Chapter 5

Worked Example of X-by-Wire Technology in Electric Vehicle: Braking and Steering

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Additional information is available at the end of the chapter

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Abstract

The chapter emphasizes on the worked example of braking system and steering system for electric vehicle. The x-by-wire technology is investigated and validated comprehensively. Brake-by-wire is considered a new brake technology that uses electronic devices and control system instead of conventional brake components to carry out braking function based on wire-transmitted information. However, the physical parameters associated with braking function cause nonlinear characteristics and variations in the braking dynamics, which eventually degrade stability and performance of the system. Therefore, this study presents the design of fuzzy-PID controller for brake-by-wire (BBW) to overcome these undesired effects and also to derive optimal brake force that assists to perform braking operation under distinct road conditions and distinct road types. Electric power-assisted steering (EPAS) system is a new power steering technology for vehicles especially for electric vehicles (EV). It has been applied to displace conventional hydraulic power-assisted steering (HPAS) system due to space efficiency, environmental compatibility, and engine performance. An EPAS system is a driver-assisting feedback system designed to boost the driver input torque to a desired output torque causing the steering action to be undertaken at much lower steering efforts.

Keywords: x-by-wire, brake-by-wire, steer-by-wire

1. Introduction

In recent times, potential energy, environment, and economic interests have stimulated motorized industry to develop and enhance efficient, clean, and sustainable vehicle, particularly, for city transportation. This new invention should not contingent on oil as a sole of energy source. Additionally, reducing engine size, replacing mechanical components by electrical devices, transferring request information electronically instead of mechanically, and designing integrated control systems are considered other targets that automotive manufactures are aiming to attain in producing new means of transportation. At that juncture, the automotive industry introduced electrical vehicle (EV), which is driven by alternative energy sources that provide magnificent means for efficient, clean, and environmentally urban transportation.

The trend technology toward electronic components and circuits coming from their technical merits not only reduces the weight of vehicles but also has the potential for a large number of integrated functions and features. Some of these new electronically operated systems are taken place under the concept of x-by-wire, which involves brake-by-wire, throttle-by-wire, and steer-by-wire. These electrical vehicle subsystems yet still undergo considerable challenging issues that need intensive study and investigation in order to find out appropriate design and powerful operated system.

This chapter presents x-by-wire technology implementation in electric vehicle. BBW is a new brake technology in which mechanical and hydraulic components of traditional brake systems are replaced by electric circuits and devices to carry out the function of braking in a vehicle by wire-transmitted information. The advantages of electronic devices such as reducing vehicle weight and increasing brake performance are considered the main purpose trends of the automotive industry toward this new brake technology. Another application known as n EPAS system is a driver-assisted feedback system designed to boost the driver input torque to a desired output torque causing the steering action to be undertaken at much lower steering efforts. Particle swarm optimization (PSO) algorithm is implemented as tuning mechanism for fractional-order PID (FOPID) controller. The aim of this controller is to track the assist current generated by lookup table. The results show the performance and efficiency of using PSO algorithm for FOPID tuning.

The motivation of this study is to enhance the safety aspects for the vehicle while attaining any desired speed. To achieve that, an optimal brake force at different road types and conditions and for different brake commands must be obtained within a reasonable time and without vehicle sliding.

2. BBW design and principle of work

The proposed design of BBW used in this study is schematically illustrated in **Figure 1**, which includes one wheel of vehicle model as seen inside the dotted box. According to the figure, the suggested principle of work of BBW is adopted which is demonstrated as follows:

Primarily, reducing (or halting) vehicle speed comes as a result of pressing down on the brake pedal by the driver. The braking pedal of BBW is usually equipped with several electronic sensors that provide redundant information about braking request. Thus, when a brake force applies to the brake pedal, three possible sensors are usually utilized to measure required braking force: (1) pedal displacement sensor (measures pedal displacement as a result of applying force on the pedal) [3], (2) force sensor (measures applied force on brake pedal), and (3) pressure sensor (measures applied pressure to brake pedal) [5]. In addition to that, the brake pedal of BBW may not necessarily be as the general brake device, rather than it could be a hand-adjacent device placed at the steering wheel that enables driver to apply brakes with

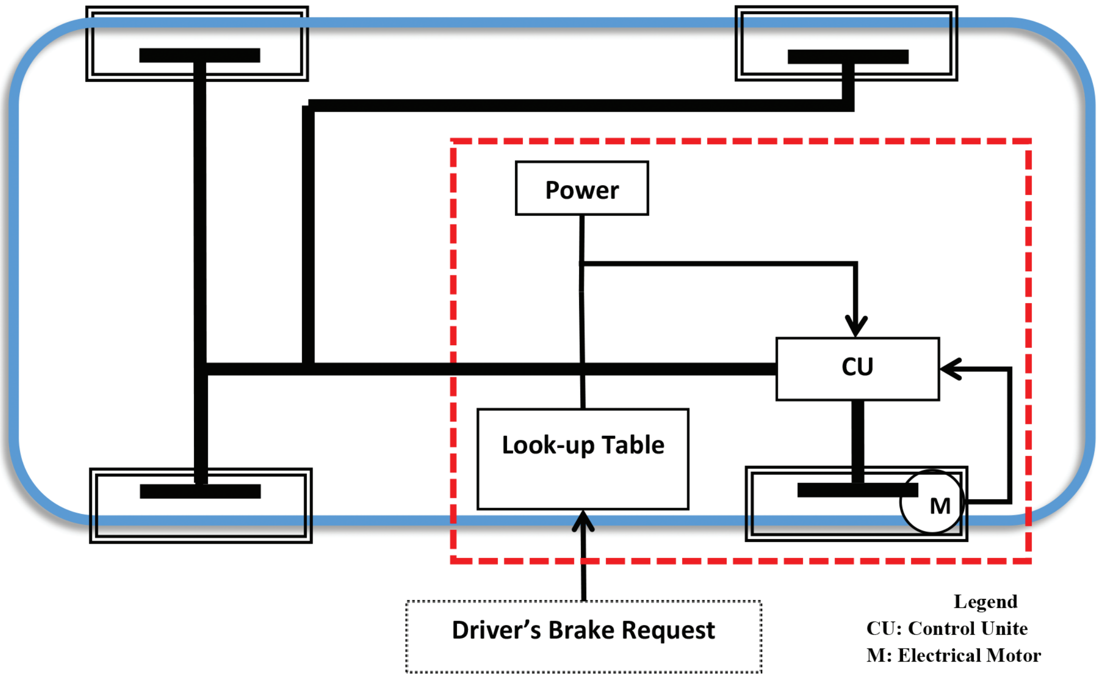

Figure 1. Proposed BBW architecture for one-wheel brake model.

