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# FPGA-Controlled HBCCPWM Technique for Induction Motor Speed Regulation

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**Abstract**

This article introduces a novel speed regulation method for three-phase induction motors that employ the HBCCPWM approach, which is implemented on a single-chip FPGA controller. The HBCCPWM technique proved superior to conventional PWM techniques, such as SPWM and SVPWM techniques, by adaption of switching frequency and improvement of total harmonic distortion (THD), which in turn improve motor performance, particularly in dynamic situations. The FPGA platform was selected due to its versatility, low latency, and superior PWM signal generation processing capabilities compared with DSPs and microcontrollers. Computer simulation using MATLAB and experimental results demonstrate robust speed control of the induction motor speeds at different frequencies (55 Hz, 60 Hz, and 65 Hz) and that the current waveform hysteresis is tightly maintained. Furthermore, this innovation exhibited reduced THD of 1.5%, significantly enhancing the power quality, when compared to traditional PWM techniques. Additionally, the paper discusses and presents a real-time monitoring system for the switching frequency, as well as the advantages of FPGA-based control technology for high-performing variable frequency AC drives.

**Keywords**: *HBCCPWM, FPGA,3-phase inverter, Frequency strategy.*

## 1 Introduction

Induction motors (IM) are widely used in industry because they are reliable, simple to maintain, and cost-effective. By changing the system currents, voltages, and frequency based on the load and application requirements, you can control their speed and torque (Sengamalai et al., 2022). Power inverters change direct current (DC) into alternating current (AC). They are designed to reduce distortion for the safety and efficiency of equipment (Conceptar et al., 2024). Induction motors are becoming more popular in homes and businesses because of the use of power electronics and cheap computing hardware. When choosing induction motor drives for small to medium power applications, you should think about the cost, how long they will last, the environment they will be used in, the power-to-weight ratio, and how easy they are to control (Azab, 2025). PWM controls the speed of a motor by controlling how semiconductor switches work. To achieve the best output torque from induction motor drives, it's important to use the AC bus voltage well. Hysteresis band current control (HBCC) improves the efficiency and reduce the THD of the AC bus compared to other methods (Osarumwense & Oriahi, 2019). In this paper used frequency strategy over rated frequency (55 Hz, 60 Hz, 65 Hz) with 3-phase inverter to drive the induction motor and to reduce the current THD.

## 2 Pulse Width Modulation

Power conversion and motion control are common uses for Pulse Width Modulation (PWM) technology. Pulse width modulation (PWM) for individual or multiple pulses, sinusoidal PWM, space vector PWM, harmonic elimination PWM, carrier frequency modulation, and hysteresis band current control are among the various modulating techniques. There are pros and cons to each method, although sinusoidal PWM and space vector PWM are the most used in commercial settings (Tawfiq et al., 2024). The carrier frequency can be easily programmed into most digital PWM generators since they are built utilizing microcontrollers or field-programmable gate arrays. When comparing digital techniques based on FPGAs and DSPs, the former has superior control capabilities and dynamic performance in PWM-controlled power converters (Lakka et al., 2011). The Spartan-3 FPGA is exceptionally well-suited for various electronic boards due to its numerous attributes: flexibility and programmability, parallel processing, hardware acceleration, high efficiency, simplicity, low latency, customizability, and adaptability, making it recommended and utilized in this work. The Xilinx 14.7 Software environment was utilized for writing the proposed VHDL code to provide the necessary signals (Mohammed et al., 2024). Hysteresis comparators facilitate PWM pulse generation by allowing a hysteresis controller to create hysteresis around a reference current (Thielmann and Hans, 2021). Modern hysteresis regulators use nonlinear feedback methods based on a hysteresis comparator. Some advantages of hysteresis current control technology include durability and ease-of-use as well as low tracking error rate, and resistance to variations in load conditions. In a three-phase circuit, the switching frequency might unexpectedly become very high and suffer fluctuations (Suhara and Nandakumar 2016). Traditional PWM methods, such as SPWM and SVPWM, are mostly applied to industrial AC motor drives. However, they have fixed switching frequencies and a higher level of harmonic distortion, which makes the power quality worse and also reduces the motor's efficiency. Moreover the microcontroller and DSP based platform suffers from sequential processing its own limited computing resource situation, thus in demanding with a high degree of dependence systems could not reach performance requirements. In much the same way traditional hysteresis current control systems still meet great problems when they don't know that the frequency of commutator current impressed by linear PWM algorithm is going to shift at all, thus destroying system stability overall. In particular two-level three-phase hysteresis controllers struggle with management of the frequency, which leads to decreased performance of motors and increased electromagnetic interference. Dynamic control strategies are needed to address these challenges by switching inside a flexible hysteresis band, varying the frequency, lowering total harmonic distortion (THD), and having a fast response time with the ability to go parallel. This project aims to address these challenges by providing an FPGA-based control system that produces HBCCPWM signals on a three-phase motor with controllable switching frequencies and lower distortion levels, to increase efficiency and speed control while under varying load conditions. PWM will minimize THD and improve the quality of the waveform (Mohammed et al., 2023; Abdulhakeem et al., 2024). As part of our study, we will evaluate the control of an induction motor for the open-loop hysteresis band current PWM control method in MATLAB and the FPGA-based HBCCPWM application, which will be assessed on a three-phase motor. The pulse generation for the HBCCPWM is shown in figure 1.

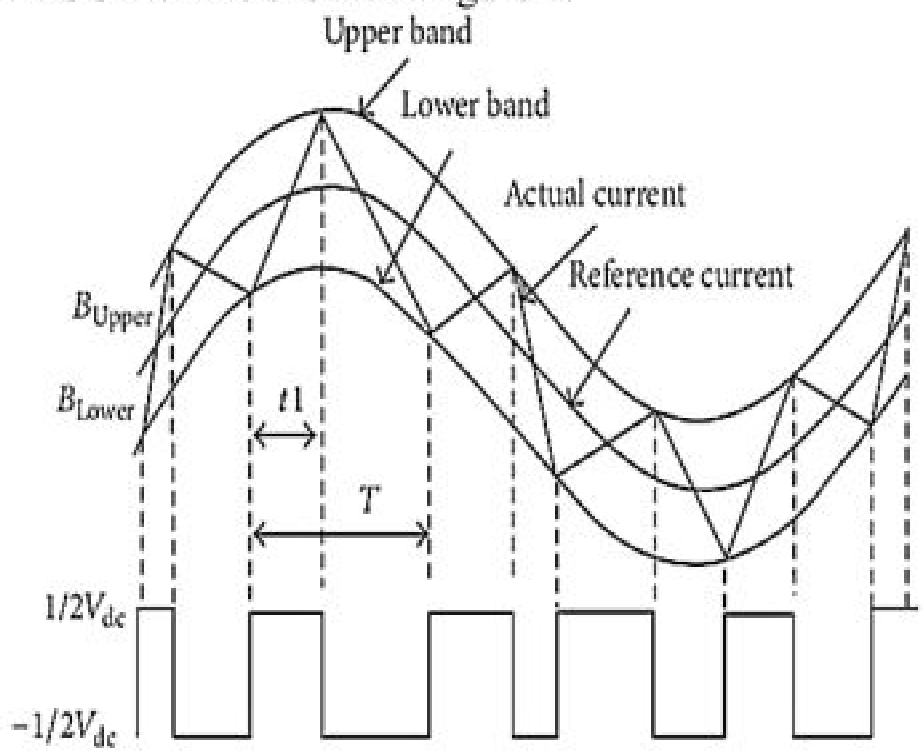


Figure 1. Create a Pulse Using HBCCPWM.

