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Development of Microcontroller-Based Inverter Control Circuit for Residential Wind Generator Application

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Abstract

The current usage level of wind power as alternative source of energy in Malaysia is very low. Ironically, some areas particularly coastal area has steady wind energy supply that is potential to generate electricity for residential use. There is urgent need to locally develop the low cost wind turbine generator that has the capability to not only supply electricity to respective household but can be connected to power grid so that excess power could be sold back to the local utility company. Recent developments of power electronic converters allow stable supply needed for grid transfer in respect to nature of wind dynamics, enhanced power extraction and low total harmonic distortion (THD). In this project, an inverter circuit with suitable control scheme design is developed to be used with a 500W permanent magnet type wind generator which is typical for residential use. Expected circuit output is single phase 240V sine wave voltage which is nominal grid voltage with the total harmonics distortion (THD) of voltage across load should not exceed 5% as recommended by IEEE Standard 519-1992. The simulation and experimental results are included in the paper.

Keywords: Micro-controller; Inverter; Boost Converter; SPWM; THD.

1 INTRODUCTION

Residential type wind generator normally is referred to small wind turbines of with capacity less than 3kW. They are normally installed at house lawn or some were even small enough to be mounted on the rooftops. They were also implemented by the consumer mainly as standalone system in remote areas not accessible to electricity grid but has high wind or part of hybrid system with photovoltaic to reduce the dependency on the electricity consumption bought from utility companies [1,2]. Due to generally low electricity consumption for residential use per household, a variable speed operation of residential type wind turbines can be implemented at areas where minimum speed of wind available between 3m/s to 7m/s. Within these speeds, voltage generated at a particular 500W wind generator permanent magnet type is around 18V to 30V [3]. One particular example of savings by consumer when using WECS: If a small wind energy system of 500W can operate for 8 hours minimum, the particular household can save about 40% from the usual electricity bills. Lately, there is an increasing trend to enable the WECS to supply excess generated energy back to the electricity grid. The public demand for this capability is high on residential type market segment particularly after introduction of net-metering policy in some countries like United States and Canada, where consumers were allowed to sold back to the utility companies to offset their consumption [1,2]. After all, promoting this policy could prove beneficial to both utility company and consumers as advantages of connecting a large number of these 'stations' to the grid are: 1. reduction of manufacturing cost to utility power stations; 2. increased reliability of the supply system and 3. reducing the consumer's bill [2].

For grid-connection feature, the quality of power generated by WECS has to meet some criteria. Energy generated must be synchronized with voltage at the grid first before being phase shifted to make possible the power transfer to the grid. For smooth synchronization process between energy generated and energy at the grid, 3 conditions must be met: 1) Voltage of generator must be equal to grid voltage, 2) Frequency of both voltages must be the same, and 3) Phase shift between the two sources must be zero [2]. Considering Malaysian grid voltage specification: The voltage of the supplied power must be maintained consistently 240V with +5% and -10% tolerance, sinusoidal AC type with frequency of 50Hz [4]. The total harmonic distortion (THD) of the voltage must be kept at minimum and according to recommended limit by IEEE Standard 519-1992: has to be kept at less than 5% [5].

Inverter is actually one type of switched-mode power supply (SMPS) that transforms voltage from direct current (DC) to alternating current (AC). Normally it is used together with boost DC-DC converter and rectifier circuit in power converter topology to increase the low AC voltage generated at wind generator terminal to nominal AC load and grid voltage. This topology has been used in WECS particularly for permanent magnet type wind generator [6]. Conventional method to increase the AC voltage was to use step-up transformer. As a SMPS variation, it has advantage over the transformer for higher conversion efficiency of up to 95% compared to 40% for transformer and wider variation of input for fixed output [7]. This has made it more suitable choice for a WECS that strive to achieve fixed output voltage from variable input voltage due to variable wind speed.

Advances in microcontroller technology have made it possible to perform functions that were previously done by analog electronic components. With multitasking capability, microcontrollers today are able to perform functions like comparator, analog to digital conversion (ADC), setting input/output (I/O), counters/timer, among others replacing dedicated analog components for each specified tasks, greatly reducing number of component in circuit and thus, lowering component production cost. Flexibility in the design has also been introduced by using microcontroller through capability of flash programming/reprogramming of tasks [8]. Microcontrollers has been used in WECS particularly grid connected to perform various functions and task from instrumentation for sensing voltage, current and frequency of power delivered to grid to optimizing output power to sensing adequate wind speed for turning ON/OFF the system [1,9].

Due to varying nature of wind, the designed system must be able to operate under various wind speed condition while maintaining optimum power supply, maintaining constant voltage and frequency. The inverter should be able to work with 500W Wind Turbine and supply 240V single phase AC for domestic use and also suitable to be transferred to grid. The measured total harmonic distortion (THD) also must be less than 5%.

2 THEORETICAL CONSIDERATION

2.1 Wind Power Consideration

Total rotational power captured by wind energy system is given by formula [6,9,10]:

$$P_t = \frac{1}{2}\rho A C_p v_W^3 A \quad (1)$$

Where ρ is Air density (kg.m^{-3}), v_w is Wind speed (m/s), C_p is Coefficient of performance, and A is Rotor rotational area (m^2).

Tip Speed to wind Ratio (TSR), is important parameter that has relation with coefficient of performance, C_p as indicated by graph in Figure 1 [6,9,10] below:

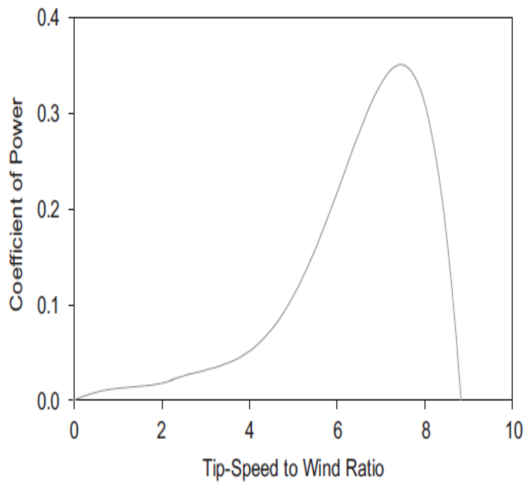


Figure 1: Relationship of TSR and C_p

TSR is calculated by formula below [6,9,10]:

$$TSR = \frac{\omega r}{v_W} \quad (2)$$

Where v_w is Wind speed (m/s), ω is Turbine rotational speed, (rad/sec), r is Turbine rotor radius (m).

