST OF ABBREVIATIONS

Symbol	Description
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
EMS	Energy Management System

Abstrak

Pada era ini, enjin pembakaran dalam ialah jenis kenderaan yang paling biasa dan popular di dunia. Oleh kerana isu alam sekitar, pelbagai jenis kenderaan telah dibangunkan dan diperkenalkan sebagai alternatif untuk menggantikan kenderaan enjin pembakaran dalaman. Kenderaan elektrik hibrid, yang menggabungkan kelebihan kenderaan enjin pembakaran dalaman dan kenderaan elektrik, dipercayai merupakan struktur kenderaan alternatif yang paling menjanjikan untuk menggantikan kenderaan enjin pembakaran dalaman.

Dalam thesis ini, model matematik mudah untuk Perodua Myvi telah dibina dan ekonomi bahan bakar disimulasikan. Ekonomi bahan bakar Myvi dengan 2 arus elektrik, siri dan kenderaan elektrik hibrid yang berbeza, dibandingkan. Model matematik dibina untuk menentukan kelayakan mengubah Myvi konvensional kepada Myvi elektrik hibrid. Strategi pengurusan kuasa untuk kenderaan dimanipulasi oleh strategi berdasarkan aturan untuk memenuhi kondisi kitaran pemanduan yang disediakan. Ekonomi bahan api Myvi disimulasikan dengan menggunakan model menghadap ke belakang berdasarkan kitaran pemacu Malaysia.

Hasil simulasi digunakan untuk membandingkan prestasi untuk kedua-dua kenderaan arkitek. Ekonomi bahan bakar untuk kedua-dua jenis seni bina dibandingkan dengan kajian.

Abstract

Today, conventional vehicle is the most common and popular vehicle type in the world. Due to the environmental issue, many kinds of vehicle had been developed and introduced as an alternative to replace conventional ICE vehicle. Hybrid electric vehicle, which combines the advantage of conventional ICE vehicle and electric vehicle is believe to be the most promising alternative vehicle structure to replace conventional ICE vehicle.

In this paper, a simple mathematical model for the Perodua Myvi had been constructed and the fuel economy of the vehicle is simulated. The fuel economy of Myvi with 2 different architectures, series and parallel hybrid electric vehicle, are compared. The mathematical model is constructed to determine the feasibility of transforming a conventional Myvi to hybrid electric Myvi. The power management strategy for the vehicle are manipulated by a rule-based strategy to fulfil the condition of the drive cycle provided. The fuel economy of the Myvi is simulated by using backward-facing model based on the drive cycle. Simulation results are used to compare the performance for both architectures vehicle. The fuel economy for both type of architecture is compared with the conventional vehicle.

1.0 Introduction

In recent decades, hybrid electric vehicle (HEV) has significant influence in automobile industry. It has now been recognized that the hybrid is one of the ideal transitional phase between the conventional all-petroleum-fuelled vehicle and the all-electric vehicles. The increasing in the emission rate of carbon dioxide gas to the atmosphere is polluting our environment and had become a critical global issue. We have to take action to reduce the emission of carbon dioxide into the atmosphere in order to prevent the global warming from getting worst from day to day. One of the main sources of the carbon dioxide gases are released from the running vehicles on Earth.

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Global climate change, caused by increasing levels of greenhouse effect gases in the atmosphere resulting from human activities, is a major issue that society is facing. CO_2 released during fossil fuel combustion is the largest contributor to ‘radiative forcing’ of climate change. ‘Radiative forcing’ is the contribution that a system component makes to disequilibrium in that system [5]. One type of radiative forcing agent that is of significant concern as a contributor to perturbations in radiative balance is the increase in atmospheric concentrations of certain constituents. The increase of concentration of certain constituents that lead to the trapping of the Earth’s radiative balance with solar energy input to the Earth and thermal infrared energy in relation to the Earth’s surface, its atmosphere, and outer, such as carbon dioxide, methane, halocarbons, and nitrous oxide, collectively called “greenhouse gases” [23]. With the invention of hybrid vehicle system technology, the fuel economy of the vehicle system can be increased noticeably while meeting increasingly stringent emission standards and drivability requirements. Hence, hybrid vehicles could play a crucial role in resolving the world’s environmental problems and the issue of growing energy insecurity. Nowadays, we have invented the technology that are able to replace the conventional fossil fuel engine, at the same time does not causes environmental pollution to our Earth. One of the ways to stop the pollution is by transitioning our conventional invention to sustainable technologies. The best place for the transition to take place is by replacing the conventional transportation to electric or hybrid electric vehicle.