## 3 FPGA- Based HBCCPWM Control Technique

In Figure 2, it shows regulation of the digital induction motor based on field-programmable gate arrays (FPGA). The FPGAs generate control signals for the semiconductor switching devices that drive the three-phase inverter (Noorsal, et al., 2022). A specific type of current control technique, sometimes referred to as a hysteresis controller, switches the phase voltage on and off based on feedback provided from the current sensor. The phase current is constrained by enlarging or narrowing the hysteresis tolerance around the desired value for research. The hysteresis control technique, is essentially developed to provide an easy and robust way to mitigate changing load conditions, which require determining the switching frequency width which typically is uncertain, as well as issues involving the safety of the inverter circuit system (Purnata, et al., 2017). The FPGA controller provides

PWM pulses to switch the three-phase inverter semiconductor devices on or off.

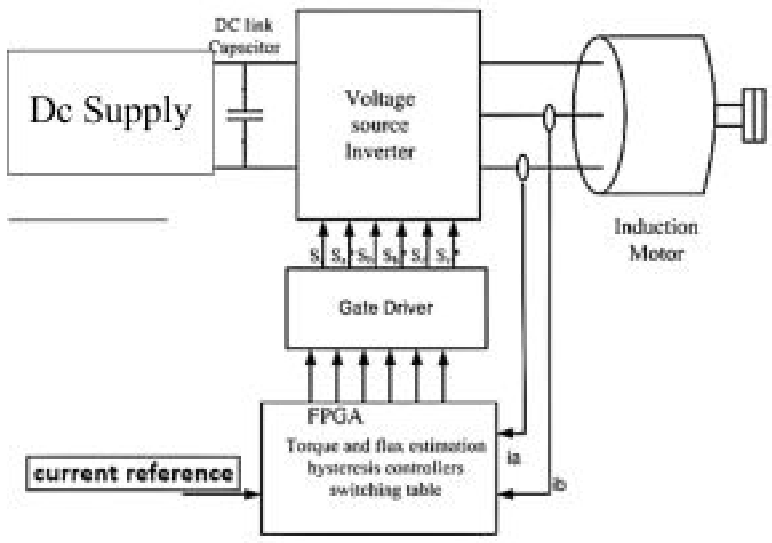


Figure 2. FPGA Based Speed Control of Induction Motor.

The integrated circuit HBCCPWM control based on FPGAs consists of six sections, which are used to modify the amplitude, frequency, phase voltage, and delay time of IGBT's. Digital switches and ADCs are some examples of external devices that can be used to vary these electrical characteristics. The blocks that were implemented in the FPGA were done in VHDL (Purnata et al., 2017; Saravanan et al., 2012). There are IGBT switches in the phase legs of the three-phase inverter, and there also has to be a delay time that is introduced between these IGBTs to prevent the shoot-through failure (Poolphaka et al., 2023). The Discrete Sine Wave module generates a reference signal of a discrete sine wave. A sine wave is used to control the speed of the motor. The sine wave is run at a frequency range of 55 to 65 Hz. Figure 3 depicts a three-phase inverter powered by an FPGA, which is used to operate the induction motor.

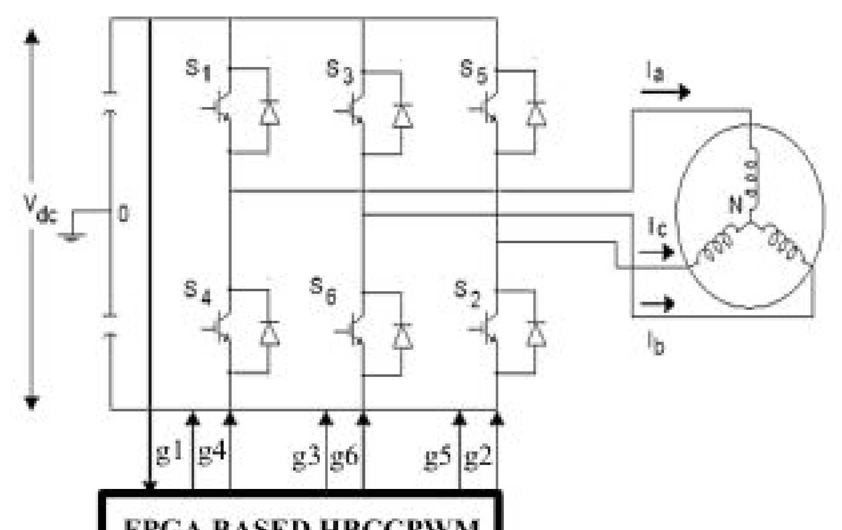


Figure 3. A Three-Phase Induction Motor That Is Fed by an FPGA.

The mathematical approach isolates control to the present waveform by calculating the error between the reference and measured currents and establishing hysteresis-based switching logic.

To define the instantaneous current error for phase i (Thielmann et al, 2021) :

$$e_i(t) = i_i^*(t) - i_i(t)$$

where i*(t) denotes the reference current and i(t) represents the measured current.

This error is limited to a hysteresis band with a half-width of (h).

$$-h \le e_i(t) \le +h$$

When ei(t) crosses the band boundaries, the inverter switch state Si changes accordingly:

$$\begin{cases} e_i(t) \ge +h \rightarrow S_i = 0(turn\ upper\ switch\ off), \\ e_i(t) \le -h \rightarrow S_i = 1(turn\ upper\ switch\ on). \end{cases}$$

This framework guarantees that the present error stays within hysteresis boundaries while autonomously adjusting the switching frequency to uphold superior current quality and little THD.

## 4 Frequency Control Technology

Variable frequency drive is the most widely used technology in industrial settings. The main advantages of a 3-phase induction motor include its starting and braking capabilities, speed variation, and the ability to reverse speed. The continuous advancement of power ratings and switching characteristics in power semiconductor devices has enabled the use of power electronic converters in both low-power and high-power variable speed drives (Khadke and Kamble, 2016). Numerous driving strategies have been devised to achieve the optimal economic operating point of a 3-phase induction motor. Today, with a contemporary high-frequency inverter controlled by an FPGA microprocessor, the motor's input frequency and voltage may be adjusted, hence enabling control over the motor's speed or torque. The speed of a squirrel-cage low power induction motor may be regulated primarily by adjusting the frequency, as seen in figure 4. In this instance, we can continually reduce costs without compromising drive efficiency. The alteration of the input frequency can affect the motor's speed and torque. Efficient wide-range speed control of the induction motor is achievable when a variable frequency AC source is accessible (Lander, 2001).

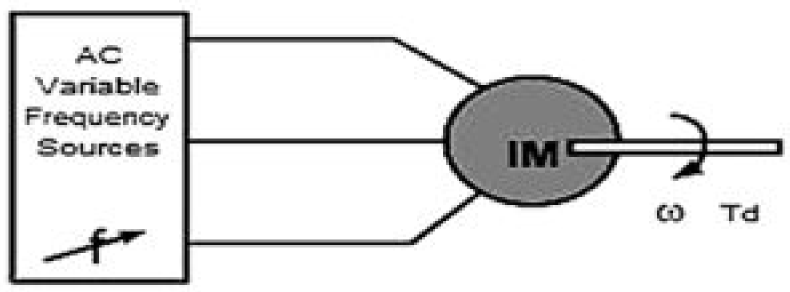


Figure 4. Frequency Regulation of Three-Phase Induction Motor Drive.

## 5 Software Simulation with Results

An induction motor drive with hysteresis band current regulation is simulated in figure 5.

