RESEARCH ARTICLE OPEN ACCESS

Design and Simulation of Low Pass Filter for Single phase full bridge Inverter employing SPWM Unipolar voltage switching

Yugendra Rao K N[1]
[1]UG Student, Department ofElectrical and Electronics Engineering,RV College of Engineering, Bangalore-059, Karnataka, India

Abstract
Sinusoidal pulse width modulation *SPWM* technique is widely preferred to other modulation techniques as the Inverter output frequency obtained is equal to the required fundamental frequency. *SPWM* with unipolar voltage switching is used as it results in cancellation of harmonic component at the switching frequencyin the output voltage, also the sidebands of the switching frequency harmonics disappear and in addition to this, other dominant harmonic at twice the switching frequency gets eliminated. Hence, due to these advantages unipolar voltage switching with *SPWM*is used for Inverter switching. In this paper, an in-depth analysis of unipolar voltage switching technique with *SPWM* as applied to a single-phase full bridge Inverter is described and designing of an efficient, active low pass filter *LPF* is discussed for an particular cut-off frequency,f_c and damping factor zeta, ζ and the filter is placed at the output side of a single-phase full bridge Inverter and therefore eliminating the harmonic component from the Inverter output voltage resulting in a pure sinusoidal ac voltage waveform.

Index Terms-*SPWM* control, Single-phasefull bridge Inverter, Unipolar voltage switching, Harmonics, *VSI* voltage source Inverter, *LPF* low pass filter, *THD* total harmonic distortion.

I. INTRODUCTION

Dc-ac converters are known as Inverters. The function of an Inverter is to change a dc-input voltage to a symmetric ac-output voltage of desired magnitude and frequency [1]. The output voltage could be fixed or variable at a fixed or variable frequency. Varying the dc-input voltage and maintaining the Inverter gain constant will result in a variable ac-output voltage. The Inverter gain is defined as ratio of the ac-output rms voltage to dc-input voltage. On the other hand, if the dc-input voltage is fixed and is not controllable, a variable output voltage can be obtained by varying the Inverter gain, which is normally accomplished by pulse-width modulation *PWM*control withinthe Inverter [2].The output voltage waveforms of ideal Inverter must be sinusoidal. However, the waveforms of practical Inverters are non-sinusoidal and contain certain harmonics. For low and medium power applications, square-wave or quasisquare-wave voltages may be acceptable, but for high-power applications low distorted sinusoidal waveforms are necessary. With the availability of high-speed power semiconductor devices, the harmonic contents of output voltage can be minimized or reduced significantly by switching techniques. In this paper an active low pass filter *LPF*has been designed at the output terminals of a single-phase full bridge Inverterto fully eliminate the harmonic component of the resultant ac voltage output waveform.Inverters find its applications in variable-speed ac motor drives, induction heating, and uninterruptible power supplies*UPS*. The input to the Invertermay be fuel cell, battery, solar cell, or any other dc source [2].

The typical single-phase ac-outputs are 1) 120V at 60Hz, 2) 230V at 50Hz, and 3) 115V at 400Hz.

II. INVERTERS

Inverters can be broadly categorized into two types:
1. Voltage Source Inverters *VSI*
2. Current Source Inverters *CSI*

GenerallyInverters can be single-phase or three-phase in nature, they are employed depending upon their low power and high power rating for variety of applications. Each Inverter type can be controlled by turning *ON* and *OFF* power semiconductor devices, like Bipolar junction transistors *BJT's*, Metal oxide semiconductor field-effect transistors *MOSFET's* or Insulated gate bipolar transistors *IGBT's* and so on. These Inverters generally used *PWM* control signals for producing an ac-output voltage. AnInverter is called avoltage source Inverter*VSI*, if the input voltage remains constant, and a current source Inverter*CSI*,if the input current is maintained constant. From the viewpoint of connection of semiconductor devices, Inverters are classified as:
1. Series Inverters.
2. Parallel Inverters.
3. Bridge Inverters.

Bridge Inverters are further classified into:
1. Half Bridge Inverter.
2. Full Bridge Inverter.

A.Pulse-width modulation switching scheme

To understand *SPWM*as applied tosingle-phase full bridgeInverter, consider a single-phase one-leg switch-mode Inverter as shown in the Fig. 1.All the topologies described in this paper are an extension of one-leg switch-mode Inverter. To understand the dc-to-ac Inverter characteristics of single-phase one-leg Inverter of Fig. 1, we shall consider an dc-input voltage,V_d and that the Inverter switches are pulse-width modulated to shape and control the output voltage. Later on it will be shown that single-phase full bridge Inverter is an extension of one-leg switch-mode Inverter.In Inverter circuits we would like the Inverter output to be sinusoidal with magnitude and frequency controllable [3],[4].In order to produce a sinusoidal output voltage waveform at a desired frequency, a sinusoidal control signal at a desired frequency is compared with a triangular waveform, as shown in Fig. 1.1a. The frequency of the triangular waveform establishes the Inverter switching frequency, $f_s$and is generally kept constant along with its amplitude, $\hat{v}_{tri}$.

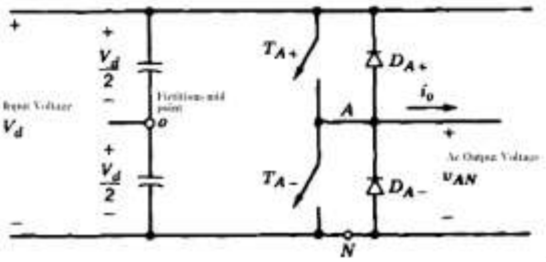


Fig. 1. Single-phase one-leg switch-mode Inverter

The triangular waveform, v_{tri} in Fig. 1.1a, is at a switching frequency, $f_s$that establishes the frequency with which the Inverterswitches are switched ($f_s$is also called the carrier frequency). The reference or control signal,$v_{control}$ is a sine wave used to modulate the switch duty ratio and has the frequency,$f_1$which is the desire fundamental frequency of the Inverter output voltage (f_1 is also called the modulating or reference frequency). Recognizing that the Inverter output voltage will not be perfect sine wave and will contain voltage components at harmonics frequencies f_1. The amplitude modulation*AM* 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 peak amplitude of triangular signal is $\hat{v}_{tri}$, which is generally kept constant.The relation between peak amplitudes of control and reference signal is,

$$\hat{v}_{control} \leq \hat{v}_{tri} \quad (2)$$

Which is clearly observed fromFig. 1.1a.