2.2 Principle of Boost (Step-up)DC-DC Converter

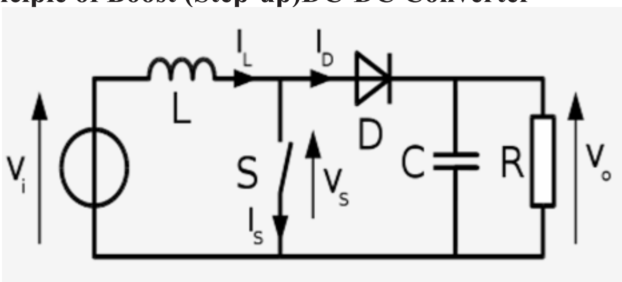


Figure 2: Boost converter schematic

Figure 2 [7] above is the basic schematic circuit of boost DC-DC converter. The basic principle of step-up (boost) DC-DC converter is as follows. When switch SW is closed for the time t_1, inductor current rises and energy is stored in inductor L. If switch is opened for time t_2, energy stored in the inductor is transferred to load through diode D_1 and the inductor current falls. For a continuous current flow, waveform for the inductor current is as in figure. If large capacitor C is connected across the load, output voltage is continuous and becomes average value. Voltage across the load can be stepped up by varying duty cycle and the minimum output voltage is V_i when k = 0 [6].

The average output voltage is [7]

$$V_o = V_i + L\frac{\Delta I}{t_2} = V_i(1+\frac{t_1}{t_2}) = V_i\frac{1}{1-k} \quad (3)$$

For a resistive load, ripple current is given by [7]

$$\Delta I = \frac{V_i}{L}kT \quad 4)$$

2.3 Principle of Inverter Circuit

Inverter circuit is used to convert a DC voltage to a sinusoidal AC voltage. A single phase inverter may be consist of H-Bridge circuit as shown in Figure 3 [2,7], and also accompanying trigger control signal generation circuit. In standard H-Bridge circuit in the Figure 4 switches A1, A2, B1 and B2 are arranged in this configuration. Input to the circuit V_{CC} is DC voltage. In voltage source inverter (VSI), switches are represented by MOSFET transistors and are voltage activated by trigger signal. Switches A1 and A2 are switched simultaneously at one half of a cycle while the switches B1 and B2 are simultaneously switched at the other half. Output of the circuit is positive and negative pulse voltage measured across the load. The load voltage varies accordingly and is in the range of +VCC and –VCC.

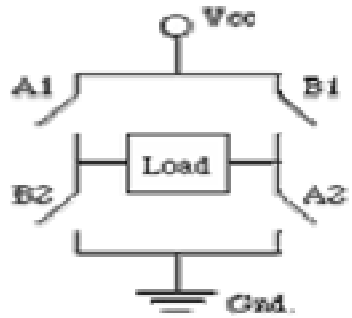


Figure 3: Standard H-Bridge circuit

Normally high frequency pulse type signals are the trigger signal for the switch gates at the H-Bridge circuit. For a sine wave VSI, sinusoidal pulse width modulation (SPWM) is an excellent choice as trigger signal that has produced sine wave output with low THD. One method to generate SPWM trigger signal is through bipolar mode switching technique as shown in Figure 4 [2,7]. In this method, a reference sine signal V_{cont} with a frequency similar to inverter output signal's frequency is compared with triangular carrier signal V_{tri} with high frequency f_s . An inverter control circuit must be included in the design to control the switching of the H-bridge gates. Usually a microcontroller is used to perform the tasks.

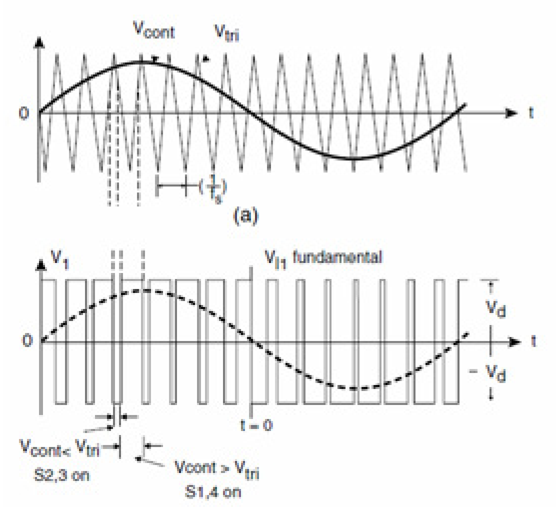


Figure 4: SPWM trigger signal generation method through bipolar switching. (a) Reference sine signal is compared with carrier sawtooth signal (b) Generated SPWM trigger signal

3 METHODOLOGY

Figure 5 below describes the block diagram of the proposed system. The scope of this project is to design DC-AC inverter circuit and simulate performance of the inverter circuit to obtain desired voltage output of 240V, 50Hz where the scope of system design consists of:

a. Design of bridge rectifier at generator output.
b. Design of suitable boost DC-DC converter to step up from low wind voltage.
c. Design of H-bridge circuit to output AC from DC.
d. Design of microcontroller circuit and programming software to control duty cycle of H-bridge circuit.
e. To test the inverter circuit in lab-scale with Wind Generator to get experimental performance data.

