Implementation and Control Logic Design of Intelligent Electric Power Steering System

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Abstract

In this paper, an intelligent electric power steering system is proposed to replace a traditional hydraulic power steering system and implemented in a real light hybrid electric vehicle. An intelligent fuzzy control algorithm is applied to yield basic assist logic, return compensation logic, damping compensation logic, and inertia compensation logic in an assist steering system. According to steering wheel angle and vehicle speed, the proposed fuzzy inference logic can provide needed assist motor current. Under experts' knowledge of fuzzy control, the electric power steering system can satisfy smooth driving. In addition, four driving modes are designed to complete the control strategy. Different driving modes have corresponding fuzzy inference strategies to complete the assist and compensation logic. Finally, the intelligent electric power steering system with a new 12V/500W EPS motor is applied in a real light hybrid electric vehicle. Experimental results demonstrate that the proposed method is reasonable and feasible.

Keywords: Electric power, assist steering, fuzzy control

1 Introduction

In past years without power steering technique, although large reduction ratio can alleviate the driving torque of drivers, it is still very tiring in fact. Thereafter, hydraulic power steering (HPS) improves this problem. In a hydraulic power steering system, driving a steering wheel is to control a pressure valve, which causes straight line motion of a rack mechanism to change tires direction through link sticks. However, environmental consciousness has been paid attention in nowadays with technique progress. Even though the HPS possesses large power and smooth output, there are still some drawbacks, such as (1) Pipes may leak. (2) Hydraulic oil may deteriorate since rising temperature when pipes and hydraulic oil rub against. (3) Check and change power steering wheel oil on a regular time. (4) Pipes are complex. (5) A hydraulic pump, a hydraulic oil storage tank, and pipes, etc, increase weight and occupy space. (6) Extra engine power is needed to drive a hydraulic pump, i.e., oil consumption will be increased. (7) A holding pressure is necessary when a vehicle moves on a straight line.

Electric power steering (EPS) does not posses above drawbacks of HPS. Additionally, there are some advantages, such as, (1) According to different driving modes, different assist power can be provided. (2) The assist motor only works in turning assist. In an EPS system, the motor is mounted on a steering column. Motor torque can be amplified and delivered by a gear box in order to alleviate drivers' torque.

In past years, there are many literatures about the EPS system. Generally, there are two research topics. The first is motor controller design or EPS mechanism design. For example, a look-up table method with fuzzy control and a traditional PID controller were proposed to achieve EPS motion [1-6]. The second is the EPS strategy analysis, which is also the priority in this paper. In general, the EPS control strategy includes the basic assist logic, the damping compensation logic, the return compensation logic, and the inertia compensation logic [7-11]. The main steering strategy is the basic assist logic, other compensation logic are auxiliary to compensate insufficient return, excessive return, and heavy steering since drive the steering wheel very quickly. Each compensation logic is independent and there is a corresponding look-up table. Input signals include the vehicle speed, the steering wheel angle, the steering wheel angular velocity, the steering wheel angular acceleration, and the drivers' torque. It can adjust compensation gains immediately to complete EPS assist characteristics [10].

In [11], an intelligent fuzzy neural network was applied to achieve the basic assist logic. However, its structure is complex and other compensation logic was not considered. Note that above literatures do not discuss a case without vehicle speed, i.e., the automatic return torque does not exist. Moreover, most literatures focus on simulations or experimental real-time platforms. Experimental results of a real vehicle are short.

In this paper, an intelligent electric power steering (IEPS) system is presented. This paper focuses on EPS strategy analysis. Based on the fuzzy inference mechanism, the basic assist logic, the damping compensation logic, the return compensation logic, and the inertia compensation logic are integrated. An advantage is that fewer memories can be occupied than those traditional look-up tables for different compensation logic. Otherwise, the fuzzy control strategy is smoother and more human than those used look-up tables. In this research, let steering wheel angle and vehicle speed be inputs. Another advantage is that less cost will be obtained than other strategies applying torque sensors. Finally, four operation modes including the stop mode, the maintain mode, the assist mode, the return mode are applied to complete the EPS system. Through a real vehicle test, it demonstrates that the goal of EPS is achieved.