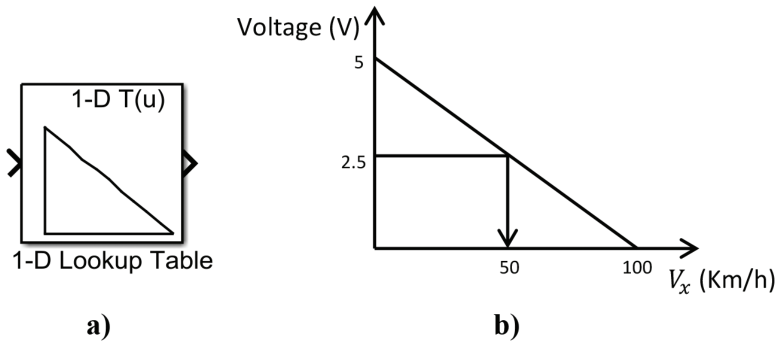

Figure 2. Lookup table of the input brake force. (a) Tool box. (b) Vehicle speed-voltage source.

hand movement as suggested in [5]. However, since the focus of this study is to design control strategy for braking action, it is assumed that braking request is already measured and available in the form of voltage source as adopted by Mingfei's design [1]. Therefore, the chosen voltage source of this study exists within a range of 0–5 V in which 0 V relates to released brake pedal and 5 V relates to fully pressed pedal. This voltage range is formulated in such a way that brake pedal input, which is in the form of voltage source, matches the desired vehicle speed by using 1D lookup table as shown in **Figure 2**. This lookup table enables a range of inputs that correspond to [0–5] Volts which in turn this range corresponds to the vehicle speed range [0–100] Km/h; for example, if the input brake pedal corresponds to 2.5 V, the relative required vehicle speed will be 50 Km/h as illustrated in **Figure 2(b)**. Nonetheless, the relative values of vehicle speed are changeable according to initial vehicle speed (vehicle speed before braking action), whereas voltage range remains constant all the time and has the capability to correspond to any given vehicle speed by updating vehicle initial speed. For instance, if the initial vehicle speed is set to 50 Km/h, the voltage range [0–5] V will correspond to the vehicle speed [0–50] Km/h as explained in **Figure 2(b)**.

Upon determining the required brake request, the braking command is then sent to the control unit (CU) via wires as shown in **Figure 1**. The CU located at the wheel after that determines exactly the control signal that must be transmitted to the brake actuator unite in order to slow down or stop the vehicle. Nevertheless, the control signal of the CU is considered the input for the electrical actuator (permanent magnetic DC motor) where this signal takes the form of the desired braking torque. Consequently, electronic actuator of the brake unit operates based on the desired braking torque which in turn decreases (or stops) vehicle speed according to the desired speed.

The control unit, however, is updated through feedback control strategies where wheel speed is considered the input to the feedback control system according to applied control strategy. Moreover, the interaction between brake pedal, control unit, electronic actuator, and wheel as well as vehicle speed is completely accomplished by wires. In view of that, vehicle brake system is designed and structured.

3. Control system design

The suggested control brake system employs fuzzy-PID controller to obtain the desired vehicle speed based on tuning of traditional PID controller. The applied control algorithm must be able to function to any required vehicle speed that is determined by the driver. The proposed control system design applied to handle this task is schematically illustrated in **Figure 3**.

As depicted in **Figure 3**, the system input (brake pedal force) is determined by the driver in the form of voltage signal ranging from 0 V (refers to release pedal) to 5 V (refers to fully pressed pedal). Upon determining the required vehicle speed by lookup table, the speed signal is then sent to the control unit which is based on either PID or fuzzy-PID controllers. The implemented control algorithm then determines the desired voltage source that must be transmitted to electrical actuator in order to generate required braking torque. The wheel speed after that is decreased by applying brake torque causing modification in overall system dynamics which in turn leads to vehicle speed deceleration.

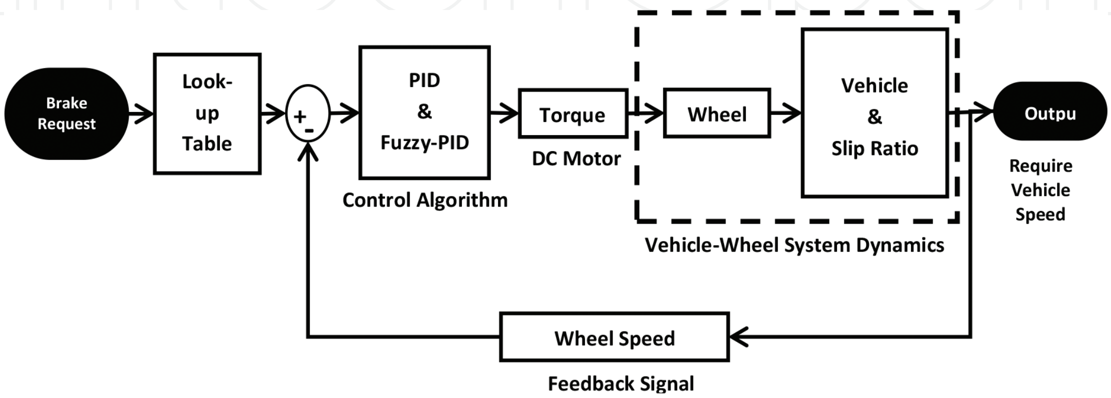

Figure 3. BBW control system design.

The error signal transmitted into control algorithm, however, is determined by the difference between input signal (desired vehicle speed) and feedback signal (wheel speed) which is given by the following relationship:

$$\text{Error} = \text{required vehicle speed (input signal)–measured wheel (feedback signal)} \tag{1}$$

The control strategy used to deliver the desired vehicle speed is based on maintaining peak slip ratio within the maximum adhesion characteristic range [0.02–0.35]. Locating peak slip ratio within the maximum friction characteristic initiated from applying ideal and accurate brake torque is capable of deriving proper and acceptable vehicle-wheel speed relationship.

The control objective of both controllers is to decrease vehicle velocity to the desired vehicle speed (5 Km/h) while maintaining slip ratio within its maximum range [0.02, 0.35]. Besides, the control algorithms are designed to operate braking action on dry asphalt road type, whereas other road types and conditions (such as wet asphalt, wet and dry cobblestone, and concrete) are applied to examine and investigate whether the controllers can handle characteristic variations of the system or not.

a) PID controller design

A cascade-form PID controller is designed based on manual tuning method, where the three terms of PID controller (proportional, integral, and derivative) are employed. Accordingly, the overall controller output is considered the sum of the contributions of the individual PID terms which is further expressed in Eq. (1), where $u\,(t)$ is the PID control signal, $e(t)$ is the error signal, and K_p, K_i, K_d are the proportional gain, integral gain, and derivative gain, respectively.

$$u\,(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t) \tag{2}$$

b) Fuzzy-PID controller design

Although PID manual tuning method provides stable output response, PID controller does not achieve the desired control specifications since the dynamics of the system has nonlinear and variant parameters which in turn degrade system performance. Therefore, fuzzy logic controller has been introduced to PID controller in order to improve the response as well as to enhance system performance based on fuzzy-PID tuning. In fact, fuzzy-PID controller is considered as a link between traditional control which has well-established theory and intelligent control that conquers traditional control problems like nonlinearity.

