

## DESIGN ANALYSIS OF LOW-PASS LC PASSIVE FILTER IN SINGLE-PHASE GRID-CONNECTED TRANSFORMERLESS INVERTER

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### ABSTRACT

Presented is the design analysis of a single-phase grid-connected photovoltaic-inverter low-pass-output filter. It minimizes switching-frequency current harmonics, improving output response. The inverter is H-bridge zero vector rectifier (HB-ZVR) transformerless topology. Switching frequencies 8kHz, 14kHz, and 20kHz were compared for validation of the simulation and the experiment.

**Keywords:** Transformerless DC-AC converter, LC filter system

### 1. INTRODUCTION

Transformerless is the norm in grid-connected voltage source inverter (VSI) designs of today. VSI with transformer decreases system efficiency around 1% to 2% (Haberlin, 2002; Burger, 2009). Ground leakage current and safety hazard issues are disadvantages of transformerless grid-connected system. Many types of topology have been introduced to reduce the drawbacks of a transformerless inverter system. They were designed with the PV array disconnected from the grid such as HB-ZVR inverter circuit as show in Figure 1 (Kerekes, 2011; Selvaray and Rahim, 2009). This design method solves the problems of constant common-mode voltage and low-amplitude ground leakage current. Another solution to eliminating ground leakage current in a transformerless system is modulation technique, which needs no additional hardware in the converter topology, most simplifying it. Some leakage-current-reducing modulation techniques are discussed in (Cavalcanti *et al.*, 2008). The grid element is not influence the level of ground leakage current in the transformerless inverter system. Therefore, the resistor is used for the simulation and experiment (Kerekes, 2011). Ground leakage current in transformerless inverter creates system losses and inject harmonics into grid (Lopez, 2010). An AC low-pass passive filter is usually positioned between inverter and grid to attenuate current harmonics injected into grid (Khaled, 2007; Hanju, 2010; Kim, 2000; Dahono, 1995). Relatively simple and needs no additional control part, its output is the focus of this study, whose calculation method shortened the design time. Basically the three type low pass filter (L, LC and LCL) circuit is

connected between the inverter and grid (Araujo, 2007). First order low pass filter (L filter) is most popular because that simplest compare the second order filter (LC filter) and third order filter (LCL filter) configuration. High inductance value and low attenuation are disadvantages of the L filter. High switching frequency is needed to reduce the harmonics (El-Habrouk, 2000). LC filter is proposed for better attenuation, reduce the losses and cost. By using LC filter the resonance frequency is proportional with the grid inductance value (Araujo, 2007). In grid connected system, LCL is producing the better decoupling between the inverter and grid impedance. This filter has low grid inductor current ripple and good attenuation at the inverter switching frequency (Hanju, 2010). When the resistor load is model in the HB-ZVR inverter circuit, the low pass LC passive filter is designed with the proposed calculation method. In this paper the calculation of LC passive filter is presented. The value of LC filter is simulated and proved with experimental results.

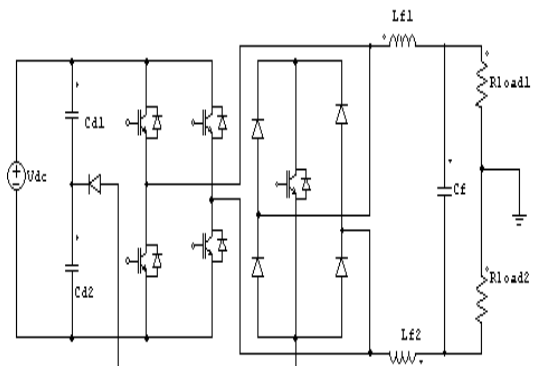


Figure 1 Topology of HB-ZVR transformerless inverter.

