Design and Fabrication of Voltage Source Inverter for Low Rated Wind Turbine

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Abstract

Low rating wind power generators have attracted the general public for distribution of power. Generally smaller rating wind turbines are fed to single phase inverters in which there is reduced power extraction. However there is need to develop three phase inverters for various applications such as irrigation systems, small scale industries, domestic applications and variable frequency drives. In view of this a three phase voltage source inverter is designed and fabricated for 1.5kW wind turbine installed at B. E.C Energy Park. SPWM and SVPWM techniques are employed for the proposed three phase inverter. The performance of both SPWM and SVPWM are compared in terms of power quality. The above results are validated by experimental setup.
Keywords: Arduino, AT89C52, SPWM, SVPMW, THD

I. Introduction

Generation of electricity through renewable energy sources has well recognized as economically competitive and environmental friendly for various day to day applications. The main resources for distributed generation system are wind turbine photo voltaic systems and fuel cells. In comparison with various renewable energy sources the applications which economical small – scale wind turbines are particularly advantageous in power generation at a house hold level.

In the rural and remote places, the small scale standalone wind turbines with a energy storage component such as battery bank is more essential for providing stable and reliable electricity. Hence there is increasing market for a grid connected small wind generating system for domestic applications and small business in rural areas. Hence there is increasing system for domestic applications and small business in rural areas. In this case excess energy from the wind generator is fed to the utility grid. A grid connected inverter structures extracts electrical energy even at low wind speed will assist in reducing capital costs as well as offer opportunities for interfacing small-scale wind turbines with the AC grid. [1]

Among then two techniques space vector pulse width modulation is more sophisticated techniques for generating fundamental sine ware which provides a higher voltage to the load and lower total harmonic distortion. A 3-phase inverter system with a 120/208 output allows loads with a wide operating range of input ac voltage to be fed 208VAC WHICH allows them to run more efficiently, typically 2-3% better then at 120V single phase AC. It provides a continuous power flow which improves efficiency. In the three phase system delivered power is constant, when voltage and current are sinusoidal and also less energy storage required than in single phase system. In view of this a three phase inverter is designed and fabricated.

This paper presents design and fabrication of 3-phase voltage source inverter for 1.5kW wind turbine installed at B.E.C Energy Park. SPWM and SVPWM techniques are employed for three – phase voltage source inverter. SPWM signals are generated by using AT89C52 microcontroller [6]. The SVPWM signals are generated by using ATmega controller through arduino software. ATmega is an 8-bit CPU and on the same clock it is 4 times faster than 8-bit PIC and 12 times faster than 8051. Power consumption is much lower compared to PIC.

FFT spectrum has analyzed to calculate total harmonic distortion for both SPWM and SVPWM methods. THD obtained for phase voltage is 20.4% for SPWM and 18.2% for SVPWM. The experimental results also show that SVPWM technique is able to generate good quality sine wave at low switching frequency as compared to SPWM methods.

II. Spwm based three phase inverter

In sinusoidal pulse width modulation technique three sine waves and a triangular carrier wave of high frequency are used to generate pulse width modulation (PWM) signals. The sinusoidal waves are displaced by 120 degree phase difference with each other which is called the reference signal. The frequency of these sine waves is chosen based on the required inverter output frequency that is 50/60Hz. The triangular carrier wave is a high frequency wave in terms of several KHz. By comparing sinusoidal signal with a triangular wave a high switching signal is generated. Whenever the reference wave is greater than carrier wave, the comparator gives out a pulse and this pulse is used to trigger the respective inverter switches. Sinusoidal pulse width modulation signal generation technique for three phase voltage source inverter is shown in Figure 1.

