Design Analysis of Low-Pass 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 transformerless. Switching frequencies 8Hz, 14kHz, and 20kHz were compared for validation of the simulation and the experiment.**

Keywords - Transformerless DC-AC converter, LC filter system.

I. 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% [1]. A new, highly effective single-phase grid-connected transformerless inverter topology proposed comprises H-bridge inverter, diode rectifier, and auxiliary switch [1] (see Fig. 1).

Leakage current and safety hazard issues are disadvantages of a transformerless grid-connected system [2]. Leakage current in transformerless inverter creates system losses and inject harmonics into grid [3]. A low-pass passive filter is usually positioned between inverter and grid to attenuate current harmonics injected into grid [4, 5, 6, 7]. Relatively simple and needs no additional control part, its output is the focus of this study, whose calculation method shortened the design time.

II. THEORY

A. 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 Vref with triangular carrier signal Vc; ON state is when Vref is greater than Vc, OFF state is when Vref is less than Vc. Fig. 2 illustrates the principle of SPWM. Equation (1) defines the modulation ratio:

$$m_a = \frac{V_{ref}}{V_c} \tag{1}$$

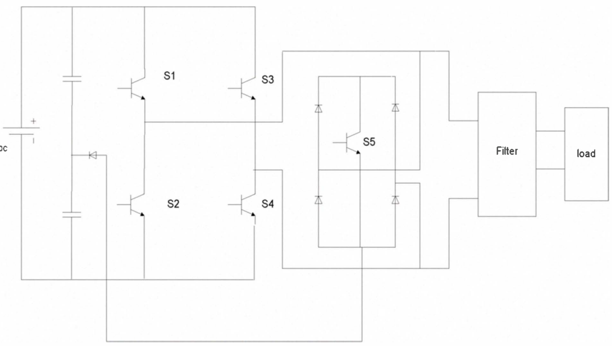

Figure 1: Topology of the proposed H-Bridge transformerless inverter

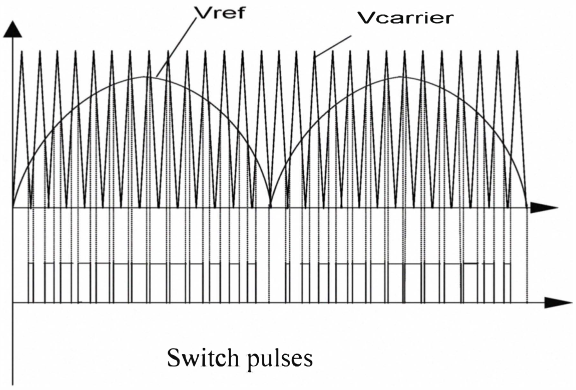

Figure 2: SPWM principle

Equation (2) defines the frequency modulation ratio:

$$m_f = \frac{f_{carrier}}{f_{reference}} \tag{2}$$

Equation (3) gives the RMS (root mean square) value for output voltage of the inverter's fundamental frequency:

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$$V_{o,rms} = m_a \frac{V_{dc}}{\sqrt{2}} \quad (3)$$

Sidebands represent the inverter's output harmonics, whose waveforms appear around the center of the switching frequency in multiples of the switching frequency [8]. Equation (4) defines the output current harmonics:

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} (I_{n,rms})^2}}{I_{l,rms}} \quad (4)$$

B. Low-pass filter design

A simple method reducing inverter output harmonic uses low-pass passive filters: L, LC, and LCL. Fig. 3 is the circuit for the LC low-pass passive filter used in this study. LC filter is second-order type of filter, where the inductor is shunt with the capacitor. Equations (5) and (6) express LC filter transfer function as derived from voltage-divider rule.

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

$$G(jw) = \frac{1}{LC(jw)^2 + jwL/R + 1} \quad (6)$$

Use of LC-filter lowers cost and losses of the inverter system. Equation (7) 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 [9]).

$$L = \frac{1}{8} \frac{V_{DC}}{\Delta_{ripple,\max} f_{sw}} \quad (7)$$

Filter capacitance is determinable by the reactive power absorbed in the filter capacitor; Equation (8) defines it. α being the reactive power factor, its value was selected to be less than 5% [10].

$$C_f = \frac{\alpha P_{rated}}{2\pi f_{line} V^2_{rated}} \quad (8)$$

Equation (9) defines the resonance frequency of the AC circuit:

$$f_r = \frac{1}{2\pi\sqrt{L_f C_f}} Hz \quad (9)$$

To avoid resonance effect and ensure carrier attenuation, filter resonance frequency should be less than carrier frequency.

