Development of Variable Frequency Drive for Compact Three-Phase Induction Motor using Discrete Components

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Abstract— The electric drive systems used in industrial application are enabling to increase the dynamic performance and reliability requirement. Nowadays, most of the home appliances and process industries use three-phase induction motor (TPIM) because they are simple and low cost and easy to maintain. Actually, these kinds of application do not require precise speed control using FPGA or microcontroller since there are low-performance types. This paper represents the design and development of low cost variable frequency drive (VFD) system for three-phase induction motor. Step-by-step in generating SPWM switching signal using different simple discrete components are explained thoroughly. The software used to design the SPWM and driver circuits are Multisim and Proteus. After simulation done, all the circuits are soldered appropriately and tested using oscilloscope. In addition, the study of relationship between speeds (rpm) with various frequencies is also thoroughly discussed. The type of induction motor used was three-phase squirrel cage induction motor model EM5001-3G. The speed of the motor was measured in RPM using industrial grade rotary encoder. So, overall experiment shows that this VFD made of discrete components are really can drive three-phase induction motor at low cost, easy to maintenance and do not require any specialist to repair it. Moreover, it does not require any programming or coding to build. This system also is simple because only used discrete electronic components which are widely available in market with extensive application notes which can be downloadable as free. This VFD drive system can be used for educational purposes where students can get an insight into three-phase inverter and they can design, build and testing the system by themselves.

Keywords—VFD, SPWM, H-Bridge inverter, TPIM

1. Introduction

The speed drive system is a device that is used to control the speed of electrical motor. A fixed speed drive comprises a frictional variable speed drive controlled by a control system to produce a constant output speed while in variable speed drive produce variable output speed [1,2]. The early days of variable speed induction motor drives, supplied by the silicon controlled rectifier (SCR) and had limitations such as poor efficiencies, large space, lower speed and etc but after power electronic introduced, it transformed everything [2,11]. Today's, adjustable speed drive was constructed with in smaller size, high efficiency, and high transient response [2, 3, 8, 9]. Currently, the control methods for induction motors can be divided into two parts that are vector control and scalar control strategies. Scalar control is simple method and to control the magnitude of the chosen control quantities [7, 8]. At the induction motor, the technique is used as Volts/Hertz constant control. Vector control is a more complex control technique. The scalar control of induction motors has some advantage like low cost, simplicity and immunity to errors of feedback signals [4, 7, 8, 10]. Moreover, not all the load needs precise control such as pump, fan and so one. By introducing variable frequency drive using discrete components, these loads may use simple, low cost, wide availability of components, extensive collection of application notes, easy to maintenance and more efficient compared to other advanced ASD controller available in the market today [9,12].

Traditionally, motors were operated uncontrolled, running at constant speeds, even in applications where efficient control over their speed could be very advantageous. In the process of industry today, electronically controlled variable speed drives systems are much easier to automate and offer much higher energy efficiency and lower maintenance than the traditional system [4, 5, 6]. The ASD controls two main elements of a motor. There are speed and torque. The speed of a motor is conveniently adjusted by changing the frequency applied to the motor. The VFD adjusts the output frequency, thereby adjusting the speed of the motor [6, 7]. The torque of a motor is controlled by a basic characteristic of every motor that is the volts per frequency ratio (V/F). Voltage/frequency (V/F) control is a model of a scalar control method which is equivalent to constant. This method is the simplest way for controlling induction machine. In this type of control, a constant ratio between the voltage magnitude and frequency is maintained [6, 7, 8,12].

Figure 1 shows the modal of an AC drive. The AC drive is supplied by the electrical network via a rectifier. The rectifier unit can be uni- or bidirectional. When unidirectional, the AC drive can accelerate and run the motor by taking energy from the network. If bidirectional, the AC drive can also take the mechanical rotation energy from the motor and process and feed it back to the electrical network. Moreover, The DC circuit will store the electrical energy from the rectifier for the inverter to use. In most cases, the energy is stored in high-power capacitors. In addition, the inverter unit takes the electrical energy from the DC circuit and supplies it to the motor. The inverter uses modulation techniques to create the needed three-phase AC voltage output for the motor. The frequency can be adjusted to match the need of the process. The higher the frequency of the output voltage is, the higher the speed of the motor, and thus, the output of the process [2,3,6].

