Harmonic Analysis of Voltage Source Inverter in Wind Power Application

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Abstract: *This paper is analysed the harmonic of a stand-alone wind turbine system with variable speed permanent magnet synchronous generator (PMSG) and a system for storing energy during wind speed and load variations. The PMSG is connected to a stand-alone load through a switch mode rectifier and a voltage source inverter (VSI). Control of the generator side converter is used to achieve maximum power extraction from the available wind power. Variable voltage and frequency supply to AC drives is obtained from a voltage source inverter. There are different pulse width modulation (PWM) techniques which essentially differ in the harmonic content of their respective output voltages. The mainly used PWM schemes for voltage source inverters are carrier-based sinusoidal PWM (SPWM) and space vector PWM (SVPWM). There is an increasing trend of using SPWM because it can be easily digital realized. Analysis of SPWM voltage source inverter has been carried out at different carrier frequencies with different loads. This VSI is fed from AC-DC converter. This paper presents the analysis of PWM inverter system including harmonic assessment of the inverter input current and output voltage. Carrier frequency 2 kHz is better than 1 kHz for this system because the total harmonic distortion of the output current decreases in the 2 kHz carrier frequency. Harmonic spectrum of output current and voltage are analysed. MATLAB program is used as an effective tool to analyse the harmonic.*

Key Words: *Converter, Harmonic, Permanent Synchronous Generator (PMSG), Stand-alone Load, Wind Power.*

1. INTRODUCTION:

In the case of wind energy conversion systems (WECSs), the interest is also focused on small units, used to provide electricity supply in remote areas that are beyond the reach of an electric power grid or cannot be economically connected to a grid. Maximum power can be extracted from the available wind power, which varies continually with change in the wind speed throughout a day, by adjusting the rotor speed of PMSG according to the wind speed variation [7]. There are two common types of interfaces between PMSG and the load. The first configuration is full bridge rectifier, the second configuration is voltage source inverter [4].The output voltage waveform of the inverter is generally non-sinusoidal and contains undesirable harmonics. Harmonic reduction can be achieved by either filtering, harmonic reduction chopping or pulse width modulation (PWM).Most modern voltage source inverters are controlled using wide variety of pulse width modulation (PWM) schemes, to obtain output AC voltages of the desired magnitude and frequency shaped as closely as possible to a sine wave [5].

Analysis of PWM inverter systems is required to determine the input-output characteristics for an application specific design, which is used in the development and implementation of the appropriate control algorithm. In addition to time domain analysis, harmonic assessment is an integral part of analysis and simulation of any power conversion system [6].

Analysis of PWM inverter systems have been mainly based on supplying balanced and linear loads [10]. However, the general drive towards automation has increased the use of a spectrum of new loads such as: computers with peripherals, telecommunication equipment, industrial robots etc. A large majority of these new loads are unbalanced and/or nonlinear in nature. In view of this, this paper presents the analysis of a sinusoidal PWM inverter system including harmonic assessment of the inverter input current and output voltage [11].

2. WIND ENERGY SUPPLY SYSTEM:

The power circuit topology of the proposed variable speed wind energy supply system is shown in Fig 1. The system consists of the following components:

- Wind turbine
- Permanent magnet synchronous generator (PMSG), which is directly driven by the wind turbine without using gearbox.
- Diode rectifier, which is directly connected to the three-phase output of wind generator.
- A voltage source inverter connected to the load through LC filter.

The DC input for the inverter is obtained by rectifying AC source by means of a diode rectifier. The DC link component is selected that the DC voltage at the inverter input is constant and ripple free. The semiconductor switching devices in the inverter are controlled by PWM signals generated by a control circuit in order to obtain nearly sinusoidal AC voltages of the desired magnitude and frequency at the inverter output.

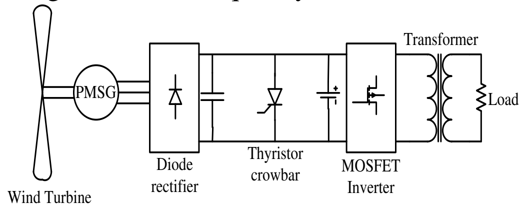

Figure 1. Variable Speed Wind Energy Supply System

3. PULSE WIDTH MODULATION CONTROL OF INVERTER:

The fundamental magnitude of the output voltage from an inverter can be controlled to be constant by exercising control within the inverter itself that is no external control circuitry is required. The most efficient method is pulse width modulation (PWM) control used within the inverter.