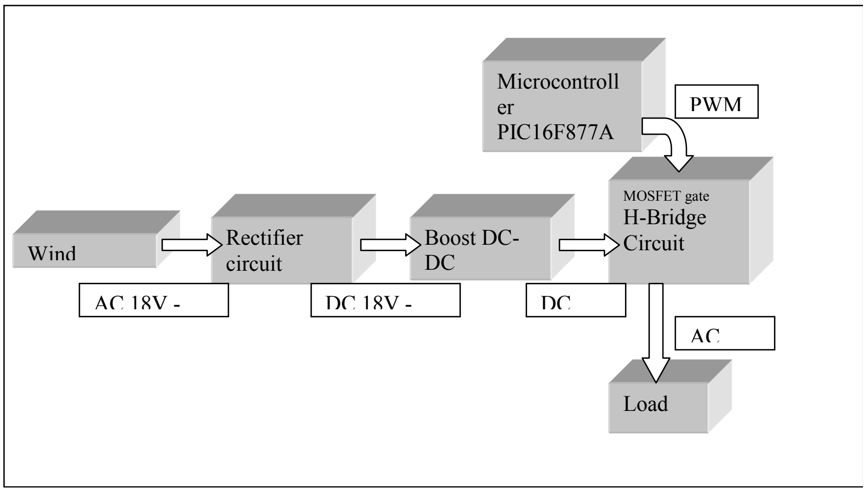


Figure 5: Block diagram of proposed system

3.1 Bridge Rectifier Circuit Design

The voltage generated at terminal by wind generator will be AC waveform type of magnitude 10V to 30V depending on the wind speed as evidence in Figure 9 shows the wind generator manufacturer performance datasheet on voltage generated at various wind speed. A bridge rectifier circuit is connected at wind generator terminal to convert the waveform to DC. Figure 6 below shows the bridge rectifier circuit design.

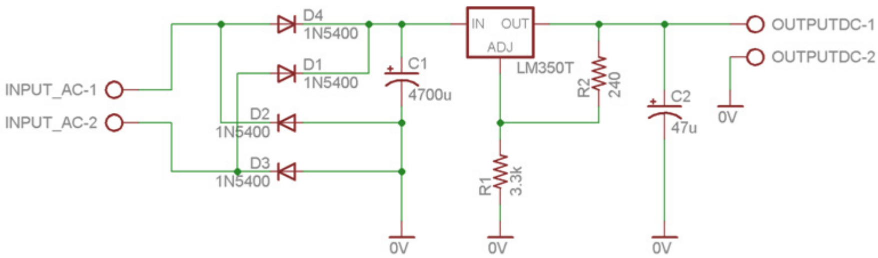


Figure 6: Bridge rectifier circuit

3.2 Boost DC-DC Converter Design

The DC output voltage from the rectifier circuit is in relatively small amplitude compared to standard nominal single phase voltage rating for use with domestic household products or to be transferred at grid. The dynamic nature of wind speed will cause small variations of voltage generated under normal operating condition. The boosts DC-DC converter circuit will step-up the unregulated DC voltage to 240V DC regulated. In this design the output of the converter is feedback and compared to set value equivalent to 240V. Then the carrier signal will be compared with the error signal to generate PWM signal. The duty cycle of PWM signal, k is determined by error gap between circuit output and set point. Output voltage is stabilized and regulated by minimizing ripple output voltage and current. Figure 7 below shows the design of Boost DC-DC converter in SIMULINK.

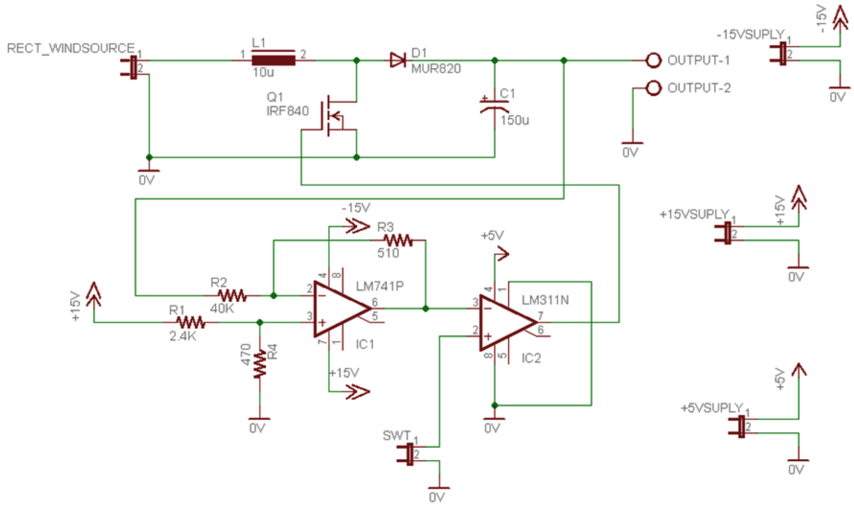


Figure 7: Design of Boost DC-DC converter in SIMULINK

3.3 Design of Inverter Control Circuit

Figure 8 below shows the proposed inverter control circuit comprising the H-bridge circuit and the control circuitry.