Fuzzy-PID scheme, in addition, can employ different structures and forms based on the input to the fuzzy controller on the one hand and on the arrangement of PID parameters and their locations with respect to fuzzy controller on the other hand. Nonetheless, these different structures are possible in the context of knowledge description and explanation, whereas they should be examined with respect to their functional behavior. The proposed structure of this study is schematically illustrated in **Figure 4**, which generates incremental and absolute fuzzy-PID signal based on direct action to tune PID parameters through fuzzy inference.

As shown in **Figure 4**, the error and rate change of error are considered as the time-varying inputs to the fuzzy logic controller (linguistic inputs), whereas tuned (proportional, integral,

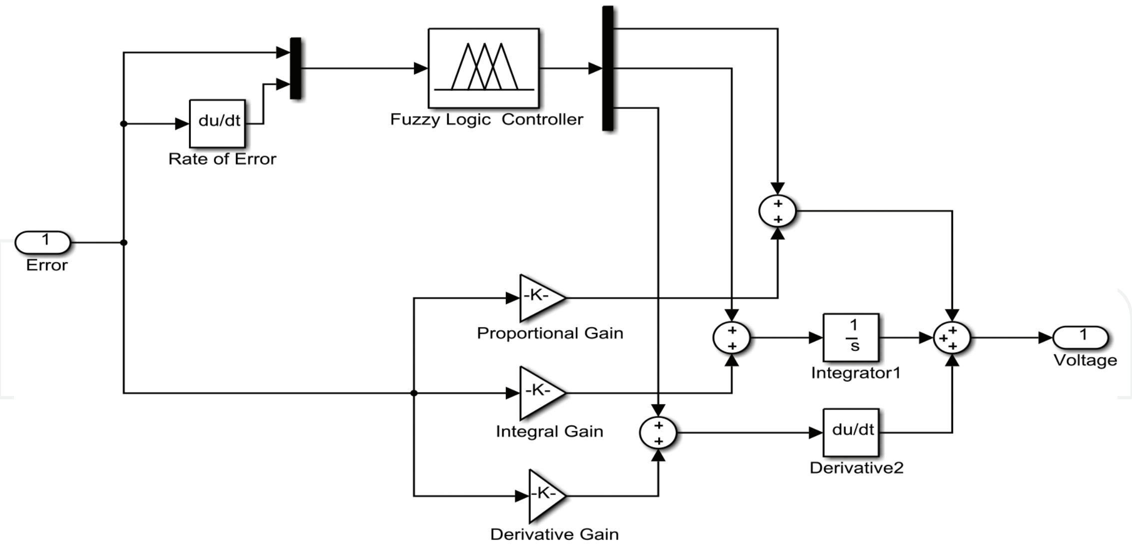

Figure 4. Fuzzy-PID controller (MATLAB Simulink scheme).

and derivative) gains are the output of the controller (linguistic outputs). Regarding linguistic inputs, there are other choices (such as integral of error) that could also be used as input variables, yet the selection variables make good intuitive sense, particularly as the input error is naturally engaged in the control problem of regulating process output around specific set point. The controller input variable however must have proper information available to provide good decision to derive vehicle speed into the desired speed to achieve high-performance operation based on fuzzy-PID tuning. On the other hand, the linguistic output variables are expressed as tuned (proportional, integral, and derivative) gains where the output values of these tuned gains are implemented to tune the conventional PID controller as shown in **Figure 4**.

The adopted linguistic values and their corresponding abbreviations in conjunction with their linguistic variables are summarized in **Table 1**.

This table provides a language to express the control decision-making process in the context of established input–output framework. For example, the statement “error is negative” can be referred to the situation where the vehicle speed curve exists above the desired speed and needs more braking force. In contrast, the statement “error is positive” can be referred to the

	Linguistic variables	**Linguistic values**	**Linguistic value abbreviation**
Input	Error	Positive, zero, and negative	P, Z, and N, respectively
	Rate change of error		
Output	Proportional gain	Positive, zero, and negative	P, Z, and N, respectively
	Integral gain	Zero, positive small, and positive large	Z, PS, and PL, respectively
	Derivative gain	Zero, positive small, and positive large	Z, PS, and PL, respectively

Table 1. Linguistic variables alongside their linguistic values and abbreviations.

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	Error			
Change in error		**N**	**Z**	**P**
	N	N	N	Z
	Z	N	Z	P
	P	Z	P	P

Table 2. Fuzzy rule base for proportional gain.

	Error			
Change in error		**N**	**Z**	**P**
	N	Z	Z	PS
	Z	Z	PS	PL
	P	PS	PL	PL

Table 3. Fuzzy rule base for integral and derivative gains.

situation where the vehicle speed curve exists below the required speed curve and needs to decrease applying torque to obtain the desired vehicle speed.

Upon determining linguistic quantification, the rule base of the control system is set to capture expert's knowledge on how to tune the system and describe applied control strategy. Since there are two input variables and three output variables, the possible rules can at most reach to 3^2 (9) rules. These rules are listed in a tabular representation form as shown in **Tables 2** and **3**.

The meaning of the above linguistic description is quantified via membership function, whereas triangular shape is considered in this study for all inputs as well as all outputs for its simplicity, linear grade distribution, and fairly limited availability of the relevant information about the linguistic terms. In due course, the selected membership functions and their associated universe of discourse as well as linguistic values of this study are revealed in **Figure 5**. The designed membership functions are overlapped, and the height of the intersection of each two successive fuzzy sets is ½.