The frequency modulation *FM* ratio, m_f is defined as,

$$m_f = \frac{f_s}{f_1} \quad (3)$$

In the Inverter shown in Fig. 1, the switches T_{A+} and T_{A-} *are* controlled based on the comparison of $v_{control}$ and v_{tri}. The following output voltage isindependent of direction of load current i_o results in,

$$v_{control} > v_{tri}, T_{A+} \text{ is on}, v_{Ao} = \frac{1}{2}V_d \quad (4)$$

or

$$v_{control} < v_{tri}, T_{A-} \text{ is on}, v_{Ao} = -\frac{1}{2}V_d \quad (5)$$

So, the output voltage of a single-phase one-leg Inverter, v_{Ao} fluctuates between $\frac{1}{2}V_d$ and $-\frac{1}{2}V_d$.Output voltage v_{Ao} and its fundamental frequency component is shown in Fig. 1.1b, which are drawn for m_f= 15,m_a = 0.8. The harmonic spectrum of v_{Ao} under the conditions indicated in Figs. 1.1a & 1.1b is shown in Fig. 1.1c, where the normalized harmonic voltage V_n, is

$$V_n = (\hat{v}_{Ao})_h / \frac{1}{2}V_d \quad (6)$$

Having significant amplitudes plotted for $m_a \leq 1$ shows three terms of importance:

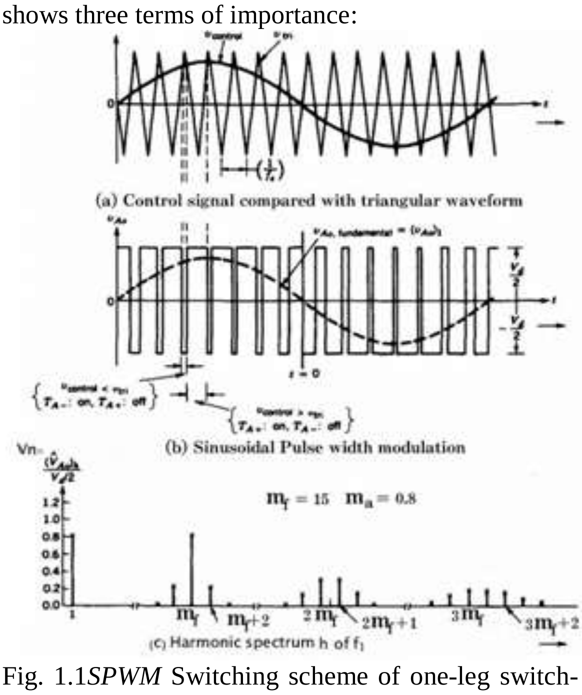


Fig. 1.1*SPWM* Switching scheme of one-leg switch-mode Inverter

1. The peak amplitude of the fundamental frequency component, $(\hat{v}_{Ao})_1$ is $m_a$times $\frac{1}{2}V_d$. This can be explained by considering a constant control voltage waveform, $v_{control}$ as shown in Fig 1.2(a). This results in an output waveform v_{Ao}.Also V_{Ao}depends on the ratioof $v_{control}$ to $\hat{v}_{tri}$ for a given V_d.

$$V_{Ao} = \frac{v_{control}}{\hat{v}_{tri}} \frac{1}{2} V_d \quad (7)$$

Assuming that$v_{control}$ varies very little during switching time period, i.e.,$m_f$is very large, as shown in Fig. 1.2(b). Therefore, assuming $v_{control}$ to be constant over a switching time period, Equ. (7), indicates how instantaneous average value of v_{Ao} varies form one switching period to next. This instantaneous average is same as the fundamental frequency component of v_{Ao}. The foregoing argument shows why $v_{control}$ is chosen to be sinusoidal to provide a sinusoidal output voltage with fewer harmonics. Let the control voltage vary sinusoidally at a frequency $f_1 = \omega_1/2\pi$, which is desired frequency of theInverter output [5].

$v_{control} = \hat{V}_{control} \sin\omega_1 t$(8)

Substituting Equ. (8)in Equ. (7), shows that the fundamental frequency $(v_{Ao})_1$ varies sinusoidally and is in phase with $v_{control}$ as a function of time,

$(v_{Ao})_1 = \frac{\hat{v}_{control}}{\hat{v}_{tri}} \sin\omega_1 t \frac{Vd}{2}$

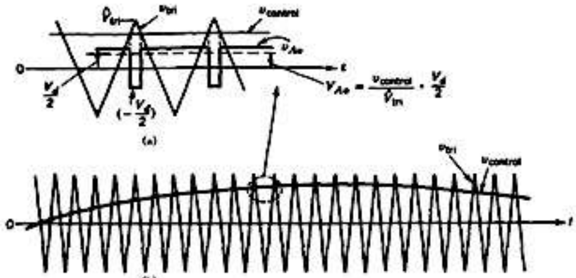
$= m_a \sin\omega_1 t \frac{Vd}{2}$(9)

Therefore,

$(\hat{V}_{Ao})_1 = m_a \frac{Vd}{2}$, $m_a < 1$(10)

Fig.1.2 Sinusoidal pulse-width modulation *SPWM*

Which shows that in an *SPWM*, the amplitude of the fundamental frequency component of the output



voltage varies linearly with m_a(m_a< 1).

2. The harmonics in the Inverter output voltage waveform appear as sidebands, centered around the switching frequency and its multiples, i.e.,around m_f , $2m_f$, $3m_f$ and so on. This pattern holds good for m_a< 1. For a frequency modulation *FM* of $m_f \leq 9$, which is always the case except in high power ratings, the harmonic amplitudes are almost independent of m_f, though m_f defines the frequencies at which they occur. Theoretically, the frequencies at which voltage harmonics occur is indicated byEqu.(11). Harmonic order h corresponds to k^{th} sidebands of j times frequency modulation ratio, m_f. For the fundamental frequency indicated in Equ.(12).

$f_h = (jm_f \pm k) f_1$(11)

$h = (jm_f) \pm k$(12)

Where, the fundamental frequency, f_1 corresponds to $h=1$. For odd values of j, the harmonics exist only for even values of k. For even values of j, the harmonics exist only for odd value of k.The normalized harmonics, $(\hat{v}_{Ao})_h / \frac{1}{2}V_d$ are tabulated as a function of amplitude modulation, m_a, for $m_f \geq 9$. Only those with significant amplitudes up to j = 4, in Equ. (12)are shown in Table1.The relation betweenac-output voltage, v_{AN} and dc-input voltage, V_d across the fictitious mid point 'O', as seen from Fig.1 is,

$v_{AN} = v_{Ao} + \frac{Vd}{2}$(13)

Therefore, the relation between harmonic voltage components v_{AN} and v_{Ao} is as shown,

$(\hat{v}_{AN})_h = (\hat{v}_{Ao})_h$(14)

Table. 1 shows that amplitude of the fundamental frequency component of the output voltage, $(\hat{V}_{Ao})_1$ varies linearly with m_a as described by Equ. (10).

3.The harmonic m_f can be an odd integer, Choosing m_f as odd integer results in an odd symmetry [$f(-t) = -f(t)$] as well as half wave symmetry [$f(t) = -f(t + \frac{1}{2}T_1)$] with time origin as shown in Fig. 1.1b, which is plotted for m_f = 15 and m_a< 1. Therefore, only odd harmonics are present and the even harmonics are eliminated form the waveform of v_{Ao}. Hence, only the coefficients of the sine series in the Fourier analysis are present, and those for cosine series are zero, i.e., a_o and $a_n$are zero. The harmonic spectrum is plotted as $f_h$in reference with fundamental frequency,$f_1$as governed by the Equ. (11), is shown in Fig 1.1c.

