An Ideal Steady State Output Voltage of a Single-Phase PWM Inverter

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Abstract: This paper presents investigation on the performance of a single phase PWM inverter system using Insulated Gate Bipolar Transistors (IGBTs). For obtaining optimum voltage waveforms, the firing and commutation instants must be scheduled properly. The control circuit for such a system has been studied and implemented.
Effect of the ratio of the carrier frequency to the reference frequency on the voltage harmonic content has been discussed and presented.
It is well known that for inductive loads, snubber circuits become necessary. In the present paper, a method has been devised to calculate the proper values of the snubber circuit parameters. The validity of the devised method has been checked by using it with different operating conditions.
Waveforms and harmonic spectrums for load voltage have been simulated and presented using SIMPLORER software.

Key words: PWM inverter, harmonic reduction, snubber circuit

1 INTRODUCTION

In PWM inverter system, the semiconductor devices are switched on and off many times within a half-cycle to generate a variable voltage, at a desired frequency, which has normally low harmonic content.

Among several PWM techniques, sinusoidal PWM is the best one [Bose, 2002; Dubey, 1989]. An isosceles triangle carrier wave is compared with the modulating sine wave and the crossover points determine the instants of triggering and commutation. The fundamental output voltage can be varied by variation of the modulation index (m) [Berde, 1988; Murphy et. al., 1988]

For high power applications, thyristors are used. However, for low power applications IGBTs are very attractive in dc link converters due to the absence of commutation circuitry [Bimbhra, 2002; Mohan et. al., 1989; Skvarenina, 2002]. Thus, in the present work, IGBTs are adopted in the PWM inverter circuit.

When the load is inductive, its inductance helps in filtering, partially, some of the harmonic content of the current, hence reducing current distortion. This inductance, however, affects the dynamics of the IGBT resulting, at least, in a highly disturbed output voltage. In such a case, snubber circuits are necessary. In the present paper, a method has been devised to calculate the proper values of the snubber circuit parameters. Although, it started by trial and error, the devised method landed to an expression which can be applied to any inductive load.

The validity of the devised method has been checked by using it at different operating conditions.

For the purpose of analysis, SIMPLORER software has been used.

2 POWER AND CONTROL CIRCUIT OF A 1-PHASE□□PWM INVERTER

The firing pulses of the PWM inverter are obtained at the instants of intersection of the carrier wave and the reference sine waves. It is well known that better output voltage is obtained from the PWM inverter if the maximum of the carrier wave is synchronized with zero of the reference wave. Further, frequency of the carrier wave (f_c) is related to the frequency of the reference wave (f_r) as follows [Bimbhra, 2002; Mohan, 1989]

$f_c = 2\ n\ f_r$;   n = 1, 2, 3, 4, ……………. (1)

The power and control circuit of a 1-ϕ PWM inverter as fabricated in SIMPLORER software is shown in Fig. 1.

