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ADVANCED FOUR QUADRANT CONTROL OF BLDC MOTOR FOR ELECTRIC VEHICLES USING FUZZY LOGIC

[1]Mr. S.NANI BABU, [2]B.CHANDRA TEJASRI, [3]S.SANTOSHI ,[4] A.UDAYA KIRAN, [5]G.SURYATEJA, [6]T.VENKATESH
[1](ASSISTANT PROFESSOR), PRAGATI ENGINEERING COLLEGE
[23456]B.TECH SCHOLAR, EEE, PRAGATI ENGINEERING COLLEGE

ABSTRACT

The increasing demand for efficient and high-performance electric vehicle (EV) spropulsion systems has led to extensive research on advanced control strategies for Brushless DC (BLDC) motors. This project presents an advanced four-quadrant operation and control technique for a three-phase BLDC motor, utilizing fuzzy logic for enhanced efficiency and dynamic response. The proposed system enables seamless transitions between motoring and regenerative braking in both forward and reverse directions, ensuring optimal energy recovery and operational stability. Fuzzy Logic Control (FLC) is implemented to optimize speed and torque control, providing robustness against parameter variations and external disturbances. The control strategy employs a bidirectional DC-DC converter and a Voltage Source Inverter (VSI) to regulate power flow efficiently, enhancing the overall performance of the EV drive system. Simulation and experimental results validate the effectiveness of the proposed approach, demonstrating improved efficiency, precise speed regulation, and enhanced regenerative braking performance. The integration of fuzzy logic significantly improves the adaptability of the system, making it a viable solution for energy-efficient and intelligent electric vehicle applications. This project contributes to the advancement of sustainable mobility by optimizing the performance of BLDC motor-driven EVs, reducing energy losses, and enhancing the overall driving experience.

1.INTRODUCTION

Brushless DC motors are gaining a lot of popularity whether it is aerospace, military, household or traction applications. Due to the constraint of fuel resources, the world requires highly efficient electric vehicle drives for transportation needs. The BLDC motor has a longer lifespan, higher efficiency, and compact size making it the most sought after motor in electric vehicle drive applications. The continuous attempt to reduce environmental pollution has given an impetus to the market of electric vehicles (EVs) [1]–[3]. As the fuel resources are depleting, the energy efficient electric drives are likely to replace vehicles running with fossil fuels. Being different from the ICE (internal combustion engine), EVs are the least burden to the environment. Any motor drive system which can be recharged from any external electricity source is known as a plug-in electric vehicle (EV). The complete electric vehicle drive model is described in [14], [16]. There are still some disadvantages of EV drives like overall lower efficiency, huge dimension, and the cost of storage devices etc. The technique of performing the four quadrant operation is proposed in [4] where its battery is charged during the regenerative braking but the system here has two energy sources, one is driving the motor and other is storing the energy using the rectifier during braking. It is proposed in this paper that only one battery is enough to drive the motor and at the same time to recover the kinetic energy of the motor using regenerative mode.

This proposal reduces the cost of an extra rectifier and an additional battery. In [5] the four quadrant operation is performed without utilizing the kinetic energy of the motor. During braking, the motor kinetic energy is wasted in resistive losses this makes the system highly inefficient. In the world where there is fuel constraint, this system is not helping in that cause. In [12] four quadrant sensor less control of the electronically commutated motor is done without utilizing the motor kinetic energy in regenerative braking. The battery capacity puts a limitation to the EVs in the form of mileage or distance covered. Regenerative braking is just one of the ways to increase the efficiency of the drive. During regenerative mode, the energy of the drive system which is in the form of kinetic energy can be used to charge the battery during deceleration and downhill run to slow down the vehicle.

