



# MINIMISATION OF TORQUE RIPPLE IN BLDC MOTOR USING HYBRID CONTROLLER

**Atanu Tarafdar,**

Department of Electrical Engineering,  
NITTTR Chandigarh, India  
atanu.jgecee@gmail.com

**Ritula Thakur,**

Department of Electrical Engineering,  
NITTTR Chandigarh, India  
ritula@nitttrchd.ac.in

**Abstract :** This paper proposes an Adaptive Neuro-Fuzzy Inference System (ANFIS)-based intelligent DC-link voltage controller for minimizing torque ripple in Brushless DC (BLDC) motor drives. The controller adaptively adjusts the DC-link voltage during commutation intervals to achieve smoother current transitions and improved electromagnetic torque profiles under varying speed and load conditions. A complete BLDC drive model is developed in MATLAB/Simulink, and the proposed approach is evaluated at both low-speed and high-speed operating points. Simulation results show that the ANFIS controller significantly reduces torque ripple, enhances current waveform symmetry, and improves transient stability compared to the baseline intelligent controller. The proposed method demonstrates strong potential for high-performance electric drives, automotive systems, and robotics applications requiring precise torque control..

**IndexTerms -** ANFIS, BLDC, Torque ripple reduction, DC-link voltage control

## I. INTRODUCTION

### I. Introduction

BLDC motors are widely used in electric transportation, robotics, industrial automation, and household appliances due to their high efficiency, compact structure, and excellent power density. Their trapezoidal back-EMF and simple electronic commutation make them attractive for low- and high-power applications alike. However, BLDC drives inherently experience significant torque pulsations, particularly during commutation, because the phase currents cannot change instantaneously in the presence of winding inductance and non-ideal back-EMF waveforms. These torque fluctuations are directly linked to mechanical vibration, acoustic noise, and reduced control precision, which limits the suitability of BLDC machines in high-performance environments where smooth torque delivery is essential[1]. A substantial body of research has explored torque ripple suppression through various strategies such as current shaping, voltage modulation, direct torque control (DTC), and converter-assisted commutation. PWM modulation techniques have been shown to significantly influence both commutation and non-commutation torque ripple components, leading to several modulation refinements that aim to manage freewheeling currents and minimize phase-to-phase disturbances [2]. Other studies have introduced auxiliary hardware such as step-up circuits, which momentarily boost the dc-bus voltage during commutation to achieve faster current transitions and reduced torque ripple, although these solutions typically increase circuit complexity and component stress [3]. More advanced control approaches—such as DTC employing hybrid voltage vectors, overlapping sector strategies, and open-end winding topologies—have also shown promise in reducing commutation-induced disturbances while retaining fast dynamic response. Nonetheless, these methods frequently require complex switching tables, precise parameter estimation, or computationally heavy algorithms, which limits their applicability in cost-sensitive or embedded systems [4]. Parallel to BLDC research, related work on other motor types such as switched reluctance machines (SRMs) reinforces the broader significance of torque ripple reduction in electric drives. Studies have demonstrated that ripple-induced vibration and acoustic noise are serious concerns, prompting the development of multi-stage control schemes, current profiling methods, and optimization-based torque shaping techniques to achieve smoother operation [5]. Recent surveys on torque ripple mechanisms further emphasize that BLDC performance is heavily influenced by commutation behaviour, structural design, and control strategies. A comprehensive review on ripple sources and mitigation strategies highlights that torque pulsations stem from multiple factors, including non-ideal back-EMF, freewheeling diode conduction, current distortion, Hall-sensor uncertainties, converter nonlinearities, and PWM switching patterns. These issues collectively affect vehicle drivability, energy efficiency, and acoustic comfort, especially in electric vehicle propulsion systems where smooth torque delivery is essential [6]. Despite the availability of advanced algorithms such as FOC, DTC, MPC, CIV-based control, and intelligent approaches, guaranteeing ripple-free operation over diverse