Table. 1. Generalized harmonics V_{Ao} for large m_f
*Harmonics appear across the carrier frequency and it's multiples

B.Harmonic analysis with variation of frequency modulation ratio m_f and variation of amplitude modulation ratio m_a

h \ m_a	0.2	0.4	0.6	0.8	1.0
1 Fundamental	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

1. *Synchronous PWM,Small($m_f \leq 21$)*

For small values of m_f, the triangular signal, v_{tri} and control signal, $v_{control}$ must be synchronized to each other (synchronous *PWM*) as shown in Fig. 1.1a. This synchronous *SPWM* requires m_f to be an integer. Synchronous *PWM* is preferred to asynchronous *PWM*, where m_f is not an integeras it results in sub-harmonics of fundamental frequency, f_1 which is very undesirable in most applications [6].

2. *Large m_f (m_f>21)*

The amplitudes of sub-harmonics due asynchronous *SPWM* are small at large values of m_f. Therefore, at larger values of m_f, the asynchronous *SPWM* can be used where the frequency of triangular waveform is kept constant, whereas the frequency of $v_{control}$ varies, resulting in noninteger values of m_f. However, if the Inverter is supplying a load such as an ac motor, the sub-harmonics at zero or close to zero frequency, even though small in amplitude, will result in large currents that will be highly undesirable. Therefore, the asynchronous *SPWM* must be avoided.

3. *Over amplitude modulation (m_a> 1)*

In our previous discussion amplitude modulation ratio, m_a<1, corresponding to a sinusoidal *PWM* in a linear range. Therefore, the amplitude of the fundamental frequency voltage $(\hat{V}_{Ao})_1$ varies linearly with m_a, as derived in Equ. (10). In this range of $m_a \leq 1$, *SPWM* pushes the harmonics into high-frequency range around the switching frequency, f_s and its multiples. In spite of desirable feature in *SPWM* in the linear range, one of the drawbacks is that the maximum available amplitude of the fundamental frequency component is not as high as we wish. This is a natural consequence of notches in the output voltage waveform of Fig.1.1b.If the amplitude of the control signal, $\hat{v}_{control}$ is greater than the amplitude of the carrier signal, $\hat{v}_{tri}$ then by Equ.(1), yields m_a> 1, resulting in over-modulation. Over-modulation causes the output voltage to contain many more harmonics in the side-band when compared with the linear range ($m_a \leq 1$), as shown in the Fig. 1.3a. The harmonics with dominant amplitudes in the linear range may not be dominant during over-modulation. More significantly, with over-modulation, the amplitude of the fundamental frequency, $(\hat{V}_{Ao})_1$ does not vary linearly with amplitude modulation ratio, m_a, i.e., it does not obey Equ. (10). The normalized peak amplitude of the fundamentalfrequency component, $(\hat{v}_{Ao})_1/\frac{1}{2}V_d$ as a function of amplitude modulation ratio m_a, isshown in Fig. 1.3b. Even at larger values m_f, $(\hat{v}_{Ao})_1/\frac{1}{2}V_d$ depends on m_f in the over-modulation region. Which is contrary to the linear range $m_a \leq 1$, where $(\hat{v}_{Ao})_1/\frac{1}{2}V_d$, varies linearly with m_a, almost independent of m_f, provided m_f>9.With over-modulation regardless of m_f, it is recommended that a synchronous *SPWM* operation to be used, thus meeting the requirement indicated previously for a small value of m_f.

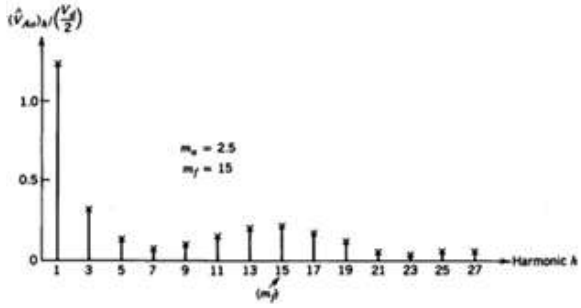


Fig. 1.3a.Harmonics in the fundamental frequency caused by over-modulation for given value of m_a = 2.5 and m_f= 15.

In induction motor drives over-modulation is used normally. For sufficiently large values of m_a, the Inverter voltage waveform degenerates from a pulse-width modulated waveform into a square wave. Hence, the over-modulation region is avoided in uninterruptible power supplies *UPS* because of a stringent requirement on minimizing the distortion in output voltage. It can be concluded that in the over-modulation region with m_a> 1.

$$\frac{Vd}{2} < (\hat{v}_{Ao})_1 < \frac{4}{\pi}\frac{Vd}{2} \quad (15)$$

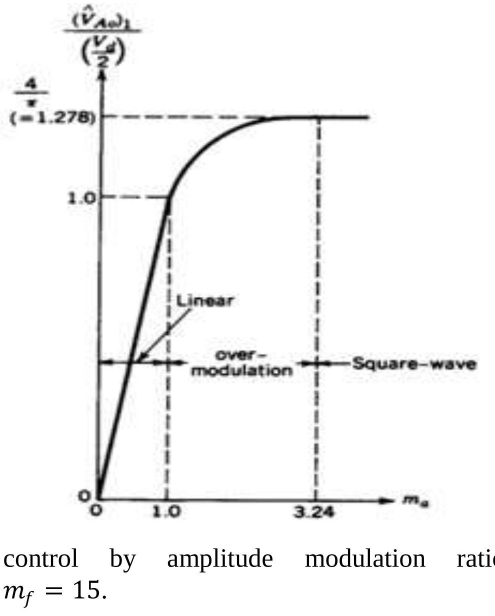


Fig.1.3 b. Voltage control by amplitude modulation ratio, m_a for $m_f = 15$.

III. SINGLE-PHASE FULL BRIDGE VOLTAGE SOURCE INVERTER

A Single-phase full Inverter is shown in the Fig.2a,consists of two one-legs as discussed before. With thedc-input voltage,$V_d$the maximum ac-output voltage isV_d, which is twice that of a single-phase half bridge Inverter whose ac-output voltage is, $\frac{Vd}{2}$. This implies that for the same power,the output current and the switch currents are one-half of those for a half-bridge Inverter. At high power-levels, this is a distinct advantage, since it requires less paralleling of devices [7].

A. Workingof single-phase full bridge VSI

It consists of four transistors, when transistors (switches) T_{A+} and T_{B-} are turned on simultaneously, the input voltage, V_d appears across the load. If transistors $T_{B+}$and T_{A-} are turned on at the simultaneously, the voltage across the load is reversed and is $-V_d$. The waveform for the output voltage in the case of R-load is shown in the Fig.2b.If two switches: one upper and one lower(diagonally)conduct at the same time such that the output voltage is $\pm V_d$, the switch state is 1, where these switches are off at the same time, the switch state is 0.

