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Design of speed control for brushless DC motor used for electric vehicle based on adaptive neuro-fuzzy inference system

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Abstract. This paper presents a study for control the brushless DC motor speed applied in an electric vehicle. The configuration of the proposed method is an Adaptive Neuro-fuzzy inference controller applied to an electric vehicle's dynamics model. Matlab Simulink was used to build the configuration based on an accurate mathematical model for electric vehicle and the motor. Results proved that ANFIS has rapid robustness efficiency, also in the domain of the motor response characteristics. ANFIS expressed superior proficiency. Moreover, the controller shows good speed tracking and anti-interference ability in a typical city driving environment.

1. Introduction

There are many applications using DC motors such as electric vehicles, heavy trucks, aircraft and ships, besides small industries like toys, tools and electronic devices. Nowadays, electric vehicles either hybrid or pure electric vehicles, are growing rapidly. Many studies focusing on precise control of vehicle drive motors. The nonlinear features of electric vehicle drive motors and the use of BLDC motor are considering the torque of the motor, power density, and it is cost [1]. The development of semiconductor electronics in the 1970s allowed the commutator and brushes to be eliminated in DC motors. In brushless DC motors, an electronic servo system replaces the mechanical commutator contacts [2]. The conventional control of BLDC motor using such as PID control satisfies some of the applications needs, but the control of the BLDC motor for electric vehicle cannot fulfil the control and comfort requirements of drivers [3-5].The electric vehicle configuration has two subsystems, which are an electric motor and the mechanical vehicle body [6, 7]. The EV used traction motors for propulsion and can be classified to three types, based on the production of the power source; powered from an external power station, stored electricity from an off-board generation system and onboard electrical generator such as an internal-combustion engine. Usually, the motor used in EV should have some characteristics, which are the motor should have a simple structure, lightweight, small volume, easy to maintain, simple control, high performance, and the torque should be capable to drag the vehicle with carrying a load [8].

Electric motors are mechanically very simple and often achieve 90% energy conversion efficiency over the full range of speeds and power output and can be precisely controlled. They can also be combined with regenerative braking systems that have the ability to convert movement energy back into stored electricity. This can be used to reduce the wear on brake systems and consequent brake pad dust also reduces the total energy requirement of a trip. Some of the conventional control has been utilized in electric vehicle control, but these controllers have a shortcoming with nonlinear and uncertain conditions. Thus intelligent control is well known as a strong solution [9, 10]. Most of the current researches on BLDC motor control focusing on the implementation of ANFIS to control the motor [11]. However, it also has strong robustness to changes in the parameters of the regulated object. The introduced controller in this study is an adaptive neural fuzzy inference system, which the controller, the BLDC motor and the vehicle model have implemented using Matlab Simulink. The results obtained showed satisfied accuracy and suitable performance.

2. Brushless Dc Motor Mathematical Modeling

The simple configuration has used for the motor winding voltage balance as given in equation 1:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} r & 0 & 0 \\ 0 & r & 0 \\ 0 & 0 & r \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

Where u represent the stator winding voltage; i represent the stator winding current; and e is stator winding EMF. L, M and p represent respectively the inductance between any two-phase windings, where it is the differential operator p=d/dt. If we assume the BLDC motor between the three-phase winding represent as follows:

$$\begin{aligned} & i_a +_b +_c = 0 \\ & M_{ia} + M_{ib} + M_{ic} = 0 \end{aligned} \quad (2)$$

The electromagnet torque obtains by equation 3;

$$T = \frac{1}{\omega}(e_a i_a + e_b i_b + e_c i_c) \quad (3)$$

3. Mathematical Modelling of Electric Vehicle

The electric vehicle has two subsystems: one is the electric system, and the second one is the mechanical system. To create an accurate mathematical model for electric vehicle, it is essential to analyze the velocity, time and road parameters with considering all forces have an impact on the vehicle operation. The modelling needs balancing between all these forces, which it classified to road load and motive force. Figure 1 illustrates the forces' acts on vehicle movement.

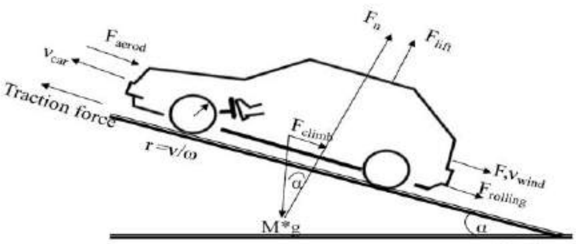

Figure 1. The forces influencing on the electric vehicle.

