A Single-Phase Bridge Inverter For Grid-Connected Photovoltaic (PV) Application

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***Abstract* —This paper proposed a grid-connected photovoltaic (PV) power conversion system based on a Single-Phase Bridge Inverter that converts DC to AC power. The topology is based on a Single-Phase full-Bridge DC-AC Inverter and four Insulated-Gate Bipolar Transistor (IGBT) are to be used as switching devices. The output voltage source from boost converter was used in the system for the input voltage source of PV inverter. The boost converter must maintain its voltage output that comes from the PV array solar power for the inverter able to generate 240V, 50Hz. For this case, voltage source inverter with fixed DC link will be operated with DC voltage held constant. The Sinusoidal Pulse Width Modulation (SPWM) technique was used to synchronize the output voltage and frequency to the grid. A Microcontroller 16F877A was suitable to generate the required pulses to control the output of the inverter. MATLAB SIMULINK and PSIM simulations were used to compare with the experimental hardware result.**

***Keywords* – Sinusoidal Pulse Width Modulation, microcontroller PIC16f877A, single-phase inverter.**

I. INTRODUCTION

Nowadays grid-connected photovoltaic system is the most increasing photovoltaic application. This system is used an inverter that converts the direct current into alternating current. A DC-to-AC converter is known as inverter that used to change a dc input voltage to a symmetric ac output voltage of desired magnitude and frequency [1]. As known, this system involves a single grid-tie inverter connected to a series string of PV panels. The limitations have been found when used the PV panels where the maximum power point tracking (MPPT) is performed for the entire series string of PV panels, which is not optimal given variations among panels and variations in illumination of each panel [2]. A permanent defect or even a temporary shade to a single panel in an array that occurred, which is controlled by a single inverter, limits the performance of the entire string[2].

The development of Single-Phase Bridge Inverter will be presented in this paper. This inverter used Sinusoidal Pulse Width Modulation (SPWM) technique generated by a microcontroller. Microcontroller is able to store the required commands to generate the necessary waveforms to control the frequency of the inverter through proper design of switching pulses. The SPWM technique was used to produce pure sinusoidal wave of voltage and current output.

The SPWM technique is widely used in power electronics to digitize the power. The sequence of voltage pulses can be generated by the on and off of the power switches. This technique is characterized by constant amplitude pulses with different duty cycle for each period. The width of this pulses are modulated to obtain inverter output voltage control and to reduce its harmonic content [3]. Conventionally, to generate this signal, triangle wave as a carrier signal is compared with the sinusoidal wave whose frequency is the desired frequency.

The conventional method will be replaced with using the microcontroller in proposed alternative. The use of the microcontroller brings the flexibility to change the real-time control algorithms without further changes in hardware [3]. It is also has advantages such as low cost and small size design of control circuit for the Single-Phase Bridge Inverter.

II. SYSTEM OVERVIEW

The purpose of this project is to built a complete set hardware of Single-Phase Bridge Inverter with Bipolar SPWM controller scheme. The hardware design consist three parts which are power circuit, gate driver circuit and controller circuit.

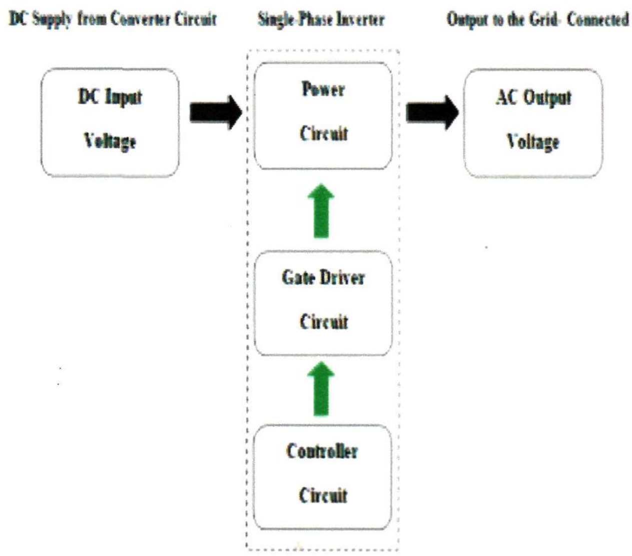

Figure 1 : Block diagram of the Single-Phase SPWM Inverter.