### 2. THEORY

#### 2.1 Sinusoidal Pulse Width Modulation (SPWM) Technique and harmonic

Sinusoidal pulse width modulation (SPWM) is an inverter controller technique in which the output voltage is controlled by the ON and the OFF states of the switches. The states are pulses obtained by comparing reference

signal  $V_{ref}$  with triangular carrier signal  $V_c$ ; ON state is when  $V_{ref}$  is greater than  $V_c$ , OFF state is when  $V_{ref}$  is less than  $V_c$ . Figure 2 illustrates the principle of SPWM. Equation 1 defines the modulation ratio ( $m_a$ ) in case  $m_a$  less than 1 (Mohan *et al.*, 2003).

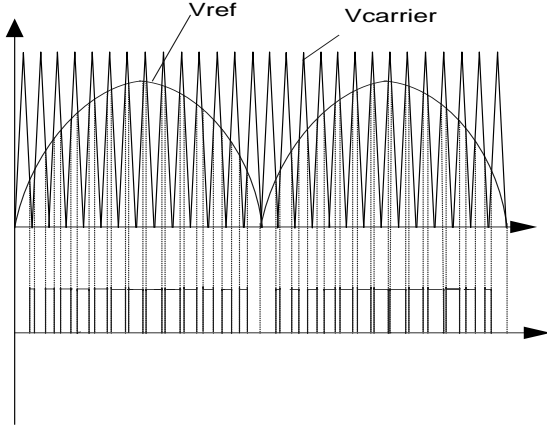


Figure 2 SPWM principle

$$m_a = \frac{V_{ref}}{V_c} \quad (1)$$

Equation 2 gives the RMS (root mean square) value for output voltage ( $V_o$ ) of the inverter's fundamental frequency (Hart 2011):

$$V_{o,rms} = m_a \frac{V_{dc}}{\sqrt{2}} \quad (2)$$

Sidebands represent the inverter's output harmonics, whose waveforms appear around the center of the switching frequency in multiples of the switching frequency (Hart 2011). Equation 3 defines the output current harmonics based on the Fourier series method (Hart 2005).

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} (I_{n,rms})^2}}{I_{1,rms}} \quad (3)$$

Where  $I_n$  is the non-fundamental frequency output current term and  $I_1$  is the fundamental frequency output current term.

## 2.2 Low-pass Filter Design

A simple method reducing inverter output harmonic uses the LC low-pass passive filters. Second order filter is represented by LC circuit, where the inductor is shunt with the capacitor as shown in Figure 3. Equations 4 and 5 express LC filter transfer function as derived from voltage-divider rule (Anca, 2009).

$$G(jw) = \frac{1}{LC(jw)^2 + jwL/R + 1} \quad (4)$$

$$G(jw) = \frac{V_o}{V_{in}} \quad (5)$$

Use of LC-filter lowers cost and losses of the inverter system. Equation 6 is for filter inductance. The maximum ripple current was chosen to be 5%-20% (typical value of maximum ripple current is 20% of rated current (Wang, 2003)).

$$L = \frac{1}{8} \frac{V_{DC}}{\Delta_{ripple,max} f_{sw}} \quad (6)$$

Filter capacitance is determinable by the reactive power absorbed in the filter capacitor; Equation 7 defines it.  $\alpha$  being the reactive power factor, its value was selected to be less than 5% (Wang, 2003).

$$C_f = \frac{\alpha P_{rated}}{2\pi f_{line} V_{rated}^2} \quad (7)$$

Equation 8 defines the resonance frequency of the LC filter circuit (Khaled, 2007):