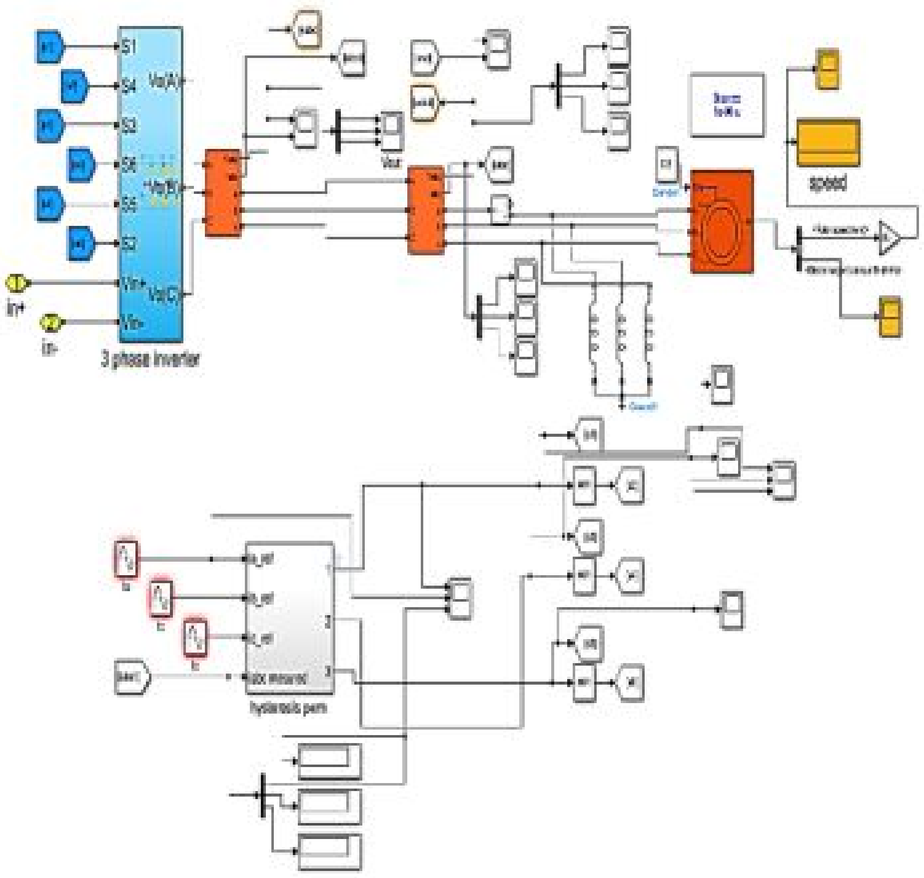


Figure 5. Modelling of HBCCPWM for Three Phase Inverter with Induction Motor Drive.

A pulse width modulation method with a band value of 0.4 is appropriate for an open loop system. Here are the parameters of the induction motor that was utilized for the simulation:

Rotor type: squirrel cage.
Voltage (line-line): 400V.
Frequency: 50Hz.
Number of poles: 4 pole machine.

Figures 6, 7, 8, 9, 10, 11, 12, 13 and 14 display the phase voltage, output speed, and currents produced by the induction motor when the open loop control is set to hysteresis band current control pulse width modulation at frequencies of 55 Hz, 60 Hz, and 65 Hz.

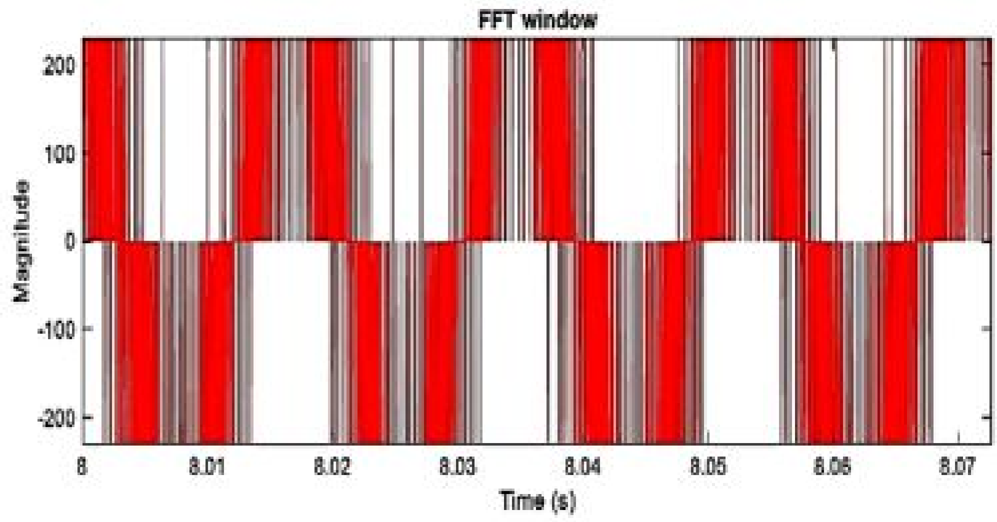


Figure 6. Output Voltage Using HBCCPWM for Fref 55Hz.

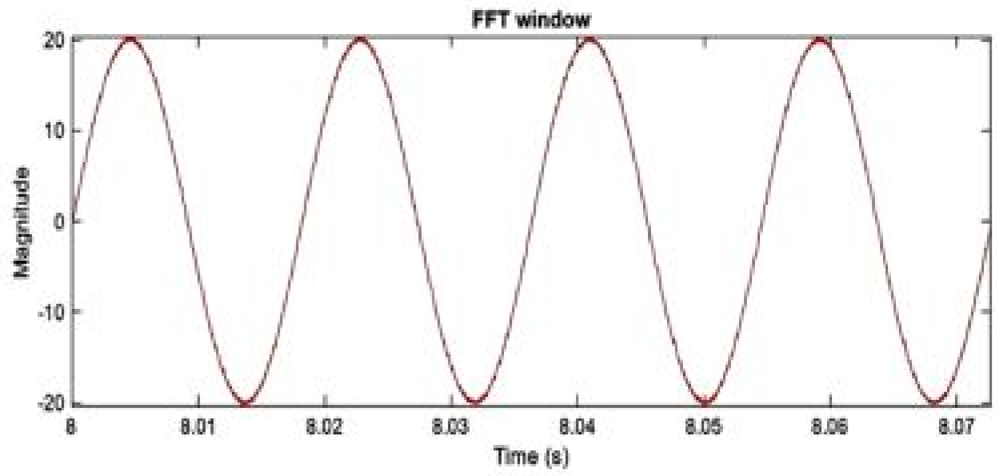


Figure 7. Output Current Using HBCCPWM for Fref 55Hz.

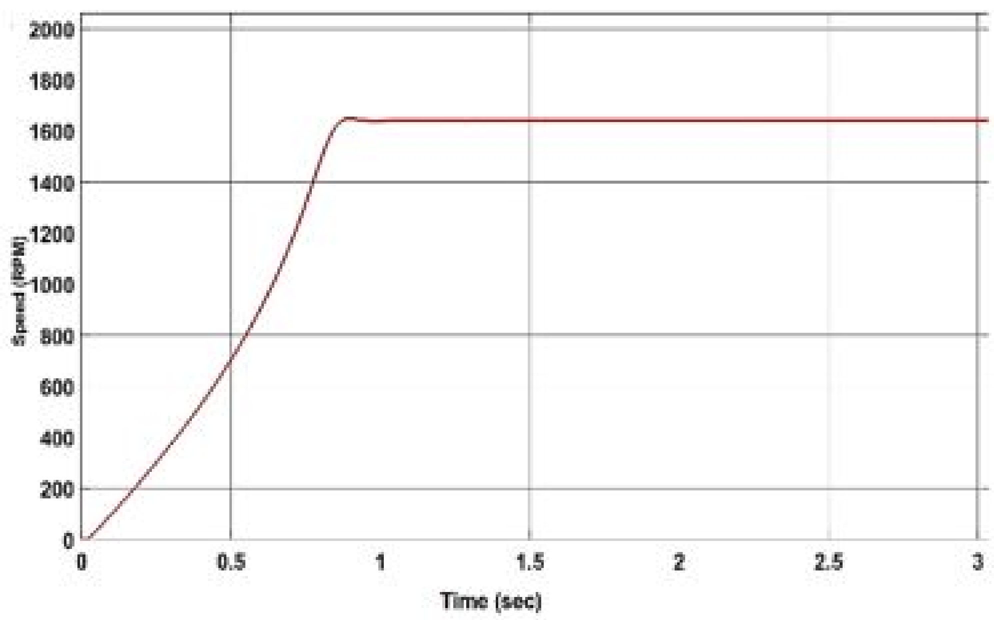


Figure 8. Output Speed of I.M for Fref 55Hz.

