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Study on stability and control analysis for cascade hybrid electric vehicle

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Abstract. This research contributes in studying the configuration of hybrid electric vehicles (HEV) which have been developed and used in modern days. The hybrid topologies that combine multiple power sources with motive force to increase the driving function are also studied. The objectives of this study are to determine the time and frequency domain equations that characterize the relationship between the input, output, and state variables for the forward path of car motive dynamics system. In this paper, a block diagram of HEV forward path with feedback signal and controller gain was proposed while assuming the motor to be an armature controlled direct current. The transfer function and state-space were developed and its stability was analyzed and used to describe the car motive dynamics. Matlab and Simulink were used to simulate the system. The simulation results showed the state-space and transfer function of HEV system with excess motive force of 2650 N. The results clearly indicated that the designed controllers were able to improve the steady-state, transient analysis, and desired output. It was also demonstrated that the step input with proportional-integral-derivative controller was efficient in term of the best transient response with zero steady-state error. While, bode plot graph illustrated that the system was inherently stable.

Keywords: hybrid electric vehicle; classical control; stability analysis; cascade system; frequency domain; modeling and simulation

1. Introduction

Around the world, one of the major end user sectors that consumes energy is transportation

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sector. Tough environmental management and insufficiency of fossil fuels have forced the authority and administrative party to promote and analyze for the alternate means of on route transportation. Today, most of the transportation systems use a system that has internal combustion engine (ICE) which have been considered and commercialized in the last certain decades (Jordan 2004). However, there are many problems that come together with the use of ICE in transportation system, for examples, global warming, air pollution, and rapid depletion of the earth's ozone layer (Hofman *et al*. 2005) and (Chan 2002). In order to overcome this problems, electric vehicles (EV), hybrid electric vehicles (HEV), and fuel cell electric vehicles (FCEV) are introduced to the world. These three types of vehicles are demanded for a purpose of replacing the use of ICE and making a better exploitation of their advantages (Zulkifli *et al*. 2015) and (Pisu and Rizonni 2007).

Hybrid vehicle uses two or more power sources in order to move the vehicle meanwhile HEV specifies that one source of power is coming from an electric motor and the other source is typically provided by ICE in which design is to run on gasoline or diesel fuel for propulsion proposed (Zulkifli *et al*. 2015 and Yadav *et al*. 2011). In a common hybrid vehicle, it has one form of gasoline with the engine which works as the fuel converter and the other one is an electrical storage device (Sciarretta and Guzzella 2007) and (Musardo *et al*. 2005). Basically, HEV has proven to increase the driving functions of the vehicle propulsion system in which it can enhance the fuel consumption, emission, comfort, performance and safety (Wenyong *et al*. 2007) and (Preitl and Bauer 2007). The electric motor used in HEV has been proven to improve the fuel consumption and vehicular emission while the ICE can extend the range capability of HEV.

There are many types of HEVs, such as battery and batter hybrids, battery and capacitor, diesel ICE and battery, and etc. Hybrid electric vehicles with implementation of electric motor produced high torque where car can be stopped from moving at a very low speeds. This characteristic shows that electric motor can provide the initial motion to a vehicle and the engine can take over as the primary power source once the vehicle is moving in the most efficient speed range which eventually will lower the emission and also increase the fuel efficiency (Sánchez-Repila *et al*. 2006). Motors are the most important component of HEV drive systems. The electric traction motor drives the wheels of the vehicle. For a common vehicle, the engine must ramp up before a full torque can be produced but for hybrid vehicles, an electric motor produces full torque at low speeds. The motor has low noise and higher efficiency. HEV's characteristics includes good off the line acceleration, good fault tolerance, good drive control and having a flexibility in relation to voltage variations (Keibriarei *et al*. 2015).

The architecture of this prototype shows the operation of HEV which consists of the engine as the main power source and adding the extra torque value achieve from electric machine to serve as a generator in the system (Saeed *et al*. 2016). This will cause the regenerative in braking energy and the fuel energy is converted to electric energy and recharges the batteries. The controller is the important part as to develop the strong relationship between engine and the electric machine. Because, it can enhance the power-split from this relation that can help to increase fuel efficiency, low harmful gasses emissions from the car that are good for our environment, good drivability, and charge management of battery state. In addition, it also contains the electrical storage device, which batteries store the electricity and used when required.