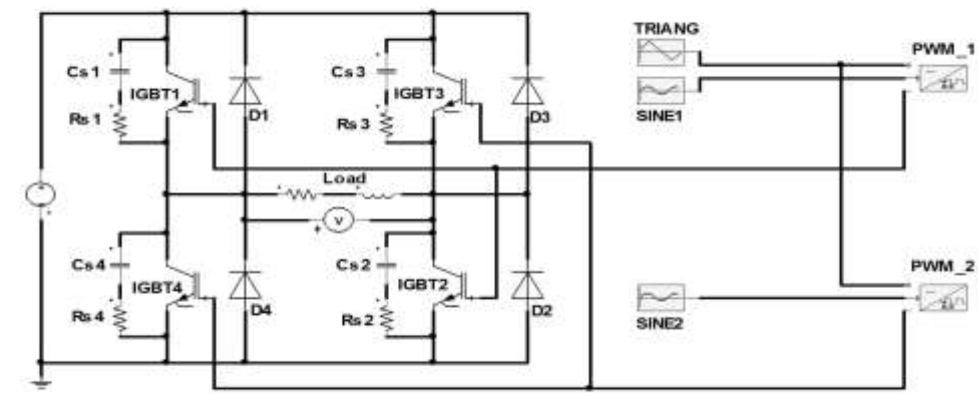
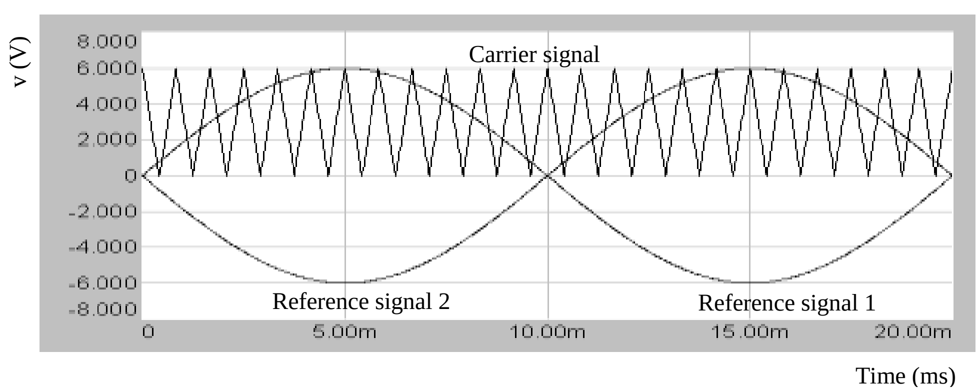


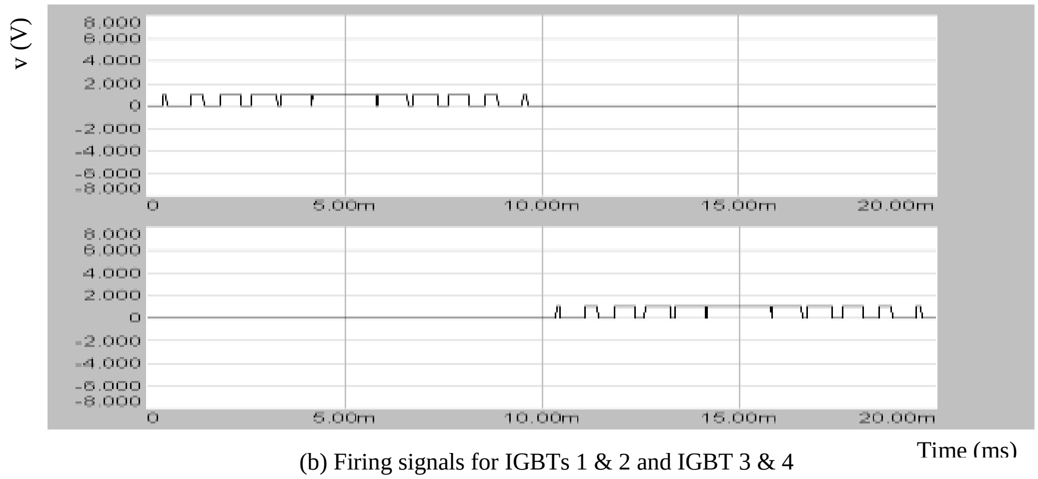
Fig. 1 Power and control circuit of a 1-ϕ PWM inverter

The block TRIANG provides the carrier signal and the blocks SINE1 and SINE2 provide the reference signals. These signals are illustrated in Fig. 2 (a).



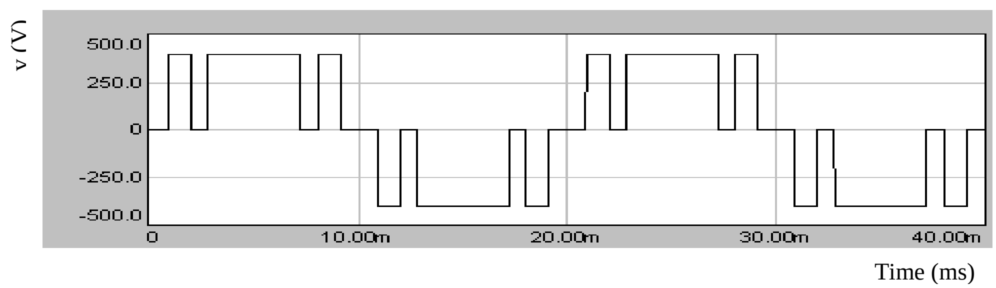
(a) Carrier and reference signals

These signals are compared in a comparator (blocks PWM_1 and PWM_2) and the resulting firing signals are shown in Fig. 2 (b).