operating conditions remains challenging [7]. Sensor accuracy is another critical factor in torque ripple performance. As shown in studies on Hall-sensor-based BLDC drives, even minor asymmetries in sensor placement can distort commutation timing, leading to elevated current ripple, acoustic noise, and degraded dynamic response. An improved switching-point estimation method was introduced to compensate for sensor misalignment and reduce phase current distortion, demonstrating that control precision plays a major role in ripple suppression [8]. In addition to improving sensor reliability, recent work explores power converter and inverter topologies to reduce ripple. Multi-level inverter configurations and open-end winding structures offer additional voltage vectors that can align the stator current more accurately with the trapezoidal back-EMF. A multilevel voltage space-vector scheme for dual-inverter open-end-winding BLDC drives has shown substantial torque ripple reduction by minimizing error voltage vectors and enabling flexible PWM operation across speed ranges. These topological advancements reduce switching losses and expand the control flexibility of BLDC drives but introduce additional hardware complexity [9]. Similar ripple mitigation challenges have also been widely studied in PMSM and induction motor platforms. Predictive torque control (PTC) methods, for instance, have been improved with duty ratio regulators to reduce torque and flux ripple, especially in low-speed operating regions where conventional DTC exhibits large ripple and variable switching frequency. Likewise, ripple reduction in three-level NPC inverter-fed induction motors has been achieved using interleaving duty-cycle modulation to maintain constant switching frequency and minimize flux droop in low-speed operation, demonstrating the universal need for ripple suppression across motor types [10]. Beyond control strategies, researchers have also examined machine structural enhancements for ripple mitigation. Studies on Vernier and wound-field machines demonstrate that torque pulsations can be reduced significantly by embedding optimized flux barriers in the rotor. Using topology optimization and Maxwell stress-based analysis, these designs achieve smoother torque profiles without sacrificing torque density or magnet utilization efficiency, providing insights applicable to BLDC machine improvement as well. Foundational work on BLDC commutation torque dynamics further highlights the inherent limitations of current shaping during the commutation interval. Classical techniques often struggle because BLDC drives exhibit a large electrical time constant, making precise current wave shaping difficult when inductance delays the rising and falling of currents. The well-cited neural network-PSO controller introduced an optimal DC-link voltage regulation approach that adaptively increased the input voltage during commutation to keep phase currents close to their ideal values, demonstrating that DC-link modulation can directly influence torque smoothness without complex current profiling [11]. More recently, DC-link voltage modulation techniques have gained significant attention for torque ripple mitigation in BLDC drives, adding a front-end DC converter allows dynamic DC voltage shaping synchronized with commutation intervals. By adjusting both DC voltage and DC current to match rotor position and harmonic conditions, this method successfully mitigates freewheeling diode conduction effects and phase-current misalignment, achieving up to 40% reduction in torque ripple under experimental validation this demonstrates that intelligent adjustment of the DC-link offers an effective alternative to traditional current or PWM modifications, especially for low-speed applications [11]. Collectively, these works confirm that achieving consistently low torque ripple across different operating conditions remains an open challenge. Existing methods—whether based on PWM refinement, predictive control, multi-level inverters, or structural improvements—either require additional hardware, depend on accurate machine parameters, or involve complex computations. This motivates the need for more adaptable control techniques capable of learning nonlinear relationships and adjusting the DC-link behaviour dynamically without heavy reliance on precise motor modelling.

The remainder of this paper is organized as follows. Section II presents the system modelling, baseline BLDC configuration, and Section III describes control architecture. Section IV the design and implementation of the proposed ANFIS-based DC-link controller. Section V discusses the performance results and compares them with existing approaches. Finally, Section VI concludes the paper and highlights potential directions for future work.

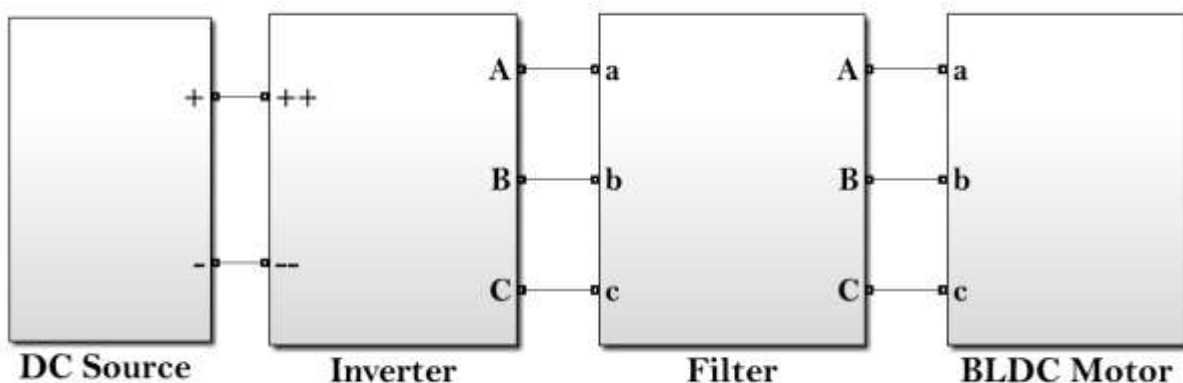


Fig1 Functional block diagram Model of the proposed system

## II. System Description

### Fig1 Functional block diagram Model of the proposed system

The proposed BLDC drive system consists of several interconnected modules responsible for energy conversion, power processing, and electromechanical motion generation. The overall architecture is shown in Fig. 1

#### A.DC SOURCE

This block provides the required DC input voltage to the drive system. It represents either a battery or rectified AC source typically used in EVs, drones, or industrial drives. The supplied DC voltage serves as the primary energy source for the converter and inverter stages. The stability and quality of this input voltage significantly influence the current dynamics and torque characteristics of the BLDC motor.

