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Torque ripple reduction in PMSM for FCEVs using ANFIS controller

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ABSTRACT

Globally, there is a growing emphasis on switching to green energy, particularly in the transportation sector, due to the effects of global warming, as seen by rising carbon footprints. Fuel cell electric vehicles (FCEVs) are one such technology that has attracted a lot of interest because of their availability, ease of use, high efficiency, and silent operation. Fuel cells are employed along with batteries to drive the vehicle much farther. Motors like permanent magnet synchronous motor (PMSM) provide the driving force for the vehicle, owing to their high torque at variable speeds and compactness. In such systems, it is necessary to have intelligent controllers that can align with the load requirement by means of a consistent and optimized power distribution. The torque ripple phenomenon, which has an impact on dynamic performance and operational stability, is one of the main limitations in the operation of PMSMs. In this work, smart control techniques, which are a combination of adaptive neuro fuzzy inference systems (ANFIS) and proportional-integral (PI) control, are employed to demonstrate the application of PMSM in conjunction with field-oriented control (FOC). Simulation results indicate that the proposed ANFIS-based FOC reduces torque ripple as compared to conventional PI control under varying load conditions.

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1. INTRODUCTION

Battery electric vehicles (BEVs) are limited by range and can be bulky for long-distance travel. Furthermore, the bigger the battery, the longer it takes to get charged. Batteries also have a limited lifespan; their performance depletes with time, and we need to consider the mitigation of the disposal of aged-out batteries, which pose an environmental hazard [1]. In comparison with a battery, fuel cells generate electrical energy instead of storing it and do so as long as the fuel supply is maintained. Fuel cell electric vehicles (FCEVs) offer various benefits, including a rapid refuelling time that makes them suitable for long-distance journeys. Fuel cells cannot react to sudden transient speed and torque variations due to the time required to change the fuel supply rate and fuel reaction rate. This supply time gap should be mitigated intelligently by the use of battery packs.

Although direct current (DC) machines are well known for their ease of control, alternating current (AC) motors have advantages such as lower maintenance and higher efficiency [2]. In the case of electric vehicles (EVs), the choice for motors includes induction motors, brushless DC motors, and permanent magnet synchronous motors (PMSMs). As loads are non-linear, the control system for fuel injection should be dynamic and fast-responsive [3], which leads to reduced efficiency. PMSMs are generally preferred in EVs due to lower torque ripple, higher torque density, good low-speed performance, higher efficiency and lower acoustic noise compared to brushless DC (BLDC) motors [4]. BLDC motors are well known for simpler control strategies, such as step control, which limit performance optimization. Ha and Van Hai [5] present an adaptive neuro-fuzzy inference system (ANFIS)–based torque controller for an in-wheel single-sided axial flux permanent magnet synchronous motor (AFPMSM) used in electric vehicles. The proposed ANFIS controller is designed within a field-oriented control framework and compared with conventional proportional integral (PI) and fuzzy logic controllers. MATLAB/Simulink results demonstrate that ANFIS provides superior torque tracking, reduced torque ripple, improved efficiency, and better robustness to parameter variations. The study highlights the effectiveness of intelligent hybrid control strategies for enhancing torque performance and stability in in-wheel AFPMSM-based electric vehicle traction systems. Chaudhary *et al.* [6] present a topology featuring a modified boost DC-DC converter connected to the PMSM via field-oriented control (FOC). The study highlights the use of the FOC strategy for fuel-cell-based EVs equipped with PMSMs. Regenerative braking artefacts by means of a bi-directional converter have not been considered. Basappa and Viswanathan [7] propose FOC on ANFIS for PMSM-based EVs handling nonlinearities. ANFIS-based approach gives smoother performance, but does not evaluate torque ripple, which is a key parameter for use in EV's.

Table 1 presents a comparison of commonly used control techniques, including FLC [8], particle swarm optimization (PSO), and FOC. The FLC-based values exhibit a maximum torque ripple of 13.5% as compared to multiobjective PSO of 7.3% and 77.6% with hysteresis band current controller [9]. The findings from the table above highlight the significant ripple in traditional methods, such as FLC, PI control-based FOC, and traditional FOC. By leveraging smart control techniques such as PSO or ANFIS-based control, EVs can operate with much higher precision and provide a smoother drive experience in EVs.

