TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol.12, No.1, January 2014, pp. 57 ~ 64
DOI: http://dx.doi.org/10.11591/telkomnika.v12i1.3590

Experimental Investigation of the Transient Output Impedance of Single Phase On-Grid Inverter

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Abstract

The development of the technologies for connection of the photovoltaic systems to the electrical grid imposed the need of good connection of the interaction between the connecting power converter and the electrical grid. This paper presents research on the output impedance, based on experimental investigation of single-phase on–grid inverter. Its main objective was to identify the unknown output impedance of the commercial on-grid inverter through the waveforms at the point of common coupling (PCC) to the electrical grid, and then perform stability analysis between the inverter, represented by Norton equivalent model, and the grid by verifying the satisfaction of the Nyquist stability criterion.

Keywords: *on-grid inverter, impedance identification, stability analysis, Norton equivalent circuit*

1. Introduction

With reference to the huge number of renewable energy systems connected to the electrical grid the research and development on the on-grid inverters many constraints and optimizations are needed in order to assure the optimal interaction between the renewable system and the electric grid. In order to improve this cooperation research on the topic consists of three main directions. First the improvement of the topology in terms of reduction of the number of the components building the inverter itself [1] , [2] , second improvement of the synchronization methods of the inverter and the electrical grid [3] , [4] and third analysis and improvement of the stability of the on-grid inverter regarding the specific constraints of the electrical grid.

In order to analyze the stability of the on-grid inverter it is very important to identify some of its main components and parameters and its output impedance through which it is connected to the electrical grid. As usually the on-grid converters are commercial product, such parameters as the output impedance are not communicated in their datasheet. In order however to identify it, in many researches is presented the method of the “black-box” behavioral identification. “Black-box” model is mathematical model oriented to system level analysis. Bigger part of them is focused on DC systems [5] , [6] , [7] , [8] and for the moment, only few analyze the AC systems [9] , [10] , [11] . Approach for both type of systems DC and AC is similar- they can be both based on transient response measurements evaluated by means of Nyquist stability criteria in order to perform stability analysis of the system [5] , [9] .

Some AC system analysis methods are based on a passive impedance network as a model to capture the behavior of the system [12] [14] . Results of such a research show that the model can be used to predict system performance of power distribution system which constraints for an optimal operation of the on-grid inverter are presented in [13] . They show the importance of the measurement of the inverter output impedance as well as the grid impedance at the point of common coupling.

Similar conclusions are presented in [14] where first, an identification method of the on-grid inverter by Norton equivalent circuit is proposed and then stability analysis of the grid behavior according to its parameters is executed. The authors of [15] [15] also use Norton equivalent circuits as model of single and three-phase on-grid inverters in order to identify their influence on the harmonic spectrum of the low-voltage network.

Received June 20, 2013; Revised August 8, 2013; Accepted September 9, 2013

This paper is inspired mainly by [14] [13] and aims to present a case study of a method of evaluation of the output impedance of on-grid inverter and analysis of its stability regarding to the electrical grid to which it is connected

This rest of the paper is organized as follows: Section 2 introduces the problem formulation, Section 3 presents the results of the experimental analysis and in Section 4 are stated the conclusions.

2. Problem Formulation

As the on-grid inverter function is to inject current into the electrical grid, it is current controlled and more often its equivalent circuit is presented as Norton equivalent circuit or an ideal current source in parallel to impedance.

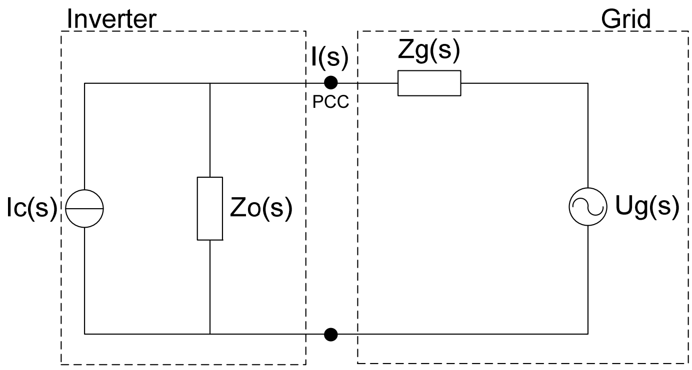

Figure 1. Norton equivalent circuit of on-grid inverter

From the Norton equivalent circuit are derived the following equations describing the current at the output of the on-grid inverter, described in the Laplace domain.