#### B. DC-AC INVERTER

The DC-AC inverter converts the input DC voltage into three-phase AC waveforms necessary to energize the BLDC motor windings. It operates using a standard six-switch bridge configuration and generates the 120° conduction sequence required for trapezoidal back-EMF machines. The inverter directly shapes the phase currents during commutation, making it a critical element influencing torque production and ripple behaviour.

#### C.FILTERS

A set of electrical filters is placed between the inverter and the motor to smooth the switching ripples produced by PWM operation. These filters reduce high-frequency components, stabilize the output voltage, and ensure that the motor windings receive cleaner current waveforms. This contributes to lower electromagnetic interference and improved torque smoothness.

#### D. BLDC Motor

The final block is the Brushless DC motor, modelled with trapezoidal back-EMF characteristics and a three-phase stator configuration. When supplied with filtered AC currents, the motor generates electromagnetic torque and mechanical rotation according to its electrical and mechanical dynamics. The motor output includes speed, torque, and phase current responses, which are used to evaluate system performance under different load and operating conditions.

## III CONTROL TOPOLOGY

An ANFIS is employed to regulate the DC-DC converter and generate the required DC-link voltage for torque ripple mitigation in the BLDC drive is shown in fig2. The ANFIS controller provides an adaptive nonlinear decision-making framework capable of learning the relationship between motor operating conditions and the optimal voltage required during commutation intervals. The BLDC drive uses a DC-DC converter whose output voltage must be adjusted continuously to reduce torque ripple during commutation. In the extension model, an ANFIS controller is placed in the voltage regulation loop to decide how much the DC-link voltage should increase or decrease at every instant. The controller receives two inputs: the error between the desired and actual value, and the change in this error. Based on these two signals, the ANFIS generates a reference voltage for the DC-DC converter. This reference value is then used to update the PWM duty cycle so that the converter supplies the required voltage to the inverter. By modifying the duty cycle according to operating conditions, the converter delivers a smooth and adaptive DC-link voltage. This helps the incoming phase current rise faster and the outgoing phase current decay smoothly, reducing the imbalance that normally produces torque ripple. The entire control process works in real time and does not require complex motor parameters.

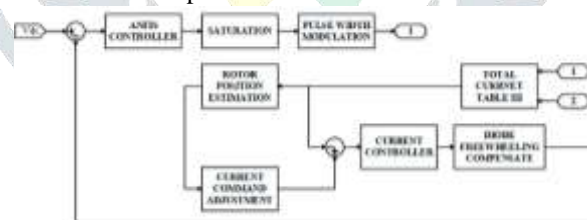


Fig2 controlling Diagram

#### A. Input Features and ANFIS Structure

The controller utilizes two input variables—error ( $e$ ) and change in error ( $\Delta e$ )—which represent the deviation of the system from its reference and the rate at which this deviation evolves. These features allow the controller to anticipate rapid current variations that occur during commutation. A first-order Sugeno-type ANFIS model is used, where fuzzy membership functions and rule parameters are optimized through hybrid neural learning to capture the nonlinear behaviour of the BLDC drive.

#### B. DC-Link Reference Voltage Generation

Based on its learned inference rules, the ANFIS controller produces a reference DC-link voltage  $V_{dcref}$ . This voltage command represents the optimal level required to shape the phase current trajectories during commutation. Increasing the DC-link voltage accelerates the rising current in the incoming phase, while reducing it prevents excessive current build up, thereby maintaining smoother current transitions.

#### C. Duty-Cycle Adjustment of the DC-DC Converter

The generated reference voltage is compared with the actual DC-link voltage, and the resulting error is processed to determine the PWM duty cycle for the DC-DC converter. By continuously adjusting the duty ratio, the converter supplies a dynamically modulated voltage profile that follows the ANFIS command, enabling real-time shaping of current slopes in the inverter-fed BLDC motor.

#### D. Torque Ripple Reduction Mechanism

Commutation torque ripple primarily occurs due to unequal current slopes between outgoing and incoming phases. The ANFIS-controlled DC-DC converter minimizes this imbalance by appropriately modifying the DC-link voltage during each commutation period. Because the controller learns nonlinear current-torque relationships, it provides superior compensation capability compared with fixed-rule or linear controllers, especially under varying load and speed conditions.

#### E. Benefits of ANFIS-Based Control

- Adaptive voltage regulation across operating conditions
- Strong nonlinear mapping capability
- Reduced dependence on accurate motor parameters
- Effective mitigation of commutation-induced torque ripple
- Improved transient response and smoother current profiles.

#### IV PROPOSED METHOD

The ANFIS controller is developed through a systematic data-driven procedure that enables it to learn the nonlinear relationship between motor operating conditions and the optimal DC-link voltage required for smooth commutation. The complete development process follows the flowchart shown in Fig. 3 and is described below.