Therefore, in order to save the fuel consumption, the HEV was designed with a systematic control which electric motor provided the additional power during accelerating or climb by assisting the engine (Yadav *et al*. 2011). Other than that, it performs fuel efficiency through controlling the high-voltage battery power by essentials control system design for engine power

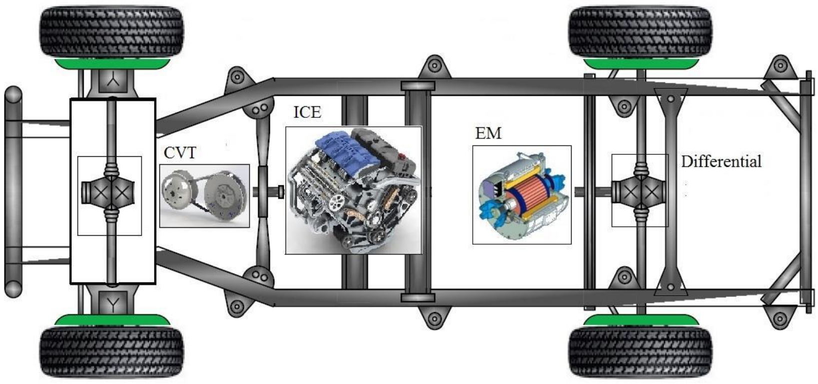


Fig. 1 The mechanical powertrain configuration

and speed (Yan *et al*. 2014). The emission products of this vehicles are only water and heat. According to (Peeie *et al*. 2016), as to fulfilled the higher demand in increasing fuel economy and diminishing air pollution, the HEV was appropriately designed with minimized the operation of ICE through the regenerative of braking power resulted from energy storage devices and electric drives in this vehicle.

In 2015, National Highway Traffic Safety Administration (NHTSA) has conducted a study about the crashes of HEV and conventional ICE cars involving the pedestrian and bicyclist. The result has shown that accident rate for HEV was higher compared to that of conventional car which frequently occurred in zones with low speed limits (Jayavant and Thakur 2016). Thus, with this problem, we are triggered to study on how to obtain stability of the HEV's performances due to modifications in the driving conditions and also to improve the HEV's speed in adaptation to actual traffic conditions. This is to ensure that for any types of traffic conditions, HEV car is able to adapt to the situations.

There are many controllers that have been developed to control either the engine power or speed for HEV (Yakub *et al.* 2018). These are the ways to pursuit improvement in fuel economy, environmentally friendly, and sustainable energy use. The good control of the HEV system can reduce the fuel consumption over a driving period (Zia 2016). It means that the fuel consumption for HEV is much lower than that of conventional car with the same distance of driving that nowadays, the energy of the HEV can be controlled using many types of the controller such as PID controller, gain scheduling method, fuzzy logic, neural network and others.

According to (Lulhe and Date 2015), the most important parts in designing the controller in HEV is the consideration of torque and velocity, which is the architecture of the belt-coupled parallel of HEV as shown in Fig. 1. However, to design a good system of HEV that operates with both fuel and electrical energy that consists of energy storage devices and electric drive inefficient mode is not an uneasy task. Thus, as a solution, we are motivated to study on how to design the best controller to improve the HEV's speed and get the desired output with the selected inputs that can determine the best transient response and reach zero steady-state error. Therefore, the stability test through root locus and bode plot analysis is necessary for close-loop stability system.

The structure of this study consists of five major parts. First, the objective, problem statement, research scope, and related literature are explained in Section 1. Next, the topologies of hybrid electric vehicle models are elaborated in Section 2. Then, the control approaches are explained and

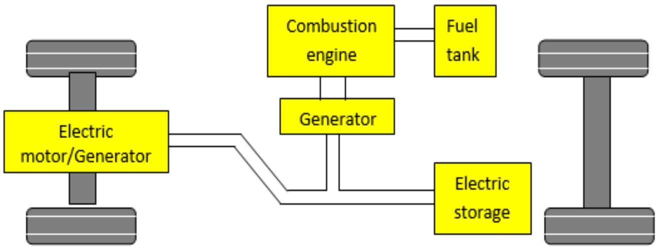


Fig. 2 Physical diagram of serial hybrid electric vehicle

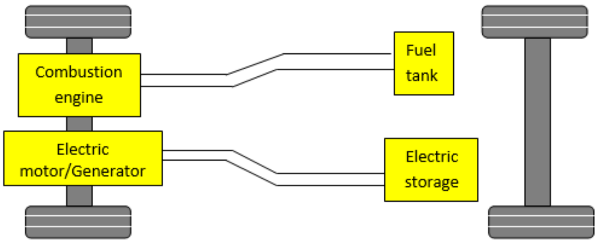


Fig. 3 Physical diagram of parallel hybrid electric vehicle

applied for a forward and cascade systems through the classical control such as PD, PI, and PID controllers in Section 3. These include the stability analysis technique through time and frequency domain. Moreover, computer simulation has been tested to justify, examine, and evaluate the proposed method on the hybrid electric vehicle dynamics model, and the results are discussed in Section 4. Finally, the paper is concluded and possible future works are given in Section 5.