Figure 1 shows the system is basically has three parts of hardware design with input DC voltage from converter circuit output and the output AC voltage to the grid-connected, which are power circuit or full bridge circuit, gate driver circuit and controller circuit for generating SPWM pulses.

SPWM signal generated by microcontroller. A microcontroller 16F877A will be used in the project to generate the required pulses to control the output. The output are then fed to gate drivers which contains four independent electrical-isolated MOSFET drivers. After this, the outputs of the gate drivers are distributed to power switches in full bridge arrangement. The output of the inverter has square waveform due to the switching pattern [3].

A. CONTROL CIRCUIT

The controller circuit has been designed by using PIC16F877A to create the SPWM signal for switching the Insulated-Gate Bipolar Transistor (IGBT). The controller circuit produces a proper signal to trigger the power circuit accordingly. The basic schematic circuit design as shown in Figure 2.

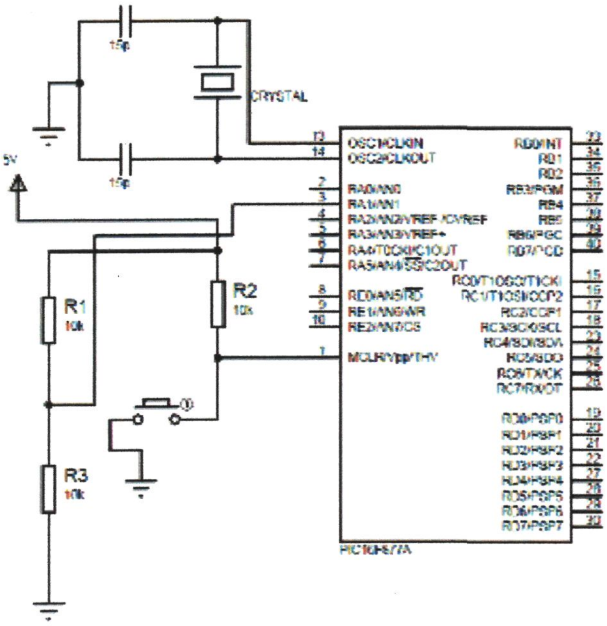

Figure 2: Controller circuit by using PIC16F877A.

PIC16F877A was used in this project because of its low power, high performance Reduce Instruction Set Computer (RISC) with only 35 single words instruction to learn and provide 10 bit, up to 8 channels Analog-to-Digital Converter (A/D) module. The device is manufacturing using Microchip's high-density non-volatile memory technology.

By combining an enhanced 16-bit CPU with high speed FLASH/EEPROM technology on a monolithic chip, the Microchip PIC16F877A is a powerful computer that provides a highly flexible and cost effective solution to many embedded control applications [4].

Basically, the microcontroller consist of several micro devices such as transistor, amplifier, capacitor and etc. Microcontroller will run 56 based on program that user implemented in this chip. In this project, Microchip PIC16F877A microcontroller runs at 20MHz with 8Kbytes of flash memory and 256 Bytes EEPROM.

The microcontroller is developed as the controller circuit to make the design simpler, more reliable and the most important one is to reduce their dimensions and components.

B. GATE DRIVER CIRCUIT

Basically, there are two fundamental categories for gate driver. These are high side and low side drivers. High side means the source of IGBT of the power element can float between ground and high voltage power rail while low side means the source of the IGBT is always connected to ground [3]. For the gate driver, IR2101 to operate as a bootstrap circuit, the Vbs voltage is used to provide the supply to the high side driver circuitry of the gate driver. Vbs is the voltage difference between the Vb and Vs pins on the gate driver IC. Figure 3 shows the connection of gate driver circuit and IR2101 will be used as gate driver in the project.

