



DESIGN AND IMPLEMENTATION OF THREE PHASE VARIABLE VOLTAGE IGBT INVERTER FOR THE CONTROL OF INDUCTION MACHINES

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Abstract: The focus of this project is to design and construct a three- phase, 2KVA, Microcontroller based, Insulated Gate Bipolar Transistor (IGBT) inverter for the control of an induction motor. The firing pulses were obtained from a PIC16F877A microcontroller. The microcontroller was chosen as an efficient and easy to build inverter controller for induction machines. The theory of operation of the inverter-fed induction motor was determined using the three phase inverter switching sequence. The inverter was used to drive a three phase induction machine with no load, the variation of voltage and speed with varying modulation were recorded and the phase current obtained from the induction motor was compared with the theoretical phase current. The waveform from the theoretical switching sequence of the devices agreed with that obtained in the laboratory. The lower order harmonics were suppressed by using fewer semi-conductor devices in the power flow path.

Keywords: IGBT; microcontroller; inverter; firing pulses; induction motor; driver circuit

I. Introduction

Induction motors are sized for maximum loads and are operated at a constant full speed, because they are supplied with power from AC line at a fixed – sinusoidal voltage and fixed frequency. They are being preferred to their DC motors counterparts because of their low cost maintenance with superior speed-torque characteristic. Electronic control of power are now increasingly applied to induction motor control as a result of the development in the world of electronics over decades which have made possible a lot of techniques to meet the ever increasing demand. Inverters are types of electronic control device that convert direct current (DC) input voltage to alternating current (AC) output voltage of desired voltage and frequency. Inverters have no moving parts and hence they are used in a wide range of applications, from small switching power supplies in computer and electronics, industrial controls to large utility as High-Voltage Direct Current application that transport bulk power. Inverters are commonly used to supply AC power from rectified AC source voltage or DC source voltage such as solar panel or batteries. They are used in induction heating which is a method of providing fast, consistent heat for processing of metals or any other electrically conductive materials. It is also used in traction systems which have the sole purpose of preventing wheel spin from occurring in traction. Formerly, DC series motors were preferred for traction applications, as their drive system are relatively simple but nowadays, more precise digital algorithms, have been developed to control power inverters with the purpose of driving induction motors, which makes them a far better choice than DC series motor .

Inverters are of many types and are classified variously. It can also be differentiated by the number of phases of the output: single phase or multi phase which is the most applicable for industrial uses. The main types of inverter are classified according to their source input - current source inverter (CSI) and the voltage source inverter (VSI). A CSI inverter is the dual of a six-step voltage source inverter. With a current source inverter, the DC power supply is configured as a current source rather than a voltage source. The inverter silicon controlled rectifiers SCRs are switched in a six-step sequence to direct the current to a three- phase AC load as a stepped current waveform. In the voltage source inverter, the DC voltage is changed when commutation takes place. The input DC voltage to an inverter may be a rectified AC source or from a battery. The needs for variable voltage and frequency have made inverter circuit to gain popularity in industrial drives. Some of the control strategies which made this possible are; Pulse width modulation (PWM), digital simulation switching techniques, digital signal processor (DSP) based controller, etc [4]. Inverter-driven induction machine are now the prime choice of variable speed drives in a wide field of application due to their low cost, simple and rugged construction, high reliability, minor maintenance, and well developed control algorithm. In fact with the inverter as power supply, the induction machine operational conditions are much different from the conventional supply

with fixed voltage and frequency, which implies that the design of induction machines should be reconsidered to make them more suitable for inverter-driven variable speed drive.

The rest of this paper work is sectioned as; system modeling and analysis, results and discussions, and conclusion.

II. Selection of Power Semi-Conductor Device for the Inverter

With the radical converter technology, it is conspicuous that the speed control of an induction motor can be achieved by the power semi-conductor (switching) circuits. The choice of switching device for the variable inverter is a momentous part in circuit design consideration. The common switching elements are either the thyristor or the transistor. Transistor switches does not require commutating technique like the thyristor. As a result of improvement going on; for instance MOSFET inverter can now handle high voltage in the KVA range. GTO has a faster switching speed than the regular thyristor and can withstand higher current than the transistor or MOSFET. The insulated gate bipolar transistor (IGBT) tends to combine the features of both the bipolar junction transistor (BJT) with that of MOSFET and is now popularly used in the industries. The IGBT is suitable for many applications in power electronics, especially in Pulse Width Modulated (PWM) servo and three-phase drives requiring high dynamic range control and low noise. Hence, it was chosen for this project work.

III. System Modeling and Analysis

Many researchers have worked on inverter controllers under pure resistive R and R-L load to obtain load current and rms output voltage characteristics. This can be extended to induction motor by reducing the equivalent circuit of the induction motor to equivalent impedance.

A. R-L Modeling of a Three-Phase Induction Motor

Considering the equivalent circuit of a controlled three phase induction motor as shown in figure 1, the current flowing through the induction motor is obtained by divided the phase voltage by the total impedance.