2. Process system modelling

Nowadays, the use of HEV on the road is becoming more popular and this includes for the country of Malaysia. HEV is fueled up by internal combustion engine and an electric motor in which the energy used is stored in the batteries (Fajri *et al.* 2016). Electric motors, used in HEV are mostly oriented on DC machines or brushless DC motors. Furthermore, the technology that used for HEV is regenerative braking which makes the wheels to slow down after the resistance is applied by the electric motor to the drivetrain. The motor is turned by the energy from the wheels in the meantime, which acts as generator by converting energy into electricity. The battery stores this electricity and will be used by electric motor when needed. Besides that, there is additional power that is provided by electric motor to assist the engine for the car to accelerate or even climb (Park *et al.* 2016). In HEV, there are multiple ways to arrange the flow of power in which we have three types of hybrid vehicle configuration as followed: series hybrid, parallel hybrid, and combine hybrid.

2.1 Series hybrid

In series hybrid, the ICE will connect to a generator in order to produce electricity for pure

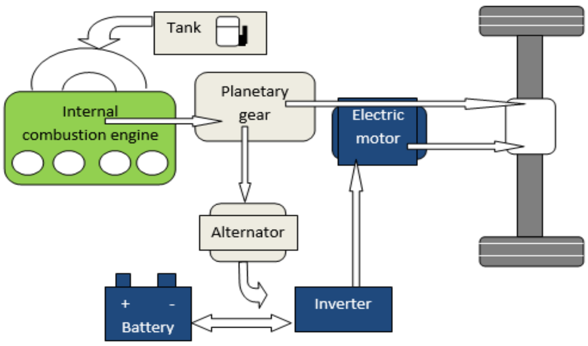


Fig. 4 Physical diagram of combined hybrid electric vehicle

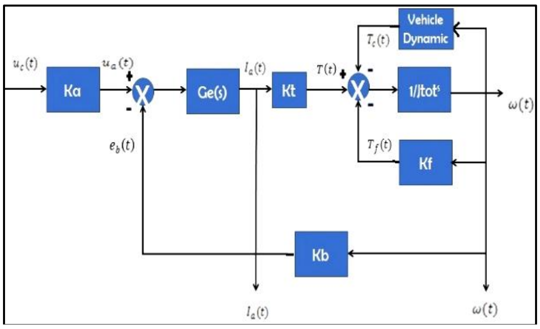


Fig. 5 The block diagram of a hybrid vehicle forward path

Table 1 The block diagram parameters

Parameters and Definition	
K_A	The power amplifier gain
$G_e(s)$	The transfer function of the motor electric circuit that composed of a series inductor and resistor, L_a and R_a respectively
k_t	The motor torque constant
J_{tot}	The sum of the motor inertia (J_m), the inertias of the vehicle (J_{veh}), and the two driven wheels (J_w) both of which are reflected to the motor shaft
k_f	The coefficient of viscous friction
k_b	The back electromotive force (emf) constant.
$e_b(t)$	Back emf
$T(t), T_f(t), T_c(t)$	Motive torque, friction torque, load torque

electric propulsion which will be stored in a battery and also the inverter itself will invert the DC current to AC current since electrical motor works well with AC current (Saeed *et al*. 2016). The block diagram of series hybrid is shown in Fig. 2. There are some advantages of series hybrid configuration in which as followed; ICE can operate at its very narrow optimal region because of mechanical decoupling between the ICE and wheels and the torque-speed characteristics of electric motor is near to ideal which make multi gear transmission needless. Since this is a human invention, the series hybrid configuration also has some disadvantages; the overall efficiency is reduced because the energy is converted twice, firstly from mechanical to electrical and then back to mechanical, two electric machines are needed and a big traction motor is required therefore only large vehicles have enough space for this bulky engine system.

2.2 Parallel hybrid

The parallel hybrid electric vehicle shown in Fig. 3 shows that it allows both electric motor and ICE to deliver power in order to drive the wheels since both of ICE and electric motor are attached to the drive shaft in which the propulsion may be supplied by ICE only, by electric motor only or by both electric motor and ICE. There are some advantages and disadvantages of this parallel hybrid configuration.

The advantages are such as; energy loss is less because no energy form conversion occurs like in series hybrid configuration and it is compact due to having small traction motor and no generator needed. There are also some disadvantages of parallel hybrid configuration which are the engine operation points cannot be fixed in a narrow speed region as the mechanical coupling occurs between engines and driven wheels and the configurations of mechanical and control strategy are complex.

2.3 Combined hybrid

Combine hybrid or known as split power hybrid electric car displayed in Fig. 4 is the configuration that combine both features of series hybrid and parallel hybrid. The configuration of combine hybrid is however needed an additional electric machine and also planetary gear unit (Yadav *et al*. 2011). The planetary unit used in combine hybrid is to allow some of ICE power to be applied mechanically and drive electric motor into motion.