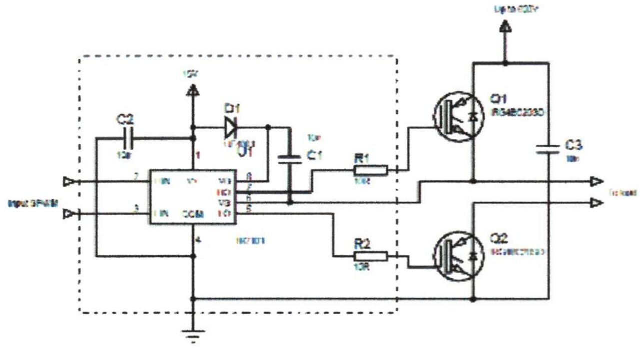

Figure 3 : The connection of IR2101 gate driver.

This driver needs supply in the range of 10V to 20V to ensure that the gate driver is fully enhanced the power IGBT. The Vbs supply is the floating supply that sits on the top of the Vs voltage. There are various methods to generate the Vbs supply. One of these is bootstrap method [3]. This method is simple and inexpensive but has some limitations. The duty cycle and the on time are limited by requirement to refresh the charge in the bootstrap capacitor Cbs. Selecting the suitable bootstrap diode is very important. The bootstrap diode must be fast enough to switch the inverter switches. Therefore, an Ultra Fast Diode, UF4001 is used in this circuit.

C. POWER CIRCUIT

The power circuit topology chosen is Single-Phase Full Bridge Inverter. It consists of DC voltage source or converter circuit output, four switching elements (IGBTs) and the loads. The circuit diagram of Single-Phase Full Bridge Inverter using fully controlled semiconductor power switches is shown in Figure 4.

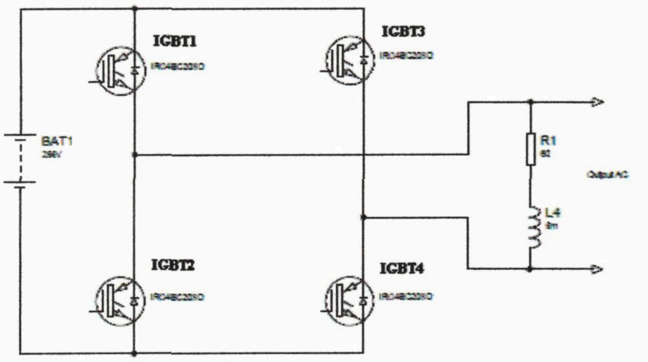

Figure 4 : Single-Phase Full Bridge Inverter schematic circuit.

The IGBT turns ON and OFF according to the pulses. Two IGBT (IGBT1 and IGBT4) will be turned ON when the PWM pulse is high and the other two (IGBT2 and IGBT3) will be turned ON when the PWM pulse is low. IGBT1 and IGBT3 cannot turn ON at the same time because it can cause a short circuit and the IGBT will be destroyed. The same apply to IGBT2 and IGBT4.

III. SWITCHING STRATEGY AND HARMONICS

A Sinusoidal Pulse Width Modulation (SPWM) technique is used in this work and the result with possible reversal voltage if this system used inductive loads. A change in current directions due to PWM switching will result in current and voltage spikes being generated with two possible situations where the current spikes maybe generated in the short circuit path and voltage spikes will be induced as a result of change in the current direction across the inductance with its associated current spiked [5]-[6]. These could be damaging the switches in used due to stress. A systematic switching is very important that allows for the energy flowing in the IGBTs decay.

A. BIPOLAR SWITCHING

Two types of switching scheme in pulse width modulation (PWM) inverter circuit are bipolar and unipolar switching scheme. The control of switches for sinusoidal PWM output requires a reference signal (Sinusoidal Wave) and a carrier signal (Triangular Wave). For this project, bipolar switching scheme is will used to ON and OFF the IGBT.

Bipolar switching is a switching of the electronic switch that produces output voltage between +Vdc and –Vdc. Figure 5 shows the output of Pulse Width Modulation according to the condition below :

Vo = +Vdc when Vsine < Vtri

Vo = -Vdc when Vsine > Vtri

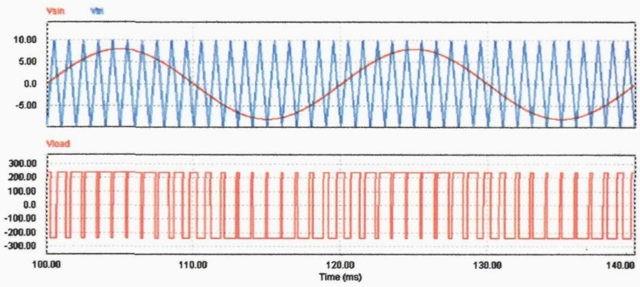

Figure 5 : Pulse Width Modulation Output (Bipolar Switching).