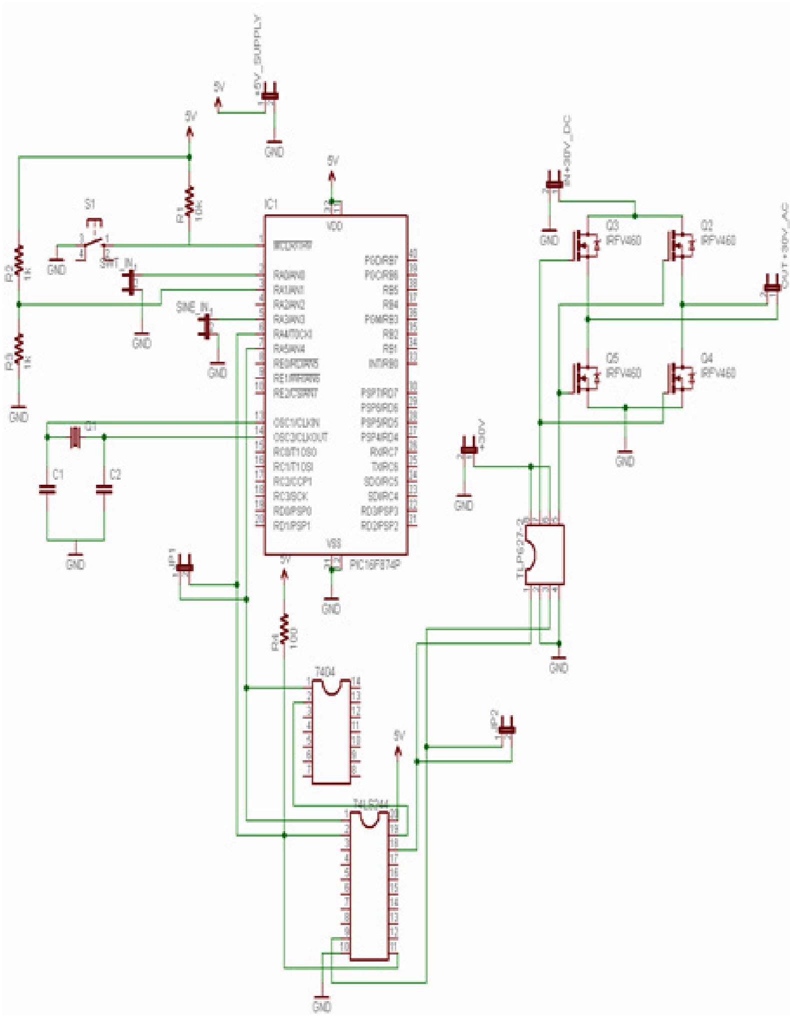


Figure 8: Inverter Control Circuit

The type of inverter implemented in the system is voltage-source-inverter (VSI) and the control technique implemented in the system is Sinusoidal pulse-width modulation (SPWM)[7]. Using this technique, the microcontroller PIC 16F877A is used to generate the required PWM train of pulses to drive and switch on the H-bridge MOSFET transistors.

The PIC generates a reference sine wave based from lookup table with frequency of 50Hz. The signal is then compared with the sawtooth wave of 2kHz as a carrier frequency using the internal comparator of the PIC. The output of the comparator will represent the desired PWM. A pulse signal which the frequency was synchronized with sine was generated by the PIC as control pulse. The pulse will be distributed to two channels where one of it is inverted. The PWM pulse train and control pulses signal were then fed into Tri state buffers SN74244 Data Transceiver. The output is two channels of PWM train pulse switching ON and OFF at 180 degree out of phase. The two signals are then connected to necessary conditioning elements to be able to switch ON the MOSFET transistors at the H-bridge. Now the generated PWM will switch two diagonal MOSFET transistors of the H-bridge simultaneously at one of the two halves and the other two diagonal transistors at the other half. The output of H-bridge is connected the load through LC filtering to achieve desired AC sinusoidal waveform.

3.4 Experiemental Rig and Hardware Setup

In the lab-scale experimental rig, a 300W geared DC motor will be coupled with wind generator through an inertia disk to simulate wind speed and wind blade rotor. Bridge rectifier is connected after wind generator to feed DC voltage to the inverter control circuit as the output is AC. The output of inverter will be connected to either dump load or grid. The DC motor will be programmed to run at various speed to simulate variability of wind speed while necessary performance parameter will be evaluated. Figure 8 shows the proposed lab-scale experimental rig. Figure 10 (a) and (b) show the experimental rig for wind generator simulator and turbine rotational speed and generator terminal output measurement. Figure 11 shows 500W wind generator manufacturer performance datasheet. Figure 12 shows the 500W voltage generated at terminal of wind generator simulator rotated at different speed.

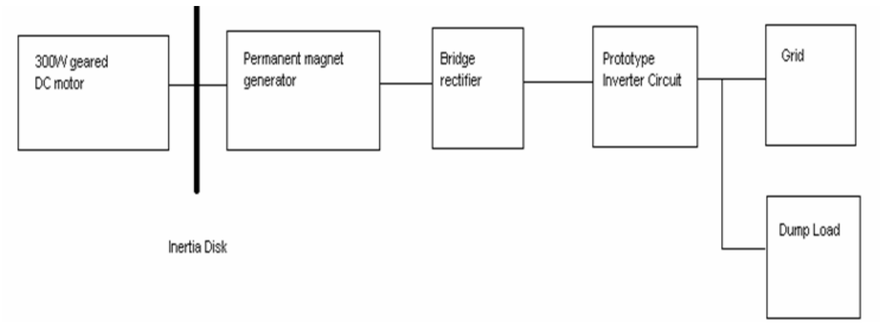
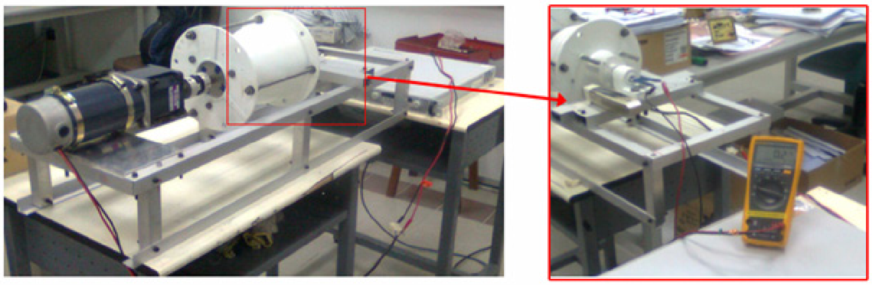
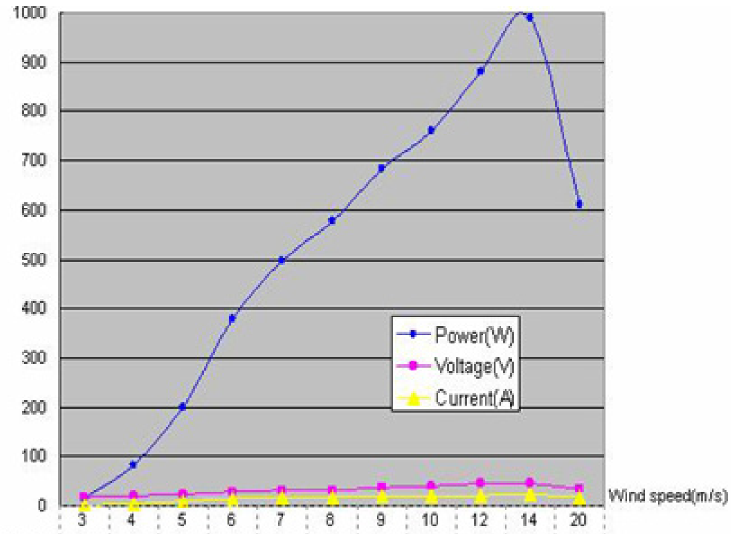