The disturbance torque on the EV system can obtain by considering all forces, which are as follows;

$$F_{Total} = F_{aero} + F_{rolling} + F_{\text{clim}\,b} + F_{linear\_acc} + F_{angular\_acc} \quad (4)$$

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Where, the rolling force is the force depends on vehicle speed, weight and the contact of the tires on the road route. Rolling force can be calculated by the following equation;

$$F_{rolling} = F_{normal\_force} * C_r * \cos(\alpha) = M * g * C_r * \cos(\alpha) \quad (5)$$

In the case of the vehicle moving straight surface, the value of cos(α) become one. The rolling resistance torque can be calculated by equation 6;

$$T_{rolling} = (M * g * C_r * \cos(\alpha))r_r \quad (6)$$

As for aerodynamic drag force, it is the force that resists the movement of the electric vehicle due to the air force; This force is a function of the vehicle linear velocity, and it can be found by the following expression;

$$F_{aerodynamic} = \frac{1}{2} * \rho * A * C_d * V_{vehicle}^2$$

Or

$$\theta_m(s) = \left[\frac{1}{s}\right] \cdot \omega_m(s).$$

$$F_{aerodynamic} = \frac{1}{2} * \rho * A * C_d * (V_{vehicle} + V_{wind})^2 * \mathrm{s}\,ign(V_{vehicle} + V_{wind}) \quad (7)$$

To calculate the torque of the aerodynamic, we can use the following equation;

$$T_{aerodynamic} = (\frac{1}{2} * \rho * A * C_d * V_{vehicle}^2) * r_r \quad (8)$$

Where C_d is the coefficient of the aerodynamic drag, which depends on the vehicle shape, and r_r is the rotor winding resistance. For aerodynamics lift force, which is the difference between the vehicle's upper and lower pressure, and it is a function in vehicle's velocity. This force is given by;

$$F_{lift} = \frac{1}{2} * \rho * C_L * B * V_{vehicle}^2 \quad (9)$$

Where B is the electric vehicle reference area, and C_L is the lift coefficient, which ranges between (0.10 to 0.16). This coefficient depends on the air density and the vehicle's frontal area. The force of wind also is a force effect on a vehicle's movement. Factors' impacts in this force are the shape, frontal area and the velocity of the vehicle. The following formula describes this force;

$$F_{wind} = \frac{1}{2} * \rho * C_d * A * (V_{vehicle} + V_{wind})^2 \quad (10)$$

The force of a climbing hill is a force required to drag the vehicle's weight when the vehicle climbs up or moving down. This force depends on the weight and the angle of the hill; the following expression demonstrates this force;

$$F_{\mathrm{clim}\,b} = M * g * \sin(\alpha) \quad (11)$$

When the vehicle moving on a level surface, the angle is zero, so this force becomes zero. The normal force is exerted on the road. It has given by the equation 12;

$$F_{norm} = F_{c\lim b} - F_{lift} \tag{12}$$

The force required to increase the speed of the vehicle is called the linear-acceleration force and angular-acceleration. The following expressions describe these forces respectively;

$$F_{linear-acc} = M\frac{dv}{dt} = \left[M + \frac{J_{weel}}{r^2}\right]\frac{dv}{dt} \tag{13}$$

$$F_{angular-acc} = (J\frac{G^2}{r_{wheel}})\frac{dv}{dt} \tag{14}$$

The total force can be found from previous equations as follows;

$$F_{total\_force} = [M*g*\sin(\alpha)] + [M*g*(C_{r0} - C_{r1}*v)sign(v)] + \left[\frac{1}{2}*\rho*A*C_d*(V_{vehicle} + V_{wind})^2*sign(V_{vehicle} + V_{wind})\right] + \left[(M + \frac{J_{wheel}}{r^2})\frac{dv}{dt}\right] + \left[(J\frac{G^2}{r_{wheel}})\frac{dv}{dt}\right]$$

4. Design of ANFIS Controller Based On Speed-Current Double Closed Loop Control System.

The design configuration is built based on the structure of double closed loops direct current control systems of DC motor. The current and speed controllers are designed according to inner to the outer loop, to ensure there is no static error in the system. In order to confirm the efficiency of the system, in the first stage, the controller is adjusted for DC motor without a load of electric vehicles, where the speed loop is tuned using PID and the current loop adjusted by utilizing PI controller. In the second stage, the load of the electric vehicle is added to design. In this stage, the outer, which is the speed loop is regulated using a PID controller to generate training data for ANFIS and later replaced by ANFIS. The inner loop adjusted using a PI controller for controlling the current. The structures of the current regulator and speed regulator are selected reasonably, by adjusting the parameters of the regulators to achieve system requirements. The stability of the system analysed by simulation curve, the simulation curve obtained based on parameters tuning.

