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DESIGN AND SIMULATION OF ELECTRIC VEHICLE FED WITH PERMANENT MAGNET SYNCHRONOUS MOTOR BY FUZZY LOGIC CONTROLLER

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Abstract: *Electric vehicles (EVs) have gained significant traction in recent years due to their environmental benefits and improved performance. Permanent Magnet Synchronous Motors (PMSMs) are widely used in EVs owing to their high efficiency, power density, and torque characteristics compared to others from 1990s. However, precise control of PMSMs is crucial for optimal performance and energy efficiency. Traditional control methods often face challenges in adapting to dynamic operating conditions and disturbances. This research explores the implementation of a Fuzzy Logic Controller (FLC) of PMSMs in EVs. The PID controller, while widely used, faces limitations in handling complex nonlinear systems. It depends on precise mathematical tuning can be time consuming. PID controllers may struggle to adapt to unexpected disturbances in operating conditions. Fuzzy logic controllers can effectively handle nonlinear systems, adapt to changing conditions, making them a suitable alternative to PID controllers in achieving performances like speed response and torque ripple reduction. The design and simulation of electric vehicle fed with PMSM by fuzzy logic controller (FLC) can be carried out in MATLAB/Simulink*

Keywords: **Permanent Magnet Synchronous Motors (PMSMs), Fuzzy Logic Controller (FLC)**

1. INTRODUCTION

Due to the benefits that they provide, permanent magnet synchronous motors are becoming increasingly common. The machine's mathematical modeling allows for a better understanding and provides insight into the influence of each variable on the machine's dynamics and to design an appropriate control system for the motor. This work provides a mathematical model of a PMSM (permanent magnet synchronous motor), and this model has been simulated via utilize MATLAB/Simulink tools. The results obtained verify the model's effectiveness to work under different controllers. This model can be used in various control strategies such as PI controller, field-oriented control and direct torque control. The development of control technology and permanent magnetic materials has led to the widespread usage of PMSMs. The paper represents motor dynamics, electromagnetic characteristics and control strategies to simulate and analyze motor behavior accurately through simulation, parameter optimization overshoot analysis and rise time to refine and validate the model’s accuracy against experimental data and theoretical expectations. It helps in understanding design and optimization of PMSM systems for a wide range of electric vehicle applications.[1-5]

2. Mathematical Modelling of PMSM

The model of PMSM can be defined in natural three phase reference frame (ABC frame), in equivalent two-phase frame (α-β frame) and in synchronously rotating reference frame (D Q frame). The model is constructed from first principles in ABC frame and then suitable transformations are used to get the model in the two latter frames of reference. The transformations are dependent on the positions of the axes in each reference frame relative to each other and on the definition of the rotor position angle. Rotor position angle can have two different definitions (D-alignment and Q-alignment). The 3-phase system mathematical model is rarely used in control design. This method is known as the time-varying model. The flux linkage, voltage and current equations which are used to analyze the performance of PMSMs are described both in equation form and matrix form. The machine's mathematical modelling allows for a better understanding and provides insight into the influence of each variable on the machine's dynamics and to design an appropriate control system for the motor. This work provides a mathematical model of a PMSM (permanent magnet synchronous motor), and this model has been simulated via utilize MATLAB/Simulink tools. For simulation of a PMSM drive system detailed modelling of the system is required. Figure.1 illustrates a conceptual cross-sectional view of 3-phase 2-pole of PMSM along with two reference frames[6-10].

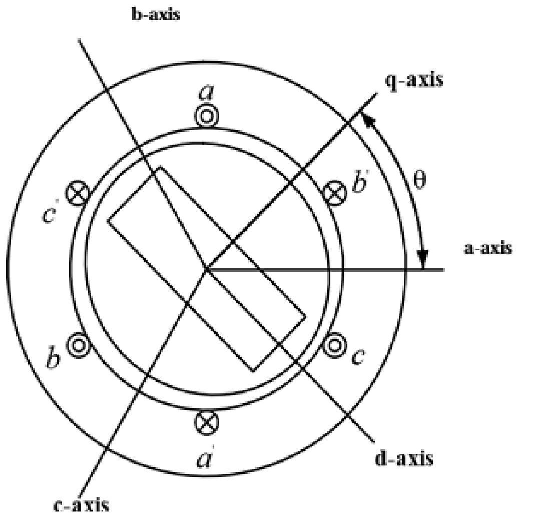

Figure 1: Permanent Magnet Synchronous Motor

In the most studied cases of the PMSM, the per-phase equivalent circuit model (ECM) neglecting the core loss is illustrated in the figure 2, while the d- and q- axis ECMs are demonstrated as shown in Figure 3 and figure 4. In Figure 2, Rs is the winding resistance of per phase, and the power loss of Rs presents the copper loss of the PMSM. Ls is the synchronous inductance, which is an equivalent inductance of self-inductance and the mutual inductance per phase. The PMSM is excited by PMs, and the PM flux is described by λf, while rotating PMs induce the back electromotive force E0 in the phase winding, which is proportional to the rotor speed in electrical angular frequency, ωe. Moreover, Ip and VP are the phase current and voltage, respectively. To realize the vector control of the PMSM, ECM or mathematical, model in the three-phase stationary reference frame needs to be transformed to the two-phase rotational reference frame, as shown in Figure 3 and 4, where Vd and Vq are the d- and q-axis terminal voltages, Id and Iq are the d- and q-axis armature currents, and Ld and Lq are the d- and q- axis inductances, respectively.