The commonly used PWM control techniques are:

- Single pulse width modulation (Single PWM)
- Multiple pulse width modulation (MPWM)
- Sinusoidal pulse width modulation (SPWM)

The typical output waveforms of inverters are square-wave, step-wave and sinusoidal pulse width modulation (SPWM) wave. The control circuits for square-wave and step-wave inverters are simple, but the harmonic content is high in the output voltage. Therefore, large filter circuit is required and that handles the large power output from the inverter. In SPWM inverter, though the control circuit is complex, the residual harmonic content in the output voltage is high frequency, so the filter circuit is small. In this paper, sinusoidal pulse width modulation (SPWM) technique is used for controlling the inverter as it can be directly controlled the inverter output voltage and output frequency according to the sine functions.

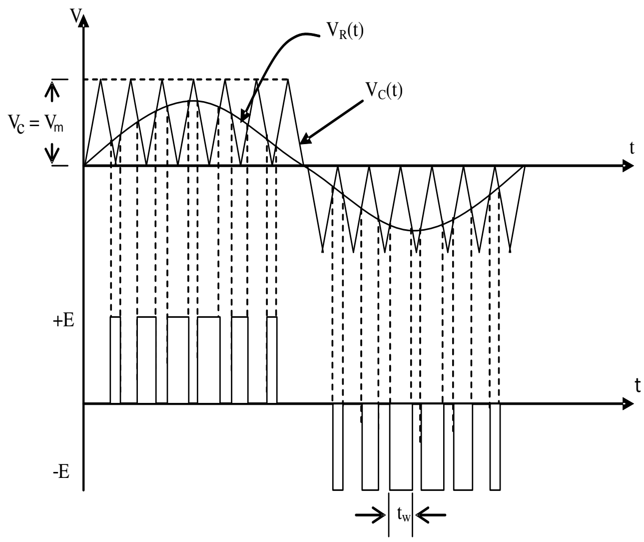

Figure 2. Reference Signals and Output Voltage Waveform of SPWM

In sinusoidal pulse width modulation, the output voltage is controlled by varying the on-off periods so that the on periods (pulse width) are longest at the peak of the wave. The switching times are determined as shown in Fig 2. $V_R(t)$ is a reference modulating sinusoidal wave of amplitude V_m and frequency f_m, which is equal to the desired output frequency of the inverter. A high frequency triangular carrier wave $V_C(t)$ with an amplitude V_C and frequency f_c is compared with the reference sine wave. The switching points are determined by the intersection of the $V_C(t)$ and $V_R(t)$ waves. The pulse t_w is determined by the time during which $V_C(t) < V_R(t)$ in the positive half cycle of $V_R(t)$ and $V_C(t) > V_R(t)$ in the negative half cycle of $V_R(t)$.

Two control parameters that regulate the output voltage are the chopping ratio and modulation index. The frequency ratio f_c/f_m is known as the chopping carrier ratio N. It determines the number of pulses in each half cycle of the inverter output voltage. The ratio $V_m/V_c$is called the modulation index. It determines the width of the pulses and therefore the rmsvalue of the inverter output voltage. The modulation index is usually adjusted by varying the amplitude of the reference wave while keeping the carrier wave amplitude fixed. The inverter output frequency is varied by varying the reference wave frequency.

The harmonic in the inverter output voltage waveform appear as sidebands, centeredaround the switching frequency and its multiples, that is, around harmonics m_f, $2m_f$, $3m_f$, and so on. This general pattern holds true for all values of m_a in the range 0 to 1. Generalized harmonics of V_{A0} for large m_f is shown in Table 1.

Table1.Generalized Harmonics of V_{A0} for a Large m_f

Harmonic	Modulation ratio m_a				
	0.2	0.4	0.6	0.8	1.0
1	0.2	0.4	0.6	0.8	1.0
m_f	1.242	1.15	1.006	0.818	0.601
$m_f \pm 2$	0.016	0.061	0.131	0.220	0.318
$m_f \pm 4$					0.018
$2m_f \pm 1$	0.190	0.326	0.370	0.314	0.181
$2m_f \pm 3$		0.024	0.071	0.139	0.212
$2m_f \pm 5$				0.013	0.033
$3m_f$	0.335	0.123	0.083	0.171	0.113
$3m_f \pm 2$	0.044	0.139	0.203	0.176	0.062
$3m_f \pm 4$		0.012	0.047	0.104	0.157
$3m_f \pm 6$				0.016	0.044
$4m_f \pm 1$	0.163	0.157	0.008	0.105	0.068
$4m_f \pm 3$	0.012	0.070	0.132	0.115	0.009
$4m_f \pm 5$			0.034	0.084	0.119
$4m_f \pm 7$				0.017	0.050