In this paper, have to design and implement efficient and easy to handle, simple, cheaper, and not so precise, variable speed drive controller for three-phase induction motor (TPIM) using discrete components. Moreover, must generate three-phase signal control and high frequency signal carrier using discrete components to produce PWM control circuit. The frequency control method also had been used with PWM control circuit to control the speed of three-phase induction motor. The H-bridge inverter circuit consists of power IGBTs were needed to be triggered. The triggering pulses are sending from the PWM control circuit. By following this way, the H-bridge inverter produces the alternating current to feed the TPIM. By having simple and low cost VFD circuit enables students can build their own circuit to test and adjust speed of TPIM. Moreover, students too nurture more about electric drive system via applying control signal, carrier signal PWM so on in building the VFD circuit. Since the component are low cost and easily available in market not only student, but the other age users also enable to buy and can repair themselves when the VFD malfunction.

2. EXPERIMENTAL SETUP

In general-purpose application, electric drives operate in an open-loop manner without any feedback. Figure 2 shows the block diagram for speed control of TPIM. 240V AC power supply has been used to feed three-phase rectifier and filter to supply power source to the three-phase IGBT inverter circuit. Then, the circuit was connected to the three-phase induction motor (TPIM). The speed of the TPIM was controller by the PWM controller circuit. According to the Figure, the PWM controller circuit connected to optocoupler circuit, so that it galvanically isolate the control circuits and help protect against damage caused by high voltages in the dc bus. Another primary purpose of this circuit is to provide a high degree of common-mode rejection (CMR) and help prevent the fast switching of the pulse-width modulation (PWM) signals from erroneously driving the IGBT. The purpose of gate driver circuit is drive the power IGBT's with high and low output channels, provide the floating channel for boot strap operation.

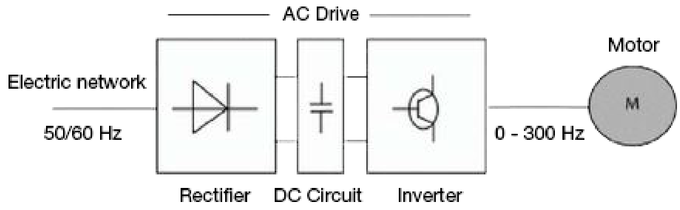


Figure 1: Model of AC Drive

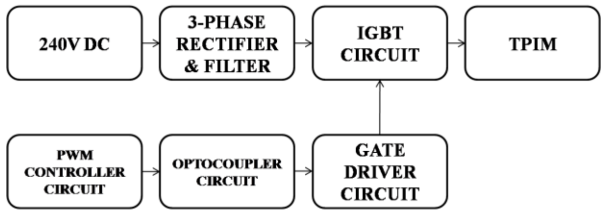


Figure 2: Block Diagram for Speed Control of TPIM

The PWM circuit was made using analog circuit which is more robust, simple, low cost and widely available components in the marketplace. In Figure 3 shows a block diagram of variable frequency drive of TPIM using conventional method. Operational amplifier TL074, TL082, LM311 and EL4N25, specific resistors and capacitors were used to generate PWM. IR2130 driver were used as driver circuit to drive H-bridge inverter. Here, PWM driver circuit was used to provide the pulses to be fed into the driver circuit. Inverter circuit or H-bridge consists of three SKM200GB123D IGBT modules to provide alternating currents to the TPIM. The IGBTs has needed to be triggered by the PWM that generated from the control circuit. TPIM was used as a loading part.

The simulation of the PWM or control circuit has been done using Multisim 11.0 software. The simulation need to do part by part to confirm that each of the electric components can generate the triggering pulses to trigger the power IGBT. Figure 4 showed the part of the PWM control circuit using Multisim 11.0 software.