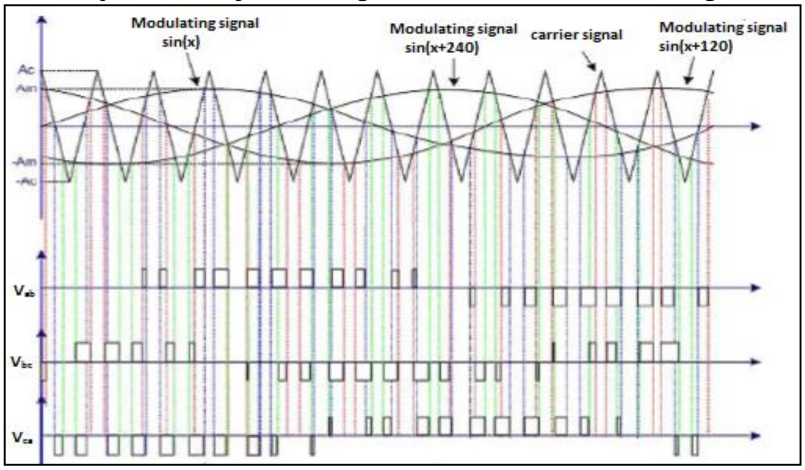

Fig. 1: Sinusoidal Pulse Width Modulation

AT89C52 microcontroller is used to implement SPWM in the three-phase inverter. Based on the input frequency the microcontroller computes the PWM pulse widths on carrier cycle basis.

The modulating signal is a sinusoidal at the inverter fundamental frequency. At the carrier frequency, the modulating signal is sampled at regular intervals. N_{max} is the number of samples in a fundamental period given by [11],

$$N_{max} = f_s / f \quad (1)$$

The three phase modulating signals are [6]

$$V_a = V_m \sin(\omega t) \quad (2)$$

$$V_b = V_m \sin(\omega t - 2\pi/3) \quad (3)$$

$$V_c = V_m \sin(\omega t - 4\pi/3) \quad (4)$$

The area of two levels PWM pulse should be equal to the shaded area under the modulating signal as illustrated in Fig.2 [6],

$$\frac{V_s}{2} \cdot t_{wa}(n) - \frac{V_s}{2} \cdot \{T_s - t_{wa}(n)\} = V_m \sin(n\omega t) \cdot T_s \quad (5)$$

Solving (5), the width of PWM pulse is given by,

$$t_{wa}(n) = \frac{T_s}{2}\left[1 + \frac{2V_m}{V_s}\sin(n\omega T_s)\right] \quad (6)$$

$$t_{wa}(n) = \frac{T_s}{2}\left[1 + M\sin(n\omega T_s)\right] \quad (7)$$

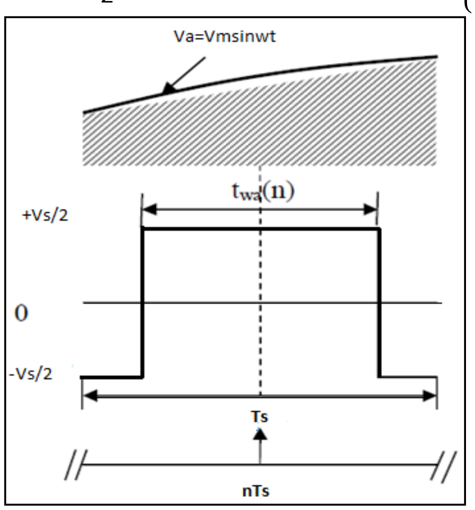

Fig. 2: Pulse width calculations for two level PWM

M=2Vm/Vs, is the index of modulation, the pulse width for phase A is given by equation (7)
The pulse widths for phases B and C are (8) & (9)

$$t_{wb}(n) = \frac{T_s}{2}\left[1 + M\sin\left(n\,\omega\,T_s - {2\pi}/{3}\right)\right] \quad (8)$$

$$t_{wc}(n) = \frac{T_s}{2}\left[1 + M\sin\left(n\,\omega\,T_s - {4\pi}/{3}\right)\right] \quad (9)$$

Adding (7), (8) and (9) results,

$$t_{wa}(n) + t_{wb}(n) + t_{wc}(n) = \frac{3T_s}{2} \quad (10)$$

From (10), the PWM pulse width for phase C can be obtained as,

$$t_{wc}(n) = \frac{3T_s}{2} - \{t_{wa}(n) + t_{wb}(n)\} \quad (11)$$

The structure of typical 3-phase voltage source inverter is shown in figure 3 which drives the star connected load. The performance of the proposed PWM scheme is studied with three phase voltage source inverter. Sa, Sb and Sc are the switching functions for phases A,B and C respectively. Each switching function has two level status either -1 or +1. Where, -1 drives the bottom transistor and +1 drives the top transistor of the inverter.