4. THE HARMOF INVERTER HARMONIC:

The harmonic pollution caused by the converter is usually caused by the transmission, the electromagnetic radiation and the induction coupling in three ways, other users of the power grid can not work properly or cause electrical accidents. The harm of harmonics is mainly reflected is voltage waveform distortion of public power grid, increase power transformer and induction motor copper loss and iron loss, efficiency decline, noise, etc. Power capacitors are over current, over heat and over voltage; electrical switches and protective equipment produce insulation damage, tripping error and protection of false operation, etc. It should be noted that the higher harmonics will also be on the computer, communications equipment, instrumentation, television and audio equipment, carrier remote control equipment to produce interference, resulting in communication interruption, the measurement results are not allowed, the use of functional quality decline.

5. ANALYSISOF INVERTER OUTPUT WAVEFORM:

Fast fourier transform (FFT) method is used to analyse the output waveform of SPWM inverter. For the output power quality of inverter, total harmonic distortion (THD) voltage and current are calculated.

A. Fourier Series Analysis for SPWM

The fourier analysis apporach is a common way to analyse the frequency harmonics in the frequency domain of inverter output voltage. In steady state, this waveform repeats with a frequency f_1 which is called the fundamental frequency and time period: $T_1=1/f_1$. In addition to a dominant component at the fundamental frequency, it contains components at higher frequencies that are multiples of the fundamental frequency, which can be calculated by fourier series method.

The fourier series for a periodical signal is represented as below:

$$f(\omega t) = F_0 + \sum_{n=1}^{\infty} f\ (\omega t) \tag{1}$$

$$= \frac{1}{2}a_0 + \sum_{n=1}^{\infty} \{a_n\cos(n\omega t)+b_n\sin(n\omega t)$$

Where $F_0 = \frac{1}{2}a_0$ is the average value.

f(ωt) is a periodical signal with a period ; a_n and b_n can be calculated by;

$$a_n = \frac{1}{\pi}\int_0^{2\pi} f(\omega t)\cos(n\omega t)d\omega t \quad n = 0, ..., \infty$$

$$b_n = \frac{1}{\pi}\int_0^{2\pi} f(\omega t)\sin(n\omega t)d\omega t \quad n = 1, ..., \infty$$

Table2.Use of Symmery in Fourier Analysis

Symmetry	**Condition**	**Properties**
Even	$f(-\omega t) = f(\omega t)$	$b_n = 0$ $a_n = \frac{2}{\pi}\int_0^{\pi} f(\omega t)\cos(n\omega t)d\omega t$
Odd	$f(-\omega t) = -f(\omega t)$	$a_n = 0$ $b_n = \frac{2}{\pi}\int_0^{\pi} f(\omega t)\sin(n\omega t)d\omega t$

It should be noted that the calculation of a_n and$b_n$can be simplified by use of PWM waveform symmetry properties. The properties of even and odd are summarized in Table 2. The certainfourier coefficients are zero in special case.

B. Total Harmonic Distortion

The amount of distortion in the voltage or current waveform is quantified by means of an index called the total harmonic distortion (THD).

For total harmonic distortion voltage;

$$THD_v = \sqrt{\sum_{h=2}^{\infty}\left(\frac{V_{sh}}{V_{s1}}\right)^2} \quad (2)$$

$$= \frac{\sqrt{(V_s^2 - V_{s1}^2)}}{V_{s1}}$$

For total harmonic distortion current;

$$THD_i = \sqrt{\sum_{h=2}^{\infty}\left(\frac{I_{sh}}{I_{s1}}\right)^2} \quad (3)$$

$$= \frac{\sqrt{\left(I_s^2 - I_{s1}^2\right)}}{I_{s1}}$$

Where, V_{sh} is the rms value of the n[th] harmonic of output voltage and V_{s1} is the rms value of the fundamental harmonic of output voltage and V_s is the rms value of the output voltage. The rms values of the waveforms are computed as the square root of the sum of rms squares of all individual components, i.e.,

$$V_{rms} = \sqrt{\frac{V_1^2 + V_2^2 + V_3^2 + ... + V_{hmax}^2}{\text{Length of output voltage}}} \quad (4)$$

Where, I_{sh} is the rms value of the n[th] harmonic of output current and I_{s1} is the rms value of the fundamental harmonic of output current and $I_s$is the rms value of the output current. The rms values of the waveforms are computed as the square root of the sum of rms squares of all individual components, i.e.,

$$I_{rms} = \sqrt{\frac{I_1^{\,2} + I_2^{\,2} + I_3^{\,2} + \ldots I_{hmax}^{\,2}}{\text{Length of output current}}} \tag{5}$$

Where V_h and I_h are the amplitude of a waveform at the harmonic component h. In the sinusoidal condition, harmonic components of V_h and I_h are all zero, and only V_1 and I_1 remain.