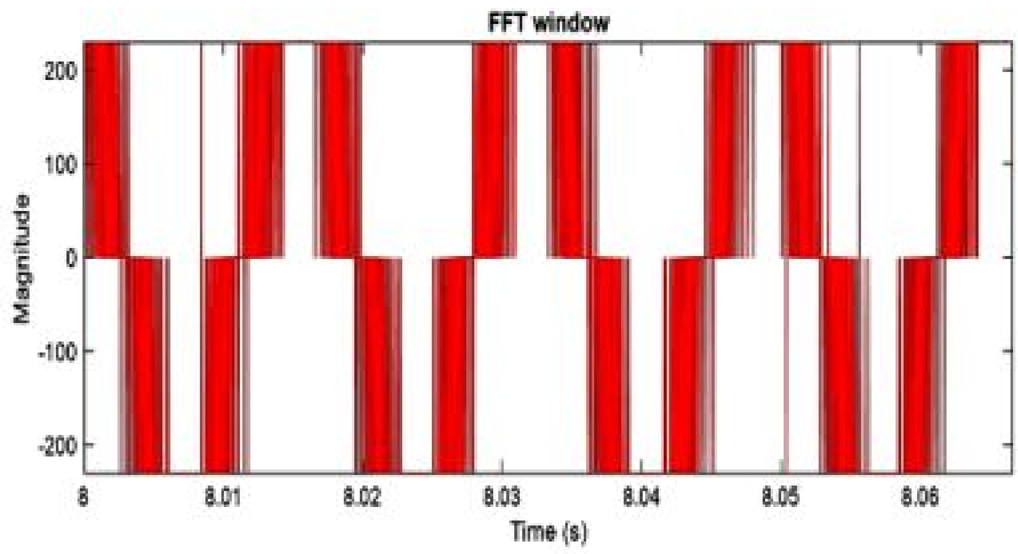


Figure 9. Output Voltage Using HBCCPWM for Fref 60Hz.

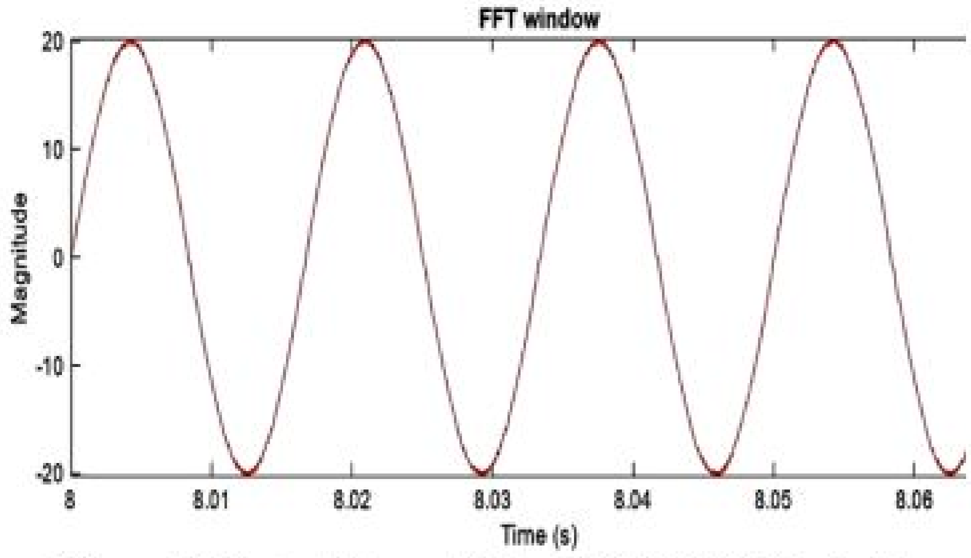


Figure 10. Output Current Using HBCCPWM for Fref 60Hz.

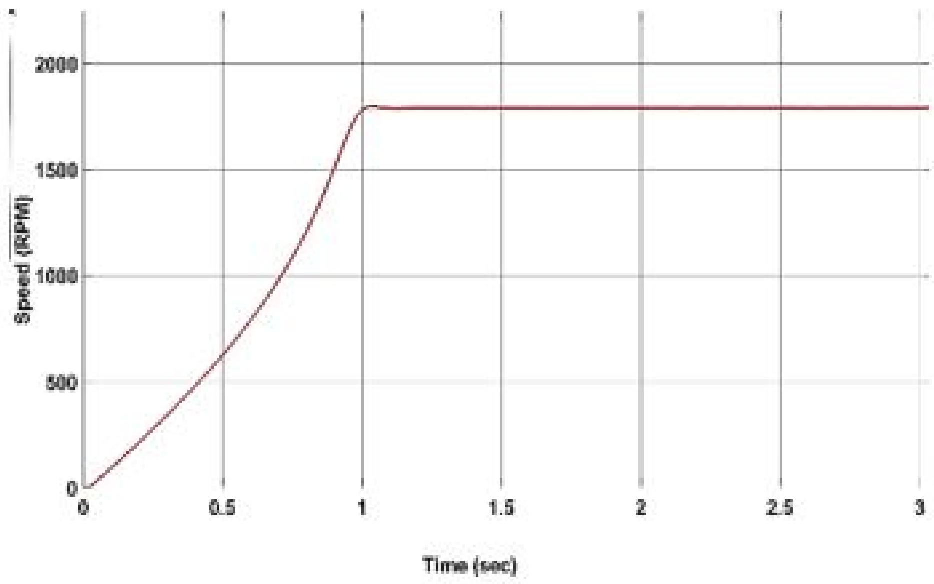


Figure 11. Output Speed of I.M for Fref 60Hz.

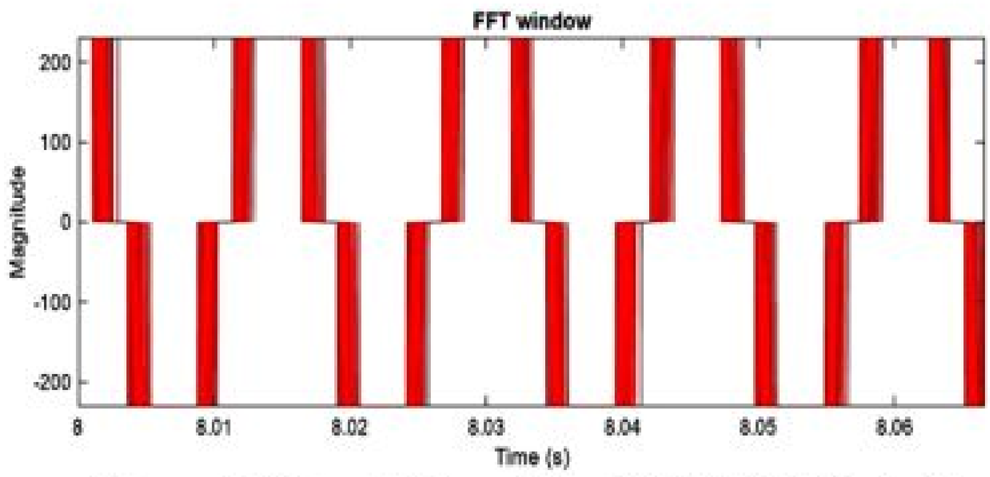


Figure 12. Output Voltage Using HBCCPWM for Fref 65Hz.