Since a clear picture on the linguistic variables, rule base, and membership functions have been explained, we move to the important issue of how the exact fuzzy controller works. In doing so, the first component of fuzzy controller is fuzzification process which is the act of acquiring the value of the input variable and defining numeric magnitudes for the membership function that are set for that variable. After that, the inference mechanism takes the action through two steps:

1. Matching the premise associated with all the rules to the controller inputs to determine which rules apply to the current condition. In other words, each rule in the rule base has different premise membership functions on the one hand and function of error and change

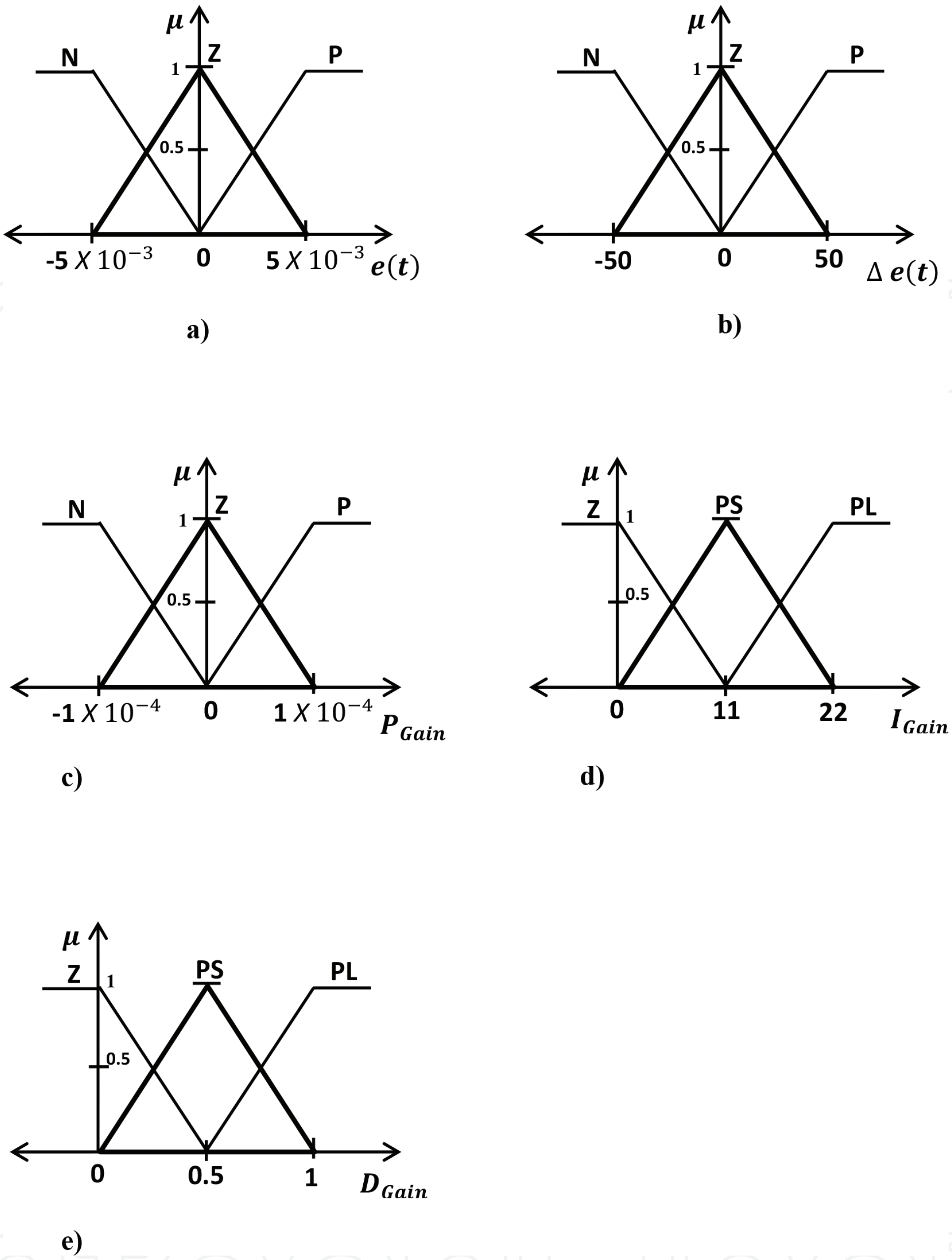

Figure 5. Membership functions and their corresponding values. (a) Membership functions and their values for error input $e(t)$. (b) Membership functions and their values for change of error $\Delta e(t)$. (c) Membership functions and their values for proportional gain. (d) Membership functions and their values for integral gain. (e) Membership functions and their values for derivative gain.

in error on the other hand; therefore, the quantification of the certainty that each rule base applies to the current condition can be obtained upon providing specific values for the error and change in error.

2. Determining the conclusion (what the control action to take) that should be applied by using selected rules to relate to the current situation. This conclusion is classified with a fuzzy set that signifies the certainty that the input to the plant should undertake various values.

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Therefore, as long as the input to the inference process (set of rules) is on, its corresponding output operates which is in the form of implied fuzzy sets. However, these implied fuzzy sets are then converted to crisp values (numeric values) by combining their effects to give the most certain controller outputs. The defuzzification process is obtained by bisector method which divides the area by a vertical line into two equal subregion areas. In addition, the mean of maximum and the largest of maximum are also applied to the system for the purpose of validity in which both of them provide close output result.

4. Simulation result and analysis

The vehicle model and controller algorithms are examined in MATLAB software. For the results of investigation and analysis, the initial vehicle-wheel speeds are set to 100 Km/h, whereas the desired vehicle speed is set to 5 Km/h. The reason of choosing 5 Km/h as the desired vehicle speed instead of zero Km/h is because slip ratio magnitude goes to infinity as vehicle speed approaches zero which in turn leads to inappropriate output behavior. On the other hand, selecting the desired low speed helps to examine maximum slip ratio that controls algorithm derives; hence, the ability to evaluate control performance and output response of the system will be more effective and visible.

The output responses of fuzzy-PID controller for dry asphalt road type are presented in **Figure 6**, whereas **Figure 6(a)** demonstrates the output responses of vehicle-wheel, and **Figure 6(b)** shows the output responses of slip ratio. Yet, the output responses of traditional PID controller are imposed in the same figure (**Figure 6**) to illustrate the comparison between traditional PID controller and fuzzy-PID controller.

As shown in **Figure 6(a)**, both controllers could derive stable output response smoothly. However, the output performance of the fuzzy-PID controller is much better than conventional PID controller since PID controller derives large steady-state error on the one hand and takes long time (approximately 15 seconds) to approach the desired vehicle speed (5 Km/h) on the other hand. In contrast, fuzzy-PID controller overcomes these problems being provided better output performance with zero steady-state error. As a result, fuzzy-PID controller could obtain the required vehicle speed within approximately 9 seconds which in turn assists to reduce stopping vehicle time 60% as compared to PID controller and more importantly the ability of fuzzy-PID controller to eliminate steady-state error to zero. Therefore, fuzzy-PID controller shows superior and outstanding controller.

On the other side, the output response of slip ratio associated with vehicle-wheel speed as shown in **Figure 6(b)** reveals smooth output response particularly before attaining the desired output speed. As depicted from the figure, the maximum slip ratio is the same for both controllers which approximately equals to 0.027. Though the maximum slip ratio magnitude seems a small value, the main cause for vehicle-wheel deceleration is considered since friction force between road surface and wheel surface principally depends on the slip ratio magnitude even though if the slip ratio possesses very small magnitude that may reach to mili-slip ratio.