$$f_r = \frac{1}{2\pi\sqrt{L_f C_f}} \text{ Hz} \quad (8)$$

Filter

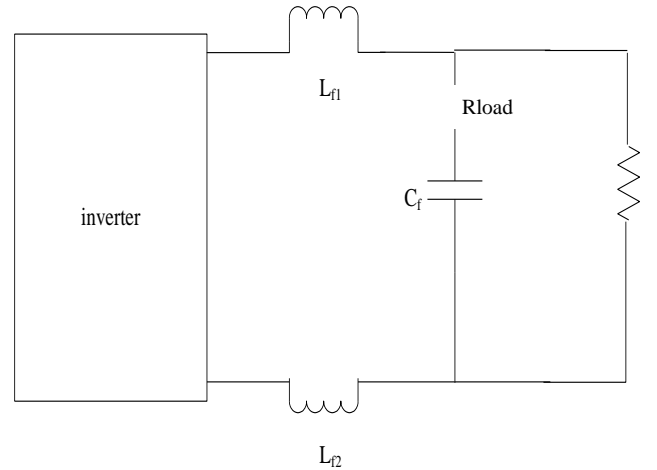


Figure 3 LC filter circuit

### 3. SIMULATION RESULTS

The low pass LC passive filter value resulting from the calculation was simulated on the PSIM program; see Table 1 for the simulation's parameter values. Figure 4 is the unfiltered output-current waveform, Figure 5 the unfiltered FFT-inverter current output. The harmonic peak of output current  $i_o$  at 8kHz read 1.21A. Figures 6 and 7 are the results for LC-filtering between the VSI and the grid load; the output current harmonic peak reduced from 1.21A to 6.03mA. Figures. 8 and 9 are the switching frequencies tested. Figure 10 the frequency response of the LC filters when used 8kHz. The cut-off frequency is 3.75 kHz.

Table 1 Parameter Values for HB-ZVR inverter topology

Parameter	Value
$L_f$	3.6mH
$L_{f1}, L_{f2}$	1.8mH
$C_f$	2uF
$R_{load}$	15Ω
$V_{dc}$	60V
$F_{sw}$	8 kHz, 14 kHz, 20 kHz
$C_{dc1}, C_{dc2}$	250uF