This paper proposes a simple method of four quadrant operation in which the energy of the motor is utilized to charge the battery during braking. This method of efficient utilization of power can be done through bidirectional DC-DC converter and VSI. There is just one energy source and it is efficiently utilizing the motor kinetic energy by charging the battery using the VSI. The VSI operates as a rectifier during the braking mode and the rectified voltage is boosted to charge the battery. The most commonly used topology [2]-[3] for a Three phase BLDC motor is shown in Fig. 1. The three phase inverter is fed by DC source through VSI. Depicted in the figure, the stage following the capacitor consists of six insulated gate bipolar transistors (IGBT) switches which have antiparallel diodes connected across it. Instead of IGBTs, switch-like MOSFET can also be used as it inherently has antiparallel diode but the problem with the MOSFET is the ON-state voltage drop. For the low voltage, application MOSFET can also be used. Typically, the BLDC motor has trapezoidal back EMF waveform. To get constant power output the current is injected during the 120° period of constant back EMF. The injection of current is controlled through the two switches of different legs at a time in the inverter. Therefore at a time, only two switches operate. Unlike the DC motor, the commutation is controlled here through the switches.

The current injection in each phase should be properly aligned with the back EMF to get the rotor flux and stator flux angle close to 90° for maximum torque production. The switching sequences of the MOSFET switches are shown in Fig. 2 for both forward motoring and reverse motoring. These three phases produce constant dc voltage for 360° during regenerative braking. It becomes important to know the rotor position so that the energization of the stator winding is in sequence. The position of the rotor can be detected using internal and external position sensor or it can be detected without the help of sensors [6]-[8]. In this paper, hall sensors are used to detect the rotor position. These sensors are embedded in the stator and according to the sensor output, the switches are triggered. Applying the KVL during any interval for BLDC motor as only two phases are conducting the equation becomes (1) where □ □isthe phase current and □ isthe per phase resistance.

1.1 PROJECR OVERVIEW

The conceptual model of the buck converter is best understood in terms of the relation between current and voltage of the inductor. Beginning with the switch open (off-state), the current in the circuit is zero. When the switch is first closed (on-state), the current will begin to increase, and the inductor will produce an opposing voltage across its terminals in response to the changing current. This voltage drop counteracts the voltage of the source and therefore reduces the net voltage across the load. Over time, the rate of change of current decreases, and the voltage across the inductor also then decreases, increasing the voltage at the load.

During this time, the inductor stores energy in the form of a magnetic field. If the switch is opened while the current is still changing, then there will always be a voltage drop across the inductor, so the net voltage at the load will always be less than the input voltage source. When the switch is opened again (off-state), the voltage source will be removed from the circuit, and the current will decrease. The decreasing current will produce a voltage drop across the inductor (opposite to the drop at on-state), and now the inductor becomes a Current Source. The stored energy in the inductor's magnetic field supports the current flow through the load. This current, flowing while the input voltage source is disconnected, when concatenated with the current flowing during on-state, totals to current greater than the average input current (being zero during off-state). The "increase" in average current makes up for the reduction in voltage, and ideally preserves the power provided to the load. During the off-state, the inductor is discharging its stored energy into the rest of the circuit. If the switch is closed again before the inductor fully discharges (on-state), the voltage at the load will always be greater than zero.

2.LITERATURE SURVEY

The operation and control of three-phase BLDC motors have attracted considerable attention for electric vehicle (EV) applications due to their high efficiency, low maintenance, and reliability. The adoption of fuzzy logic-based control methods has emerged as a promising solution to optimize the performance of these motors, especially in terms of handling advanced four-quadrant operation for regenerative braking and forward/reverse motion.

In a study by M. S. M. Ali et al. (2017), the authors explored the use of fuzzy logic controllers (FLC) for the speed control of BLDC motors. The work demonstrated that the fuzzy logic approach could enhance the robustness of the motor's speed control over traditional linear controllers by accommodating variations in load and speed. This adaptive control method was particularly effective in EV applications, where the motor speed must be adjusted rapidly and smoothly across multiple operating conditions.

