



## Development of a Variable Frequency Drive for Irrigation Pump Control

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Received: 08 November 2025, Accepted: 11 February 2026, Published: 31 March 2026

### KEY WORDS

Variable Frequency Drive, Irrigation System, Pump Control, Power Electronic Technologies and Variable Speed Drive.

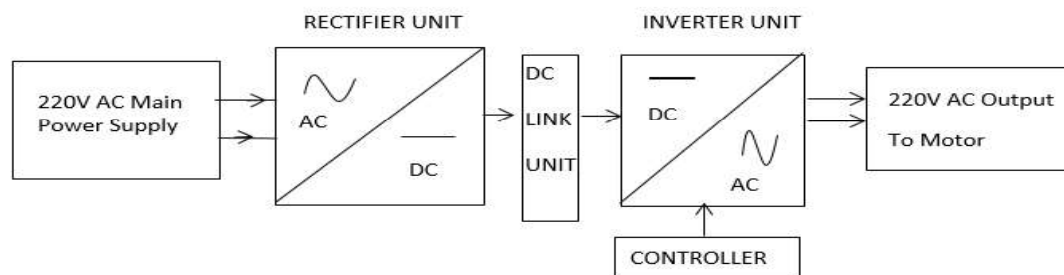
### ABSTRACT

This work presents the development of an affordable variable frequency drive for irrigation applications. The variable frequency drive system was designed to control the speed of irrigation pumps based on water demand hence, minimizing energy wastage and optimizing water distribution. The development of this work involved the selection of locally sourced power electronic components as well as the development of a controller for typical irrigation requirements. Field testing and performance analysis showed a substantial potential of this technology for enhancing agricultural water management practices hence, reducing operational cost for farmers. This variable frequency drive is intended to function correctly when supplied with an AC voltage between 180V and 230V, at a frequency of 50Hz. Its operational output frequency ranges from 10Hz to 50Hz. During testing, the efficiency of the variable frequency drive was found to be 79.3%, while its voltage-frequency accuracy was 89.6%. The maximum attainable speed recorded was 2930rpm. A lot of time was spent during the development of this work. This is so because, it took a lot of research and testing to get the right program that the microcontroller needs to operate at its best. The results of this work's testing are consistent with those of commercially available Variable Frequency Drives.

### 1.0 INTRODUCTION

Effective and efficient irrigation systems enhance agricultural productivity hence, the need for irrigation, which is the artificial application of water to the soil through various systems of tubes, pumps and sprays. Irrigation is usually used when natural water sources are not sufficient to provide plant water demand and in areas where rainfall is irregular or dry times of drought is expected (Hussain et al, 2022). Most irrigation systems in use today make use of fixed pump speed which often result in excess energy consumption and wastage of water. In order to overcome the limitations with fixed speed irrigation system, there is the need to develop irrigation systems with adjustable speed hence the need for Variable Frequency Drives which are power electronic technologies capable of addressing the inefficiency in fixed speed

irrigation system by increasing/decreasing the number of alternating current cycles per second hence controlling the speed of pumps to meet the varying irrigation demands in an irrigation system. This reduces energy consumption, extends lifespan of equipment and reduces water wastage. This work aims to contribute to the advancement of smart and sustainable irrigation solutions for the agricultural sector. A Variable Frequency Drive is a type of motor controller which drives an electric motor by varying the frequency of the power supplied to the electric motor. Figure 1 depicts a typical VFD block diagram



**Figure 1:** Block Diagram of VFD

The Rectifier unit is the first component of a variable frequency drive that converts AC power from mains to DC power using diodes and other switching devices. The DC power from the rectifier section is stored in the DC link and made available to the inverter unit that makes use of electronic switches like MOSFETs and IGBTs to convert DC power back to AC power. The Controller Unit is the unit of the VFD that essentially regulates the frequency of the output power from the inverter unit by controlling the on/off time of the electronic switches.