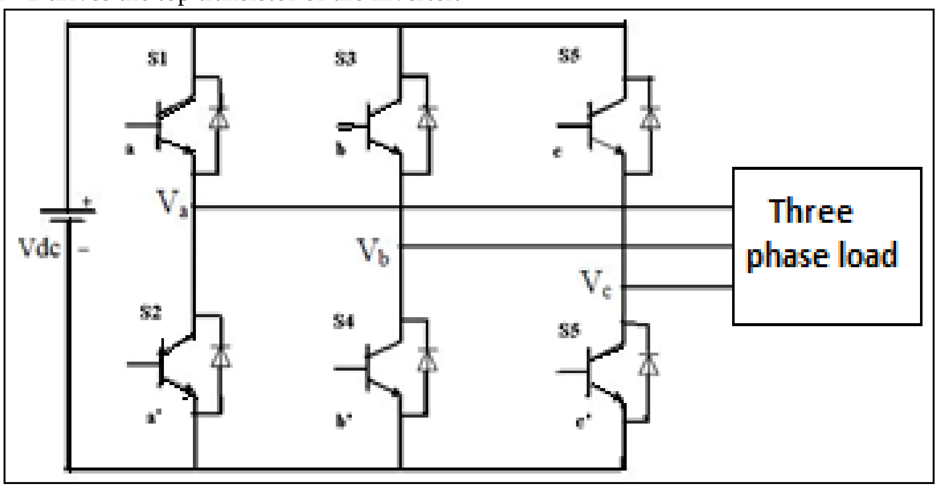

Fig. 3: Structure of typical 3-phase VSI

Supply voltage Vdc=24V, modulation index M=1 at f=50Hz, and carrier frequency f = 1.2 kHz.

III. SVPWM BASED THREE PHASE INVERTER

SVPWM technique refers to special switching actions of the six power transistors of a 3-phase voltage source inverter or power converter. The structure of a typical 3-phase voltage source inverter is shown in the Figure 3. The line to line voltage and the line to neutral voltage vectors can be obtained by the following matrices [4]. Where Vab,Vbc and Vca are the line values and Van, Vbn, and Vcn are phase voltages. a, b, c are the switching variable vectors and S1, S2 and S3 are the switches of the inverter [4].

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc}\begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}\begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (12)$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{V_{dc}}{3}\begin{bmatrix} 2 & -1 & 2 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad (13)$$

The space phasor can be defined by using two voltages Vα and Vβ which are determined by the following equations [4].

$$V_\alpha = \frac{3}{2}\cdot V_{an} \quad (14)$$

$$V_\beta = \frac{\sqrt{3}}{2}\cdot [V_{bn} - V_{cn}] \quad (15)$$

The space phasor voltages can be obtained from following equations.

$$v_s = v_\alpha + jv_\beta \quad (16)$$

$$\alpha = \tan^{-1}\left(\frac{V_\beta}{V_\alpha}\right) \quad (17)$$

It should be noted that at any instant of time there are only eight possible positions of the voltage space phasor. Hence inverter can be switched to create vectors V1, V2, V7 and V0 in some sequence.

The SVPWM treats the sinusoidal voltage as a constant amplitude vector revolving at fixed frequency. This SVPWM scheme approximates the reference voltage Vref by the eight switching pattern combination (V0 to V7). The vectors (V1 to V6) divides the plane into six sectors of 60 degree each and the reference vector is generated by two adjacent non-zero vectors and two zero vectors.

The ATmega328P is a 8-bit microcontroller with low power CMOS based on the advanced virtual Risc enhanced architecture. It provides 32K bytes of In-system programmable flash with read- while write capabilities, 1K bytes EEPROM, 2Kbytes SRAM, 23 general purpose I/O lines, 32 general purpose working registers, three flexible counters with compare modes and a 6-channel 10 bit ADC[12].

