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# Design and Development of Three-Phase Voltage Source Inverter for Variable Frequency Drive

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**Abstract.** Three phase induction motors are the workhorse of industry. Variable speed operation of the motor enables substantial energy savings through implementation of variable frequency drives. This project concerns on the design and implementation of three-phase voltage source inverter (VSI) for variable frequency drive. The focus was to generate variable frequency output suitable to be fed to the induction motor for the purpose of variable speed control. SPWM signal was generated through SIMULINK algorithm. The VSI circuit was designed, fed with SPWM trigger signal and simulated for variable frequency output in terms of line-to-neutral and line-to-line voltage across R-L load. In the experimental setup, the real VSI system was developed, the SPWM trigger signal generated through SIMULINK and interfaced to hardware using Arduino microcontroller. The output is dropped across resistive load and parameters line-to-neutral and line-to-line voltage was measured. Three set of output voltage with frequency of generated at 20Hz, 50Hz and 70Hz. Thus, experimental result validated that variation of frequency of voltage output of the VSI has been successfully achieved.

## 1. Introduction

Three phase induction motors are the workhorse of industry, constituting to about 85% of all types[1]. This is attributed to their simplicity, ruggedness, low-cost and ease of maintenance[2]. They are mostly utilized to drive compressor, blower fans, pumps and conveyors in most industry ranging from palm oil, sugar and rice mill, to cement and steel plant. Previously, they were only operated as fixed speed due to fixed supply nominal frequency. Compared to fixed-speed drive, variable speed operation of induction motor performed superior with better efficiency, energy savings and significant cost reduction through less frequent downtime for maintenance[1], [2]. In the sugar mills, it is used for centrifugal pump where the speed control have been applied to reduce energy usage whereby, 50% energy savings could be attain by reducing 20% of pump or fan speed[3].

Adjustable speed drive operation could be attained through several ways. Mechanical means however, lacks flexibility of speed change during operation. For wound rotor type of induction motor, external variable resistor connected to slip ring of the motor enabled adjustable speed operation. However, operation through variable resistance was highly inefficient due to high loss[4]. For squirrel cage induction motor though, a more popular method to implement adjustable speed drive operation would be through variable frequency drive.



The variable frequency drive (VFD) speed control is based upon the concept of varying the frequency of the three-phase alternating current (AC) voltage supply to the stator of induction motor. As the stator frequency is varied, the synchronous speed and thus the rotor speed can be varied[4]. Figure 1 shows a topology of variable frequency drive connected to induction motor. Three phase AC source is rectified to DC using diode, and then fed to three phase voltage source inverter (VSI) where the three-phase output is fed to the stator of induction motor. The frequency of the output can be varied by controlling the switching of the VSI. Previously, Silicon Controlled Rectifiers (SCR), was used as switches. However, SCR lack switching OFF control therefore, extra auxiliary circuitry needed to be integrated to control the VSI. With implementation of MOSFET and IGBT transistors as switches, pulse control becomes manageable and can be generated through computer algorithm. MATLAB/SIMULINK software provides platform of not only simulation of system design but also enables model deployment and hardware integration[5]. In this sense, more complex pulse such as Sinusoidal Pulse Width Modulation (SPWM) can be generated through the program and interfaced as signal output to the VSI hardware circuit.

This project concerns on the design and implementation of three-phase voltage source inverter for variable frequency drive. The focus was to generate variable frequency output suitable to be fed to the induction motor for the purpose of variable speed control. SPWM signal was generated through SIMULINK algorithm. The VSI circuit was designed, fed with SPWM trigger signal and simulated for variable frequency output in terms of line-to-neutral and line-to-line voltage across R-L load. In the experimental setup, the real VSI system was developed, the SPWM trigger signal generated through SIMULINK and interfaced to hardware using Arduino microcontroller. The output is dropped across resistive load and parameters line-to-neutral and line-to-line voltage was measured. Three set of output voltage with frequency of will be generated at 20Hz, 50Hz and 70Hz to demonstrate variable frequency output.

