Analysis of a single phase inverter for photovoltaic systems operating in a weak electric grid

Gorazd Štumberger, Sebastijan Seme, Klemen Deželak, Andrej Hanžič, Jože Voršič

University of Maribor
Faculty of Electrical Engineering and Computer Science
Smetanova 17, 2000 Maribor, Slovenia
phone: +386 2 220 7075, fax: +386 2 220 7272
e-mail: gorazd.stumberger@uni-mb.si

Abstract. Single-phase inverters for photovoltaic systems are normally analyzed when they are connected to the strong electric grid with low impedance. This work focuses on analysis of a single-phase inverter operating in a weak electric grid with relatively high impedance. Presented are experimentally determined results for the inverter’s efficiency, voltage and current total harmonic distortion and power factor. The results presented show substantial contents of sub harmonic components in the inverter’s output current.

Key words: photovoltaic system, single-phase inverter, experimental methods, efficiency, power factor, THD

1. Introduction

Operational characteristics of single-phase inverters for photovoltaic systems [1]-[5] are normally determined by tested performed in a strong electric grid with low impedance. However, photovoltaic system can be also connected to the electric grid at the end of radial distribution line which is often the case in rural areas. In this case the grid impedance is relatively high.

In the case study, this work focuses on analysis of a single phase inverter for photovoltaic systems operating in a weak electric grid where impedance is just below one Ohm. In order to eliminate the impact of solar cells and changing solar irradiation on obtained results, the tested inverter is supplied from a DC voltage source. During the tests currents and voltages on the inverter input and output were measured. They were used to determine input and output power of the inverter, its efficiency and power factor. By applying Fourier analysis current and voltage total harmonic distortion is determined. The results presented show high presence of sub harmonic components in inverter output current caused by the maximum power point tracking algorithm.

2. Experimental Set-up

Experimental set-up consists of the tested single-phase inverter, a variable DC voltage source, a transformer, current and voltage measurement chains and a signal processor board dSpace DS 1103 which is used as data acquisition system with sampling frequency 10 kHz.

The inverter’s input and output currents were measured by appropriate LEM currents sensors while differential probes were applied for voltage measurement.

The variable DC voltage source consists of an autotransformer, a full wave input rectifier and a capacitor with relatively high capacity. In order to simulate a weak electric grid the tested inverter was connected to the electric grid through a transformer which had the same rated power as inverter.

Different operating points of the inverter, which means different output powers, were set by changing DC voltage on the inverter’s input.

3. Analysis

The inverter input voltage $u_{DC}$ and current $i_{DC}$ as well as output voltage $u_{AC}$ and current $i_{AC}$ were sampled with sampling frequency 10 kHz in 1 s long time window. Their RMS values in this window were determined by (1) to (4), while active input and output power were determined by (5) and (6):

\[ U_{DC} = \sqrt{\frac{1}{N} \sum_{k=1}^{N} u_{DC}^2 (k)} \]  
\[ I_{DC} = \sqrt{\frac{1}{N} \sum_{k=1}^{N} i_{DC}^2 (k)} \]  
\[ P_{in} = U_{DC} I_{DC} \cos \theta \]  
\[ P_{out} = U_{AC} I_{AC} \cos \theta \]

where $\theta$ is the phase angle between $u_{DC}$ and $i_{DC}$.
\[ U_{AC} = \sqrt{\frac{1}{N} \sum_{k=1}^{N} u_{AC}^2(k)} \]  
(3)

\[ I_{AC} = \sqrt{\frac{1}{N} \sum_{k=1}^{N} i_{AC}^2(k)} \]  
(4)

\[ P_{DC} = \frac{1}{N} \sum_{k=1}^{N} u_{DC}(k) i_{DC}(k) \]  
(5)

\[ P_{AC} = \frac{1}{N} \sum_{k=1}^{N} u_{AC}(k) i_{AC}(k) \]  
(6)

where \( N \) is the number of samples while \( k \) denotes the sample. The RMS values of individual harmonic components were determined by Fourier analysis. They were used to determine THD for inverter input and output currents and voltages. The THD was calculated in two ways. By (7) for fundamental harmonic component 50 Hz and 40 higher order harmonics:

\[ THD_{I_{AC}} = \frac{\sum_{h=1}^{40} I_{h_{AC}}^2}{I_{I_{AC}}^2} \]  
(7)

where \( I_{h_{AC}} \) denotes RMS value of inverter output current harmonic component \( h \), and by (8):

\[ THD_{I_{AC}} = \frac{I_{h_{AC}}^2 - I_{I_{AC}}^2}{I_{I_{AC}}^2} \]  
(8)

where RMS values of all harmonic components present in inverter output current contribute to the THD. The power factor \( PF \) is calculated by (9).

\[ PF = \frac{P_{AC}}{U_{AC} I_{AC}} \]  
(9)

4. Results

Results measured during the tests preformed on tested single-phase inverter are presented in Figs.1 to 5 and in Tables 1 and 2. All results are given as functions of output power \( P_{AC} \). Fig. 1 shows RMS values of inverter input DC current \( I_{DC} \) and voltage \( U_{DC} \) together with input power \( P_{DC} \). Fig. 2 shows RMS values of output current \( I_{AC} \) and voltage \( U_{AC} \) while power factor \( PF \) and efficiency \( \eta \) are shown in Fig. 3.