A. Flow chart of SVPWM

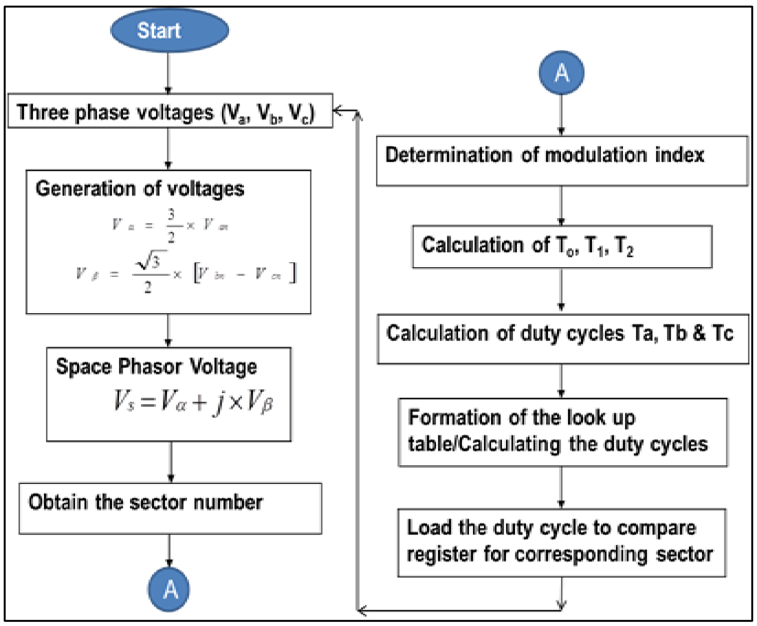

Fig. 4: Flow chart of SVPWM

IV. POWER STAGE AND DRIVE CIRCUIT

Power stage module of inverter is designed by six high power IRFP460 MOSFETs supporting up to 20A, 250Volts, turn on delay time – 18ns, turn off delay time – 110ns. The DC power supply given is 24V. All the MOSFETs are mounted on proper heat sink and protected by snubber circuit and fuse. The microcontroller board is isolated from power stage by HEX4049 drive circuit which is suitable for gate driving circuit of power MOSFETs. The designed three phase inverter is shown in Fig.5.