$$I(s) = \frac{I_c(s).Z_o(s)}{Z_o(s)+Z_g(s)} - \frac{U_g(s)}{Z_o(s)+Z_g(s)} \quad (1)$$

Assuming that $I_c(s) = \frac{I_c}{s}$ and $U_g(s) = \frac{U_g}{s}$ and replacing them in (1) we can obtain the following expression for I(s):

$$I(s) = \frac{I_c.Z_o(s)}{s.(Z_o(s)+Z_g(s))} - \frac{U_g(s)}{s.(Z_o(s)+Z_g(s))} \quad (2)$$

From (2) we can derive the equation describing the on-grid inverter output impedance Z_o(s) or:

$$Z_o(s) = \frac{s.I(s).Z_g(s)+U_g(s)}{I_c-s.I(s)} \quad (3)$$

On the other hand, to analyze the stability of the photovoltaic system connected to the grid through on-grid inverter, we have to prove that it operates stably. For that purpose, we rearrange the expression for the inverter output current as follows:

$$I(s) = \left(I_c(s) - \frac{U_g(s)}{Z_o(s)}\right).\frac{1}{1+\frac{Z_g(s)}{Z_o(s)}} \quad (4)$$

As the current and voltage sources can be assumed stable when unloaded and the inverter is stable when the grid impedance is zero, so the stability of the inverter operation can be proved by satisfaction of the Nyquist stability criterion by the ratio of the grid impedance to the inverter output impedance- $Z_g(s)/Z_o(s)$.

The main idea for the definition of the unknown output impedance of the on-grid inverter consists in: 1. Assuming that the grid impedance value is known $Z_g(s)$, as well as the value of the grid voltage U_g. 2.Define the time response of the variation of current I(t) in case of step variation of the inverter current Ic(t) with a known step in transient conditions such as initial start. 3. From the variation of the current I(t) it is defined its Laplace transform I(s). 4. from (3) is defined the expression for the output impedance Zo(s).5. This expression can be used for the stability analysis of the on-grid inverter when it is connected to the grid.

3. Results and Analysis

For the purpose of this research, it is analyzed inverter with output power of 1.2kW.

In this part are presented experimental results of the output current I(t) of on-grid inverter during the initial start of the system. From the following four pictures presented below, we can observe the analysis of the behavior of the on-grid inverter through different processes that occur when a generation form the photovoltaic system starts. In all the oscillograms, the voltage waveform from the Ch2 of the scope corresponds to a current probe of 100mV/A.

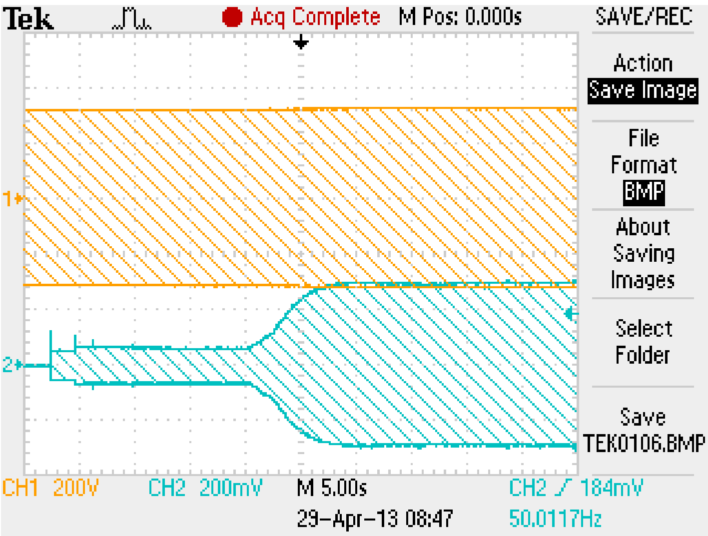

Figure 2. Experimental results after initial start of the on-grid inverter: Ch1 denotes the grid voltage; Ch2 denotes the output current signal. The time span is (-25s,25s).

In Figure 2 is presented the start process of the on-grid inverter. During the first 2.5s, the inverter is not injecting any current to the grid. This period is followed by one first interval of intermittent increase of 0.5A for 2.5s. After that, there is a new intermittent variation of 0.2A for 15s. It is followed by the third interval corresponding to the steady state maximum output power of the photovoltaic modules. During this period, the output current increases step-by-step until it reaches its steady state value

In Figure 3 are presented only the first two intervals. In Figure 4-is presented the step-by-step variation of the current. In Figure 5.is presented the current corresponding to the steady state maximum power.