In the hardware development, PWM control circuit and H-bridge inverter has been designed and build successfully. For the controlling part, the sinusoidal pulse and the triangular pulse were generated separately. The three-phase sine wave generation circuit generates three-phase sinusoidal waveforms according to the commanded normalized synchronous frequency, 50Hz and the commanded normalized voltage. The circuit is designed using low cost, low noise and high speed J-FET quad operational amplifier TL074 IC and some discrete components. This circuit enables the three sine waves displaced in 120° phase difference as reference signals for three phase inverter. The output frequency is the same as the reference signal frequency. A single phase shifter is used at the output of circuit to create -120° phase difference and two phase shifters to create -240° phase difference. Apart from that, the three-phase inverter was designed to operate at a switching frequency of f_S = 5.0 kHz. Therefore, the output of a carrier frequency generation circuit has the same frequency. The triangular carrier waveform generator circuit formed around IC TL082.Then, both pulses has been compared using comparator. The comparator circuit designed using three ICLM311. LM311 is highly flexible voltage comparator. The ability to operate from a single power supply of 5.0 V to 30 V or ±15 V split supplies, as commonly used with operational amplifiers, makes the LM311 a truly versatile comparator. Moreover, the inputs of the device can be isolated from system ground while the output can drive loads referenced either to ground, the VCC or the VEE supply. This flexibility makes it possible to drive DTL, RTL, TTL, or MOS logic. The output can also switch voltages to 50 V at currents to 50 mA. Thus, the LM311 can be used to drive relays, lamps or solenoids. In this part, the comparator circuit produce three-phase PWM wave. As in Figure 3, the three-phase PWM block comprised of three ICLM311. Each of the three-phase sine waves is compared with the common triangular carrier waveform with three complementary comparators to produce the three-phase PWM signals. The outputs of the comparator are drive signals for the succeeding optocoupler and gate drive circuit. Furthermore, Gate drive optocoupler are widely used in motor drive applications because they provide high-output current and fast switching speed. In this part, the circuit builds with EL 4N25. EL 4N25 known as Gallium Arsenide Diode Infrared source optically coupled to a Silicon npn phototransistor. It also contains high direct-current transfer ratio and base lead provided for conventional transistor biasing. EL 4N25 provides high-voltage electrical isolation about 1.5-kv, or 3.55-kv rating and have high speed switching. The 240 VDC supply was used to feed the H-bridge as shown in Figure 1. The DC supply has been inverted to drive the TPIM as a loading part. Figure 5 showed the hardware development board which consists of PWM control circuit and H-bridge inverter. The outputs of the control circuit have been used to trigger the power IGBT.