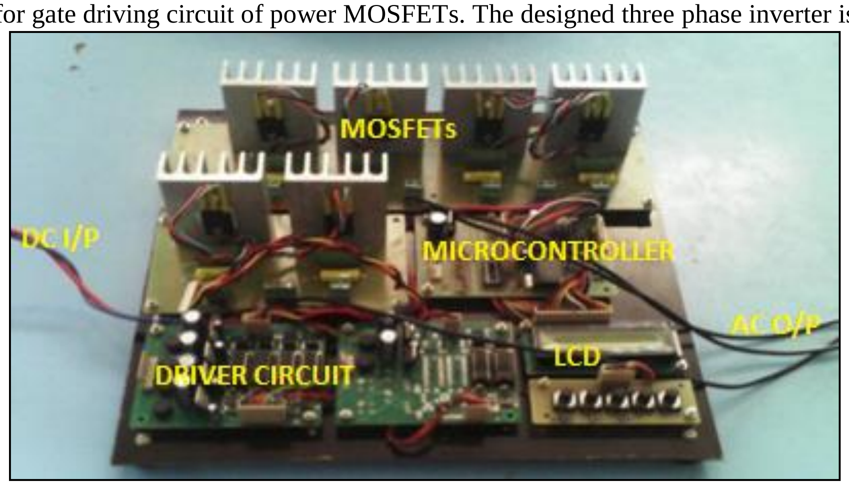

Fig. 5: Three phase inverter

V. EXPERIMENTAL SETUP

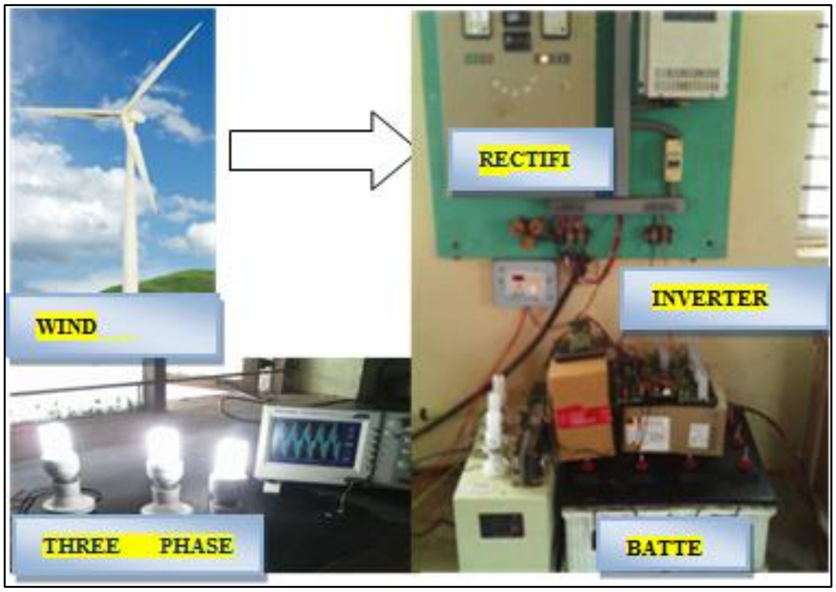

Fig. 6: Voltage source inverter connected to 1.5kW wind turbine at B.E.C Energy park

The overall experimental setup of the inverter connected to small rating wind turbine of 1.5kW installed at B.E.C Energy Park is shown in Fig.6. The three phase AC obtained from the wind turbine is connected to the rectifier which converts to DC voltage of 24Volts. This 24Volts DC obtained is stored in the batteries of 12Volt, 100AH each. The input to the inverter is fed through the battery that is 24Volts, which in turn connected to the three phase lighting load of 11 Watts CFL each connected in star.

VI. EXPERIMENTAL RESULTS

A. SPWM Results

The Fig. 7 represents the line to neutral voltage of the SPWM inverter at 50Hz frequency.

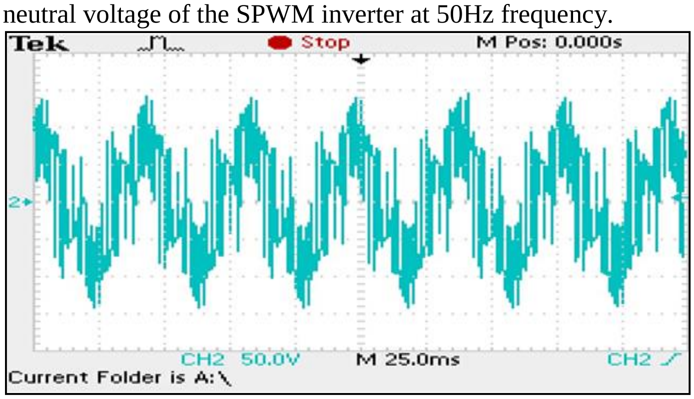

Fig. 7: Line to neutral SPWM Inverter output voltage at 50Hz frequency

The Fig.8 represents the line to line voltage of the SPWM inverter at 50Hz frequency.

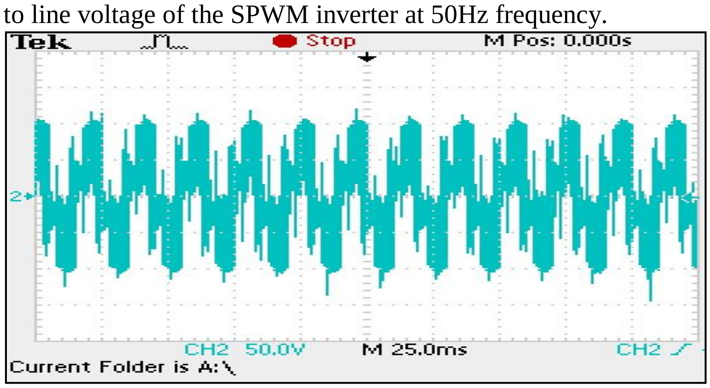

Fig. 8: Line to Line SPWM inverter output voltage at 50Hz frequency

For the above said SPWM based inverter the FFT spectrum has been analyzed to calculate the Total Harmonic Distortion (THD) The Fig. 9 shown below represents the FFT spectrum of line to line voltage at the output of the inverter. The THD obtained is 24.4%. The voltage THD is calculated by equation (21).