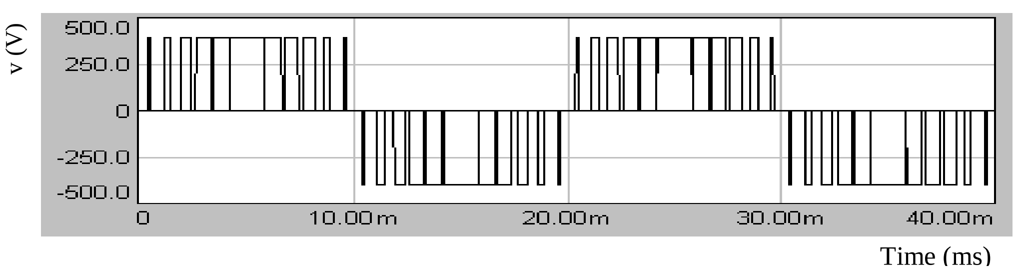


(b) Firing signals for IGBTs 1 & 2 and IGBT 3 & 4
Fig. 2 Control signals

For R-load, the snubber circuits are not required, in Fig. 1. The above circuit is first simulated, with R-load only, to obtain the output voltage considering a low value of carrier frequency, as obtained from Equation (1), $f_c = 2 \times 4 \times 50 = 400$ Hz, then a higher value of carrier frequency, $f_c = 2 \times 12 \times 50 = 1200$ Hz. The output frequency, f_o, is taken as 50 Hz. The simulated voltage waveforms for the above two cases are shown in Fig. 3.



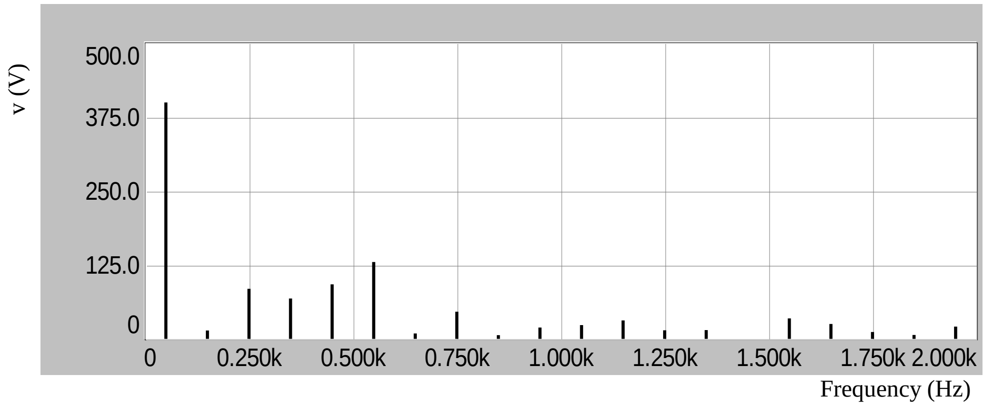
(a) $f_o = f_r = 50$ Hz, $f_c = 400$Hz



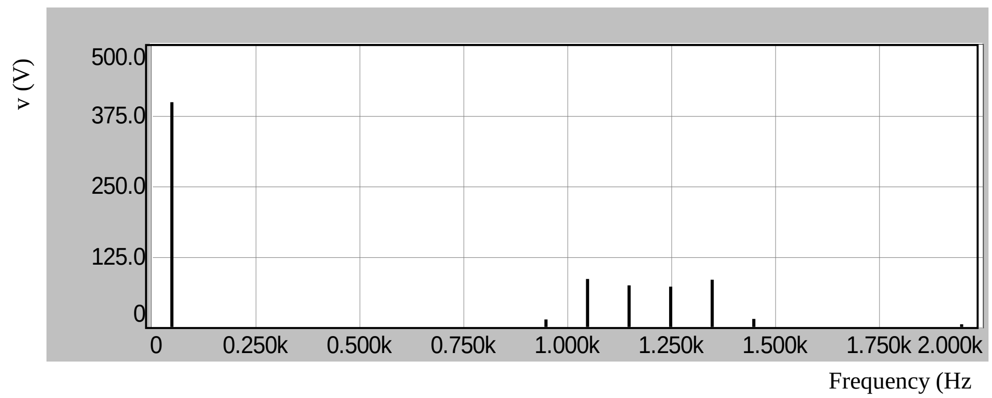
(b) $f_o = f_r = 50$ Hz, $f_c = 1200$Hz
Fig. 3 Output voltage waveforms **(**R-load)

