Andrius PLATAKIS[1, 2], Vytautas BLEIZGYS[1, 2], Audrius LUCINSKIS[1, 2], Algirdas BASKYS[1, 2]

Vilnius Gediminas Technical University (1), Center for Physical Sciences and Technology (2)

Investigation of Photovoltaic Inverter Power Quality

Abstract: *The results of the investigation of the Total Harmonic Distortion (THD) of the single-phase full-bridge voltage source photovoltaic inverter with the first order low pass L-C-R filter are presented. The investigation has been performed using simulation and experimentally. The simulation is accomplished using Simulink software, the experimental investigation – using the 1 kW inverter prototype. The impact of the inverter carrier signal frequency and capacitance of the L-C-R filter capacitor on the THD and filter capacitor current has been analyzed.*

Streszczenie. *Przedstawione zostały wyniki badań zniekształceń harmonicznych (THD) jednofazowego mostkowego przekształtnika fotowoltaicznego z filtrem dolnoprzepustowym LCR pierwszego rzędu. Prowadzono symulacje w programie Simulink oraz badania eksperymentalne przy wykorzystaniu prototypu przekształtnika o mocy 1 kW. (**Badania jakości energii przekształtnika fotowoltaicznego**).*

Keywords: photovoltaic inverter, power quality, low pass filter, filter capacitor.
Słowa kluczowe: przekształtnik fotowoltaiczny, jakość energii, filtr dolnoprzepustowy, pojemność filtrująca.

Introduction

The direct use of the DC voltage produced by the photovoltaic cells is limited. Therefore, in many situations the conversion of the DC voltage to the standard AC voltage using a photovoltaic inverter is needed. One of the main problems of the conversion is the quality of the power generated by the inverter.

The inverter converts the DC voltage to the required specification AC voltage [1-5]. Voltage source inverters (VSI) are most widely used because they are analogous to the voltage source, i.e. to the electricity source, which is provided by the electrical net. VSI forms a sinusoidal voltage with the controlled amplitude, frequency and phase.

To achieve acceptable power losses the transistors of the inverter operate as switches. Because of this, the VSI generates voltage pulses at its output, i. e. the voltage spectrum consists of many harmonics. Since the photovoltaic inverter should provide a sinusoidal voltage, the low pass filter must be employed between the inverter output and the load to attenuate the harmonics. The quality of the inverter output voltage and power losses mainly depend on the performance of the filter, therefore, the investigations in field of the low pass filters used for the photovoltaic inverters are of high importance.

The inverter structure and voltage forming principle

The circuit diagram of a single-phase full-bridge voltage source inverter is given in Fig.1. The inverter consists of a direct current voltage source v_i , filtering capacitors C_+ and C_-, power switches S_{1+}, S_{1-}, S_{2+}, S_{2-} and diodes D_{1+}, D_{1-}, D_{2+}, D_{2-}. The state of the switches is varied according to the sine law during the modulation. Such modulation is called Sinusoidal Pulse Width Modulation (SPWM). The frequency of the modulation signal is f_c and the amplitude is $\hat{v}_c$, the frequency of the carrier signal is f_Δ and the amplitude is $\hat{v}_\Delta$. The amplitude modulation index is calculated using equation

(1) $$m_a = \frac{\hat{v}_c}{\hat{v}_\Delta}$$

and the frequency modulation index is calculated by the following equation:

(2) $$m_f = \frac{f_\Delta}{f_c}.$$

When $m_a \leq 1$, the amplitude of the main harmonic of the output voltage v_o meets the condition $\hat{v}_{o1} = m_a \cdot v_i$. When m_f is an even number, harmonics in the output voltage occur at these frequencies:

(3) $$f_n = lm_f \pm k \, ,$$

where n is the harmonic number, k = 1,3,5… and l = 2,4,6…

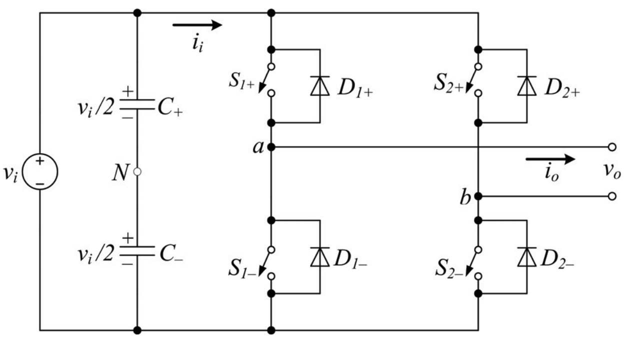


Fig.1.The circuit diagram of single-phase full-bridge voltage source inverter

The output filter, which was used in the investigated inverter, is a passive first order low pass L-C-R filter (Fig. 2) [3, 6]. The filter must effectively filter higher order harmonics and minimally attenuate the main harmonic of the output voltage v_o. The cut-off frequency of the filter is expressed by the following equation:

(4) $$f_c = \frac{1}{\pi \cdot \sqrt{L \cdot C}}$$

and the nominal impedance can be calculated by equation:

(5) $$R_0 = \sqrt{\frac{L}{C}} \, .$$

The quality of the inverter output power strongly depends on the filter configuration and component parameters. The quality of the output power (mainly the output voltage) also depends on the carrier frequency because the output filter must be tuned to effectively reduce harmonics around the carrier frequency.

The investigation of the single-phase full-bridge voltage source photovoltaic inverter with the first order low pass L-C-R filter was performed in two stages: using simulation and experimentally.

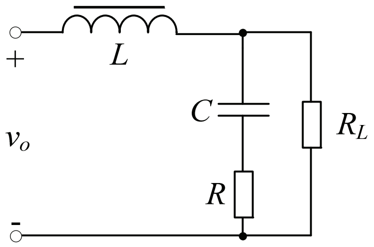


Fig.2. Passive first-order low-pass L-C-R filter

Simulation results

Simulation of the inverter with the low pass filter was performed using Matlab Simulink software. A model of single phase inverter with an output filter was created. The model consists of a DC source, four switches based on the IGBT transistors, the output L-C-R filter, load and the PWM signal generator block. This model allows us to change parameters of components and observe output signals. The investigation was accomplished using Simulink built-in calculation and measurement blocks, which perform Fast Furrier Transformation (FFT) of the inverter output voltage. The results were obtained at different carrier frequencies and different capacitances of the output filter capacitor. The inductance of the inductor was constant – 1.5 mH with the active resistance of 0.2 Ω. The active resistance *R* (Fig. 2) of the filter was 0.02 Ω [3]. It is used for resonance dampening.

Two characteristics were observed during simulation: Total Harmonic Distortion (THD) (Fig. 3) of the output voltage and the maximal current of the inverter output filter (Fig. 4). The THD directly denotes the quality of the inverter output voltage. The THD is expressed using the following equation:

$$THD = \frac{\sqrt{U_2^2 + U_3^2 + \cdots + U_n^2 + \cdots}}{U_1} \cdot 100, \qquad (6)$$

where U_1, U_2,…, U_n are the amplitudes of the appropriate harmonics. The dependence of THD of the inverter output voltage on the carrier frequency at various capacitances of the filter capacitor is presented in Fig. 3. As can be seen, in the case when the carrier frequency is not higher than 18 kHz, the THD of the inverter output voltage is conversely proportional to the carrier frequency. This happens because the filter impedance increases at the higher frequency.

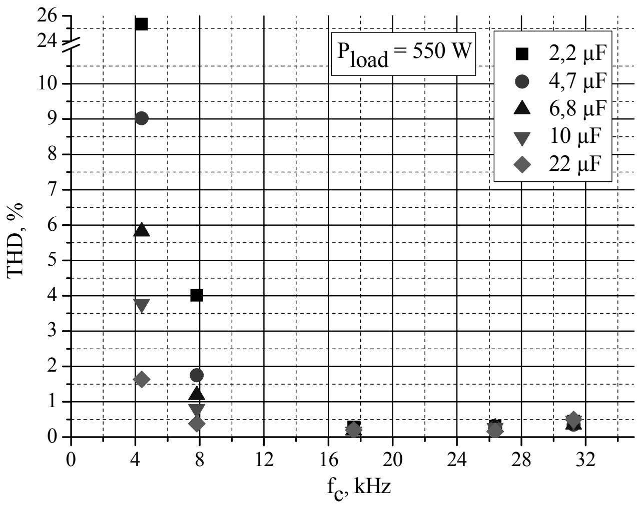


Fig.3. The dependence of THD of the inverter output voltage on the carrier frequency at various capacitances of the filter capacitor (simulation results)

The THD of the inverter output voltage is also dependent on the capacitance of the output filter capacitor. As its value is increased, the THD decreases. This is due to the fact that higher capacitance pushes the cut-off frequency of the filter to lower frequencies. The reduction of the THD in this manner is possible if the carrier frequency is low. A further increase of the capacitance does not lower the THD. Furthermore, it increases the filter capacitor current increasing the losses. The dependence of the maximal current of the inverter output filter capacitor on the carrier frequency is given in the Fig. 4.