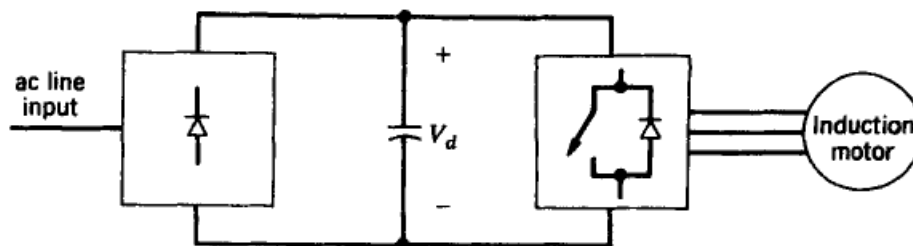


Figure 1: PWM VSI with diode rectifier[6]

## 2. Switching Control of the Three-Phase Voltage Source Inverter (VSI)

### 2.1. Three-Phase VSI

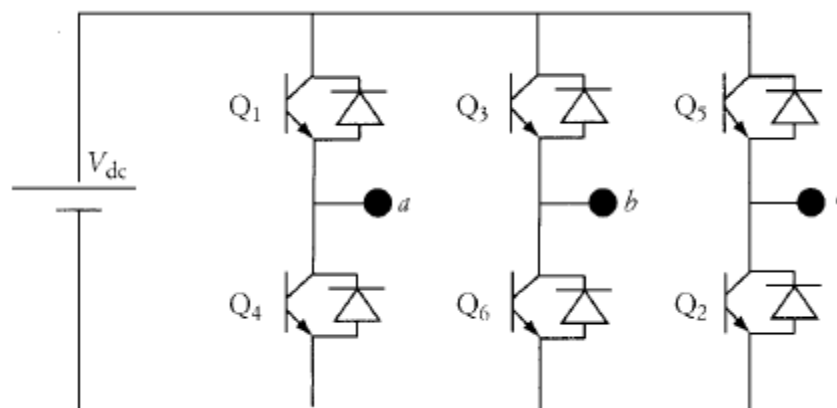


Figure 2: Three-phase VSI circuit[6]

Three-phase voltage source inverter (VSI) topology is shown in Figure 2. The VSI converts DC power to three-phase AC power. The input is DC source (usually rectified DC from nominal three phase AC supply) and the output is through three lines a,b and c. Each of the output line is connected through a leg consisting of top and bottom switches. Apparently six switches are employed where switch Q1 and Q4 for first leg, Q3 and Q5 for second leg and Q5 and Q2 for third leg. For each pair of switches on a leg only alternate switching is allowed to prevent short-circuit[6]. Usually IGBT or MOSFET are employed as switches and can be turned on and off based from gate pulses. The switching can be controlled through either one the following conduction modes; a) 120-degree or b) 180-degree[7], [8]. The switching of three-phase VSI using 120-degree conduction mode and resultant line to neutral voltage is shown in Figure 3. The conduction duration for each of the transistors is 120-degrees for every switching sequence, at every 60-degree duration in one-cycle. Compared to the 180-degree conduction mode, the 120-degree conduction mode requires only two transistors to be turned-on at every 60-degree duration and performs the six mode of operation within one cycle. Thus, major advantage of using 120-degree conduction mode is less susceptible to short circuit[8]. From Figure 3, peak voltage of line to neutral voltage is equal to  $2/3 V_{dc}$ . In Figure 4, line-to-line voltage is obtained by measuring differential voltage of each of the three line to neutral voltage and the peak voltage is equal to  $V_{dc}$ .