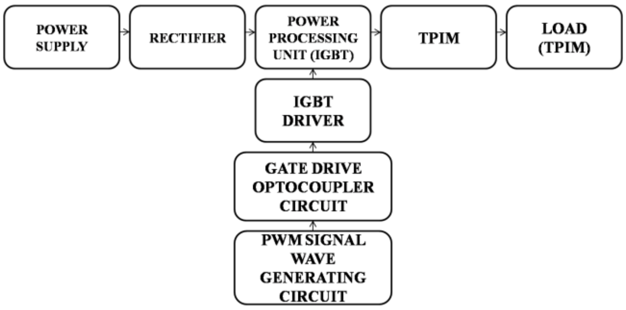


Figure 3: System block diagram of VFD of TPIM

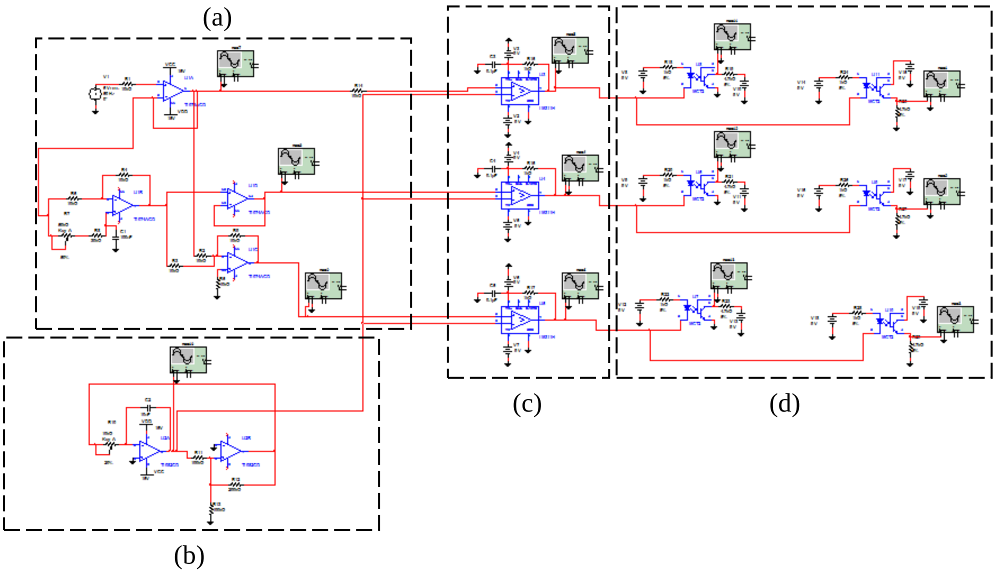


Figure 4: Multisim Simulation of PWM controller circuit (a) three-phase sine wave generation circuit (b) triangular wave generating circuit (c) comparator circuit (d) optocoupler circuit

Figure 6 showed the outputs of PWM pulses of comparator 1, comparator 2 and comparator 3 from Multisim simulation. The entire output signal waves were fed into optocoupler EL4N25. The PWM pulses were used to provide the pulses to the driver circuit. The output from driver circuit was used to switch ON and OFF the power IGBT based on timing of the frequency control system.

Only one IGBT module are able to switch ON and OFF at the same time. The circuit for the H-bridge inverter using Protheus software showed in Figure 7.The IGBT will receiving the triggering pulses from the driver circuit to turn ON and OFF continuously. The outputs of the H-bridge driver were used to run the TPIM. The speed of the induction motor is directly proportional to the supply frequency. Basically, the best ways to control the speed is by varying the frequency. Figure 8 shows complete soldered of H-Bridge board and Figure 9 shows hardware of IGBTs Bridge.

3. RESULTS AND DISCUSSION

The JFET-input operational amplifiers in the TL074 are designed as low-noise amplifier with low input bias and offset currents and fast slew rate. The TL074 op-amp used as three phase shifter sine wave with 0°,120° and 240°. The input sine wave with approximate 6V is shifted into three-phase. The 50K potentiometer used to shift the phase of initial sine wave. The result gained from oscilloscope is shown in Figure 10 below.