Figure 9: Proposed Lab-scale experimental rig



(a) (b)

Figure 10: (a) Experimental rig for wind generator simulator; (b) Turbine rotational speed and generator terminal output measurement



	3	4	5	6	7	8	9	10	12	14	20
Power(W)	14.4	80	198	378	495	576	684	760	880	989	612
Voltage(V)	18	20	22	28	30	32	36	40	44	46	34
Current(A)	0.8	4	9	13.5	16.5	18	19	19	20	21.5	18

Figure 11: 500W Wind Generator Manufacturer Performance Datasheet

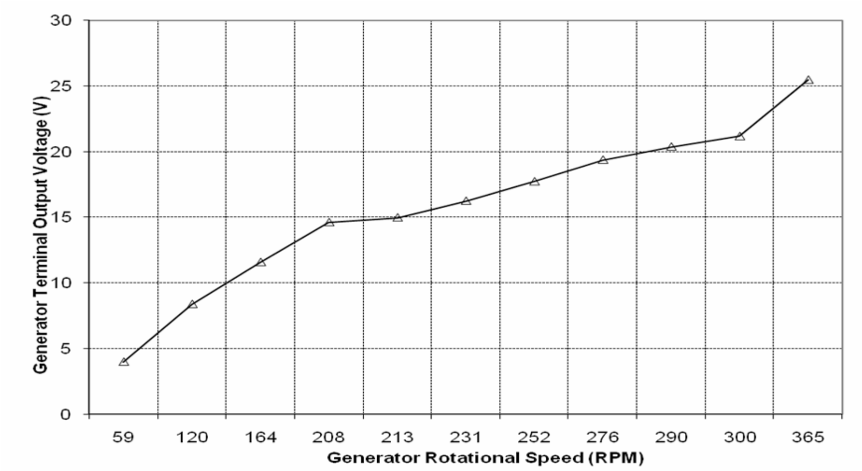


Figure 12: 500W Voltage generated at terminal of wind generator simulator rotated at different speed.

4 RESULTS AND DISCUSSION

4.1 Simulation Results

The rectifier circuit and DC/DC boost converter were simulated using MATLAB SIMULINK software and tested at different input voltage from 18V to 26V to simulate different wind speed condition. As shown in figure 13, rectifier circuit convert the AC voltage generated at the wind generator terminal to continuous DC voltage. There is however dropping of 2V at this stage.

Figure 14 shows the output voltage of the boost DC-DC converter. From the graph, minimum input voltage that can be step up to minimal luminal voltage at grid is 18V.

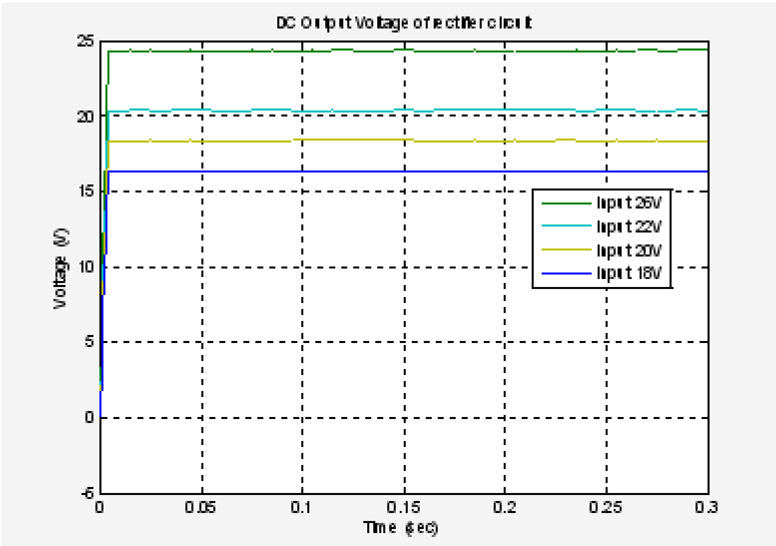


Figure 13: Simulated output of rectifier circuit.

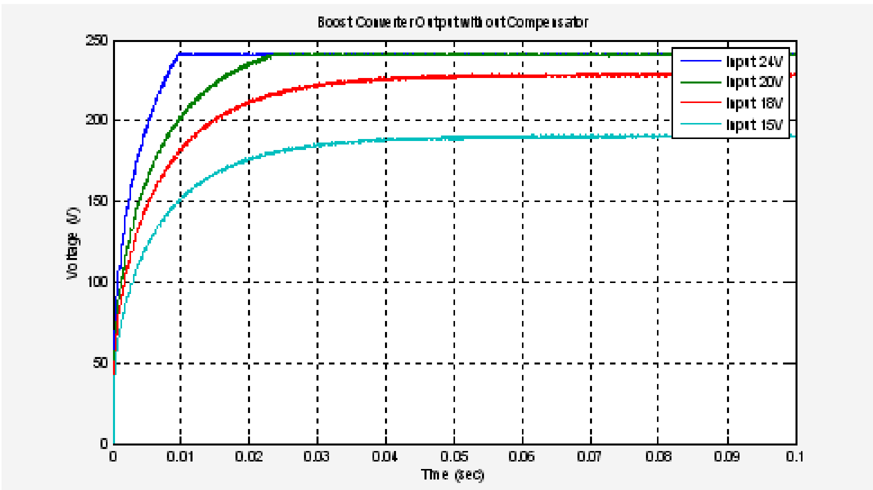


Figure 14: Simulated output of Boost DC-DC Converter

Figure 15 shows the simulation of the design model of inverter system. The simulation was also done using software MATLAB SIMULINK. For this simulation, the input voltage was 240V DC. The purpose of the simulation was to test where there the developed design of the system could obtain sinusoidal AC voltage of 240V with frequency of 50Hz and voltage THD within 5%. Figure 16 to 18 shows the various stages of generation of trigger SPWM signal in two channels.