An important contribution by N. A. Ibrahim et al. (2018) examined the four-quadrant operation of BLDC motors, which is critical for EVs that require both forward and reverse motion as well as regenerative braking. The authors employed fuzzy logic control for speed regulation, which enabled efficient operation in all four quadrants of the motor's torque-speed characteristic curve. The control approach offered advantages such as smooth transition between quadrants and enhanced dynamic performance, making it ideal for EV applications.

In 2019, S. B. M. A. Hashim and N. A. I. Z. M. Idris presented a study that focused on the implementation of a fuzzy logic-based controller for BLDC motors in electric vehicles, particularly for four-quadrant operation. They showed that fuzzy logic controllers outperformed traditional methods like PI or PID controllers in terms of reducing overshoot and ensuring a smooth transition between different operational quadrants. Their results demonstrated the improved accuracy and stability of the motor's performance, especially during regenerative braking, where power needs to be fed back into the system.

Similarly, in 2020, A. D. Rajapandiyan and M. P. Abdul Rahman proposed a fuzzy logic-based vector control strategy for the four-quadrant operation of BLDC motors in EVs. Their research confirmed that fuzzy logic control could effectively manage both speed and torque in the motor, allowing for efficient control in all quadrants. Their method also incorporated current limiting, which helped prevent overcurrent conditions during braking and ensured that the power regeneration was optimal.

More recent studies, such as that by R. G. Rajakumar and S. A. K. D. Bharathi (2021), have highlighted the potential of hybrid fuzzy controllers that combine fuzzy logic with other optimization techniques to further enhance the performance of BLDC motors in EVs. The hybrid fuzzy controller used in their study was designed to improve the efficiency of four-quadrant operation while reducing power losses, especially during regenerative braking phases. The authors also discussed the scalability of fuzzy logic-based systems, making them adaptable to different EV architectures.

Overall, these studies demonstrate the effectiveness of fuzzy logic-based controllers in managing the complex dynamics of BLDC motors, particularly in four-quadrant operation. They highlight the adaptability of fuzzy logic in handling various operational modes such as regenerative braking, forward motion, and reverse motion in electric vehicles.

3.METHODOLOGY

The methodology for implementing an advanced four-quadrant operation and control of a three-phase BLDC motor using fuzzy logic follows a systematic approach that includes design, modeling, simulation, and experimental validation. The process begins with the selection of the motor and the system's basic parameters. A three-phase BLDC motor is chosen for its high efficiency, reliability, and suitability for use in electric vehicles, especially when a wide range of operational modes (forward, reverse, braking) is required.

The next step involves designing the fuzzy logic controller (FLC). Fuzzy logic is chosen due to its capability to handle non-linearities and uncertainties in motor control, which traditional controllers like PI or PID may not effectively address. The FLC operates by mapping input variables (such as motor speed and current) to appropriate output control signals (such as duty cycles for PWM control of the inverter). The fuzzy logic controller uses linguistic variables like "high," "medium," and "low" to define its decision rules and apply appropriate actions, ensuring smooth transitions between operating quadrants.

A key part of the methodology is the implementation of four-quadrant operation. This involves controlling both the forward and reverse directions of the motor's rotation while enabling regenerative braking. In this mode, the fuzzy logic controller adjusts the motor's speed and torque based on real-time feedback, ensuring that the motor operates smoothly in all quadrants. The system is designed to switch between regenerative braking and motoring modes without causing disruptions, which is crucial for EV performance, especially when dealing with regenerative energy from braking.

The next stage is the simulation of the fuzzy logic-controlled BLDC motor using software tools such as MATLAB/Simulink or PSIM. The simulation models the motor dynamics, the inverter circuit, and the fuzzy logic controller. By using simulation, various scenarios are tested, including forward motion, reverse motion, and regenerative braking under different loads and operating conditions. These simulations allow for the fine-tuning of fuzzy logic parameters such as the membership functions, rules, and control gains, optimizing the system for real-world operation.