2 EPS system description

According to the motor mounted location, the EPS system can be divided into three types, which are a column assist type, a pinion assist type, and a rack assist type, respectively. There is serious noise request in the column assist type since the type is closest to drivers than other two types. Oppositely, the column assist type is farthest to the engine and chassis than other two types. The request of water and heat proof can be reduced. The pinion assist type is better than the column assist type in shock and noise. An advantage of the rack assist type is that the assist motor can be mounted on any locations of the rack. Therefore, the rack assist type has the elasticity of mechanism integration in chassis. In applications, the column assist type is popular and small power nowadays. For this reason, this research is based on the column assist type.

2.1 EPS hardware system structure

Figure 1 shows the hardware structure of the EPS system. Two sensors which are an angle sensor and a speed sensor are applied to detect the steering wheel angle and the vehicle speed, respectively. The two sensors return feedback signals real-time to the EPS controller for the assist strategy analysis. Through the closed-loop control of the assist motor, the assist motor can provide desired output torque. Thus, the produced motor torque combines with the driver torque to drive the rack.

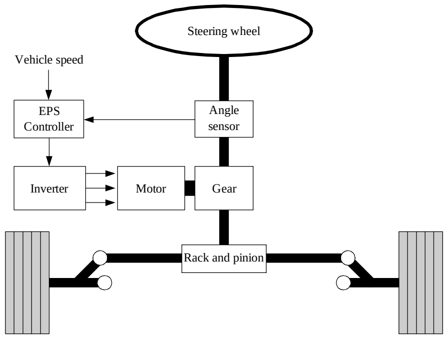


Figure1: EPS hardware structure

2.2 EPS System model

An EPS dynamic model can be represented as Fig. 2. According to the Newton motion law, the dynamic equations of an EPS system can be represented as Eq. (1)-(3) [4].

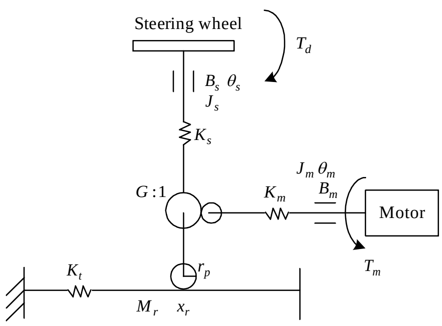


Figure:2 EPS dynamic model

$$J_s \frac{d^2\theta_s}{dt^2} + B_s \frac{d\theta_s}{dt} + K_s\left(\theta_s - \frac{x_r}{r_p}\right) = T_d \qquad (1)$$

$$M_r \frac{d^2 x_r}{dt^2} + B_r \frac{dx_r}{dt} + K_t x_r = \frac{K_s}{r_p}\left(\theta_s - \frac{x_r}{r_p}\right) + \frac{GK_m}{r_p}\left(\theta_m - \frac{Gx_r}{r_p}\right) \quad (2)$$

$$J_m \frac{d^2\theta_m}{dt^2} + B_m \frac{d\theta_m}{dt} + K_m\left(\theta_m - \frac{Gx_r}{r_p}\right) = T_m \quad (3)$$

where T_d is the driver torque, θ_s is the steering wheel angle, r_p is the radius of the pinion. J_s and J_m are the rotational moment of inertia of the column steering and the motor, respectively. B_s , B_r , and B_m are the viscous damping coefficient of the column steering, the rack, and the motor, respectively. K_s , K_t , and K_m are the torsion bar stiffness, the spring stiffness, and the motor shaft stiffness. x_r is the rack position. M_r is the mass of the rack. T_m is the motor torque, θ_m is the motor angle, and G is the motor gear ratio. Note that $K_t x_r$ in (2) is the automatic return torque of the front tires while a car is turning. While the steering wheel angle is under 180°, the automatic return torque is almost linear to the steering wheel angle.

