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SIMULATION OF HYBRID ELECTRIC VEHICLE BASED ON A SERIES DRIVE TRAIN LAYOUT

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Abstract

This paper provided a validated modeling and a simulation of a 6 degree freedom vehicle longitudinal model and drive-train component in a series hybrid electric vehicle. The 6-DOF vehicle dynamics model consisted of tire subsystems, permanent magnet synchronous motor which acted as the prime mover coupled with an automatic transmission, hydraulic brake subsystem, battery subsystem, alternator subsystem and internal combustion engine to supply the rotational input to the alternator. A speed and torque tracking control systems of the electric power train were developed to make sure that the power train was able to produce the desired throttle torque in accelerating the vehicle. A human-in-the-loop-simulation was utilized as a mechanism to evaluate the effectiveness of the proposed hybrid electric vehicle. The proposed simulation was used as the preliminary result in identifying the capability of the vehicle in terms of the maximum speed produced by the vehicle and the capability of the alternator to recharge the battery. Several tests had been done during the simulation, namely sudden acceleration, acceleration and braking test and unbounded motion. The results of the simulation showed that the proposed hybrid electric vehicle can produce a speed of up to 70 km/h with a reasonable charging rate to the battery. The findings from this study can be considered in terms of design, optimization and implementation in a real vehicle.

Keywords: Modeling, validation, hybrid electric vehicle, 6-DOF vehicle longitudinal model, human in the loop simulation

Abstrak

Artikel ini menyediakan simulasi dan pemodelan 6 darjah kebebasan model kenderaan bujuran dan komponen pemacu dalam kenderaan elektrik hibrid sesiri. Model dinamik kenderaan 6 darjah kebebasan mengandungi sub-sistem tayar, motor segerak magnet kekal yang bertindak sebagai pemacu utama yang di pasangkan dengan sebuah transmisi automatic, sub-sistem brek hidraulik, sub-sistem bateri, sub-sistem pengecas lampau dan sub-sistem enjin pembakaran dalam untuk membekalkan masukan putaran kepada pengcas lampau. System kawalan jejakan halaju dan daya kilas pemacu elektrik di bangunkan untuk memastikan pemacu tersebut mampu menghasilkan daya kilas pendikit yang di kehendaki dalam keadaan memecutkan kenderaan. Kaedah manusia dalam gegelung simulasi di gunakan sebagai mekanisme menilai keberkesanan kenderaan elektrik hibrid yang di cadangkan. Simulasi yang dicadangkan digunakan sebagai keputusan awalan bagi mengenalpasti keupayaan kenderaan dari segi penghasilan kelajuan maksimum dan keupayaan pengecas lampau untuk mengcas bateri. Beberapa ujian telah di jalankan semasa simulasi yang dikenali sebagai pecutan mengejut, ujian pecutan dan brek, gerakan sejenak dan keputusan simulasi menunjukkan cadangan kenderaan elektrik hibrid boleh menghasilkan kelajuan sehingga 70 km/h dengan kadar pengecasan bateri yang munasabah. Penemuan dari kajian ini boleh di pertimbangkan dari segi rekaan, pengoptimuman dan implimentasi pada kenderaan sebenar.

Kata kunci: Permodelan, pengesahan, kenderaan elektrik hibrid, model 6 DOF kenderaan bujuran, manusia didalam gegelung simulasi

1.0 INTRODUCTION

Purchasing a vehicle is an important economic decision by a consumer and it also contributes to a nation's economy. Consumers are expected to consider both the capital and operating costs when making their purchase decisions. The technology embodied within a vehicle will determine the operating costs. Consumers are tied up to major operating cost such as gasoline, which is determined by the vehicle's fuel efficiency. The extraordinary volatility in the cost of gasoline during the past few years has raised the level of uncertainty among consumers on future prices [1]. Hence, it causes consumers to be more concerned on the variability and expected mean level of gasoline prices in making their decision to purchase. Also, the decision on purchasing vehicle will impact global warming due to carbon dioxide emissions and the nation's dependence on energy.

Addressing this problem, several programs have been designed to reduce these emissions by increasing fuel efficient vehicles, including the recently enacted increase in the required corporate average fuel economy (CAFE) standards [2]. A hybrid vehicle has been introduced as a problem solver to the issue of potential disruptions to oil supply and spike in gas prices. Hybrid vehicles have the capability to reduce petroleum usage; thus, this model has been promoted by various government programs, including tax incentives [3]. Hybrid vehicles which the batteries can be recharged via online charging where the charging system through the engine coupled with the alternator have the additional advantages of further lowering the use of imported petroleum and lowering the total greenhouse gas emissions.