Table 1. Comparison of control techniques for PMSM drives

Controller	Torque ripple	Inference
FLC	0.135	Good
Multiobjective PSO	0.073	Fast
FOC	0.776	Poor

2. METHOD

The inherent issue with FCEVs is the torque ripple, which leads to jerks while driving the vehicle. It also increases ambient noise and mechanical stress, and reduces drive-train efficiency. The primary reasons for torque ripple are fuel injection, control strategy slowness, inverter harmonics, and battery internal resistance. This paper shall address countering fuel injection, control strategy slowness, and torque ripple reduction by using an ANFIS controller. A closed-loop FOC for fuel cell electric vehicles employing PMSM motors. The system parameters, voltage, current, and speed, are sensed and fed to the controller, as shown in Figure 1(a). Figure 1(b) shows the control operation with the ANFIS controller.

The initial research began with choosing an off-the-shelf PMSM motor simulation in MATLAB. It is crucial to design a smart controller, such as ANFIS, to produce a fast and more concise output response to variations in the load. Fuel cells operate at a nominal DC voltage and are slow to react to sudden changes in load, leading to transients. Thus, an additional battery is employed in parallel, which not only supplies transient power but can also store energy during braking [4]. There are different types of controllers suggested in [5], such as the PI controller, ANFIS controller, fuzzy controller, and neural network [6], sliding mode controller [7].

DC-AC converter/inverter is needed to feed the DC voltage to the PMSM motor. The control strategy is based on techniques such as direct torque control (DTC) [10] and FOC. The proposed topology includes 2 energy sources, viz.: fuel cell and battery packs. Fuel cells cannot be recharged by supplying current and can only dissipate power through the use of fuel, and thus can be called a unidirectional power source [8]. Thus, on light loads, the residual power from the fuel cell's operation is used to recharge the battery. The output voltage of the fuel cell drops under various scenarios, such as concentration drop, activation drop, and an increase in the output current. Thus, there is a need for voltage stabilization at the output of the fuel cell [9]. Batteries, on the other hand, can either supply power to the load under various light-load conditions or can be recharged as well with residual power and regenerative braking.