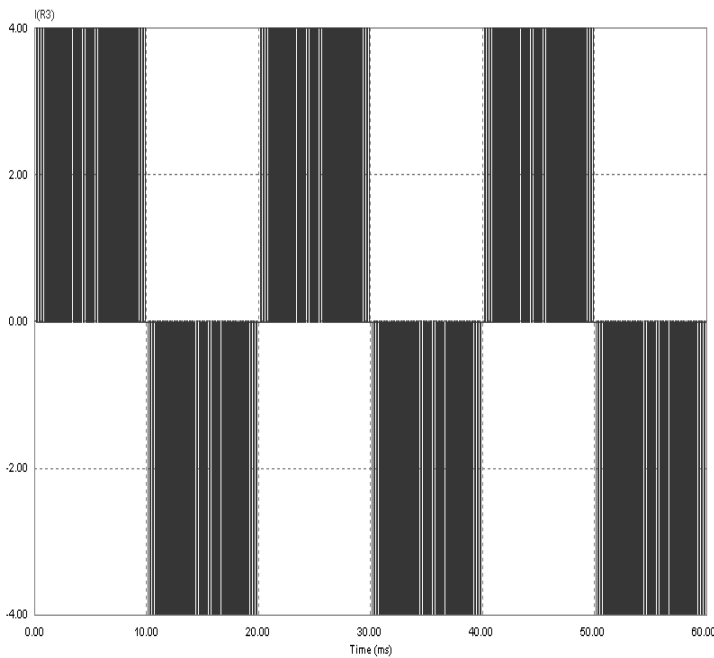


Figure 4 Unfiltered inverter output current

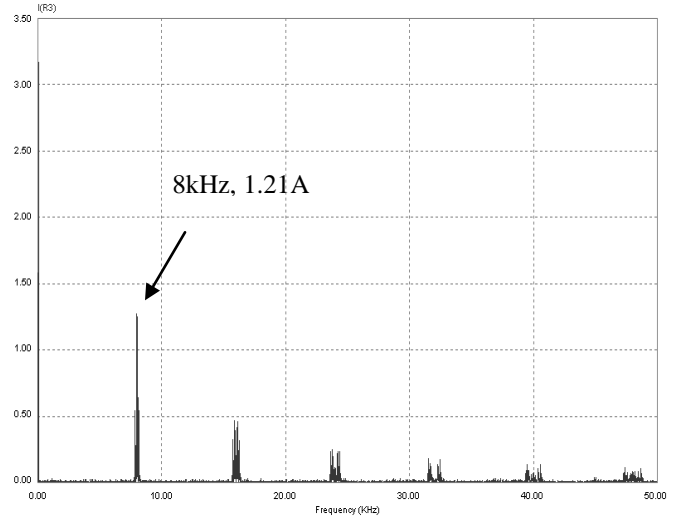


Figure 5 Unfiltered FFT-inverter output current

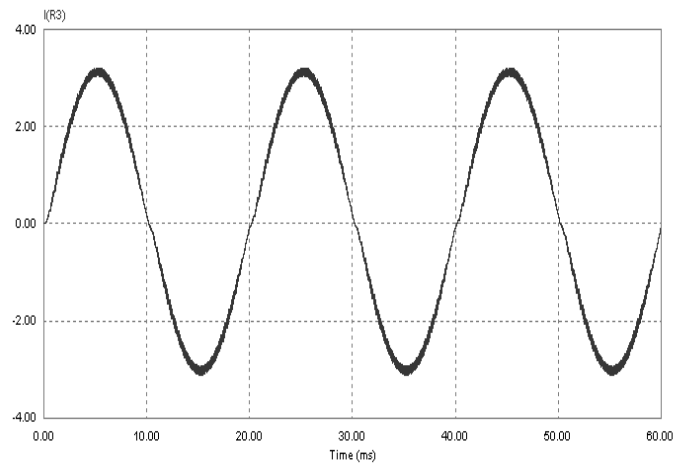


Figure 6 LC-filtered output current

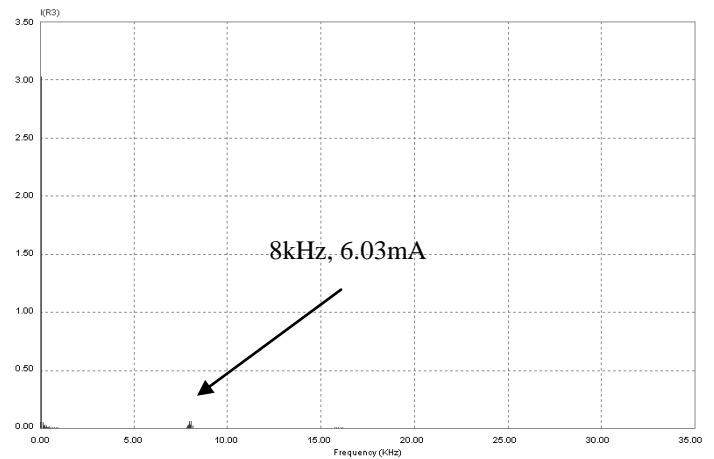


Figure 7 LC-filtered (8kHz) FFT-inverter output current

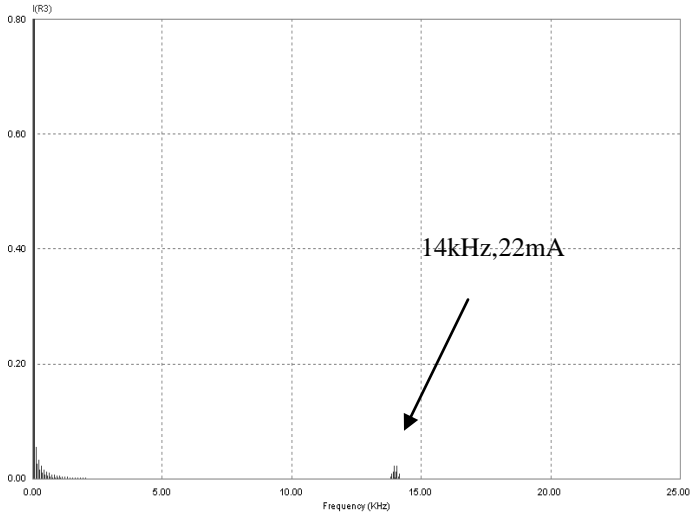


Figure 8 LC-filtered (14kHz) FFT-inverter output current

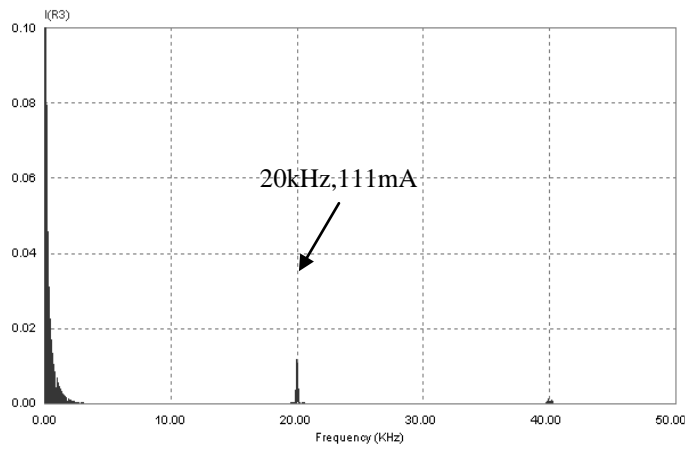


Figure 9 LC-filtered (20kHz) FFT-inverter output current

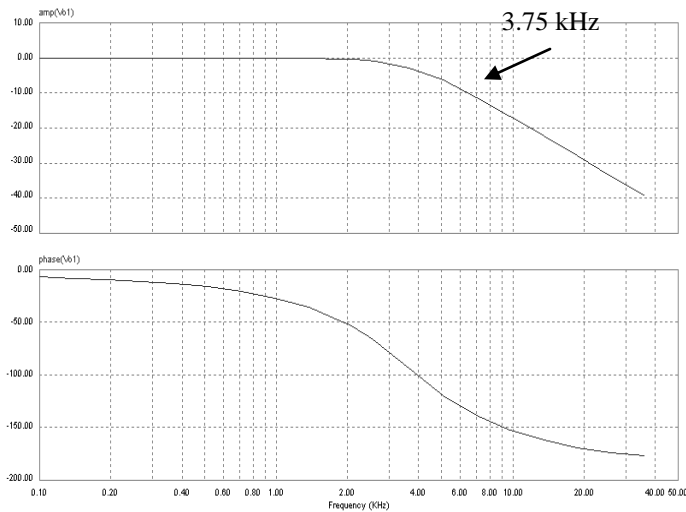


Figure 10 LC-filtered frequency response,  $f_r = 3.75\text{kHz}$

#### 4. EXPERIMENT RESULTS

A prototype was built to test the theoretical operation of the LC filter design. An experiment was set up in which the same parameters as those of the simulations were used. Control of the prototype was by TMS320F2812 DSP. Figure 11 shows the S1-S5 switching patterns, generated for the H-Bridge transformerless inverter topology. Figures 12 and 13 are experiment results for the output inverter current tested with, and without, LC filter. Values of switching frequency were also tested on the prototype.