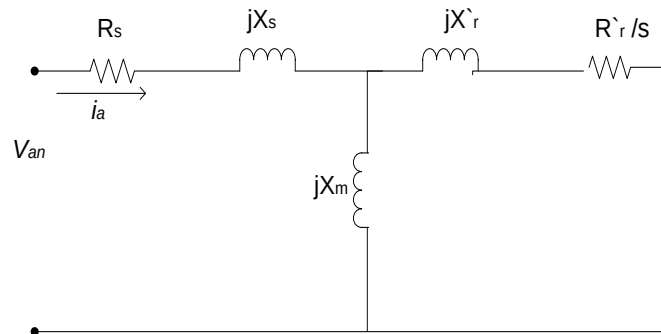


Figure 1: The RMS equivalent circuit of the induction motor.

If $X_m^2 \gg R_s^2 + X_s^2$, then the magnetizing reactance X_m may be moved to the stator winding to simplify further; this is shown in figure 2

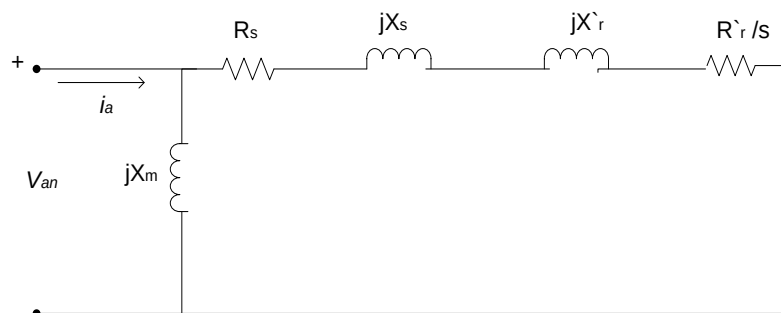


Figure 2: approximate per-phase equivalent circuit.

The input impedance per-phase of the motor becomes

$$Z_{eq} = \frac{jX_m \left[\left(R_s + \frac{R'_r}{s} \right) + j(X_s + X'_r) \right]}{\left(R_s + \frac{R'_r}{s} \right) + j(X_s + X'_r) + jX_m}$$

This can be simplified further to equivalent; resistance R_{eq} , inductance X_{eq} and load angle ϕ as shown in

$$Z_{eq} = R_{eq} + jX_{eq}$$

Where R_{eq} , X_{eq} and load angle ϕ are defined as;

$$R_{eq} = \frac{X_m X_T \left(R_s + \frac{R'_r}{s} \right) (X_m - 1)}{\left(R_s + \frac{R'_r}{s} \right)^2 + X_T^2}$$

$$X_{eq} = \frac{\left(R_s + \frac{R'_r}{s} \right)^2 X_m + (X_m X_T)^2}{\left(R_s + \frac{R'_r}{s} \right)^2 + X_T^2}$$

Or

$$L_{eq} = \frac{X_{eq}}{2\pi f}$$

Therefore the load angle ϕ is expressed as:

$$\phi = \tan^{-1} \left(\frac{\left(R_s + \frac{R'_r}{s} \right)^2 + X_m (X_T)^2}{X_T \left(R_s + \frac{R'_r}{s} \right) (X_m - 1)} \right)$$

Where:

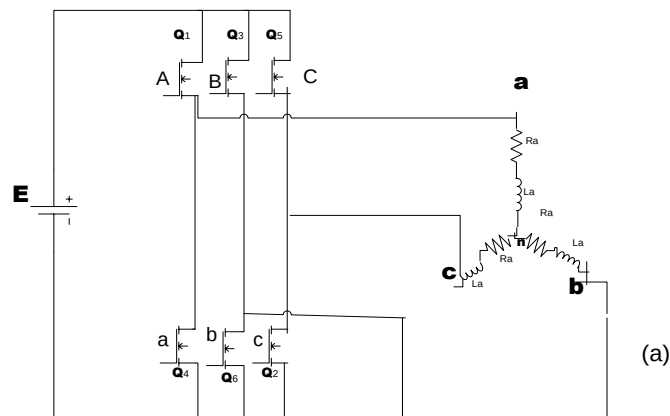
$$X_T = X_s + X'_r$$

The expression for instantaneous energy current per phase at every 60° interval is given by:

$$i = \frac{V_{ph}}{Z_{ph}} \left(1 - e^{-t/\lambda} \right)$$

$$\text{Where; } \lambda = \frac{L_{eq}}{R_{eq}} = \text{Time Constant}$$

An equivalent circuit of a star connected three-phase induction machine load connected to a three-phase inverter operating at 120-degree conduction is shown in figure 3.