Authors' multiple experiments show that the lengths of the first two intervals as well as the currents' values during these periods remain conserved always during the initial start. For this purpose, the following research uses the first interval shown as scaled capture in Figure 6.

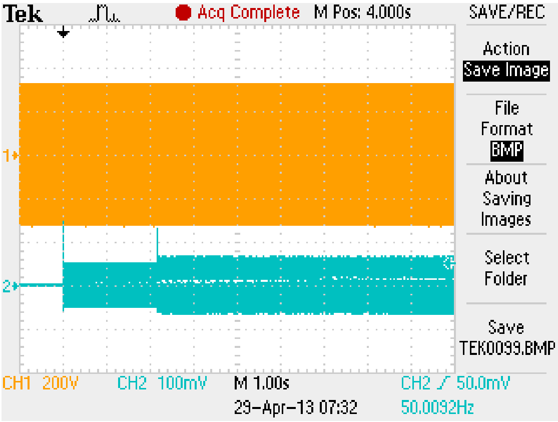

Figure 3. Experimental results after initial start of the on-grid inverter: Ch1 denotes the output voltage signal; Ch2 denotes the output current signal. The time span is (-5s,5s).

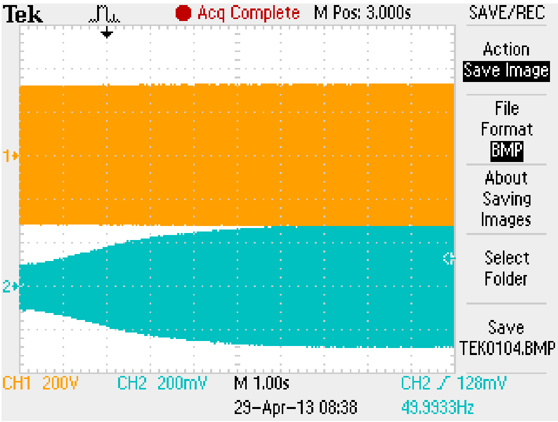

Figure 4. Experimental results after initial start of the on-grid inverter: Ch1 denotes the grid voltage; Ch2 denotes the output current signal. The time span is (-5s,5s).

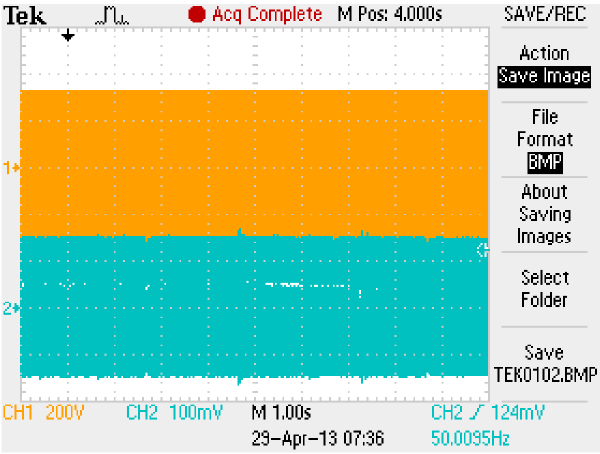

Figure 5. Experimental results after initial start of the on-grid inverter: Ch1 denotes the grid voltage; Ch2 denotes the output current signal. The time span is (-5s,5s).

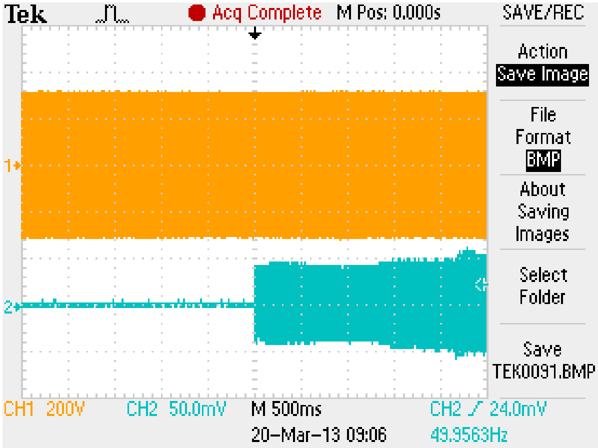

Figure 6. Experimental results after initial start of the on-grid inverter: Ch1 denotes the grid voltage; Ch2 denotes the output current signal. The time span is (-5s,5s).

Based on the experimental results of Figure 6 the curve of the on-grid inverter output current is described by means of measurements of its value on different points of the time. The measures values are presented in Table 1.