The objectives of this work are to:

- 1 Develop the Rectifier unit of the VFD
- 2 Develop the DC link unit of the VFD
- 3 Develop the H-Bridge Inverter unit of the VFD
- 4 Assemble all Developed units of the VFD
- 5 Case the entire Developed VFD panels
- 6 Test the VFD
- 7 Record the VFD test results
- 8 Analyze the Test results of the VFD

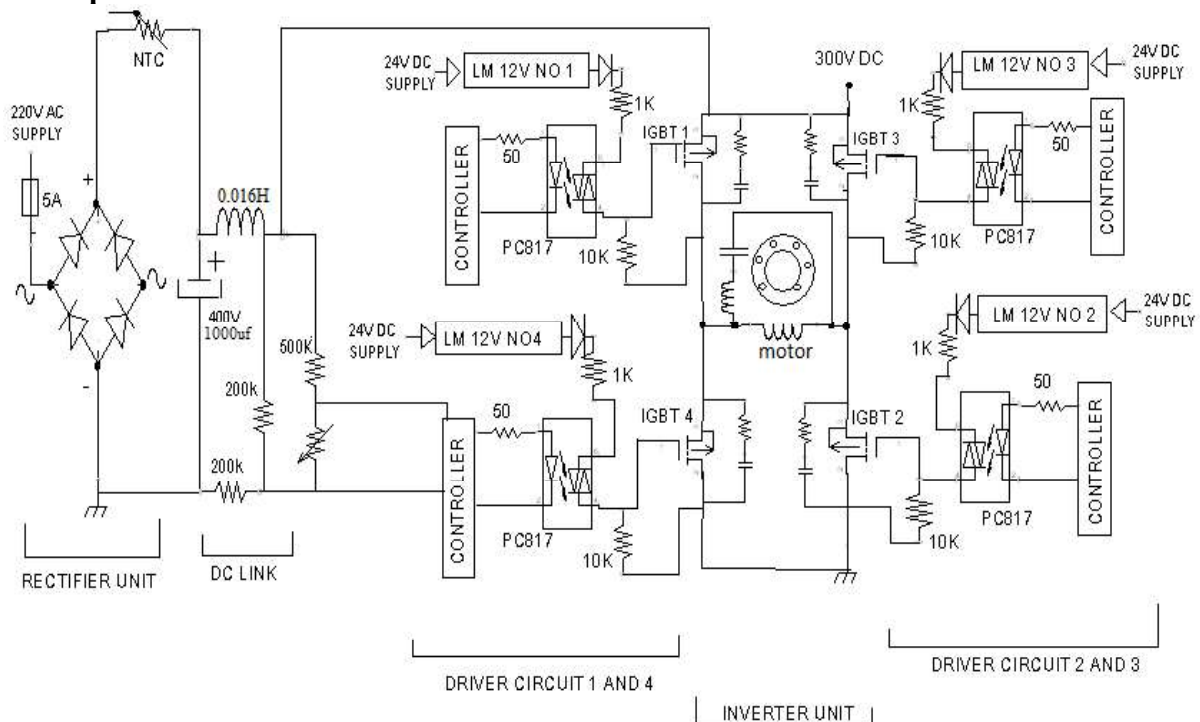
## 2.0 MATERIALS AND METHODS

In this VFD, single Pulse Width Modulation is the technique used to vary the width of the elapsed time between the leading and trailing edges of a single pulse of the voltage supplied across the load. The switching of the pulse width is controlled by a microcontroller unit that functions as a small computer on a single integrated circuit. The output of the microcontroller is then connected to the IGBT gate driver that amplifies the low-power supplied from the controller IC to a high-current capable of switching the IGBT for irrigation pump control.

## 2.1 Materials and Equipment

Some of the materials and equipment used in this research work include: Soldering iron rated 220V and 40W, Soldering lead, Fluke 15B MAX Digital Multi-meter, Bread boards, Arduino microcontroller board, Tincad Electrical circuit Design software, Bridge Rectifier Diode rated 35A and 1000V, Fuse rated 5A, Capacitor rated 400V and 1000 $\mu$ F, Step-down Transformer rated 220V-24V, Bridge Rectifier rated 220V and 1A, IGBT(60N60) rated 600V and 60A, Resistors rated; 10 $\Omega$ , 50 $\Omega$ , 1k $\Omega$ , 5k $\Omega$ , 10k $\Omega$  and 100k  $\Omega$ . The rating for resistors used in the gate driver circuits were all gotten from IC pic817 manufacturer's data sheet. (Onsemi, 2024).

## 2.2 Experimental Procedure



**Figure 2: Circuit Diagram of Developed VFD**

### Rectifier

This unit utilizes a single bridge rectifier chip (MIC KBPC3510) to convert 220V AC power from mains to DC power. MIC KBPC3510 was chosen because, according to manufactures data sheet, it has a high current and voltage handling capacity of 30A and 1000V.