Comparing Fig. 3 (a) and (b) suggests that the output voltage improves as the carrier frequency is increased.

The superiority of using higher values of carrier frequencies becomes more evident by comparing the simulated harmonic spectrums of the two cases as shown in Fig. 4 (a) and (b) for $f_c = 400$ Hz and $f_c = 1200$ Hz respectively.



(a) f_c = 400 Hz



(b) f_c = 1200 Hz

Fig. 4 Harmonic spectrums of output voltage (R-load)

However using very high value of f_c will increase the switching losses of the inverter devices and requires faster switching devices. In this paper, we have attempted f_c = 1200 Hz as the carrier frequency for single phase operation [Mohan, 1989].

3 SINGLE PHASE PWM INVERTER FEEDING AN RL-LOAD

When the load is inductive, it is well known that snubber circuit is necessary for protecting any semiconductor device from damage or false triggering which may result, at least, in a distorted output voltage of the inverter [Skvarenina, 2002; Mohan, 1989].

Fig. 5 presents the voltage waveform across a (2 + j 0.005) inductive load, when the PWM inverter is operated without snubber circuit.

As seen the output voltage is much distorted as compared to that shown in Fig. 3, when the load is resistive. This ensures that, for an inductive load, snubber circuit is necessary for a better output voltage waveform.

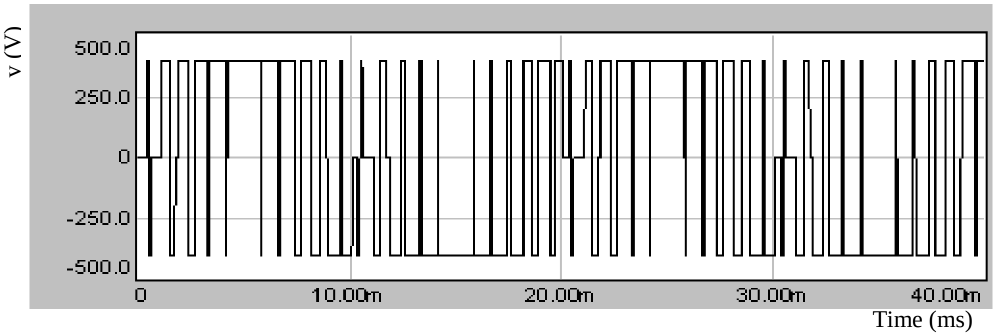


Fig. 5 Output voltage waveform of the PWM inverter feeding an inductive load (without snubber circuit)

As seen the output voltage is much distorted as compared to that shown in Fig. 3, when the load is resistive. This ensures that, for an inductive load, snubber circuit is necessary for a better output voltage waveform.

4 DESIGN OF THE SNUBBER CIRCUIT

The parameters of the snubber circuit are selected using an equation which has been devised by trial and error as well as inspection.

Similar expression has been used in [Jürg Waldmeyer, Björn Backlund 2008] although obtained differently. They also estimated snubber power loss. In [Angelo L. Gattozzi and John A. Pappas 2003], snubber and triggering circuits have been combined. However, addition diodes and resistors have been used.

In the present paper, the method attempted is explained in what follows:

After a lot of trials, the value of the snubber resistance (R_s) is made equal to the load resistance (R). Then for a particular value of load inductance (L), the value of the capacitance C_s is varied over a wide range. For each value of (C_s) the output voltage is examined closely till an optimum PWM voltage is reached, by inspection. In this manner the value of C_s is selected corresponding to different values of (L).

