# Variable frequency drive based on full-bridge class D for single-phase induction motor

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**ABSTRACT**

The issue with induction motors lies in speed regulation, which can be addressed by adjusting the motor voltage; however, this affects torque. In contrast, a variable frequency drive (VFD) changes the motor frequency while maintaining a constant voltage. A VFD controller with constant sinusoidal voltage and adjustable frequency can be implemented using an Arduino and a class D full-bridge MOSFET amplifier inverter. This paper discusses the electronic speed control (ESC) of induction motors using VFD regulation, demonstrating how changes in frequency affect motor speed. The system involves an induction motor controlled by a VFD comprising three main components: an AC-to-DC converter, a class-D full-bridge MOSFET inverter, and a variable-frequency sinusoidal signal source. VFDs operate with constant voltage and variable frequency. This method includes the design and testing of VFD hardware and software. The VFD components include: a class-D full-bridge switching inverter, a sinusoidal signal frequency generator (30–70 Hz), an Arduino with custom software, an SMPS power supply, and a step-up transformer. The results indicate that the class-D full-bridge inverter can effectively regulate motor speed through VFD control. The motor speed is almost directly proportional to the frequency: at 30 Hz, the speed is 860 RPM; at 50 Hz, 1472 RPM; and at 70 Hz, 2035 RPM.



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## 1. INTRODUCTION

Most electric drives used in industry are induction motors [1]. Generally, the speed of an induction motor is constant, whereas in industrial applications, a motor with adjustable speed is needed, making this a significant issue. The speed of an induction motor can be changed by adjusting the voltage and frequency [2], [3]. To address this problem, a variable frequency drive (VFD) is used. A VFD is a device capable of providing a constant voltage while varying the frequency to control the speed of an induction motor. To control the motor speed, a motor control and drive system can be implemented using various methods. The speed of an induction motor can be influenced by the supply frequency, changing the number of motor stators, and adjusting the power input [4], [5]. The use of VFDs in industrial applications has increased dramatically.

The current issue is that VFD modules available on the market are in the form of programmable logic controller (PLC) modules and are quite expensive, making it difficult to create hardware with microcontrollers and VFD inverter software using readily available components. By applying the methods and principles of a full-bridge class-D audio amplifier and providing a variable frequency sinusoidal signal input (30–70 Hz), we can build a VFD inverter to control the rotational speed of an AC motor. The solution to the problem of a constant voltage VFD controller with variable frequency can be implemented using an Arduino variable frequency generator, where its signal is fed into a full-bridge class-D MOSFET amplifier inverter.

The advantage of VFDs in induction motors is their ability to save energy consumption. VFDs are now commonly used to control motor speed [4], [6], [7]. By using a VFD, electrical power and mechanical output power are optimized so that the motor can operate at the most efficient speed [8], [9]. A VFD consists of three main components: an AC to DC converter, an inverter, and a variable sinusoidal frequency source [10], [11]. The inverter output voltage can be controlled in terms of both magnitude and frequency (constant voltage-to-frequency ratio). There are two types of class-D amplifiers: half-bridge and full-bridge [12], [13]. The inverter controls the ON/OFF duty cycle of the metal-oxide-semiconductor field-effect transistor (MOSFET) [14].

Several studies on the speed control of induction motors with VFD using full-bridge switching have been conducted by previous researchers. Regarding the speed control of induction motors [3], [10], [14]. Regarding the speed control of induction motors through VFD [1], [2], [4]-[9], [11]-[13], [15]-[27]. Regarding the writing or theory of full-bridge switching [18], and regarding the writing or theory of class D full-bridge [28]-[36]. None of these previous researchers has discussed speed control settings for induction motors using the VFD method with a class D full-bridge amplifier, where the variable frequency sinusoidal signal generated by the Arduino is converted into pulse width modulation (PWM). This research focuses on the speed control of VFD induction motors using the class D full-bridge.