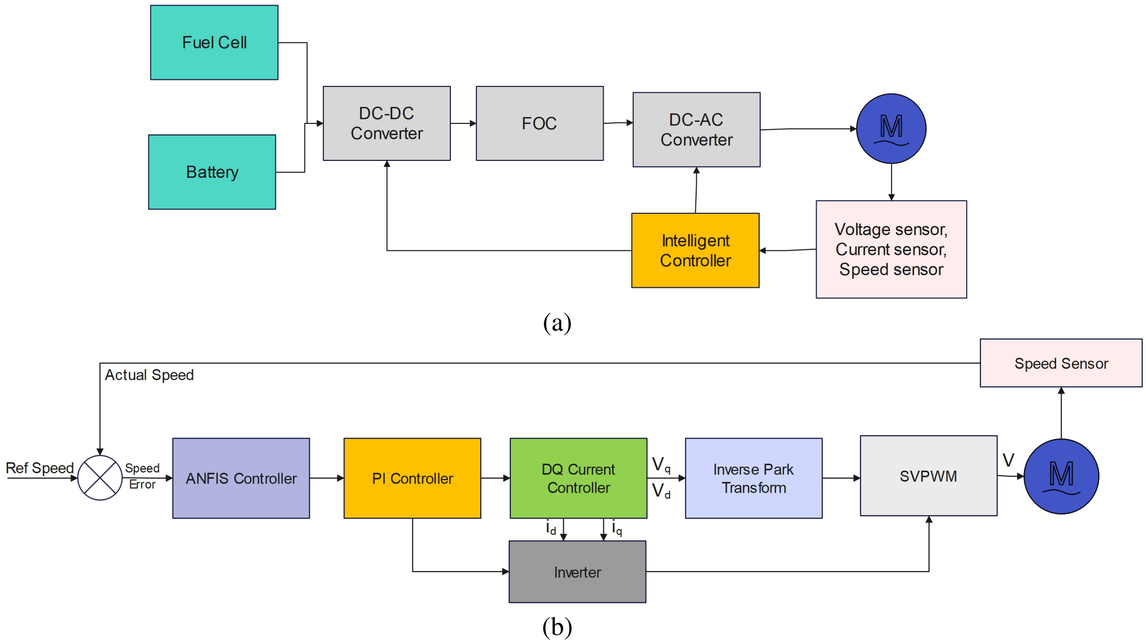


Figure 1. Proposed system block diagram: (a) proposed system of fuel cell with battery EV system and (b) FOC block diagram with ANFIS

2.1. Bidirectional converter

A bidirectional DC-DC converter is employed to bridge the connection between a fuel cell and a battery, as shown in Figure 2, due to the difference in rating and dynamic load. This converter shall play a crucial role in regulating and managing the desired output voltage, current, and power. The converter achieves buck-boost functionality by transferring energy between two inductors and capacitors through controlled switching, which controls the output voltage [11]. The control can be adjusted by varying the duty cycle of the switch, the switching frequency, and other aspects based on the load and input conditions.

The flowchart, as shown in Figure 3 explains the 3 modes of operation of bidirectional converter, viz.: i) fuel cell supply mode (boost operation) explains that the fuel cell supply mode indicates that all the load power is supplied by the fuel cell, ii) battery assist mode indicates that power to the load is supplied by both the fuel cell and battery combined, and iii) regenerative braking mode which supplies power back to the battery during braking operation. This means that the transients of the load are not directly seen by the fuel cell and are borne by the battery output. The output shown in Figure 4(a) depicts the regulation of 0.1% with the steady state converter voltage of 58 V. Figure 4(b) shows the equivalent MATLAB simulation model.