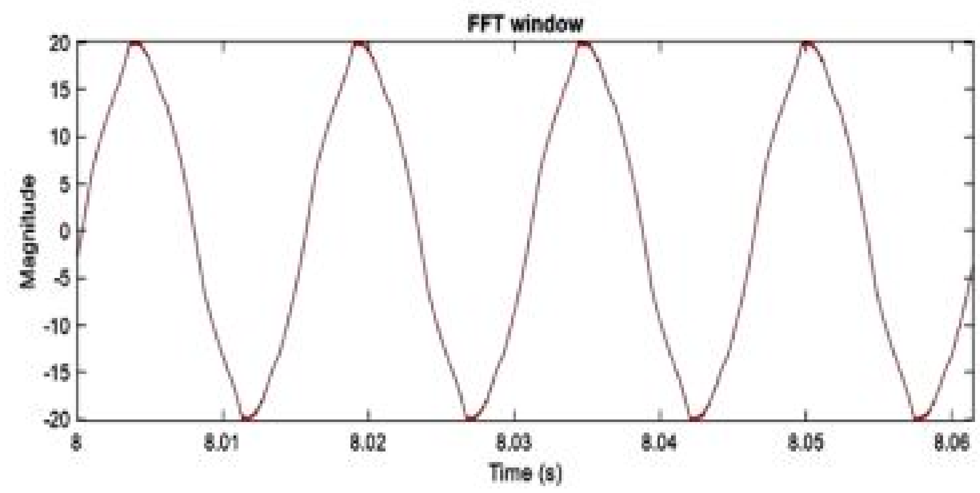


Figure 13. Output Current Using HBCCPWM for Fref 65Hz.

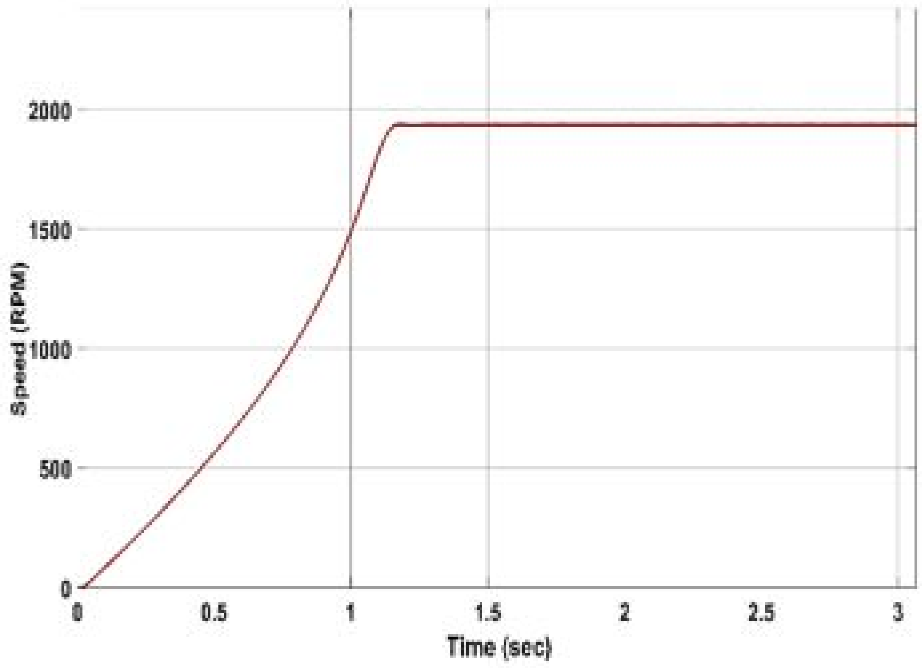


Figure 14. Output Speed of I.M for Fref 65Hz.

In table 1 show the simulation results of THD for current, voltage and the speed for the induction motor with HBCCPWM technique.

Table 1. The Results of the Modeling Frequency Method with HBCCPWM.

| **Reference Frequency (Hz)** | | **Type of Load** |
|---|---|---|
| | | **HBCC with Induction Motor Load** |
| ***55*** | THD V | 10.4 % |
| | THD I | 0.71 % |
| | Speed | 1643 RPM |
| ***60*** | THD V | 6.5 % |
| | THD I | 0.89 % |
| | Speed | 1792 RPM |
| ***65*** | THD V | 10.8 % |
| | THD I | 3.99 % |
| | Speed | 1939 RPM |

## 6 Hardware Implementation with Results

The hardware implementation of an FPGA-based speed control system for a three-phase induction motor are show in Figure 12.

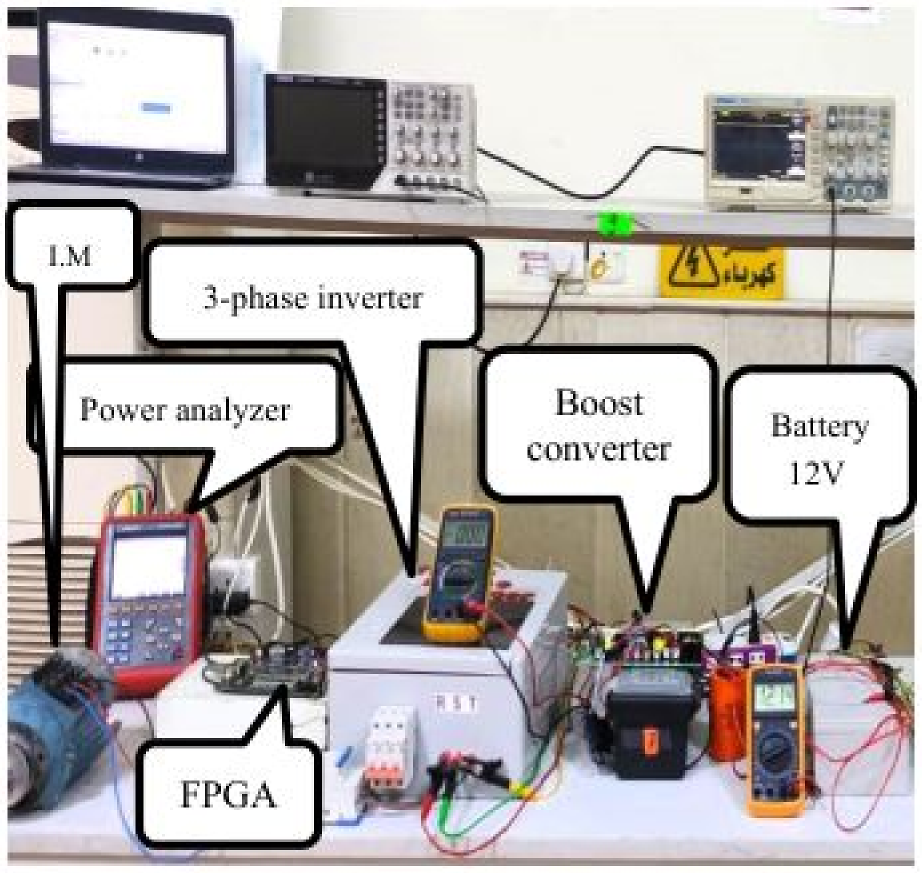


Figure 12. Hardware Implementation.

The systems use a hysteresis band current control pulse width modulation technique for open loop control at frequencies of 55 Hz, 60 Hz, and 65 Hz, respectively, with switching frequencies of 1485 Hz, 1260 Hz, and 975 Hz, respectively. High-frequency switching intrinsically produces electromagnetic interference (EMI). Spectral analysis of the motor currents and inverter voltages revealed dominant electromagnetic interference components at the switching frequencies (1–1.5 kHz). To alleviate conducted and radiated electromagnetic interference (EMI), the subsequent steps were executed:

Snubber networks utilised in IGBT switches to mitigate voltage overshoots. Shielded motor cables and common-mode chokes for emission reduction with these countermeasures, the conducted EMI levels adhered to CISPR 11 Class A limitations.

In Figure 13, 14, 15, 16, 17, 18, 19, 20, 21 shows all the results THD, FFT for current and voltage.