2.4 HEV system forward path

By drawing the block diagram of the HEV system such a forward path which illustrated in Fig. 5, we assumed that the motor will be an armature controlled dc motor. The parameters of the block diagram are illustrated in Table 1 while the parameters for the hybrid vehicle are as in Table 2. From Fig. 5, the input variable $u_c(t)$ is the command voltage from the electronic control unit and $T_c(t)$ is the load torque. The output variables are the motor angular speed which is represented by $\omega(t)$ and the armature current of the motor angular speed which is represented by $I_a(t)$. It can be seen that

$$u_a(t) = K_A \cdot u_c(t) \tag{1}$$

$$e_b(t) = -k_b \cdot \omega(t) \tag{2}$$

$$L_a \cdot \dot{I_a} + R_a \cdot I_a(t) = u_a(t) - e_b(t) \tag{3}$$

By substituting Eqs. (1) and (2) into Eq. (3), then we will have

$$J_{tot} = J_m + J_{veh} + J_w \tag{4}$$

$$T(t) = k_t \cdot I_a(t) \tag{5}$$

Table 2 Parameter of hybrid vehicle (Park *et al.* 2016)

Parameter	Value
Speed controller, $G_{sc}(s)$	$100+\frac{40}{s}$
The torque controller and power amp, $K_A G_{tc}(s)$	$10+\frac{6}{s}$
Current sensor sensitivity, K_{cs}	0.5
Speed sensor sensitivity, K_{ss}	0.0443
$\frac{1}{R_a}$, $\frac{1}{J_{tot}}$	1, $\frac{1}{7.226}$
Total drive train efficiency, $n_{tot}k_t$	1.8
Back emf, k_b	2
r = tire radius, i_{tot} = total transmission ratio, $\frac{r}{i_{tot}}$	0.0615
$pC_wAv_o\frac{r}{i_{tot}}$	0.6154
$D = k_f$, friction torque	0.1

$$T_f(t) = k_f \cdot \omega(t) \tag{6}$$

The resulting state-space represents that the system has two inputs and two outputs. By rewriting the equations

$$\dot{I_a} = -\frac{R_a}{L_a} \cdot I_a(t) - \frac{k_b}{L_a} \cdot \omega(t) + \frac{K_A}{L_a} u_c(t) \tag{7}$$

$$\dot{\omega} = \frac{k_t}{J_{tot}} I_a(t) - \frac{k_f}{J_{tot}} \omega(t) - \frac{1}{J_{tot}} T_c(t) \tag{8}$$

By arranging the Eqs. (8)-(9) to matrix form

$$\begin{bmatrix} \dot{I_a} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} -\frac{R_a}{L_a} & -\frac{k_b}{L_a} \\ \frac{k_t}{J_{tot}} & -\frac{k_f}{J_{tot}} \end{bmatrix} \begin{bmatrix} I_a \\ \omega \end{bmatrix} + \begin{bmatrix} \frac{K_A}{L_a} & 0 \\ 0 & -\frac{1}{J_{tot}} \end{bmatrix} \begin{bmatrix} u_c \\ T_c \end{bmatrix} \tag{9}$$

$$\begin{bmatrix} I_a \\ \omega \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} I_a \\ \omega \end{bmatrix} \tag{10}$$

3. Controller design approaches

3.1 PID controller

In industrial control systems, a proportional-integral-derivative (PID) controller is commonly used in control system. A PID is a universal control loop feedback mechanism which can be either open-loop system or closed-loop system. A PID method is by calculating an error value as a difference between a measured process variable and a desired set point. The value can be