## 2. METHOD

A variable frequency drive consists of five parts: an AC to DC converter, an inverter (DC to AC converter), PWM, V/F control, and speed control. The V/F control block calculates the output frequency f applied to the motor as needed and performs speed control [16]. Figure 1 shows the open-loop control configuration in the form of a block diagram [14]. Figure 1 explains that the AC voltage is supplied to the rectifier circuit (converter), which converts the AC voltage into a DC voltage as a power supply for the inverter circuit. The inverter is the most important part because it will convert the DC voltage into AC voltage using a square wave approach that is converted into a sinusoidal waveform by chopping the DC voltage with an SPWM signal, where the pulses of the signal are adjusted to control the motor's voltage and frequency. An important component of the VFD is PWM, which is the main technique used to control motor speed. VFD is used to change the voltage and frequency entering the motor according to the predetermined frequency. This method is suitable for speed adjustment and can achieve high speeds (adjustable frequency up to 70 Hz) easily, especially when speed regulation with varying loads becomes important [14]. By changing the frequency of the AC voltage, the motor speed can be adjusted to the desired value.

A variable frequency drive (VFD) is used to control the speed and frequency of the motor, and by adjusting the speed, the motor can operate under various loads. The estimated equivalent circuit diagram of the induction motor, with reference to the stator, is shown in Figure 2 [8]. Where $V_1$, $R_1$, and $X_1$ represent the voltage, resistance, and leakage reactance of the stator winding. $X_m$ is the magnetizing reactance, and $R_c$ represents the core loss. The equivalent circuit diagram per phase, with the rotor current referred to the stator ($I_2$), is shown in (1) [7].

$$I_2 = \frac{V_1}{R_{eq}+\frac{R_2(1-s)}{s}+j(X_{eq}+X_2)} \tag{1}$$

The values of $R_2$ and $X_2$ are equal to the rotor's leakage resistance and reactance, while $s$ represents the slip. The induced electromagnetic torque is shown in (2) [7].

$$T = \frac{P}{\omega} = \frac{3V_1^2 R_2/s}{\left(R_{eq}+\frac{R_2}{s}\right)^2+\left(X_{eq}+X_2\right)^2} \tag{2}$$

Where $P$ is the number of poles and $\omega$ is the motor's angular velocity. The curve depicting the torque variation with slip according to (2) is shown in Figure 3 [7].

An induction motor is a motor with constant speed when supplied with constant frequency and voltage. The speed of this motor can be changed by changing the number of poles, changing the supply frequency, or changing the supply voltage. There is a direct relationship between the motor speed and the motor's operating frequency, as shown in (3) [7].

$$ns = 60f/P \tag{3}$$

Where $ns$ is the synchronous speed, $f$ is the main frequency, and $P$ is the number of poles.

In most inverters in VFD devices, the frequency is changed by adjusting the sinusoidal pulse width modulation (SPWM) data parameter value in the microcontroller. In this research, the author attempts to create a VFD built with an inverter using a full-bridge class D amplifier powered by a variable sinusoidal frequency signal input generated by a sine generator using Arduino. The sinusoidal input signal is multiplied by a sawtooth signal, which then generates PWM, which is subsequently fed to the full-bridge MOSFET switch and LC filter. This variable frequency VFD inverter can be simulated using MATLAB as shown in Figure 4.

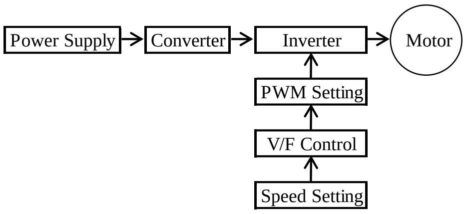



Figure 1. Open-loop control block diagram

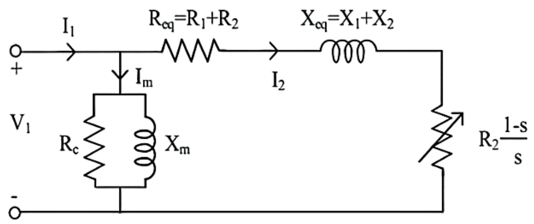



Figure 2. Estimated equivalent circuit diagram of an induction motor

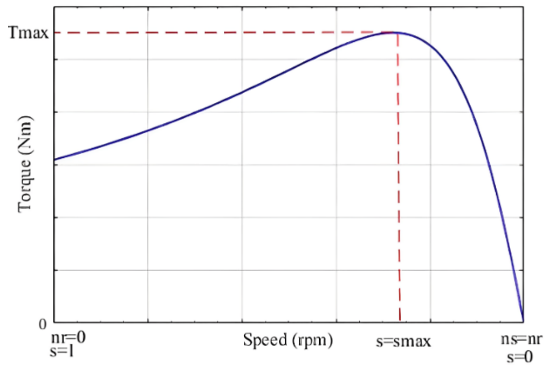



Figure 3. Speed-torque characteristic [7]