### DC Link

The DC Link consists of a capacitor and an inductor for smoothing and storing the DC power received from the rectifier unit. The capacitor and inductor ratings are calculated as shown:

$$C = I_{LOAD} / f_r \Delta V_r \quad (1)$$

Where  $C$  = capacitance (Farads),  $I_{LOAD}$  = DC Load current (Amps),  $f_r$  = ripple frequency (Hz),  $f_r = 2f_{supply}$ ,  $\Delta V_r$  = allowable ripple voltage (volts peak to peak)

Therefore,  $C = 2 / (2 \times 50 \times 20) = 0.001F = 1000\mu f$ . A value of 400V was chosen for this capacitor because the capacitor voltage rating must exceed the main supply voltage of 220V.

$$L = V_r / 2\pi f_r \Delta I \quad (2)$$

Where  $L$  = inductance (H),  $f_r = 2f_{\text{supply}}$ ,  $I_{\text{ripple}}$  = allowable ripple current (A)

Therefore,  $L = 20 / (2\pi \times 100 \times 2) = 0.016\text{H}$

### Inverter Unit

The inverter unit converts DC to AC using a configuration of four H-Bridge IGBTs. A square wave AC power output can be produced by reversing the direction of flow of a direct current source when each IGBT is turned on and off at the appropriate times. Single pulse width modulation technique was used for this project. Because of the features listed in the manufacturer's data sheet in Table 1, IGBT 60N60 was chosen for this project.

**Table 1:** Features of IGBT (60N60) from the Manufacturer's Data Sheet. ([Onsemi](#), 2024)

$V_{\text{ces}}$	$I_{\text{c}}$	Turn-on delay time	Turn-off delay time	Operating junction Temperature
600V	60A	18ns	104ns	-55 °C to + 175 °C

The heat generated inside each IGBT was transferred into the surrounding air using heat sinks whose sizes were determined by the IGBT junction temperature in Table 1.

### Controller Unit

The controller unit is the brain of the entire system that controls the timing and switching of the IGBTs. The microcontroller used in this work is an Arduino microcontroller which is inexpensive and commercially available.

1ms dead time was inserted after each gate pulse as shown in Figure 4 to prevent the H Bridge from short-circuiting the positive and negative DC supply from the DC Link. During the positive half cycle, G1 and G2 are turned on while G3 and G4 are turned off. During the negative half cycle, G1 and G2 are turned off while G3 and G4 are turned on. The equation relating the frequency and period of the gating pulse is;

$$T = 1/f \quad (3)$$

$T$  = Period of pulse,  $f$  = Frequency of pulse

The output waveform of this VFD is a square wave whose total RMS and THD are given by;

$$V_{\text{rms}} = (2\sqrt{2} / \pi)V_{\text{dc}} \approx 0.9003V_{\text{dc}} \quad (4)$$

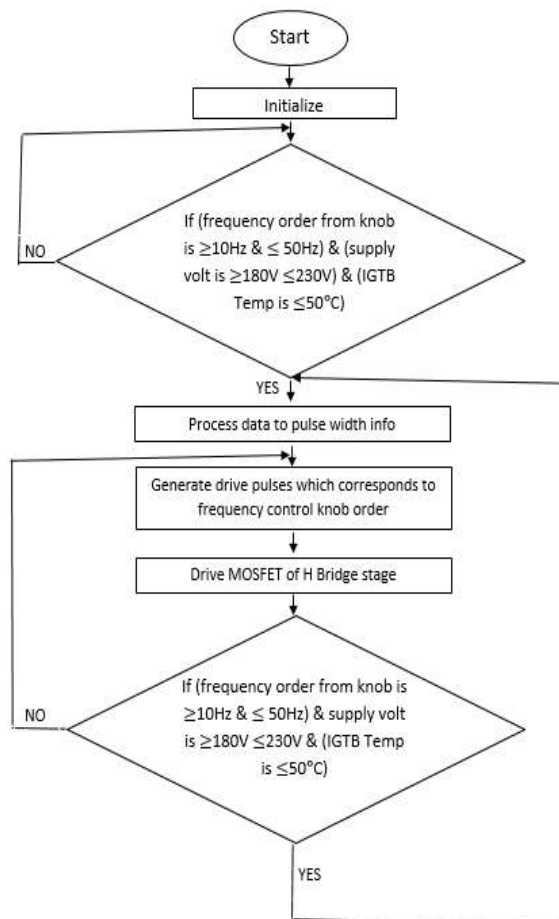
$$\text{Total Harmonic Distortion (THD)} = \frac{V_{\text{dc}}}{V_{\text{rms}}} \approx 0.4350/0.9003 \approx 0.483 \text{ (48.3\%)} \quad (5)$$

In the gating signal shown in Figure 4, only one pulse per half cycle was used. The width of the pulse was varied to control the VFD output voltage while keeping the ratio of Volt/Hertz constant. A constant Volt/Hertz ratio ensures the pump's torque is roughly constant hence preventing overheating and stalling.