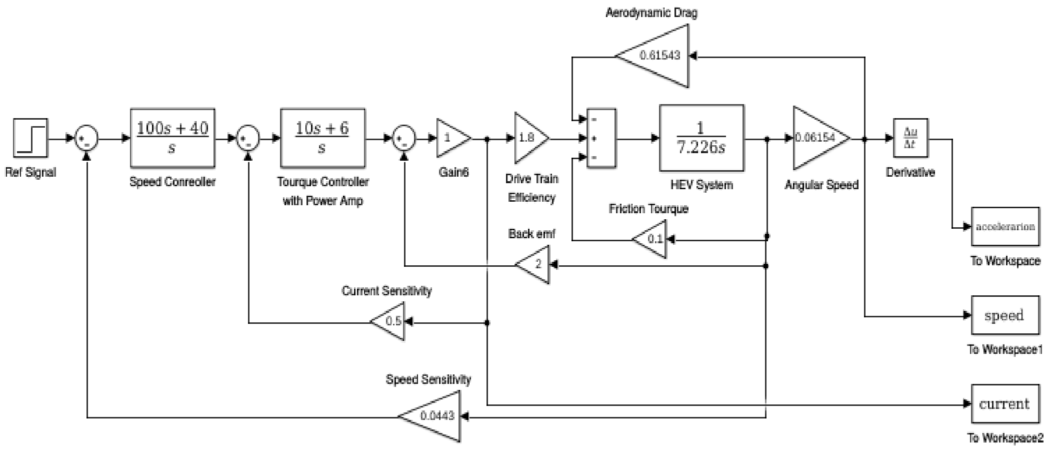


Fig. 6 Cascade control of the hybrid vehicle system

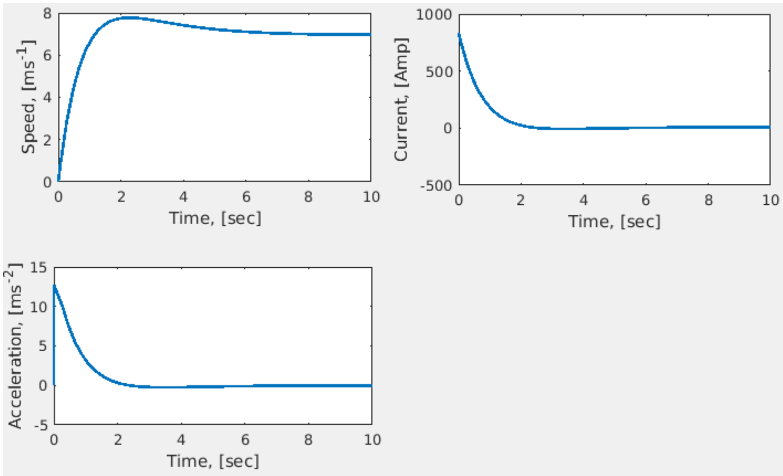


Fig. 7 Vehicle responses

determined using PID tuner in Simulink Software. The PID controller in Eq. (11) is used for the controller toward the reduction of vibration in suspension system.

$$u(t) = K_p\, e(t) + K_i \int e(t)\, dt + K_d \frac{d}{dt} e(t) \tag{11}$$

3.2 Stability test

Analysis by using Routh-Hurwitz stability criteria is used to check the stability of the transfer function when approaching steady state. This method also is used to obtain the range of gains for the controller. By applying the close loop, we obtain,

$$\frac{(1000s^2 + 1000s + 240)K_p}{1 + 1630s^4 + 2843s^3 + 1803.2s^2 + 490.12s + 47.76 + (1000s^2 + 1000s + 240)K_p} \tag{12}$$

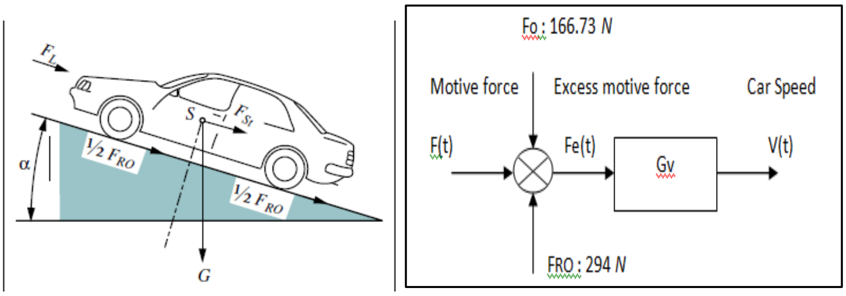


Fig. 8 Illustration of running resistances for a car moving uphill (Bosch 2007)

Table 3 The block diagram parameters

ρ	Density of air (kgm^{-3})	1.2
f	Coefficient of rolling resistance	0.02
g	Gravitational acceleration (ms^{-2})	9.8
m	Mass of car (kg)	1500
C_w	coefficient of aerodynamic drag	0.5
A	Cross-section of the car (kgm^{-2})	2
V_{hw}	The head-wind velocity (ms^{-1})	0
α	Gradient angle (^{0})	5
a	Acceleration of a car (ms^{-2})	20
k_m	Coefficient that compensates for the apparent increase in vehicle mass due to rotating masses	1.2

By taking the denominator,

$$1 + 1630s^4 + 2843s^3 + 1803.2s^2 + 490.12s + 47.76 + (1000s^2 + 1000s + 240)K_p \qquad (13)$$

From $-\left(\frac{1630(490.12+1000Kp)-(1803.2+1000Kp)(2843)}{2843}\right) > 0$ and from $-\left(\frac{(2843(48.76+240Kp)-(490.12+1000Kp)(-798382.1502+1213000)}{-798382.1502+1213000}\right) > 0$, we obtain the range of K_p as $0.204 < K_p < 0.658$.

Fig. 6 shows the simulink model for possible cascade control of HEV that employed in this paper.