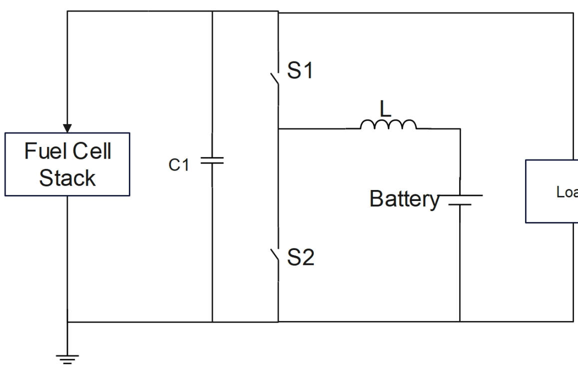


Figure 2. Bidirectional converter schematic

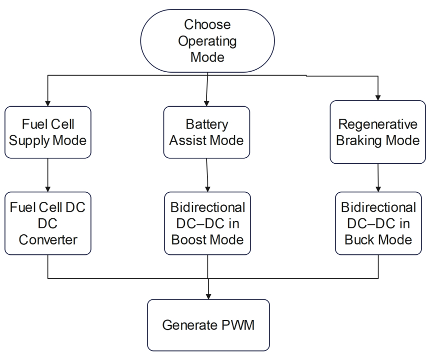
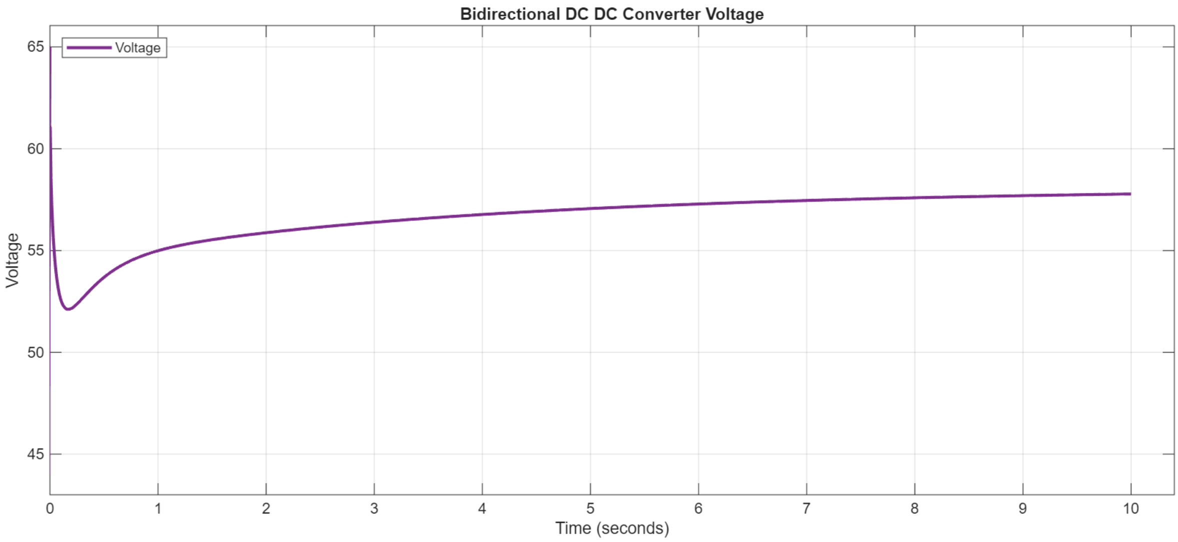
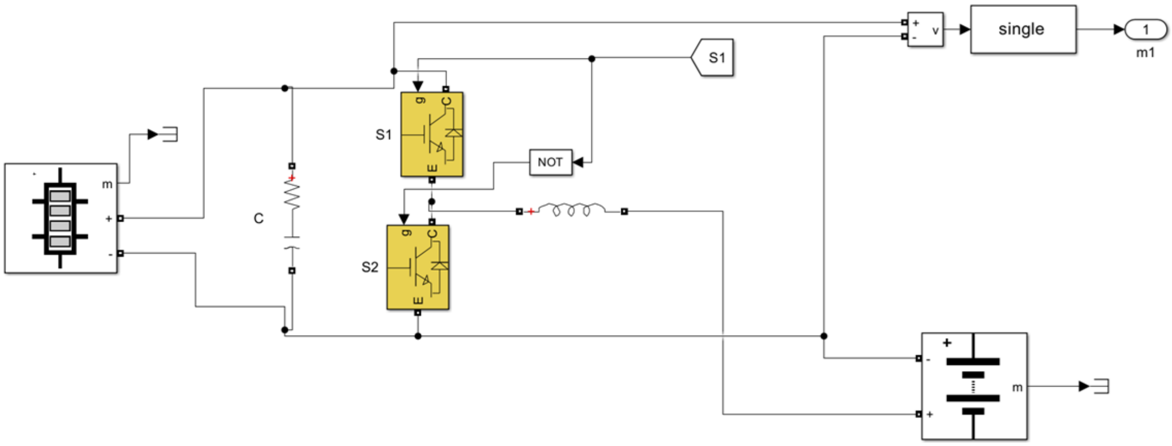


Figure 3. Bidirectional converter



(a)



(b)

Figure 4. Bidirectional converter: (a) DC output and (b) MATLAB simulation

2.2. Permanent magnet synchronous motor

PMSM motors are the preferred choice for FCEVs due to their superior characteristics, improved efficiency, compact size, reduced noise levels, and rotor inertia [12]. The motor rating needs to be carefully chosen to match the maximum torque required and current rating, and this can be achieved by selecting intelligent controllers. The intelligent controller controls the DC-DC converter as well as the DC-AC inverter. The main purpose of FOC is to maintain the stator and rotor fields perpendicular to each other to produce maximum torque [13]. The control signal is aligned with the magnetic field of the rotor. The three-phase stator currents I_a, I_b, I_c are converted into 2-phase stationary frame (I, Q) known as Clarke's Transform. By using the angle θ_r and Park's transform, stationary currents are converted into a rotating reference frame known as the d-q frame (I_d, I_q). The error observed between the reference current, derived from the computation of stator flux, and the actual current is fed to the controller for current control, which converts the difference into voltage terms used for PWM generation [14]. Two control modes are used in FOC, viz.: current control and speed control. As the loads are nonlinear, the motor torque changes rapidly, which affects the current requirement; maintaining voltage regulation during load switching [15]. The fundamental equation of torque (T_e) in a PMSM is as in (1).

$$T_e = \frac{3p}{2}(\psi_m i_q + (L_d - L_q)i_d i_q) \tag{1}$$

Where p number of poles, ψ_m rotor flux linkage. i_d, i_q, L_d, L_q D and Q axis stator current and inductance.