The rms value of the supply current can be computed as;

$$I_{supply(rms)} = \sqrt{\frac{I_1^{\,2} + I_2^{\,2} + I_3^{\,2} + \ldots + I_n^{\,2}}{\text{Length of supply current}}} \tag{6}$$

The average value of the supply current can be computed as;

$$I_{supply(avg)} = \frac{I_1^{\,2} + I_2^{\,2} + I_3^{\,2} + \ldots + I_n^{\,2}}{\text{Length of supply current}} \tag{7}$$

6. PROGRAM FLOWFOR SPWM INVERTER:

The topology of inverter and sinusoidal pulse width modulation (SPWM) switching scheme are expressed in above. MATLAB program was used to find the theoretical harmonic spectrum based on mathematic analysis. Program flow for design analysis of SPWM inverter is shown in Fig 3.

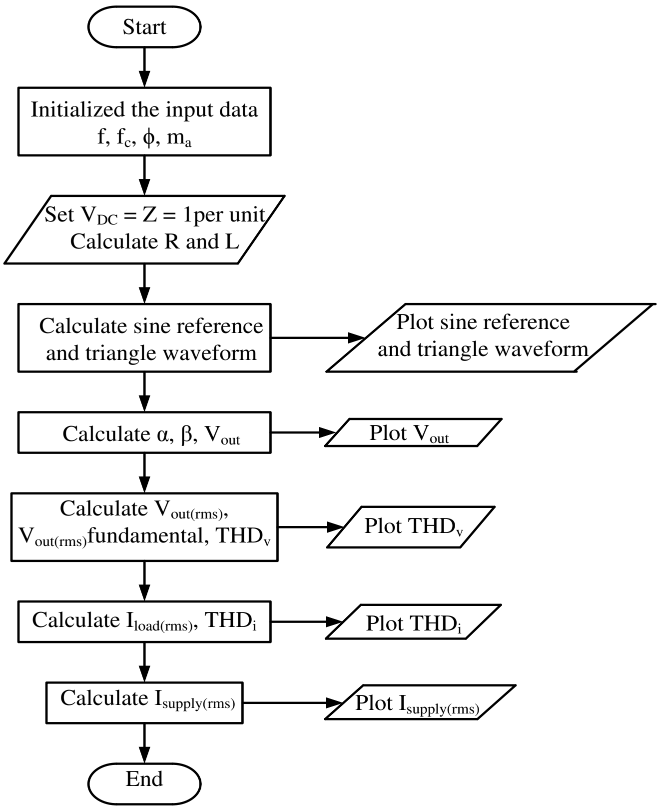

Figure 3. Program Flow for Design Analysis of SPWM Inverter

7. MATLAB PROGRAMFOR SPWM INVERTER:

MATLAB program is used as an analytical tool for the SPWM inverter. Fundamental frequency (f_1) of inverter is 50 Hz, carrier frequency (f_c) is 2 kHz, load angle(ϕ) is 10 degree and modulation index (m_a) is 0.8.

The switching functions were generated by using the sinusoidal pulse width modulation technique. The saw tooth function in MATLAB was used to generate the carrier signal of the desired frequency. The carrier signal frequency used for the simulation was 2 kHz. Reference sine wave and carrier triangular wavecomparison is shown in Fig 4.