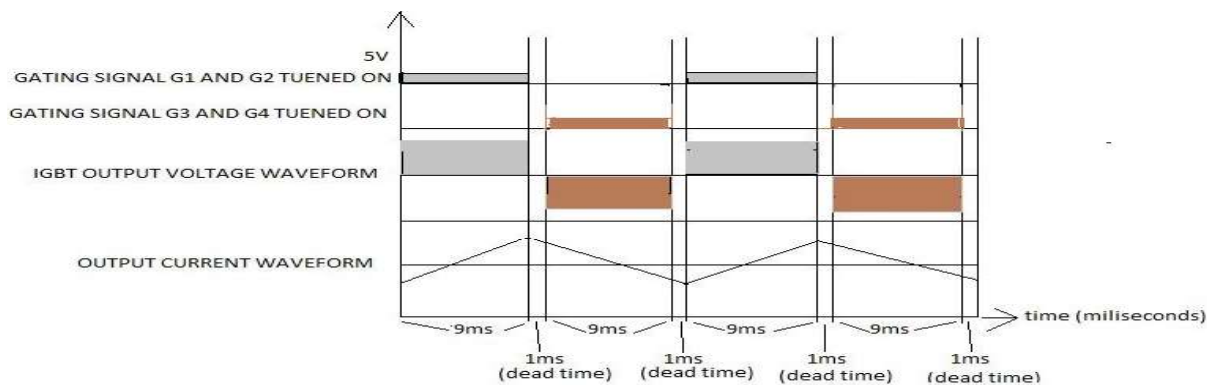
The fuse rated 5A in the VFD, prevents excess current from flowing into the VFD circuit. The Controller unit also provides automatic shutdown protection, when it detects overcurrent via a resistor arrangement shown in Figure 2.

1ms dead time was written into the microcontroller programme, to prevent shoot-through within the IGBTs also, a resistor of 10K $\Omega$  was used to connect the gate and drain terminals of each IGBT to ensure quick turn off time hence, preventing shoot-through.

This VFD's under voltage lockout and overvoltage protection were made possible by a feedback circuit made up of resistors that feed the microcontroller with measured voltage levels. The microcontroller stops the VFD's operation when the supply voltage level falls below 180V AC or rises above 230V AC. The entire circuit is protected from overheating by the NTC thermistor used in the circuit.



**Figure 3:** Flow Chat for the Controller Unit



**Figure 4:** Gating Signal Diagram from Controller to IGBT Driver

## Protection Unit

### Construction and Assembling Procedure of VFD

The Arduino microcontroller was programmed via a software on a PC. Upon completion of the microcontroller programming, the programmed Arduino microcontroller board was then connected to all other electronic components of the VFD via bread boards. After carrying out all necessary tests on the connected circuits, the circuits were found to work properly hence, installed inside the VFD casing.

## 3.0 RESULT AND DISCUSSION

This project was tested in Edo University Uzairue's workshop. The VFD was first connected to a 220V AC power supply thereafter, a 1HP water pumping machine was connected to the VFD.

The motor became energized immediately the pump's start button was turned on thereafter, the speed control knob was used to control the speed of the pump.

It should however be noted that the design of this VFD is such that the initial startup rpm of the motor is 10rpm. This is a safety measure which was put in place to ensure the safety of the irrigation pump and its operator during start-up. When higher speed was required, the speed knob was used to increase the motor speed as required. This process was repeated several times in the Laboratory and the obtained readings were recorded, as shown in Table 2. Some of the difficulties encountered during the design and construction process of this work include the selection of the appropriate IGBT for this work as well as writing the correct microcontroller programme needed for the microcontroller to function as a standard VFD controller. These difficulties were resolved by extensive research on IGBT manufacturers data sheet and Arduino microcontroller programming language.