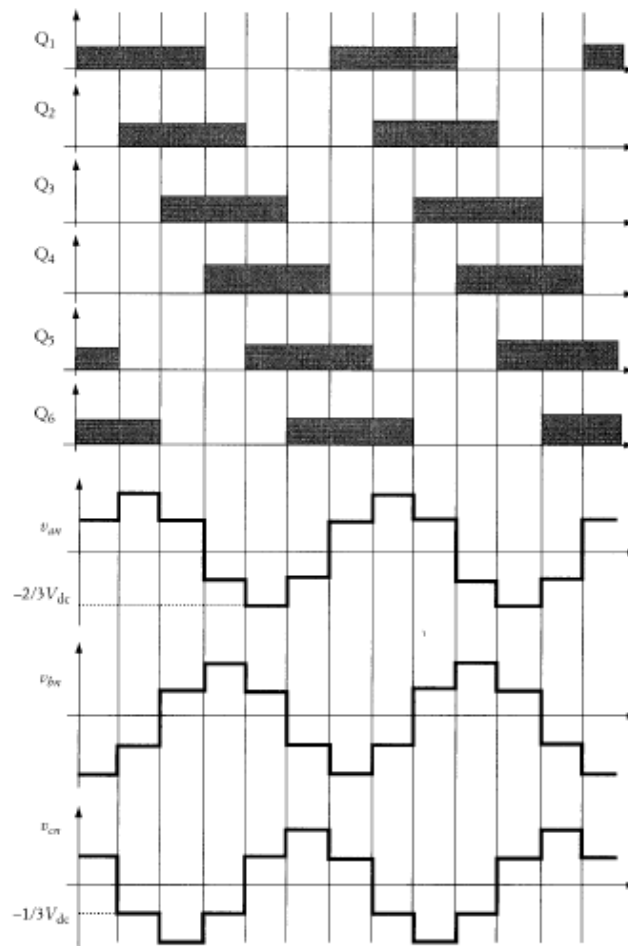


Figure 3: 120-degree conduction mode at top and line to neutral voltage waveform at bottom[6]

## 2.2. Sinusoidal Pulse Width Modulation (SPWM) Control Signal

If regular square wave pulse were fed through the gates of VSI switches, the line to neutral voltages would be such in Figure 3. However, total harmonic distortion (THD) of these signals would be as high as 30%[9]. Employing pulse width modulation (PWM) signal allows more precise control of voltage through controlled conduction in the pulse-width of the trigger signal[6]. In this case, since

desirable output voltage waveform for a variable frequency drive is sinusoidal with low THD, sinusoidal pulse width modulation (SPWM) trigger signal is employed. SPWM is generated through comparison between triangular wave as the carrier signal and the three phase sinusoidal waves as the control signal[4]. Figure 4 illustrates how the comparison is made, in which three reference sinusoidal signal with fundamental frequency was set to be the same with inverter sinusoidal output, denoted as  $v_{ra}$ ,  $v_{rb}$  and  $v_{rc}$ , phase-shifted by 120 degree from each other as control element. The carrier element is the triangular wave with much higher frequency. Comparator output denoted by 'g1' and 'g3' shown were two out of three channels SPWM pulse generated. The pulse would be fed individually to the gates of all six switches of the VSI. Figure 5 shows line-to-line voltage of inverter output generated through SPWM trigger.

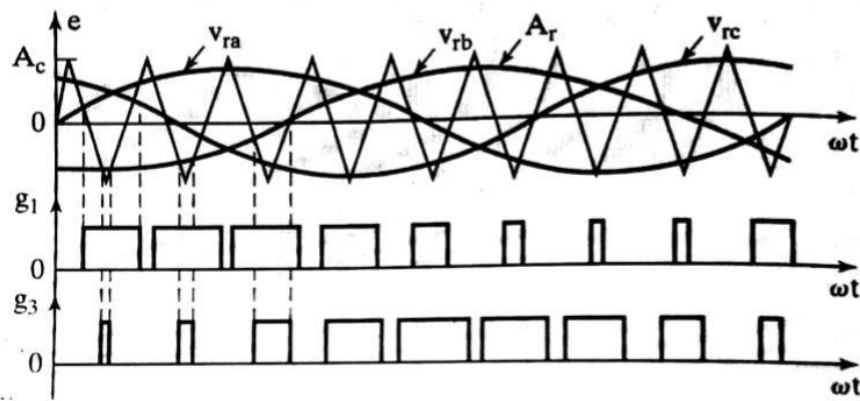


Figure 4: Comparison between carrier signal and three phase-shifted sinusoidal control signals for SPWM trigger pulse generation[4]