Fig. 6 presents the relation between load inductance (L) and snubber capacitance (C_s), which results in best voltage waveforms, maintaining equal values of load resistance (R) and snubber resistance (R_s). For the design purpose, R is taken randomly, as 2 Ohms, thus R_s = 2 Ohms too.

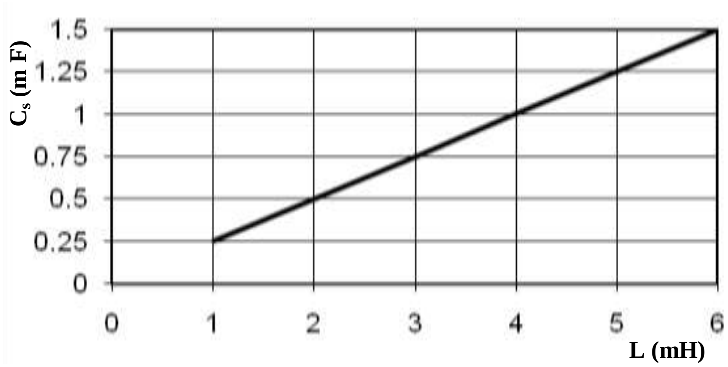


Fig. 6 Relation between load inductance (L) and snubber capacitance (C_s)

As shown, the load inductance (L) is related linearly with the snubber capacitance (C_s). Thus, it can easily be deduced that, $C_s = 0.25$ L. This equation, can be written as $C_s = L/4$ or $C_s = L/2^2$, i.e. $C_s = L/R^2$, from which the following equation is obtained

$R\ C_s = L/R$
Or
$R\ C_s = L/R$ ………………………………….. (2)

Where $R_s = R$

The above equation reveals that, for optimum shape of output voltage of the PWM inverter, snubber circuit time constant (τ_s) must equal to load time constant (τ), keeping $R_s = R$. It may be noted that losses of snubber circuit is out of the scope of this paper.

5. PERFORMANCE OF PWM INVERTER WITH SNUBBER CIRCUIT

For R = 2 Ohm and L = 5 mH the values of snubber circuit parameters obtained from Equation (2) are R_s = 2 ohm and $C_s = \frac{0.005}{2^2} = 1.25$ mF. Of course, this value varies depending on the load. Using these values, the load voltage is obtained and presented in Fig. 7.

Comparing this figure with Fig. 5, reveals the superiority of the voltage waveform when snubber circuits are used. Fig. 7 also, proves the correctness of Equation.(2).

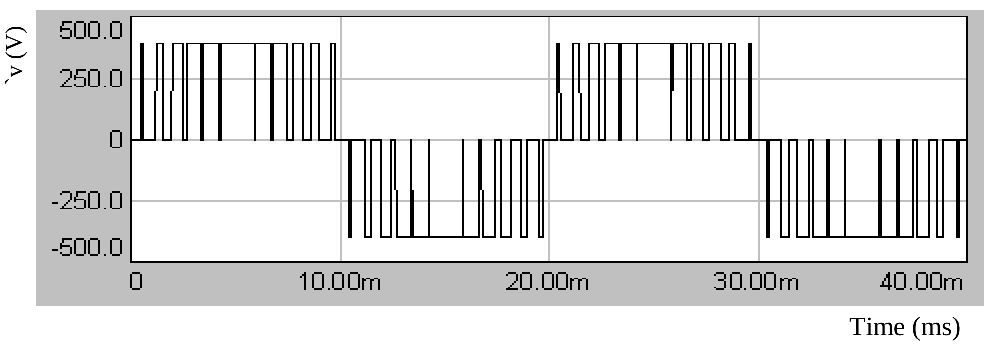


Fig. 7 Output voltage waveform of the PWM inverter feeding an inductive load
(R = 2 Ohm and L = 5 mH, R_s = 2 Ohm, C_s = 1.25 mF)

The correctness of this equation is again validated by changing the load inductance to 10 mH and correspondingly C_s is adjusted to 2.5 mF and the waveform so obtained is shown in Fig. 8.