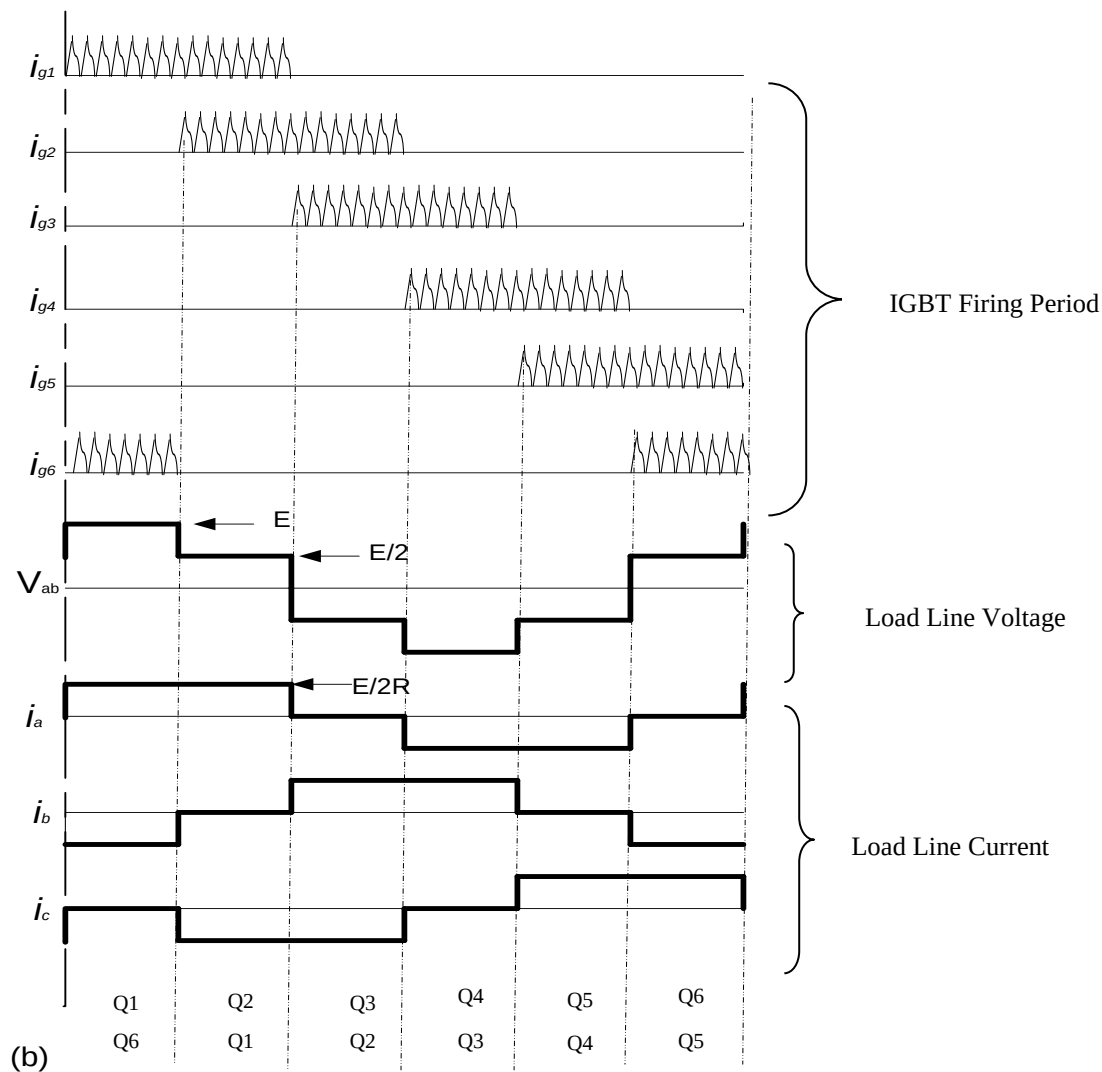


Figure 3 Three-phase bridge inverter with 120degree conduction (a) circuit (b) waveforms.

The IGBT switches are assumed to be ideal switches. The DC source is switched in six steps to synthesis the three-phase output. The table 1 below shows the switch state for a three-phase voltage source inverter. Assuming that the inverter has a three-phase balanced load as shown in figure 3, this is:

$$V_{an} + V_{bn} + V_{cn} = 0$$

Table 1: Conduction Switching Sequence of a Three-Phase Inverter

Mode	Phase Voltages			Turn on upper switch	Turn on lower switch
	V_{an}	V_{bn}	V_{cn}		
1	$E/2$	$-E/2$	0	Q ₁	Q ₆
2	$E/2$	0	$-E/2$	Q ₁	Q ₂
3	0	$E/2$	$-E/2$	Q ₃	Q ₂
4	$-E/2$	$E/2$	0	Q ₃	Q ₄
5	$-E/2$	0	$E/2$	Q ₅	Q ₄
6	0	$-E/2$	$E/2$	Q ₅	Q ₆

The system equivalent circuit for Mode 1-6 at their respective time intervals are shown below in figure 4