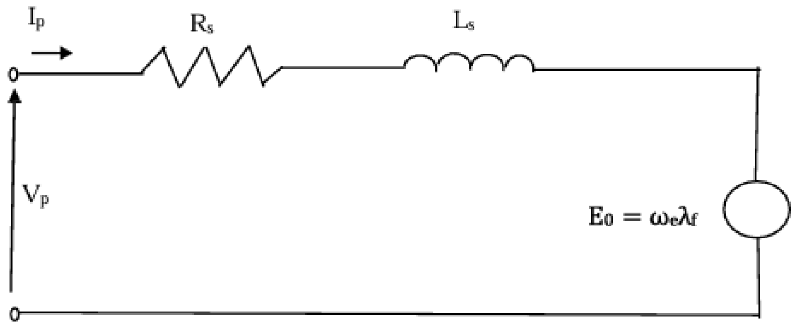

Figure 2: Conventional per-phase ECM of PMSM

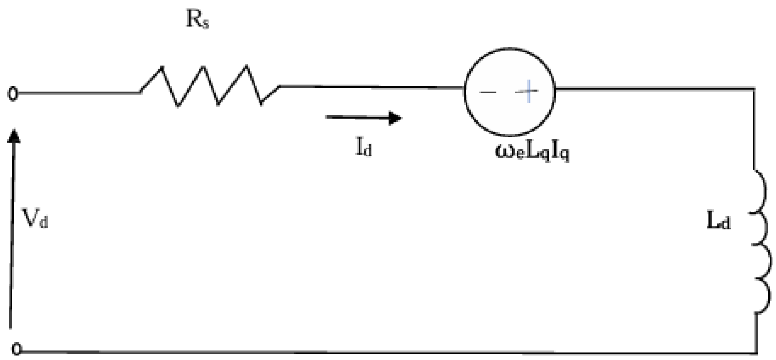

Figure 3: Equivalent circuit reference to d-axis

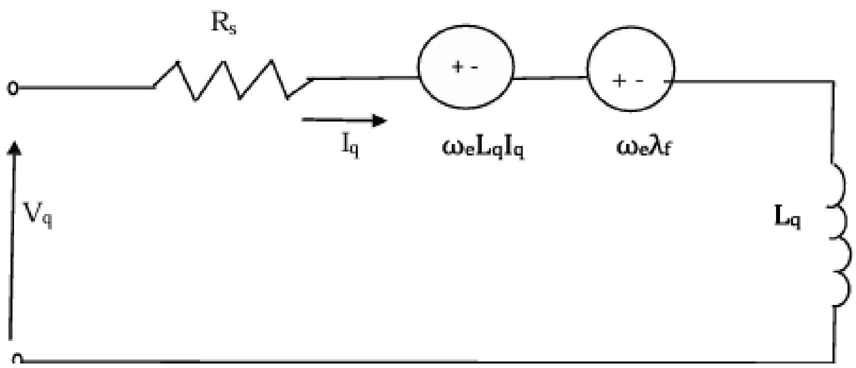

Figure 4: Equivalent circuit reference to q-axis

Mathematical models mentioned above cannot provide high-precision solutions during motor design, control and optimization due to the absence of the core loss. The copper loss can be estimated via the power loss in winding resistance Rs, while the core loss cannot be predicted from any parameters in these models. Actually, the core loss may rise significantly and exceed the copper loss when the motor speed increases and the load torque.

From the equivalent circuit diagram figure 3 can be expressed as

$$V_d = R_s I_d - \omega_e L_q I_q + P L_d I_d$$
$$= R_s I_d - \omega_e \lambda_q + \frac{d}{dt}\lambda_d$$

$$\frac{d}{dt} I_d = \frac{1}{L_d}(v_d + \omega_e L_q I_q - R_s I_d)$$

$$I_d = \int \frac{1}{L_d}(v_d + \omega_e L_q I_q - R_s I_d)$$

From the equivalent circuit diagram figure 4 can be expressed as

$$V_q = R_s I_q + p L_q I_q + \omega_e L_d I_d + \omega_e \lambda_f$$

$$= R_s I_q + P L_q I_q + \omega_e (L_d I_d + \lambda_f)$$

$$V_q = R_S I_q + \omega_e (L_d I_d + \lambda_f) + \frac{d}{dt} L_q I_q$$

$$\frac{d}{dt} I_q = \frac{1}{L_q}(V_q - R_s I_q - L_d \omega_e I_d - \lambda_f \omega_e)$$

$$I_q = \int \frac{1}{L_q}(V_q - R_s I_q - L_d \omega_e I_d - \lambda_f \omega_e)$$

Where,

ω_e = electrical speed

R_s = stator resistance

L_d, L_q = The inductance on the d-q axis

i_d, i_q = The stator current on d-q axis

V_d, V_q = The stator voltages on d-q axis

λ_d, λ_q = The flux linkages of stator on d-q axis

λ_f = Permanent magnet flux

The ECMs and mathematical models mentioned above cannot provide high-precision solutions during motor design, control and optimization due to the absence of the core loss. The copper loss cannot be predicted from any parameters in these models. Actually, the core loss may rise significantly land exceed the copper loss when the motor speed increases and the load torque grows. Ignoring the core loss also leads to underestimation of other performance. The stator flux linkage in the d-q reference frame as shown in Figure 5. In conclusion, due to the neglecting of core loss component, the drawbacks of the conventional ECMs of the PMSM mainly contain:

- Inconvenience for the core loss calculation, control and optimization.