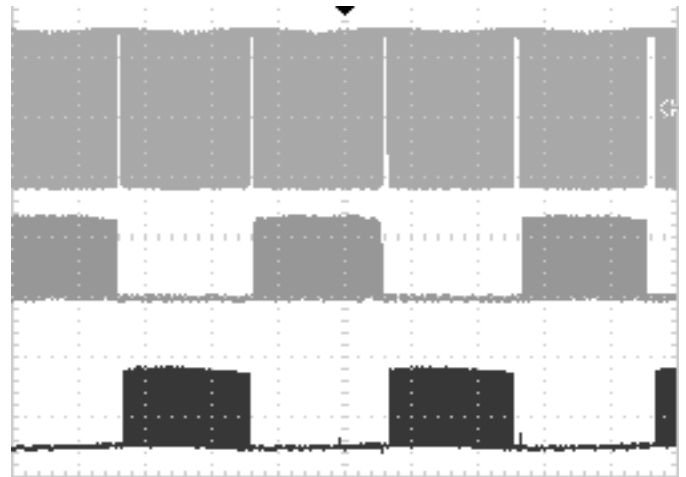


Figure 11 Switching patterns

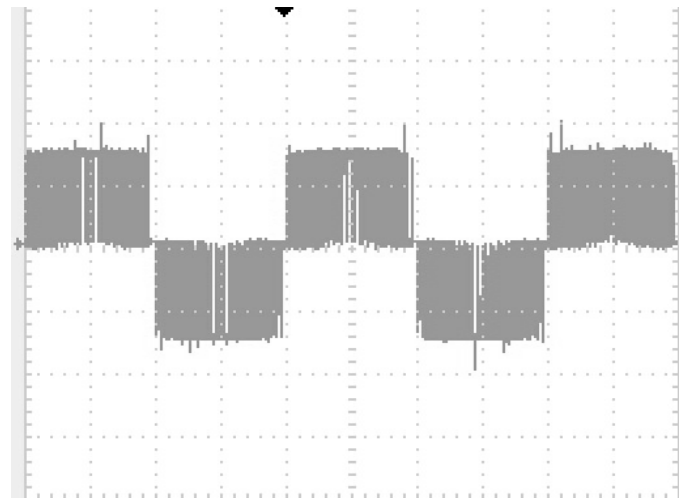


Figure 12 Unfiltered inverter output

Figures 14, 16, and 18 are the output voltages and currents measured, showing output voltage against decreased switching frequency. Figures 15, 17, and 19 are the THD results for each of the switching frequencies. Grid-injected harmonics was found to be the least at 8kHz switching frequency. Figure 20 is THD versus modulation ratio (ma) curve for the various switching frequencies. The proposed low-pass passive filter was designed and calculated for 8kHz switching frequency.