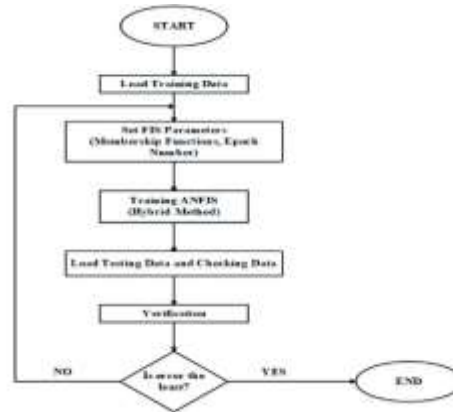


Fig 3 flow chart of ANFIS

#### A. Data Preparation

The first stage involves loading the training and testing datasets that represent the dynamic behaviour of the BLDC drive. These datasets include input variables such as error ( $e$ ) and change in error ( $\Delta e$ ) along with the desired output voltage reference. The dataset captures both steady-state and transient operating conditions to ensure that the ANFIS model generalizes well across different speed and load levels.

#### B. Input–Output Definition

After data acquisition, the input and output variables for the controller are defined. The two inputs (error and change in error) reflect the real-time deviation of system performance, while the output corresponds to the optimal DC-link reference voltage. This mapping serves as the basis for generating the fuzzy inference system (FIS).

#### C. FIS Generation

A first-order Sugeno-type FIS is generated using the defined data. Initial membership functions are automatically created to form the fuzzy rule base. These initial rules serve as the starting point for the adaptive training process. The generated FIS provides the structural framework on which the neural learning algorithm operates.

#### D. ANFIS Training

During the training phase, the FIS parameters—including membership function shapes, rule weights, and linear coefficients—are optimized using a hybrid learning algorithm that combines least-squares estimation and gradient descent. The training process minimizes the error between the ANFIS output and the target voltage reference. Through iterative updates, the ANFIS model learns the nonlinear voltage control characteristics required to shape the current slopes during commutation.

#### E. ANFIS Testing and Validation

After training, the model is tested using the reserved testing dataset to evaluate its generalization capability. The output is compared with the desired voltage values, and performance indicators such as mean squared error (MSE) or percentage error are analysed. If the error exceeds the acceptable threshold, the model is retrained by refining the FIS structure or adjusting training parameters. Once the performance criteria are satisfied, the ANFIS controller is finalized.

#### F. Integration with DC–DC Converter Control

The trained ANFIS model is integrated into the DC–DC converter control loop of the BLDC drive. In real-time operation, the controller receives the instantaneous error ( $e$ ) and change in error ( $\Delta e$ ) and generates the corresponding DC-link voltage reference. This voltage reference is used to regulate the converter duty cycle, ensuring that the DC-link voltage dynamically adapts to commutation conditions.

#### G. Torque Ripple Reduction Mechanism

By supplying an adaptively modulated DC-link voltage, the ANFIS controller ensures smoother current transitions between outgoing and incoming phases during commutation. This reduces the mismatch between actual and ideal phase currents, which is the primary contributor to torque ripple. Thus, the ANFIS-based approach offers superior real-time compensation capability compared with conventional linear controllers.

#### V SIMULATION RESULTS AND DISCUSSION

The performance of the proposed ANFIS-based DC–DC converter control was evaluated under different operating conditions. The analysis focuses on the key performance indicators such as DC-link voltage behaviour, stator current quality, torque profile, and the THD of voltage and current. The results consistently demonstrate improved waveform smoothness and reduced THD, confirming the effectiveness of the ANFIS controller.

Case 1 — High Speed (1500 rpm) and High Torque (3 NM)