3 EPS system analysis and design

3.1 Fuzzy steering strategy design

In this paper, the EPS controller is shown as Fig. 3. There are two inputs, including the vehicle speed and the steering wheel angle. The EPS controller can handle the motor current to produce desired motor torque. Herein, the controller is only designed to achieve the reference motor current. Thus, desired motor torque is also obtained. The insufficient torque will be provided by the driver. Generally, the control strategy in an EPS system includes the basic assist logic, the return compensation logic, the damping compensation logic, and the inertia compensation logic. In addition, we design four driving modes in this paper, including the stop mode, the assist mode, the return mode, and the maintain mode. The assist mode includes the basic assist logic and the inertia compensation logic. The return mode includes the return compensation logic and the damping compensation logic. According to driving behavior, a suitable mode can be chosen by the modes decision unit in Fig. 3.

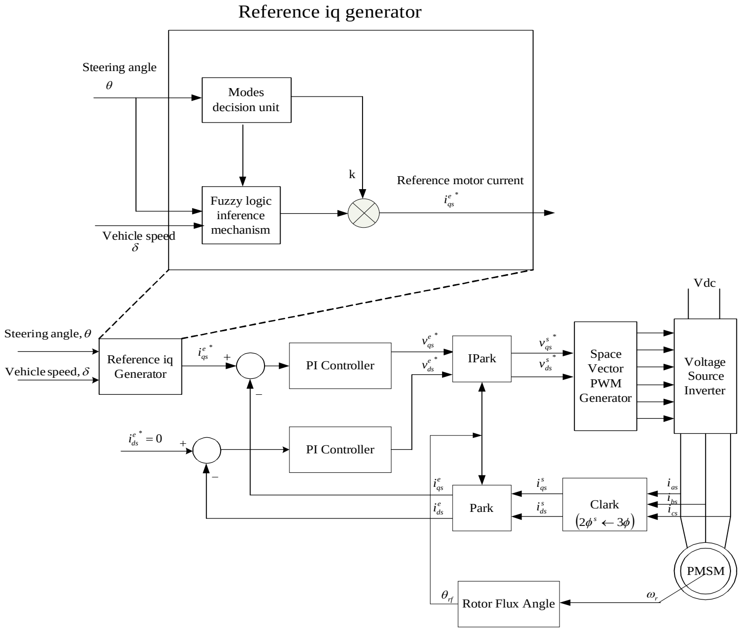


Figure3: Block diagram of the IEPS system

Firstly, the steering wheel angle is between 5° and -5° , i.e., the driver does not really turn. Therefore, the stop mode is excited and the motor does not work. Secondly, if the assist mode is excited, the assist motor current can be obtained through an assist fuzzy inference mechanism. Larger steering wheel angle is referred to larger motor torque needed. Moreover, larger vehicle speed is referred to smaller needed motor torque on same steering wheel angle. This design is to avoid turning danger since high sensitivity on high vehicle speed. According to the above statement, an assist fuzzy rule base can be designed. It is called as the basic assist logic. Since only the steering wheel angle is considered, heavy steering feeling emerges while the steering wheel is driven fast. Thus, the inertia compensation logic is necessary. In this paper, the volume of inertia compensation is decided by steering wheel angular acceleration. The larger angular acceleration is corresponding to a larger output gain of the assist fuzzy inference engine. For these reasons, the heavy steering feeling will be improved.

In the return mode, it includes the return compensation logic and the damping compensation logic. The return compensation is excited while the vehicle is on low speed or zero speed. This main reason is that the automatic return torque can not completely overcome friction between tires and a road. Then, the steering wheel angle can not return to zero. Therefore, the return compensation logic can provide suitably return torque to assist the steering wheel angle forward to zero. Additionally, an over returning phenomenon emerges on high vehicle speed while the return mode is excited. Therefore, the damping compensation logic is applied to reduce the oscillation. Note that the automatic return torque exists in the return mode. Thus, smaller motor current is considered than those in the assist mode. Briefly, the return compensation logic works on low vehicle speed and the inertia compensation logic works on high vehicle speed, respectively. According to the above statement, a return fuzzy rule base can be designed.

