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Efficient Current Control Tracking in BLDC Motors for Electric Vehicles: A Comparative Analysis

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***Abstract*—Currently, traditional automotive emissions contribute significantly to ever-worsening environmental issues. Furthermore, given the environmental calamity and low energy efficiency of conventional autos, manufacturing electric automobiles is a viable option. Electric vehicles (EVs) are gaining attraction due to a variety of factors, including cost reduction, climate change, and environmental consciousness. Electric vehicles (EVs) have grown in popularity as a result of their improved performance, efficiency, and lack of carbon emissions. This paper proposes an efficient controller for an EV current tracking control driven by a BLDC motor. The current is controlled using a quasi-square method. Conventional controllers such as PI and PID controllers are employed first, and the system is then evaluated using a hybrid Fuzzy Logic controller, which enhances the system even more, and is also considerably superior to other controllers. For system modelling and controller design, the MATLAB-SIMULINK platform is employed.**

***Index Terms*— electric vehicle, PI controller, PID controller, hybrid fuzzy logic controller and BLDC motor.**

I. Introduction

After the growing need for technological breakthroughs, sustainable energy use, and severe rules and regulations for environmental safety, research and development trends in electric vehicles (EV) are continuously gaining relevance in the automotive sectors. For rapid advancement in EV technology, an efficient motor with intelligent control techniques is thought necessary. The entire efficacy of an EV system is heavily influenced by the actuator system's reliability and durability.In industry, there are primarily two types of dc motors. The first is a traditional dc motor, which generates flux by passing current through the field coil of a stationary pole structure. The second type is the Brushless DC (BLDC) motor, which uses a permanent magnet instead of wire-wound field poles to generate the required air gap flux. A permanent magnet synchronous motor with a trapezoidal back EMF waveform is commonly referred to as a BLDC motor. BLDC motors do not employ brushes for commutation; instead, they are electronically commutated, as the name implies. High-performance BLDC motor drives have been popular in recent years for variable-speed drive systems in industrial applications and EV's.
Voltage-source current-controlled inverters are used to power a BLDC motor for traction [1]. The inverter generates a quasi-square current waveform whose amplitude Imax is proportional to the shaft torque of the system. The torque and speed can be changed by adjusting the phase-currents. A BLDC motor's phase currents

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can be managed in one of two ways: by measuring the phase currents or by measuring the dc connection current. In the first scenario, the control is difficult since three quasi square current templates with a shift of 1200 are required. Due to step changes and delays, these existing models are difficult to follow.

Current-controlled inverters (pulse width modulation – PWM type) are widely utilised in high-performance servo drives. Current controllers play a crucial part in BLDC motors since stator current is proportional to established torque. Hysteresis control is the most extensively utilised because to its quick responses, lack of load information, and ease of application. Current controllers with hysteresis, on the other hand, have a variety of disadvantages. In the steady state, the current ripples are enormous. During service, switching frequencies vary, resulting in intermittent inverter operation and PWM noise. (3), (4).

The speed control of electric vehicles uses a variety of controllers, including PID, fuzzy logic controllers, and neural networks. Traditional PID controllers are ineffective in higher-order, non-linear, and complicated systems, despite their widespread use due to their simplicity. Because of higher performance features such as robustness against system perturbation and parameter fluctuations, the hybrid Fuzzy PID control has become an industrial standard controller that has replaced conventional PID controllers. In industrial control applications, it also helps to improve disturbance rejection control and minimises control effort and energy waste. Rule-based, analytical, and numerical methods can all be used to optimise the hybrid Fuzzy PID controller.

We propose a current control approach for a BLDC drive system that uses only one controller for all three phases, in contrast to traditional controllers.

II. Mathematical Modelling of BLDC Motor

As shown in Figure 1, an EV's dynamics can be classified into vehicle and motor dynamics. The transmission unit, which includes the gearing system, connects these dynamics. A typical BLDC motor's construction is shown in Figure 2. A three-phase induction motor with one or more permanent magnets on the rotor side is akin to the development of a BLDC motor. It has a stator winding that is fixed and a powerful permanent magnet rotor. Three different sets of windings are also exposed to three different voltages [1, 7]. Figure 2 [1] shows how to collect rotor positions in order to generate control signals.