Hybrid electric vehicles (HEV) are the combination of gasoline and electric powered to drive the vehicle [4]. The main function of the 100 or more horsepower is to generate enough power to accelerate the vehicle from rest. Meanwhile, the engine might only need to produce ten to twenty horsepower in order to maintain the cruising speeds of the vehicle [5]. Basically, a hybrid electric vehicle is contained with an electric motor and batteries to power up the motor. Moreover, the vehicle also has varying engine sizes and control strategies which are used to run at single speed by producing maximum efficiency [6]. The main purpose of the engine is to provide the necessary power during cruising on the highway in order to charge the battery and maintain the battery voltage to supply electric energy for the electric motor.

Basically, HEV can be classified into three classes that differ in the way the vehicle uses gasoline and electrical power, namely parallel HEV [7], series HEV [8] and series-parallel HEV [9]. In a parallel HEV, gasoline is provided to a conventional internal combustion engine (ICE), while the batteries supply is used to power the electric motor [10]. The vehicle transmission, which turns the wheels, can be powered by either the engine or the electric motor. All mass produced hybrids use the vehicle itself to recharge the batteries

during a normal driving. It can be assumed that the batteries of all parallel HEV can be recharged by the vehicle itself, even though there are some customized parallel HEV using batteries which can be recharged by plugging into an electric grid. The other type of hybrid is a series HEV in which the gasoline engine and electric motors have no mechanical connection to the engine. The ICE is turned, running the generator when the battery pack energy supply is not sufficient for demand. The small engine is specially designed to be used as a generator and is never intended to directly power the transmission to propel the vehicle. When the battery power is low, the engine automatically provides the electricity and the energy needed to power the electric motor [11], [12]. Meanwhile, for the series-parallel HEV, it is a combination of both the system series and parallel. The system utilized the power split to change the driving mode, using engine or electric or both.

Several research works on developing HEV have been done in the past few years. The development of hybrid vehicle was pioneered by the Pieper Establishments of Liege and by Vendovelli and Priestly Electric Carriage Company of 1899 [13], [14]. Pieper vehicle was designed as a parallel HEV with a small air cooled gasoline engine assisted by an electric motor and lead-acid batteries. Vendovelli and Priestly developed the first series HEV [14]. This vehicle was a tricycle with two rear wheels powered by an independent motor. In the early development of HEVs, it has several disadvantages such as the use of independent motor to drive the vehicle in a series configuration and used lead acid power source for the electric motor used in both configurations. The problem during development at this time was the lead acid power source energy which was not taking a longer time to supply the electric energy and the weight of the lead acid battery affected the vehicle weight.

In the era of modern technology, the most significant efforts in the development and commercialization of HEVs are made by Japan manufacturers. In 1977, Toyota released the Prius sedan in Japan and followed by Honda, who released Insight and Civic Hybrid [15]. Moreover, Toyota Prius, by using a combined configuration, gives the drawbacks of HEV where it still used large capacities of ICE coupled to the generator to recharge the battery. Besides that, these types of HEV have combined the series and parallel configuration to propel the vehicle. These types of configurations are needed to better control the strategy because the system is more complicated [16]. This is different for the Honda manufacturer, where it developed the HEV based parallel configuration that also give disadvantages in the urban area but the configuration is effective in a highway driving range. The engine and electric motor are connected to a mechanical transmission to turn the wheel of the vehicle. In a combination mode during acceleration, the energy of the engine and the electric motor is through the planetary gear [17], [18]. Besides that, at low speed, only the engines drive the

vehicle. This configuration also needed the small capacity of battery pack and small electric motor [19].

In conjunction with the previous researches' efforts to reduce the air pollution in urban areas and fuel consumption, the series hybrid electric vehicle (SHEV) was proposed in this study. The proposed SHEV was developed based on a series drive train layout, where an internal combustion engine (ICE) was separated from the power chain. The role of the ICE that acted as the prime mover was taken over by a permanent magnet synchronous motor (PMSM), where the electric power was supplied by battery. The PMSM, which can be referred as the electric prime mover, was coupled with the automatic transmission to channel the drive torque to the wheels, while the ICE in the vehicle was coupled with an alternator and acted as the electric power generator. Since the investigation of the SHEV in a real vehicle was costly, the preliminary investigation on the ability of SHEV was observed through a simulation study.