- Poor theoretical foundation to support the motor efficiency prediction, thermal management, and cooling design.
- Overestimation of the output electromagnetic torque and power for a given input current, resulting in lower control performance.
- Exacerbation of the parameter sensitivity of the model-based motor control system, such as the model predictive control.

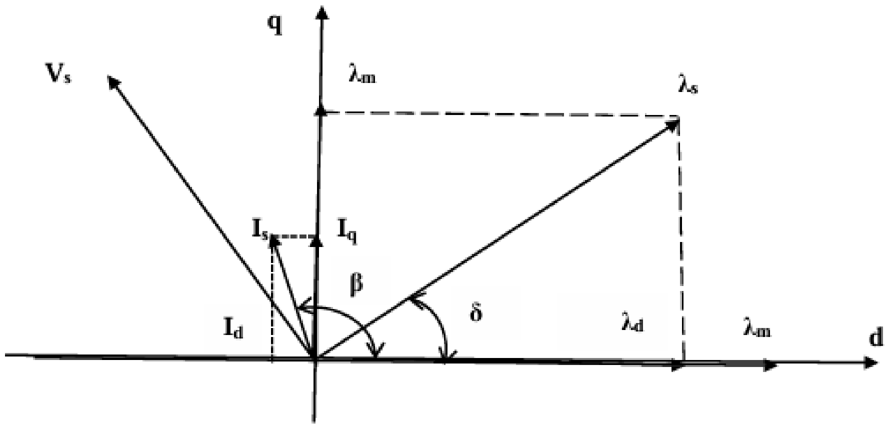

Figure 5: The stator flux linkage in the d-q reference frame

2.1 ELECTROMAGNETIC TORQUE EQUATION

The electromagnetic torque of the PMSM is comprises permanent-magnet torque and reluctance torque. the permanent-magnet torque is connected only to the q-axis current and the permanent-magnet flux linkage, while the reluctance torque is affected mainly by the q- axis and d-axis inductance.

$$T_e = \frac{P}{2}\left(\frac{3}{2}\right)(\lambda_d I_q - \lambda_q I_d)$$

From the equations 2.4 and 2.5 $\lambda_d = L_d I_d + \lambda_f$, $\lambda_q = L_q I_q$ we get T_e

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)[(L_d I_d + \lambda_f) I_q - L_q I_q I_d]$$

$$= \frac{p}{2}\left(\frac{3}{2}\right)(L_d I_d I_q + \lambda_f I_q - L_q I_q I_d)$$

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)((L_d - L_q) I_d I_q + \lambda_f I_q)$$

The equation that represents the mechanical torque is given as

$$T_m = T_L + b\omega_m + J\frac{d\omega_m}{dt}$$

$$J\frac{d\omega_m}{dt} = T_m - T_L - b\omega_m$$

$$\frac{d\omega_m}{dt} = \frac{1}{J}(T_m - T_L - b\omega_m)$$

$$\omega_m = \int \frac{1}{J}(T_m - T_L - b\omega_m)$$

Where,

T_e, TL= electromagnetic and load torque

T_m= mechanical torque

P = No. of Poles

J = moment of inertia

B = fraction factor

3. VEHICLE DYNAMICS

The rolling resistance is primarily due to the friction of the vehicle tire on the road. Friction in bearings and the gearing system also play their part. The rolling resistance is approximately constant, and hardly depends on vehicle speed. It is proportional to vehicle weight.The equation is: $F_{rr} = \mu_{rr} mg$

where μrr is the coefficient of rolling resistance. The main factors controlling μrr are the type of tyre and the tyre pressure. Any cyclist will know this very well; the free-wheeling performance of a bicycle becomes much better if the tires are pumped up to a high pressure, though the ride may be less comfortable[11-13].