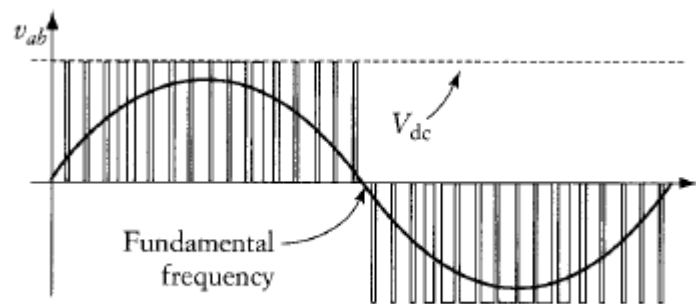


Figure 5: Line-to-line voltage of inverter output triggered by SPWM pulse[6]

### 2.3. Implementing Switching Algorithm for Three-Phase Voltage Source Inverter (VSI)

Based from method explained in Section 2.1 and 2.2, switching strategy was developed using SIMULINK block diagram as shown in Figure 6. Three control signals (namely phase A, B and C) 120-degree phase-shifted to each other with fundamental frequency set to be equal to inverter output frequency were compared to triangular carrier signal with frequency set to 5kHz. The comparator output consists of three channels containing phase-shifted SPWM signals. Output from phase A was fed to the gate of Q1 while inverted version fed to Q4. Output from phase B fed to Q3 and inverted version to Q6 while output from phase C and its inverted version fed to Q5 and Q2 respectively.

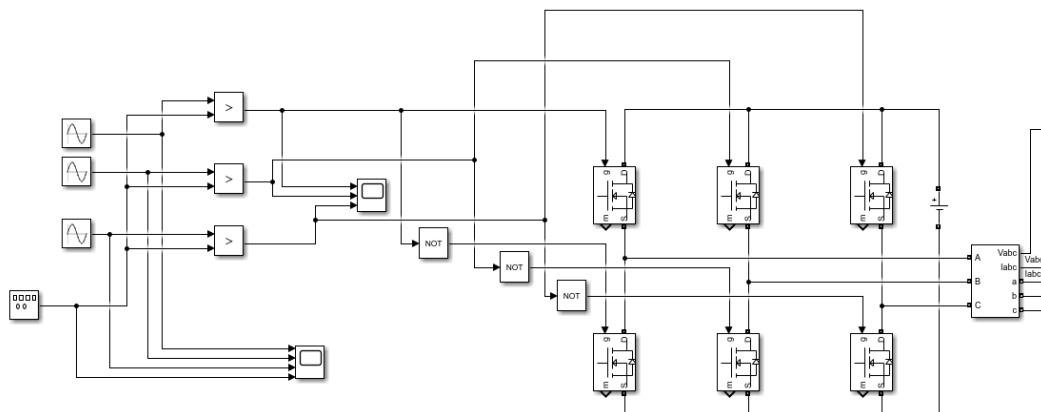


Figure 6: Switching control algorithm implementation for Three Phase VSI using SIMULINK blocks

### 3. Simulation of Variable Frequency Operation of Three-Phase VSI

In Figure 7, an open loop variable frequency drive system was developed, derived from conceptual diagram in Figure 1. Apparently, VSI output will be connected to drive three phase induction motor. For variable speed operation of induction motor, the VSI must be able to output sinusoidal voltage and current at different frequencies. In the proposed system, variation of frequency will be controlled real-time through SIMULINK input settings. Ultimately, signal generation algorithm will be produced through SIMULINK before being interfaced to hardware as trigger signals through Arduino. VSI was simulated through MATLAB/SIMULINK to generate line-to-neutral and line-to-line inverter output voltage at three different frequencies: 20Hz, 50Hz and 70Hz representing low, medium and high speed of induction motor. Figure 8 shows the simulation block diagram for variable frequency output.