The simulation study of proposed SHEV was made via integrating an electric prime mover model with a validated 6-DOF full vehicle model that consisted of a tire subsystem, brake subsystem and automatic transmission subsystem. The longitudinal model that had been developed was based on a traction model that had been developed to evaluate the behavior of the vehicle's longitudinal speed, wheel speed and longitudinal slip. In ensuring that the PMSM can produce a variety of input torque to the wheels, a PI and PID controllers were utilized as the speed and torque controller. To make the simulation realistic, a Human in the Loop Simulation (HITLS) was used where human interaction was needed to associate with virtual modeling and simulation in order to replace the drive cycle as an input and it had been used by many researchers to evaluate the simulation result. Thus, in this simulation study, the interaction between human and the simulation were made via the excitation of the throttle and the brake input was an actual one from the driver (human) using a play station II game pad. The reason for using the HITLS method was to make the simulation as close as possible in describing the dynamic of a real vehicle and to mockup the hybrid vehicle. HILTS was an efficient and a useful method in the early stage of the project development for the purpose of collecting data to set broad parameters, but the important decisions required a human-in-the-loop testing on a full mission simulation [20].

This paper was organized as follows: The first section presented the introduction and review of some related works. The second section presented the mathematical derivations of the transmission model, ICE modeling, drive torque modeling, prime mover model and alternator model. The following section discussed about the simulation parameter. The fifth section discussed on the simulation result by comparing the model with the HILS and normal simulation and the final section contained the conclusion of this paper.

2.0 MODEL FOR SHEV SIMULATION

In developing a simulation of HEV in a Matlab Simulink software, a vehicle dynamics model was needed. Hence, a vehicle longitudinal model was used in this study. Since the parameters to be observed were focused on the potential of the vehicle to give the maximum speed and the capability of the vehicle in climbing a hilly road, the lateral dynamic of the vehicle was neglected. Because of that, a six degree of freedoms (6 DOF) passenger vehicle model was considered where it consisted of a single sprung mass (vehicle body) connected to four unsprung masses (wheels) [21]. As shown in Figure 1, the sprung mass was represented as a single plane model and was allowed to pitch as well as to displace in a longitudinal direction. The proposed full-vehicle model was developed partially by referring from Aparow [22]. However, it was different in terms of the parameters in several subsystems such as the engine model, which used the transmission modeling and ICE modeling. Since the drive torque of the vehicle was generated from an electric motor, the modeling of the motor by using PMSM will be discussed in the following section. The technical parameters of the vehicle model are defined in Table 1.

2.1 Electric Power Train Model

In this study, the system can be classified into several subsystems such as electric motor, engine, battery, generator, torque converter, transmission, and final drive differential to transfer electrical power to the wheel during the acceleration phase. The power train system was assumed to be the front wheel drive, where the electric motor will transmit the electrical power to the mechanical power through transmission and the final drive to propel the front wheels. Once the vehicle was in a dynamic condition, it was assumed that the electric motor speed was equivalent to the wheel speed scaled by the gear ratio and the drive transmission system.

Otherwise, it had to be assumed that the torque converter was in operation and provided a variation of the amount of torque multiplication at lower speed, increasing the breakaway acceleration. In this condition, the actual torque that was delivered to the wheel came from the combination of the converter slip, throttle setting and the wheel angular velocity. Hence, during a braking condition, the effect of the engine torque only occurred at the front wheels, since the vehicle was in a front wheel drive. Figure 1 shows the block diagram of the vehicle power train model.
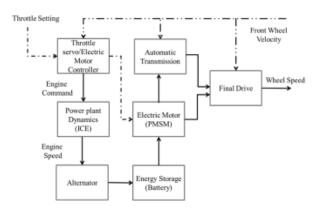
Figure 1 Power train block diagram

2.2 Electric Prime Mover Modeling

The permanent magnet synchronous motor consisted of a stator and a rotor, where the structure of the stator winding was constructed in such a way it was able to produce a sinusoidal flux density in the air gap of the machine. This type of electric motor had been modeled by Husain and Rahmat [23], [24]. The structure of the rotor was similar with a brushless direct current (BLDC) motor which contained a permanent magnet motor. Hence, the permanent magnet synchronous motor was modeled in the d-q frame such as:

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \tag{1}$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} - \omega_e L_d i_d + \omega_e \lambda_{pm} \tag{2}$$

where

v_d	= d-axis voltage
v_q	= q-axis voltage
i_d	= d-axis current
i_q	= q-axis current
R_s	= stator phase resistance
L_d	= d-axis inductance
L_q	= q-axis inductance
λ_{pm}	= permanent magnet flux linkage
ω_e	= angular frequency of stator