$$THD\ [\%] = 100 * \sqrt{\sum_{h=0}^{h=\infty} \left(\frac{V_h}{V_1}\right)^2} \qquad (17)$$

Where V_h: Amplitude of harmonic voltage
H: Order of harmonic
V_1: Amplitude of fundamental voltage

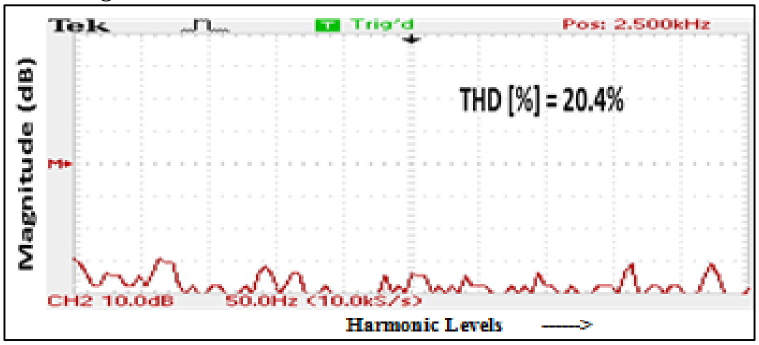

Fig. 9: Phase voltage THD at output of inverter

B. SVPWM Results

From the above results and discussions of SPWM it has been revived that, when FFT is analyzed the THD in case of SPWM is higher. To overcome this aspect the space vector pulse width modulation method has been implemented . The SVPWM pulses obtained are symmetric about the axis which eliminates the even harmonics and reduces the odd harmonics.

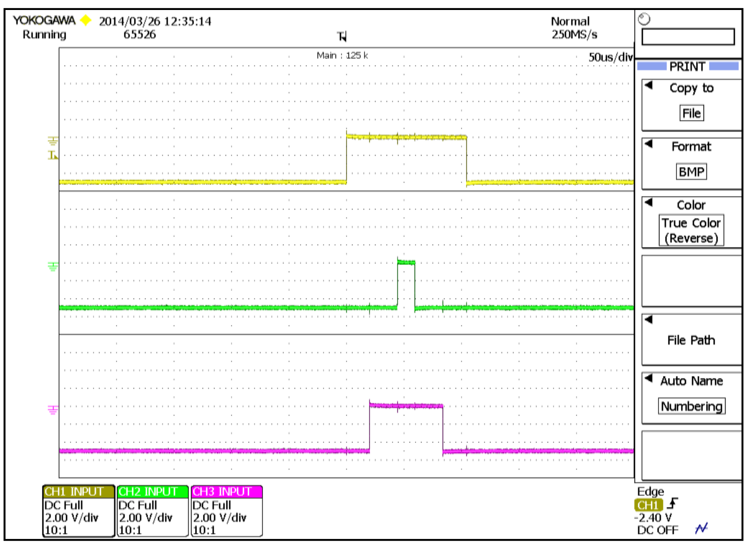

Fig. 10: Generation of SVPWM pulses

Fig. 11 shows the phase voltage at the output of the inverter at carrier frequency f_c = 3kHz which is observed in the CRO.

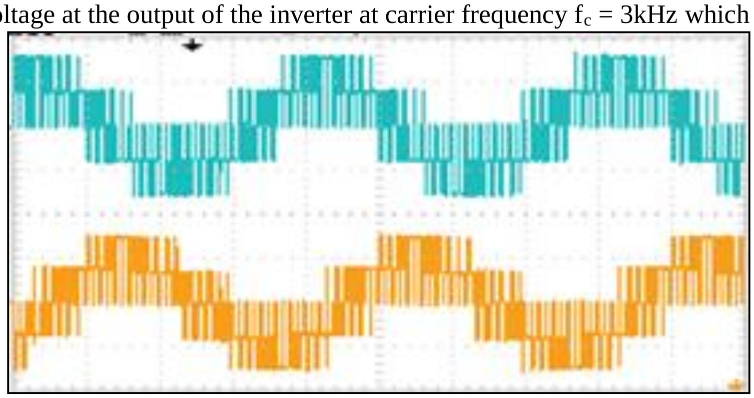

Fig. 11: Phase voltages at fc = 3kHz

Fig. 12 shows the phase voltages at the output of the inverter at carrier frequency f_c = 20kHz and Modulation index (M) = 0.5 which is observed in the CRO.