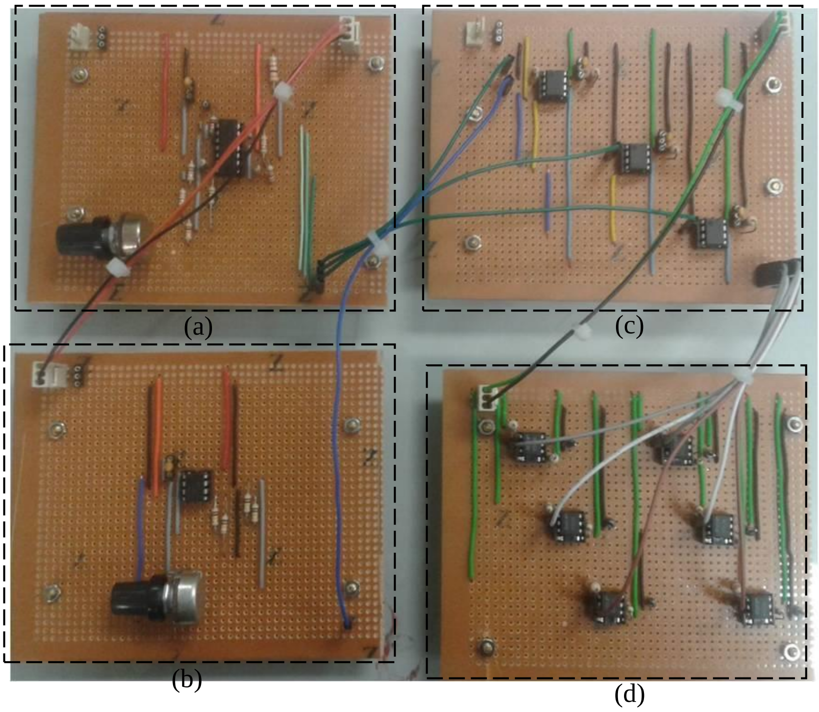


Figure 5: Hardware development PWM control circuit (a) three-phase sine wave generation circuit (b) triangular wave generating circuit (c) comparator circuit (d) optocoupler circuit

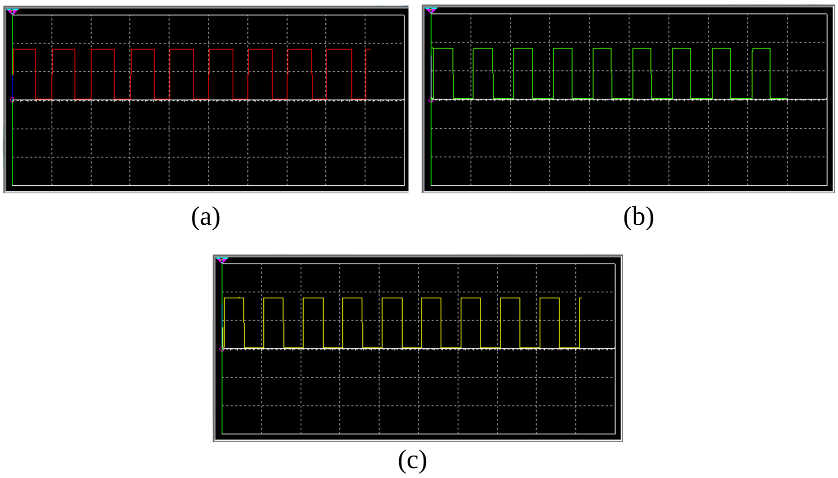


Figure 6: PWM outputs (a) first comparator (b) second comparator (c) third comparator