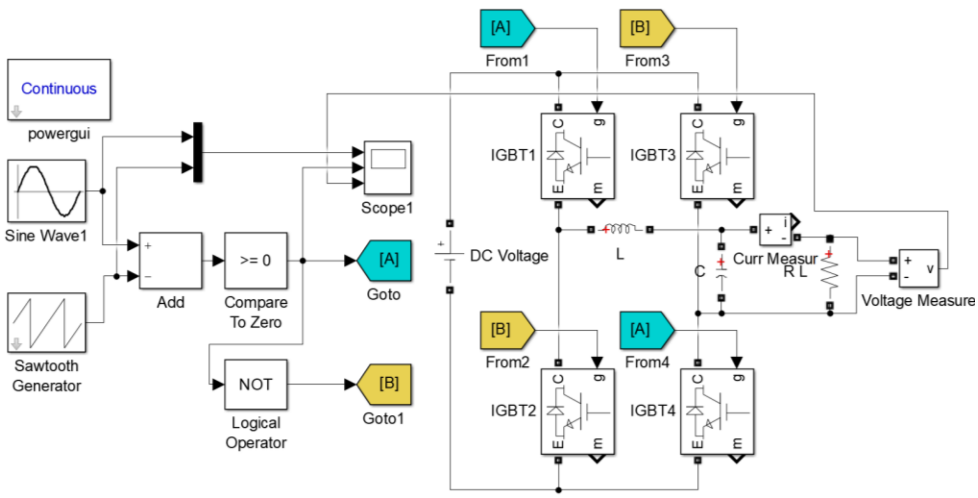



Figure 4. VFD inverter simulated using MATLAB

Figure 4 explains the block diagram of a pure sine inverter with its components, which include sinusoidal signals, sawtooth signals, a signal multiplier, a NOT gate, full-bridge IGBT or MOSFET switches, an LC filter, and an oscilloscope. The input is a pure sinusoidal signal with variable frequency and a high-frequency sawtooth signal up to 10 kHz, while the output is a PWM signal. Using the parameters Vsine and Vsawtooth, the mechanism involves multiplying these two signals by varying the amplitude of Vsine and the width of Vsawtooth, producing a PWM signal that is then divided into two: signal A, which does not pass through the NOT gate, and signal B, which passes through the NOT gate. Signals A and B are sent to the full-bridge MOSFET or IGBT switching circuit to generate an SPWM signal. To obtain a pure sine signal, the SPWM signal passes through an LC filter to remove the high-frequency PWM components, leaving only the pure sine signal. To implement the open-loop VFD as shown in Figure 1 and based on the block diagram in Figure 4, a VFD block diagram was created as shown in Figure 5.

Figure 5 illustrates the block diagram of the VFD, which consists of: a sinusoidal signal generator with Arduino, a PWM generator with a class D converter, a full-bridge MOSFET, an LC filter, and a transformer. This frequency generator is synthesized by Arduino using the Timer 0 control function and Compare-Match interrupts from the Arduino microcontroller (ATmega328). Timer 1 of the ATmega328 is set to 10 kHz to generate a PWM signal. This program contains the ATmega328 microcontroller registers configured according to the datasheet. The software is written in the Arduino programming language and compiled using the Arduino IDE software. The frequency generator circuit with Arduino is shown in Figure 6.

The microcontroller circuit was built using Arduino components, along with the flowchart of the Arduino microcontroller software, as shown in Figure 7. The frequency generator circuit was tested by measuring the output frequency and peak-to-peak voltage. The measurement results of the output frequency and peak-to-peak voltage are shown in Table 1.