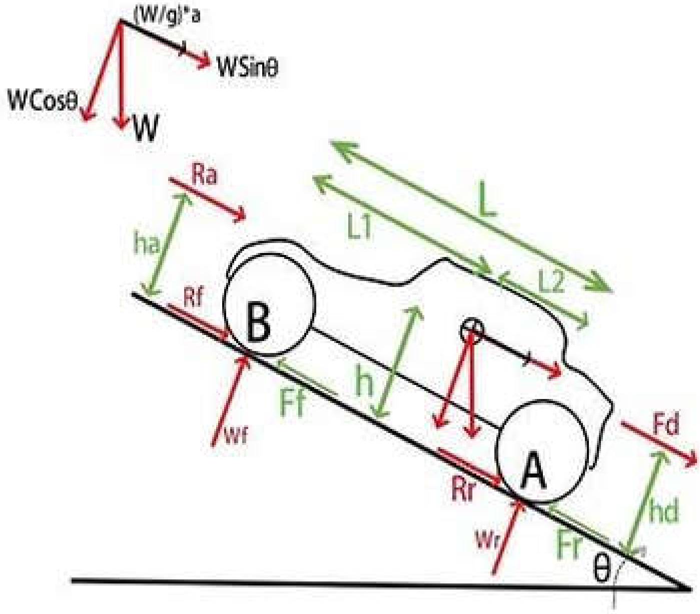

Figure 6: The forces acting on a vehicle moving along a slope

The value of μ_{rr} can reasonably readily be found by pulling a vehicle at a steady very low speed, and measuring the force required. Typical values of μ_{rr} are 0.015 for a radial ply tyre, down to about 0.005 for tires developed especially for electric vehicles. **Aerodynamic drag:** This part of the force is due to the friction of the vehicle body moving through the air. It is a function of the frontal area, shape, protrusions such as side mirrors, ducts and air passages, spoilers, and many other factors.

The formula for this component is: $Fad = 0.5\rho ACdv^2$

where ρ is the density of the air, A is the frontal area, and v is the velocity. Cd is a constant called the drag coefficient. The drag coefficient $C_d$can be reduced by good vehicle design. A typical value for a saloon car is 0.3, but some electric vehicle designs have achieved values as low as 0.19. There is greater opportunity for reducing Cd in electric vehicle design because there is more flexibility in the location of the major components, and there is less need for cooling air ducting and under-vehicle pipework. However, some vehicles, such as motorcycles and buses will inevitably have much larger values, and C_d figures of around 0.7 are more typical in such cases. The density of air does of course vary with temperature, altitude and humidity. However, a value of 1.25 kg.m−3 is a reasonable value to use in most cases. Provided that SI units are used (m2 for A, m. s−1 for v) then the value of Fad will be given in Newtons.

Grad Force: The force needed to drive the vehicle up a slope is the most straightforward to find. It is simply the component of the vehicle weight that acts along the slope. By simple resolution of forces, we see that: F_{hc}= mg sin(ψ)

Acceleration force: If the velocity of the vehicle is changing, then clearly a force will need to be applied in addition to the forces. This force will provide the linear acceleration of the vehicle, and is given by the well- known equation derived from Newton’s second law, F_{la} = ma.

Clearly the axle torque $=F_{te}\,r$, where r is the radius of the tire, and F_{te} is the tractive effort delivered by the powertrain.

If G is the gear ratio of the system connecting the motor to the axle, and T is the motor torque, then $T = F_{te}r/G$ and $F_{te} = T_G / r$.

Axle angular speed = v/r rad. s−1

So, motor angular speed ω = (G v)/r rad. s−1

Similarly, motor angular acceleration ω = (G a)/r rad.

The torque required for this angular acceleration is: T = IG (a/r)

where I is the moment of inertia of the rotor of the motor. The force at the wheels needed to provide the angular acceleration $(F\omega a)$ is found by combining this equation with equation, is written as : $F_w*a = (G/r)*IG(a/r)$

$$F_w = (IG^2 *a)/r^2$$

the gear system is 100% efficient, it causes no losses. Since the system will usually be very simple, the efficiency is often very high. However, it will never be 100%, and so it should refine the equation by incorporating the gear system efficiency η_g.

The force required will be slightly larger, so equation can be refined to:

$$F_{wa} = I\,a\,G^2/\eta_g\,r^2$$

Typical values for the constants here are 40 for G/r and 0.025 kg.m^2 for the moment of inertia. These are for a 30 kW motor, driving a car which reaches 60 kph at a motor speed of 7000 rpm. Such a car would probably weigh about 800 kg. The IG^2 term in equation will have r^2 a value of about 40 kg in this case. It will quite often turn out that the moment of inertia of the motor I will not be known. In such cases a reasonable approximation is to simply increase the mass by 5% in equation, and to ignore the Fωa term.

TOTAL TRACTIVE EFFORT:

The total tractive effort is the sum of all these forces: Fte= Frr + Fad + Fhc+ Fla + Fωa where, Frr is the rolling resistance force,

Fad is the aerodynamic drag, given by equation.

Fhc is the hill climbing force, given by equation.

Fla is the force required to give linear acceleration

Fωa is the force required to give angular acceleration to the rotating motor,

It should note that Fla and Fωa will be negative if the vehicle is slowing down, and that Fhc will be negative if it is going downhill.

4. SIMULATION OF EV FED WITH PMSM USING MATLAB

4.1 SIMULATION CIRCUIT OF PMSM:

The circuit includes the following blocks

- Park Clark Transformation block
- Three phase voltages
- Id and Iq current calculation block
- Torque calculation block
- Speed calculation block
- Dynamics of Electric Vehicle
- Controllers

The complete simulation diagram of PMSM is shown in figure 7 The simulation circuit diagram includes mainly five blocks namely, three phase voltage block, park Clark transformation block, current calculation block, torque calculation block and speed calculation blocks. The simulation circuit diagram approach enables control of PMSM in a more intuitive and managing way, reducing complexity of controlling three phase systems. It is used extensively in motor control applications for precise and efficient control of PMSM motors[14],[15].