With hybrid electric power or electric power vehicle, we can achieve significant cost savings simultaneously reduce the emission of greenhouse effect gases to the atmosphere. However, electric power vehicle does not significantly saving environment due to the electric grid carbon intensity of the country is high. So, one of the best solution for us now is by using the gasoline-electric hybrid power vehicle. [24]

HEVs are a combination of electrical and mechanical components. Three types of energy sources of electricity for hybrids are batteries, fuel cell system (FCs), and capacitors. Each device has a low cell voltage, and, hence, requires many cells in series to obtain the voltage demanded by an HEV. [11]

An HEV cannot charge up the battery of the vehicle by plug in into a source of electricity. A HEV charge up the battery of the vehicle through regenerative braking and operating of internal combustion engine (ICE). In regenerative mode, the electric motor of the vehicle which also act as the generator will capture the energy lost during braking the vehicle and convert it into electrical energy. The energy then is stored into the battery and ready to be used when the vehicle required more torque for acceleration. [21]

A HEV consists of complex electrical and mechanical components. Its powertrain control problems are always complicated and often have conflicting requirements. Many control design objectives are very difficult to formalize, and many variables that are of the greatest concern are not measurable. For example, designing an optimum strategy for the HEV that enable the ICE to propel at the optimum overall efficiency. Due to the complexity of the powertrain of HEV, the optimum strategy for the HEV are always a critical problem for us. In term of optimizing, it can be expressed as three layer: (i) structural optimization, (ii) parametric optimization and (iii) control system optimization. For structural optimization, the objective of structural optimization is defined in terms of the powertrain structure. Meanwhile for parametric optimization, it is defined by optimizing parameters of the fixed structure which would influence the performance of the vehicles. The objective of the control system optimization is to find the best energy management system (EMS). Various methods address these optimization problems, but there is still no solution had been designed to optimize the problem simultaneously considering the three layer optimization. [6]

Hybrid vehicles normally have two, or more power sources which are used to produce, store and deliver power to the vehicle, and this power sources are usually refer to an internal combustion engine and an electric motor (EM). Generally, the combination and the design of the powertrain of the hybrid electric architectures can be split into three categories: series, parallel and series-parallel topologies.

1.1 Series hybrid

In series hybrid system, unlike conventional vehicle, the internal combustion engine operate to drive the electric generator instead of directly driving the wheels. The electric motor is act as the only sole power source which providing power to the wheels. The engine-generator is responsible to charge up the battery pack at the same time powers up the electric motor that moves the vehicle. When large amounts of power are required by the vehicle, the electric motor will tend to draw electricity from both the batteries and the generator in order to generate enough power to fulfil the driver demand.