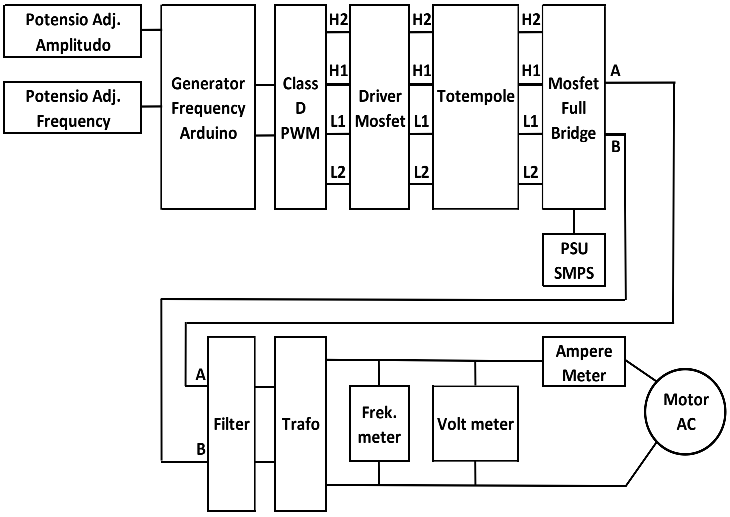
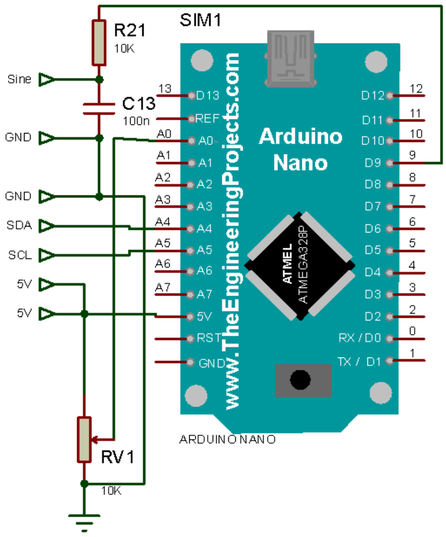



Figure 5. VFD block diagram



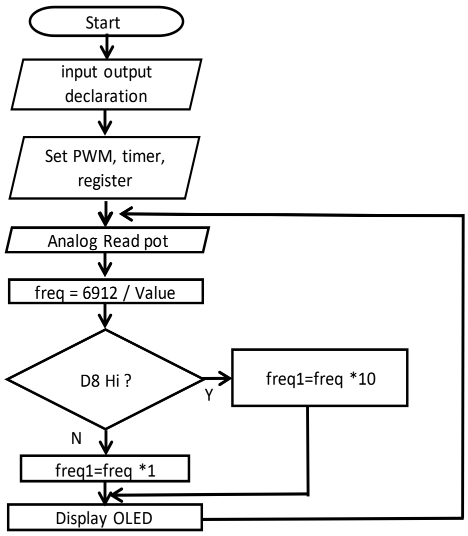




Figure 6. Frequency generator circuit with Arduino

Figure 7. Flowchart of Arduino microcontroller software for sinusoidal signal generator

The class D converter circuit, built using op-amp components, functions to multiply the analog signal with a high-frequency sawtooth signal, producing a PWM signal that is then fed into the logic circuit and subsequently to the full-bridge switching circuit [28]-[36]. The class D converter circuit is shown in Figure 8. The class D converter circuit was tested by providing a sinusoidal signal at the input and observing the triangular waveform and the output signal from the comparator, based on the waveforms in Figures 4 and 8, as shown in Figure 9.

Table 1. Arduino frequency generator measurements

| Freq (Hz) | Freq test (Hz) | Vpp |
|---|---|---|
| 30 | 30 | 4.28 |
| 35 | 35 | 4.23 |
| 40 | 40 | 4.19 |
| 45 | 44.9 | 4.19 |
| 50 | 49.8 | 4.15 |
| 55 | 54.9 | 4.07 |
| 60 | 59.7 | 4.03 |
| 65 | 64.7 | 4 |
| 70 | 69.9 | 3.96 |