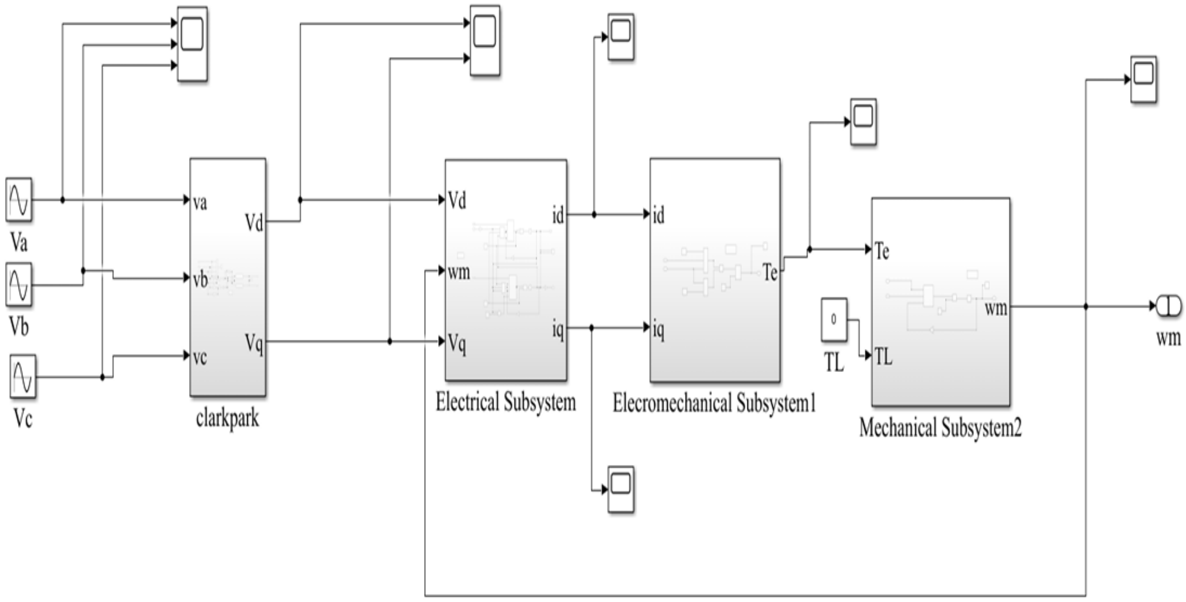

Figure 7: Simulation circuit of PMSM

4.2 Simulation circuit of Electric Vehicle dynamics

Electric vehicle dynamics refers to the study of how electric vehicles behave and respond to various driving conditions and external forces as shown in figure 8. While the basic principles of vehicle dynamics still apply to electric vehicles, there are some differences due to the unique characteristics of electric powertrains.

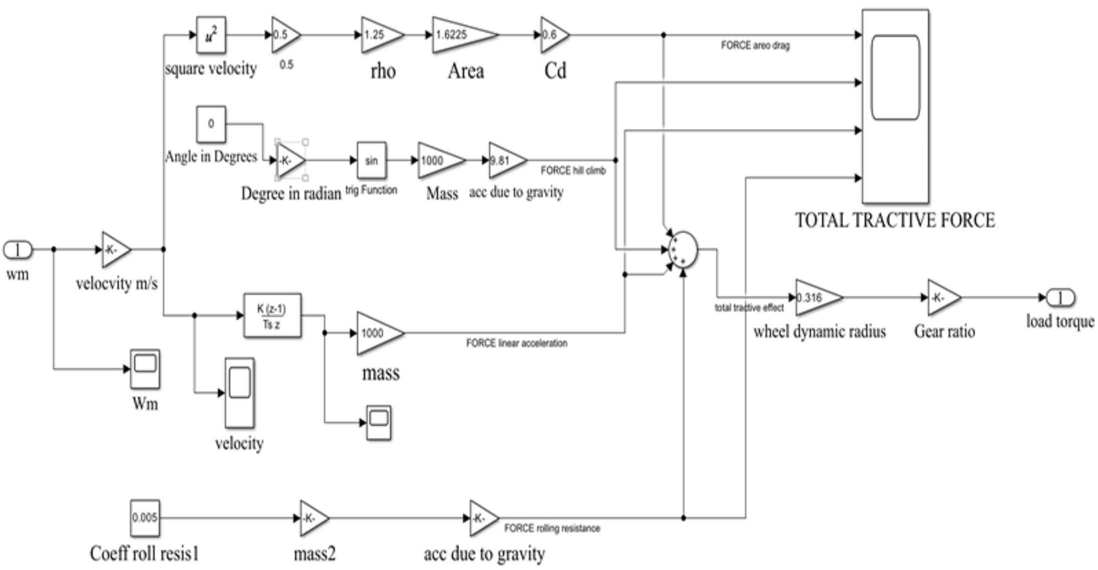

Figure 8: simulation of Electric Vehicle dynamics

4.3 PMSM fed with PI controller to Electrical Vehicle

The figure 9 shows the torque ripple reduction control of PMSM using PI controller connected to the electric vehicle. The figure consists the reference speed and with PI controller. The 3-phase supply is given to the Clark Park transformation to get 2 phase supply later to the PMSM model to get the load torque of electric vehicle**.**