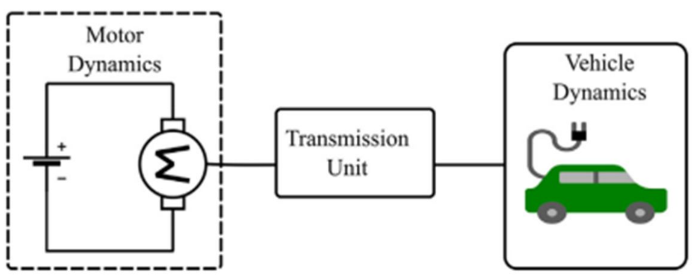

Figure 1. EV dynamic model

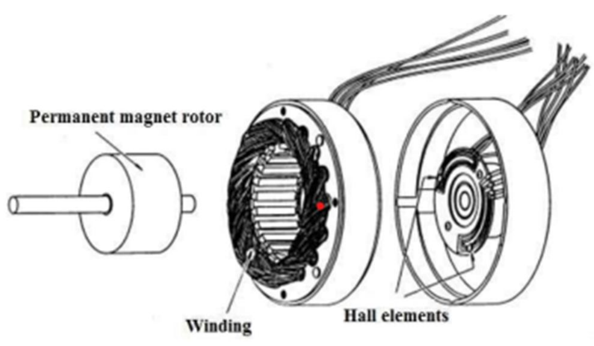

Figure 2. Construction of BLDC motor

A synchronous motor with a permanent magnet on the rotor and armature winding on the stator is known as a BLDC motor. BLDC motors are an inside-out form of DC motors with permanent magnets on the stator and armature windings on the rotor.

In a BLDC motor, there are three stator windings and permanent magnets on the rotor. As magnets have a high resistance, rotor-induced current can be ignored. In terms of phase variables, there are three windings.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + p \begin{bmatrix} L_a & L_{ba} & L_{ca} \\ L_{ba} & L_b & L_{cb} \\ L_{ca} & L_{cb} & L_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

Assume that equal stator resistance is used and that the rotor reluctances do not change with angle.

$$L_a = L_b = L_c = L$$
$$L_{ab} = L_{ca} = L_{cb} = M$$

Hence,

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (2)$$

but

$$i_a + i_b + i_c = 0 \quad (3)$$

Therefore,

$$Mi_b + Mi_c = -Mi_a \quad (4)$$

Hence

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (5)$$

On re-arranging

$$p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1/L-M & 0 & 0 \\ 0 & 1/L-M & 0 \\ 0 & 0 & 1/L-M \end{bmatrix} \left[\begin{bmatrix} V_a \\ V_c \\ V_c \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \right] \quad (6)$$

Electromagnetic torue is,

$$T_e = \frac{(e_a i_a + e_b i_b + e_c i_c)}{\omega_r} \quad (7)$$

Motion Equation is,

$$\rho\omega_r = \frac{(T_e - T_L - B\omega_r}{J} \quad (8)$$

Phase back-EMF’s,

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = E \begin{bmatrix} f_a(\theta) \\ f_b(\theta) \\ f_c(\theta) \end{bmatrix}, (E = k_e\omega_r) \quad (9)$$

Trapezoidal function,

$$f_s(\theta) = \begin{cases} (6/\pi)\theta & (0 < \theta \le \pi/6) \\ 1 & (\pi/6 < \theta \le 5\pi/6) \\ -(6/\pi)\theta + 6 & (5\pi/6 < \theta \le 7\pi/6 \\ -1 & (7\pi/6 < \theta \le 11\pi/6) \\ (6/\pi)\theta + 12 & (11\pi/6 < \theta \le 2\pi) \end{cases} \quad (10)$$

III. EV SPEED CONTROL STRATEGY

People are becoming more aware of zero-polluting EV's as their environmental consciousness grows. A storage battery and an electromotor are part of an electric vehicle's dynamic system. DC motors, ac motors, and reluctance motors are all extensively used in EV's. Brushless dc motors (BLDCM) are highly efficient and have excellent timing. It also has a simple structure, good dependability, and is simple to maintain. As a result, it's used frequently. Electronic commutation takes the place of mechanical commutation in BLDCM. The electronic commutator is a high-power switch transistor. The controller makes an attempt to efficiently manage the car's speed and control the power flows. As a result, the controller must be able to track the vehicle's desired speed. The motor driving control system includes a microprocessor-based controller and a three-phase inverter.