It can be proved that if C_s is increased or decreased out of Equation (2), the output voltage waveforms will be distorted as illustrated in Fig. 9 (a) and (b), respectively.

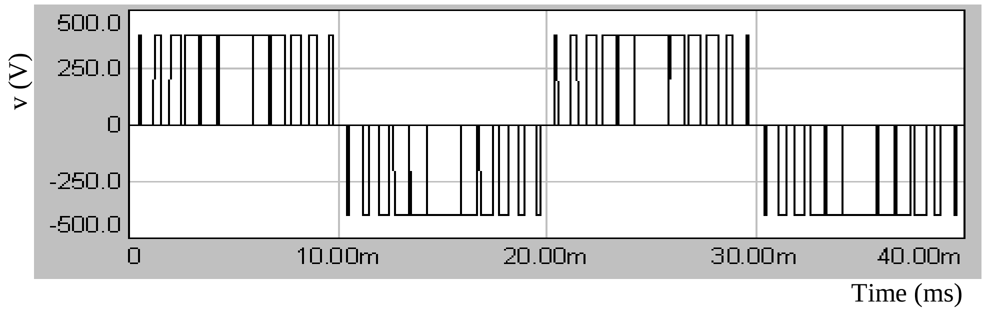
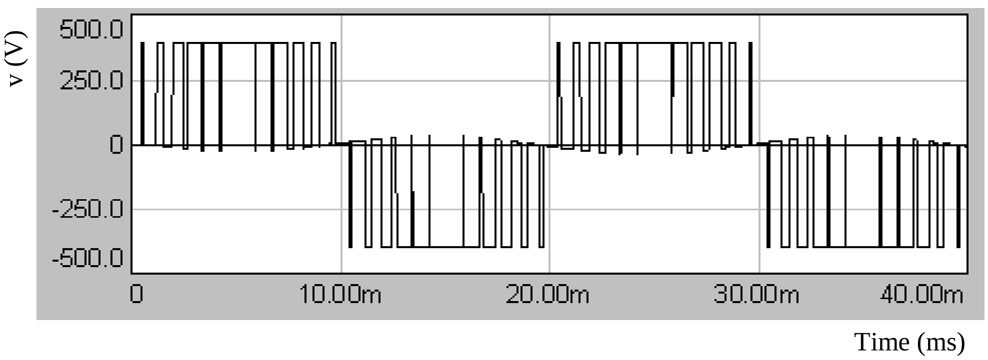
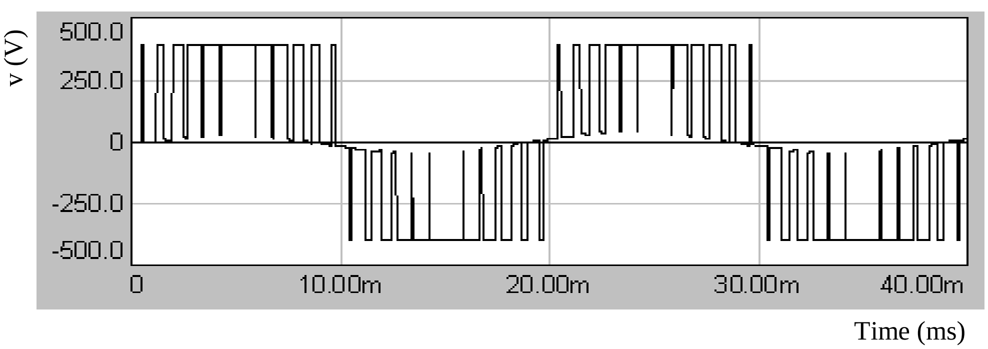


Fig. 8 Output voltage waveform of the PWM inverter feeding an inductive load
(R = 2 Ohm and L = 10 mH, R_s = 2 Ohm, C_s = 2.5 mF)