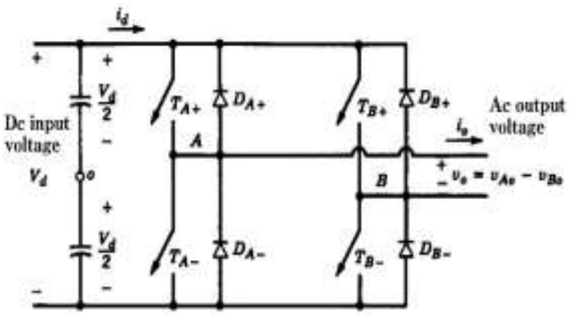


Fig. 2a. Single-phase full bridge Inverter *VSI*

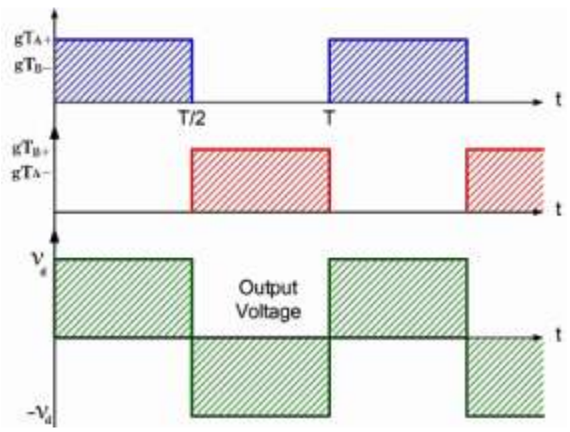


Fig. 2b. Voltage waveforms of single-phase bridge Inverter*VSI*

The switching is done by applying gating pulses for the diagonal pair of transistors gT_{A+} andgT_{B-} respectively for the single-phase full bridge Inverter, to obtain ac-output voltage at the load terminals. Hence, there are five switching combinations for the single-phase full bridge Inverter, which is as shown in Table 2.Therefore, the output voltage is given as a difference of individual one-leg voltages, v_{Ao} and v_{Bo} of the single-phase full bridge Inverter, which is,

$v_o = v_{Ao} - v_{Bo} = \pm V_d$(16)

Table 2. Switching states of a single-phase full-bridge *VSI*

State	State No	Switch state*	V_{Ao}	V_{Bo}	V_o
T_{A+}, T_{B-}: on &T_{B+},T_{A-} : off	1	10	$V_d/2$	$-V_d/2$	V_d
T_{B+} ,T_{A-}: on &T_{A+} , T_{B-} : off	2	01	$-V_d/2$	$V_d/2$	$-V_d$
T_{A+} , T_{B+} : on &T_{A-} , T_{B-}: off	3	11	$V_d/2$	$V_d/2$	0
T_{A-} , T_{B-} : on &T_{A+} , T_{B+}: off	4	00	$-V_d/2$	$-V_d/2$	0
T_{A+} , T_{B-} , T_{B+} , T_{A-} : off	5	off	$-V_d/2$	$V_d/2$	$-V_d$
			$V_d/2$	$-V_d/2$	V_d

The rms output voltage of single-phase full bridge Inverter is obtained by,

$v_0 = \sqrt{\left(\frac{2}{T}\right)\int_0^{T/2} V_d^2\,dt} = V_d$(17)

Where, $V_d$is the ac symmetrical output voltage, which is twice that of a single-phase half bridge Inverter and *T* is the time period of the output rms voltage.The instantaneous output voltage is expressed by Fourier series as,

$v_0 = \frac{a_0}{2} + \sum_{n=1,2,3\ldots}^{\infty}(a_n cos\ nwt + b_n sin\ nwt)$(18)

Due to the odd-wave symmetry of the Inverter output voltage along x-axis, both a_0 and $a_n$co-efficientsare zero,and we get b_n as,

$b_n = \frac{1}{\pi}\left[\int_{-\pi/2}^{0} -V_d \sin nwt\, dwt + \int_0^{\pi/2} V_d \sin nwt\, dwt\right] = \frac{4V_d}{n\pi}$
(19)

Which gives the instantaneous output voltage v_o as,
$v_o = \sum_{n=1,3,5\ldots}^{\infty} \frac{V_d}{n\pi} sin\ nwt$

= 0 for = 2, 4, 6,....(20)

Where ,$V_d$is the dc-input voltage and *n* an integer

B.SPWM with Bipolar voltage switching for single-phase full bridge Inverter

As discussed earlier diagonally opposite switches (T_{A+} ,T_{B-})and(T_{B+} ,T_{A-}) from the two legs A and B in Fig. 2a, are switched as switch pairs 1 and

2, respectively. The output waveform Inverterleg A is identical to the output waveform of basic one-leg Inverter in section II, which is determined in same manner by comparing $v_{control}$ andv_{tri} in Fig. 3a.

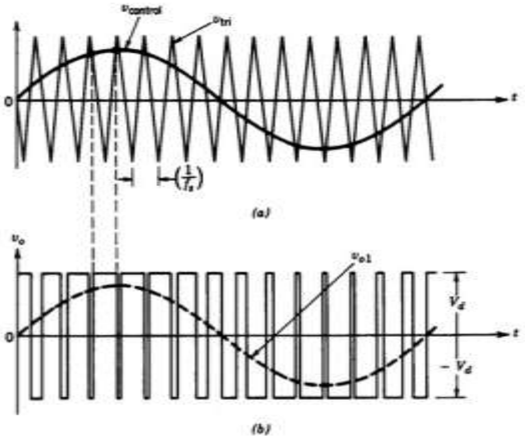


Fig. 3.*SPWM* with Bipolar voltage switching

The output of Inverter leg B is negative of the leg A output; for example, when T_{A+} is on and v_{Ao} is equal to$+\frac{Vd}{2}$,when T_{B-} is on $v_{BO}$is$-\frac{Vd}{2}$, hence

$v_{Ao}=-v_{BO}$(21)

and

$v_o(t)=v_{Ao} - v_{Bo} = 2v_{Ao} = V_d$(22)

The output voltage, v_o waveform is shown in Fig.3b, the analysis carried out for one-leg Inverter also applies to single-phase full bridge type of *SPWM* switching. Therefore, the peak of the fundamental frequency component in the output voltage, $(\hat{V}_{Ao})_1$can be obtained form Eqns. (10), (15) and (22) as,

$(\hat{V}_{Ao})_1 = m_a V_d, m_a \leq 1$(23)

and

$V_d < (\hat{v}_{Ao})_1 < \frac{4}{\pi} V_d$, $m_a > 1$(24)

In Fig. 3a, we observe that output voltage,$v_o$switches between $+V_d$ and $-V_d$voltage levels. Hence, this type of switching is called a *SPWM* bipolar voltage switching [8].