The torque comprises two parts: magnetic torque, the more dominant, produced by the interaction between the permanent magnet flux and the quadrature current i_q, and reluctance torque, which is produced by the differences in inductance between d and q axes. The problem with operating the PMSM at rated flux is that the maximum speed is limited by stator voltage, rated current, and back electromagnetic force (EMF) [16]. In such scenarios, the option is to go with field weakening control of the motor, which controls the D-axis current by inducing a negative value. By doing so, the rotor flux linkage reduces and thus higher speeds above base speed are possible.

PMSM motor has a sinusoidal type of back EMF that interacts with the stator currents to produce the motor torque [17]. Distortions caused in the back EMF shall further increase the torque ripple. Owing to its sinusoidal back EMF, the motor shall have smooth torque production and lower harmonics as compared to other motors. Stator current analysis is essential for understanding its control characteristics, performance expectations, and achievable efficiency. They are 120-degree phase-shifted and balanced in ideal conditions [18]. Under loaded conditions, the stator current increases proportionally to maintain the torque, thereby introducing harmonics due to saturation and potentially non-linearities [19]. These can be balanced out by means of a closed-loop control by employing an additional PI controller.

The Park transform involves converting 3-phase stator currents, which are sensed using a current sensor, into a non-rotating DQ-axis frame [20]–[22]. The purpose of doing so is to simplify the operation in a 3-phase rotating frame. The degree of freedom in a PMSM includes current, voltage, torque, and speed [23]. The MATLAB model used in this work is shown in Figure 5.

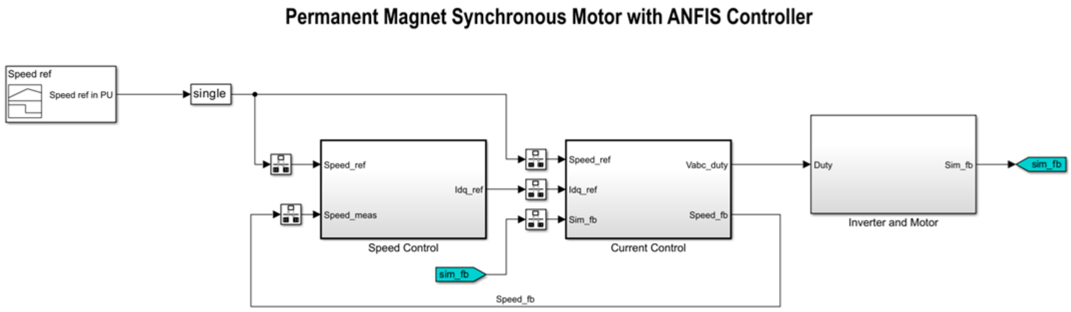


Figure 5. MATLAB simulation model

2.3. PI controller and ANFIS controller

A PI controller is a very commonly used feedback controller to minimize the error as compared to the reference, which combines proportional and integral action to past error [24]. The system transfer function can thus be defined as (2).

$$u(t) = K_p e(t) + K_i \int e(t)dt \tag{2}$$

Where K_p is the proportional gain K_i is the integral gain, and $e(t)$ is the error. PI controllers in this work have been used in a couple of stages as: i) control of I_d and I_q with respect to reference; ii) firing angle control of bi-directional DC-DC converter.

ANFIS controller is an artificial intelligence-based control technique that incorporates a neural network with a rule-based reasoning of fuzzy logic. It represents an advanced control strategy for PMSM that combines the strengths of neural networks and fuzzy logic systems. ANFIS controllers are particularly valuable in electric vehicle drive systems requiring precise torque control, high precision positioning systems and robotics [25], [26]. Due to this hybrid approach of using both PI and ANFIS, we can effectively mitigate the effects of non-linear motor and load dynamics.