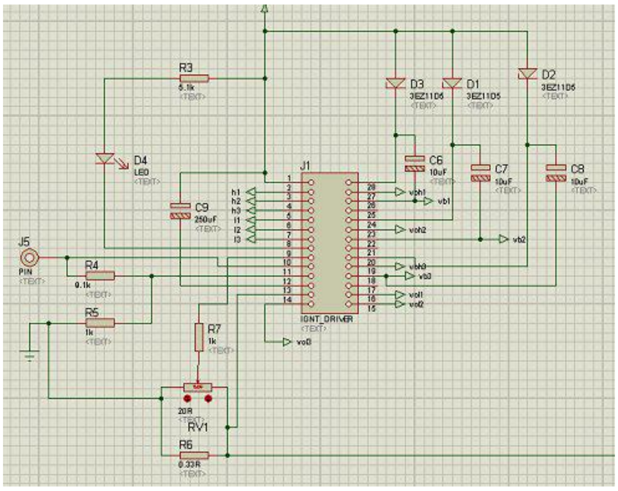


Figure 7: H-Bridge driver circuit

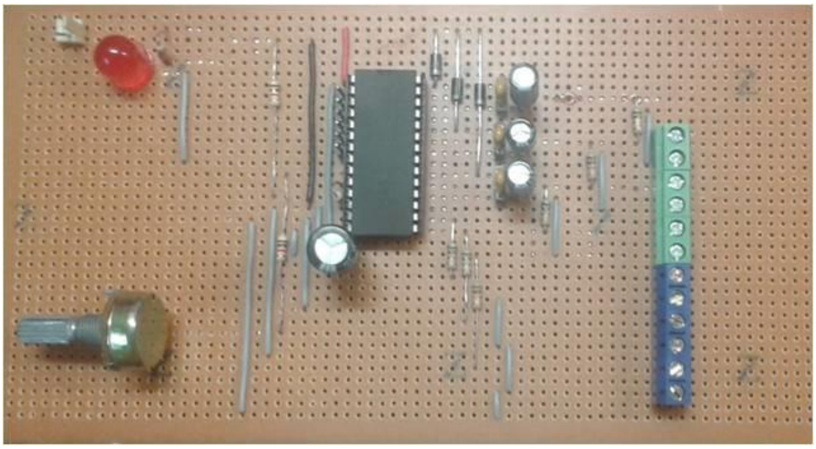


Figure 8: Hardware development H-Bridge board

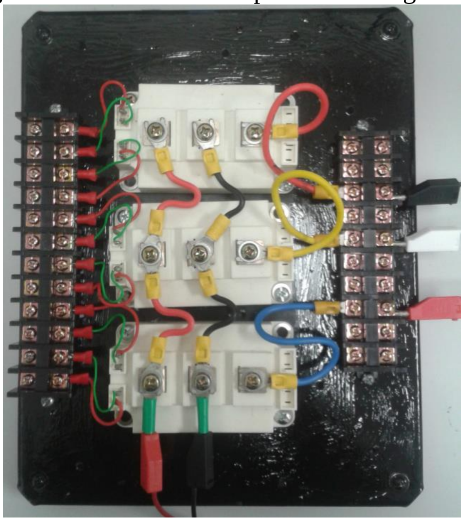


Figure 9: Hardware of IGBTs Bridge

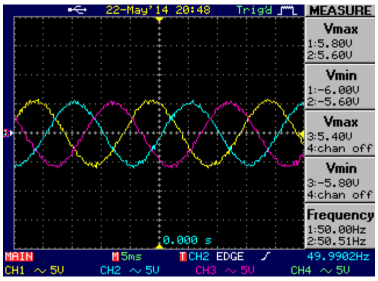


Figure 10: Three-phase sine waveform output

The TL082 IC is low cost, high speed, dual JFET input operational amplifier with an internally trimmed input offset voltage which called as BI-FET II™ technology. TL082 require low supply current yet maintain a large gain bandwidth product and fast slew rate. In addition, well matched high voltage JFET input devices provide very low input bias and offset currents. The 10K potentiometer used to gain the required high carrier signal frequency. This circuit produces a triangular waveform, V_{tri}, with a frequency of f_b, which is given by

$$f_b = \frac{200K}{4 X 100K X 1K X 100nF}$$

From the equation above, the f_b will be approximately 5.0 kHz and has peak-to-peak amplitude, V_m, given as,

$$V_m = 2 X 7V X \frac{100K}{200K}$$

where V_{max} is the maximum output voltage of IC TL082 with about 7V. Then, V_m will be about 7V and an offset of V_{of},

$$V_{of} = 5 X \frac{100K}{100K}$$

where V_{of} will be 5V. The result gained for this circuit from oscilloscope is shown in Figure 11.

The comparator circuit builds using the LM311 series which is a monolithic, low input current voltage comparator. The device is also designed to operate from dual 9V supply voltage. This circuit generates three-phase PWM outputs. The oscilloscope result gained for this circuit is shown as Figure 12.

The optocoupler circuit generates three high and low PWM outputs from three outputs of PWM gained from LM311 comparator. These six optocouplers is act as the isolator and since optocoupler act as isolator, it changes only the shape of waveform without changing other characteristics. Voltage of average 9V and frequency 1.37 kHz are maintained along the waveform. These optocouplers will protect the circuit of low voltage part from any unwanted damages if there is over-current or extremely high voltage flow. The oscilloscope result gained for this circuit is shown as a pair as Figure 13.