1.Filter analysis for VSI with SPWM Bipolar voltage switching scheme

The principle describing harmonic reduction in the Inverter, using 2nd order low pass filter is discussed, the same analogy isalso applicable for*SPWM* unipolar voltage switching scheme. For sake of simplicity, fictitious active 2nd order *LPF* will be used at the dc- side as well as ac- side, as shown in Fig. 3.1a. The switching frequency, f_s is assumed to be very high approaching infinity. Therefore, to filter out high switching frequency components inac-output voltage, $v_0$anddc-input current, $i_d$the energy storing elements C_1 and C_2 of the 2nd order *LPF*, required in both ac- and dc-side filters must be approaching zero, as shown in Fig 3.1a.This implies that the energy stored in the filters is negligible. Since the instantaneous power input must be equal to the instantaneous power output. Having these assumptions made output voltage, $v_0$in Fig 3.1a, is a pure sine wave at fundamental output frequency ω_1,

$V_{o1} = v_0 = \sqrt{2}V_o \sin \omega_1 t$(25)

The load is as shown in Fig. 3.1a, where e_o is a sine wave at fundamental frequency ω_1, then the output current,$i_o$will also be sinusoidal and would lag $v_0$for an inductive load such as an ac motor [9].

$i_o = \sqrt{2}I_o \sin(\omega_1 t - \theta)$(26)

Where θ is the angle by which$v_0$leads i_o.

On the dc-side, the 2nd order *LPF*will filter out high switching frequency components in i_d andi_d^* will only consist of dc and lowfrequency components. Assuming that no energy is stored in the filters,

$V_d(t) i_d^*(t) = v_o(t) i_o(t) = (\sqrt{2}V_o \sin\omega_1 t) \times (\sqrt{2}I_o \sin(\omega_1 t - \theta))$(27)

Hence,

$i_d^*(t) = \frac{V_o I_o}{V_d}\cos\theta - \frac{V_o I_o}{V_d}\cos(2\omega_1 t - \theta) = I_d + I_{d2}$(28)

$= I_d - \sqrt{2} I_{d2} \cos(2\omega_1 t - \theta)$(29)

Where,

$I_d = \frac{V_o I_o}{V_d}\cos\theta$(30)

and

$I_{d2} = \frac{1}{\sqrt{2}}\frac{V_o I_o}{V_d}$(31)

Equ. (28),for i_d^*shows that it consists of a dc component I_d, which is responsible for the power transfer from $V_d$on the dc side of the Inverter to the ac side. Also i_d^* contains a sinusoidal component at twice the fundamental frequency. The Inverter input current, i_d consists of i_d^* and the high frequency componenets due to Invertersswitching's, as shown in Fig. 3.2.

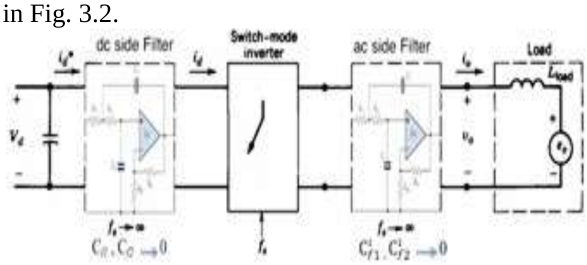


Fig. 3.1a Inverter with Fictitious filter on the dc- and ac-side

In practical systems, the previous assumption of a constant dc voltage as the input is not entirely valid. Usually this dc voltage is obtained by rectifying the ac utility line voltage. A large capacitor is used across the rectifier output terminals to filter dc voltage.

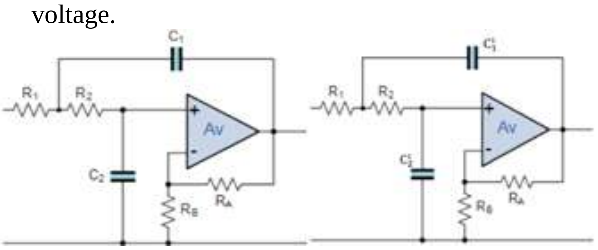


Fig. 3.1b Enlarged image of the dc- side and the ac-side filter

The ripple in the capacitor voltage, which is also the input to the Inverter, is due to two reasons;

1. The rectification of the line voltage does not result in a pure dc.
2. The current by a single-phase Inverter form a dc side is not a constant dc but has a second harmonic component of fundamental frequency, in addition to a high switching frequency components as described byEqu. (29)

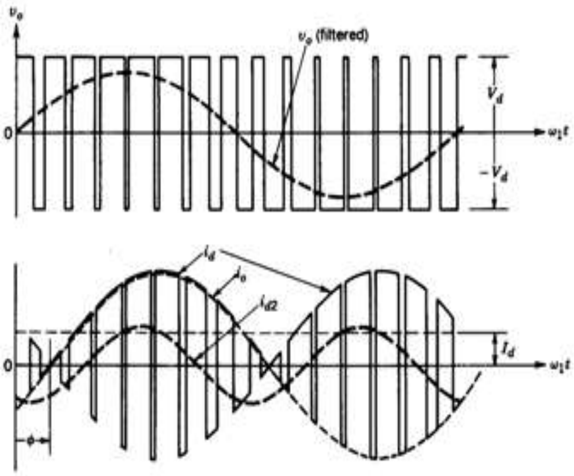


Fig. 3.2. The dc-side current in a single-phase Inverter with *SPWM* bipolar voltage switching

C.SPWM with unipolar voltage switching for single-phase full bridge Inverter

The legs A and B of the single-phase full bridge Inverter are controlled separately by comparing v_{tri} with $v_{control}$ and$-v_{control}$,respectively. As shown in Fig 4a, the comparisonof $v_{control}$ with triangular waveform,v_{tri} results in the following logic signal to control the switches in leg A:

$v_{control} < v_{tri}$: T_{A+}on and $v_{AN} = V_d$(32)
$v_{control} > v_{tri}$: T_{A-}on and $v_{AN} = 0$

The output voltage of Inverter leg A with respect to negative dc bus N is shown in the Fig 4b. For controlling the leg B switches,$-v_{control}$ is compared with the same triangular waveform, which yields the following:

$-v_{control} > v_{tri}$:T_{B+} on and $v_{AN} = V_d$(33)
$-v_{control} < v_{tri}$: T_{A-} on and $v_{AN} = 0$

Table 4. Output voltages of a single-phase full bridge Inverter employing unipolar voltage *SPWM* switching

Switches	LegA	Leg B	Output voltage
T_{A+} , T_{B+}: on	$v_{AN}= V_d$	$v_{BN}= V_d$	$v_o = 0$
T_{A+} , T_{B-}: on	$v_{AN}= V_d$	$v_{BN}= 0$	$v_o=V_d$
T_{A-} , T_{B-}: on	$v_{AN}= 0$	$v_{BN}= 0$	$v_o = 0$
T_{A-} , T_{B+}: on	$v_{AN}= 0$	$v_{BN}= V_d$	$v_o= -V_d$