### 3.1 Experimental Results

The speed control knob used in this work is a 10k $\Omega$  variable resistor and its effective resistance sensed by the microcontroller determines the output frequency of the VFD. Using the recorded data in Table 2, equation (4) was derived as the relationship between knob effective resistance and VFD output frequency.

$$\text{Output frequency of VFD} = \frac{\text{Effective resistance of speed knob}}{\text{Total resistance of speed Knob}} \times 50 \quad (6)$$

Table 3 shows the measured VFD output voltage, each time the VFD frequency was varied using the speed control knob. Using the readings in Table 3, the graph in Figure 5 was plotted.

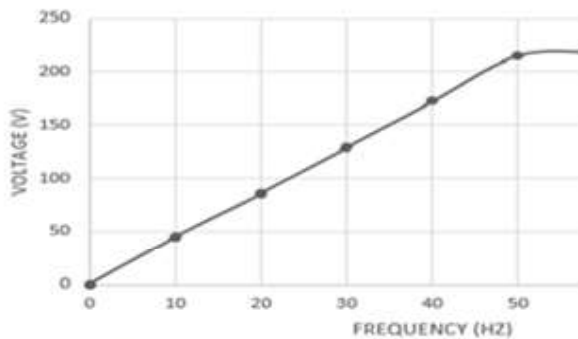


Figure 5: V/f Chart for Developed VFD

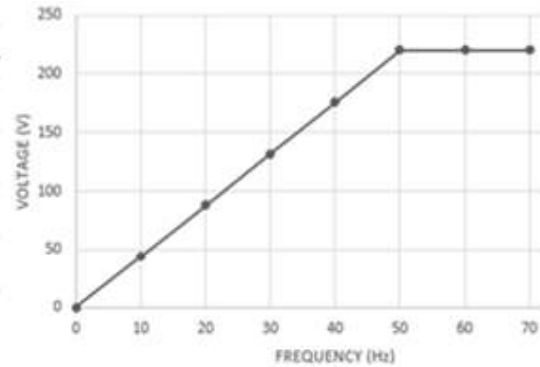


Figure 6: V/f for Commercially Available VFD

From the graph in Figure 5 we can conclude that for every change in frequency of the VFD there was a corresponding change in voltage for instance, when the frequency was 20Hz, the output voltage was 86V and when the frequency was increased to 50Hz, the output voltage increased to 218V.

Table 2: Knob Resistance and Corresponding VFD Output Frequency

Effective Resistance of Knob	2kΩ	4kΩ	6kΩ	8kΩ	10kΩ
VFD Output Frequency (Hz)	10Hz	20Hz	30Hz	40Hz	50Hz
Speed of Pump (rpm)	590	1170	1750	2349	2930

Table 3: Measured Speed, Voltage and Flow Rate during VFD Performance Test

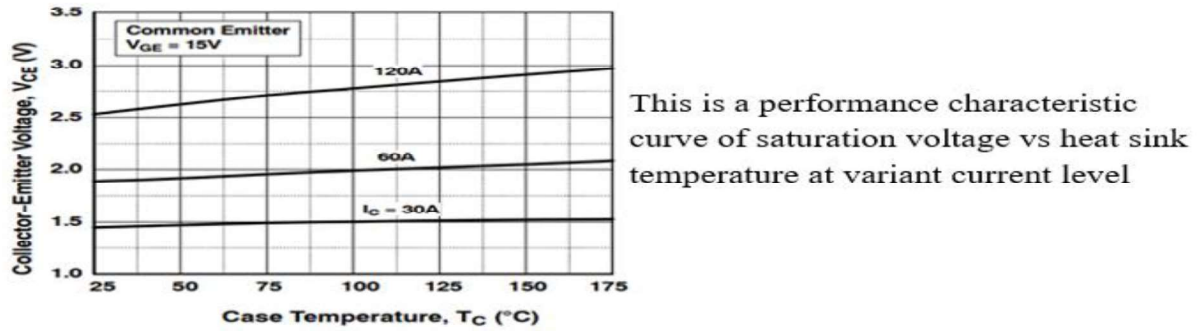
SPEED (rpm)	FREQUENCY (f)	VOLTAGE (v)	PERIOD (T)	FLOW RATE (Q)
590	10 Hz	45V	100ms	12 L/min
1170	20 Hz	86V	50ms	24 L/min
1750	30 Hz	140 V	40ms	39 L/min
2349	40 Hz	190 V	29ms	48 L/min
2930	50 Hz	218 V	22.2ms	60 L/min

$$\text{Constant (k)} = 4.4 = \text{Voltage(V)}/\text{Frequency(Hz)} \quad (7)$$

$$\text{Constant (k)} \propto \text{Torque (T)} \propto (\text{V}^2 / \text{f})^2 \quad (8)$$

Equation (7) defines the liner slope in Figure 5 hence, represents the constant torque control region.