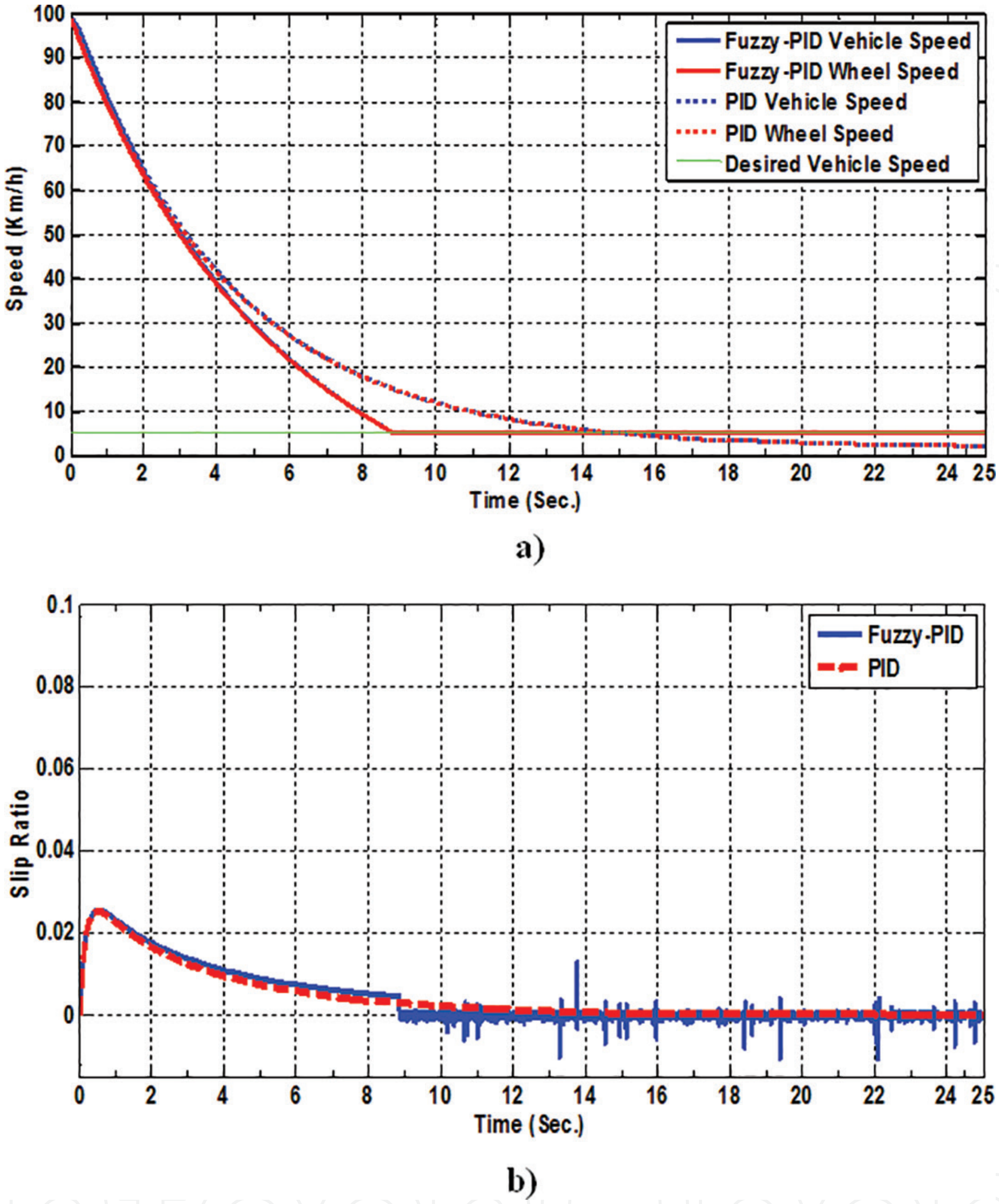

Figure 6. Output responses of fuzzy-PID controller for dry asphalt road type. (a) vehicle-wheel speed. (b) Slip ratio.

This fact is clearly observed from **Figure 6(b)**, especially within the time interval [2, 4] seconds, where the slip ratio of fuzzy-PID controller output response (blue line) has larger magnitude than PID output response (red line) by mili-values. This slight divergence that fuzzy-PID created, by trivial increases in slip ratio magnitude, leads to dramatically improve and enhance output response by decreasing vehicle stopping time 60% as compared to conventional PID controller.

As shown in the table, the slip ratio increases as the adhesion characteristic decreases. For instance, the maximum adhesion characteristic of dry asphalt is about 1.18 which is considered a large value; hence, its magnitude-derived slip ratio is small (0.027 for PID controller and 0.028 for fuzzy-PID controller). In contrast, the wet cobblestone adhesion characteristic has a small value (0.34), and therefore its derived slip ratio has a large value (0.26 for PID controller and 0.33 for fuzzy-PID controller).

Road-type controller-type	Max. adhesion char.	PID	Fuzzy-PID
Asphalt (dry)	1.18	0.027	0.028
Asphalt (wet)	0.8	0.035	0.035
Concrete	1.1	0.028	0.029
Cobblestone (dry)	1	0.085	0.087
Cobblestone (wet)	0.34	0.26	0.33

Table 4. Maximum derived slip ratios for PID and fuzzy-PID controllers.

The other significant notice that can be observed from **Table 4** is the maximum slip ratio of fuzzy-PID controller which is slightly larger than the one derived by PID controller, meanwhile fuzzy-PID performance is considered superior and much better than PID performance as demonstrated above. Accordingly, the slip ratio magnitude is considered extremely important in braking operation even though if it possesses very small value since braking process depends on the road-wheel surfaces. Nonetheless, a certain magnitude range of slip ratio is permissible where if its magnitude exceeds that range, the operating system may undergo unwanted behavior (wheel locks up or losses the control) particularly if it goes to a large value (more than 0.5).

It is also concluded that the mathematical derivation and its investigation of the brake system model are accurate and valid particularly because the examination and exploration of the output results are entirely identical to the analysis and investigation of each system's variable as demonstrated in Section 3. Besides, the suggested feedback control signal which is based on wheel speed was able to deliver detailed and thorough information about the status of braking system which assists to update system's variable effectively.

5. EPAS system

EPAS presents the continuing future of power-assisted steering technology for passenger vehicles and has already been started to appear in high-volume, lead-vehicle applications; more flexible than traditional hydraulic power-assisted steering (HPAS) system, the fact of EPAS is to supply steering assistance to the driver utilizing an electrically controlled electric motor. EPAS is a classic exemplary case of a smart actuator operating under feedback control. It can provide necessary assist torque in different car speeds and different driver torques [6]. It has been reported in [6] that among electric power-assisted steering (EPAS) system available for passenger cars, EPAS systems provide the best fuel consumption [7–9]. The plot shown in **Figure 7** indicates that EPAS systems have the lowest fuel consumption in comparison to hydraulic power-assisted steering (HPAS) system with savings in excess of 3.0% in average and up to 3.5% in city driving [6].