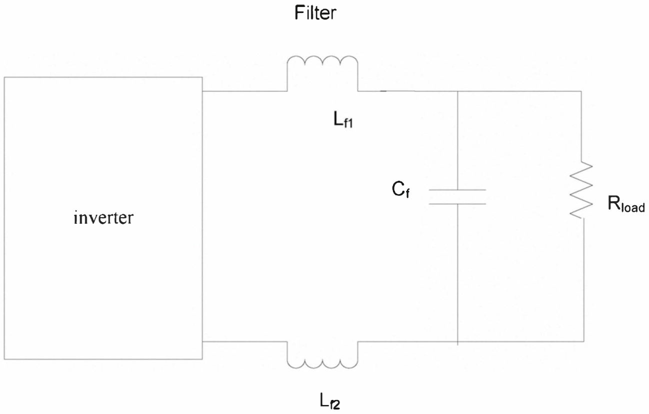

Figure 3: LC filter circuit

III. SIMULATION RESULTS

The LC filter value resulting from the calculation was simulated on the PSIM program; see Table 1 for the simulation's parameter values. Fig. 4 is the unfiltered output-current waveform, Fig. 5 the unfiltered FFT-inverter current output. The harmonic peak of output current i_o at 8kHz read 1.21A. Figs. 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. Figs. 8 and 9 are the switching frequencies tested. Fig.10 the frequency response of the LC filter when used 8kHz switching frequency. The cut-off frequency is 3.75 kHz.

Table 1: Parameter Values

L_f	3.6mH
L_{f1}, L_{f2}	1.8mH
C_f	2uF
R_{load}	15ohm
V_{dc}	60V
f_{sw}	8kHz,14kHz,20kHz
C_{dc}, DC-link capacitor	250uF
Dead time	0.8u sec