In this research, we analyse the response of the speed of car, car acceleration, and motor armature current with the reference signal input, $rv(t) = 5\ u(t)$, as a step input with zero initial value, a step time = 0 second, and a final value of 5 volts were set in the simulink model as shown in Fig. 7.

Based on Fig. 7, it indicates that the speed responses have a little overshoot (12%) and the output response of 7 from our simulation does not follow the step input that has been set to 5. This is because there are some steady state errors occured in this system. The sytem can be improved to get the desired output by adding a suitable controller to the sytem. Fig. 7 also illustrates the correct response for acceleration of the car, and the motor armature current.

4. Simulation process

4.1 Scenario description

Fig. 8 shows the illustration of a running resistance which consists of aerodynamic drag force, F_L, rolling resistance, F_{RO}, climbing resistance, F_{st}, and motive force, F, for a car moving uphill. The total running resistance, F_w, can be calculated as $F_w = F_{RO} + F_L + F_{st}$. Table 3 displays the parameters used in the simulation process. In this scenario, the mathematical equation of the nonlinear system was developed and elaborated to get the vehicle transfer function. To solve for the total running resistance, we need to find and elaborate the equation for aerodynamic drag force, rolling resistance, climbing resistance, and motive force.

The equation of rolling resistance, F_{RO} and aerodynamic drag force, F_L are

$$F_{RO} = f\,G \cos\alpha = f\,mg \cos\alpha, \quad F_L = 0.5\,\rho\, C_w\, A\, (V + V_{hw})^2 \tag{14}$$

The equation of climbing resistance, F_{st} is

$$F_{st} = G \sin\alpha = mg \sin\alpha \tag{15}$$

When car is moving uphill, the motive force will give pressure to the drive wheels, so the surplus force is used, $F - F_w$ to accelerate the car. The acceleration's equation is formed of the surplus force, car mass, m and coefficient, k_m that compensates for the apparent increase in vehicle mass due to rotating masses

$$a = \frac{F - Fw}{m.k_m} \tag{16}$$

where

$$\begin{gathered} F = (F_{RO} + F_L + F_{st}) + k_m ma \\ F = f\,mg \cos\alpha + 0.5\,\rho\, C_w\, A\, (V + V_{hw})^2 + mg \sin\alpha + k_m ma \end{gathered} \tag{17}$$

Substitute the parameter to the equation and simplify with assumption of the car needs to maintain its speed after reaching V = 60 km/h while climbing a hill with a gradient $\propto$ =5°, the equation of excess motive force, F_e is

$$F_e = F(t) - F_{RO} - F_o = 20\,V + 1800\,dv/dt \tag{18}$$

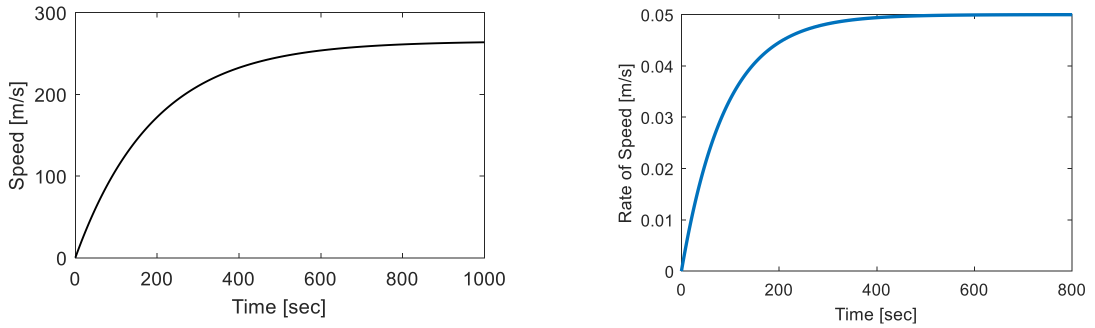
Changing into Laplace transform for both sides of Eq. (18)

$$F_e\,(s) = 20\,V(s) + 1800s\,V(s) \tag{19}$$

4.2 Result and discussion

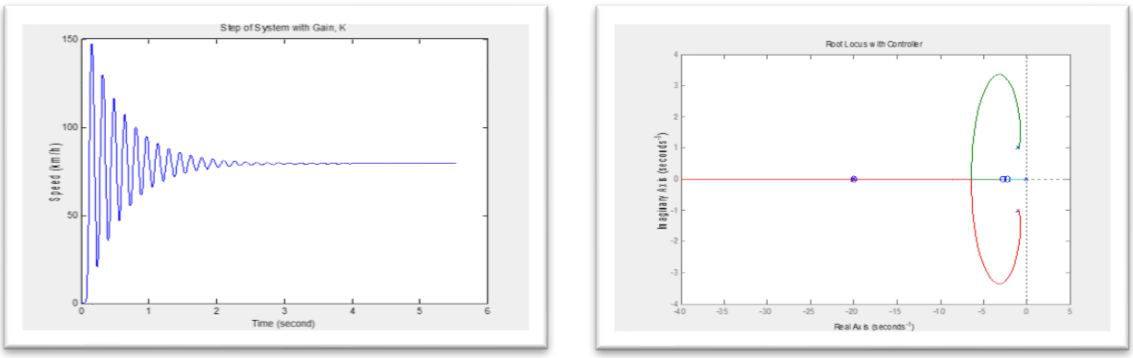
Based on Fig. 9, the system is stable due to no overshoot, smaller time constant and faster system response. Firstly, the inputs are set to different three inputs which are the step, ramp, and sine wave. While to control the speed of HEV, the outputs are set as velocity and acceleration. Then the PD, PI, and PID were designed using the block diagram of HEV with a feedback signal. The parameter's value of the block diagram was taken from (Zulkifli *et al*. 2015).