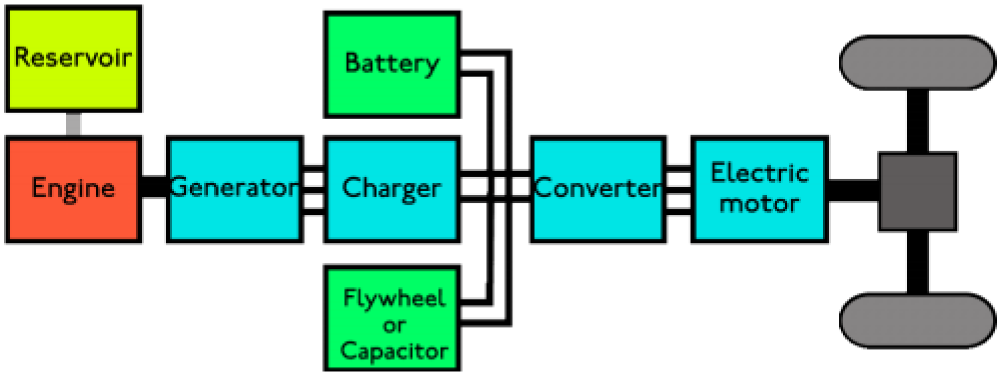

Figure 1: General Structure of Series Hybrid Electric Vehicle [18]

Generally, in series hybrid electric vehicle, there is no need for complex transmission between motor and wheel for the vehicle, as electric motors are efficient over a wide speed range.

There are advantages and also disadvantages for series hybrid electric vehicles. For the disadvantages of series hybrid electric vehicles, the internal combustion engine and the generator are not directly designed to power the vehicle. At the same time, the electric motor are designed to handle the full power of the vehicle. Due to the powertrain design of series HEV, the transmission of power from the internal combustion engine to the electric motor are not efficient due to the conversion energy from mechanical to electrical back to mechanical again. Hence, the overall efficiency is inferior compared to a conventional transmission during long distance travelling due to the energy conversions between the series hybrids electric systems.

For the advantages of series hybrid vehicles, first of all, there is no mechanical link in between the combustion engine and the wheels. This allow the ICE engine to operate in its efficiency region without considering the changes in speed of the vehicle. Hence it is suitable for city driving since the drive cycle in city involve a lot of drive-and-go. [14]

1.2 Parallel hybrid

Parallel hybrid vehicle consist of both internal combustion engine and an electric motor which connected parallel by a mechanical transmission.

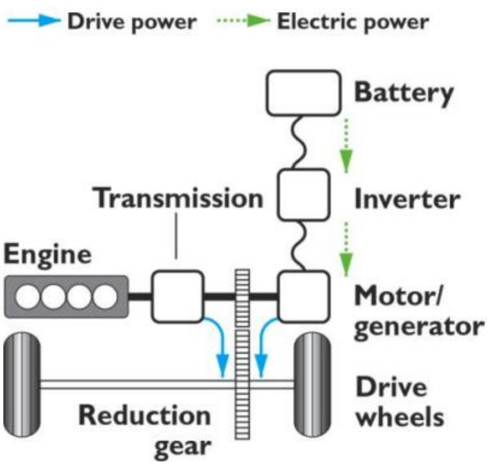

Figure 2: General Structure of Parallel Hybrid Electric Vehicle [17]

In parallel hybrid vehicle, normally the electric motor is combined with generator into one unit which are able to replace the conventional starter motor. The battery in the parallel hybrid system will be recharged during the vehicle undergo regenerative braking, and during cruising. The battery cannot be charged if the vehicle is not moving due to the mechanical link between the wheel and the motor.

To optimise the powertrain control for parallel hybrid vehicle, the parallel configuration supports diverse operating modes such as electric power only, ICE power only, ICE + electric power, ICE + battery charging and regenerative braking.

There are advantages and also disadvantages for parallel hybrid electric vehicles. For the disadvantages of parallel hybrid electric vehicles, The ICE operates depend on the speed of the vehicle, thus engine sometimes is forced to operate out of the efficiency region which directly causes the efficiency of the engine is reduced. Besides that, the mechanical link between the wheel and the motor causes the battery cannot be charged when the vehicle is idle. For the advantages of parallel hybrid vehicles, first of all, there is large flexibility to switch between electric and ICE power. Moreover, the overall efficiency for the parallel hybrid electric vehicle is higher when the vehicle is undergo cruising and long-distance highway driving. [18]