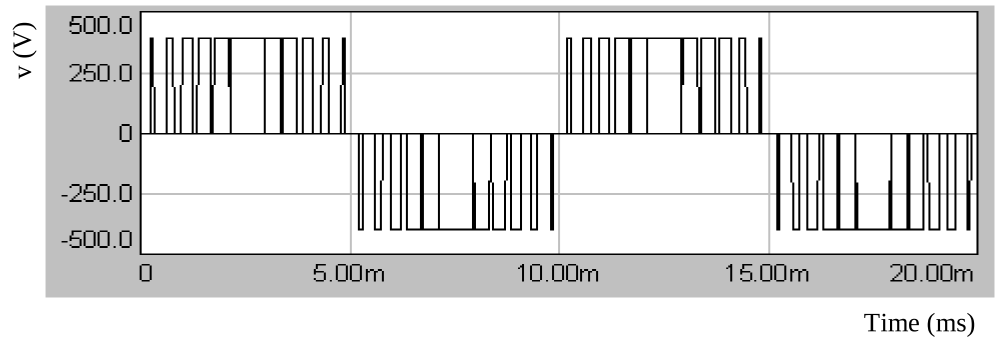
(a) (R = 2 Ohm and L = 5 mH, R_s = 2 Ohm, C_s = 1.5 μF)



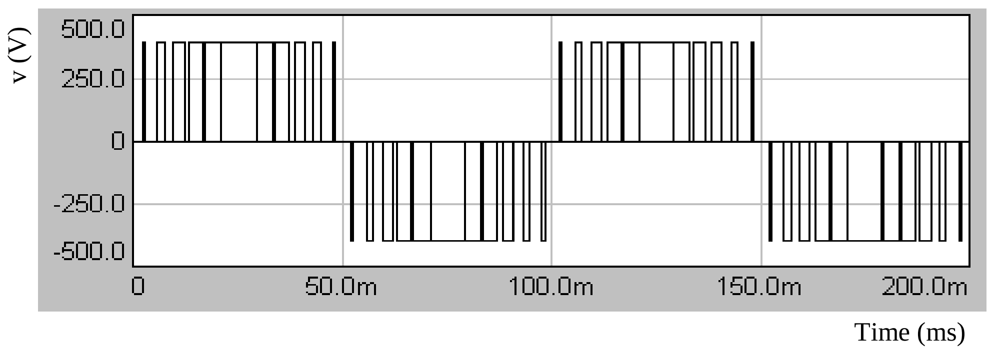
(b) (R = 2 Ohm and L = 5 mH, R_s = 2 Ohm, C_s = 1 mF)

Fig. 9 Output voltage waveform of the PWM inverter feeding an inductive load
(with incorrect value of C_s)

Equation (2), holds true for any output frequency. This fact is also illustrated in Fig. 10 (a) and (b), for 100 Hz and 10 Hz respectively. Note that the carrier frequency is now adjusted according to Equation (1) for n = 12.



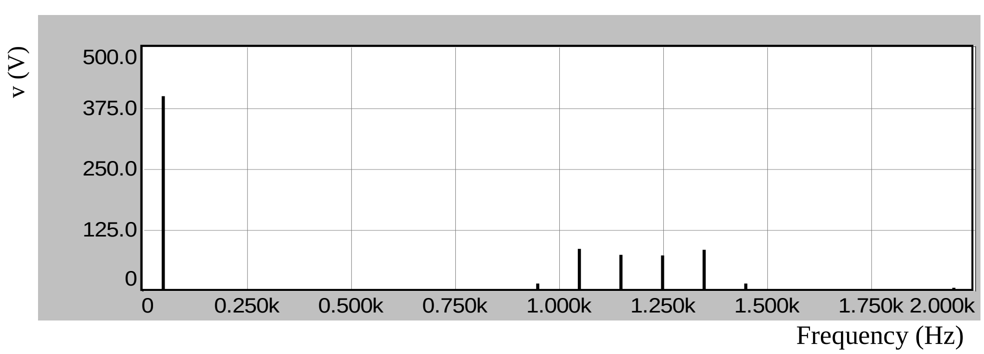
(a) f_o = 100 Hz, f_c = 2400 Hz, R = 2 Ohm and L = 5 mH, R_s = 2 Ohm, C_s = 1.25 mF