According to the steering torque, automobile speed as well as road conditions, the system can provide the real-time assistant torque through assist motor to help driver steering and make steering easier and gentle, which guarantees that the driver has the best steering feel in the variety of operating conditions. At present, the design for the assist motor control have mainly two methods: the first one is motor current loop control based on classical control theory and the other one is

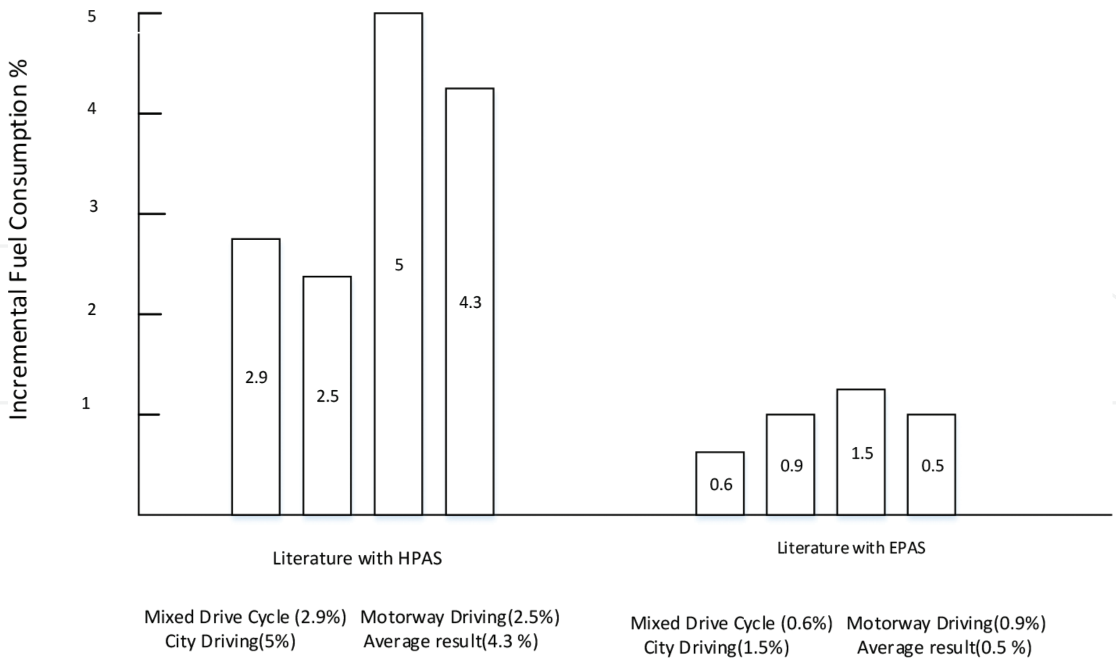

Figure 7. Typical EPAS fuel consumption saving.

the state-space model H_∞ control or sliding mode control based on modern control theory [10]. Literature [11] using the motor current tracking control based on conventional PID achieved good results. But the system was not designed for different car speeds. Literature [12] established an EPAS mathematical model, and the simulation results showed that the strategy could achieve the desired characteristics, but the vehicle speed was not taken into account; the results had certain limitations [13, 14], using a sliding mode control that improved the system stability and anti-disturb capability but that increased the complexity of the control system, which set higher requirement of the computing power to the control ship. That is not beneficial to the promotion of products.

The aim of this study in EPAS is to control the electric motor to supply the appropriate assist torque to decrease the driver's steering effort in various speeds. The EPAS control must ensure the generation of the desired assist torque, a stable system with a large amount of assistance. The most important issue is electric motor tracking precisely the target current. To develop the electric motor current tracking performance, particle swarm optimization (PSO) algorithm is applied as tuning mechanism for fractional-order PID (FOPID) controller.

6. System modeling

The EPAS includes a torque sensor, which senses the action of the driver along with the action of the automobile; an ECU, which performs calculations on assisting force based on signals from the torque sensor; a motor, which creates turning power based on the output from ECU; and a reduction gear, which increases the turning force from the motor and transfers it to the steering system and pinion and rack (**Figure 8**).

The parameters associated with the rack model are M_r (steering tie rod mass), B_r(steering tie rod damping coefficient), R_s(radius of pinion steering), and K_r(tire spring rate) (**Table 5**).

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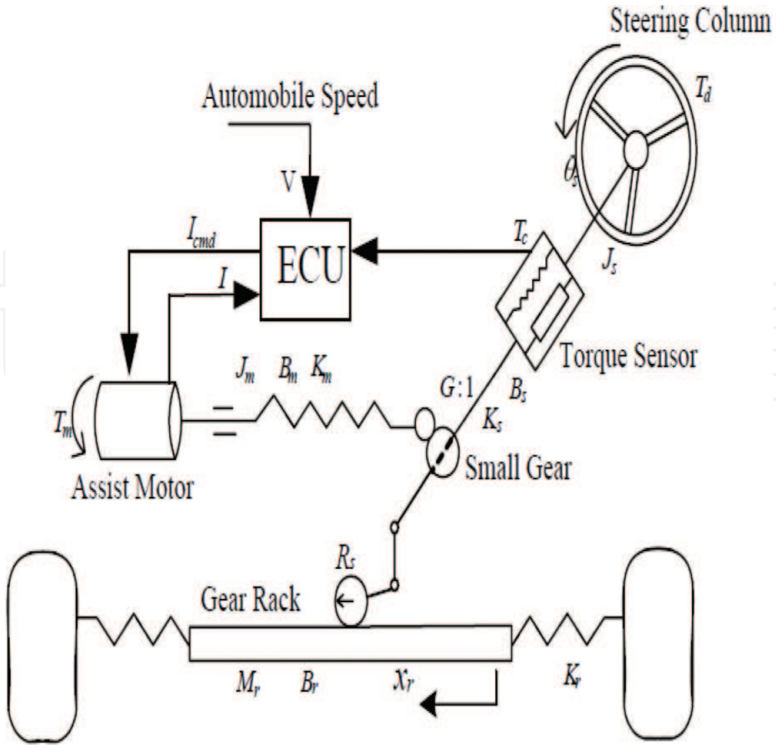

Figure 8. EAPS dynamic model.