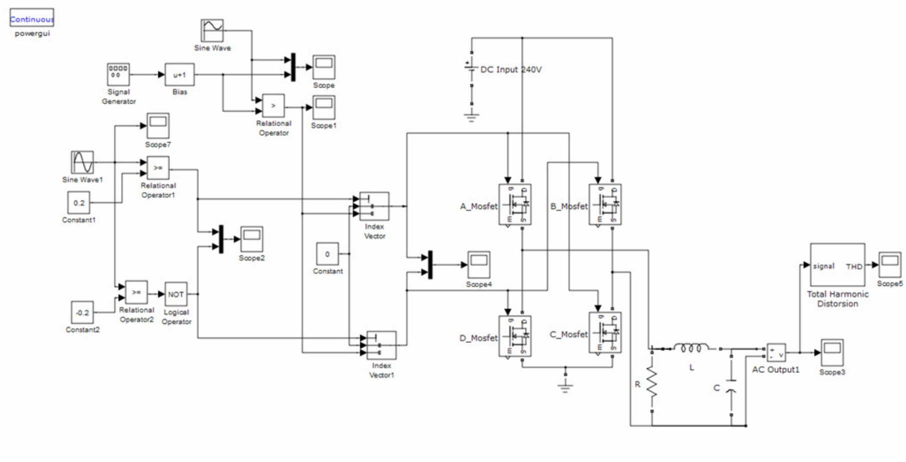


Figure 15: Simulation of designed inverter control circuit in SIMULINK

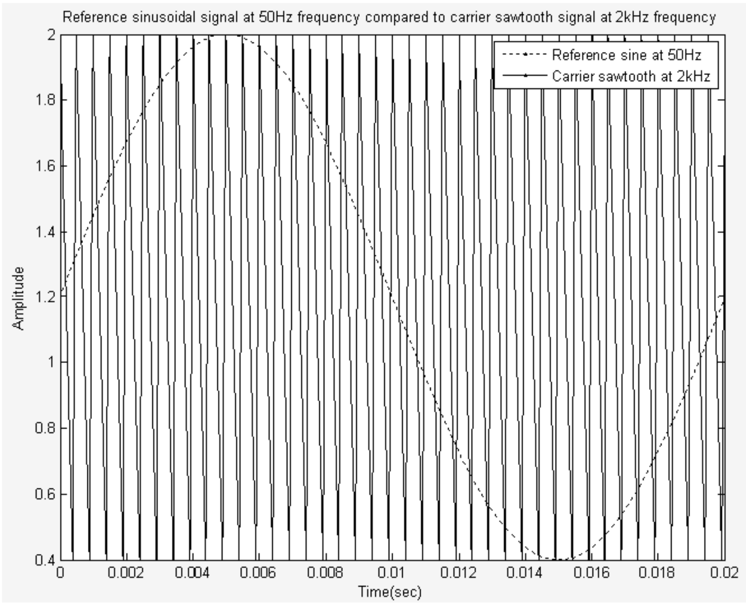


Figure 16: Simulated comparison of reference sine with carrier sawtooth signal using bipolar SPWM method in SIMULINK

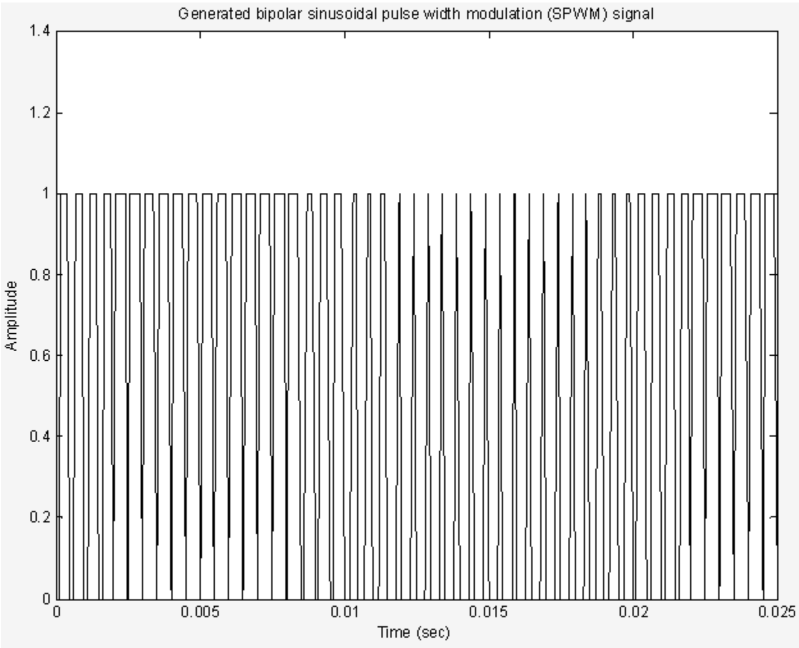


Figure 17: Simulated generated SPWM trigger signal using bipolar switching method in SIMULINK