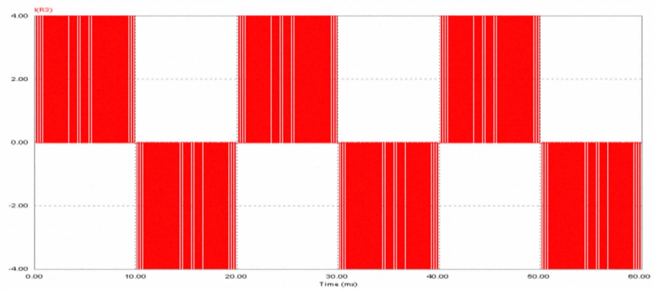

Figure 4: Unfiltered inverter output current

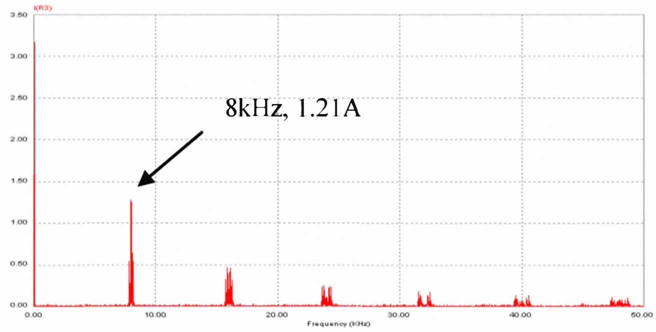

Figure 5: Unfiltered FFT-inverter output current

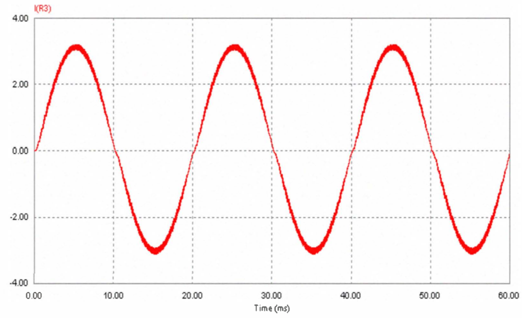

Figure 6: LC-filtered output current

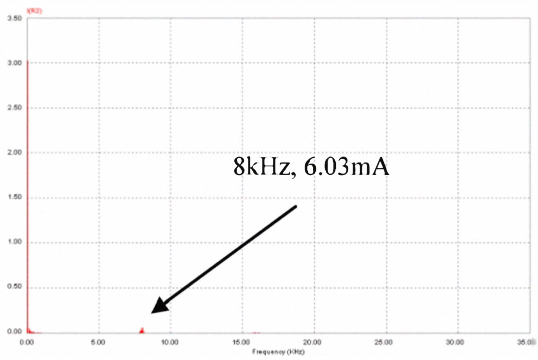

Figure 7: LC-filtered (8kHz) FFT-inverter output current

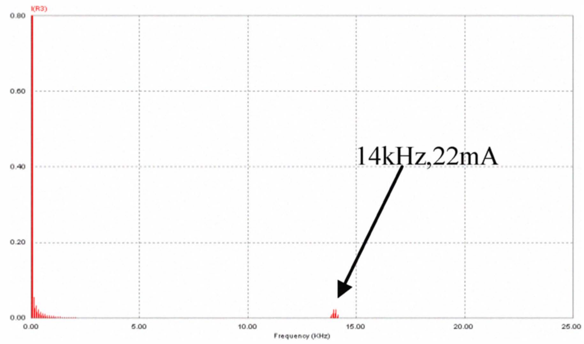

Figure 8: LC-filtered (14kHz) FFT-inverter output current

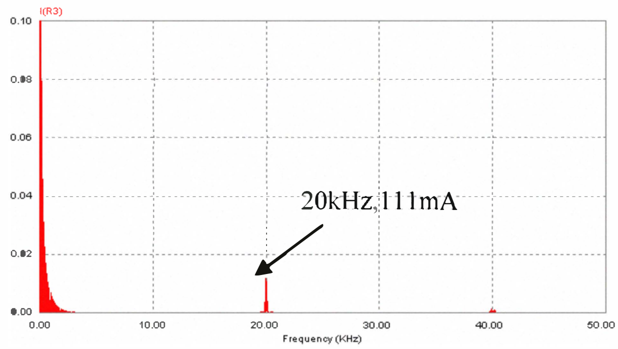

Figure 9: LC-filtered (20kHz) FFT-inverter output current

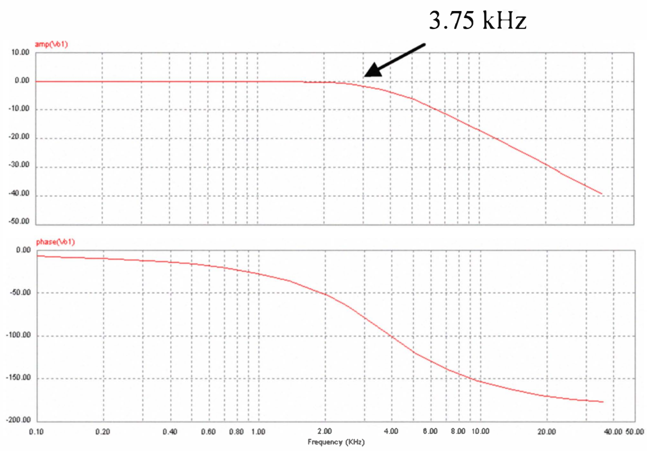

Figure 10: LC-filtered frequency response, fr = 3.75kHz

IV. 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. Fig. 11 shows the S1-S5 switching patterns, generated for the H-Bridge transformerless inverter topology. Figs. 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. Figs. 14, 16, and 18 are the output voltages and currents measured, showing output voltage against decreased switching frequency. Figs. 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.

Fig. 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. 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.

Fig. 21 is the system efficiency, which, at 8kHz switching frequency, was found to be 88%.