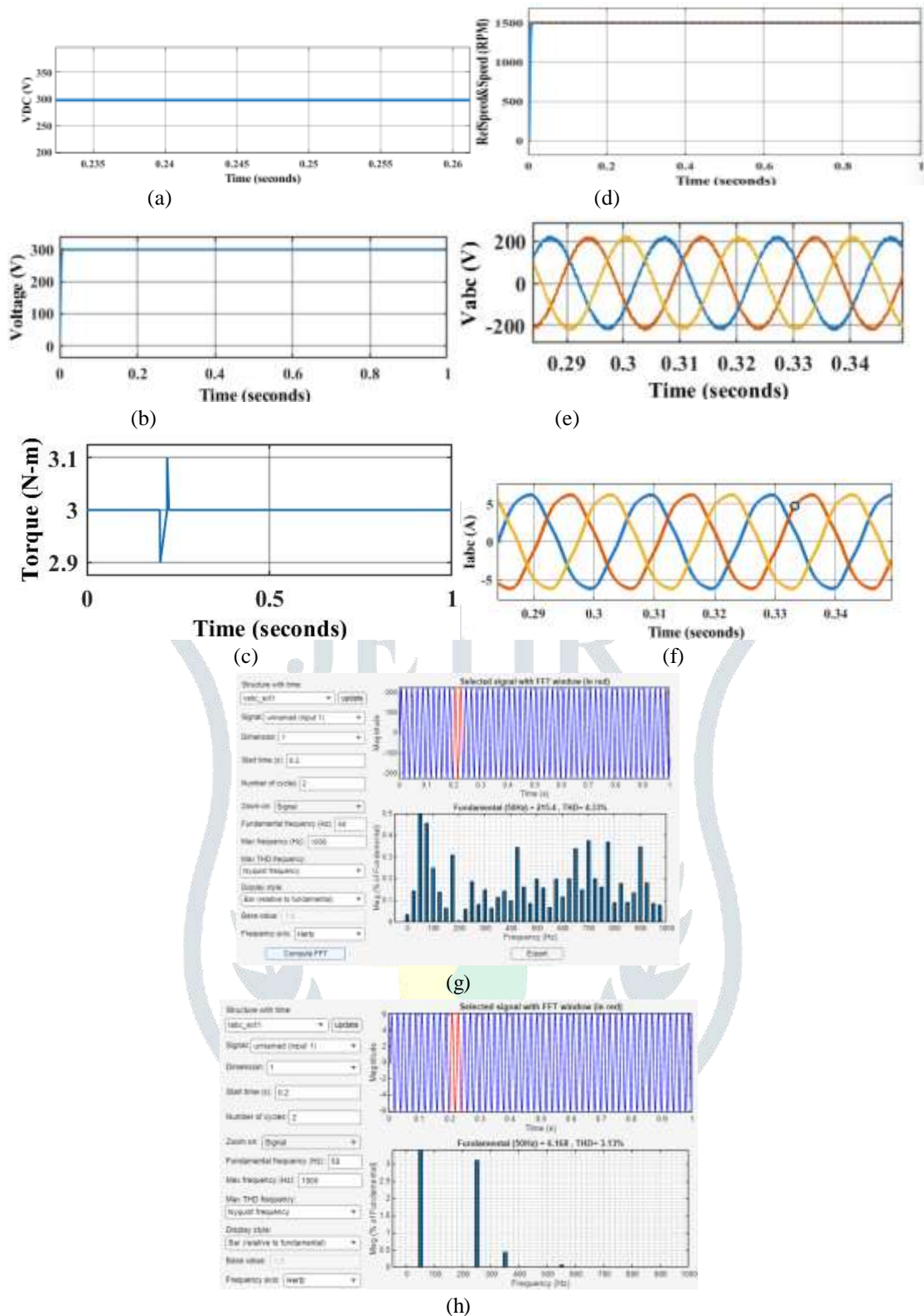


Fig 5 Simulation Results obtained under High Speed (1500 rpm) and High Torque (3 NM)

At the rated high-speed condition of 1500 rpm with a load torque of 3 NM, the ANFIS-controlled system demonstrates stable and well-regulated behaviour. The DC-link voltage follows a smooth profile, indicating that the controller modulates the converter output effectively during commutation intervals. This adaptive voltage shaping helps the inverter produce cleaner phase currents with reduced distortion.

The torque waveform remains steady with minimal fluctuation throughout the operation, showing that the ANFIS control successfully suppresses commutation-induced variations even under high dynamic loading. The measured THD values for both current and voltage are relatively low, confirming the improved quality of the electrical waveforms. Additionally, the motor speed tracks the 1500 rpm reference accurately with fast settling and no observable overshoot. These results confirm that the ANFIS-based converter control maintains strong stability and waveform purity during high-speed conditions.

Case 2 — Low Speed (300 rpm) and Low Torque (1 NM)