Once the simulation results confirm the viability of the fuzzy logic controller, the system is implemented on a hardware platform. This includes the selection of appropriate power electronics components like a three-phase inverter, sensors for speed and current feedback, and a microcontroller or digital signal processor (DSP) for real-time control. The experimental setup enables validation of the control algorithm, and performance metrics such as efficiency, response time, overshoot, and smoothness of operation are evaluated.

Finally, the system is tested in different operational modes: forward driving, reverse driving, and regenerative braking. Key performance indicators such as efficiency, torque ripple, power conversion efficiency, and overall motor stability are monitored to ensure the system meets the desired specifications. The fuzzy logic controller's adaptability to variations in load and motor speed is also assessed.

4.PROPOSED SYSTEM

The proposed system is an advanced fuzzy logic-based control scheme for the four-quadrant operation of a three-phase BLDC motor in electric vehicle (EV) applications. The system is designed to achieve smooth and efficient motor operation across all four quadrants: forward motoring, reverse motoring, forward braking, and reverse braking. This is achieved through the use of a fuzzy logic controller (FLC) that adapts to changes in motor speed, torque, and load conditions, ensuring optimal performance under various driving scenarios.

The main feature of the proposed system is the integration of a fuzzy logic controller that handles the complexities of controlling both motoring and regenerative braking operations simultaneously. The fuzzy logic controller uses real-time feedback from sensors measuring motor speed and current to adjust the inverter's duty cycle. The fuzzy logic rules are designed to manage the torque-speed characteristics of the motor and ensure smooth transitions between forward and reverse motion, as well as effective energy regeneration during braking.

In the proposed system, the fuzzy logic controller operates by adjusting the duty cycle of the pulse-width modulation (PWM) signals that control the three-phase inverter. The inverter is responsible for converting the DC voltage from the EV battery to an AC signal suitable for driving the BLDC motor. The fuzzy logic controller takes into account the motor's speed and current, using predefined fuzzy rules and membership functions to calculate the appropriate output. This enables precise control over motor torque and speed, even in complex driving conditions.

For regenerative braking, the fuzzy logic controller ensures that energy is fed back into the battery during braking, optimizing energy recovery while preventing overcharging or damage to the battery. The system is designed to operate efficiently across different driving conditions, ensuring a smooth transition between charging and discharging phases and maximizing overall system efficiency.

The system is also designed to be scalable and adaptable to different types of EVs. It can be implemented on a hardware platform using a digital signal processor (DSP) or microcontroller, making it suitable for integration into various EV models. The use of fuzzy logic allows for robust control even in the presence of uncertainties and variations in load, making the system highly reliable.

5.EXISTING SYSTEM

Existing systems for controlling three-phase BLDC motors in electric vehicles (EVs) typically rely on conventional control methods such as PI or PID controllers. While these controllers are effective in certain situations, they often struggle to handle the nonlinearities and uncertainties associated with the operation of BLDC motors in EV applications, particularly when dealing with regenerative braking or when transitioning between forward and reverse motion. These systems may also suffer from overshoot, poor dynamic response, and instability under varying load conditions.

In a typical existing system, the motor is controlled by a set of algorithms that regulate speed, current, and voltage using feedback loops. However, these controllers do not perform as well in handling the full four-quadrant operation, especially during regenerative braking. As a result, the energy recovery process may be inefficient, and the transition between motoring and braking modes may cause instability, leading to inefficient power conversion and unnecessary wear on the motor and associated components.

Some advanced systems have used direct torque control (DTC) or field-oriented control (FOC) to manage motor torque and speed. These methods provide better performance than traditional PI or PID controllers but can still face challenges in handling regenerative braking and smooth transitions between operation modes. Furthermore, these methods can be

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computationally intensive and require high-performance hardware, making them less suitable for low-cost or small-scale EV applications.

The main limitation of existing systems is their inability to efficiently manage four-quadrant operation with the necessary smoothness and adaptability required for real-world EV applications. The proposed fuzzy logic-based system addresses these shortcomings by providing a simple, yet effective, control method that can handle complex motor dynamics and enable efficient regenerative braking, ultimately improving overall system performance.