Table 1. Measurement of the values of the output current at different points of the time

t, s	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2
I, A	0.45	0.45	0.48	0.48	0.46	0.48	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.48	0.48	0.49	0.48	0.5	0.5	0.48

In order to find out the function that describes best the measured curve an approximation with different functions of the Curve Fitting Tool of Matlab Software was done. The curve of 14th degree polynomial is the closest to the measured curve so it was assumed that the measured curve of Figure 6 is described by the function presented in (5):

$$\begin{aligned} I(x) = {} & 4.13e^{-042}x^{14} - 5.262e^{-038}x^{13} + 3.087e^{-034}x^{12} - 1.122e^{-030}x^{11} \\ & + 2.855e^{-027}x^{10} - 5.398e^{-024}x^{9} + 7.728e^{-021}x^{8} - 8.31e^{-018}x^{7} \\ & + 6.548e^{-015}x^{6} - 3.65e^{-012}x^{5} + 1.37e^{-009}x^{4} - 3.214e^{-007}x^{3} \\ & + 4.096e^{-005}x^{2} - 0.001948x + 0.45 \end{aligned} \qquad (5)$$

In Figure 7 is presented the curve drawn from the measured values and the approximation curve of the 14th degree polynomial as well as the residuals form the fitting that show the quality of the fitting.

From the obtained expression for I(t) we can find its expression in the Laplace domain:

$$I(s) = \frac{4.31e^{053}s^{14} - 1.866e^{051}s^{13} + 7.846e^{049}s^{12} - 1.847e^{048}s^{11} + 3.149e^{046}s^{10}}{9.578e^{053}s^{15}}$$

$$- \frac{4.159e^{044}s^{9} - 4.516e^{042}s^{8} + 4.012e^{040}s^{7} - 2.984e^{038}s^{6} + 1.876e^{036}s^{5} - 9.923e^{033}s^{4}}{9.578e^{053}s^{15}} - \qquad (6)$$

$$- \frac{4.29e^{031}s^{3} - 1.416e^{029}s^{2} + 3.138e^{026}s - 3.449e^{023}}{9.578e^{053}s^{15}}$$

Then the expression for I(s) is replaced in (3) and one can easily identify the expression for $Z_o(s)$, which is necessary in order to execute the stability analysis of the system.

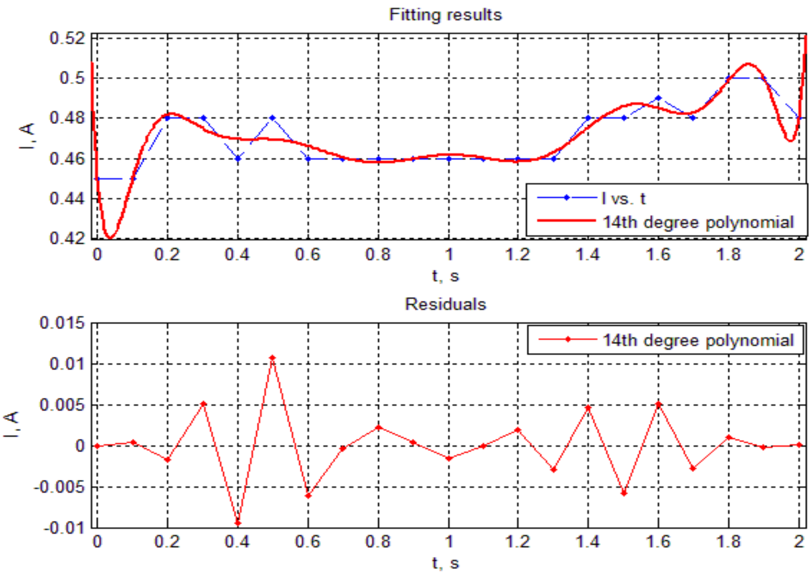

Figure 7. Simulation results of the fitting of the curve of the inverter output current I

For the purpose of the research a measurement of the impedance of the grid to which the inverter is connected was done.

$$Z_g(s) = R_g + s.L_g \quad (7)$$

It has the following parameters:
R_g=12.3 mΩ
L_g=123 μH

By using MATLAB command window and after several mathematical transformations operated by the same software we have drawn the frequency response of the inverter. It is presented in Figure 8.