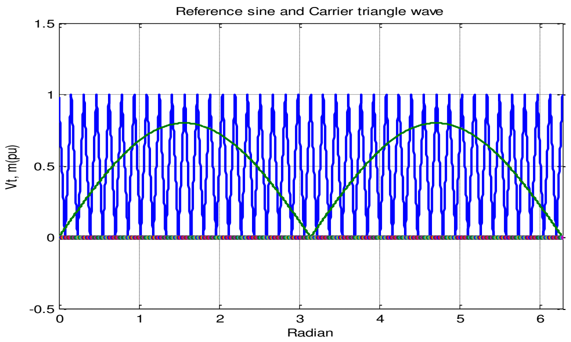

Figure 4. Reference Sine Wave and Carrier Triangular Wave

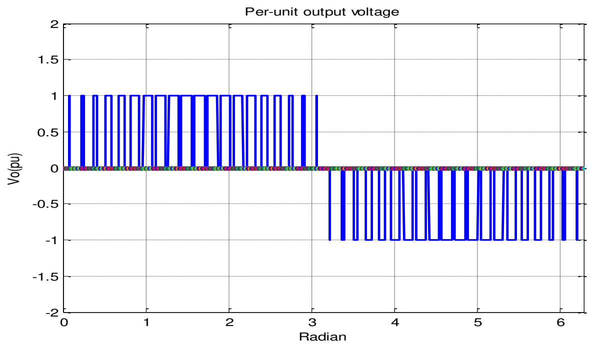

Figure 5. Per-unit Output Voltage Waveform of SPWM Inverter

In order to source an output with a PWM signal, transistor or other switching technologies are used to connected the source to the load when the signal is high or low. The per unit output voltage of inverter is shown in Fig 5. It can be seen that the per unit output voltage varies between 1,0 and -1.

The rms value of the output voltage of inverter is;

$V_{out(rms)} = 0.7134$ per unit

The rms value of the output voltage fundamental component is;

$V_{out(rms)} = 0.5654$ per unit

Harmonic voltage spectrum of SPWM inverter is shown in Fig 6 and Fig 7. The output voltage consists of the fundamental (50 Hz) component and higher order switching frequency harmonics as can be seen from the FFT. From Fig 6, 39th and 41st harmonics are the highest but low order harmonics are eliminated. Therefore, the higher order switching frequency harmonics are 1950 Hz and above. From Fig 7, 19th and 21st harmonics are the highest and low order harmonics are maintained.

Total harmonic distortion of inverter voltage at 2 kHz carrier frequency;

$THD_{vo} = 0.7695$

Total harmonic distortion of inverter voltage at 1 kHz carrier frequency;

$THD_{vo} = 0.7796$

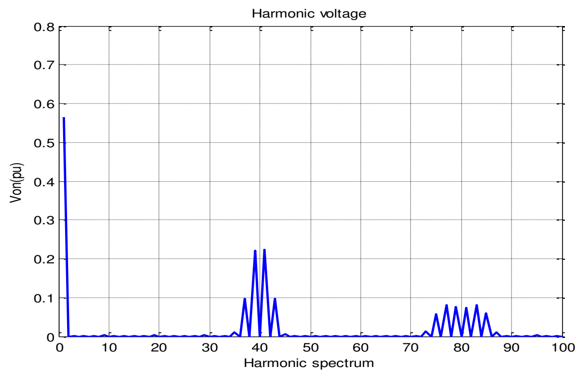

Figure 6. Harmonic Voltage Spectrum at 2 kHz Carrier Frequency

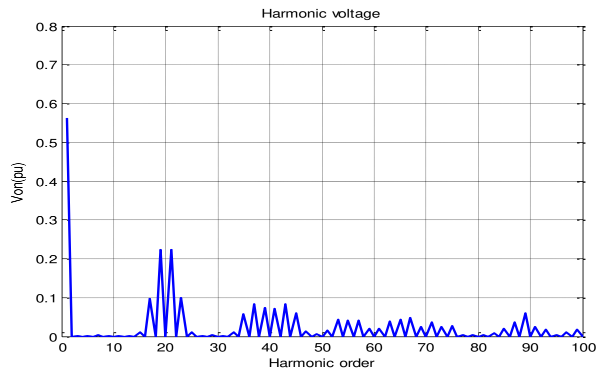

Figure 7. Harmonic Voltage Spectrum at 1 kHz Carrier Frequency

Output current waveform of SPWM inverter at load angle $\phi = 10$ degree is shown in Fig 8. In Fig 9 and Fig 10, harmonic current spectrum of SPWM inverter is stated. It should be noted that harmonic contents of SPWM inverter is relatively small.