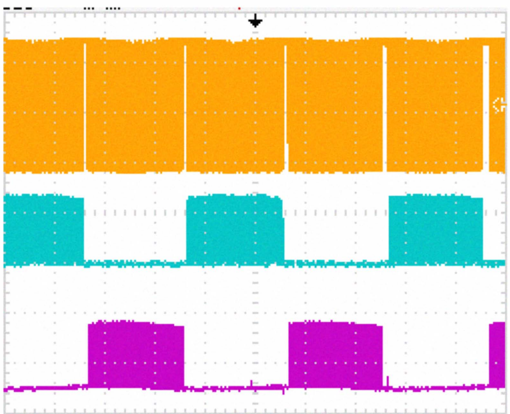

Figure 11: Switching patterns

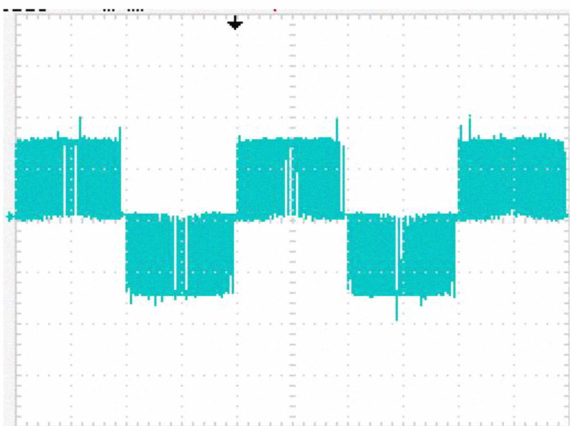

Figure 12: Unfiltered inverter output

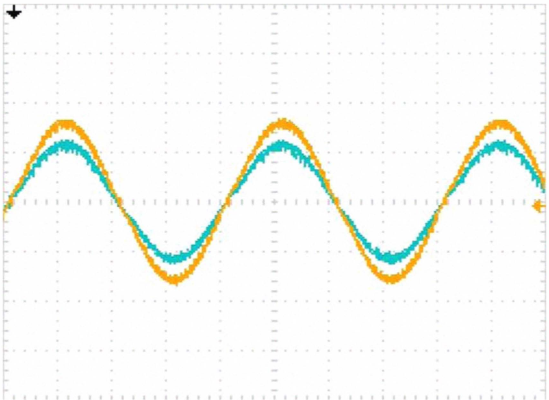

Figure 13: LC-filtered output voltage and output current

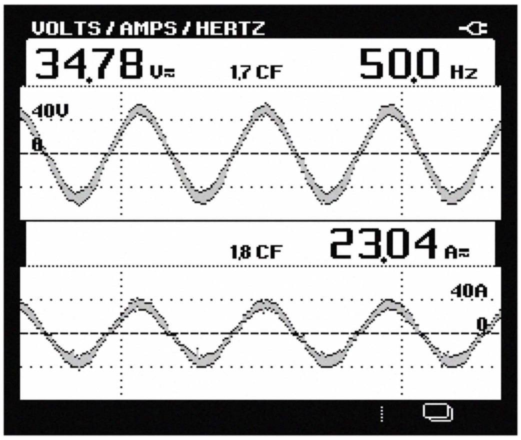

Figure 14: Inverter voltage and current outputs, fs=20 kHz

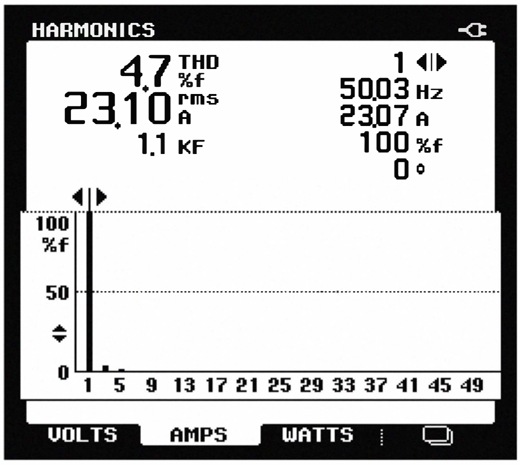

Figure 15: Inverter output-current THD, fs=20 kHz

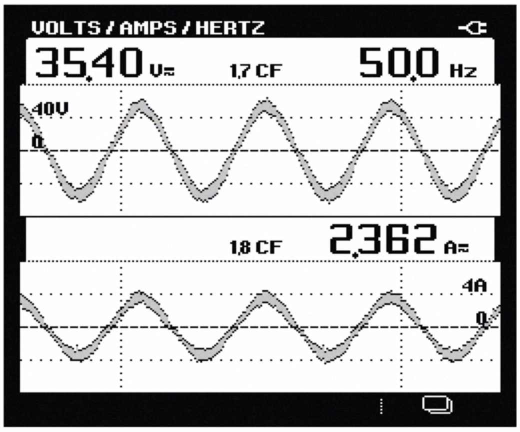

Figure 16: Inverter voltage and current outputs, fs=14 kHz

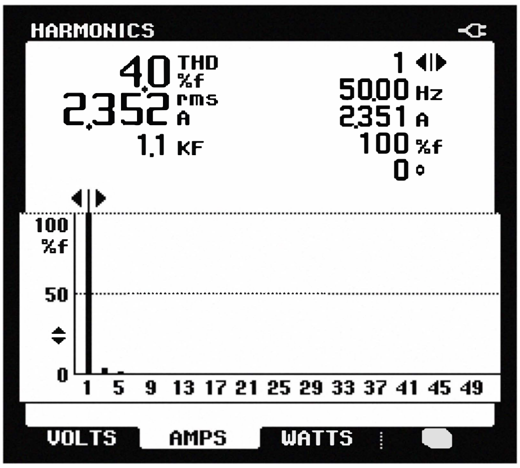