The H-Bridge circuit build using IR2130 IC to drive IGBT's with high and low output channels; provide the floating channel for boot strap operation. Moreover, to turn IGBT on and off, higher voltage is needed and this can be provided by gate driver circuit. By following the datasheet of IR2130, gate driver can provided voltage between 10V to 20V. Since, the V_{cc} applied is 15V in this circuit, the high and low output voltage from gate driver is approximately 15V. By combining high side and low side output voltage of the driver, IGBT can be turned on and off. The oscilloscope result gained for this circuit is shown as a pair as Figure 14.The voltage of 15V is recorded since V_{cc} provided is 15V. The shape of signal waveform is maintained about frequency of 1.2 kHz.

The three-phase induction motor is connected via Y-connection and then the three-phase output of the IGBT is connected to the motor input. It successfully turns the motor. Then, rotation per minute with PWM is measured with different reference signal frequency while the motor is running. The rpm of TPIM is measured using rotary encoder.

Figure 15 shown the test results of TPIM when it was running at different frequency. In the experiment, the lowest frequency is 40 Hz at 95.6 rpm while the highest frequency is 65 Hz at 125.6 rpm. The development of VFD has been tested at desired speed by changing the frequency using the function generator. The rpm is directly proportional to frequency applied. When the frequency is increases the spindle speed of TPIM also increases. This proves that the synchronous speed is directly proportional to the supply frequency [1]. When there is changes occur on frequency, the synchronous speed and motor speed can be control high or low the normal full-load speed. Hence, development of low cost VFD was successful and enables to adjust the speed of TPIM by adjusting frequency.

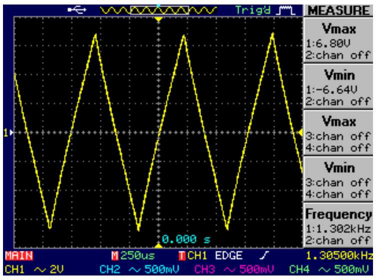
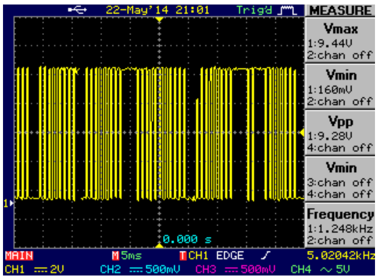
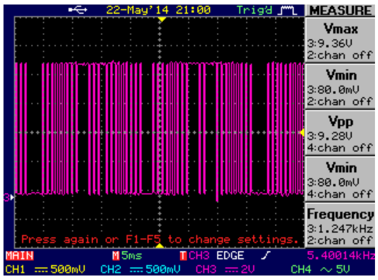


Figure 11**:** Three-phase sine waveform output



(a)



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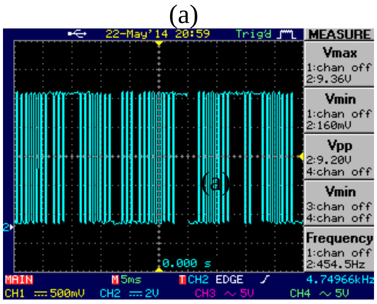

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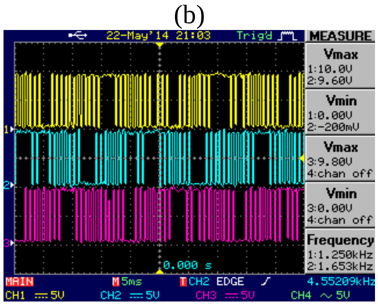
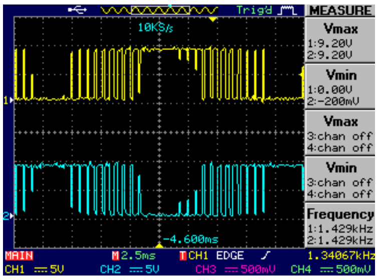
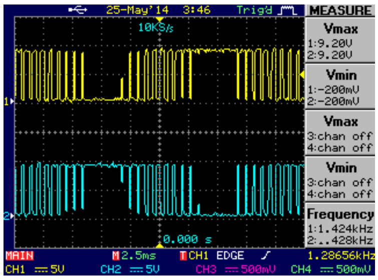