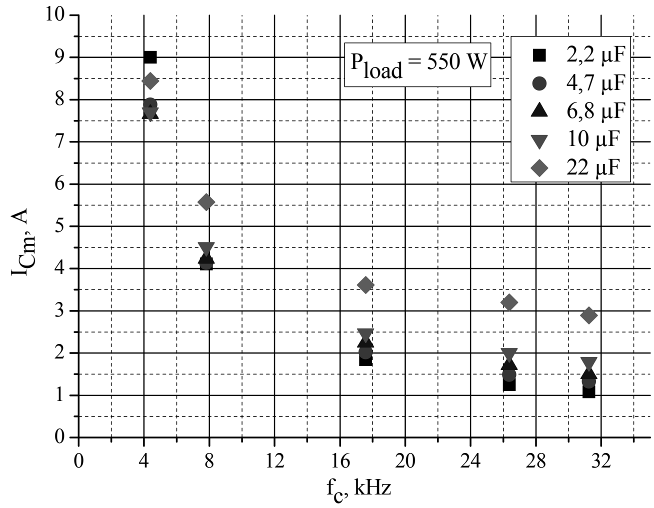
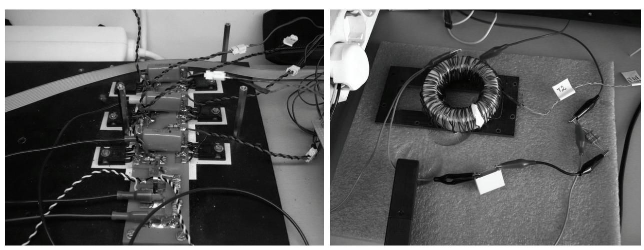


Fig.4. The dependence of the maximal current of the inverter output filter capacitor on the carrier frequency at various capacitances of the filter capacitor (simulation results)

Experimental investigation

The inverter prototype with the output filter was assembled for the experimental investigation (Fig. 5). The prototype is able to provide an active power of up to 1 kW. Four switches based on the IGBT transistors (Fig 5a) connected in full-bridge configuration with respective driving circuitry were used. An output filter (Fig. 5b) with 1.5 mH inductance and 0.2 Ω active resistance inductor was used. The inductor windings are wound on a specific iron powder core T300A-26 with distributed air gap. The capacitor of the filter was swappable. An embedded system based on the PIC18F4520 microcontroller was employed for generation of the control signals for the IGBT transistors for the realization of the SPWM modulation method. The embedded system was employed for the observation of inverter parameters and data collection as well. Six incandescent light bulbs were used as the active load of the inverter. The Tektronix TPS 2024 oscilloscope with isolated channels along with Tektronix A622 current probe was used to observe the output voltage and current of the inverter.



a b

Fig.5. Inverter IGBT switches (a), output filter (b)

A FFT function was applied for analysis of the output voltage harmonics. The magnitude of the carrier signal first harmonic was measured (Fig. 6). As can be seen, the first harmonic of the carrier signal is attenuated by 7.8 dB and the second one – by 21 dB. The same measuring technique was applied at different carrier frequencies and the output filter capacitor capacitances. The results are shown in Fig. 7.

As can be seen from the measurement results, the attenuation of the carrier signal first harmonic follows the THD trend (Fig. 3) obtained during the simulation. The highest attenuation occurs at the same carrier frequency of 18 kHz. This is true for all output filter capacitor values except for 2.2 μF. The attenuation also decreases by a fraction when the carrier frequency is increased up to 26 kHz and 32 kHz. The attenuation is high when the output filter capacitor capacitance is highest – 22 μF. However, attenuation decreases when the carrier frequency is 32 kHz.

The highest capacitor capacitance guarantees the best attenuation at low carrier frequency. On the other hand, the current of the capacitor, which determines the power losses in the filter, becomes high when the capacitance is high. The dependence of the maximal current of the inverter output filter capacitor on the carrier signal frequency obtained experimentally is given in Fig. 8.