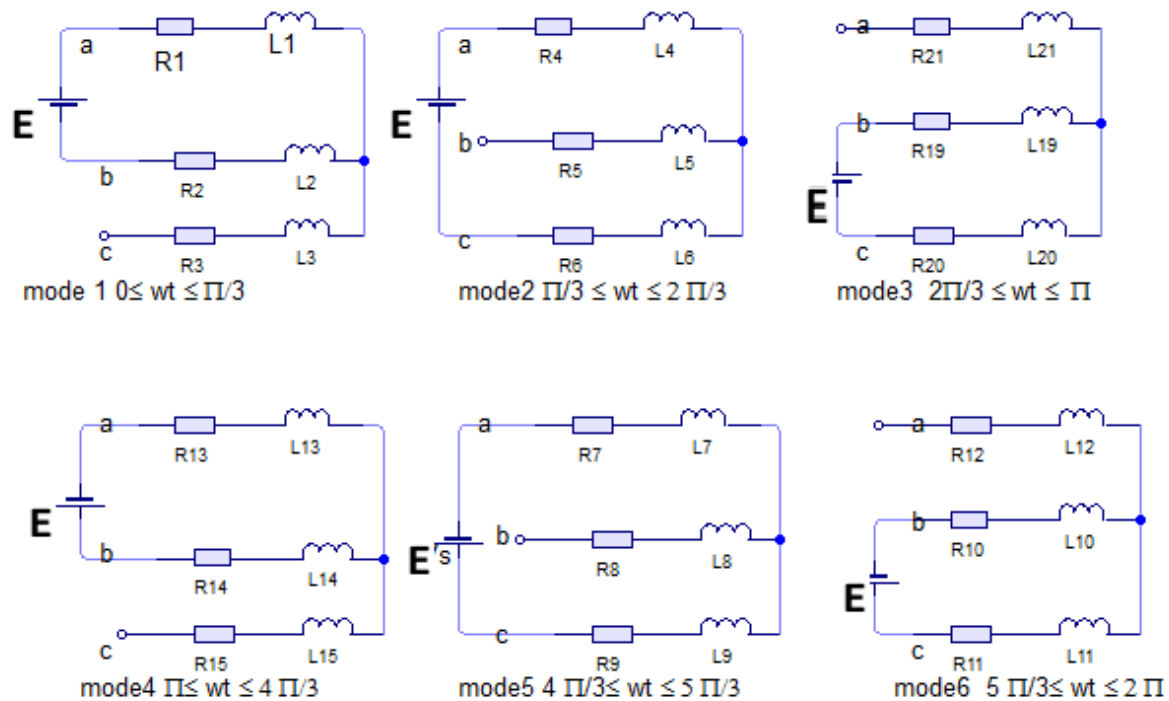


Figure 4: The system equivalent circuit for Mode 1-6

Sample Motor Data

The operating characteristics parameters of the three-phase induction motor from the laboratory are shown in below:

Table 2: Sample Motor Data

Quantity	Symbol	In Actual Unit
Voltage Rating	V_s	220V
Operating Frequency	F	50Hz
Number of Poles	P	4
Stator Winding Resistance	R_s	19.5Ω
Rotor Referred Resistance	R'_r	6.7Ω
Stator Winding Reactance	X_s	18.2Ω
Rotor Referred Reactance	X'_r	18.2Ω
Magnetizing Reactance	X_m	201Ω
Rated speed	N	1440rpm
Winding Connection Type		Star
Calculated Slip Speed	N_s	1500rpm

The parameters and expressions above were used to evaluate theoretical motor stator phase currents at different inverter voltage levels which were compared with the laboratory values as shown in table

IV. Design and Implementation

A. The PIC16F877A Microcontroller

A PIC16FF877A is a computer control system on a single chip. It has many electronic circuits built into it. The microcontroller will then step through these instructions and execute them one by one. The list of these instructions given to the microcontroller is called a program. Inside the microcontroller the written program is stored in an area called EPROM (Electrical Programmable Read Only Memory), this memory is non-volatile and is remembered when the power is switched off. The program was written in assembly language and compiled using MPLAB, the compiled file is transferred to the chip using a PICSTART PROGRAMMER.

A +5VDC was used to bias the microcontroller and it was connected to pin 1, 2, 3 as shown on the IC pin configuration. A crystal oscillator was connected on pin 13 and 14. Resistors R1-R3 is used to pull the input pins to ground to avoid the circuit generating false control commands. Three control switches were provided for special purposes as indicated in figure 5 below; S_1 is to start the program in the microcontroller, S_2 and S_3 are used to decreases and increases the gate pulse width respectively, which were connected to pin 2, 3 and 4. The outputs of the six pulses were taken from pin 33, 34, 35, 36, 37 and 38.

B. DESIGN OF THE IGBT DRIVER (IR2110)

The driver isolate the low voltage circuit from the high voltage side, also use to step-up the pulse voltage from the microcontroller to +10VDC . The output from PIC16F877A was connected to pin 10 and 12 of the IR2110 IC. Two separate power supply was use to bias the IC, +12VDC was connected on pin 3 and +5VDC was connected on pin 9. Pin 1 is the low level output, pin 5 is the ground and pin 7 is the high level output as shown in figure 5.