The Sinusoidal Pulse Width Modulation (SPWM) bipolar switching is most popular controller for the inverter. In bipolar switching type, the triangular waveform, Vtri is switching frequency, fs which establishes the frequency that the inverter switches are switched (fs is also called the carrier or switching frequency). The control signal, Vcon is used to modulate the switch duty ratio with frequency, fr which is the desired fundamental frequency of the inverter voltage output (fr is also called the modulating frequency), recognizing that the inverter output will not be a perfect sine wave because containing voltage components at harmonic frequencies of fr [7] and these signals show in Figure 6 below. The amplitude modulation ratio, m_a is defined as :

$$m_a = \frac{\hat{V}_{control}}{\hat{V}_{tri}} \quad (1)$$

Where $\hat{V}_{control}$ is the peak amplitude of the control signal. The amplitude $\hat{V}_{tri}$ of the triangular signal is generally kept constant. The frequency modulation ratio mf is

$$mf = \frac{f_s}{f_r} \quad (2)$$

The Root-Means-Square (RMS) value output voltage of the fundamental frequency component, Vor is

$$V_{or} = 0.707 m_a V_{dc} \quad (3)$$

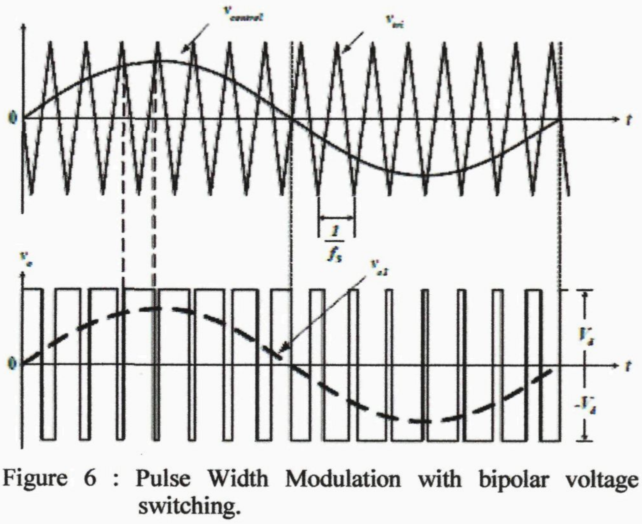

Figure 6 : Pulse Width Modulation with bipolar voltage switching.

For the harmonics, it appeared as sideband, centered around the switching frequency and its multiples in the inverter output voltage waveform [7]. Its multiples that's mean around harmonics mf, 2mf, 3mf and so on. This general pattern holds true for all values of m_a in the range 0-1.

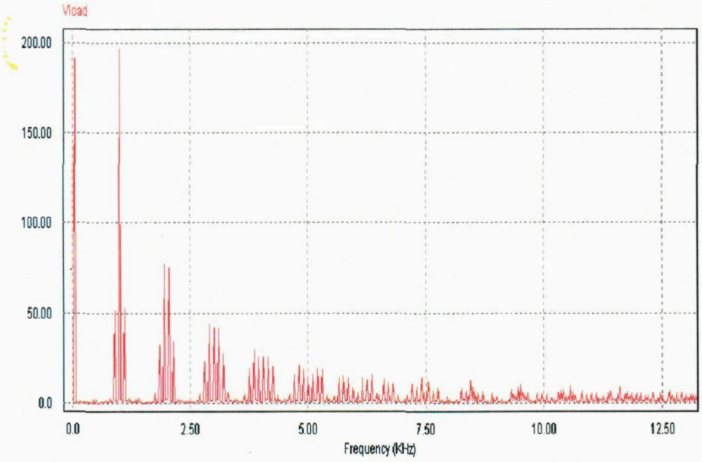

Figure 7 : Harmonics of Sinusoidal Pulse Width Modulation with bipolar voltage switching (single-phase).