The mechanical part of the permanent magnet synchronous motor (PMSM) can be modeled as:

$$\tau_e = J_s \frac{d\omega_s}{dt} + B_v \omega_s + \tau_c + \tau_s \tag{3}$$

where the torque shaft can be defined in equation 4:

$$\rho_s = \tau_s \omega_s \tag{4}$$

where

J_s	= moment inertia shaft
τ_e	= torque electromagnetic
τ_c	= torque coulomb
B_v	= viscous friction coefficient
ρ_s	= power shaft
τ_s	= torque shaft
ω_s	= speed shaft

The coupling between the electrical and mechanical parts can be defined by:

$$\tau_e = \frac{3}{2}\frac{P}{2}\left(\lambda_{pm} i_q + \left(L_d - L_q\right) i_d i_q\right) \tag{5}$$

$$\omega_e = \frac{P}{2}\omega_s \tag{6}$$

Where P is a number of poles and is electric shaft speed.

2.3 The d-q Transformation Modeling

The d-q modeling was related with the transformation of the three phase variable in the *abc* coordinate system into an equivalent two phase system that had an arbitrary speed in a reference frame. This model was used to model and analyze the permanent magnet synchronous motor. Hence, in the d-q coordinate system, it was defined as the d-axis, which was the direct magnetic axis of the resultant mutual interaction of two orthogonal magnetomotive forces (mmf), while the q-axis was the quadrature to the direct axis. In this modeling, the Park transformation was used. The three phases winding *abc* was placed in the stator with two winding d and q placed in the rotor. The calculation of the current and flux were given by Park [23], [25] as:

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = I_{abc \to dq}\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix}, \begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = I_{abc \to \alpha\beta}\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix}, \begin{bmatrix} f_d \\ f_q \end{bmatrix} = I_{\alpha\beta \to dq}\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} \tag{7}$$

where

$$I_{abc \to dq} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta+2\pi) & \cos(\theta+\frac{2\pi}{3}) \\ \sin\theta & \sin(\theta-2\pi) & \sin(\theta-\frac{2\pi}{3}) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \tag{8}$$

$$I_{abc \to dq} = \frac{2}{3}\begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \tag{9}$$

$$I_{\alpha\beta \to abc} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \tag{10}$$

where

$$I_{dq \to abc} = I^{-1}_{abc \to dq}, I_{\alpha\beta \to abc} = I^{-1}_{abc \to \alpha\beta}, I_{dq \to \alpha\beta} = I^{-1}_{\alpha\beta \to dq}$$

The *abc* variables were obtained from the d-q variable through the inverse of the Park transform,

$$I_{dq \to abc} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \quad (11)$$

where the current of the d-q frame model may be obtained from the 3-phase voltages through the previous equation as:

$$i_a = i_q \cos\theta - i_d \sin\theta \quad (12)$$

$$i_b = i_q . 0.5 (1.7321 \sin\theta - \cos\theta) + (\sin\theta + 1.7321 \cos\theta) i_d . 0.5 \quad (13)$$

$$i_c = -i_a - i_b \quad (14)$$

2.4 The *d-q* Transformation Modeling

The vector control of the permanent magnet synchronous motor (PMSM) was to perform the current control loop of a field oriented drive of a PMSM. The advantage of a vector control in their system was that the vector control can deliver high performance to the PMSM based on the desired input. The vector control of the PMSM was defined based on the dynamic model by considering the current as an input as shown below [26].

$$i_a = I_s \sin(\omega_r t + \alpha) \quad (15)$$

$$i_b = I_s \sin\left(\omega_r t + \alpha - \frac{2\pi}{3}\right) \quad (16)$$

$$i_c = I_s \sin\left(\omega_r t + \alpha + \frac{2\pi}{3}\right) \quad (17)$$

For the special case when i_d was forced to be zero, $\lambda_d = \lambda_{af}$. The expression of the torque will then be:

$$\tau_e = \frac{3}{2} \frac{P}{2} \lambda_{af} i_q \quad (18)$$

where

$$k_e = \frac{3}{2} \frac{P}{2} \lambda_{af} \quad (19)$$

since the magnetic flux linkage of the permanent magnet synchronous motor (PMSM) was a constant and the torque was directly proportional to the *q*-axis current. The technical specifications of the PMSM are shown in Table 2.