Parameters	Symbols	Value	Units
Driving wheel moment of Inertia	J_s	0.04	$k_g.m^2$
Driving wheel damping	B_s	0.362	$N.m.s.rad^{-1}$
Pinion radius	R_s	0.0078	m
Rack and wheel assembly mass	M_r	32	K_g
Viscous rack damping	B_r	650.5	$N/\left(\frac{m}{s}\right)$
Motor gear ratio	G	16.5	
Motor stiffness	K_m	125	$N.m.rad^{-1}$
Motor inductance	L	0.0015	Henry
Motor resistance	R	0.15	Ohm
Motor torque constant	K_a	0.02	$N.m.s.rad^{-1}$
Motor EMF constant	K_b	0.02	$v.s.rad^{-1}$
Motor moment of Inertia	J_m	0.000452	$k_g.m^2$
Motor damping	B_m	0.003339	$N.m.s.rad^{-1}$
Steering column stiffness	K_s	115	$N.m.s.rad^{-1}$
Tire spring rate	K_r	91,061	N.m

Table 5. Parameters of EPAS system [14, 15].

7. EPAS controller

The function of ECU is to collect the torque sensor and the vehicle speed signal, select a suitable motor target current by an assist characteristic curve, execute a control by comparing with the feedback actual current, and then drive the DC motor.

8. Fractional-order PID (FOPID) controllers

Fractional-order PID (FOPID) controller denoted by $PI\lambda D\mu$ was proposed by Igor Podlubny [16] in 1997. It is an extension of conventional PID controller where λ and μ have fractional values. **Figure 9** shows the block diagram of FOPID controller. The fractional-order PID (FOPID) controller is a generalization of the PID controller. The transfer function of the controller is written by the equation below:

$$C(s) = K_p + \frac{K_i}{S^{\lambda}} + K_d S^{\mu} \tag{3}$$

where K_p, K_i, and K_d are the proportional gain, integral gain, and derivative time constants, respectively, and λ and μ are fractional powers.

where μ and λ are an arbitrary real numbers. Taking μ = 1 and λ = 1, a classical PID controller is obtained. Thus, FOPID controller generalizes the classical PID controller and expands it from point to plane as shown in **Figure 10**. This expansion provides us much more flexibility

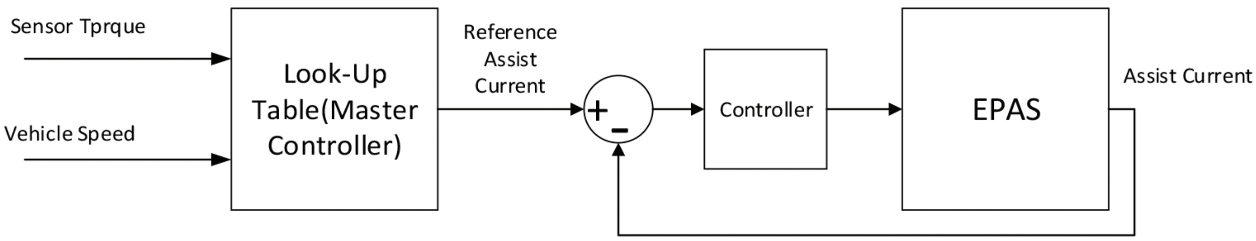

Figure 9. Fractional-order PID controller.

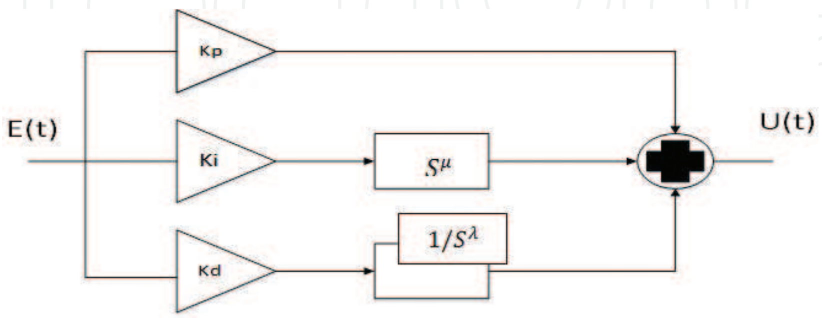

Figure 10. Control strategy.

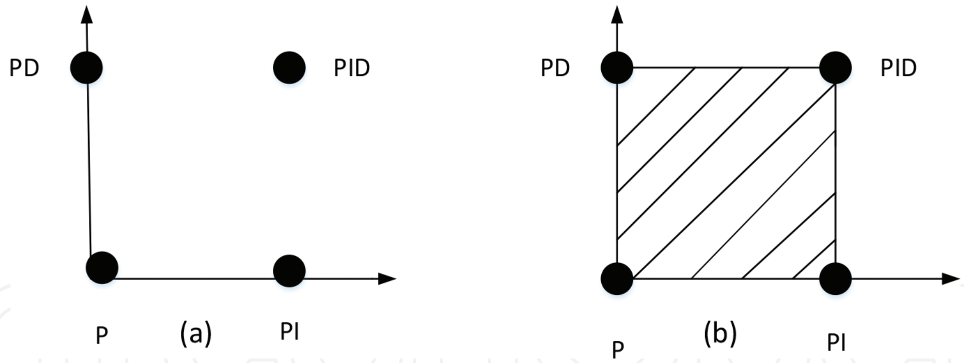

Figure 11. (a) Classical PID controller and (b) FOPID controller.

in designing PID controller and gives an opportunity to better adjust the dynamics of control system. This increases the robustness of the system and makes it more stable. However, with increase in parameters to be tuned, the optimization problem associated with the system becomes more difficult [17]. For achieving a certain performance, it is desired to develop a systematic algorithm for the FOPID optimization as shown in **Figure 11**.

9. Simulation results

Figure 12 shows an open-loop response of system, as depicted in the figure below, that motor current cannot follow the step unit. The close-loop unit step response of EPAS system using classical PID controller and PSO-FOPID are shown in **Figure 13**.

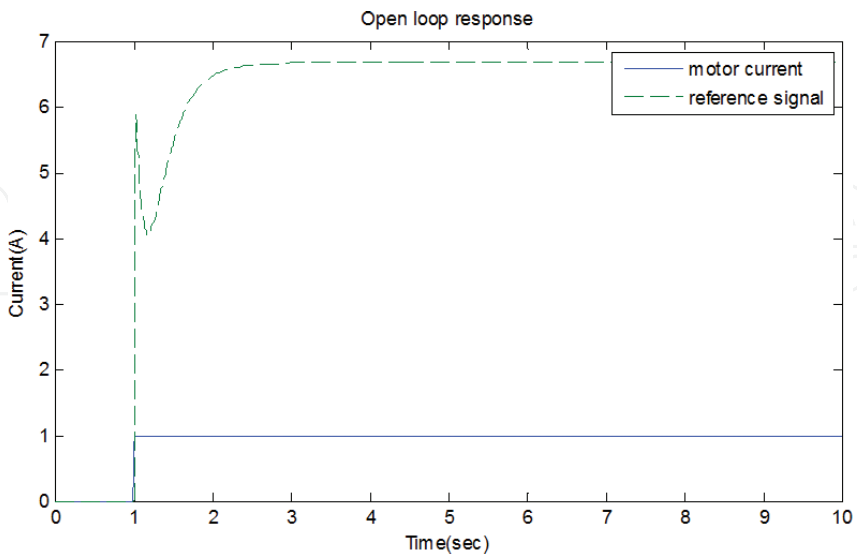

Figure 12. Unit step response of EPAS open-loop system.