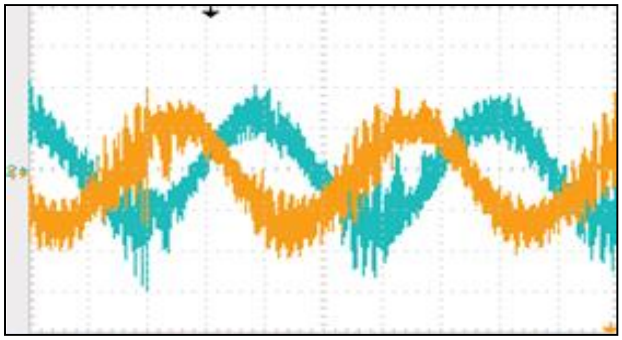

Fig. 12: Phase voltages at fc = 20kHz & M = 0.5

Fig. 13 shows the phase voltages at the output of the inverter at carrier frequency f_c = 20kHz and Modulation index (M) = 1 which is observed in the CRO.

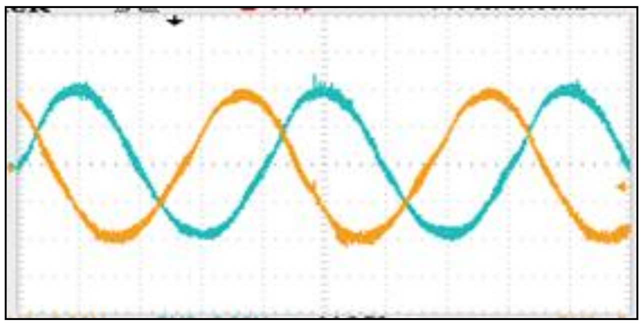

Fig. 13: Phase voltage at fc = 20 kHz & M=1

For the above said SVPWM based inverter the FFT spectrum has been analysed to calculate the total harmonic distortion. The Fig. 14 represents the phase voltage FFT spectrum at 20 kHz carrier frequency at the output of the inverter. The THD obtained is 18.2%.

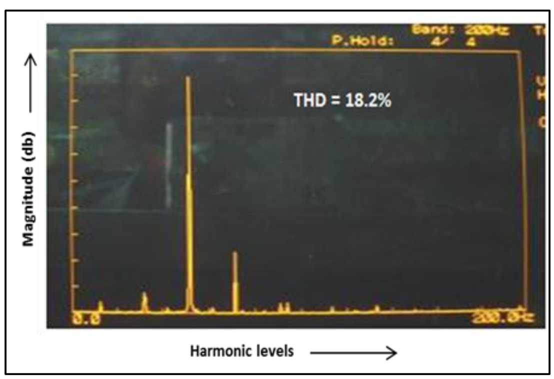

Fig. 14: Phase voltage at 20 kHz carrier frequency

VII. COMPARISON OF SPWM AND SVPWM

Table - 1
Comparison of SPWM and SVPWM

Sl. No	*SPWM*	*SVPWM*
1.	*Generate high harmonic distortion in the output voltage or current*	*Generate low harmonic distortion in the output voltage or current*
2.	*For m=0.5, amplitude of fundamental for V_{ab} is $V_{dc}/2$, amplitude of line to line is 3/2 V_{dc}*	*Maximum possible voltage without over modulation is 1/3 V_{dc} amplitude of line to line is V_{dc}*
3.	*DC utilization of SPWM is low*	*DC utilization is better then SPWM*
4.	*It treats the three phase quantities separately*	*In SVPWM, the three phase quantities are treated using single equation know as space vector*
5.	*Extension of scheme into over modulation range is difficult*	*Extension of scheme into over modulation scheme is easy*
6.	*Independent on number of levels, number of phase, level of DC voltage unbalance and modulation modes*	*Depends on number of levels, number of levels, number of phase, level of DC voltage unbalanced and modulation modes.*

Comparison of output voltage of inverter for SPWM and SVPWM and is shown in table-1.2. Ii is observed that SVPWM is having 15% higher utilization of DC bus as compared to SPWM technique.