Figure 5 and Figure 6 reveal that the performance of this developed VFD is as good as that of commercially available VFDs.



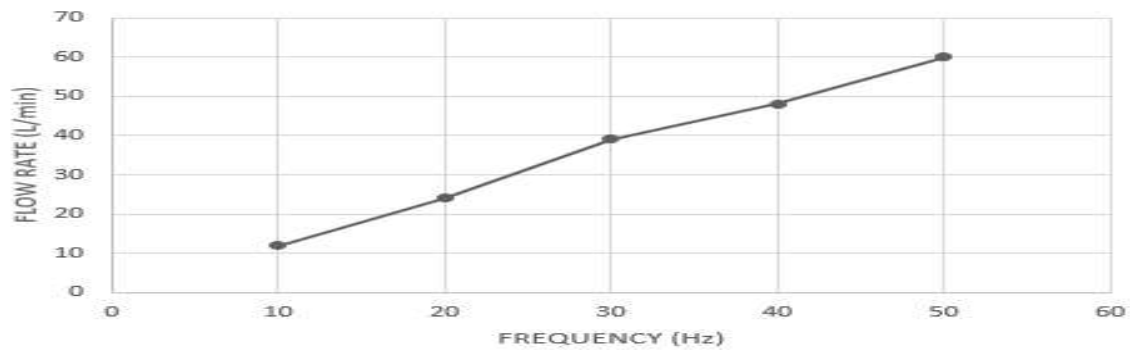
**Figure 7:** Temperature Performance Characteristics of IGBT 60N60

Figure: 8 shows that any increase or decrease in VFD output frequency results in a corresponding increase or decrease in pump rate.

$$N_s = (120 \times f)/p \tag{9}$$

$N_s$  = Synchronous speed of induction motor (rpm),  $f$  = Supply frequency,  $P$  = Number of poles

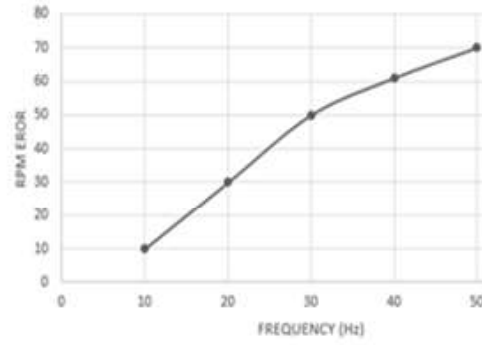
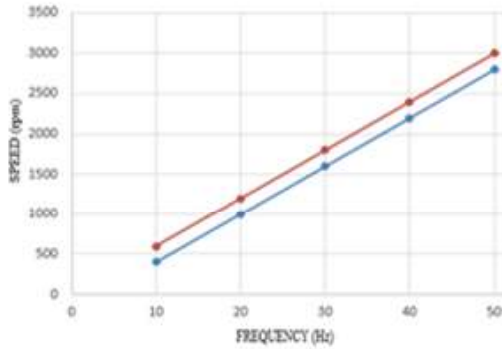
The calculated rpm values in Table 4 were obtained using equation (9). Additionally, Table 4 revealed that the VFD speed error is less than 10%.



**Figure 8:** Graph of Frequency versus Flow Rate during Performance Evaluation

**Table 4:** Data of Recorded and Calculated Speed versus Frequency of VFD

<b>Frequency (Hz)</b>	10	20	30	40	50
<b>Calculated motor speed (rpm)</b>	600	1200	1800	2400	3000
<b>Measured motor speed (rpm)</b>	590	1170	1750	2349	2930
<b>Rpm error</b>	10	30	50	61	70
<b>Measured temperature of heat sink</b>	27°C	30°C	35°C	47°C	50°C



**Figure 9: Calculated and Actual Recorded Speed Vs Frequency**      **Figure 10: RPM Error Vs Frequency Change**

The red and blue lines in the chart shown on Figure 9, represent the calculated speed response and actual recorded speed response of the developed VFD to frequency changes. This result demonstrates that the performance of the programmed microcontroller unit is close to that of standard commercially available VFD controllers. The chart in Figure 10 was plotted from the data in Table 4. The chart shows that increase in VFD output frequency results in more rpm error.