Non-linear control, as provided by the ANFIS controller, learns and models PMSMs' characteristics effectively [27]. It can dynamically adjust its control rules in real time as conditions (load, speed, temperature) change. Thereby, we can say that ANFIS minimizes energy losses and improves drive efficiency [28] and achieves good speed and torque tracking. Furthermore, it optimizes control parameters without requiring manual tuning. Therefore, we can say that this controller works in tandem with the PI controller to ensure ripple-reduced torque and intelligently balance fuel cell and battery power.

The ANFIS controller design for fuel cell EVs comprises the following stages [29], and it is as shown in Figure 6. Fuzzification of the input to generate the membership grade of the input. Rule-based optimization by means of removing rarely used rules and by the use of the genetic algorithm (GA), to select optimal values. In this work, hybrid controllers are employed, which are a combination of PI and ANFIS, to stabilize performance. The fuzzy logic controller employs a proportional-integral (PI) configuration, where a fuzzy inference system (FIS) utilizes speed error and its derivative values to generate the required q-axis current values, thereby maintaining the desired motor speed. No changes were made to the ANFIS structure from MATLAB; the rules below were optimized to improve the performance with FCEVs.

- If the error is negative and the rate is also negative, the output is -1.
- If the error is positive and the rate is also positive, the output is 1.
- All other cases (error and rate differing in sign), output is 0.

The model configurations include the following parameters for the ANFIS tuning, viz.: Kp, Ki, controller scaling factors (C_0, C_e,C_d) are derived from the conventional PI controller gains. Table 2 gives the ANFIS tuning parameters, and Table 3 gives the PI Controller tuning parameters for current control and firing angle control. These values are chosen on a trial-and-error basis.

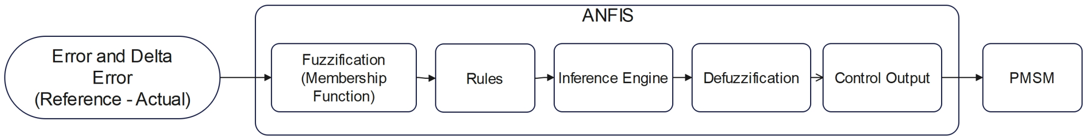


Figure 6. ANFIS control block diagram

Table 2. ANFIS tuning parameters

Parameter	Value
Error scaling factor (Ce)	1
Change in error scaling factor (Cd)	0.15149
Output scaling factor (C0)	15.177

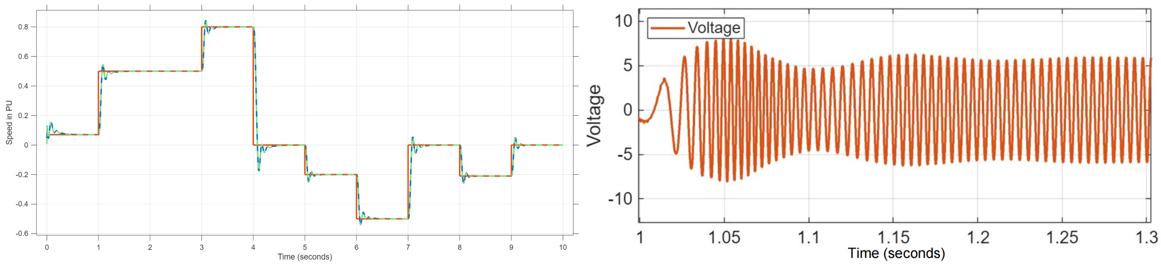
Table 3. PI tuning parameters

Parameter	Current controller (1)	Firing angle control (2)
Kp	5	0.3005
Ki	1	0.2291