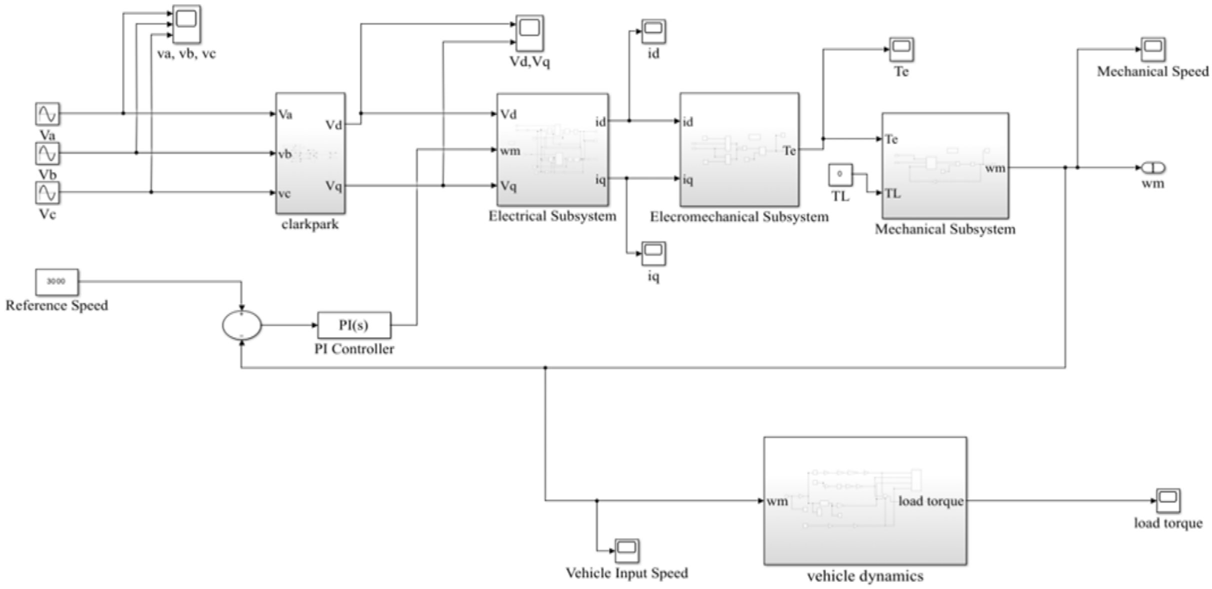

Figure 9 : PMSM fed with PI controller to EV for load torque calculation

4.4 PMSM with Fuzzy Logic Controller for Electric Vehicle

The figure 10 shows the speed control of PMSM using fuzzy logic controller. The figure consists the reference speed and with fuzzy logic controller. The 3-phase supply is given to the Clark Park transformation to get 2 phase supply, later to the PMSM model to get the speed control of electric vehicle. the torque ripple reduction control of PMSM using PI controller connected to the electric vehicle. The figure consists the reference speed and with PI controller. The 3-phase supply is given to the Clark Park transformation to get 2 phase supply later to the PMSM model to get the load torque of electric vehicle.

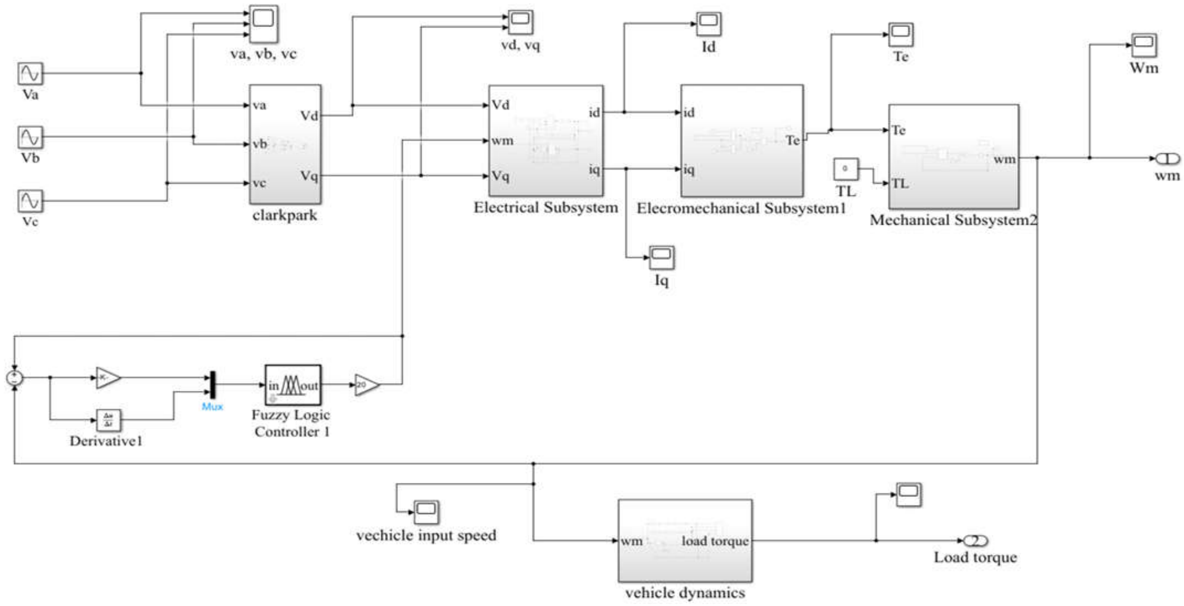

Figure 10: PMSM fed with Fuzzy Logic Controller to EV for load torque calculation

5. SIMULATION RESULTS

5.1 Simulink result for speed control of PMSM with PI control

Speed can be achieved through various means, including controlling the voltages and frequency supplied to the motor. Factors such as motors design, load torque and control strategy will influence how quickly and efficiently the motor can reach and maintain the desired speed of 2000 RPM from 3000RPM as shown in figure 11.