1.3 Problem Statement

Determining fuel economy for HEVs is more challenging and more complex compare to conventional vehicles due to its combination of two distinct power sources: a chemical fuel and electricity. Drive cycle is one of the main factors that determine the fuel consumption of HEVs. This is due to the fuel consumption of HEVs is greatly influenced by the recharging events occur during the distance driven throughout the whole drive cycle. Besides, the powertrain control within the HEVs is also one of the major factors influencing the fuel economy of the vehicles [19]. Since the emission of CO_2 had direct relationship with the fuel consumption of the vehicle, the fuel economy of the HEVs will directly affect the emission of CO_2 to the atmosphere. [25]

1.4 Objectives

- To understand the powertrain control within the series and parallel hybrid electric vehicle.
- To model the series and parallel hybrid vehicles.
- To simulate the fuel economy for both of the series and parallel hybrid electric vehicles.

1.5 Scope of Work

This project will focus on simulating the fuel economy for both types of HEVs. Throughout the process, in depth study is required to identify the parameters and variables that will affect the efficiency of the HEVs. By obtaining the model of the HEVs, we will be able to simulate the fuel economy for both type of the HEVs.

By input the actual velocity drive cycle from different situations can be obtained such as urban driving, highway driving, and others, the fuel economy and other parameters of HEVs that will directly affect the efficiency and also fuel consumption of HEVs are required to be simulated. The graph of the state of HEVs is generated by using Matlab. Code are required to be programmed by using Matlab before the simulation process started. The model of the HEVs and the parameters are required to be programmed into Matlab by using coding and the fuel economy can be generated.

2.0 Literature Review

In order to improve the fuel economy and to reduce the carbon dioxide emissions rate of automobile, the automotive industry had to come out with new solution to replace conventional ICE vehicle with new invention. Hybrid electric vehicles (HEV) nowadays are designed with a smaller engine and an energy storage system compared to conventional ICE vehicle with the same power rating. Although the component sizing of HEV are smaller than conventional ICE, but the performance of HEVs are able to keep up with conventional ICE simultaneously having a better fuel economy. By using simulation software, the computational power allow us to implement a new control strategy and a HEV simulation for the prediction of engine alterations on overall vehicle performance. [10]

However, there is no standard solution for the optimal size or ratio of the internal combustion engine and the electric system. The optimum choice includes complex trade-offs between the heat engine and electric propulsion system on one hand and cost, fuel economy, and performance on the other. Each component, as well as the overall system, have to be optimized to give optimal performance and durability at a low price. In this paper, the effects of different type of hybrid electric vehicle on fuel economy are being studied. [3]

For hybrid vehicles, the powertrain control system is the main topic in the existing literature. A hybrid power train control is developed by using pre-computed optimal strategies. The researcher computed optimal control for certain routes that is travelled frequently by the user. In practical experiments, the optimal control strategies for these routes could save up to 10% of fossil fuel compared to standard depleting-sustaining strategies. [22]

The regenerative braking energy is the key on improving the fuel economy of the HEV. The fuel consumption are mostly dependent on how much the regenerative is generated and how well the energy is used during the HEV is travelling. Condition such as fuel consumption, emission and driveability of HEV without over depleting the state of charge (SOC) of the battery are the challenge for the design of optimizing the HEVs. By simulating both types of architecture of HEVs, it would allow us to further understanding about the fuel consumption, emissions and driveability of the HEV. [20]

3.0 Methodology

In order to obtain the fuel consumption rate of the series and parallel hybrid electric vehicle, computer modelling and simulation through 'backward facing model' are going to be used to simulate the fuel consumption rate and other parameter of the HEV by following to the desired drive cycle we provided.

Mathematical modelling and simulation can be used to reduce the expenses and length of the design cycle of hybrid vehicles by testing configurations and energy management strategies before prototype construction begin.

The transient vehicle system models can be divided into two main categories based on the direction of calculation. Models that start with the tractive force required at the wheels and work towards the engine are called "backward facing models" [7]. Vehicle models that work start from the engine toward the wheels and work in transmitted and reflected torque are called "forward facing models". Backward facing models approach simplifies the calculation process and eliminates the need to iteratively solve at each time step [4]. Meanwhile, forward-facing models better represent real system setup and are preferred where controls development and hardware-in-the-loop will be employed.