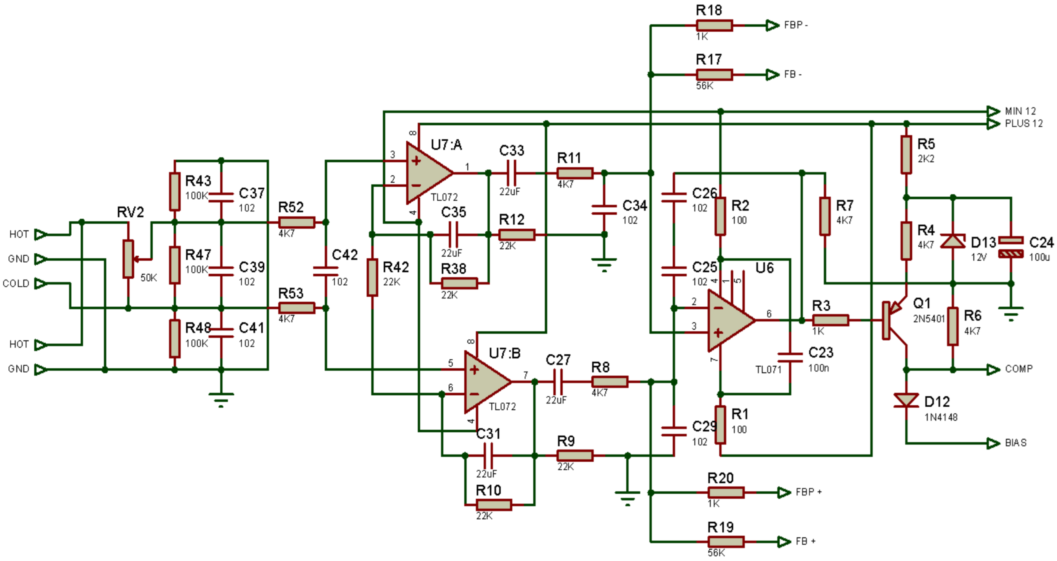



Figure 8. PWM generator circuit with a class D converter

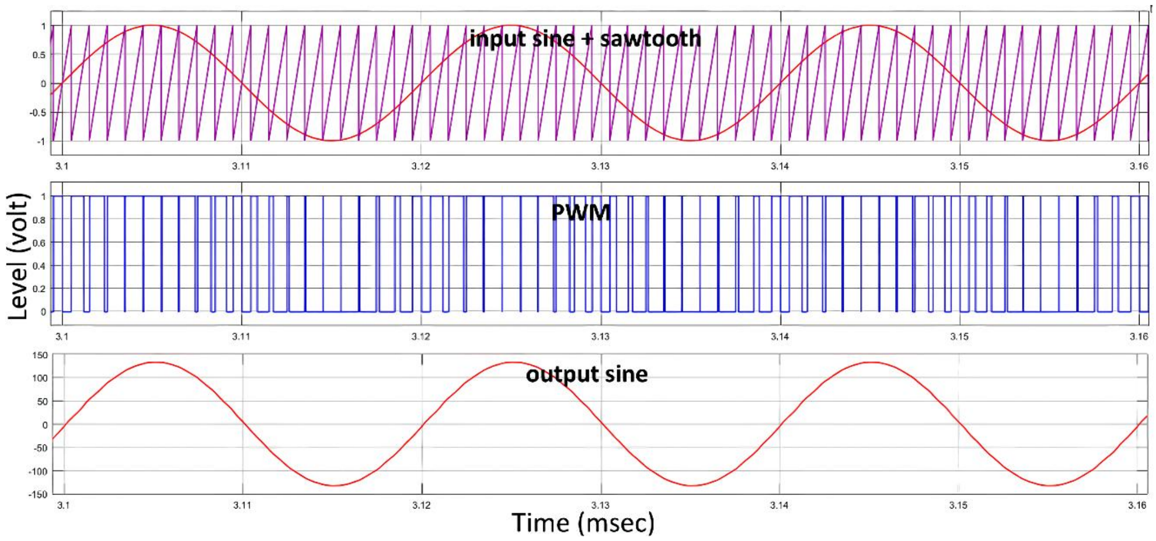



Figure 9. Input sinusoidal, input ramp, output PWM, and output sinusoidal

The MOSFET driver circuit is created using the IC IR2110, designed to operate at high voltage. This circuit includes two pre-designed drivers, featuring high-side and low-side drivers for push-pull operation. The MOSFET driver circuit is built using the IR2110 IC. The current amplifier circuit is constructed using a totem pole configuration with TIP41 and TIP42 transistors. This circuit functions to boost the current, enabling it to supply a current of 4 A to 4 MOSFET gate pins. By using TIP41 and TIP42 transistors, the maximum current that can be provided is 6 A.