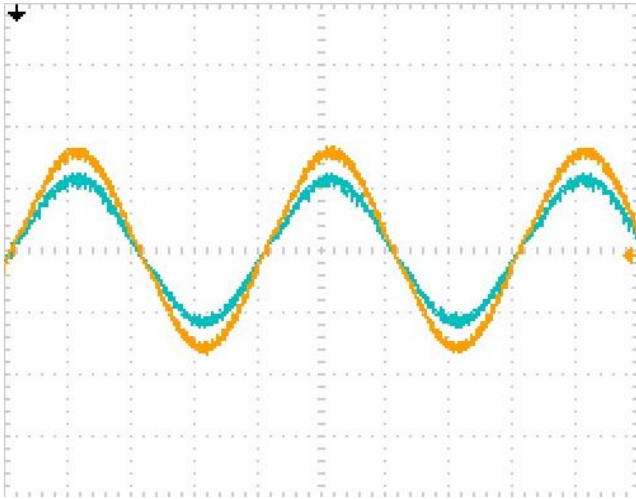


Figure 13 LC-filtered output voltage and output current

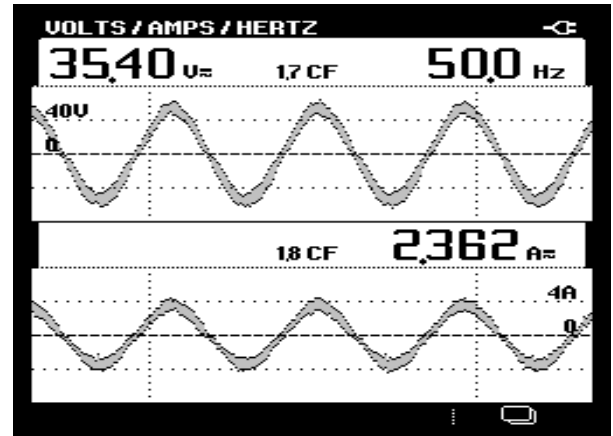


Figure 16 Inverter voltage and current outputs,  $f_s=14$  kHz

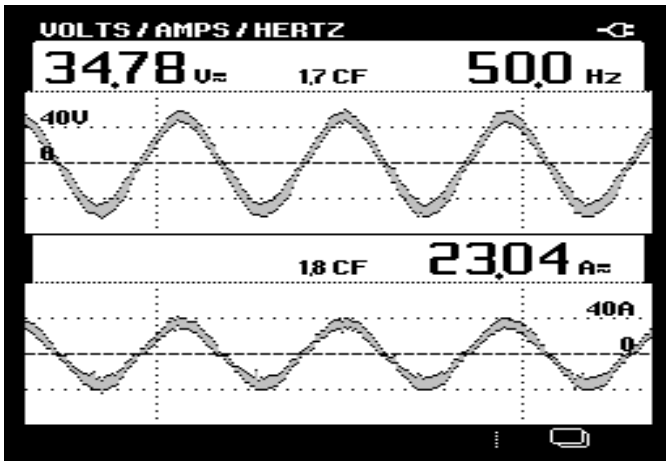


Figure 14 Inverter voltage and current outputs,  $f_s=20$  kHz

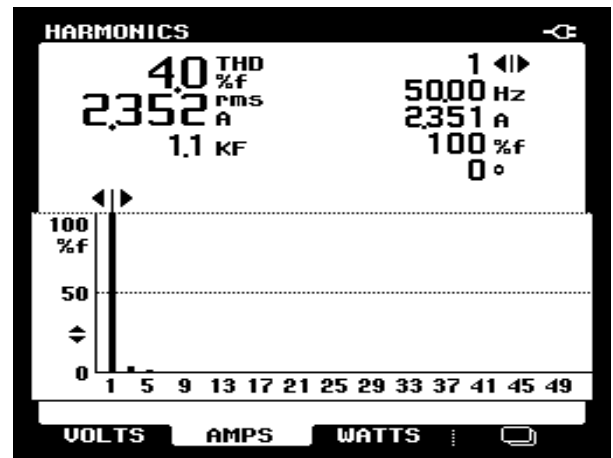


Figure 17 Inverter output-current THD,  $f_s=14$  kHz

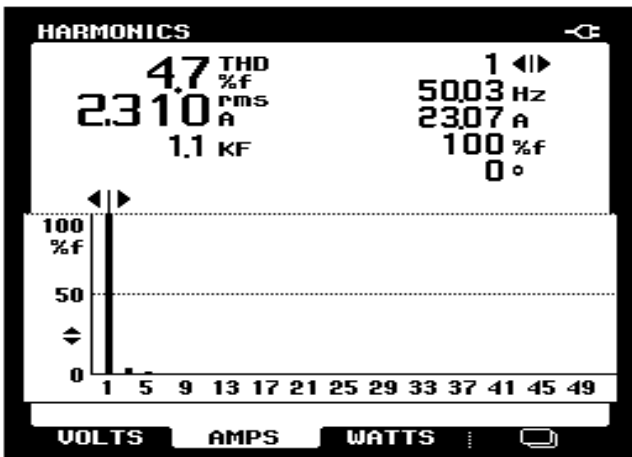


Figure 15 Inverter output-current THD,  $f_s=20$  kHz

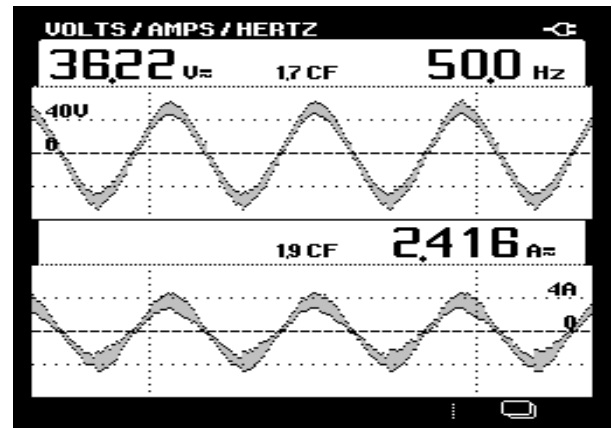


Figure 18 Inverter voltage and current outputs,  $f_s=8$  kHz

THD was found to decrease little and slowly with increases in modulation ratio. The THD at 8kHz switching frequency thus bettered those at the other switching frequencies. Figure 21 is the system efficiency, which, at 8kHz switching frequency, was found to be 88%.