The Sinusoidal Pulse Width Modulation (SPWM) with bipolar voltage switching have harmonic contents as shown as in Figure 7. This is the harmonics pollution and it will be attenuated by the filter.

IV. SIMULATION RESULTS

A. *MATLAB SIMULINK SIMULATION*

The simulation had been conducted to get the reference data. The data from the hardware of project inverter had been compared with the reference data.

The simulation had been conducted by using MATLAB SIMULINK. The schematic circuit as shown as in Figure 8 has been designed on simulink designer. Then the system has been run to get the reference data for hardware experiment.

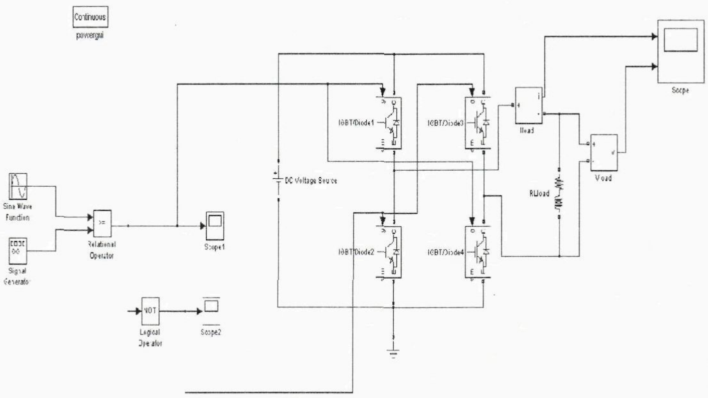

Figure 8 : The schematic circuit for the inverter.

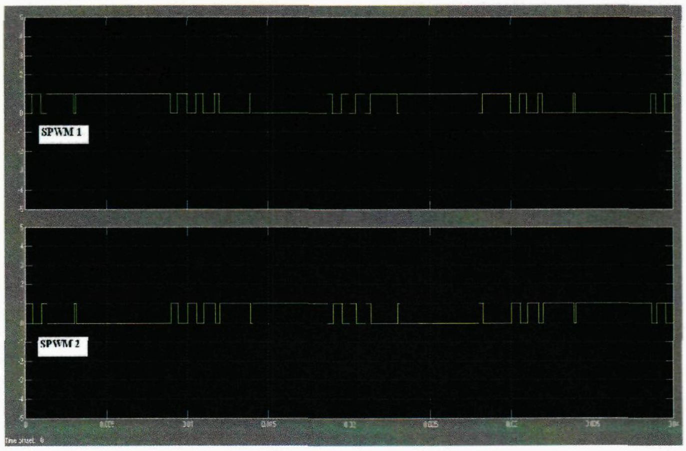

Figure 9 : SPWM signal for switching in MATLAB SIMULINK.

Figure 9 shows the switching signals from scope waveform for switching the IGBTs. The SPWM 1 signal is for switching power switches S1 and S4 or IGBT/Diode1 and IGBT/Diode4 because it's at the same leg and the signal should be the same. On the other hand, the SPWM 2 signal is for switching power switches S2 and S3 or IGBT/Diode2 and IGBT/Diode3. Besides that, the SPWM 1 signal is opposite with the SPWM 2 signal.

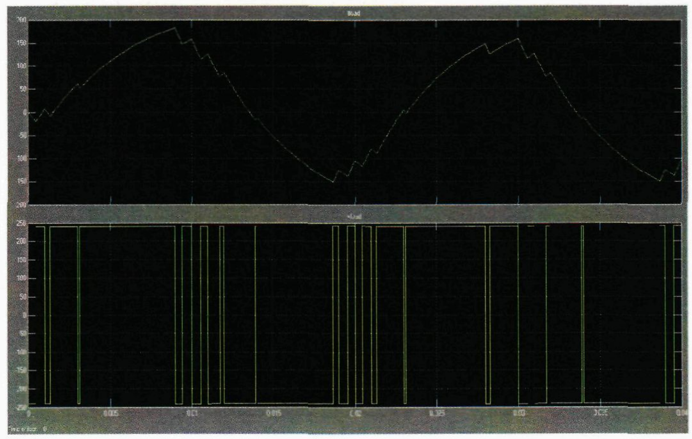

Figure 10 : Output waveform for the current and the voltage of the inverter from simulation.