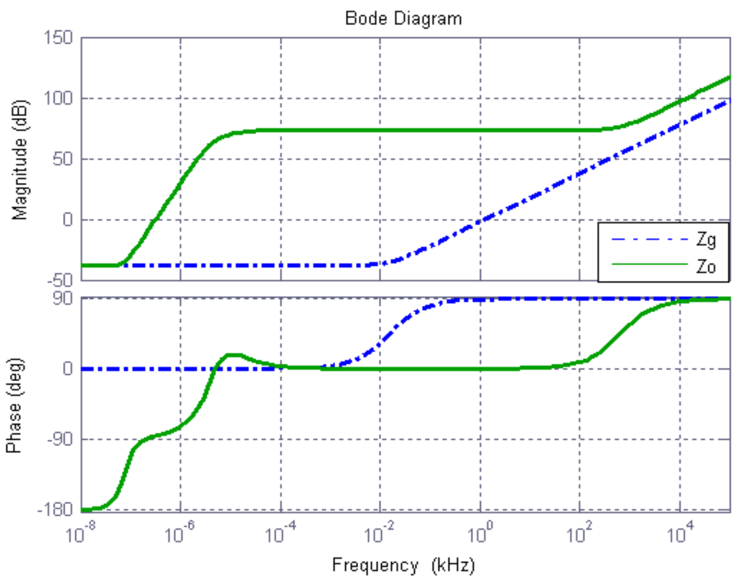

Figure 8. Frequency response of the inverter output impedance and the grid impedance

According to[16] [14] and the close loops automatic regulation rules [16] , as long as the ratio $Z_g(s)/Z_o(s)$.is less than one the system is stable. Instability can be observed at frequencies where this inequality is not satisfied. Frequency responses of Z_g and Z_o show that when the on-grid inverter is connected to a grid with impedance having the parameters of Z_g, there is no possibility to observe any instability.

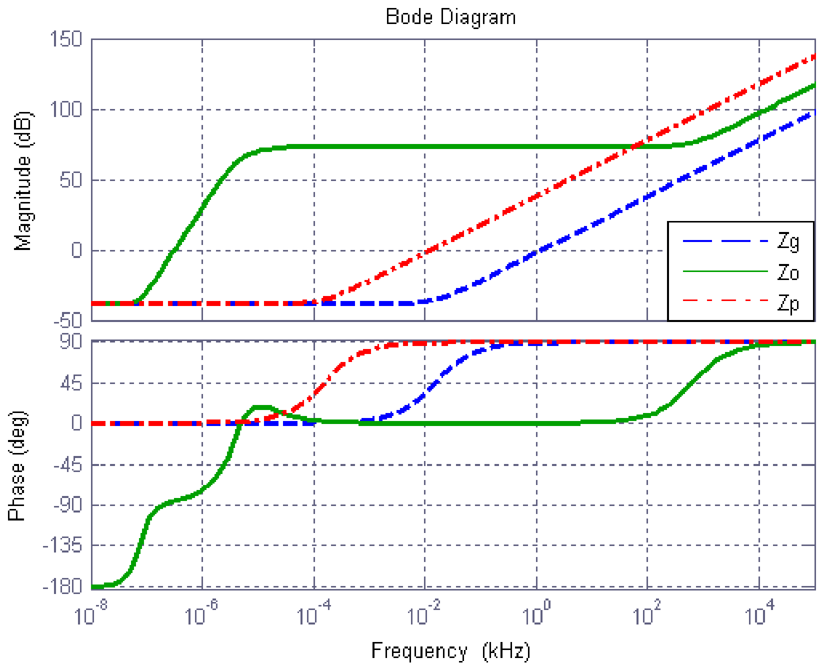

Figure 9. Frequency response of the inverter output impedance and the two different grid impedances

In order to prove the here above statement the same analysis was executed when the on-grid inverter is connected to electrical grid with different parameters.

$$Z_p(s) = R_p + s.L_p \tag{8}$$

Its impedance is Z_p is bigger and has the following parameters:

R_p=12.3 mΩ
L_p=123 mH

The results of this analysis are presented in Figure 9. In Figure 9. one can observe that there is only intersection between the inverter output impedance Z_o(s) and the grid impedance Z_p(s) at frequency of 80 kHz, where the phase difference is 90 degrees which means that there is sufficient phase margin in system stability at all points. Figure 9. proves that the on-grid inverter impedance remains significantly bigger than the grid impedance without any possibility to produce instability in a large bandwidth.

4. Conclusion

This paper presents a method for experimental definition of the output impedance of an on-grid inverter. It is an easy method to define commercial inverter output impedance from a measured and tracked data of the operation of the inverter by using the impedance stability criterion for grid-connected inverters. The simulation frequency analysis proves theoretical expectations for the behavior of the inverter under different grid conditions. The bigger is the output impedance of the on-grid inverter the less sensitive it is to the variation of the grid impedance.

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