2.5 Battery Model

In the simulation of the hybrid electric vehicle, a battery model was needed. This battery model was the main component in a hybrid electric vehicle, as the system energy source was to actuate the electric motor propulsion system. The battery model was a lumped dynamic characterization of a Lithium ion battery. The open circuit voltage was a function of the traction battery state of charge and the mathematical parameter for the Lithium ion battery. In this study, the battery Lithium ion type was considered and the battery model had been used by [27], [28]. The simplified battery model can be written as:

$$I_{batt} = V_{oc} \pm \sqrt{V_{oc}^2 - 4R_{int}P_{batt}}/2R_{int} \quad (20)$$

$$V_{batt} = V_{oc} - R_{int}I_{batt} \quad (21)$$

where
I_{batt} = battery current
V_{batt} = battery voltage
R_{int} = resistance
V_{oc} = voltage of charge

Thus, the state of charge (*SOC*) can be calculated from the maximum capacity of the battery as follows:

$$SOC = (capacity_{max} - Ah_{used})/Capacity_{max} \quad (22)$$

$$Ah_{used} = \int I_{batt}/3600 \, dt \quad (23)$$

where
Ah_{used} = battery capacity

2.6 Electric Power Generator

Since the vehicle was developed based on the series drive train layout, the ICE was totally separated from the power train system. The ICE was coupled with the alternator which acted as the electric power generator to supply the current during the charging process [29]. So, in this study, the generator was modeled as ICE and the electric power generator where the function of ICE in this study was to supply the rotational input to the generator.

The generator model was empirically derived from the data taken at several voltage, field current and speed operating points [30]. By using the voltage, field current and speed as the input, the generator current output was determined by functional relationships. In developing the power train model, the generator was included as a subsystem to show the function supplies energy to the battery or energy storage. The generator was assumed to be at 80 amps over a voltage operating range from 300 to 450 volts. The generator output can be represented as a function generator of field current, speed, voltage and temperature, where the output field's current was a separate dynamic control component. The generator of the output current was approximated at a certain speed and varied in the output voltage. The varying output voltage can be expressed as:

$$I_{gen} = f(\omega_{gen}, I_{field}, V_{gen}) \qquad (28)$$

where

I_{gen} = generator output current
ω_{gen} = generator rotational speed
I_{field} = generator Field current
V_{gen} = generator output voltage

The field current can be derived in a mathematical definition as follows:

$$V_{field} = L_{field}\, dI_{field}/dt + R_{field}I_{field} \qquad (29)$$

where

L_{field} = generator field inductance
R_{field} = generator field resistance
V_{field} = generator voltage output

2.7 Electric Power Generator

The vehicle dynamic model was developed based on the mathematical equations from the previous vehicle handling equations by using the MATLAB SIMULINK software. The relationship between the vehicle body motions, engine dynamic, tire model, longitudinal slip and the layout of the hybrid electric vehicle (engine, generator, battery, electric motor, battery management, and transmission) are clearly described in Figure 2. In this model, there were two inputs used in the dynamic analysis of the vehicle, namely the torque input and the steering input which came from a driver. The developed model was able to study the response in longitudinal and lateral directions.

Figure 2 Series hybrid electric vehicle simulation model

3.0 SPEED AND TORQUE TRACKING CONTROL OF THE ELECTRIC VEHICLE

The control strategy for the speed and torque control of the electric prime mover is shown in Figure 3. Two loops were employed in the controller schemes which were the inner loop and outer loop controllers. The inner loop controller was for the speed controller of the PMSM motor, while the outer loop controller was used as the torque controller for tracking periodic reference inputs. As shown in Figure 3, the adaptive PID (APID) controller was represented as the torque controller, while the PID was represented as the speed controller. The reference input to the control system was the desired drive torque of the vehicle and the desired speed of the vehicle.

The effectiveness of the combination for both of the controller structure in the torque tracking control and speed control of the PMSM had been examined before by Rahmat [24]. The author had mentioned the method to tune the parameter of PID controller and configure the parameter in the table. The control strategy based PID controller was used because it was proven to be effective in many applications, easy to maintain and easy to implement in the i/o device [31].
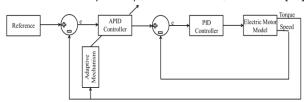

Figure 3 Control structure of electric motor [24]