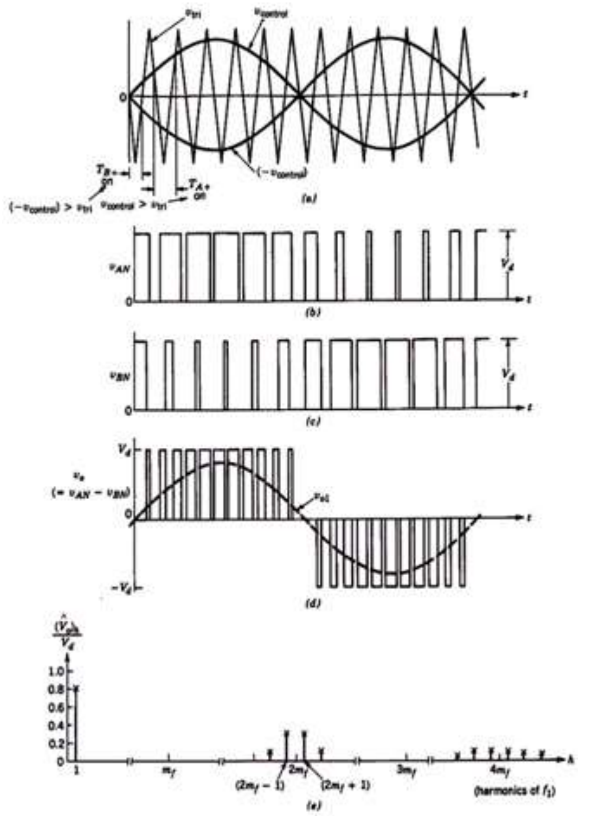


Fig. 4. *SPWM* with unipolar voltage switching for single-phase full bridge Inverter

Because of feedback diodes in antiparallel with the switches, the foregoing voltages given by Eqns.(32)and(33) are independent of the direction of the output load current, i_o.Hence from the Table 4, it is seen that when both the upper switches, T_{A+}, $T_{B+}$and lower switches, T_{A-}, T_{B-} are on the output voltage is zero, because the current circulates through the loop (T_{A+}andD_{B+}) or($D_{A+}$and T_{B+}),respectively depending upon the direction of load current, i_o. During this interval, the input current, i_d is zero. A similar condition occurs when the bottom switches T_{A-}, $T_{B-}$are on.In this type of *SPWM* scheme, when switching occurs, the output voltage changes between zero and $+V_d$ or between zero and $-V_d$ voltage levels. Hence this type of *SPWM* scheme is called unipolar voltage switching. Unipolar voltage switching scheme has the advantage of efficiently doubling the switching frequency as far as the output harmonics are concerned, compared to the bipolar voltage switchingscheme.

Also the voltage jumps in the output voltage at each switching are reduced to V_d, as compared to $2V_d$ in the bipolar scheme as seen from Fig. 4d.The advantage of efficiently doubling the switching frequency appears in the harmonics spectrum of the output voltage waveform, where the lowest harmonics appear as sidebands of twice the switching frequency. The voltage waveforms v_{AN} and v_{BN} are displaced by 180^0 of the fundamental frequency,f_1 with respect to each other which results in the cancellation of the harmonic component at the switching frequency in the output voltage v_o=$v_{AN} - v_{BN}$.In addition,the sidebands of the switching frequency harmonics disappear. In a similar manner, the other dominant harmonic at twice the switching frequency cancels out, while its sidebands do not.

Hence,

$$\hat{v}_{o1} = m_a V_d, m_a \leq 1 \quad (34)$$

and

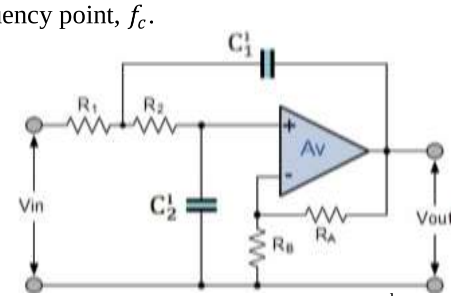
$$V_d < \hat{V}_{o1} < \frac{4}{\pi} V_d \quad (35)$$

IV. LOW PASS FILTER DESIGN

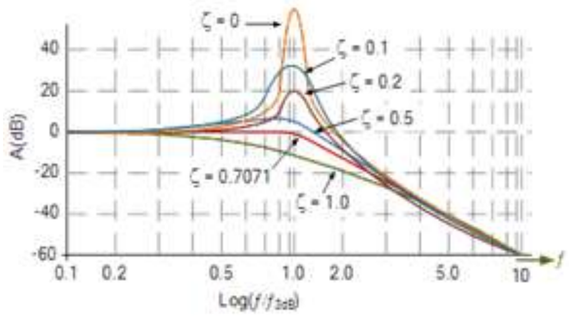
A low pass filter is adopted at the load terminals of the single-phase full bridge Inverterto attenuate the harmonic components of the fundamental frequency,$f_1$which causes non-sinusoidal Inverter output voltage. A 2nd order *LPF* is used for thispurpose, as there will be a narrower transition band and the response will be nearer to the ideal case.Assuming that the input to the Inverter is a pure rectified dc containing no ripples, the dc-side filter is eliminated and therefore, the design of ac side filter is discussed and the latter is used at the output terminals of the single-phase full bridge Inverter.

A. Second order Low pass Filter

A Sallen-key 2nd order *LPF* is used as, ac-side filter since it offers high gain greater than unity, with practically infinite input impedance and zero output impedance. Because of high input impedance and easily selectable gain, an operational amplifier is used ina non-inverting mode.The 2nd order *LPF* used requires two *RC* networks, R_1,$C_1^{\prime}$and R_2,$C_2^{\prime}$, which gives the filter its frequency response characteristics and the operational amplifier is connected in non-inverting configuration to obtain a voltage gain, $A_V$greater than unity. A schematic diagram of the 2nd order *LPF* is as shown in Fig.5, and the frequency response characteristics is as shown in Fig. 5a.A low pass filter will always be low pass in nature, but can exhibit a resonant peak in the vicinity of the cut-off frequency, i.e., the gain can increases rapidly due to resonance effects of the amplifiers gain.Filter gain also determines the amount of its feedback and therefore,has a significant effect on the frequency response of the filter, henceto maintain stability, an active filter gain, A_V must not be exceed a value of 3, and is best expressed as Quality factor Q, which represents the peakiness of this resonance peak, i.e.,its height and narrowness around the cut-off frequency point, f_c.



(a) Schematic diagram of Sallen-key 2ndorder LPF



(b) Frequency response characteristicsof 2nd order *LPF*

Fig. 5. Sallen-key 2ndorder low pass filter

Hence,thevoltage gain, A_V of an non-inverting amplifier configuration must lie in between 1 and 3, hence forcing the damping factor zeta, ζ to lie form 0 and 2 as governed by,

$$A = 3 - 2\zeta \quad (36)$$

Where,
A, is the gain of the non-inverting amplifier configuration.
and
ζ, is the damping factor, zeta given by,

$$\zeta = \frac{3-A}{2} = \frac{1}{2Q} \quad (37)$$

By substituting the value of ζ in Equ. (36), results in the gain equation as given by,

$$A_V = 3 - \frac{1}{Q} \quad (38)$$

Therefore, higher values of Quality factor, Q or lower values of zeta, ζ results in a greater peak of the response and a faster initial roll-off rate. The amplitude response of 2nd order *LPF* varies for different values of damping factorzeta, ζ. When ζ>1, the filter response becomes over-damped with its frequency response showing a long flat curve. When $\zeta = 0$, the filter output peaks sharply at a cut-off point at which the filter is said to be in under-damped condition, hence for zeta, $\zeta = 0.7071$ in the range of $0 < \zeta < 1$, the filter exhibits critically-damped response, as seen form the frequency response characteristics in Fig. 5b.