In this design, ANFIS has two inputs; each input has four triangle membership functions and 1 output linear type. The overall system has sixteen rules, with error tolerance 0 and Epoch 7. The structure is tuned by the hybrid optimization algorithm for training the FIS. The ANFIS model for controlling the speed of the electric vehicle has shown in figure 2. The parameters have used in this model are: air density (ρ)1.25 kg/m^3; maximum speed is 60 km/h; coefficient of the aerodynamic drag (c_d) is 0.8; the mass of the vehicle (M) is 1000kg; friction coefficient is 0.19; the aerodynamic factor is 0.75; the surface area of the vehicle1.5 m^2; the gravity acceleration is 9.81 m/s^2, and the gear ratio is 0.3.

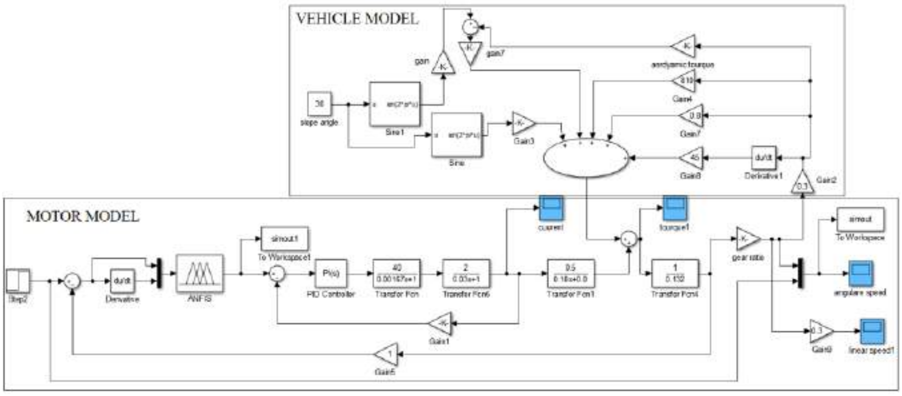

Figure 2. Matlab Simulink system model for electric vehicle and DC motor.

5. Result and Discussion

The system has been tested under two conditions. First, the system operated without vehicle load. The controller has shown a very good performance in tracking speed response and transient response characteristic as it is clearly seeming in figure 3.

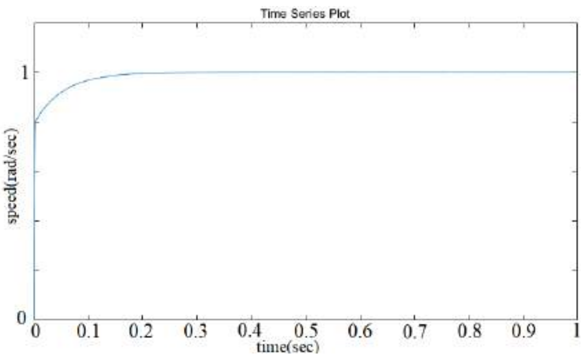

Figure 3. The response of the motor speed without vehicle load.

In the second stage, the electric vehicle has added to the model. The suggested model, to ANFIS control for outer loop and pi control for the inner loop, and by setting mechanical, electrical variables and then operating the model at (60 km/h). Obtained response as shown in fig 4 shows that using ANFIS controller outer loop and PI for the inner loop, resulted to a good system response with comfortable riding.

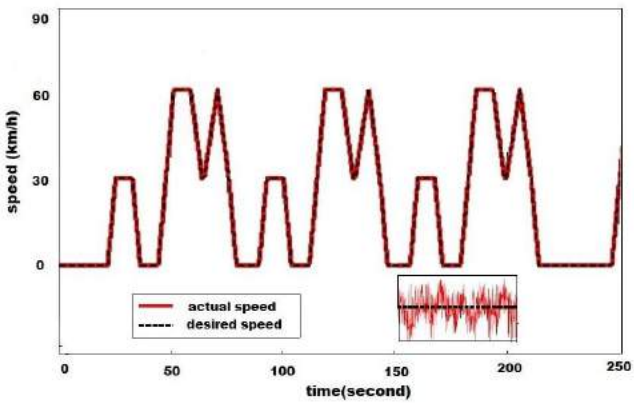

Figure 4. The response of the vehicle speed.

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6. Conclusion

In this study, both ANFIS and PI controllers were utilized in a double closed-loop configuration. The model of the electric vehicle has detailed by considering all factors. The double closed loops' control has implemented to control the speed of the vehicle. The ANFIS and PI methods have introduced in MATLAB/Simulink environment to control the speed of electric vehicle using BLDC motor. Obtained results show that the suggested technique can implement in the electric vehicle, where the controller has several features: fast response, small overshoot, and rapid dynamic and good stability.

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