The rms value of load current is;

$I_{load(rms)} = 0.5677$ per unit

Total harmonic distortion of inverter current at 2 kHz carrier frequency;

$THD_i = 0.0905$

Total harmonic distortion of inverter current at 1 kHz carrier frequency;

$THD_i = 0.1792$

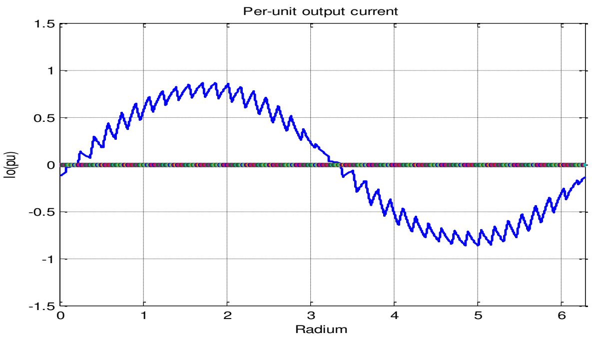

Figure 8. Output Current Waveform of SPWM Inverter

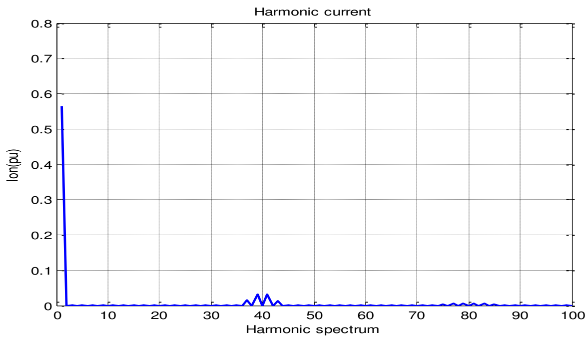

Figure 9. Harmonic Current Spectrum at 2 kHz Carrier Frequency

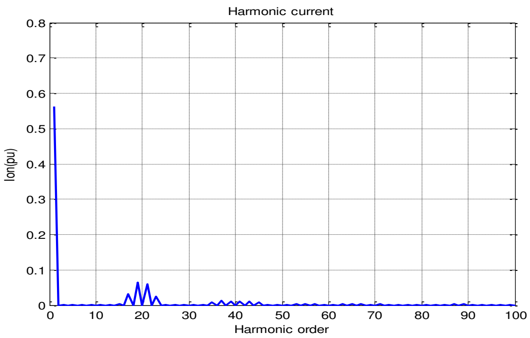

Figure10. Harmonic Current Spectrum at 1 kHz Carrier Frequency

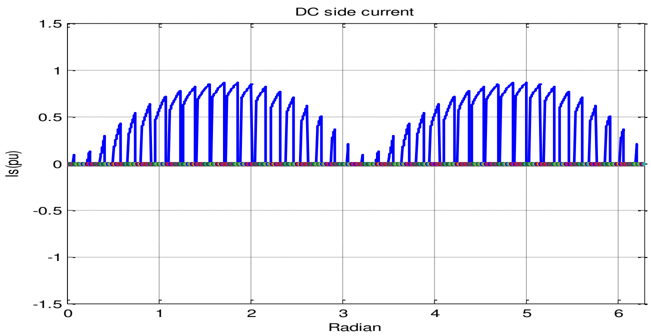

Figure 11. Output Waveform of Supply Current (DC side)

In Fig 11, the output waveform of DC supply current. From this Fig, the distortion of DC supply current is due to the inverter switching.

The rms value of the DC side supply current is;

$I_{supply(rms)}$ = 0.4658 per unit

The average value of the supply current is;

$I_{supply(avg)}$ = 0.3170 per unit

The results are compared and analysed by plotting the output harmonic spectrum and computing their total harmonic distortion comparison is shown in Table 3.If the carrier frequency increases, the total harmonic distoration of the output current and output voltage decrease.

Table 3.Total Harmonic Distortion

Carrier Frequency	THD_{V0}	THD_{I0}
1 kHz	77.96 %	17.92 %
2 kHz	76.95 %	9.05

8. CONCLUSIONS:

The analytical procedure and simulation results were presented in this paper. MATLAB program was used to analyse the harmonic contents of inverter output and design specification. In this paper, type of SPWM inverter output voltage harmonic based on sine wave modulation angular frequency as a benchmark of fourier series expansion. Simulation results for 1 kHz carrier frequency 2 kHz carrier frequency were presented. The results are compared and analysed by plotting the output harmonic spectrum. The total harmonic distortion of the output current decreases with increases in the carrier frequency. Therefore, carrier frequency 2 kHz is better than 1 kHz for this system. Carrier frequency 2 kHz is selected for the system because the harmonic contents of the SPWM inverter in this carrier frequency are relatively small.

9. ACKNOWLEDGMENT:

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