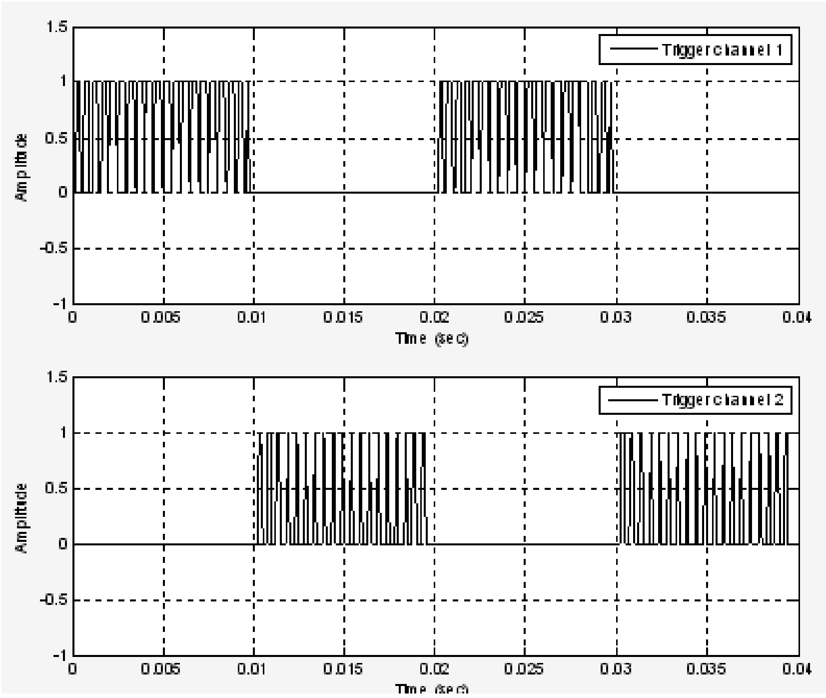


Figure 18: Simulated SPWM trigger signal in two channels in SIMULINK

Figure 19 to 20 shows the voltage output of the inverter system. Figure 19 shows the output of the inverter system after low pass LC filtering. In this design component parameter was selected as follows; L= 20mH, C= 320uF and recessive load, R= 50ohm.

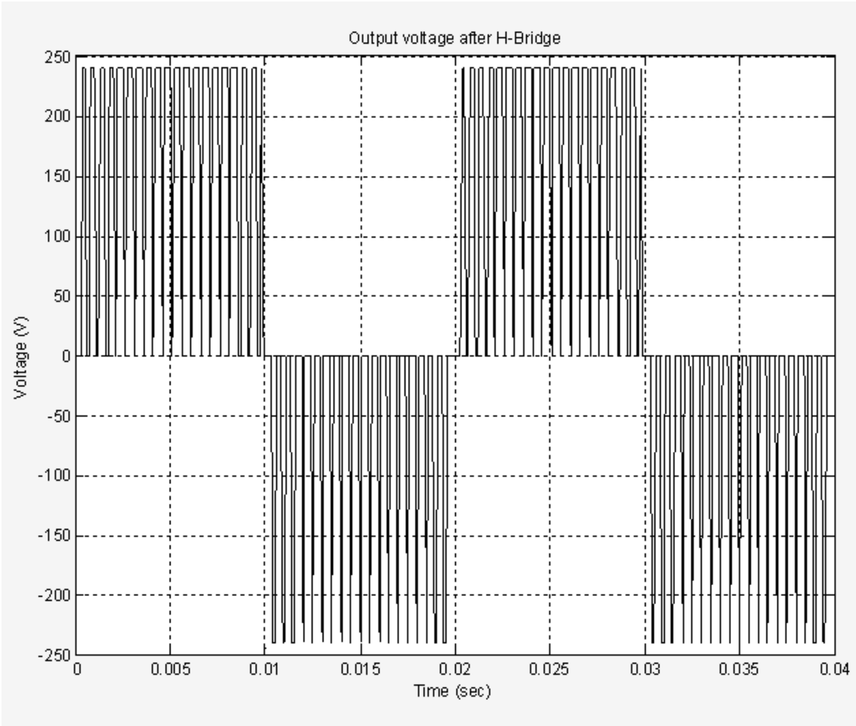


Figure 19: Simulated output voltage of H-bridge ci

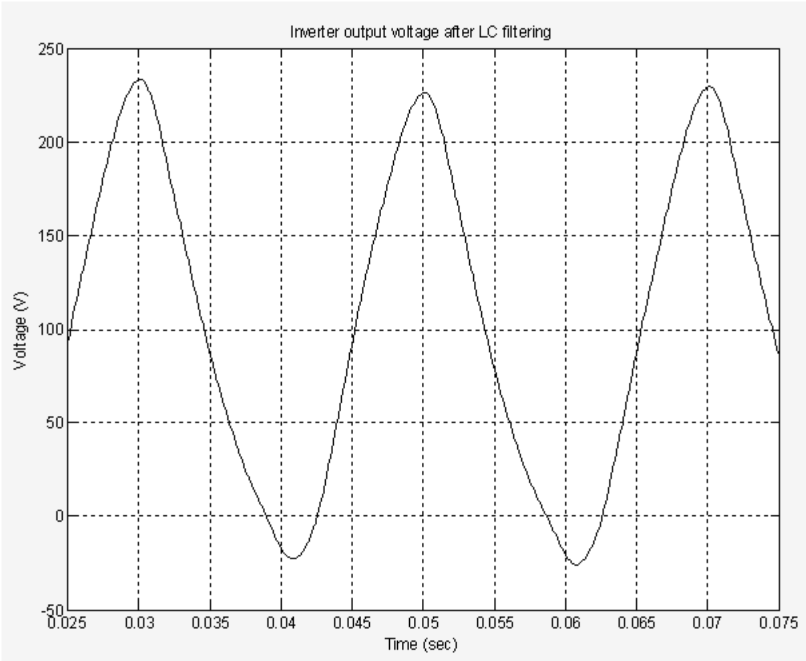


Figure 20: Simulated output voltage of inverter circuit after LC filtering

4.2 Experimental Results

The prototype printed circuit board was developed as inverter system. Figure 21 to 22 show the generation of trigger SPWM signal in two channels through bipolar switching method. Microcontroller PIC 16F877A was used in inverter prototype board with most of the operation done through microcontroller/ programming. Figure 23 and 24 show the output of the inverter system through experimental prototype board. Input to the inverter system was from DC power supply. The system was yet to be tested with wind generator simulator rig. With the DC as power supply as input the inverter system was operational with the input up to 12V before stability problem occurs.