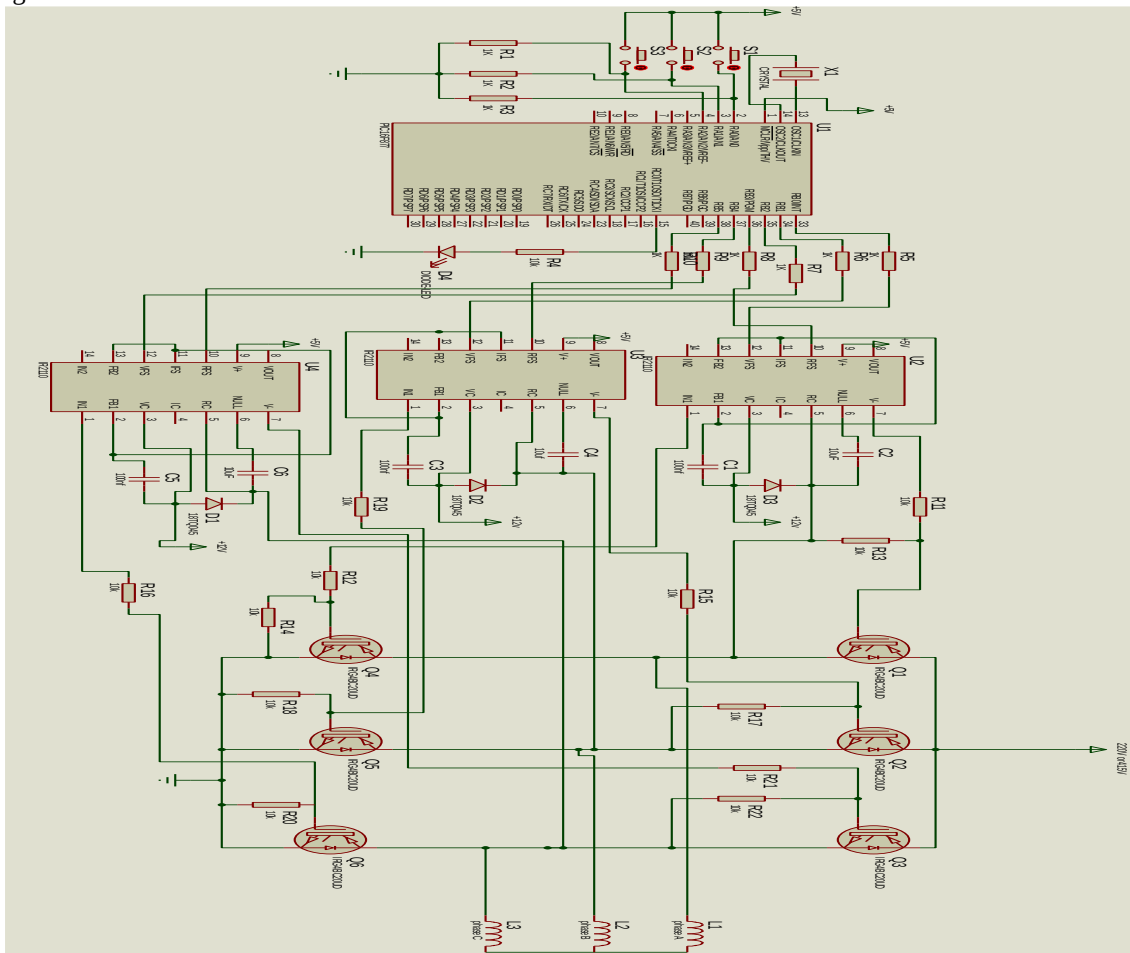
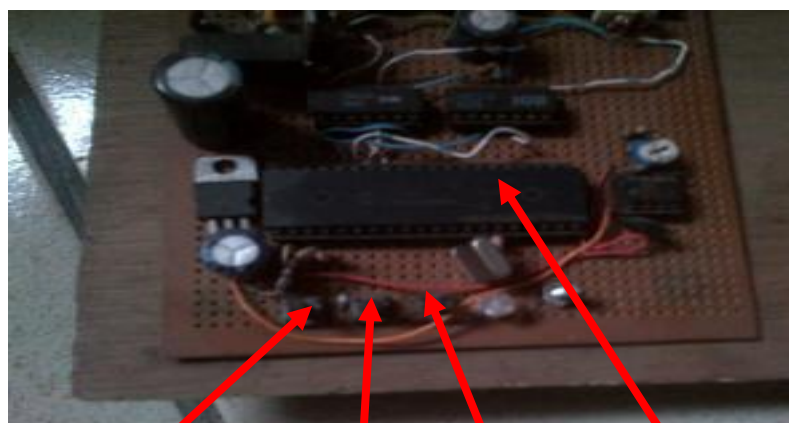