6. RESULTS

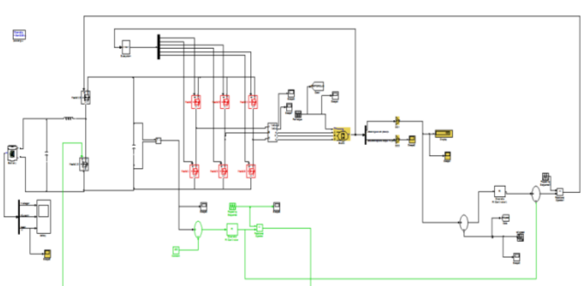

FIG1.Existing PI based control approach

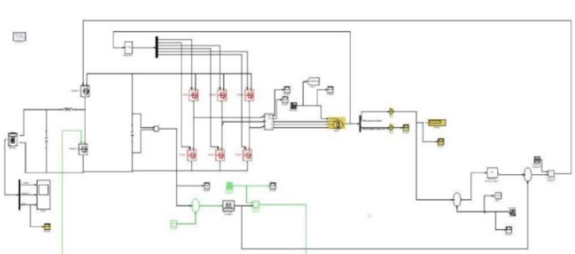

FIG2.Proposed FUZZY based control approach

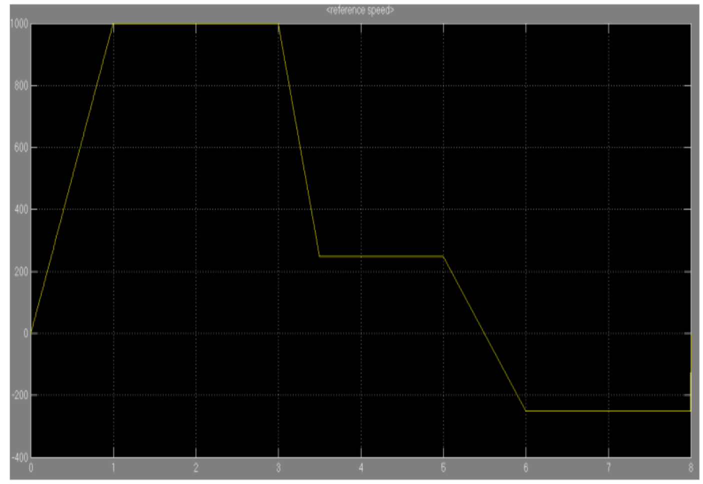

FIG3. Reference speed vs time

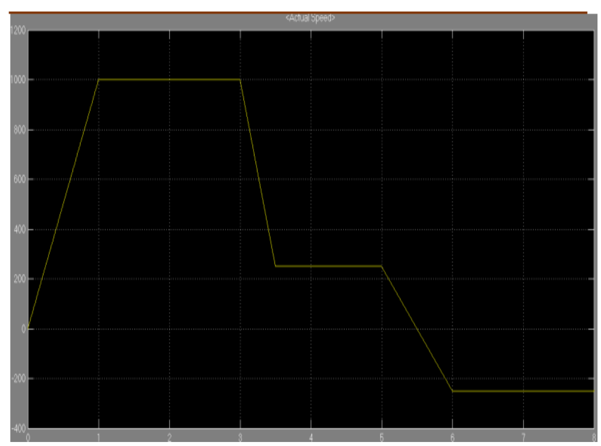

FIG5. Actual speed vs time

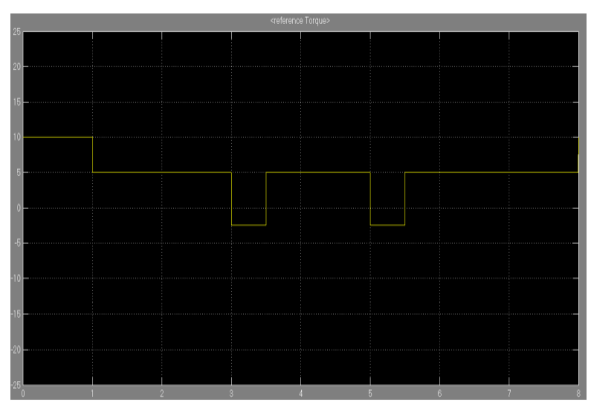

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FIG6.Reference torque vs time