4.0 SIMULATION PROCEDURES

The purpose of this study was to predict the ability and the behavior of the proposed series hybrid electric vehicle (SHEV) in terms of producing the maximum longitudinal speed with the parameters that had been considered. To achieve the target, several handling dynamic tests were used, namely the sudden acceleration test and the acceleration then braking test. Sudden acceleration test was used to evaluate the characteristics of the vehicle during a sudden increase of speed form rest. In this study, the vehicle was accelerated drastically until the speed of the vehicle became saturated for 50 seconds. There were two types of sudden acceleration tests that had been made in a level road and a gradient road. As mentioned before, the sudden acceleration test in the level road was intended to predict the maximum speed that can be achieved by the vehicle, while acceleration in the gradient road was done to predict the maximum slope that can be climbed by the vehicle. Since the study was to simulate the full SHEV, the ability of the braking system should be considered. This was the reason why the acceleration then braking test was used. The test was made via accelerating the

vehicle into a nominal speed, then maximum brake was applied to make the vehicle decelerate in speed immediately.

For the simulation to be realistic, a Human-in-the-Loop-Simulation (HITLS) was utilized. HITLS was defined as a model that required human interaction associated with virtual modeling and simulation (M&S) in the live, virtual, and constructive taxonomy. In this case, the HITLS model may conform to human factor requirements for the case of a mockup. As the name suggested, a human is always a part of the simulation and consequently influences the outcome in cases which are difficult if not impossible to reproduce exactly. So, in this simulation study, the excitation of the throttle and brake inputs was actually from the driver (human). The purpose of using this HITLS method was to make the dynamic response of a vehicle simulation as close as possible in describing a real vehicle of a series hybrid electric vehicle. As stated by [32], [33], HILTS was an effective method in the project research and development for the purpose of collecting data to set broad parameters, but important decisions required a human-in-the-loop testing on a full mission simulation. Bronaugh [20] strongly justified that a human-in-the-loop simulation was a real time simulation and should be included in a project development in order to capture the performance of a new part or new designs types. Thus, the use of HILTS in the simulations of SHEV was highly desirable to study the effectiveness of the actuator.

In this study, a plug and play game pad compatible with the computer was used. In the Matlab Software, the joystick input in the Simulink library browser was utilized to make a connection between the game pad and the simulation block diagram. Additionally, in Simulink, the joystick input cannot automatically be connected to the game pad because the output of game pad was a Boolean, where the Boolean was not merged to the mathematic equation. However, in order to connect the game pad to the Simulink, the data conversion in the Simulink library browser was chosen to convert the Boolean condition to a mathematical one. Overall, the techniques of the HILTS can be examined in the Figure 4.
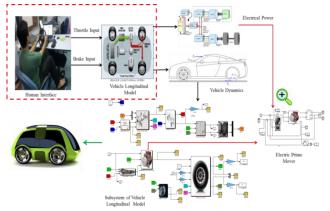

Figure 4 Human interface of a series hybrid electric vehicle

4.1 Simulation Parameter

The simulation study was performed for a period of 10 seconds using a Heun solver with a fixed step size of 0.01 second. In order to simulate the SHEV, real vehicle data specification should be included. The reason was to obtain a similar performance with a real vehicle. The values were not intended to explicitly model a single make or model of a car, but were determined as the average values for this type of vehicle. The numerical values of the 6-DOF full vehicle model parameters and the motor model parameters as well as the values are given in Tables 1 and 2:

Table 1 Vehicle Parameter

Item			Parameter
Overall Length (mm)			3395
Overall Width (mm)			1395
Overall Height (mm)			1415
Wheelbase (mm)			2280
Track Width	Front (mm)		1215
	Rear (mm)		1205
Weight (Kg)			500
Transmission	Gear Ratio	1st	3.5
		2nd	2.11
		3rd	1.392
		4th	0.971
Final gear ratio			4.722
C_d			0.29
J (Kg/m^2)			4.5
R (m)			0.2
K_{bf}(Nm/Bar)			13.33
K_{br}(Nm/Bar)			6.666
a			0.01

Table 2 Electric motor parameter

Symbol	Name	Value
V	Rated Voltage	220 V
P_{out}	Magnetic flux	900w
P	Number of poles	4
ω_m	Rated speed	1700 rpm
R_s	Stator resistance	4.3 ohm
λ_m	Flux linkage	0.272 ohm
L_q	q-axis inductance	27 mH
L_d	d-axis inductance	67 mH
I_s	Rated current	3 Amp
I_{smax}	Maximum current	2 Israted
J	Motor inertia	0.000179 kg.m^3