Figure A



S₁

S₂

S₃

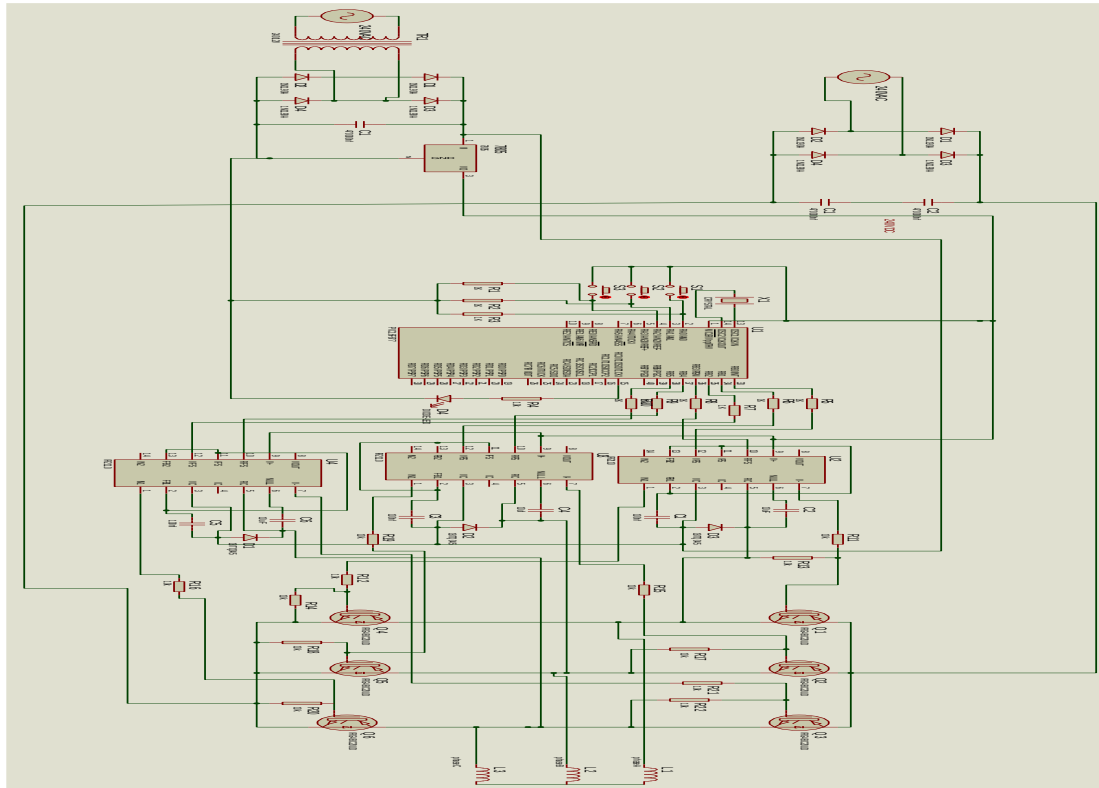
PIC16F877A

Figure B

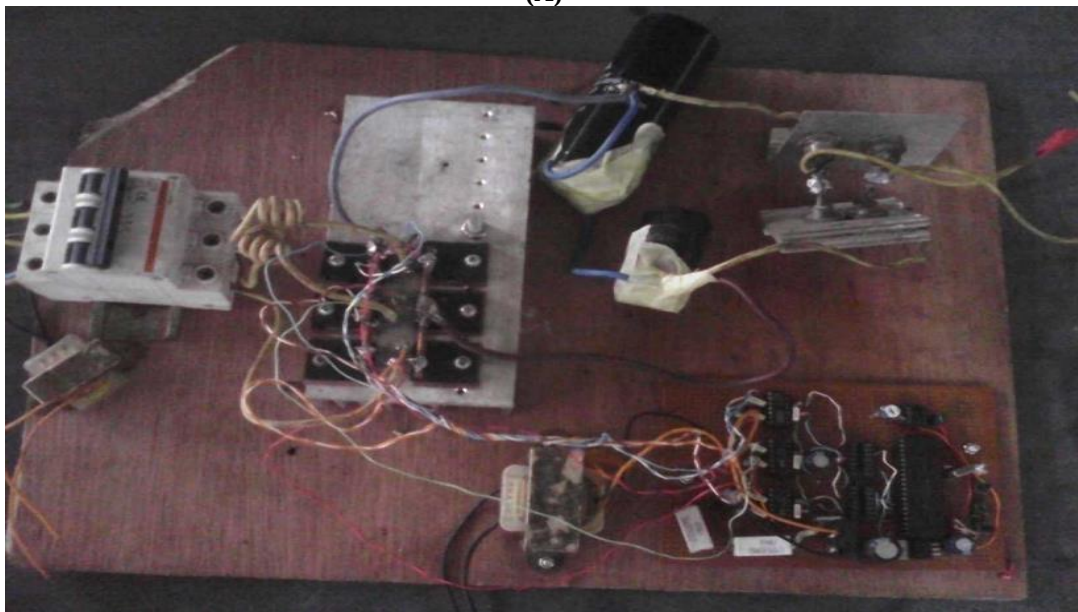
Figure 5 IGBT Driver Circuits (A) Circuit Layout. (B) Components on a Vero Board

C. Complete Variable Voltage Inverter Circuit.

Complete circuit of the variable voltage inverter is shown in figure 6. It comprises the microcontroller, IGBT driver and the inverter circuit. The microcontroller was programmed so as to generate six pulses which are 60° out of phase from each other which is in agreement with figure 3. The width of the pulses can be increased or decreased so as to vary the output voltage of the inverter. S_1 is used to start the program, S_2 is used to increase the width of the pulse and S_3 is used to decrease the width of the pulse as shown in figure 5.2. The pulses were connected to IGBT driver, it act as an isolator also use to increase the pulse voltage which is use to trigger the IGBTs. The switching of the IGBTs produces a three phase AC voltage for controlling three phase induction motor.