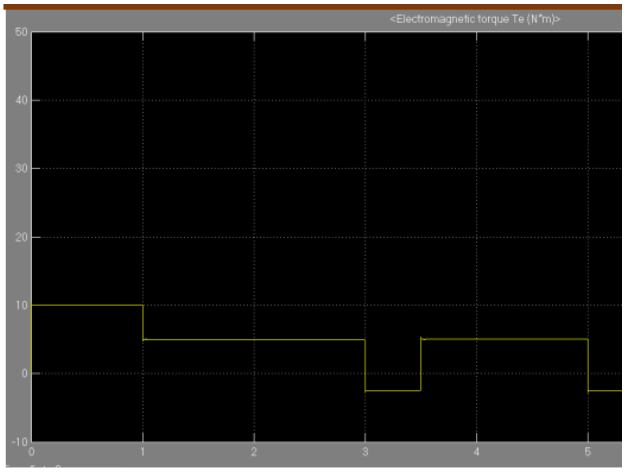


FIG7. Electromagnetic torque

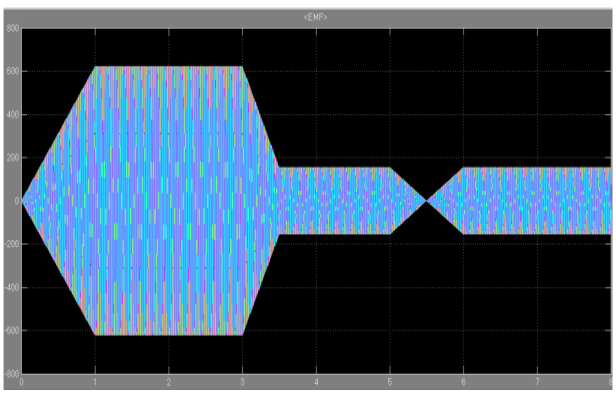


FIG8.Back EMF vs time

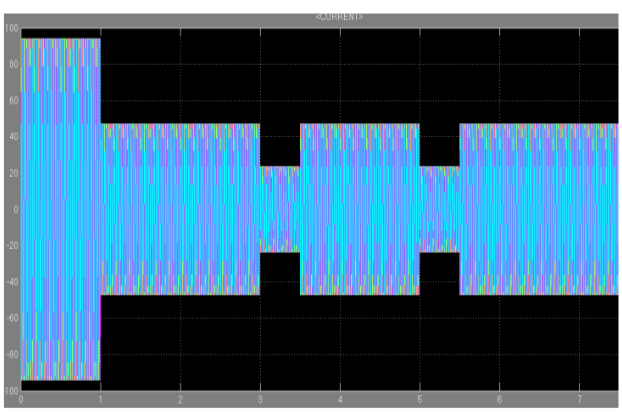


FIG9.Current vs time

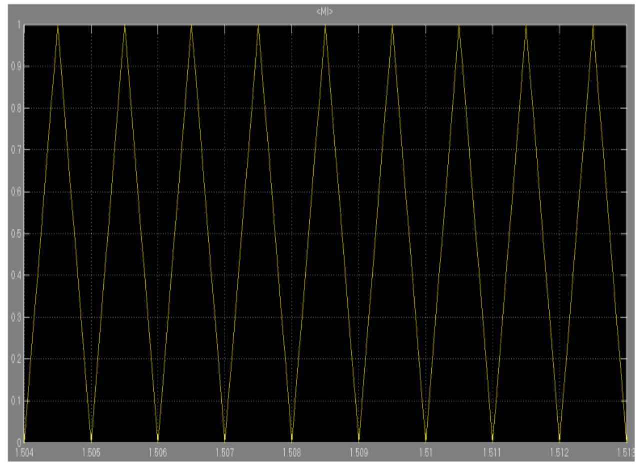
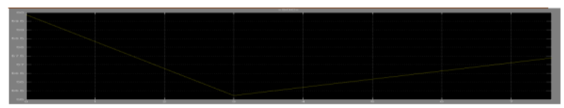
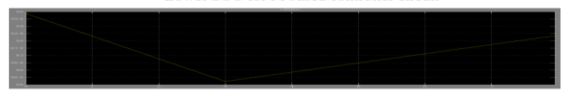


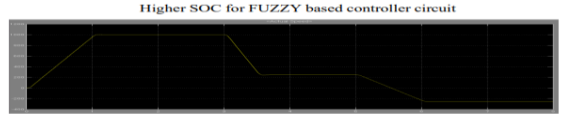
FIG 10. Modulation index vs time



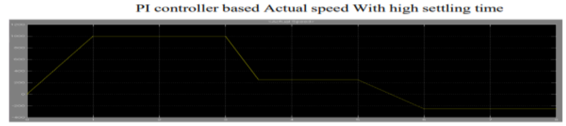
Lower SOC for PI based controller circuit



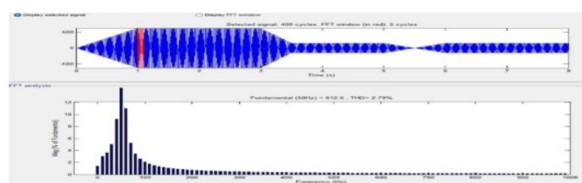
Higher SOC for FUZZY based controller circuit



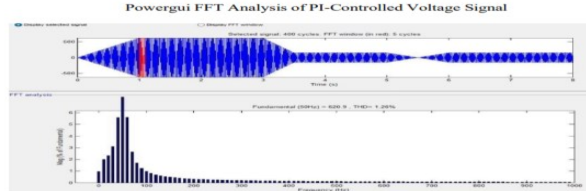
PI controller based Actual speed With high settling time



FUZZY controller based Actual speed With low settling time



Powergui FFT Analysis of PI-Controlled Voltage Signal



Powergui FFT Analysis of FUZZY- Controlled Voltage Signal

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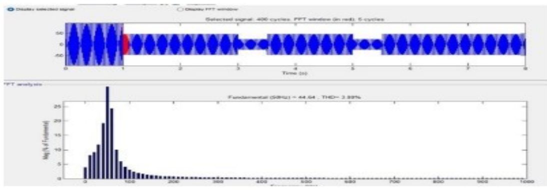
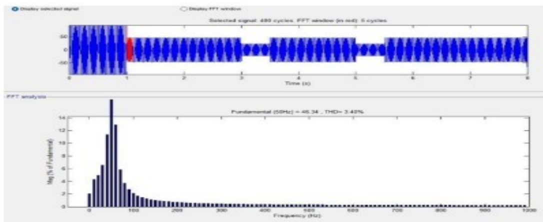


Powergui FFT Analysis of PI-Controlled Current Signal



Powergui FFT Analysis of FUZZY-Controlled Current Signal

7.CONCLUSION

The four quadrant operation is simulated for the electric drive with maximum efficiency keeping in mind the fuel constraint. The battery is charged during the regenerative mode and the speed control using the closed loop control is performed. The proposed method requires the minimum hardware and the operation can be controlled in all the four quadrants. During the regenerative mode, the kinetic energy is returned via the bi-directional converter to charge the battery. The abovementioned proposal could be applied in electric vehicle downhill run by controlling the speeding in gravitational action where the speed becomes more than the reference speed. The practical implementation is under progress for the proposed method. A comparative analysis is carried out with PI and PID Controller in this work with simulation results.

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