5.0 PERFORMANCE EVALUATION OF THE SHEV IN SUDDEN ACCELERATION TEST IN A STRAIGHT LINE

In this study, the HITLS method was applied to predict the ability of the dynamic response of SHEV to evaluate the speed of the vehicle model in a longitudinal direction. Figure 5 shows the validation of the vehicle speed between HITLS and without HITLS. The vehicle speed of HITLS is represented by a red solid line while the normal HEV simulation is represented by a blue/dashed line. The graph shows that by using the game pad as an input throttle for HITLS, the vehicle speed was closely the same as in the initial condition but at the time response of 3 seconds, the vehicle speed was a little bit increased compared to the one without HITLS. This was because the speed of the vehicle can be controlled using the acceleration pedal similar with the pedal accelerator function in a real vehicle. Thus, for the simulation without HITLS, the speed of the vehicle was fixed and cannot be controlled and the input was generated using the signal builder in Simulink. The vehicle speed for HITLS was 70 km/h in the 10 second time response. It showed that the electric motor had been controlled by the pedal accelerator to give the input. It can be seen that the response of the vehicle speed was slow under the damped because for the real vehicle, the speed was slightly increased until it was at the saturated speed in order to merge with the gear ratio in the transmission to drive the vehicle.

Thus, when using the HITLS evaluation of vehicle, a dynamic response can be achieved in a real time condition for the vehicle before the development level. Figure 6 shows the addition test in the sudden acceleration test, namely the unbounded motion. In this study, the unbounded motion was made from the game pad or pedal accelerator as an input throttle in which the pedal was pressed and released, which meant that when the pedal was pressed, it can give the input to the electric motor and when it was released, no input was shown from the driver.
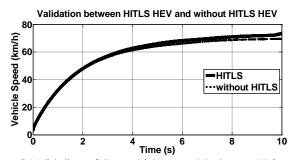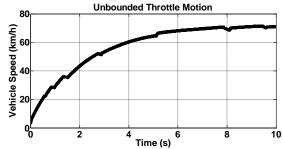

Figure 6 Unbounded throttle motion speed graph

5.1 Performance Evaluation of the SHEV in the Sudden Acceleration Test in a Road Gradient

The SHEV was examined with various gradients as shown in Figure 7. Based on the observation, the green line represented the vehicle speed on the 50 percent road gradient, which meant that the vehicle was climbing a 27 degrees slope with a speed of 23 km/h. The purple line represents the vehicle that climbed at a 60 percent gradient which was equal to 31 degree that can achieve the speed in 14.9 km/h. However, both the blue and red lines represented the vehicle that climbed at 70 and 80 percent road gradient respectively with a vehicle speed similar to the vehicle speed at 14.7 and 14.5 km/h, which meant that the vehicle climb at around 41 degrees. It can be seen from the graph that when the vehicle was climbing on the 80 percent road gradient, the speed of the vehicle declined. The result showed that the vehicle can be climbing on the maximum road gradient at 80 percent.
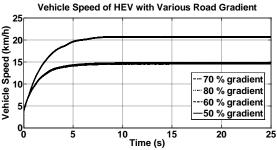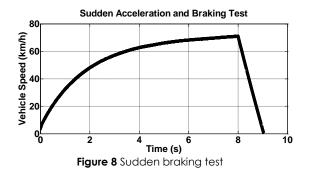

Figure 7 Vehicle test on various gradients

5.2 Performance Evaluation of the SHEV in a Sudden Acceleration then Braking Test

Based on Figure 8, the pedal accelerator responded for the vehicle during the acceleration and braking test. In this test, the accelerator pedal was to give the throttle input in order to move the vehicle. It can be seen from the result that the vehicle started at rest and then given the throttle input until the vehicle speed was saturated at the speed of 70 km/h, and then, the driver was given the brake input to stop the vehicle. In this study, human interaction was important because the throttle input and the brake input were given by human through a step in the accelerator pedal. From

Figure 5 Validation of the vehicle speed between HILS and normal simulation

the results, it took 1 second to stop the vehicle from accelerating after the brake input was applied by the driver at 8 seconds.