(A)



(B)

Figure 6 Complete Circuit of the Variable Voltage Inverter on a Vero Board.

V. Results and Discussins

The performance characteristics resulting from the three-phase inverter voltage controller as seen on the oscilloscope are shown in Fig. (8) to (13).



Figure 7 Test Rig with Controlled 3-Phase Induction Machine and the Inverter Controllers



Figure 8 Firing pulses obtained from the Control Circuit.

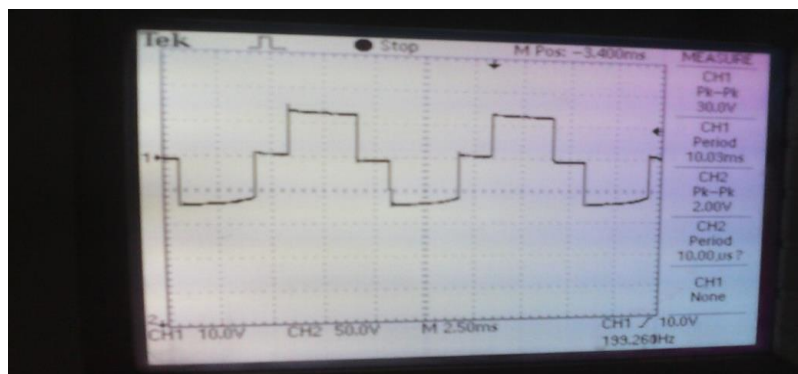


Figure 9 AC Output Voltage Waveform of Line AB

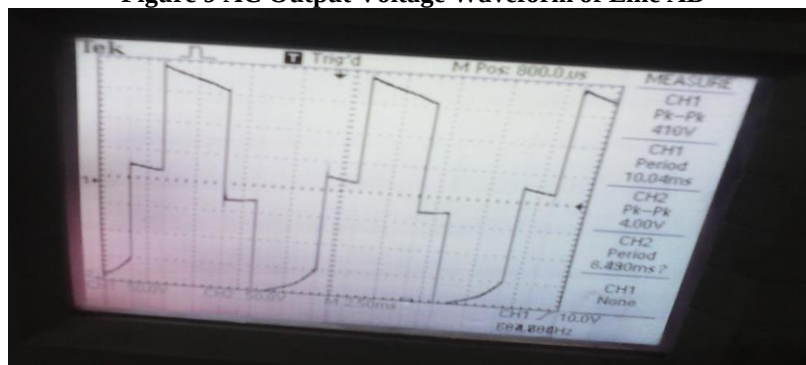


Figure 10 AC Output Voltage Waveform of Line BC.

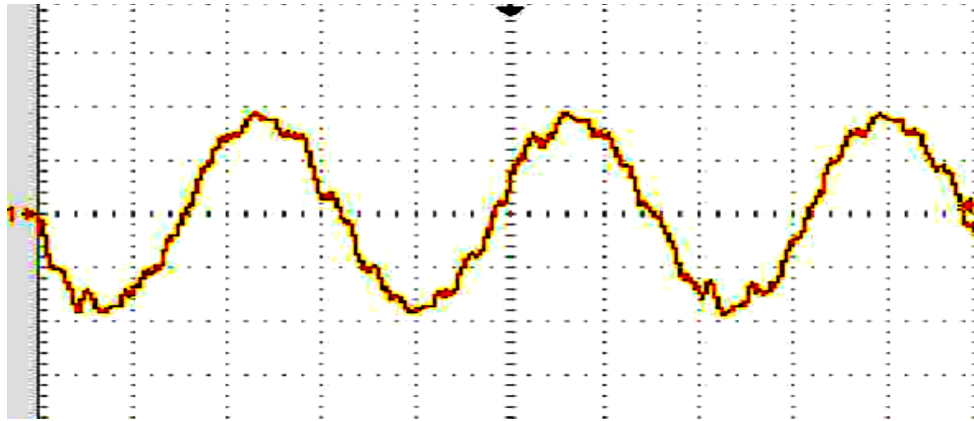


Figure 11 Current Waveform of Phase A

Table 3: Result of the Test Carried out On Induction Motor

Voltage (V)	Speed (rpm)	Measured Current (A)			Calculated Current (A)
		I _a	I _b	I _c	I
75	0	0	0	0	0
100	830	0.47	0.46	0.48	0.4557
110	830	0.47	0.44	0.48	0.5012
143	960	0.64	0.62	0.66	0.6516
183	1280	0.72	0.7	0.74	0.8339
198	1250	0.77	0.75	0.78	0.9022
210	1350	0.82	0.8	0.84	0.9569
226	1425	0.86	0.84	0.87	1.0298
240	1440	0.97	0.92	0.99	1.0936
250	1460	1.09	0.99	1.1	1.1392