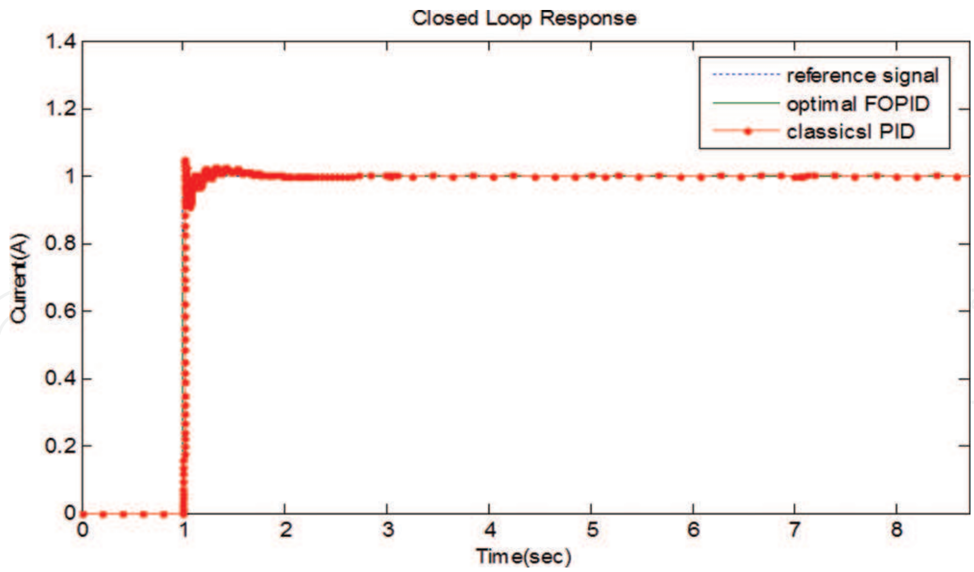

Figure 13. Unit step response of EPAS system using classical PID and optimal FOPID.

10. Controlled system in different speeds and different driver torques

Figure 14 shows three signals (i) motor current tracking of the look-up table, (ii) driving wheel input torque and (iii) the electric motor output current. The vehicle speed is 20km/h while the driver input torque is represented as a sine wave of 9 N.m amplitude.

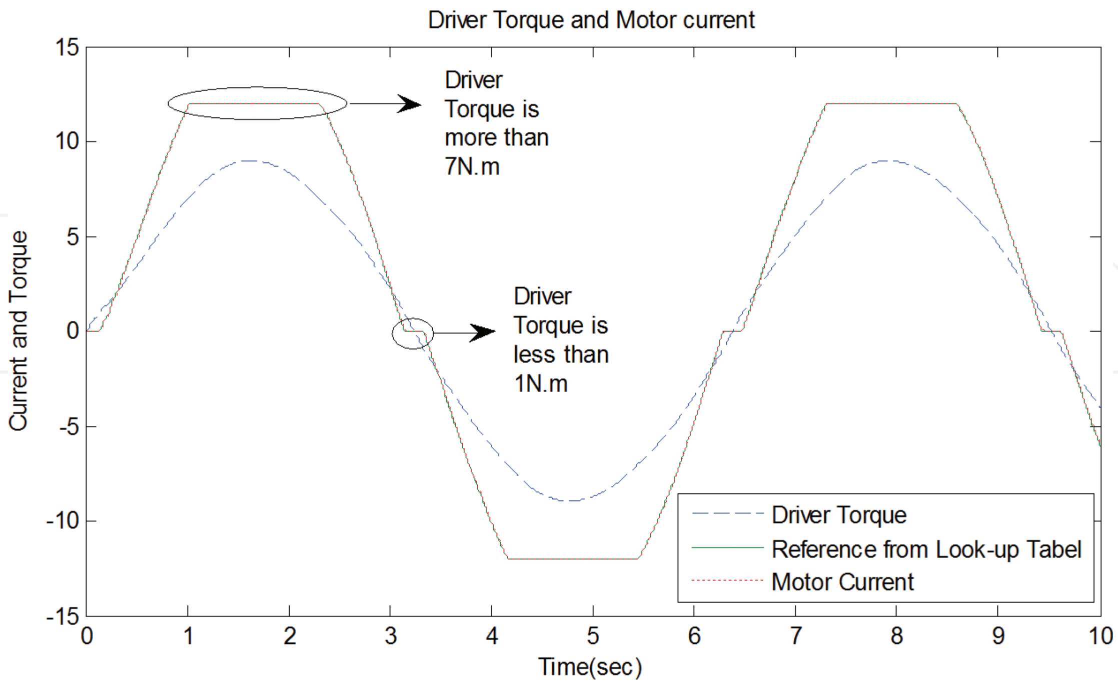

Figure 14. Driver torque and motor current in 20 km/h.

When the input torque of driving wheel T_d is less than the threshold value $T_{d0} = 1N.m$, motor does not provide power, so the assist current would be zero, when T_d is between $T_{d0} = 1N.m$ and $T_{dmax} = 7N.m$, motor current has a rising with T_d, and it depends on the car speed. When T_d is above T_{dmax}, the motor output is a constant torque.

11. Conclusion

In this study, a design of fuzzy-PID controller for BBW system is presented. In addition to that, a design structure for BBW is proposed which helps to elaborate a principle of work of the suggested BBW system. The braking mechanism and operation of BBW system are grasped and realized by obtaining mathematical derivation of the brake system based on quarter car model. Two controller algorithms based on PID and fuzzy-PID controllers are then implemented to check the validity of mathematical derivation on the one side and to operate braking mechanism of BBW on the other side. The simulation result which is conducted on different road types and conditions shows that fuzzy-PID controller is a superior and outstanding controller as compared to PID controller, where the fuzzy-PID controller assists to reduce stopping vehicle time 60% and the most important thing is the ability of fuzzy-PID controller to improve the system performance by eliminating steady-state error to zero. Besides, the result analysis and investigation demonstrate that larger adhesion characteristics lead to produce larger brake force which in turn assists to reduce vehicle stopping time.

For EPAS system, FOPID (fractional-order PID) controller has been presented, and it was tuned to control the motor current. All simulations for the whole EPAS system are implemented by MATLAB/Simulink software showing a comparison of classical PID and optimal PID tracking performance. PSO algorithm has been implemented to find optimal values of FOPID parameters. From the simulation results, it fulfills the control objectives and achieves good assistant in different speeds.

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