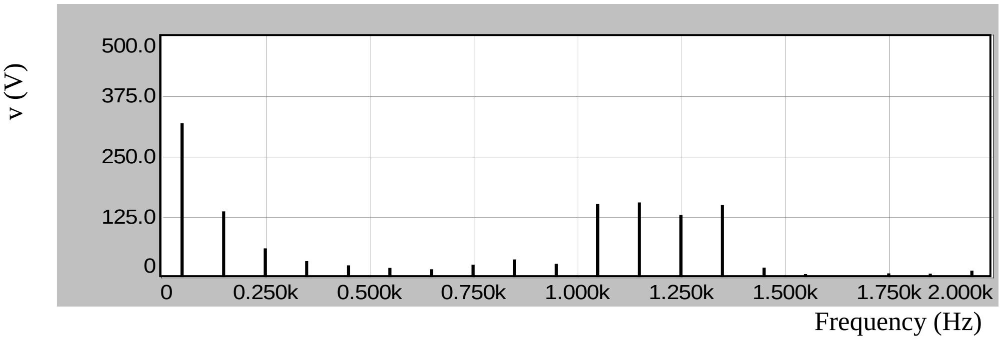
(b) f_o = 10 Hz, f_c = 240 Hz, R = 2 Ohm and L = 5 mH, R_s = 2 Ohm, C_s = 1.25 mF

Fig. 10 Effectiveness of the devised snubber circuit for different output frequencies

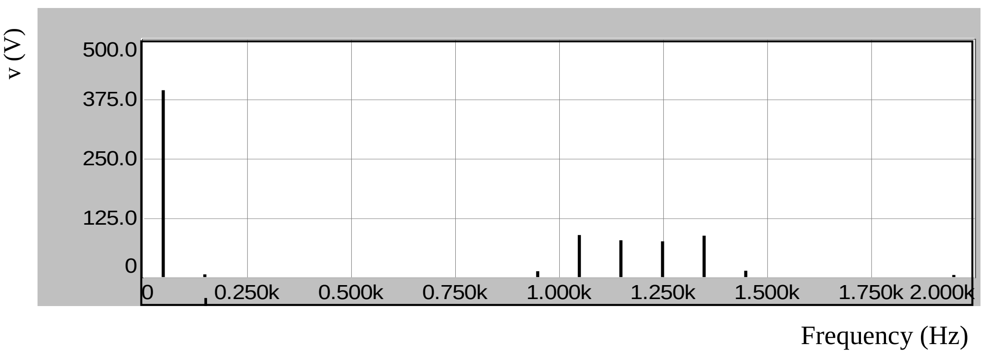
Qualitatively, harmonic spectrums reveal that harmonic content in the voltage waveform of Fig. 7 is much better as compared with that of Fig. 5, when no snubber circuit is used. The picture is also true, but to a lesser degree, when comparison is made with the harmonic content in the voltage waveform of Fig. 9 (a). This is because the value of C_s (1.5 mF) is still close to the correct value (1.25 mF). These comparisons are shown in Figs. 11 (a), (b) and (c) respectively.



(a) Harmonic spectrum of voltage waveform presented in Fig. 7



(b) Harmonic spectrum of voltage waveform presented in Fig. 5



(c) Harmonic spectrum of voltage waveform presented in Fig. 9 (a)
Fig. 11 Harmonic spectrums of output voltage,
showing the effectiveness of the snubber circuit

6. CONCLUSION

The paper presents investigation on the performance of a single phase PWM inverter feeding R-load and RL-load. IGBTs have been used as switching devices in the inverter circuit. The power and control circuits for such inverter have been developed, using SIMPLORER software, to provide the turn-on and turn-off signals to the IGBTs at the correct instants.

To obtain optimum output voltage waveforms from the PWM inverter, the maximum of the carrier wave must be synchronized with the zero of the reference wave. Further, the carrier frequency should be an even integer of the reference frequency.

For inductive loads, snubber circuits become necessary. In the present paper, a method has been devised to calculate the proper values of the snubber circuit parameters. The validity and effectiveness of the devised method has been checked by simulating the PWM inverter system with different operating conditions. Waveforms and harmonic spectrums so obtained have been presented and discussed.

In the present paper, loss aspect of the snubber circuit has been ignored which needs to be considered. This may be a subject of another paper.

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