3. RESULTS AND DISCUSSION

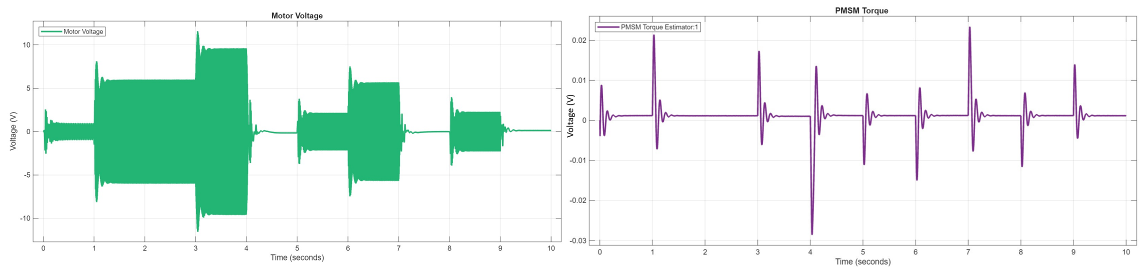
Reference speed was chosen to depict changing load conditions at time intervals of 1 second. As shown in Figure 7(a), at startup, there is a slight overshoot in rotor speed before it settles into its steady-state. The speed feedback closely follows the changes in the reference load speed with rapid settling (0.25 s), indicating a well-tuned loop. At each speed step, brief oscillations appear in speed and torque. Figure 7(b) shows the voltage transients waveform, which also indicates the transient settling with overshoot of approximately 5%. Figure 8(a) shows the motor voltage closely following the change in load demand. The controller exhibits good dynamic performance with good transient settling time (0.25 s), accurate tracking, and stable bidirectional speed control, thus making it suitable for applications such as PMSM drives in FCEVs. ANFIS controllers clearly demonstrate superior motor control with swift acceleration. Further, the low overshoot from the desired speed demonstrates crisp and precise speed control. The transients seen at the time of phase switching are a typical characteristic of PMSM. Although the sampling time of the simulation was chosen as 100 us, increasing the sampling time does not bring forward any further improvement in ripple reduction. Only changes with respect to the control technique to use, machine learning methods such as reinforcement learning, can further improve the transient settling time.

Table 4 gives the motor parameters chosen for simulation, and Table 5 gives the simulation output. Figure 8(b) shows the motor torque. Since the Iq directly controls torque as from the PMSM fundamental torque equation, it can be inferred directly that the torque control is exactly as expected.



(a) (b)

Figure 7. Speed and current comparison with reference: (a) speed comparison with reference and (b) voltage transients



(a) (b)

Figure 8. Motor voltage and torque comparison with reference: (a) motor voltage and (b) motor torque

Table 4. Motor parameters in simulation

Parameter	Value	Parameter	Value
Number of pole pairs	7	Stator inductance per phase	87.678 uH
Rated current	7.26 A	Nominal base speed	3476 rpm
Rated torque	0.3471 Nm	Rated power	200 W
Stator resistance per phase	0.293 Ω		

Table 5. Simulation output

Simulation output	Value
Voltage overshoot	5%
Torque ripple	2.35%
Settling time	0.25 s
Sampling time	100 us

4. CONCLUSION

Fuel cell-based electric vehicles have been modeled by means of a fuel cell battery system, which serves as an optimum control system to regulate fuel usage as well as charge the battery under light load conditions. The simulations have been done considering varying load conditions in practical scenarios. Smart controllers can significantly reduce torque ripple and regulate speed. In FCEVs, torque and speed must be controlled efficiently to achieve the best results. The obtained speed responses confirm that the implemented control strategy achieves accurate and stable speed regulation over a wide operating range. The motor speed consistently tracks the reference commands with minimal steady-state error, indicating effective control action. Although small transient overshoots and oscillations are observed during sudden speed changes and direction reversals, they are well damped and settle quickly, demonstrating good dynamic stability. The controller maintains smooth transitions between motoring, zero-speed, and regenerative (reverse) operation, which is critical for applications such as PMSM-based FCEVs. Overall, the results validate that the control scheme provides robust bidirectional speed control, fast transient response, and reliable performance under varying speed commands, making it suitable for practical traction drive applications. The future room for improvement is the reduction of harmonics of AC voltage, and further reduction in torque-speed ripple. It is proposed that this can be further reduced by the use of ML techniques.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Shilpa Rao Hosabettu	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	
Pushpa Rajesh Viswanathan		✓				✓		✓	✓	✓	✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal Analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject Administration
Fu : **Fu**nding Acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [SRH], upon reasonable request.

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