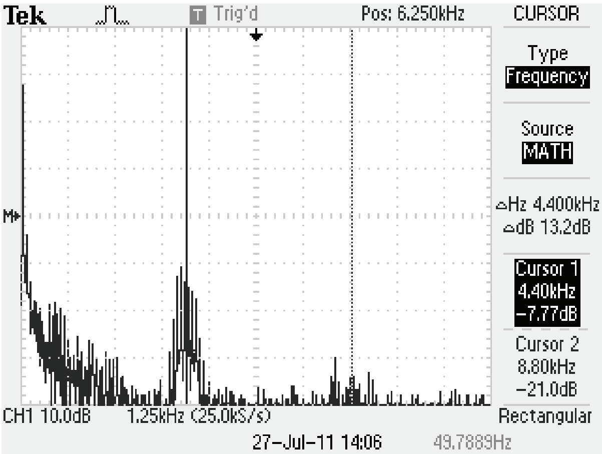


Fig.6. The attenuation of the carrier signal first harmonic by the L-C-R filter of the inverter when carrier frequency is 4.4 kHz and capacitance of filter capacitor is 6.8 μF

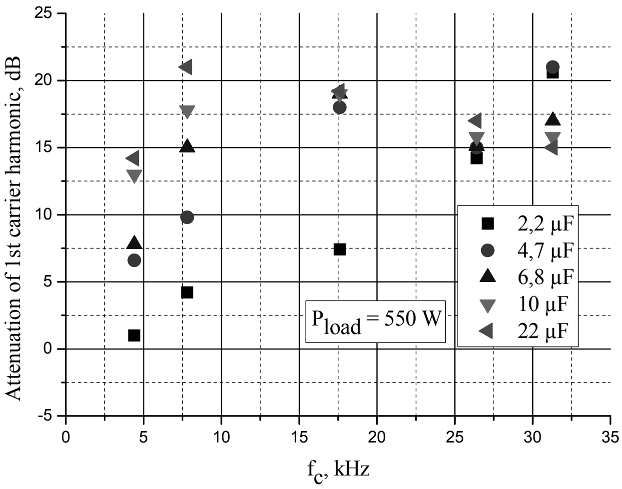


Fig.7. The dependence of the attenuation of the carrier signal first harmonic by the L-C-R filter of the inverter on the carrier frequency at various capacitances of filter capacitor (experimental results)

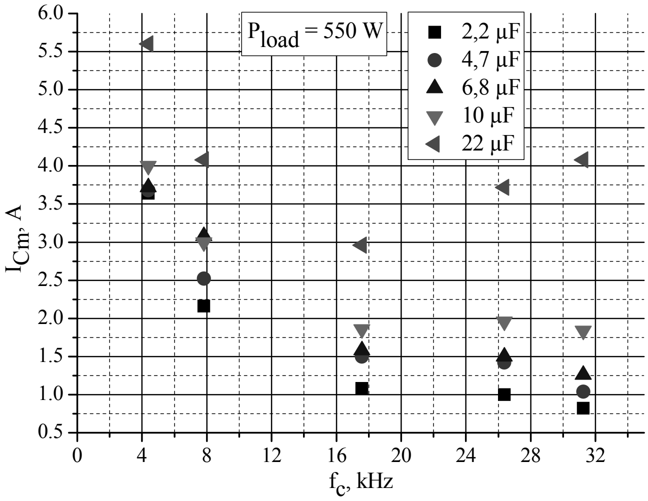


Fig.8. The dependence of the maximal current of the inverter output filter capacitor on the carrier signal frequency at various capacitances of filter capacitor (experimental results)

Conclusions

The investigation results of the power quality of the single-phase full-bridge voltage source photovoltaic inverter with the first order low pass L-C-R filter show that the lowest Total Harmonic Distortion (THD) is obtained at carrier frequency of 18 kHz. The impact of capacitance of the filter capacitor on THD at this carrier frequency is low. However, the capacitor capacitance starts to play an important role at lower carrier frequency. The THD increases significantly if the capacitance is too low in such a case. However, the increment of capacitance increases the current, which flows through the output filter capacitor and, as a consequence, reduces the overall efficiency of the inverter. Because of this, the capacitance of the filter capacitor should be chosen in such a way that a reasonable ratio between the output voltage THD and the inverter efficiency would be reached.

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***Authors:** PhD student Andrius Platakis, PhD student Vytautas Bleizgys, BSc Audrius Lucinskis, prof. dr Algirdas Baskys, Computer Engineering Department of Vilnius Gediminas Technical University, Naugarduko str. 41, 03227 Vilnius, Lithuania and Electronic Systems Laboratory of Center for Physical Sciences and Technology, A. Gostauto str. 11, 01108 Vilnius, Lithuania, E-mail: andrius.platakis@vgtu.lt*