(d)

Figure 12: (a) First-phase PWM (b) Second-phase PWM (c) Third-phase PWM (d) Three-phase PWM outputs



(a)



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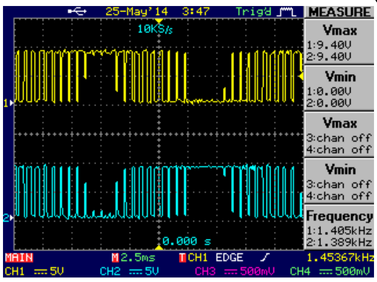

(c)

Figure 13: (a) First-phase PWM pair (b) Second-phase PWM pair (c) Third-phase PWM pair

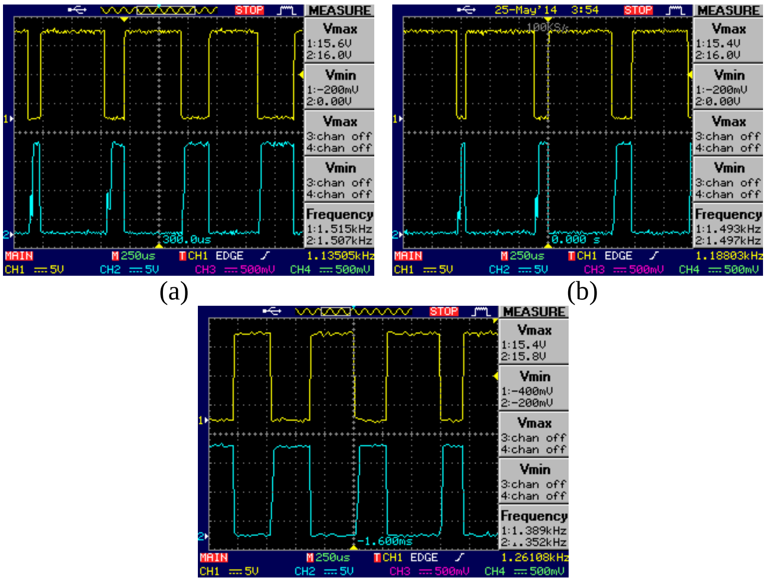

Figure 14 :(a) First-phase PWM pair (b) Second-phase PWM pair (c) Third-phase PWM pair

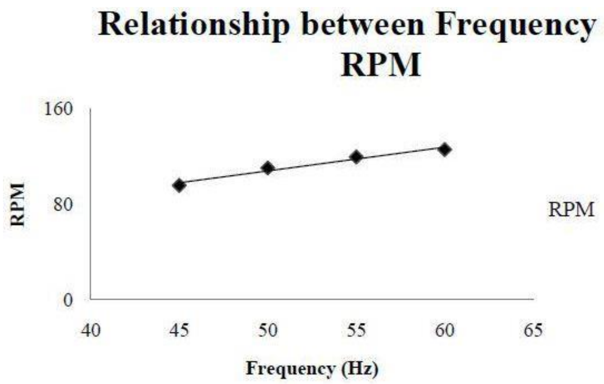

Figure 15: Relationship between RPM and Frequency

4. CONCLUSION

In this paper, the development of the speed control system using frequency control has been designed by combinations of PWM control circuit, drive circuit and H-bridge inverter using discrete components only. Variable frequency drive circuit using only discrete components for three-phase induction motor are simple, low cost, easy maintenance, not so precise but efficient to control three-phase induction motor. This will act as backbone for producing high precision and efficient closed controller using discrete components for three-phase induction motor. The components can be well adjusted and arranged properly and correctly. Moreover, all the required discrete components are also available in the electronic market today with low cost. This can contribute in the education system where students can built their own speed controller circuit for the induction motor rather than buy expensive board in marketplace. They are also will learn deeply about electric drive system consists of control signal, carrier signal, PWM and so on.

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