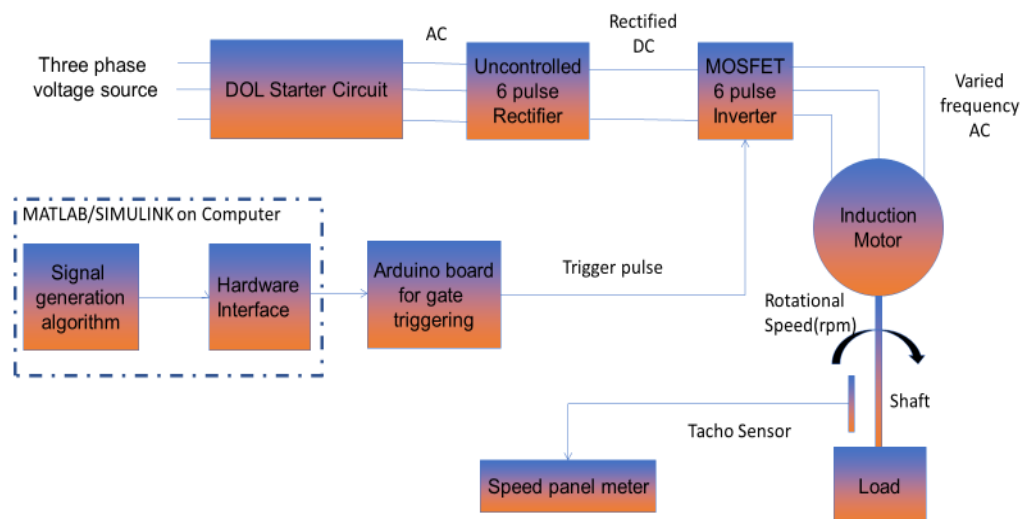


Figure 7: Open-loop architecture for variable frequency drive for three-phase induction motor

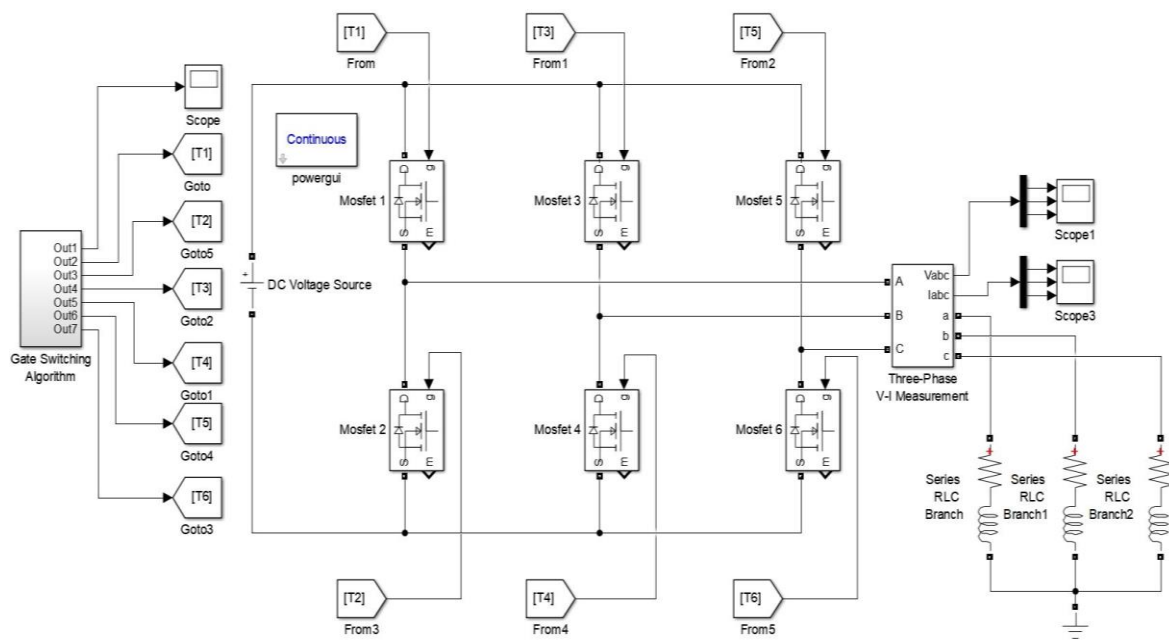


Figure 8: Simulation block diagram of the variable frequency operation of inverter circuit with RL-load

#### 4. Interfacing Switching Algorithm from MATLAB/SIMULINK to hardware through Arduino

The development of the three-phase voltage source inverter (VSI) circuit is tested within SIMULINK for validation of the three-phase switching principle, along with the SPWM switching algorithm. Once the test is successful, the switching algorithm is ‘debugged’ and ‘rebuild’ via SIMULINK’s code generation and uploaded to the Arduino micro-controller, which consecutively feeds the switching signals to the gates of the MOSFETs of the actual hardware setup. Figure 9 demonstrates the flowchart of how the algorithm was ‘build’ and uploaded to the micro-controller, while Figure 10 illustrates the switching signals measured from 2 of the six-legged MOSFETS, such that the signals are uploaded from SIMULINK to the Arduino micro-controller and fed to the gates of the three-phase MOSFETs.