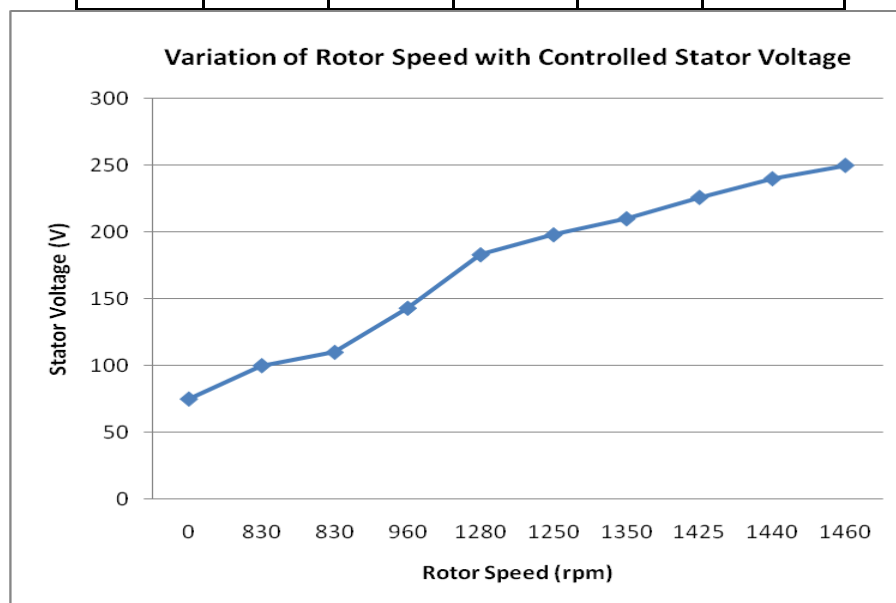


Figure 12 Graph of Stator Voltage against Rotor Speed

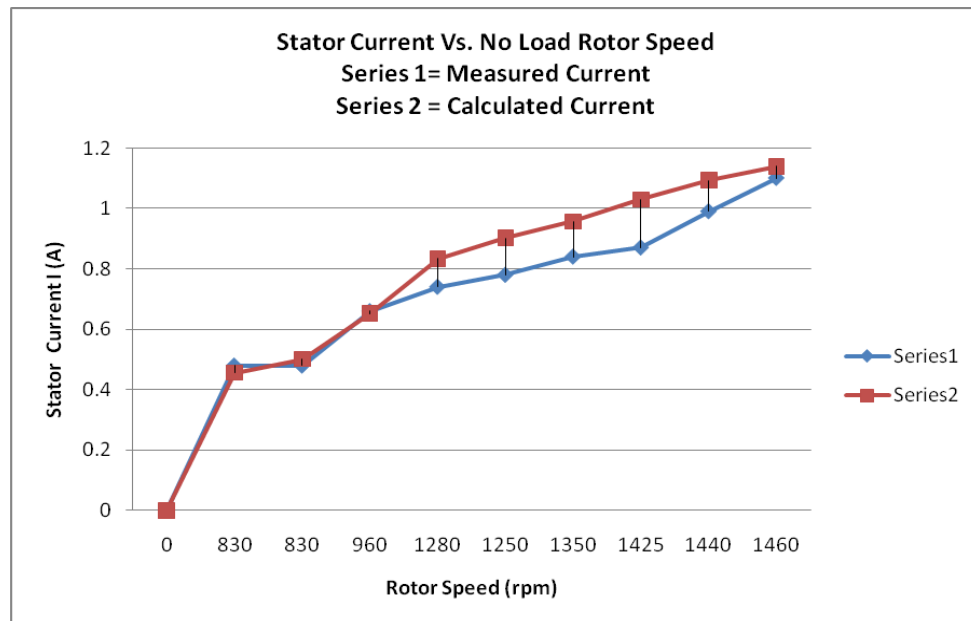


Figure 13 Graph of Stator Current versus Rotor Speed

VI. Conclusion

This work primarily focuses on proposing an efficient and portable inverter controller for an induction motor at a low cost implication. A three phase variable voltage inverter was designed and built for the control of an induction machine. The power inverter has six switches (IGBTs) that are controlled in order to generate AC output from the DC input. The microcontroller controls these six switches of which two switches will be ON at a time, when the switches are ON, current flows from the DC bus to the motor winding. Because the motor windings are highly inductive in nature, they hold electric energy in the form of current. This current needs to be dissipated while switches are off. Diodes connected across the switches give a path for the current to dissipate when the switches are off. Waveforms were obtained which are in agreement with the theoretical waveforms and the stator phase voltages obtain from the induction motor.

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