Figure 8 Sudden braking test

5.3 Performance Evaluation of the SHEV in Electrical Portion

Figure 9 shows the response of the electric motor torque. It can be seen from the result that the response of the controller on the electric motor was a faster response. The APID controller showed the overshoot occurring in 25 percent from the torque reference to supply a large torque when the vehicle started to move from rest. The input of the controller was the response from the human by the step the accelerator pedal. The settling time of the electric motor torque was 0.2 second to saturate for an optimum performance.
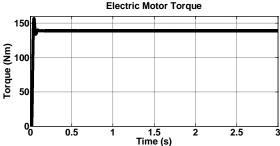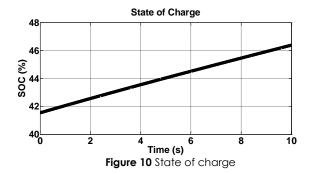

Figure 9 Response of electric motor torque

The results of the state of charge for the battery hybrid electric vehicle are shown in Figure 10. The linear graph shows the initial state of charge at 40 percent battery power. When the battery power reached 40 percent, the internal combustion engine was running to charge the battery through the generator until the battery power was in full charge. In this simulation, the battery was increasing the battery power by the generator continuously running. The results showed that the percentage of the battery was increased by 7 percent in 10 seconds when the vehicle started moving. The state of charge was related to the DC voltage on the battery, when the state of charge that started the DC voltage of the battery also increased. It can be seen from the two results in Figures 10 and 11 that the state of charge started to charge the battery at 40 percent and the

DC voltage showed the initial voltage at 250 voltage. When the state of charge was increased, the DC voltage also increased. The DC bus voltage of the battery is illustrated in Figure 11.

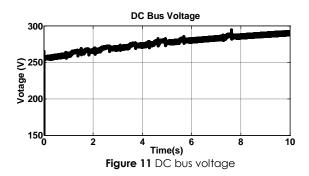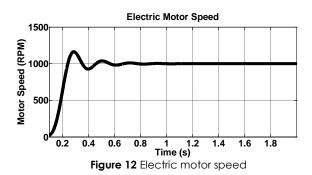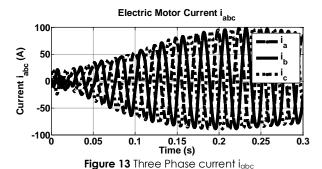**Figure 10** State of charge

Figure 11 DC bus voltage

Figure 12 shows that the electric motor speed is proportional with time. From the observation, when the human stepped on the accelerator pedal, the speed was slightly increased until it achieved the optimum speed. It can be seen that the response of the electric motor speed was shown at a 15 percent overshoot. The settling time of this electric motor speed was a 0.4 second delay when compared to the electric motor torque. This was because the electric motor torque was controlled by an advanced controller, namely the adaptive PID (APID) while the electric motor speed was controlled by a PID controller. The rise time of the speed motor was delayed because in this hybrid electric vehicle study, only the electric motor torque was controlled.
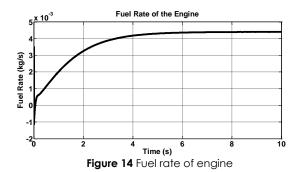

Figure 12 Electric motor speed

The magnitude of the induced current will oscillate as a sinusoidal wave as shown in Figure 13. The most common way that electricity is generated is by rotating a circular coil of wire about an axis through the coil's diameter so that the rotation is perpendicular to a strong magnetic field. From the observation, the time response from 0.01 to 0.05 second of the current was in a small sinusoidal, which meant that the vehicle started moving at the initial condition. These three phases current can be classified into three input currents which were phase *a* as denoted by the blue line, phase *b* as denoted by the green line and phase *c* which was denoted by the red line.

Figure 13 Three Phase current i_{abc}

5.4 Performance Evaluation of the SHEV Engine During Charging Condition

Figure 14 shows the fuel rate that had been used for the internal combustion engine while charging the battery pack through the alternator. The fuel rate was calculated from the mathematical model inside the engine model. The value of the fuel rate was 0.0044 kg/s, where the engine was run when the battery needed energy source. At the earlier run of the engine, the fuel rate was going up and down because of the lag in the intake port flow rate due to the fuel dynamics.

Figure 14 Fuel rate of engine

6.0 CONCLUSION

As a conclusion, a simulation of a series hybrid electric vehicle model had been developed based on a 6-DOF vehicle longitudinal model. This had prompted the investigation of the possible benefits of an Adaptive PID (APID) and PI controller based feedback control in controlling the torque and speed of the electric motor. The effects of the control system on the vehicle were simulated using Simulink where a human in the loop simulations method was used to simulate the capabilities of the hybrid electric vehicle. The purpose of this simulation was to evaluate the maximum speed that can be achieved by the vehicle, the maximum gradient that can be climbed by the vehicle and also the capability of the proposed electric system to charge the battery. Several tests had been used, namely the sudden acceleration test on the straight path, the sudden acceleration test on the road gradient and the sudden braking test to evaluate the braking capability. Simulation results showed that the vehicle was able to accelerate up to 80 km/h in a straight path and able to climb up to 80% with a speed of 14.7 km/h.

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