The controllers were simulated in MATLAB and Simulink. Model and the graphs for input and output were obtained. The result of the controller was analyzed according to the characteristics of transient response and steady state error. The parameter values such as rise time, overshoot,



(a) (b)

Fig. 9 Speed analysis in m/s of a car when the car is moving uphill (b) a hybrid vehicle with excess motive force of ΔF_e = 2650 N



(a) Step of system with gain, *K* (b) Root locus of the system with PID controller

Fig. 10 Hybrid vehicle system

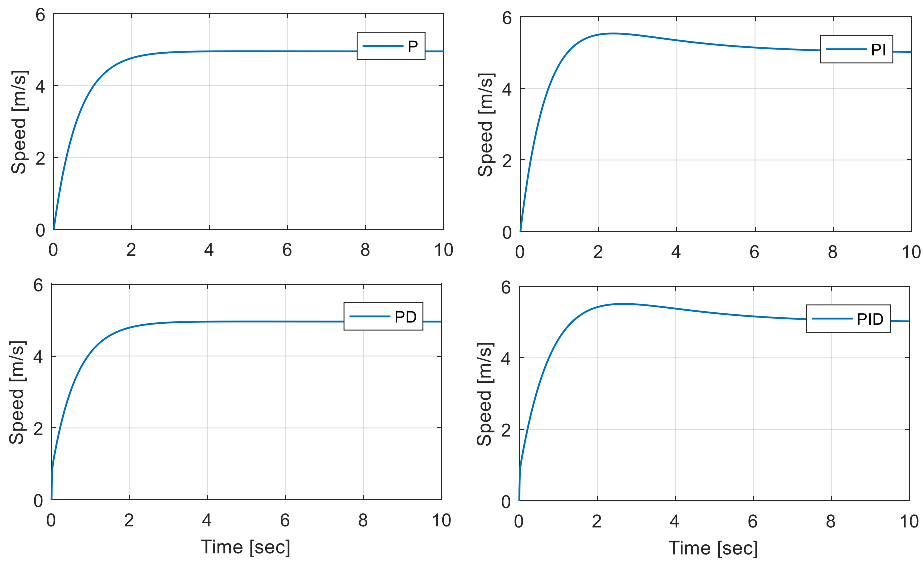
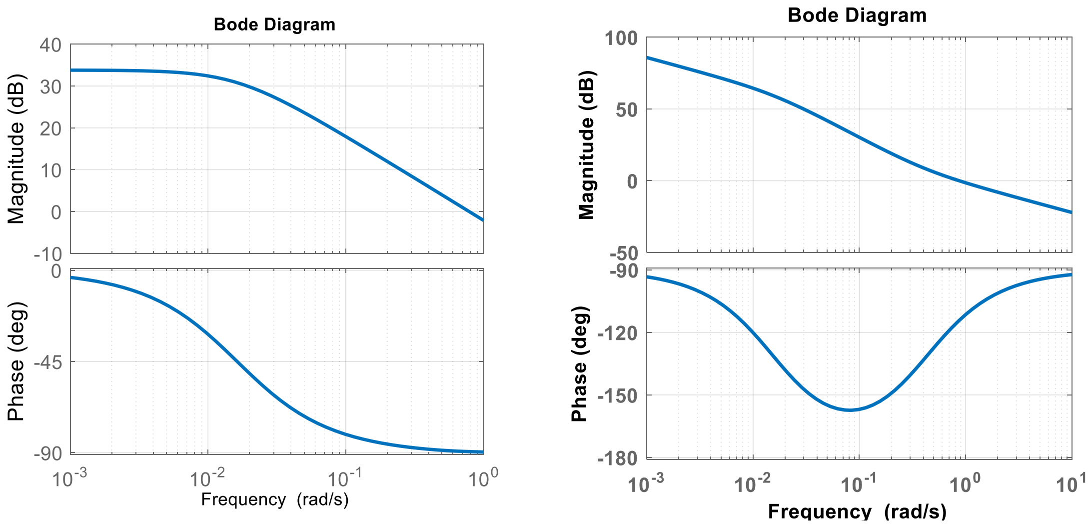