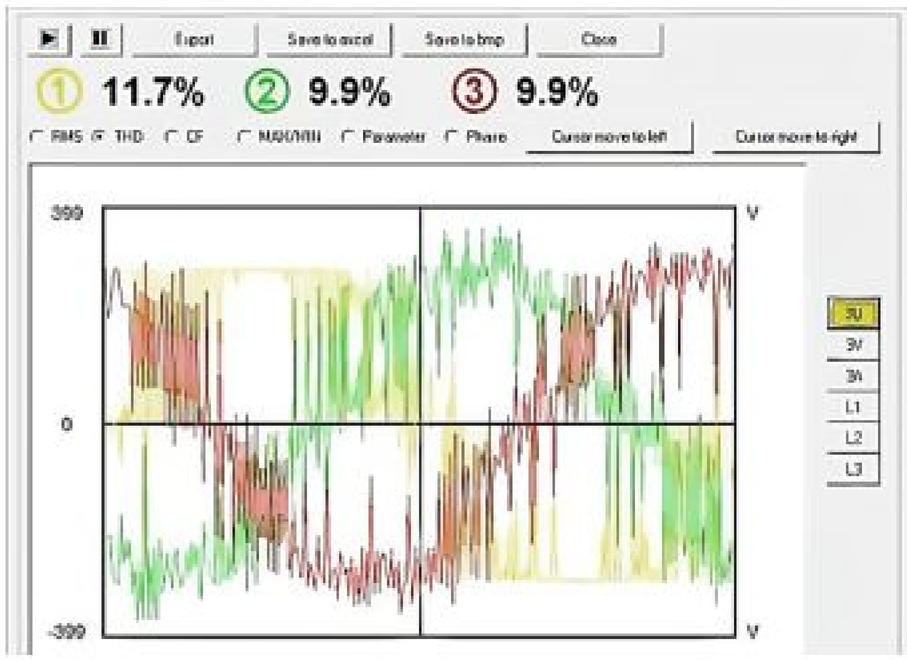


Figure 13. THD of Output Voltage for Fref 55 Hz by Power Analyzer.

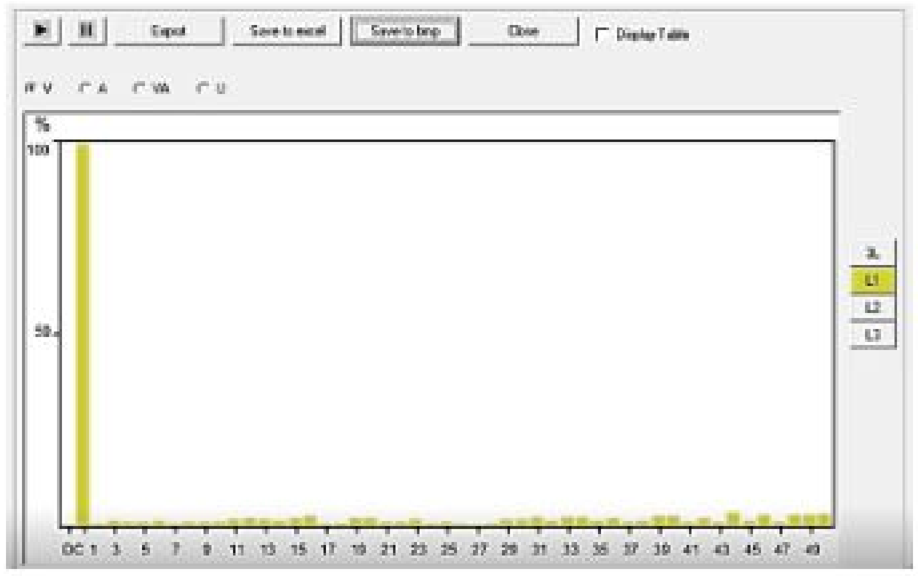

Figure 14. FFT of Output Voltage with Induction Motor for Fref 55 Hz by Power Analyzer.

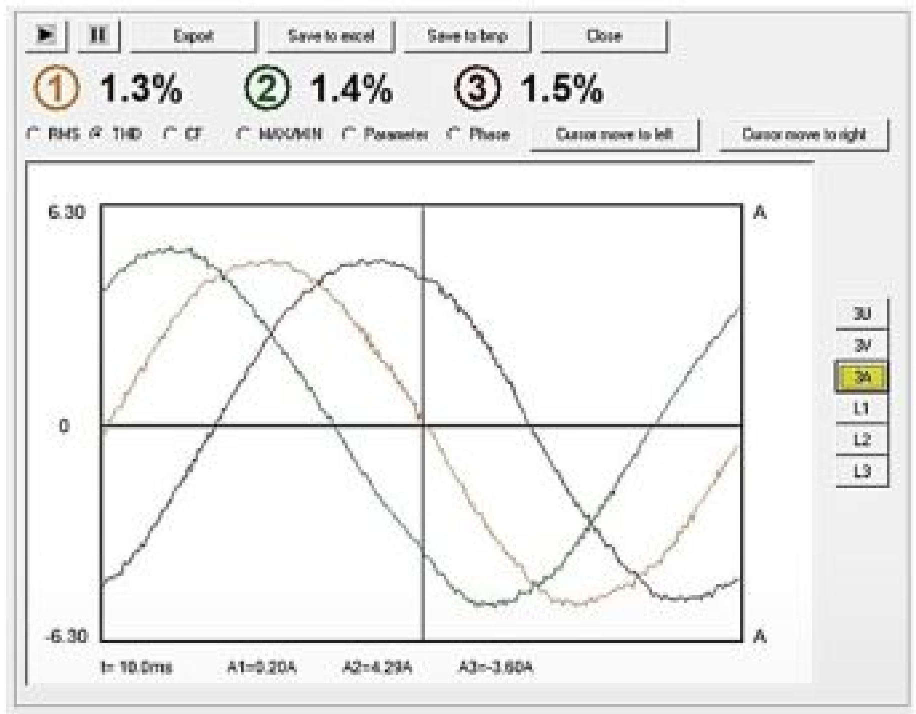


Figure 15. THD of Output Current for Fref 55 Hz by Power Analyzer.

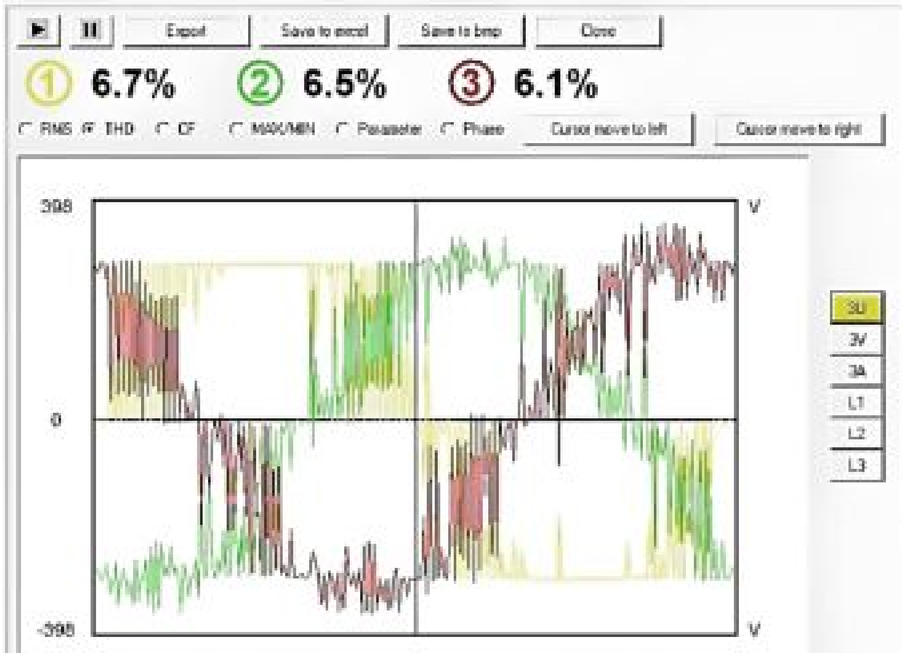


Figure 16. THD of Output Voltage for Fref 60 Hz by Power Analyzer.