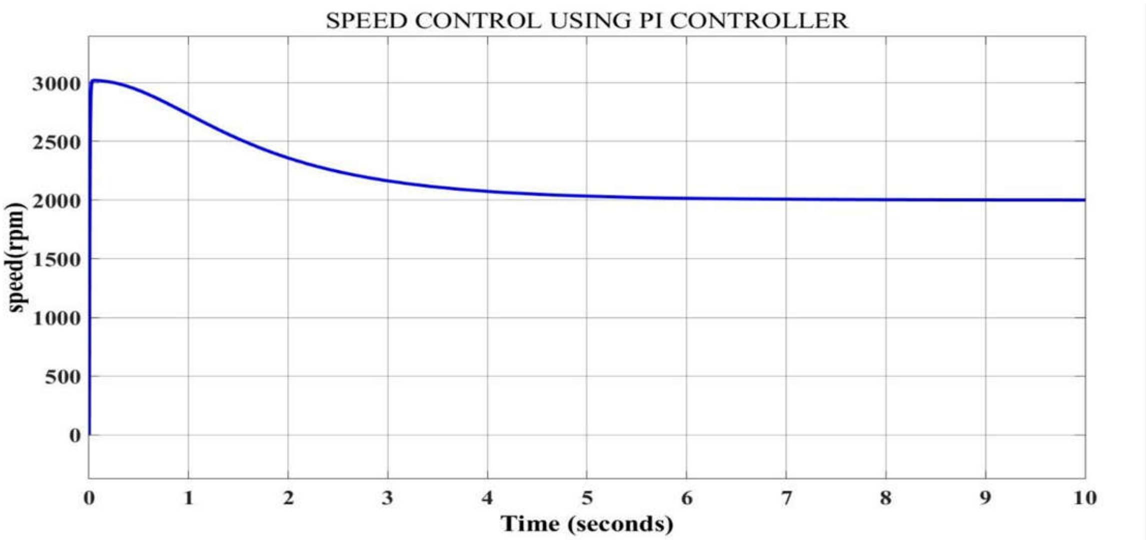

Figure 11: Speed control of PMSM fed with PI controller

5.2 Simulink result for speed control of PMSM with Fuzzy Logic Controller

Speed can be achieved through various means, including controlling the voltages and frequency supplied to the motor. Factors such as motors design, load torque and control strategy will influence how quickly and efficiently the motor can reach and maintain the desired speed of 3000 RPM as shown in figure 12.

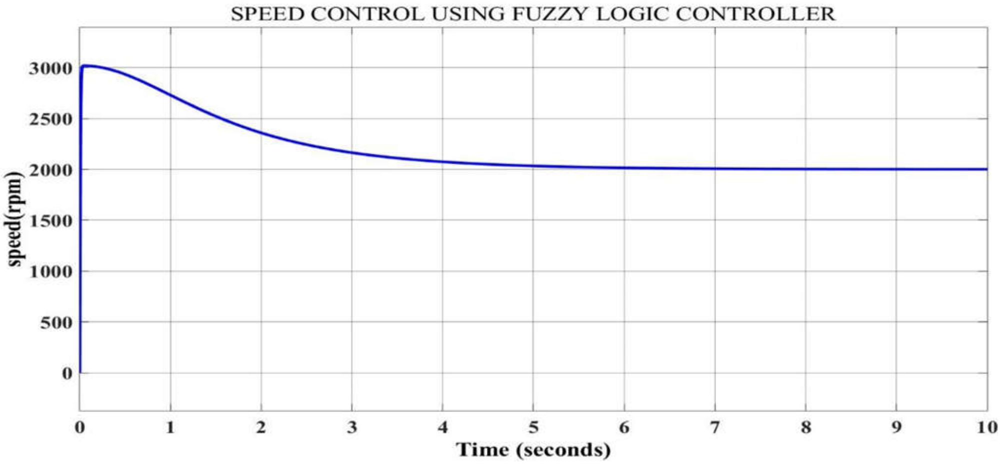

Figure 12 : Speed control PMSM fed with Fuzzy Logic Controller

5.3 Simulink result for load torque of PMSM fed with PI controller

Figure 13 represents the torque required to move the vehicle, as the speed goes on increasing load torque goes on decreasing. As the vehicle reaches reference speed the torque required to move vehicle further is very minimal.