Figure 17: Inverter output-current THD, fs=14 kHz

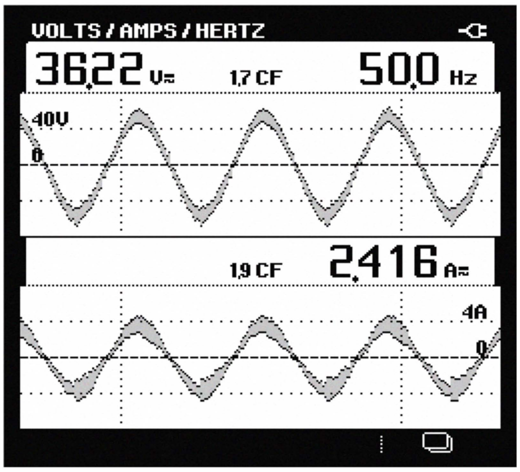

Figure 18: Inverter voltage and current outputs, fs=8 kHz

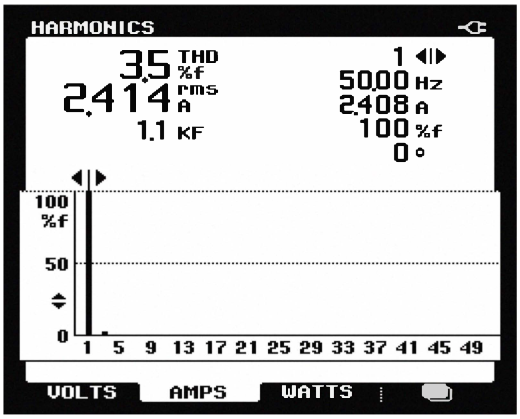

Figure 19: Inverter output-current THD, fs=8 kHz

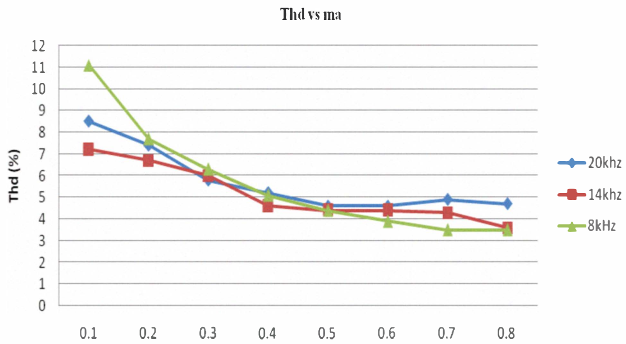

Figure 20: THD curves of the various switching frequencies

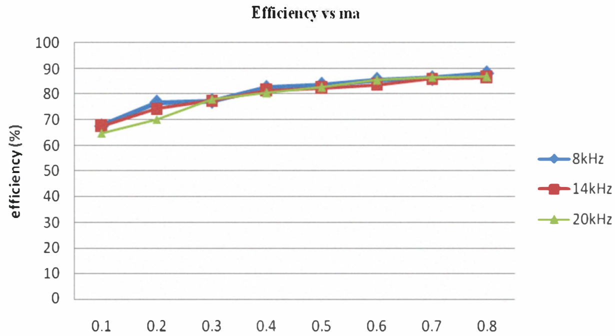

Figure 21: Efficiency of the H-Bridge transformerless inverter, measured against various switching frequencies

V. 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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