A sinusoidal signal consists of positive and negative cycles. In an inverter, we need MOSFET pairs to operate during alternating positive and negative cycles. This is achieved by constructing a full-bridge switching circuit using 2 pairs of MOSFET switches with inputs and outputs: in 1H, in 1L, in 2H, in 2L, out A, and out B. The positive and negative PWM signals enter into 1H or in 2H. The MOSFET driver circuit, totem pole, and full-bridge switching circuit are shown in Figure 10.

The MOSFET driver circuit was tested by connecting it to the full-bridge MOSFET switching circuit and applying a 5 V pulse signal or voltage to the inputs in 1L, in 2L, in 1H, and in 2H. The totem pole current amplifier circuit was tested by connecting it to the MOSFET circuit and applying a 12 V pulse signal or voltage to the inputs in 1L, in 2L, in 1H, and in 2H. The switching circuit was tested by connecting a load consisting of a series of eight 12 V incandescent light bulbs between outputs A and B. A 12 V pulse signal or voltage was applied to the inputs in 1L, in 2L, in 1H, and in 2H.

The LC filter was designed to have a low-pass filter (LPF) response with a frequency of 20 kHz and a load resistance of 2 ohms. The formulas to calculate L, C, and the frequency are given by (4)-(6).

$$L = (Rl * sqrt\ 2) / (2pi * f) \quad (4)$$

$$C = 1 / (2pi*f) * Rl * sqrt\ 2 \quad (5)$$

$$f = 1/(2\ pi\ sqroot(LC)) \quad (6)$$

The calculation results show L = 22.5 µHL = 22.5µH and C = 2.81 µFC = 2.81µF. The selected inductor value is 22.5 µH, and the available capacitor in the market is 2.2 µF. The calculated resonant frequency of the LPF is 22.89 kHz. A step-up transformer was selected to handle a voltage of 60 V with a current of 30 A and a total power of 1800 watts, with a primary voltage of 60 Vac and a secondary voltage of 220 Vac.

Based on Figures 6, 8, and 10, the research flowchart was created, which includes design, methodology, measurement, testing, as well as the preparation of all components and devices for testing equipment, as well as the measurement equipment, as shown in Figure 11. Figure 11 explains the flowchart for the design of the filter, the design of the full-bridge switch, the totem pole design, and the MOSFET driver design, which can be seen in Figure 10. The class D converter design is shown in Figure 8, while the signal generator design can be seen in Figure 6. The testing of the variable frequency drive (VFD) was conducted by observing the RPM values for frequencies ranging from 30 Hz to 70 Hz. The research module that has been created is shown in Figure 12.