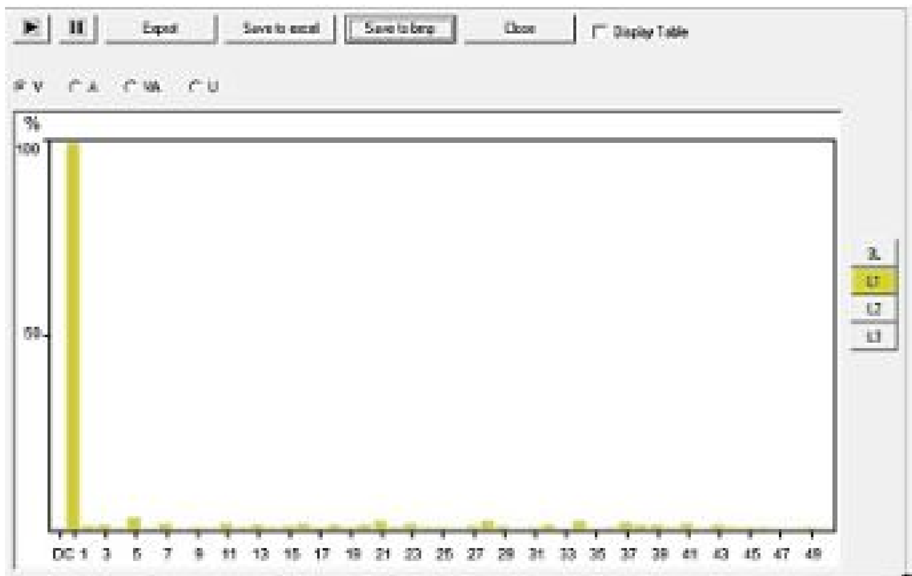


Figure 17. FFT of Output Voltage with Induction Motor for Fref 60 Hz by Power Analyzer.

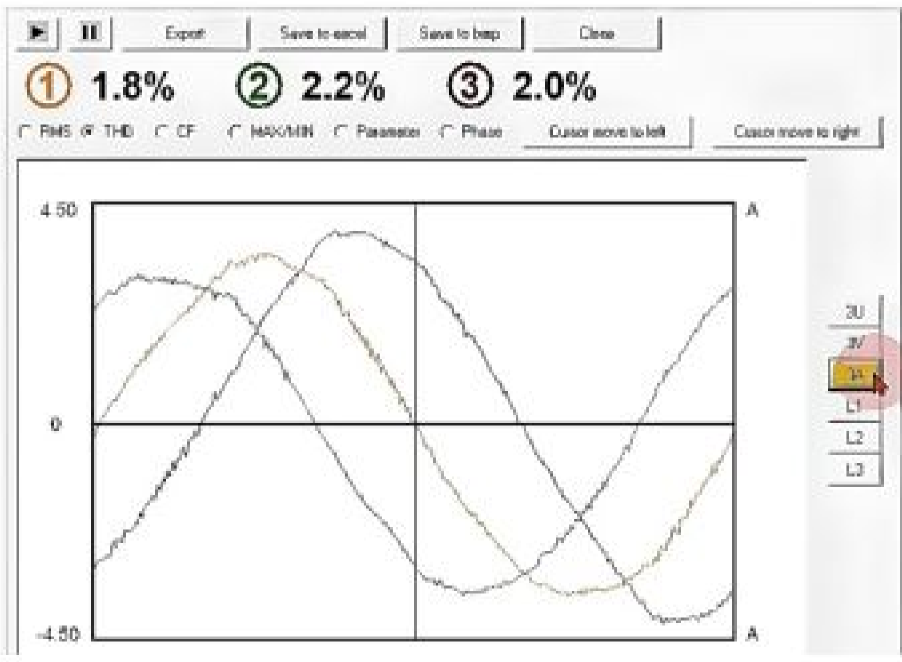


Figure 18. THD of Output Current for Fref 60 Hz by Power Analyzer.

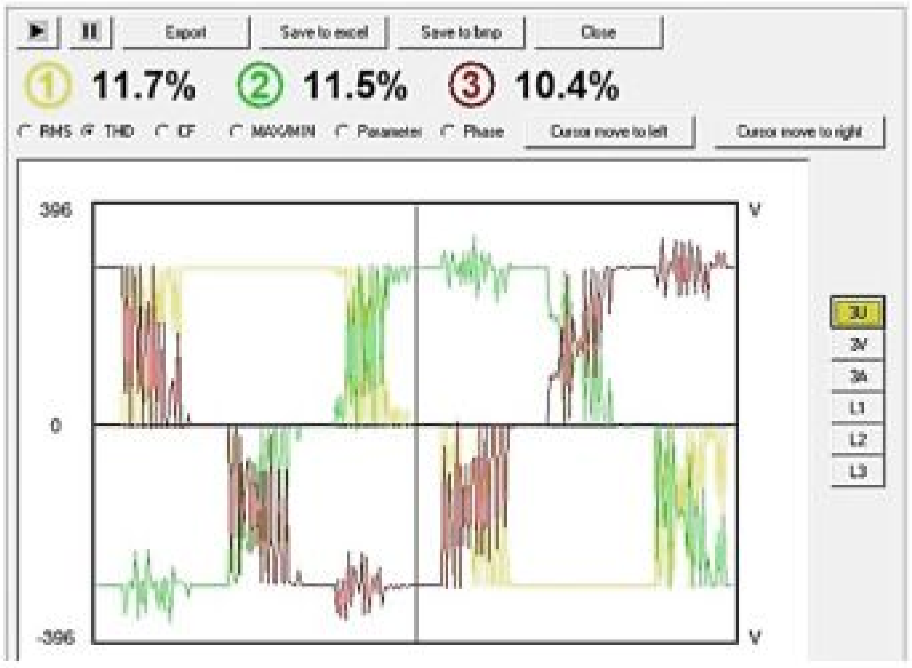


Figure 19. THD of Output Voltage for Fref 65 Hz by Power Analyzer.

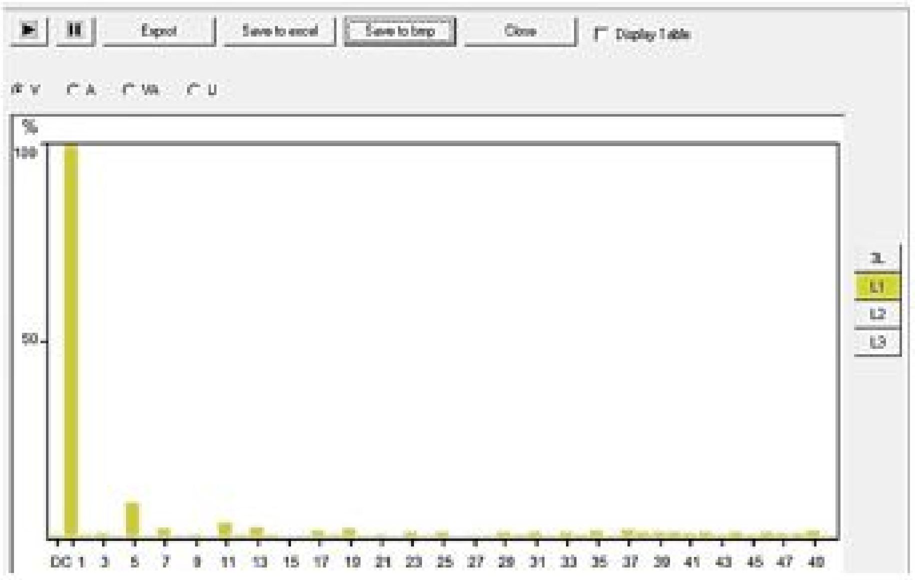


Figure 20. FFT of Output Voltage with Induction Motor for Fref 65 Hz by Power Analyzer.