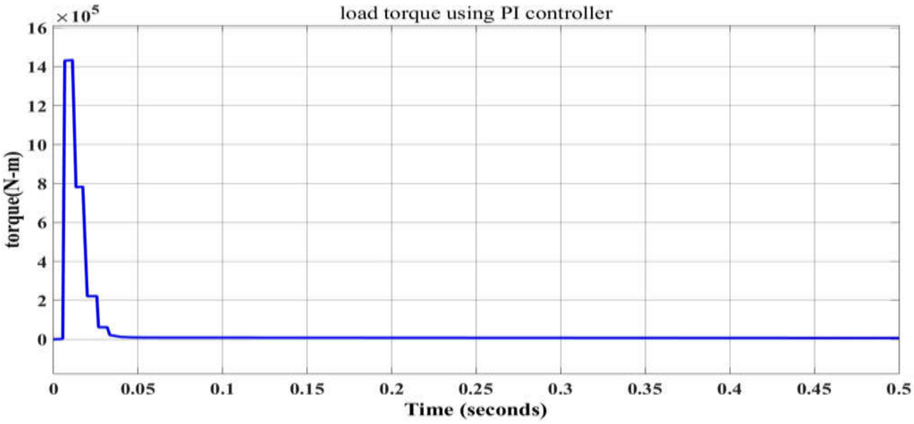

Figure 13 : Result for load torque of PMSM fed with PI controller

5.4 Simulink result for load torque of PMSM fed with Fuzzy Logic Controller

Figure 14 represents the torque required to move the vehicle, as the speed goes on increasing load torque goes on decreasing. As the vehicle reaches reference speed the torque required to move vehicle further is very minimal.

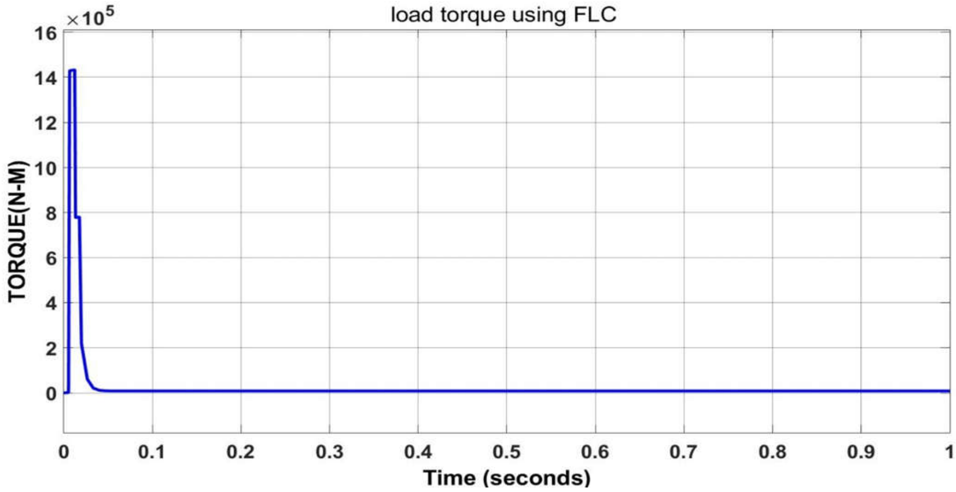

Figure 14 : Result for load torque of PMSM fed with FLC

Table 1: Comparison Between Results of PI Controller and Fuzzy Logic Controller

PARAMETER	PI CONTROLLER	FUZZY LOGIC CONTROLLER
VOLTAGE INPUT	240 VOLTS	240 VOLTS
SPEED	3000 RPM	3000 RPM
LOAD TORQUE	8460 N-M	8413 N-M
RISE TIME	485.816 μSec	944.144 μSec
OVERSHOOT	1.479 %	0.991 %
SETTLING TIME	15.455 mSec	12.906 mSec

Table1 shows The model also integrates the dynamics of the electric vehicle, such as vehicle mass, friction, and load. For controlling the PMSM, different strategies are implemented and tested, including a conventional PI (Proportional-Integral) controller and an intelligent Fuzzy Logic controller, each influencing the motor’s performance differently. The simulation results allow for comparative analysis of control strategies in terms of torque response, speed regulation, and overall system efficiency, offering insights into the optimal design and control of EV drive systems.

CONCLUSION

This work focused on the design and simulation of an electric vehicle (EV) powered by a Permanent Magnet Synchronous Motor (PMSM), incorporating both Proportional-Integral (PI) and Fuzzy Logic Control (FLC) strategies for enhanced performance. The simulation was executed using MATLAB/Simulink, and the results affirm the advantages of intelligent control in modern electric drive systems. The primary objectives were to achieve efficient speed control, minimize torque ripple, reduce overshoot, and optimize dynamic response characteristics such as rise time. The PI controller, being a conventional linear control method, showed acceptable performance under steady-state conditions but exhibited limitations in handling nonlinearities and sudden load variations. In contrast, the FLC demonstrated a more adaptive and robust response, particularly in transient states. In terms of speed control, the FLC provided a faster settling time and more precise tracking of the reference speed, with significantly lower overshoot. The rise time was notably shorter, allowing the system to reach the desired speed quickly without introducing instability. This enhanced responsiveness is critical for applications such as EVs, where rapid and smooth acceleration is essential. Moreover, the FLC exhibited superior performance in controlling torque ripple. The torque produced by the PMSM under FLC control was smoother, reducing mechanical vibrations and improving overall vehicle comfort and component lifespan. Such improvements contribute to better energy efficiency and reliability of the drive system. In conclusion, the implementation of FLC in the control loop of a PMSM-driven electric vehicle results in enhanced dynamic performance, reduced overshoot, improved rise time, and minimized torque ripple compared to traditional PI control.

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