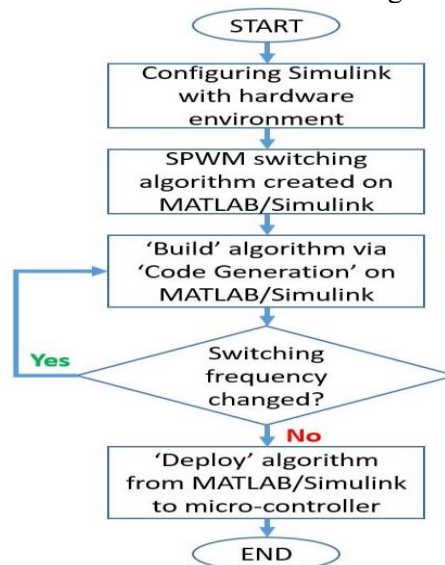


Figure 9: Flowchart for ‘SIMULINK-Hardware’ deployment



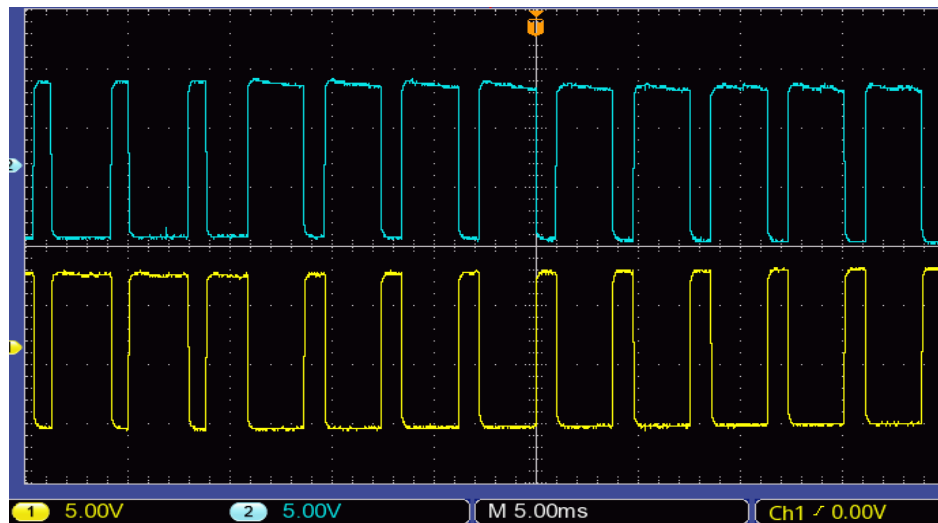


Figure 10: SPWM switching signal measured from three-phase MOSFET gates.

### 5. Experimental Setup

Figure 11 demonstrates the overall setup of between SIMULINK and the actual hardware of the three-phase voltage source inverter, and the connection between the Arduino micro-controller with the rest of the elements of the three-phase voltage source inverter (VSI). The components used to interface between SIMULINK and three-phase inverter circuit is the Arduino UNO micro-controller. The inverter circuit, which consist of the six-legged MOSFETs and six opto-couplers, in which the opto-couplers are used to isolate the three-phase inverter circuit from the computer section of the interface. Besides that, the opto-couplers were also used as an amplifier to amplify the signal output from the pins of the Arduino UNO microcontroller to an approximate voltage level of 15-volts. Figure 11 also shows how line-to-neutral voltage were measured using digital oscilloscope.