Figs. 4 and 5 shows voltage and current THD marked as THD_{U} and THD_{I}. Fig. 4 shows both THDs determined for fundamental frequency 50 Hz and 40 higher order harmonic components. Voltage and current THDs presented in Fig. 5 are determined for fundamental frequency 50 Hz and all frequencies between 0 and 5 kHz.

The time behavior of inverter’s input and output currents, voltages and instantaneous powers as well as amplitude spectra of output instantaneous powers are shown in Figures 6 to 8.
Comparison of current THDs in Figs. 4 and 5 clearly shows that THD presented in Fig. 5 reaches higher value. The reason for this is substantial amount of sub harmonic components in the inverter output current. They are not accounted for when fundamental and higher harmonic components are used to calculate current THD.

5. Conclusion

Analysis of a single-phase inverter for photovoltaic systems operating at weak electric grid is performed in the paper. It is shown that output current of the inverter contains substantial amount of harmonic components lower than 50 Hz. They influence energy transmission and like higher order current harmonic components increase transmission losses. One of the reasons for appearance of these harmonic components is algorithm for tracking of maximal power.

Acknowledgement

This work was supported in part by the ARRS, Project No. L2-7560-1792 and P2-0115.

References

Table 1: Power, voltage and current measured on inverter input and output, power factor on efficiency given for 7 different operating conditions

<table>
<thead>
<tr>
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<th>a)</th>
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<th>c)</th>
<th>d)</th>
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<tbody>
<tr>
<td>$P_{AC\text{-output}}$ [W]</td>
<td>107.33</td>
<td>247.66</td>
<td>543.68</td>
<td>796.98</td>
<td>1043.20</td>
<td>1254.50</td>
<td>2748.00</td>
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<tr>
<td>$U_{AC\text{-output}}$ [V] RMS</td>
<td>223.9080</td>
<td>224.2371</td>
<td>223.5745</td>
<td>223.8780</td>
<td>224.0995</td>
<td>224.3813</td>
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<tr>
<td>$I_{AC\text{-output}}$ [A] RMS</td>
<td>1.0650</td>
<td>1.4622</td>
<td>2.6060</td>
<td>3.6883</td>
<td>4.7553</td>
<td>5.6697</td>
<td>12.2477</td>
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<tr>
<td>$P_{DC\text{-input}}$ [W]</td>
<td>140.5772</td>
<td>332.5651</td>
<td>579.9884</td>
<td>833.8860</td>
<td>1087.80</td>
<td>1318.00</td>
<td>2978.91</td>
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<tr>
<td>$U_{DC\text{-input}}$ [V] RMS</td>
<td>163.5200</td>
<td>181.5812</td>
<td>150.4855</td>
<td>151.1309</td>
<td>151.7242</td>
<td>154.2427</td>
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<td>$I_{DC\text{-input}}$ [A] RMS</td>
<td>0.8601</td>
<td>1.8336</td>
<td>3.9935</td>
<td>5.6252</td>
<td>7.2561</td>
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<td>PF</td>
<td>0.4501</td>
<td>0.7553</td>
<td>0.9331</td>
<td>0.9652</td>
<td>0.9789</td>
<td>0.9861</td>
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<tr>
<td>$\eta$</td>
<td>0.7635</td>
<td>0.7447</td>
<td>0.9374</td>
<td>0.9557</td>
<td>0.9590</td>
<td>0.9518</td>
<td>0.9225</td>
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Table 2: Current and voltage THD given for frequencies between 50 Hz and 2 kHz and for frequencies between 0 Hz and 5 kHz as a function of inverter output power

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<td>2748.00</td>
</tr>
<tr>
<td>THD: f=50Hz to 2 kHz</td>
<td>0.3718</td>
<td>0.1837</td>
<td>0.0935</td>
<td>0.0692</td>
<td>0.0598</td>
<td>0.0555</td>
<td>0.1005</td>
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<tr>
<td>THD: f=50Hz to 2 kHz</td>
<td>0.0250</td>
<td>0.0240</td>
<td>0.0237</td>
<td>0.0229</td>
<td>0.0222</td>
<td>0.0240</td>
<td>0.0238</td>
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<tr>
<td>THD: f=0Hz to 5kHz</td>
<td>0.9395</td>
<td>0.5949</td>
<td>0.3026</td>
<td>0.2196</td>
<td>0.1823</td>
<td>0.1426</td>
<td>0.1230</td>
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<tr>
<td>THD: f=0Hz to 5kHz</td>
<td>0.0293</td>
<td>0.0464</td>
<td>0.0500</td>
<td>0.0586</td>
<td>0.0693</td>
<td>0.0470</td>
<td>0.0289</td>
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</table>

Figure 6: Time behavior of current $i_{DC}$, voltage $u_{DC}$ and instantaneous power $p_{DC}=i_{DC} u_{DC}$ at the inverter’s input at output power $P_{AC}=247.66$ W
Figure 7: Time behavior of current $i_{AC}$, voltage $u_{AC}$ and instantaneous power $p_{AC}=u_{AC}i_{AC}$ at the inverter’s output at output power $P_{AC}=247.66$ W.

Figure 8: Amplitude spectra of inverter’s output current and voltage given in relative format the inverter’s output at output power $P_{AC}=247.66$ W.