IV. PROPOSED SPEED CONTROL METHOD

Figure 3 shows the proposed approach as a basic block diagram. Figure 4 depicts the most recent controller block diagram. The armature currents of a BLDC motor have a quasi-square waveform. Current sensors detect armature currents, which are then translated to voltage signals. The signals are then rectified, resulting in a DC element with maximum current I_{max}. It is then correlated with the required reference current I_{ref}, resulting in an error signal I_{err}, which is then transmitted via a controller to generate PWM pulses for all six inverter switches. I_{ref} is directly proportional to torque. The control just needs to regulate one DC instead of three alternate waveforms.

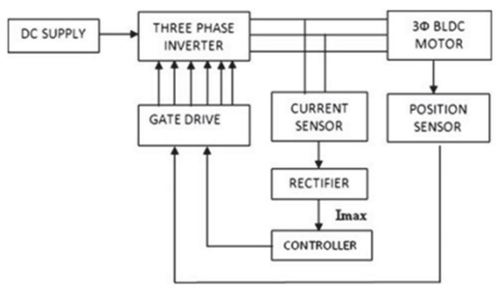

Figure 3. BLDC drive system

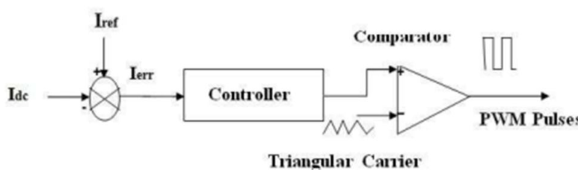

Figure 4. Current control block

The magnetic field in the stator is reversed to halt the motor. This is performed by inverting the location sensor's signals. The complete 360^0 degrees of rotation is divided into six modes, with each switch controlling one of them. The various controllers used in Figure 4 [1].

V. PROPORTIONAL-INTEGRAL CONTROLLER

Figure 5 depicts the block diagram of the Proportional-Integral (PI) controller. The integral is proportional to the integral of the error signal, and the proportional is proportional to the proportional of the error signal.

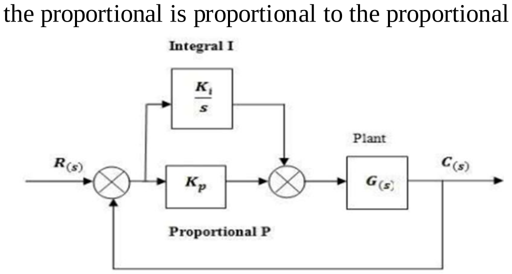

Figure 5. PI controller

Transfer function is,

$$C(s) = K_p + {}^{K_i}/_{s} \quad (11)$$

The integral gain is KI, while the proportional gain is Kp. The proportional factor or gain determines the error signal. If P is set too high, the system will become unstable.As a result, it's fine-tuned to keep the speed constant [1].

Both P and I advantages are present in the PI-controller. The proportional action increases the gain in the loop, making the system less sensitive to changes [1]. The integral action eliminates the steady state error, which may be regulated by altering the time. The proportional and integral parts are both affected by changes in the proportional constant value [1].

VI. Proportional Integral Derivative Controller

Figure 6 depicts the Proportional Integral Derivative (PID) controller's block diagram. Overshoot and settling time are reduced with the PID controller. The regenerated error is multiplied, merged, and differentiated in order to remove and generate control signals. The proportional controller stabilises the gain, however there is a steady state error. This error is reduced by the integral controller, while the rate of change of error is reduced by the derivative controller. [1].

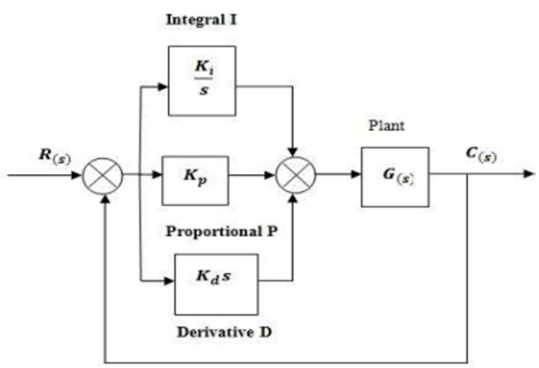

Figure 6. PID controller

Transfer function,

$$C(s) = K_p + {}^{K_i}/_{s} + K_d S \quad (12)$$

Kp denotes the proportional gain, Ki denotes the integral gain, and Kd denotes the derivative gain.