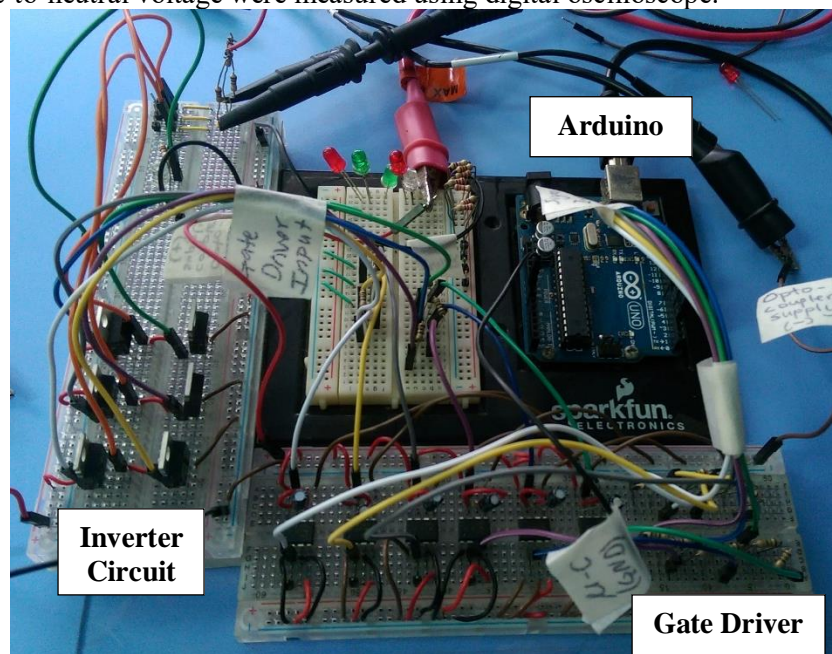


Figure 11: Connection between Arduino with the three-phase voltage source inverter (VSI)



## 6. Result and Discussion

### 6.1. Simulation Result of Three-Phase Inverter Circuit with RL-load

Figure 12 shows the waveform produced by the inverter circuit on SIMULINK, which was measured at the output of the RL-load, is of that replicates the modulation of a sinusoidal waveform. From the same figure, it can be seen that the peak voltage produced is approximately 546 volts (V). The blue, red and green voltage waveforms represent line to line voltage measured between line A-B, line B-C, and line C-A respectively.