If the stop mode, the assist mode, and the return mode are not excited, i.e., the steering wheel is being held on a fixing angle. Thus, the maintain mode works. In the maintain mode, two situations are necessary to be considered. One is on a moving situation. In the moving situation, there is the automatic return torque. Therefore, maintain torque is needed to overcome this return torque. The other is on a stop situation. In the stop situation, the automatic return torque does not exist. Therefore, the motor does not work. In summary, the proposed modes decision unit flow chart is shown in Fig. 4. Since the output universal range is normalized, the output of the fuzzy inference mechanism is between -1 to 1. By the modes decision unit, a driving mode can be decided. Finally, an output of the fuzzy inference mechanism multiplied by the gain k is the reference motor current.

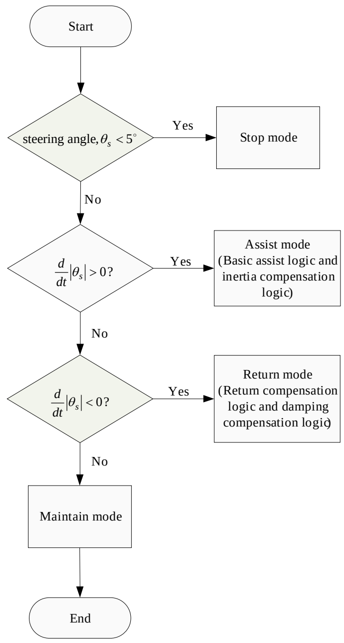


Figure4: Modes decision unit flow chart

3.2 Fuzzy logic inference system design

The basic structure of a fuzzy logic system is shown in Fig. 5.

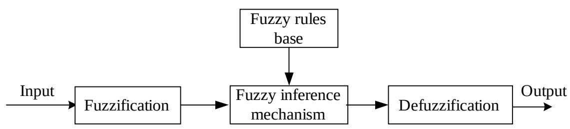
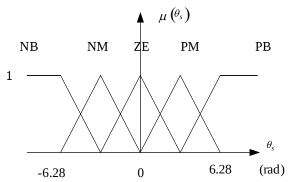


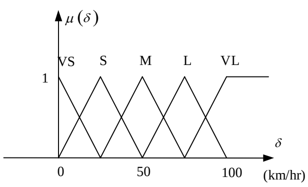
Figure5: Diagram of a fuzzy logic system

Basically, a fuzzy logic system consists of one or more inputs and a single output. Each rule describes a connection between the input and the output. Through the fuzzy inference engine, each rule maps the input fuzzy sets to an output fuzzy set. Finally, the output fuzzy set is translated to a crisp value by the defuzzification process. Choose singleton fuzzification, center average defuzzification, and Mamdani implication in the inference engine. In Fig. 3, the steering wheel angle and the vehicle speed are the inputs and the reference motor current is the output of the fuzzy inference mechanism, respectively. Figure 6 shows the input and output membership functions. The output universal range is decided by the gain k in Fig. 3. Table 1 shows the assist fuzzy rule base. The rules satisfy that larger steering wheel angle is corresponding to larger motor torque needed and larger vehicle speed is corresponding to smaller motor torque needed on same steering wheel angle. Thus, the designed assist fuzzy rule can make driving feeling smooth. The volume of the output gain k is decided by the inertia compensation logic. When the steering wheel angular acceleration is zero, the gain k is fixed. Larger steering wheel angular acceleration corresponds to larger gain k needed.