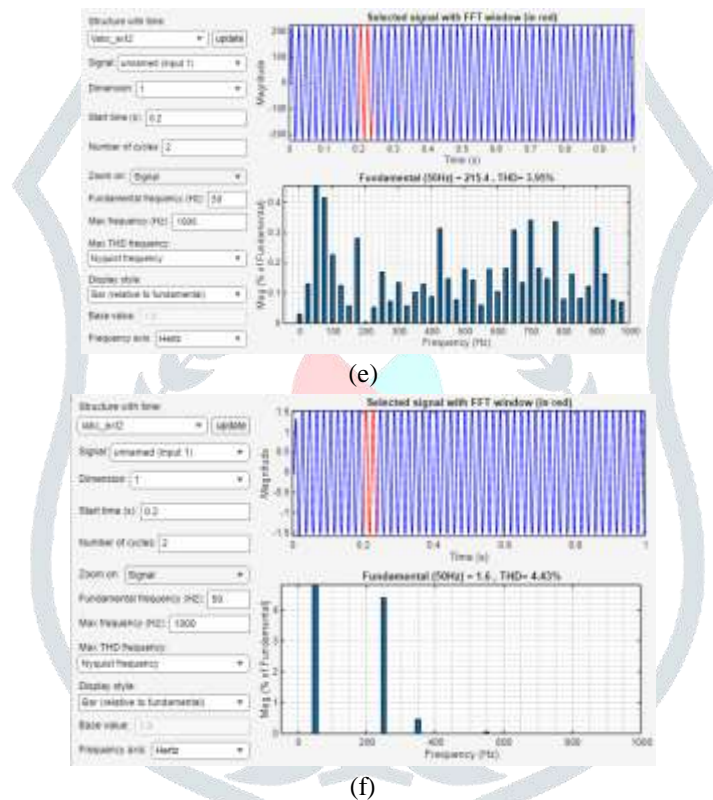
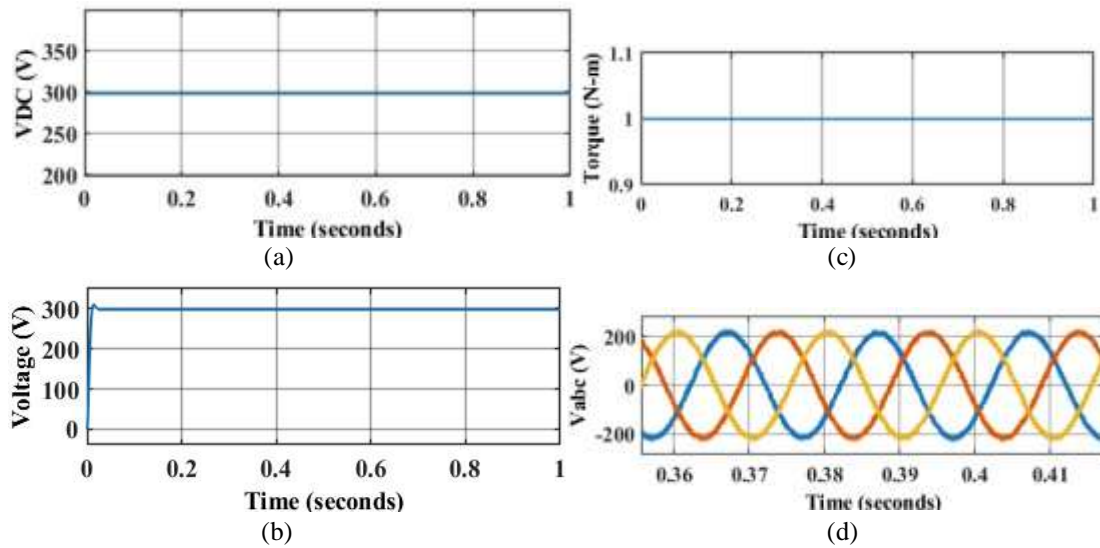
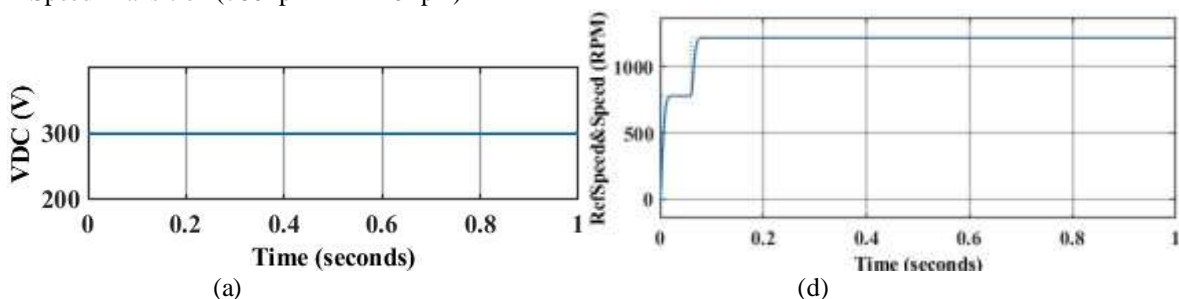


Fig 6 Simulation Results obtained under Low Speed (300 rpm) and Low Torque (1 NM)

At low-speed operation (300 rpm) with a light load of 1 NM, the ANFIS controller continues to provide smooth modulation of the DC-link voltage. This results in a clean voltage waveform and well-shaped stator currents even in the operating region where torque ripple is typically more pronounced.

The torque profile remains consistent with very small oscillations, indicating effective compensation during each commutation event. The inverter currents show reduced distortion, and the THD values are lower, demonstrating that the ANFIS controller maintains waveform quality despite the slower current dynamics at low speeds. The motor speed settles accurately at 300 rpm, showing reliable steady-state tracking.

Case 3 — Speed Transition (780 rpm → 1220 rpm)