The Figure 10 above, show the output waveform for the current and the voltage of the inverter from the MATLAB Simulink. Where the output voltage should be Vmax = +Vdc (+240V) and Vmin = -Vdc (-240V) while output current exactly 150mA. So from the result above the simulation results have met the theoretical.

B. *PSIM SIMULATION*

The simulation also had been conducted by using PSIM Simulation. The designing circuit for the inverter as shown as in Figure 11.

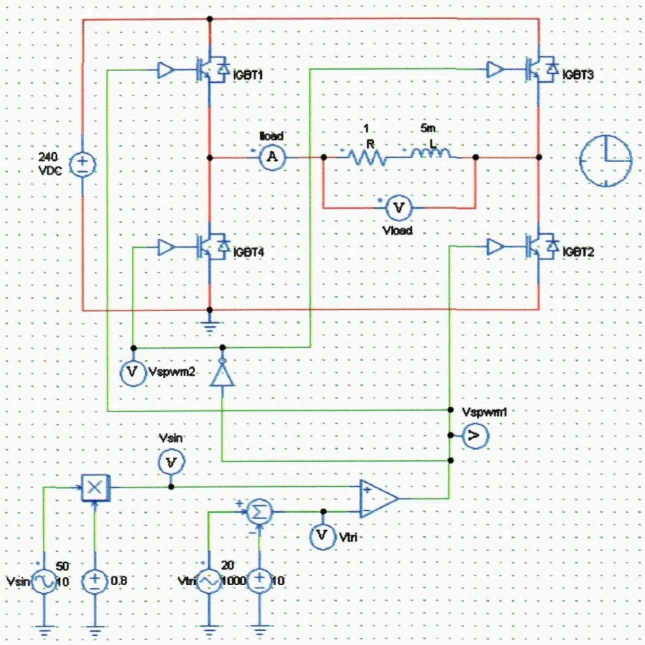

Figure 11 : The schematic circuit for the inverter.

The switching signals from scope waveform for switching the IGBTs are SPWM1 and SPWM2, as shown as in Figure 12. Its same the switching signals with MATLAB SIMULINK where the SPWM 1 signal is opposite with the SPWM 2 signal.

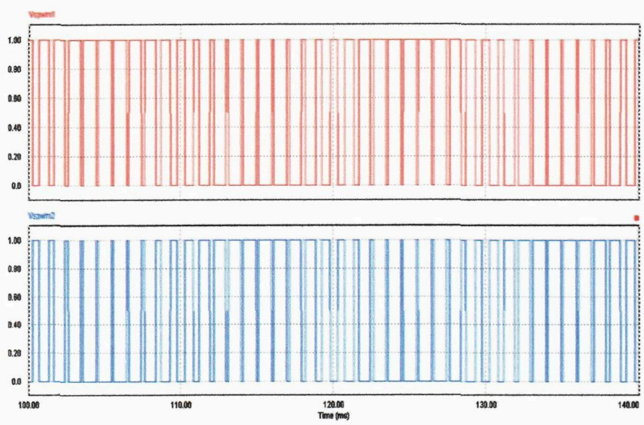

Figure 12 : SPWM signal for switching in PSIM Simulation.

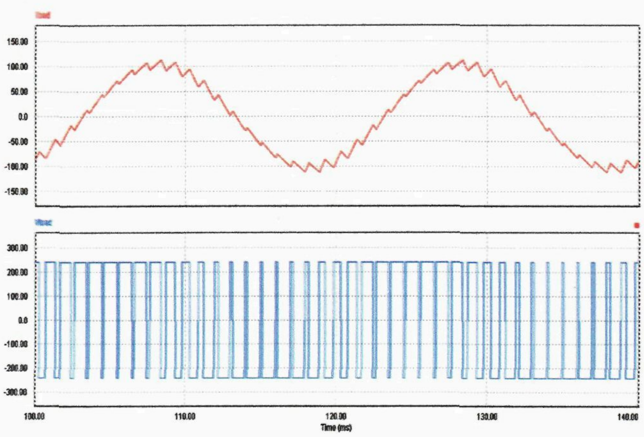

Figure 13 : Output waveform for the current and the voltage of the inverter from simulation.