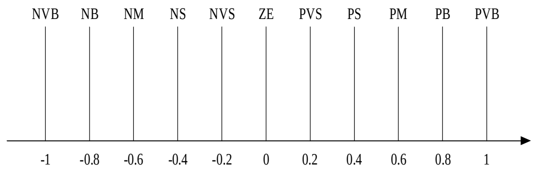
In the return mode, there are the return compensation logic and the damping compensation logic. Since the automatic return torque exists, the output gain k is smaller than that in the assist mode. In the return compensation logic, its fuzzy rules are different from the fuzzy rules in the assist mode since the automatic return torque is direct proportion to the vehicle speed and inverse proportion to the radius of the vehicle turning. It means that larger steering wheel angle with larger automatic return torque corresponds to smaller motor torque needed. On the same steering wheel angle, slower vehicle speed with smaller automatic return torque corresponds to larger motor torque needed. According to the above statement, the fuzzy rule base of the return mode can be designed as Table 2. Note that the return compensation in the return mode only works on lower or zero vehicle speed in order to help the tires going back on a straight direction. For this reason, the universal range of the membership function as shown in Fig. 6(b) is not necessary to set 100. It can be set as 50 or other smaller values. For the damping compensation logic of the return mode, the oscillation phenomenon caused by the over returning on high vehicle speed can be reduced. Therefore, the motor will provide a negative suppressing force to produce damping compensation when the steering wheel angle is on NM or PM and the vehicle speed is on VL. In summary, the assist fuzzy rule base and the return fuzzy rule base can complete easily the four assist and compensation logic.



(a)



(b)



(c)

Figure6: Membership functions. (a) Fuzzy set of steering wheel angle. (b) Fuzzy set of vehicle speed. (c) Fuzzy set of reference motor current

Table1: Fuzzy rules base of assist mode

		Steering angle, θ_s				
		NB	NM	ZE	PM	PB
Vehicle speed, δ	VL	NVS	ZE	ZE	ZE	PVS
	L	NS	NVS	ZE	PVS	PS
	M	NM	NS	ZE	PS	PM
	S	NB	NM	ZE	PM	PB
	VS	NVB	NB	ZE	PB	PVB

Table2: Fuzzy rules base of return mode

		Steering angle, θ_s				
		NB	NM	ZE	PM	PB
Vehicle speed, δ	VL	ZE	NVS	ZE	PVS	ZE
	L	PVS	PS	ZE	NS	NVS
	M	PS	PM	ZE	NM	NS
	S	PM	PB	ZE	NB	NM
	VS	PB	PVB	ZE	NVB	NB

For two input variables and twenty five rules, the output of the fuzzy logic system can be represented as

$$y = \frac{\sum_{m=1}^{25} \bar{y}^m \prod_{i=1}^{2} \mu_{A_i^m}(x_i)}{\sum_{m=1}^{25} \prod_{i=1}^{2} \mu_{A_i^m}(x_i)}, \quad (4)$$

where A_i^m is the fuzzy set for the i th input to the m th fuzzy rule and $\bar{y}^m$ is the center value of the output membership function for the m th fuzzy rule.

3.3 Motor controller design

According to the PMSM vector theory, suitable parameters of a PI controller can be chosen since previous verified results. Herein, SVPWM technique is applied to change DC voltage source. The advantage is harmonic distortion smaller than six-step square wave or sinusoidal PWM as shown in Fig. 3. There are two closed loop in this control frame. One is current loop, and the other is motor angle loop. In the current loop, i_{as}, i_{bs}, and i_{cs} are accessed via a current sensor component and get into Clarke transfer module to change coordinate axes from 3ϕ to 2ϕ by an analog-digital converter. In the other loop, the motor angle is accessed from a resolver to DSP via a SPI interface for transforming different reference coordinate axes.

Herein, there are a drive control stage and a power stage in the whole controller. The architecture of the IEPS MCU controller is shown in Fig. 7. The current command inputs to the DSP unit for proceeding relative transmit by the ECan interface. Then, the PWM signal would be amplified in the MOSFET module and transferred to the motor. At the same time, the motor also return some signals synchronously to other units. In the controller, the protective unit will cut off the PWM signal forcefully and make the motor stop when the circuit is unusual. In this situation, the MCU will send an extraordinary signal at once.