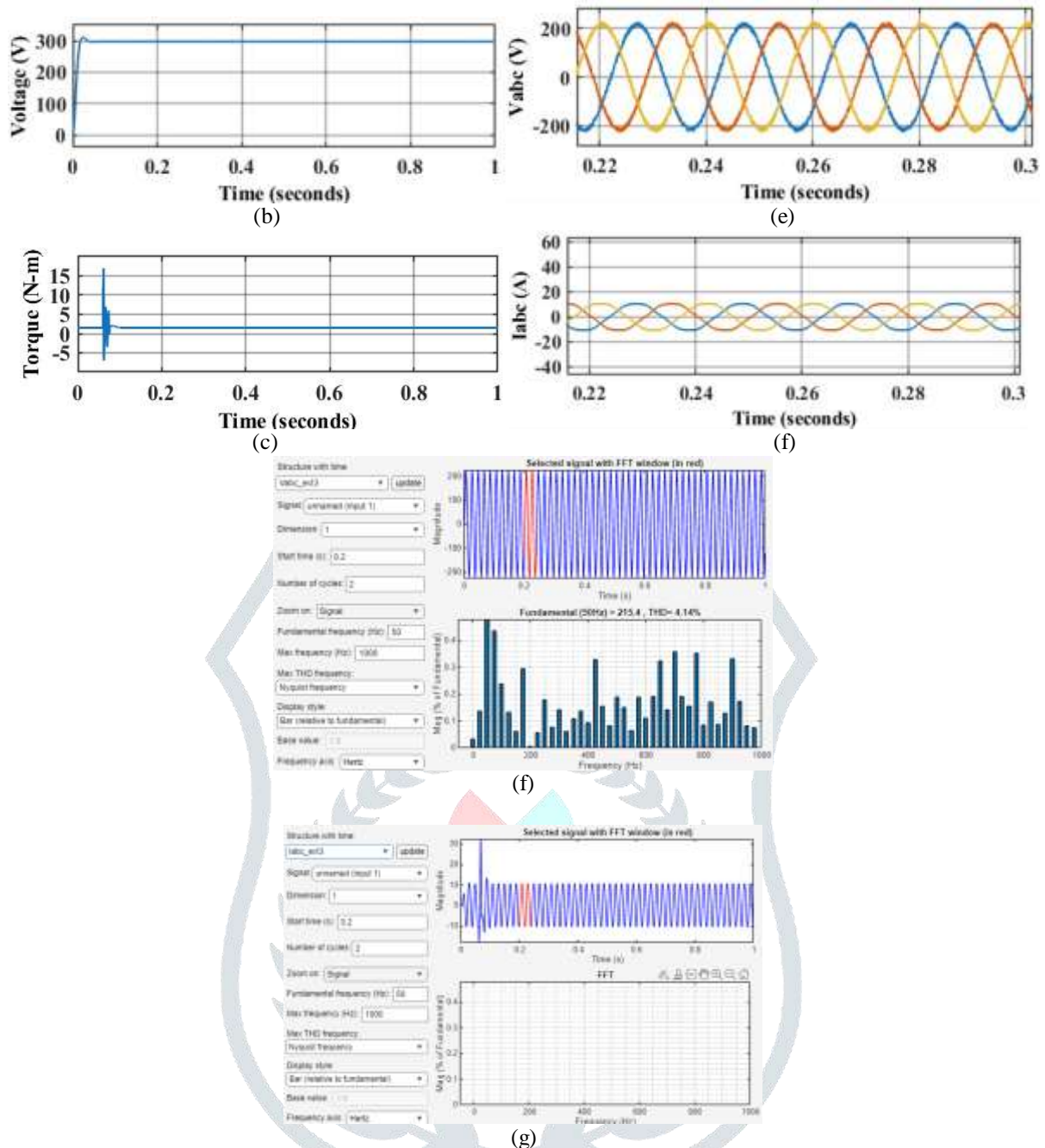


Fig 6 Simulation Results obtained underspeed changing from 780 rpm to 1220 rpm at  $t=0.06$  (s) and high torque (1.5 N.m) During the dynamic speed transition from 780 rpm to 1220 rpm, the ANFIS-based controller responds rapidly to the changing reference. The DC-link voltage increases and decreases smoothly according to the system demand, allowing the inverter currents to adjust without significant distortion. Throughout the transition, the torque waveform shows minimal overshoot, and the oscillations remain controlled. The motor accelerates to the new speed smoothly, and the measured waveforms demonstrate good transient stability. The THD levels remain low even during the speed change, confirming that the controller preserves waveform quality under dynamic conditions as well.

Table-I comparison Table

THD						
Controller	CASE1		CASE2		CASE3	
	VOLTAGE	CURRENT	VOLTAGE	CURRENT	VOLTAGE	CURRENT
ANN	6.12	5.81	5.35	5.86	5.69	5.88
ANFIS	4.28	3.13	3.91	4.43	4.09	3.59

Table 1 presents a quantitative comparison of voltage and current THD obtained using ANN and ANFIS controllers under three different operating cases. The results clearly demonstrate the superior harmonic performance achieved with the ANFIS-based control strategy. InCase 1, the ANFIS controller reduces the voltage THD from 6.12% to 4.28% and the current THD from 5.81% to 3.13%. This improvement indicates that the adaptive DC-link voltage regulation provided by ANFIS results in smoother current transitions during commutation. ForCase 2, voltage THD decreases from 5.35% to 3.91%, while current THD is reduced from 5.86% to 4.43%. The reduction confirms the effectiveness of ANFIS in maintaining waveform quality under low-speed and low-torque conditions. InCase 3, the proposed controller achieves lower voltage and current THD values of 4.09% and 3.59%,

respectively, compared to the ANN approach. Overall, the results verify that ANFIS consistently enhances waveform quality across all operating conditions.