In this studies, backward-facing model is used for the modelling and simulation. Since the drive cycle is given as the input for our studies, the fuel consumption of the engine in both series and parallel topologies are simulated.

3.1 Component Sizing of Hybrid Electric System

Due to Perodua Myvi is a conventional all-petroleum-fuelled vehicle, for the hybrid electric system, some part from Toyota Prius are being modelled. The electric motor or generator and the battery in Toyota Prius are being modelled. For the electric motor (EM), it is a permanent magnetic synchronous motor. The major specification of the EM is shown as Table 1 below. Meanwhile, for the battery part, Toyota Prius uses Nickel-metal hydride (NiMH) battery as the energy storage system. The major specification of the battery is tabulated as shown in Table 2.

Motor type	Permanent Magnet Synchronous Motor
Max Voltage	DC650V
Electric Motor Power Output	80 hp/60 kW
Torque	153 lb.-ft.

Table 1: Specification of Electric Motor/Generator of Toyota Prius [15]

Type	Sealed Nickel-Metal Hydride (Ni-MH)
Power output	36 hp/27kw
Voltage (Nominal)	201.6V
Voltage (Maximum)	650V

Table 2: Specification of Battery of Toyota Prius [15]

Hybrid vehicle modelling can be divided into two basic approaches: the Backward-Facing Approach and the Forward Facing Approach. In backward approach we assume that vehicle could satisfy the desired performance of the vehicle and how each component should work in order to achieve the performance.

In backward simulation, since the desired speed is act as a direct input to the simulation, and the fuel economy of vehicle will become the output of the study. We need to determine the net tractive force to be applied based on the speed, payload and grade profiles.

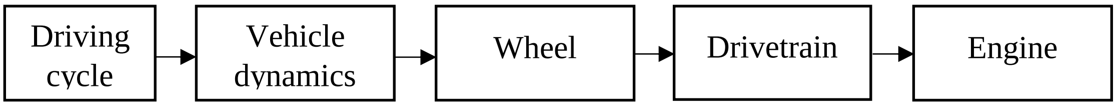

Figure 3: Backward Simulation Process

3.2 Mathematical modelling

Before the simulation process begin, the first step to investigate the fuel economy of a vehicle is the model construction process. In HEV modelling, due to the increase in number of components and multi-directional power flows and coupling of the two main energy systems increase the complexity of modelling process

The HEV model needs a pre-selection of drive train configuration between the basic alternatives of series, parallel, or complex. The drive train configuration is selected in order to determine the components needed and construction of components order in vehicle system. [1]

3.3 Component Modelling

Each component is modelled in Matlab in backward simulation of the vehicle. Each component is modelled in order to simulate the behaviour and study the outcomes of the vehicle. In backward facing, the vehicle is being assume that it is able to satisfy the desired performance. The behaviour of each component is simulated from wheel to engine.

3.3.1 Vehicle Model

For every time step, vehicle has to overcome the forces acting on it when moving. The forces acting on the vehicle includes rolling resistance, aerodynamic drag, grading resistance and acceleration force from the vehicle. The model has to calculate the required forces to accelerate the vehicle at the same time overcome the resistances acting on the vehicle in order to satisfy the desired speed defined in drive cycle data. The sum of these forces is equal to the tractive force of the driving wheels.

$$\sum F = F_a$$

$$F_{wheel} - (F_{air} + F_r + F_g) = F_a$$

$$F_{wheel} = F_a + F_{air} + F_r + F_g$$

Where

F_{wheel} = Tractive force of the driving wheels

F_{air} = Aerodynamic drag force

F_r= Rolling Resistance

F_a = Acceleration force

Aerodynamic drag

When a vehicle is traveling at a certain speed in air, it encounters a force resisting its motion. This force is referred as aerodynamic drag. Aerodynamic drag is the force of the air or air resistance that pushing the object in the opposite direction towards the motion of the object.