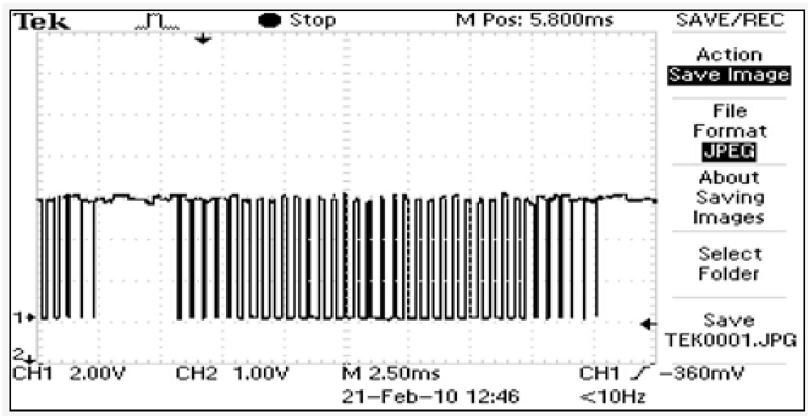


Figure 21: SPWM Trigger signal generated by microcontroller-based prototype board

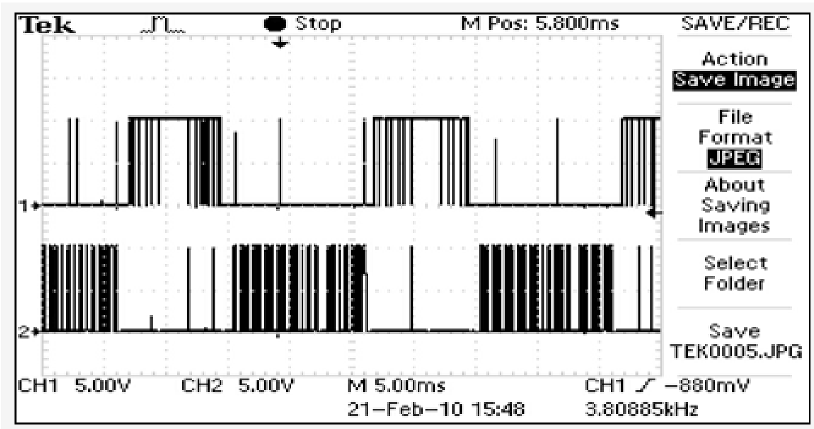


Figure 22: SPWM Trigger signals shown in two channels to the H-bridge gates

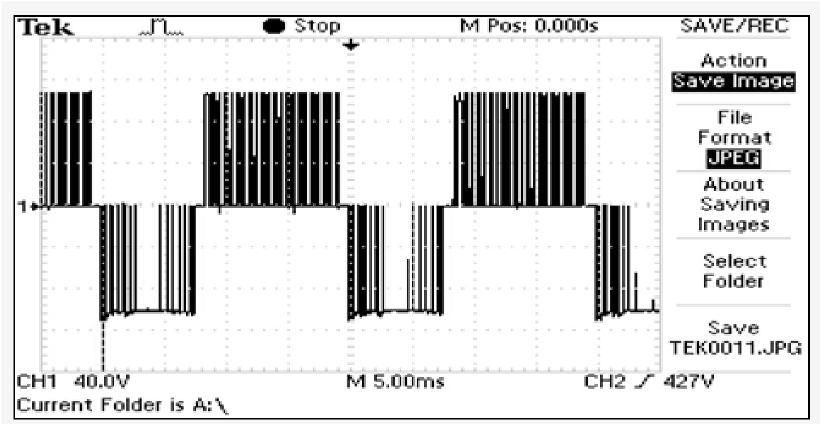


Figure 23: Voltage across resistive load at output of the prototype H-bridge circuit

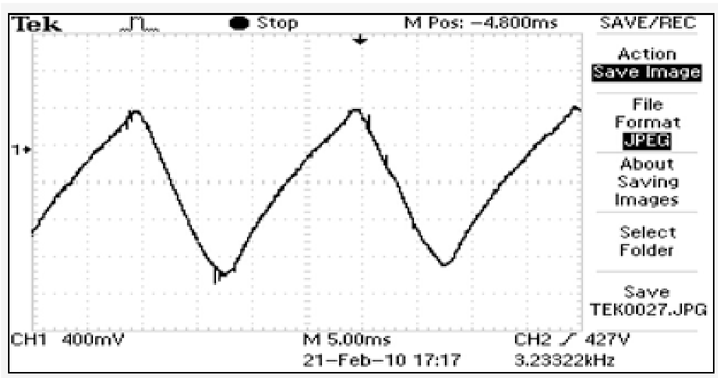


Figure 24: Voltage across resistive load after LC filtering at output of the prototype inverter circuit

5 CONCLUSION

Based on simulation results, research objective to develop inverter control circuit with proposed design has been successful to generate 240V AC voltage at 50Hz with THD of voltage less than 5%. Simulation was used as guide to design the proposed circuit system. Due to lack of adequate and steady wind speed at proposed site nearby university, wind generator simulator rig has been developed to test the performance of wind generator output on a resistive load. Voltage and current generated at the rig was used as guide to select rating for the components used in the prototype circuit board.

Based on experimental results, research objective to generate 240V AC waveform at 50Hz frequency has been partially achieved. Sinusoidal AC output voltage has been successfully generated. However the inverter prototype board could invert voltage up to 12V DC before stability problem occurs. Inclusion of soft-starter element across the MOSFET terminal at H-Bridge circuit was recommended in order to solve this problem.

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