VII. Fuzzy-Logic Controller

Figure 7 depicts the fundamental structure of a fuzzy logic controller. If-Then rules are used to determine the logical implication, and fuzzy membership functions are used to determine the value set [8]. Fuzzy membership functions can take the shape of a triangle, a trapezoid, or a bell, as seen in Figure 8. (1, 9).

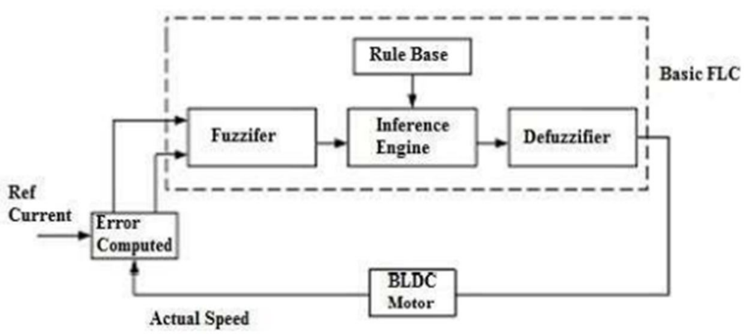

Figure 7. Fuzzy-Logic controller

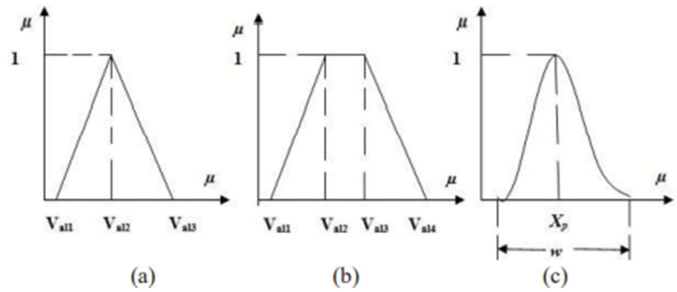

Figure 8. a) Traingle, b) Trapezoidal, c) Bell membership function

VIII. HYBRID FUZZY-PID CONTROLLER

A hybrid fuzzy- PID controller is used for better performance. The disadvantage of PID controller can be over come when the controller is modified to hybrid controller. Both the advantage of PID and Fuzzy controller can be used. For practical and industrial purpose in spite of robustness against system perturbation and parameter fluctuations, the hybrid Fuzzy PID control has become an industrial standard controller that has replaced conventional PID controllers.

IX. ANALYSIS AND DISCUSSIONS

Figure 9 shows the SIMULINK/MATLAB model of BLDC motor used in EV and figure 10 depicit the stator current waveform

For brushless DC motors in electric vehicles, this paper provides a current-controlled modulation approach. Only one controller is utilised for all three phases in this method. To analyse performance, PI, PID, and hybrid fuzzy-PID Controllers are employed.

From the Table 1 hybrid fuzzy-PID controller speed response at 1000 rpm reference speed with loaded situation is taken for the analysis purpose. The results reveal that when utilising a fuzzy controller, the system settles in 0.007 seconds and overshoot is decreased.

The results reveal that the system settles in 0.0085 sec and 0.0084 sec using PI and PID controllers, respectively, whereas the Fuzzy controller settles in 0.007 sec. The given results show that a fuzzy logic controller performs better.