B. Second order Low pass Filter design

The filter is to be designed around a non-inverting op-amp with equal resistor and capacitor values based on the specifications of damping factor zeta, ζ and cut-off frequency, f_c.The gain of an Sallen-key filter is given by Equ. (39). The cut-off frequency, f_c if the resistors and capacitors values are different is given by Equ. (40). The cut-off frequency, $f_c$if the resistances and capacitances are equal is given by Equ. (41),

$$A_V = 1 + \frac{R_A}{R_B} \quad (39)$$

$$f_c = \frac{1}{2\pi\sqrt{R_1 C_1 R_2 C_2}} \quad (40)$$

$$f_c = \frac{1}{2\pi RC} \quad (41)$$

For a specification of damping factor zeta,$\zeta = 0.7071$ and cut-off frequency,f_c = 500hz the 2nd order *LPF* is designed.

Choose, $R_1 = R_2 = R = 10K\Omega$ and $C_1 = C_2 = C$

For a specified cut-off frequency the capacitor value $C$is given by,

$$C = \frac{1}{2\pi R f_c} = \frac{1}{2\pi \times 10 \times 10^3 \times 500} = 31.81nF$$

The Quality factor, Q is given by

$$Q = \frac{1}{2\zeta} = \frac{1}{2 \times 0.7071} = 0.7071$$

The voltage gain, A_V is given by,

$$A_V = 3 - \frac{1}{Q} = 3 - \frac{1}{0.7071} = 1.5857$$

To find the values of $R_B$for a fixed value of R_A= $10K\Omega$, is found using the filter gain equation as given by Equ. (38), hence,

$$1.5857 = 1 + \frac{R_A}{R_B}$$

$$\frac{R_A}{R_B} = 0.5857$$

$$R_B = \frac{R_A}{0.5857} = \frac{10 \times 10^3}{0.5857} = 17.0735K\Omega$$

So, using the above designed values for resistors and capacitors the filter is designed to get the desired damping factor, $\zeta = 0.7071$ and cut-off frequency of, f_c = 500hz.

C. Simulation of Low Pass Filter for single-phase full bridge Inverter using SPWM unipolar voltage switching

The simulation is carried out using Matlab/Simulink platform where the *SPWM* pulses are generated using the comparator logic as shown in the Fig. 5.1a. Where $v_{control}$ and $-v_{control}$ is compared with the carrier signal,v_{tri}. The switching methodology to generate sinusoidal pulse-width modulation signal is as shown in Table. 5.

Table 5. Switching states of the *SPWM* generation logical circuit

Control signal	Comparison	Triangular signal	Switch states	
$v_{control}$	>	v_{tri}	$T_{A+}: on$	$T_{A-}: off$
$-v_{control}$	<	v_{tri}	$T_{B+}: on$	$T_{B-}: off$

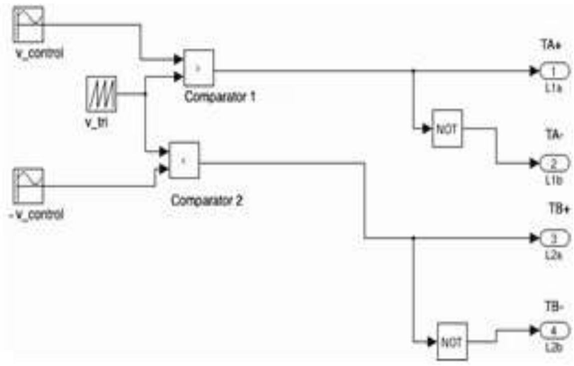


Fig. 5.1a*SPWM* signal generation for necessary switching

The pulses, which are given to the switches, are viewed separately by connecting the respective pulses given to the switches to a scope element of Simulink library, this is done so as to conform the switching sequence of the Inverter, and is as shown below in Fig. 5.1b. The pulses fed to the switches can be seen by double clicking the scope element, which is shown in Fig. 5.1c.

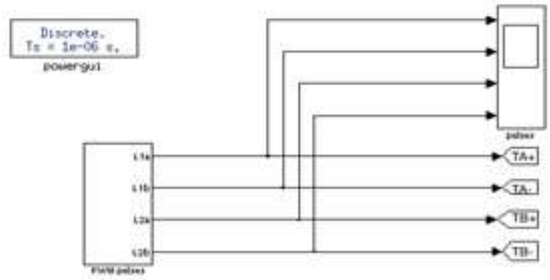


Fig. 5.1b. The pulses of the switches connecting the Scope element of Simulink

Parameters:
Switching frequency, f_s = 4000hz
PWM reference = 4V, for the range $0V$ to $5V$
Time period : 1/50 sec

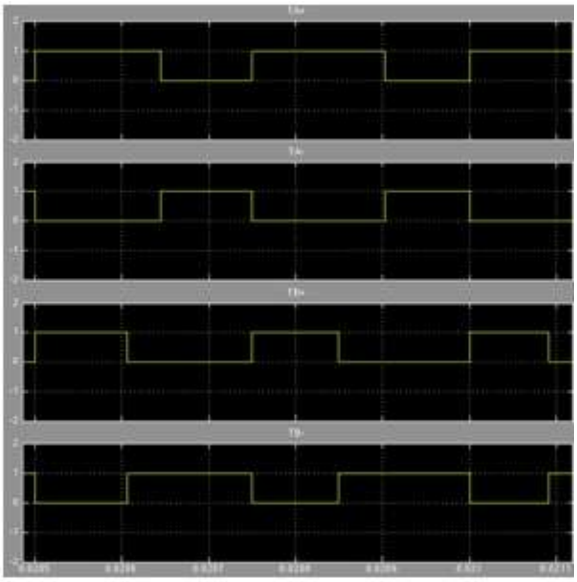


Fig. 5.1c. The pulses fed to the Inverter switches

1. Single-phase full bridge Inverter without filter

Simulink tool of Matlab is used for rigging up the single-phase full bridge Inverter without a filter as shown in Fig. 5.1d, where a dc voltage source, V_{dc} is used to supply the Inverter circuit and *MOSFET's* are used as switches for the leg's ofInverter circuit, and the output voltage and current is measured across resistive load using scope element of Simulink. The respective output voltage and current waveforms across the resistive load is shown in Fig. 5.1(e)