The figure 4.4 above, show the output waveform for the current and the voltage of the inverter from the PSIM Simulation. Compared with reference data from MATLAB Simulink can be seen that the reference data from the PSIM Simulation is similar to data from the V_{max} and V_{min} MATLAB Simulink, respectively, +240V and -240V, but a different amount of current is obtained which is 120mA. So from the result above the simulation results have still met the theoretical.

V. HARDWARE RESULT

The experiment had been done on hardware to get the result and compare it with the reference result or simulation result. Figure 14 shows the connection all part of hardware inverter where combined together to get final output result. For this project 266.57Vdc voltage input is taken from the boost converter output where voltage source inverter with fixed DC link will be operate with DC voltage held constant. The value of voltage input can be calculated by followed the equation below:

$$\frac{4V_{rms}}{\pi} = \sqrt{2}\,(V_{peak}) \tag{4}$$

Table 1 shows the data specification for the system where fulfilled this project inverter.

Table 1 : Data specification of the system

Parameter / Component		Value
Input Voltage	Vdc	266.57V
Output Voltage	Vout	240Vpeak
Modulation Frequency	*f*m	50Hz
Switching Frequency	*f*s	10kHz

Figure 15 shows the SPWM waveforms generating pulses from PIC16F877A microcontroller. SPWM1 and SPWM4 are output from port B2 to conduct the power switches of IGBT 1 and IGBT 4 while SPWM2 and SPWM4 are output from port B1 to conduct the power switches of IGBT 2 and IGBT 3. The SPWM waveforms were generated having the distortion. It can see the waveforms in Figure 15. It occur due to some factor such as the human error and the equipment fault.

The human error was occurred when calculated the pulse width modulation (PWM) by using Asymmetric and Symmetric Regular Sampling. The calculation to get SPWM waveforms were included Modulation Index, M_I, Modulation Ratio, M_R, switching frequency, f_s and so on while the equipment faults were occurred when the calibration the equipment was succeed but still have distortion at the waveform.

For Figure 16 shows the output signal from driver circuit. The output signal from driver circuit is same with output signal from controller circuit but with difference voltage level because the driver circuit had amplify the signal from controller circuit to enough voltage level for switching the IGBTs. In this figure shows one waveform SPWM from pin IC B0 that ON and OFF switching at certain time. The voltage level had amplified from 5V to 15V because to turn on the switches need voltage level between 10V to 20V.

For Figure 17 shows the waveform of the output voltage of the inverter. The input V_{dc} = 266.57V, so the output value should be Vmax = + 240Vac and Vmin = - 240Vac. The result has only shown the pulsing signal not alternating signal. The voltage output from the IGBTs are 0V because of IGBTs can't on or having error connection circuit between the driver circuit and IGBTs. The waveform was also had distortion where four IGBTs were used had problem with the switching scheme. When the delay time for switching the IGBTs not exactly correct, the switching ON and OFF the IGBTs were disturbed and may cause short circuit.

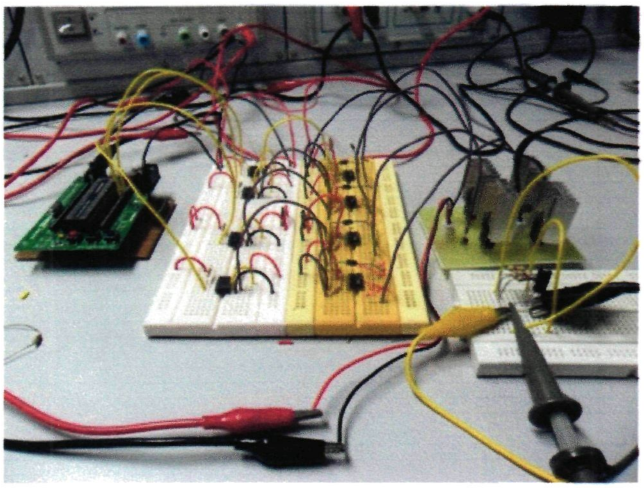

Figure 14 : The connection between the controller circuit, driver circuit and power circuit.