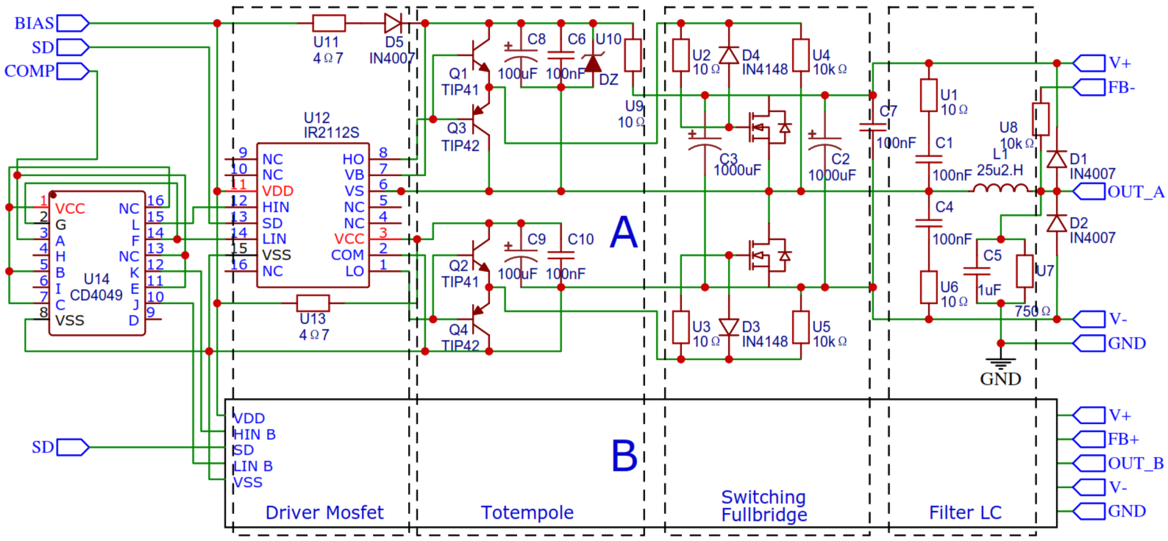



Figure 10. MOSFET driver, totem pole, full-bridge circuit, and filter LC

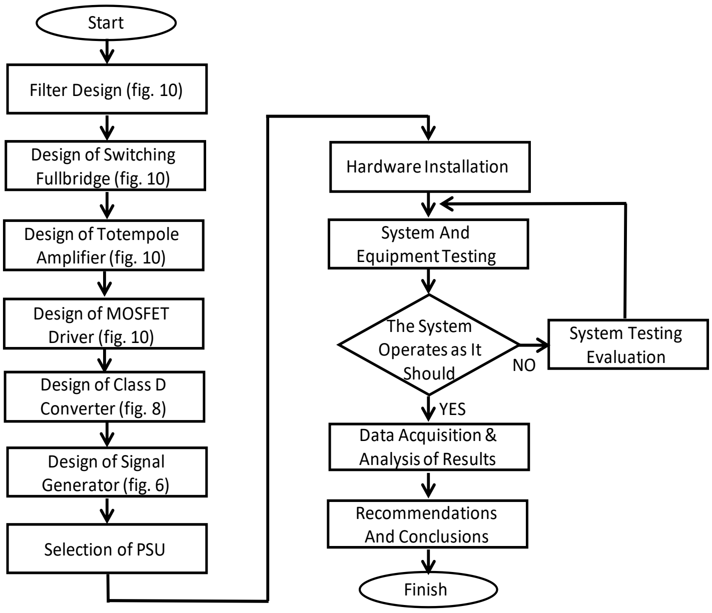



Figure 11. Research flowchart for the design and testing of PWM full-bridge ESC induction motor