Table - 2
Comparison of output voltage of inverter for SPWM and SVPWM

Sl. No	*Wind speed (m/s)*	*Output voltage of inverter V (Volts)*	
		SPWM	*SVPWM*
1.	*12.4*	*355*	*408.25*
2.	*8.9*	*340*	*389.3*
3.	*8.2*	*332*	*381.13*
4.	*7.1*	*320*	*366.72*
5.	*4.4*	*288*	*328.6*

The graphical representation of wind speed v/s output voltage of inverter is shown in Fig. 15

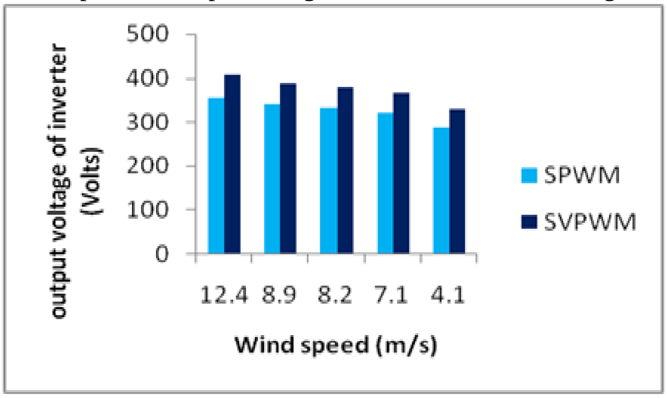

Fig. 15: Comparison of output voltage of inverter for SPWM and SVPWM

Comparison of output power of inverter for SVPM and SVPWM technique is shown in Table-1.3.

Table - 3
Comparison of output power of inverter for SPWM and SVPWM

Sl. No	*Wind speed (m/s)*	*Output of inverter P (Watts)*	
		SPWM	*SVPWM*
1.	*12.4*	*42.06*	*48.37*
2.	*8.9*	*37.22*	*42.80*
3.	*8.2*	*34.99*	*40.23*
4.	*7.1*	*27.81*	*39.9*
5.	*4.4*	*19.60*	*22.54*

The graphical representation of wind speed v/s power output of inverter is shown in Fig. 16.

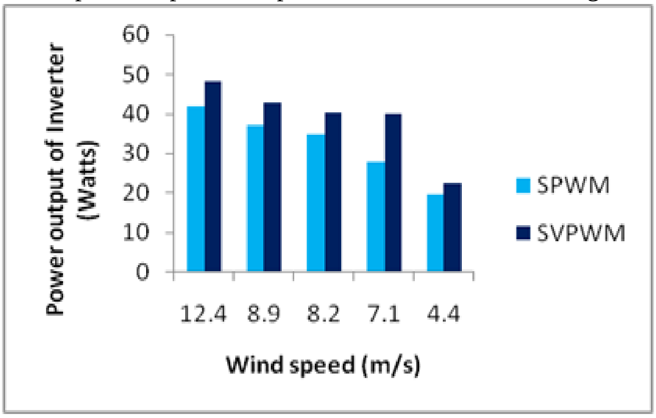

Fig. 16: Comparison of output power of inverter for SPWM and SVPWM

VIII. CONCLUSION

Three phase voltage source converter has been designed and fabricated for 1.5kW wind turbine installed at B. E. C Energy Park. SPWM and SVPWM techniques are employed for the proposed three phase inverter PWM algorithms are implemented using AT89C52 and ATmega328P respectively. The experimental results are presented from the laboratory to demonstrate the performance of inverter. It is observed from the results that THD obtained for phase voltage of inverter is 20.4% for SPWM and

18.2% for SVPWM. It is also observed that SVPWM technique is able to generate good quality sine wave as compared to SPWM.

ACKNOWLEDGEMENT

The authors would like to thank BEC Technical Education Quality Improvement Program (TEQIP-II) for providing financial assistance.

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