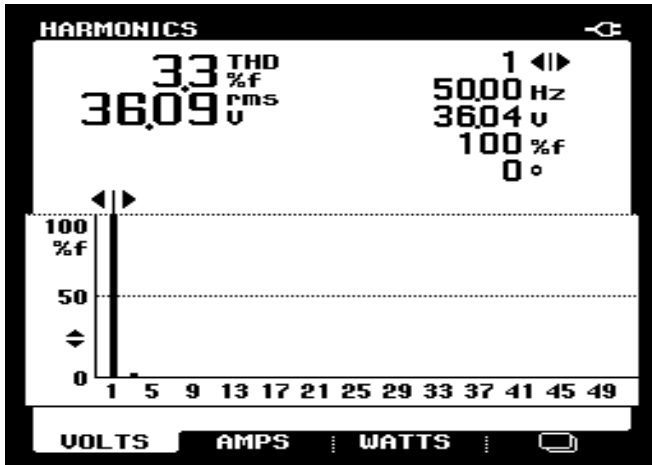


Figure 19 Inverter output-current THD, fs=8 kHz

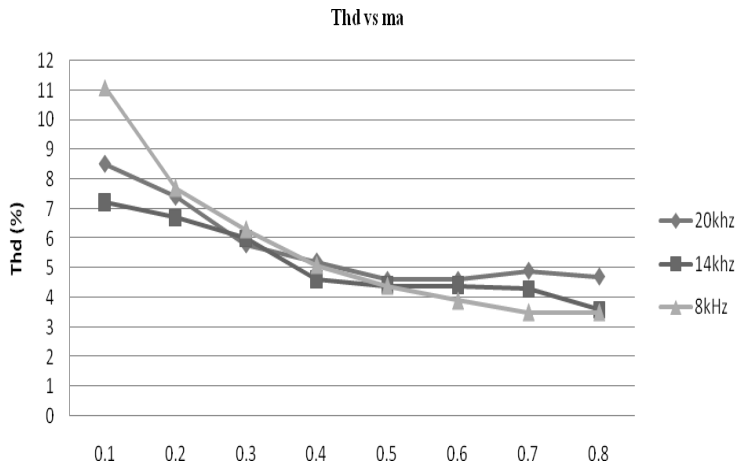


Figure 20 THD curves of the various switching frequencies

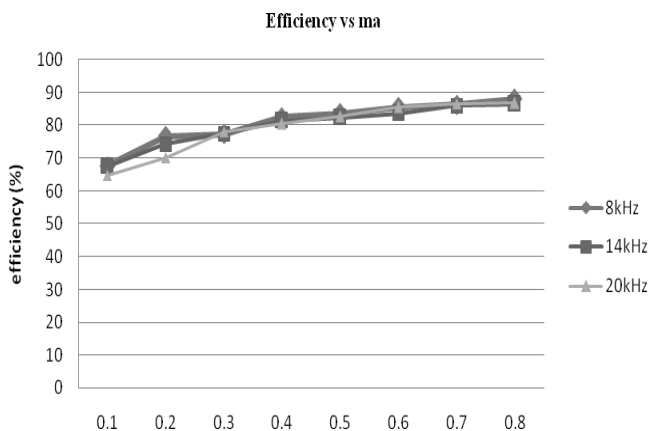


Figure 21 Efficiency of the H-Bridge transformerless inverter, measured against various switching frequencies

## 5. CONCLUSION

Outputs of an LC low-pass passive filter for a single-phase grid-connected transformerless inverter have been presented. Calculations made on equations were simulated on PSIM, a program that not only facilitated study and analysis of the basic filter, but also shortened the filter's design time. Experiment results verified the proposed design for the LC low-pass passive filter as satisfying the below-5% output THD requirement at 8kHz switching frequency

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