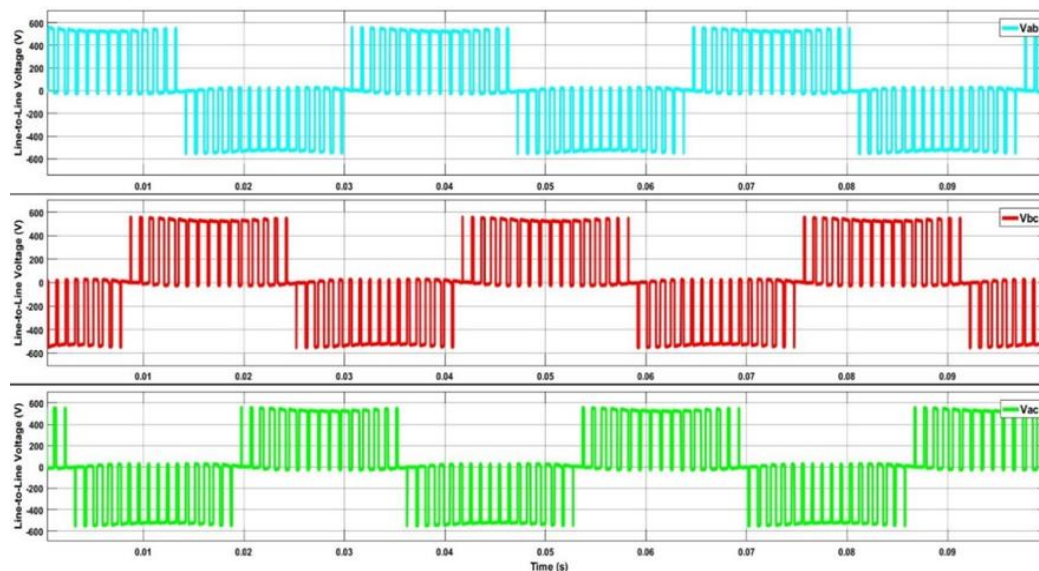


Figure 12: ‘Line-to-Line’ voltage waveform from three-phase VSI with RL-load

### 6.2. Comparison Between Simulation and Experimental Result

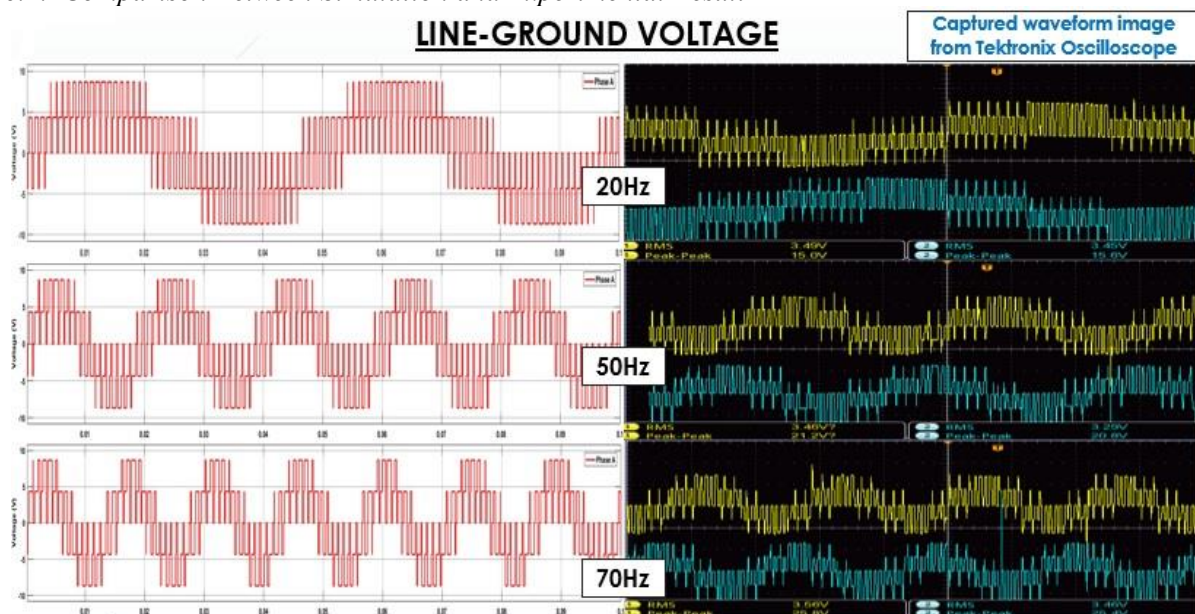


Figure 13: Line to neutral voltage generated through simulation (left) and experimental (right) at 20Hz, 50Hz and 70Hz frequency

The simulated results and experimental results, in terms of ‘line-to-neutral’ voltages are compared and the outcome from the comparison are shown in Figure13. It was observed that the experimental circuit developed managed to generate variable frequency output for line to neutral voltage when tested for 3 different frequency settings: 20Hz, 50Hz and 70Hz. For line to neutral voltage, the experimental output voltage waveform resembles the waveform of simulation output. This validates the reliability of switching control design and hardware interface to generate variable frequency output suitable for variable frequency drive.

## 7. Conclusion

Experimental circuit developed managed to generate variable frequency output for line to neutral voltage when tested for 3 different frequency settings: 20Hz, 50Hz and 70Hz. For line to neutral voltage, the experimental output voltage waveform resembles the waveform of simulation output. This proves that the ability to generate the SPWM switching signal for a three-phase motor application is plausible through the creation of the switching algorithm via MATLAB/SIMULINK, such that the signals are then ‘commenced’ via a micro-controller as a ‘medium’ to begin a digital triggering to the inverter circuit of the comprised element of the overall three-phase variable frequency drive circuit. The limitation of this work is that the inability of the circuit to ‘resist’ unexpected voltage spikes, which unbeknownst to cause a sudden ‘hike’ in current flow which leads to component malfunctions, as well as reducing the longevity of the elements of the circuit. Hence, the future work that can be performed for this work is such the improvement of the circuit itself to resist internal electrical ‘backlashes’, such as the occurrence of the mentioned voltage spikes.

## Acknowledgments

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