## VI CONCLUSION

This work demonstrated an ANFIS-based DC–DC converter control strategy for reducing torque ripple in BLDC motor drives. By adaptively regulating the DC-link voltage according to real-time operating conditions, the controller achieved smoother current transitions and minimized commutation disturbances. Simulation results under high-speed, low-speed, and dynamic operating conditions confirmed that the proposed method provides stable torque, improved waveform quality, and lower THD in both current and voltage. The ANFIS controller effectively captured the nonlinear characteristics of the drive system, enabling more accurate and flexible voltage shaping compared to conventional approaches. Overall, the proposed method enhances the performance of BLDC drives and offers a promising solution for applications requiring high torque smoothness and reliable dynamic response.

## References

- 1 Hari Krishna U Andrajevvanp “A Direct Torque Control Scheme With Integrated Commutation Torque Ripple Reduction For Bldc Motor Drives With Open-End Windings” ,Iee Open Journal Of Power Electronics,2025.
- 2 Kai Liu ,Zhiqiang Zhou, And Wei Hua “A Novel Region-Refinement Pulse Width Modulation Method For Torque Ripple Reduction Of Brushless Dc Motors”, Ieee Access ,2018.
- 3 Marcio L. M. Kimpara, Renata R. C. Reis, Luiz E. B. Da Silva, Joao O. P. Pinto, And BabakFahimi, “A Two-Step Control Approach For Torque Ripple And Vibration Reduction In Switched Reluctance Motor Drives”, Ieee Access 2022.
- 4 Xuliang Yao, Jicheng Zhao , Jingfang Wang, Shengqi Huang, And Yishu Jiang, “Commutation Torque Ripple Reduction For Brushless Dc Motor Based On An Auxiliary Step-Up Circuit”, Ieee Access, 2022.
- 5 N. Prabhu, R. Thirumalaivasan And Bragadeshwaran Ashok, “Critical Review On Torque Ripple Sources And Mitigation Control Strategies Of Bldc Motors In Electric Vehicle Applications”, Ieee Access, 2022.
- 6 Kaif Ahmed Lodi , Khaled Ali Al Jaafari And Abdur. Beig, “ Improved Duty Ratio-Based Direct Torque Control For Open-End Winding Induction Motor Drives”, Ieee Open Journal Of Industry Applications, 2025.
- 7 Krzysztof Kolano, “ Improved Sensor Control Method For Bldc Motors”, Ieee Access,2019.
- 8 Liu Yang XiangdongLiu,Jing Zhao, Lei Yang, And Lei Zha, “Investigation Of A Stator-Ironless Brushless Dc Motor With Non-Ideal Back-Emf”, Ieee Access,2019.
- 9 U. Hari Krishna Andp.P.Rajeevan, “Multi-Level Voltage Space Vector Structure Based Control Strategy With Reduced Torque Ripple For Open-End Winding Bldc Motor Drives”, Ieee Access,2024
- 10 Leticia AseyeAdase , Ibrahim MohdAlsofyani , And Kyo-Beum Lee, “ Predictive Torque Control With Simple Duty-Ratio Regulator Of Pmsm For Minimizing Torque And Flux Ripples”, Ieee Access 2019.
- 11 JuwonLee ,GyuCheol Lim And Jung-Ik Ha, “ Pulse Width Modulation Methods For Minimizing Commutation Torque Ripples In Low Inductance Brushless Dc Motor Drives”, Ieee Transactions 2019.
- 12 Lei Yang, Z. Q. Zhu 1, Liming Gong, And Hong Bin, “Pwmswitching Delay Correction Method For High-Speed Brushless Dc Drives”, Ieee Access 2021.
- 13 Liang Xu, Yang Li, Wenxiang Zhao, And Guohai Liu, “ Reduction Of Unipolar Leakage Flux And Torque Ripple In Consequent-Pole Pm Vernier Machine”, Ces Transactions On Electrical Machines And Systems, Vol. 7, No. 1, March 2023.
- 14 Qazwan Abdullah Nabil Farah, Mustafa Sami Ahmed, Nor ShahidaMohd Shah , ÖmerAydoğdu, MdhairulNizamTalib, Yahya M. Al-Moliki ,Abbas Uğurenver, Mohammeda.A. Al-Mekhalfi, Muhammadzaidaihsan, And Adeb Salh, “ Sensorless Speed Control Of Induction Motor Drives Using Reinforcement Learning And Self-Tuning Simplified Fuzzy Logic Controller”, Ieee Access 2024.
- 15 Samer Saleh Hakami , Ibrahim MohdAlsofyani , And Kyo-Beum Lee , “ Torque Ripple Reduction And Flux-Droop Minimization Of Dtc With Improved Interleaving Csfc Of Im Fed By Three-Level Npc Inverter”, Ieee Access 2019.