$$F_{air} = \frac{1}{2}\rho v^2 C_d A$$

Where

ρ = density of air (kg/m^3)

v = velocity of the vehicle (m/s)

C_d = air drag coefficient

A = frontal area of vehicle (m^2)

Grading Resistance

Grading resistance is the gravitational force acting on the vehicle. This force component is either opposes the forward motion or helps the forward motion. The grading resistance can be expressed as

$$F_g = mg\, sin\alpha$$

Tractive Force

In an automobile powertrain, it consists of a power source (engine or motor), a gearbox, driven shaft, driven wheels. The torque and rotating speed generated from the power source are transmitted to the drive wheels along the powertrain. The torque on the driven wheels, transmitted from the power plant, is expressed as

$$T_{wheel} = T_{engine}\, i_g\, \eta_t$$

where

T_{engine} = torque produced by the engine

i_g = the selected gear ratio

η_t = the transmission efficiency

Table below shows the parameters required to calculate the vehicle dynamic. [21]

Parameter	Symbol	Value
Total Gear Ratio	1st gear	11.01
	2nd gear	6.15
	3rd gear	4.03
	4th gear	2.81
Tire radius	R_{tire}	0.2915m
Frontal area	A	2.3143 m^2
Air drag coefficient	Cd	0.35
Air density	ρ	1.225 kg/m^3
Mass of vehicle + driver	m	1320 kg
Coefficient of rolling resistance	Cr	0.01†

Table 3: Parameter of the Myvi

Gear Box

A gearbox provides a number of gear ratios. The speed requirement of the vehicle determine the gear ratio of the highest gear. The space between gear ratio ensure that the engine are able to operate for all the gears to provide different performance during the drive cycle.

In our study, the proper gear is selected according to the vehicle speed to operate the engine in its optimum speed range in order to improve the fuel economy of the vehicle. The gear selection rule used in our cases are shown in Table 4:

Speed (m/s)	Gears
< 7.73	1^{st}
7.73 - 13.83	2^{nd}
13.83 - 21.09	3^{rd}
> 21.09	4^{th}

Table 4: Gear Selection Rules

The output torque of the vehicle can be obtained by multiplying the selected gear ratio with the engine input torque and the efficiency of the gearbox.

Operating Fuel Economy

Fuel economy of a vehicle is evaluated by the relationship between the total distance travelled by the vehicle and the total amount of fuel consumed by the vehicle. Vehicle fuel economy can be calculated by the equation below:

$$Fuel\ Economy = \frac{Total\ Distance}{Fuel\ Consumption}$$

Generally, the vehicle with 12.5 – 20 km/litre can be considered as vehicle that had good fuel economy or low fuel consumption. Vehicle with 8.33-12.5 km/ litre can be considered as vehicle with average fuel consumption and vehicle with fuel economy lower than 8.33 km/litre is considered poor fuel economy. [26]

Electric Motor

The electric motor, EM, is one of the main power sources in an HEV. It supplies energy to the vehicle from the battery. It produces two important outputs for the vehicle: the motor output torque for the vehicle and the power input required from the battery. The motor torque produced positive and negative power throughout the drive cycle. When the motor torque is positive, the motor torque is supplied from the battery to the vehicle. Meanwhile when the motor torque is negative, the power is charge to the battery. This only occurs during the regenerative braking and the motor is used to charge up the battery. The equations describing the EM in this study is expressed as [10]:

$$T_{EM} = i_{EM} k_{EM}$$

$$L_{EM} \frac{\partial}{\partial t} i_{EM} = U_{EM} - R_{EM} i_{EM} - \omega_{EM} k_{EM}$$

where

U_{EM} = voltage of electric motor

i_{EM} = current of electric motor

T_{EM} = output torque of electric motor

k_{EM} = magnetization of electric motor

L_{EM} = inner inductance of electric motor

R_{EM} = resistance of electric motor

ω_{EM} = rotational speed of electric motor