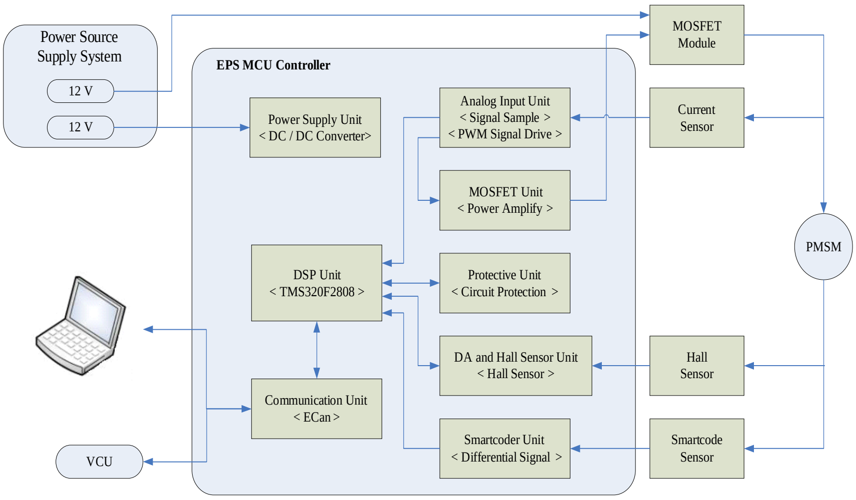


Figure7: Architecture of the IEPS MCU controller

4 Experimental Results

A new 12V/500W with high efficiency, high output torque, and low energy consumption, is applied. Figures 8 and 9 show the photographs of the developed controller and the IEPS test system, respectively. Figure 10 shows the test route of vehicle motion. A comparison drawing between vehicle speed 20 km/hr and 30 km/hr is shown in Fig. 11. It is obvious that larger motor assist current can be obtained in 20 km/hr than that in 30 km/hr for similar steering wheel motion.

Figure8: Photograph of the IEPS controller

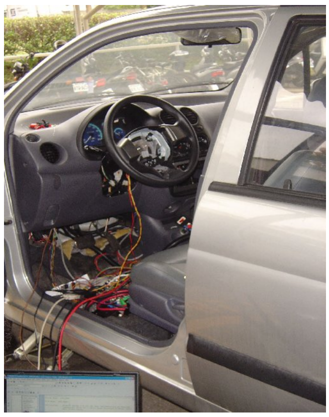


Figure9: Photograph of the IEPS test system

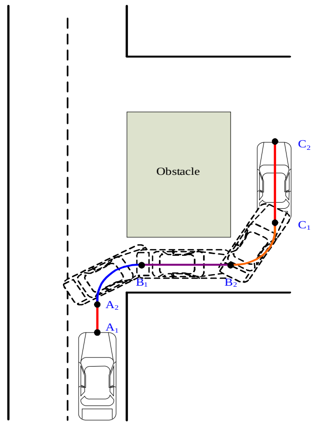


Figure10: Test route of vehicle motion

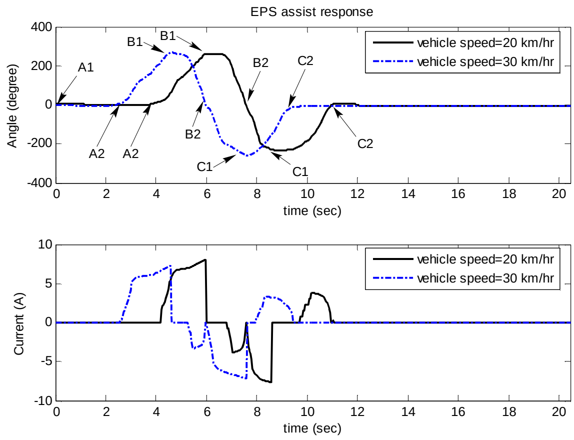


Figure11: Experimental results of the IEPS system

5 Conclusion

In this paper, an intelligent EPS system with a new 12V/500W motor is proposed. The new EPS controller and the new motor have low energy consumption and small volume. Therefore, the proposed EPS system is very suitable to mount on a vehicle for saving energy. In the control strategy, the fuzzy inference strategy completes the basic assist logic, the return compensation logic, the damping compensation logic, and the inertia compensation logic. Advantages in this paper are that the smooth driving feeling can be obtained, the fewer memories are needed than those uses look-up tables, and lower cost is needed than those use torque sensors. In the future, adaptive laws will be focused on the proposed strategy in order to develop another learning controller.

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