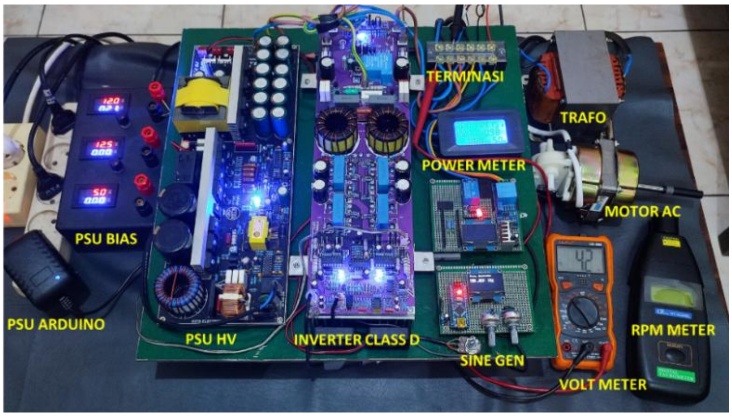



Figure 12. Module ESC VFD that has been created

## 3. RESULTS AND DISCUSSION

The full-bridge class D VFD testing was conducted with a main supply of -77 VDC, +77 VDC, and a 12 VDC bias connected. Testing of the high-side MOSFETs (closer to Vcc) involved applying a 12 V (> 5 VDC) voltage to the gate pins 1H and 2H, which caused the MOSFETs to saturate, connecting the source to the drain. When a 5 V voltage was applied to the input of the MOSFET drivers 1H and 2H, the MOSFETs saturated, indicating that the high-side MOSFET driver circuit was functioning properly. Similarly, testing of the low-side MOSFETs (closer to ground) involved applying a 12 V (> 5 VDC) voltage to the gate pins 1 L and 2 L, which caused the MOSFETs to saturate, connecting the source to the drain. When a 5 V voltage was applied to the input of the MOSFET drivers 1L and 2L, the MOSFETs saturated, indicating that the low-side MOSFET driver circuit was functioning properly. The class D driver circuit was tested by providing a 50 Hz sinusoidal input signal, and the output signal was observed using an oscilloscope, showing a PWM waveform with a duty cycle proportional to the input signal. The sinusoidal signal generator circuit was tested using an oscilloscope, and the output waveform appeared sinusoidal with a frequency ranging from 30 Hz to 70 Hz. The sinusoidal output signal from the class D amplifier was connected to the step-up transformer, and the input signal to the amplifier was adjusted using the volume potentiometer so that the transformer output produced a sinusoidal signal with a voltage of 220 VAC at its output.

The results of the VFD testing with a frequency variation from 30 to 70 Hz produced the speed of the induction motor as shown in Table 2. Referring to Figure 1 and the data in Table 2, the output results from the sinusoidal signal amplifier (class D amplifier) connected to the step-up transformer were obtained. The amplitude was adjusted using the volume potentiometer so that the transformer output produced a sinusoidal signal with a voltage of 220 VAC. The test results for the ESC of the induction motor showed that the motor's rotation could be adjusted, and the RPM could be controlled. The operating frequency range of the ESC for the induction motor is set from 30 Hz to 70 Hz. At 30 Hz, the motor's RPM is low, while at 70 Hz, the motor's RPM increases. Specifically, at 30 Hz, the motor rotates at 860 RPM; at 50 Hz, the motor rotates at 1472 RPM; and at 70 Hz, the motor rotates at 2035 RPM. Additionally, the cables leading to the motor and the power supply unit (PSU) for the MOSFET did not exhibit excessive heating.

Table 2. VFD ESC measurement results

| Freq (Hz) | rpm | Freq (Hz) | rpm | Freq (Hz) | rpm |
|---|---|---|---|---|---|
| 30 | 860 | 44 | 1294 | 58 | 1702 |
| 31 | 892 | 45 | 1329 | 59 | 1728 |
| 32 | 923 | 46 | 1355 | 60 | 1757 |
| 33 | 958 | 47 | 1383 | 61 | 1786 |
| 34 | 989 | 48 | 1422 | 62 | 1815 |
| 35 | 1019 | 49 | 1441 | 63 | 1847 |
| 36 | 1047 | 50 | 1472 | 64 | 1864 |
| 37 | 1081 | 51 | 1505 | 65 | 1894 |
| 38 | 1095 | 52 | 1526 | 66 | 1930 |
| 39 | 1142 | 53 | 1564 | 67 | 1946 |
| 40 | 1176 | 54 | 1586 | 68 | 1981 |
| 41 | 1209 | 55 | 1621 | 69 | 2000 |
| 42 | 1238 | 56 | 1647 | 70 | 2035 |
| 43 | 1271 | 57 | 1672 | | |

## 4. CONCLUSION

The VFD with full-bridge class D is capable of effectively controlling the speed of the induction motor. The operating frequency of the electronic speed control (ESC) has a direct relationship with the motor's RPM, showing an almost linear correlation and aligning with previous VFD research results. As a result, at a frequency of 30 Hz, the motor speed is 860 RPM; at 50 Hz, the motor speed is 1472 RPM; and at 70 Hz, the motor speed reaches 2035 RPM. The output voltage remains constant at 220 VAC, while the current varies between 210 mA and 240 mA. It is hoped that research on VFDs using full-bridge class D amplifiers can contribute to the advancement of scientific knowledge. None of previous researchers have discussed speed control settings for induction motors using the VFD method with a class D full-bridge amplifier, where the variable frequency sinusoidal signal generated by the Arduino is converted into PWM.

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## AUTHOR CONTRIBUTIONS STATEMENT

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

**CONFLICT OF INTEREST STATEMENT**

Authors state no conflict of interest.

**DATA AVAILABILITY**

The data that support the findings of this study are available on request from the corresponding author, [BPJ]. The data, which contain information that could compromise the privacy of research participants, are not publicly available due to certain restrictions.

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