$$\text{Efficiency of developed VFD} = \frac{\text{power delivered from vfd to motor}}{\text{power supplied to vfd}} \times 100\% \quad (10)$$

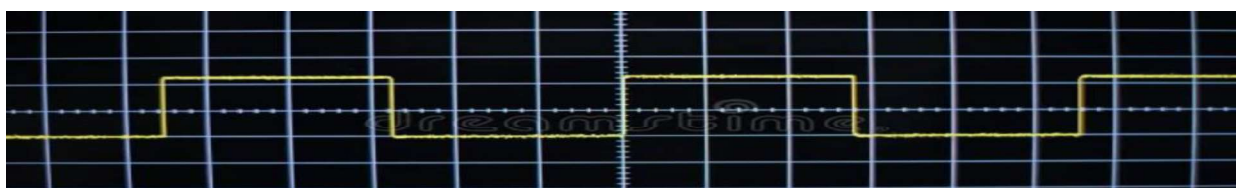
$$\begin{aligned} \text{Efficiency of VFD} &= ((V_{out}I_{out}\cos\phi_{out}) / (V_{in}I_{in}\cos\phi_{in})) \times 100\% \\ &= ((218 \times 2 \times \cos 80) / (218 \times 2 \times \cos 80)) \times 100\% = 79.3\% \end{aligned}$$

$$\begin{aligned} \text{Voltage accuracy} &= \left(1 - \left(\frac{V_{actual} - V_{set}}{V_{set}}\right) \times 100\%\right) \quad (11) \\ &= \left(1 - \frac{218 - 220}{220}\right) = 90.1\% \end{aligned}$$

$$\begin{aligned} \text{Frequency accuracy} &= \left(1 - \left(\frac{f_{actual} - f_{set}}{f_{set}}\right) \times 100\%\right) \quad (12) \\ &= \left(1 - \frac{50 - 49.7}{50}\right) = 99.4\% \end{aligned}$$

Hence volt per freq accuracy of vfd = (voltage accuracy × freq accuracy)  
 = 90.1% × 99.4% = 89.6%

It was observed that when a 1hp pump with an efficiency of 80% was used at fixed speed in a drip irrigation system on a one-hectare maize farm, the pump delivered 3600L of water per hour and consumed 0.933kwh of power but operating the same pump with the developed VFD on the same farmland, the delivered volume of water reduced to 1800L/h and power consumed reduced to 0.653kwh. This result showed that 50% of water and 30% of power was saved.



**Figure 11: Oscilloscope Traces of Developed VFD Output Voltage Waveform**

This VFD is reliable and reproducible because the materials used for its design and construction were locally available also, the recorded data obtained during the performance tests carried out on the VFD were recorded after several trials and the results obtained were found to be identical each time the performance test was carried out.

#### 4.0 CONCLUSION

Due to the unavailability of sufficient rainfall in most geographical areas, there is the need for efficient and effective irrigation systems for farming. The designed and constructed VFD in this work provides an efficient means for soft starting an irrigation pump and provides smooth speed control of the pump. VFD controlled pumps consume less energy hence, cutting down a lot of expenses on utility bill and break down maintenance. This unique method of starting the pump at a very low speed then gradually increasing the speed to obtain the needed pump rate of the pump makes it possible for the pump's motor to start up on a low current hence, eliminating the issue of voltage dip which occurs at startup of electric motors. VFD performs two key functions which includes soft start up and smooth speed control of electric motors hence can be used in refrigeration systems, incinerator blowers and electric tractions. In the nearest future VFD controlled pumps and motors will find a lot of relevance in irrigation and farming generally as most farming machines such as Planters and Pesticide Dispensers which require soft start up and smooth speed control can be driven by VFDs. In conclusion, this work has shown that developing a VFD from locally sourced materials is achievable.

#### NOMENCLATURE

f	Frequency (Hz)
E	Energy (kWh)
Q	Flowrate (L/min)
S	Speed (rpm)
V	Voltage (V)

#### Abbreviations

VFD	Variable Frequency Drive
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#### ACKNOWLEDGEMENTS

My appreciation goes to the Faculty of Engineering, Edo University Uzairue for granting me access to the use of its laboratory facilities.

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