Fig. 11 Speed response for hybrid vehicle system through P, PI, PD, and PID



(a) Bode plot without controller (b) Bode plot with PID controller

Fig. 12 Hybrid vehicle system

Table 4 The controller performances

Transient response/Controller	PD	PI	PID
Rise Time (sec)	0.0786	0.0603	0.0125
Settling Time (sec)	0.904	0.27	0.334
Overshoot (%)	3.07	0.248	0
Peak	1.03	1	0.988

Table 5 The controller performances

Bode Plot Analysis	Without controller	With Controller (PID)
Gain Margin	Infiniti	Infiniti
Phase Margin	148 degrees	65.1 degrees

settling time, steady-state error were listed to compare the controllers with different inputs.

There are three types of controller which are PD, PI and PID controllers that use three types of input which are step function, ramp function and sine wave. Each of gain of PID has been set as K_p = 10, K_i = 5, K_d = 7. The gains are selected by try and error methods.

From the root locus of the system without the controller shown in Fig. 10(b), we can conclude that the system is already stable but due to the step output of the system is compensated, a controller is required to improve the stability of the system. Next we add PID controller to improve the system. As for the requirement given, a controller is added to achieve the percentage overshoot of the system to be less than 20% and the settling time is less than 3.5 second.

As we can see from Fig. 11, both of the system use a PID block and the usual PID where the overshoot of the system using the usual PID is slightly higher than the output of the system using a PID block. This is due to the effect of the filter coefficient in the PID block. Although by using a PID block, the system is more stable, the block diagram of the system with usual PID is easier to be understood due to the easily visualized basic structure of K_p, K_i and K_d gains. Also, both of the output managed to meet the requirement of the system which is the percentage overshoot (%OS) is 4.94% and the settling time is 2.69 s.

By using a PID controller, the system also managed to achieve 80 km/h as its steady state speed due to elimination of the steady state error in the existing system. This proved that the system has achieved its stability by adding a PID controller to the system. By using a PID controller, we can see that a zero is added to the system. The system is also stable due to all of the zeroes and poles lie on the left side of the axis. From the figures above, the critical gain of the system is obtained. Based on the result, the critical gain of the system is 0.699. The optimum value is 0.707 and this proves that the system oscillates less than the optimum value of the critical gain. Hence, by using the controller, the steady state of the system is at 80 km/h. We also meet the requirements of the system which is low percentage overshoot (4.94%) and fast settling time (2.69 s). Table 4 shows the comparison between PD, PI and PID controller in transient response and steady state error at step input function.

All the controllers meet the requirements which good transient response and zero steady state error. Furthermore, PID controller shows the best transient response because it has less overshoot compared to the other controllers as shown in Table 4. PD controller is not much different to PID controller because the percentage of the overshoot is less than 3% compared to PI controller which has higher percentage of the overshoot. However, there are no changing for velocity and acceleration for the other inputs which are ramp and sine wave functions by using the three controllers. The ramp and sine wave do not meet the requirements of the system. The system can be improved by using a calculated value for the gain because in this system, the gains were obtained by using a try and error method.

System without controller as shown in Fig. 12 has a phase margin of 148 degrees and the gain margin is infinite. The system is unstable. With the PID Controller, the phase margin is reduced to 65.1 degrees and the gain margin remains infinite because there is no crossover and the phase plot never reaches -180 degrees. The system is said to be inherently stable.

5. Conclusions

In conclusion, the usage of hybrid electric vehicle benefits the environment greatly compared to the conventional fossil fuel powered vehicle. Using HEV is beneficial to the environment as it consumes less fossil fuel, a result contributed by using electrical power. It is such a revolutionized application of technology as it is much more advanced compared to traditional car/engine. The efficiency should improve from time to time as the technology advances forward. In the case scenario described in this paper, the study demonstrated that the PD, PI, and PID controller designs were able to improve the speed of HEV, and root locus and bode plot analysis of the close loop stability of the system.

The controllers were designed based on the block diagram of HEV with a feedback signal by using three inputs which were unit step, unit ramp, and sine wave. The graphs for PI, PD and PID controller and bode plot for the system were obtained using the Simulink Model. The proposed controllers and inputs results were investigated. The results clearly indicated that among three different inputs, unit step gave the best transient response and reach zero steady state error compared to unit ramp and sine wave. While, PID controller performed well compared with PD and PI controller because PID has no percentage overshoot while PI has the highest percentage overshoot. Lastly, the controller design was able to obtain the desired output of the system and improve the speed performance at reasonable response and settling times. While, bode plot graph showed that the system was inherently stable.

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