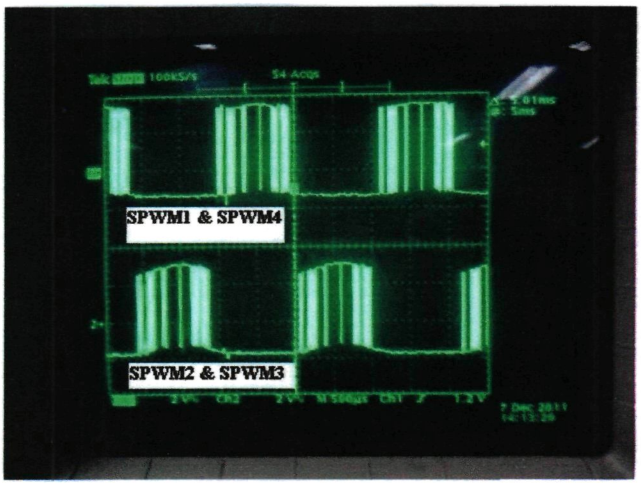

Figure 15 : Experimental output waveform of SPWM.

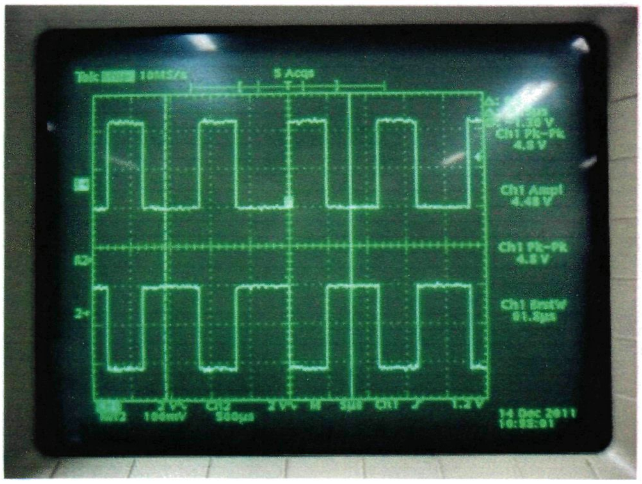

Figure 16 : Experimental output waveform of driver circuit.

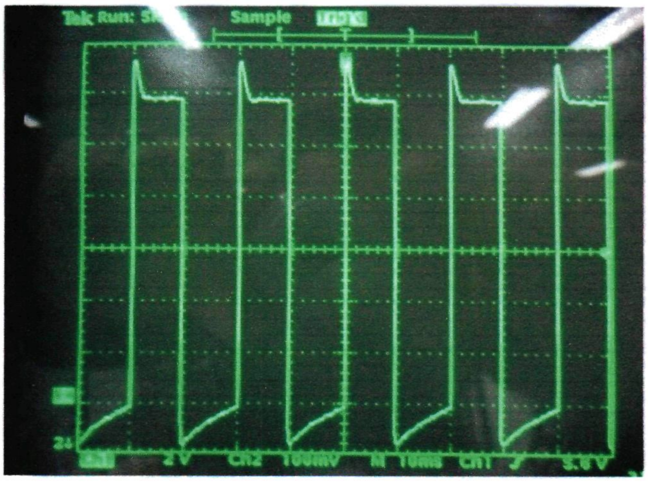

Figure 17 : Experimental output voltage waveform of the inverter.

VI. CONCLUSIONS AND RECOMMENDATION

In this project, both simulation and hardware implementation have been carried out. The software was working perfectly but only certain part of the hardware work properly. In order to achieve a much better performance, the filter will used to reduce the harmonics in the waveform. For the driver circuit, the connection between the power circuit and the control circuit must be proper to prevent any short circuit. In the other hand, the Single-Phase Bridge DC-AC Inverter can be designed and applied to obtain the output with a Sinusoidal Pulse Width Modulation (SPWM) technique.

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