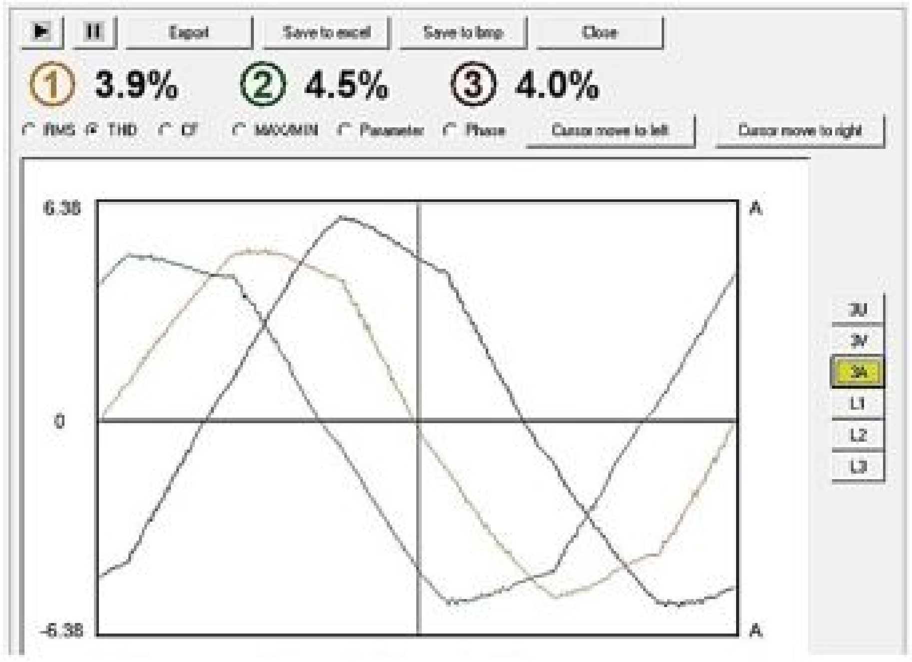


Figure 21. THD of Output Current for Fref 65 Hz by Power Analyzer.

In table 2 shows the practical results of THD for current, voltage and the speed for the induction motor with HBCCPWM technique.

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Table 2. The Results of the Practical Frequency Method with HBCCPWM.

| Reference Frequency (Hz) | | Type of Load |
|---|---|---|
| | | HBCC with Induction Motor Load |
| *55* | THD V | 11.7 % |
| | THD I | 1.5 % |
| | Speed | 1646 RPM |
| *60* | THD V | 6.7 % |
| | THD I | 2.2 % |
| | Speed | 1795 RPM |
| *65* | THD V | 11.7 % |
| | THD I | 4.5 % |
| | Speed | 1945 RPM |

The system's behaviour under several reference frequencies and load conditions was assessed using experimental and simulation data. The results show that the system achieves its best at moderate a reference frequency (55 Hz – 65 Hz), where it shows:

- As low as 1.5%, low current THD.
- Reliable motor performance.
- Considered output voltage quality.

The system presented the lowest voltage THD (6.7%) at 60 Hz, which can indicate that this frequency can represent the best trade-off among switching performance, output quality, and motor response. For higher frequencies particularly 65 Hz, the system performance worsens in the sense of current waveform quality; the THD increases significantly to 4.5%. The HBCC fixed-band limitations were caused by this reality, as they reduce the switching frequency at high fundamental frequencies to the detriment of the controller's ability to track the high-frequency changing reference signal. Current tracking is thereby less precise and ripple is higher, leading to increased harmonic content.

The strong link between simulation and experimental results is shown in Table 3 and Figure 22:

Table 3. Comparison Between Simulation and Experimental Results.

| Frequency (Hz) | Simulated THD (I) | Experimental THD (I) | Simulated speed (RPM) | Experimental speed (RPM) |
|---|---|---|---|---|
| 55 | 0.71 % | 1.5 % | 1643 | 1646 |
| 60 | 0.89 % | 2.2 % | 1792 | 1795 |
| 65 | 3.99 % | 4.5 % | 1939 | 1945 |

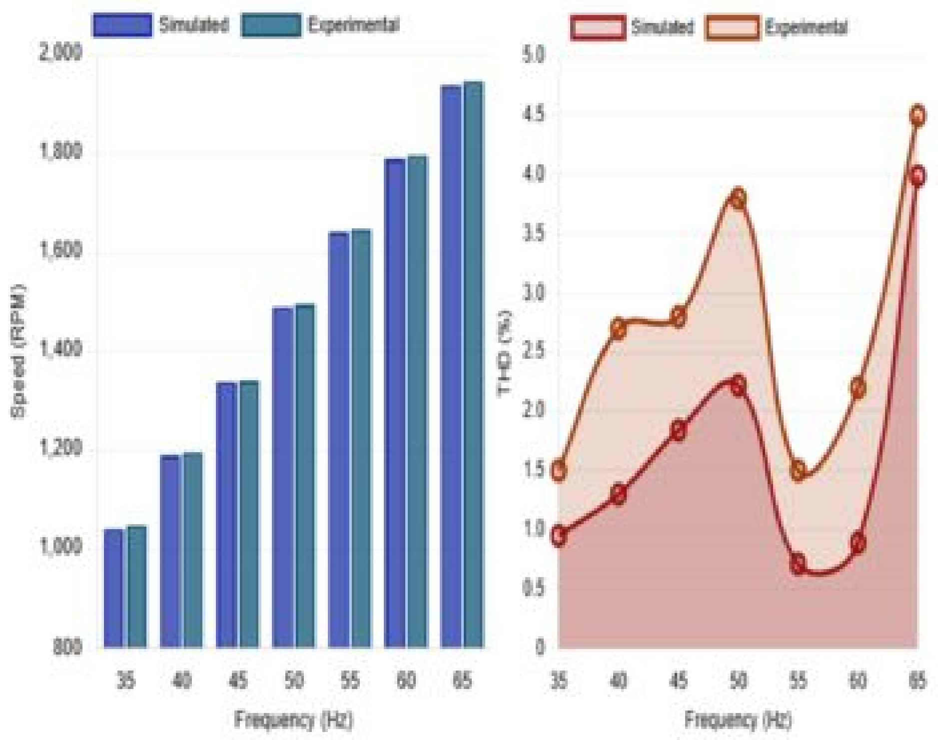


Figure 22. Correlation Between Simulated and Experimental Motor Performance Speed and Current THD.

The small Changes in THD and speed are within acceptable limits and result from:

- Non-idealities in hardware.
- Natural variables in changing motor load.

## 7 Conclusion

In this paper, it developed and evaluated an FPGA-based HBCCPWM system for regulating the speed of induction motors utilising mathematical models and empirical tests. The findings indicated that the system could precisely regulate the current, dynamically adjust the switching frequency, maintain a low overall harmonic distortion of 1.5%, and exhibit rapid responsiveness, surpassing conventional SPWM and SVPWM methods. EMI mitigation ensures compliance with industrial requirements. This technology serves as a robust foundation for high-performance, variable-frequency AC drives and has the potential for future enhancements in closed-loop and adaptive control.

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**Biography**

**Laith Akram Mohammed** was born in Mosul / Iraq, PhD. in Electrical Engineering. Assist professor, BSc 1989 MSc 2004 form University of Technology and Ph.D. 2017 from University of Mosul. Professor in Technical College/Mosul, Northern Technical University, Mosul, Iraq. My research interests in: Power Electronics, Renewable Energy, Motor Drives and power quality.

**Wissam Sami Mohammed** was born in Mosul / Iraq, he received the B.Sc. degree from the Technical Engineering College / Mosul, Northern Technical University, Mosul, Iraq, at 2017 and MSc at 2025 in Power Electronics field at the Electrical Power Engineering Technology Department / Northern Technical University /Technical Engineering College / Mosul / Iraq.