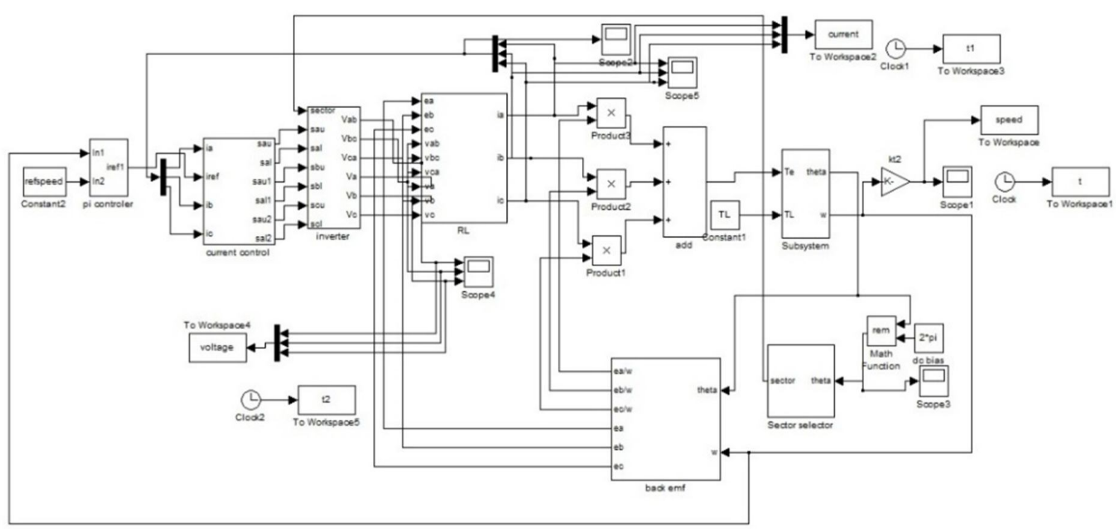

Figure 9. Simulink model of BLDC motor drive in electric vehicle

Other controllers, such as PI and PID controllers, are less efficient than hybrid fuzzy PID controllers. The PI controller has some drawbacks, including a large initial overshoot, sensitivity to controller gains Ki and Kp, and

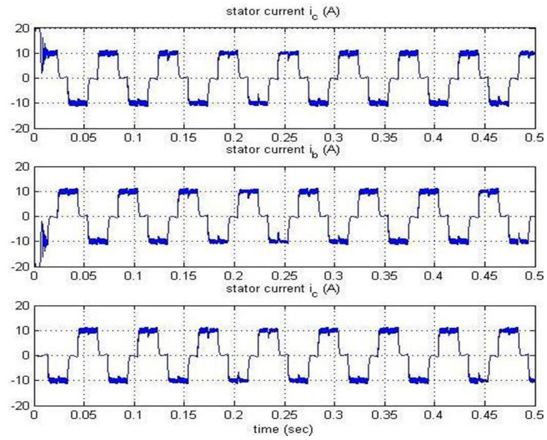

Figure 10. Stator current waveform of BLDC motor

TABLE I. ANALYSIS OF DIFFERENT CONTROLLERS

Speed (rpm)	PI Controller			PID Controller			Hybrid Fuzzy-PID Controller		
	tr(s)	%Mp	ts(s)	tr(s)	%Mp	ts(s)	tr(s)	%Mp	ts(s)
1000	0.0056	9.3	0.0085	0.0057	7	0.0084	0.006	6.3	0.007
2000	0.010	4.09	0.0127	0.0102	3.08	0.0118	0.0118	2.5	0.011
3000	0.010	5.9	0.015	0.0112	4.17	0.014	0.0113	2	0.0125
4000	0.0147	2.8	0.018	0.014	2.31	0.017	0.0149	1.5	0.016

sluggish response caused by rapid load changes. PID is a basic, consistent, easy-to-adjust algorithm with great reliability. However, because most industrial processes have varying degrees of nonlinearity, parameter variability, and uncertainty in the mathematical model of the system, tuning PID control parameters is difficult, and the system's robustness is poor, achieving the optimal state under field conditions in actual production is difficult.

X. CONCLUSIONS

The controllers used to control the current of BLDC motors, which controls the speed of BLDC motors in electric vehicles, are thoroughly explained in this study. A current control technique for a BLDC drive system has been proposed, which controls the motor speed in an electric vehicle using only one controller for all three phases. PI, PID, and hybrid fuzzy-PID controllers are used to evaluate the suggested scheme's performance. Fuzzy-PID controllers beat PI and PID controls in performance, according to extensive simulations. A comparison of controllers demonstrated the efficacy and feasibility of the proposed controller in terms of reference speed tracking and disturbance rejection.

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