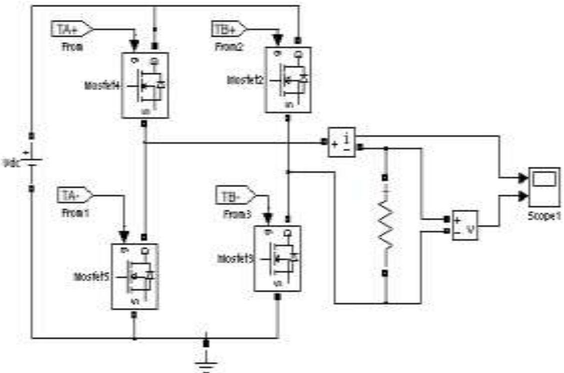


Fig. 5.1d. Single-phase Inverter without filter

Input parameters:
Dc supply voltage,$V_{dc} = 200V$
*MOSFET's*switching frequency, f_s = 4000hz

Output parameters:
Ac-output voltage, V_{ac} = 200V (square wave)
Load resistor,R = 100Ω
Ac-output current, I_{ac} = 2A(square wave)

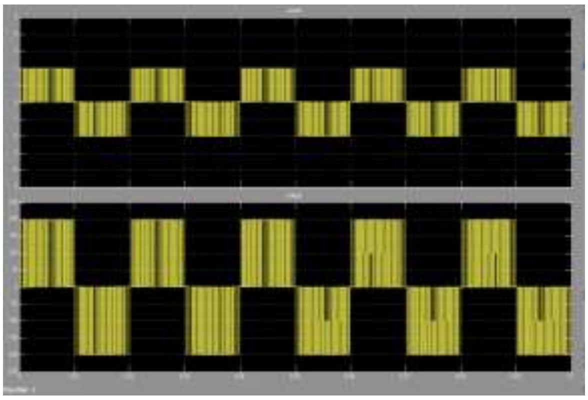


Fig. 5.1e. Output voltage and current waveforms of single-phase full bridge Inverter without filter

2. Single-phase full bridge Inverter with filter

The output of a single-phase full bridge Inverter is fed to a 2nd order *LPF* and then to the resistive load. The Simulink model of the single-phase full bridge Inverter with filter is traced in Matlab as shown in Fig. 5.2a. The output voltage and current waveforms of the single-phase full bridge Inverter is shown in Fig. 5.2b.

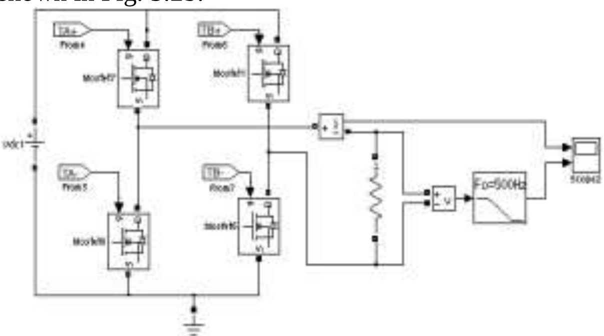


Fig. 5.2a. Simulink model of single-phase full bridge Inverter with filter

Input parameters:
Dc supply voltage, $V_{dc} = 200V$
MOSFET's switching frequency, f_s = 4000hz
Output parameters:
Ac-output voltage, V_{ac} = 200V (sine wave)
Load resistor,R = 100Ω
Ac-output current, I_{ac} = 2A (sine wave)

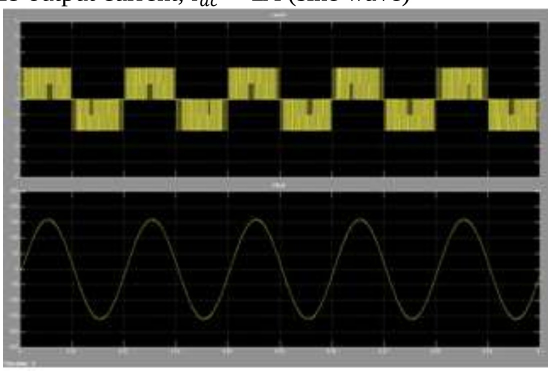


Fig. 5.2b.Output voltage and current waveforms of single-phase full bridge Inverter with filter

IV. CONCLUSION

In this paper, by the use of 2nd order *LPF* in an Inverter, it is clear that total harmonic distortion, *THD* is reduced drastically, by means of using the filter at the output ofan Inverter, results in near sinusoidal Inverter output, which can be clearly observed from the simulation results obtained.

In order to reduce *THD* to a greater extend the filters can be cascaded, hence resulting in 99.9% pure sinusoidal output waveform of an Inverter.Inverters find its application in domestic applications like *UPS*, Induction heating etc.,Inverters also can be synchronized to the power grid which provides better power reliability,making us less dependent on the power generation sector, this can be achieved by using an *LCL* filter connected at the output side of an Inverter and stepping the voltage up by power transformers for grid connection purposes, which finds latest application in renewable energy technologies.

REFERENCES

[1] B.D. Bedford and R.G.Hoft, *Principles of Inverter Circuits.* New York: John Wiley & Sons. 1964.

[2] M.H. Rashid, Power Electronics, Circuits, Design and Applications. 3rd Ed; Pearson Education Inc.

[3] H. Pankaj, G. Pravin and Prashant, "Design and Implementaiton of carrier based Sinusoidal PWM Inverter," *International Journal of Advanced Research in Electrical and Instrumentation Engineering.*,vol 1, Issue 4, October. 2012.

[4] A.K. Sharma and Nidhi Vijay, "Unipolar and Bipolar SPWM voltage modulation type Inverter for Improved Switching frequencies," *International Journal of Engineering Sciences and Research.*, vol 3, Issue 8, August. 2014.

[5] Ned Mohan, T.M. Undeland, W.P. Robbins, *Power Electronics, Coverters, Application and Design.* 3rd Ed; Wiley Education Inc.

[6] M Sachin and P Khampariya, "Simulaiton of SPWM single phase Inverter", *International Journal of Innovative Research in Advanced Engineering.*, vol 1, Issue 9, August. 2014.

[7] M. Boostt and P.D. Ziogas, "State-of-the Art PWM Techniques: A Critical Evaluation," *IEEE Power Electronics Specialists Conference*, pp. 425-433, 1986.

[8] J.W.A. Wilson and J.A. Yeamans, "Instrinsic Harmonics of Idealized Inverter PWM Systems," *IEEE/IAS Anuall meeting*, pp. 611-616, 1986.

[9] Y. Murai, T. Watanabe and H. Iwasaki, " Waveform Distrotion and Correction circuit for PWM Inverters with Switching Lag-Times,"*IEEE/IAS Anuall meeting*, pp. 436-441, 1985.

AUTHORS

First Author – Yugendra Rao K N, 6th Sem
B.E, Electrical and Electronics engineering
student, RV College of Engineering, Bangalore-5600059.

His primary research areas include power electronics and distributed generation, renewable energy systems, power quality, high-power converters and motor drives.

Email-id: yugendra.raokn.1994@ieee.org