Online grid impedance estimation for single-phase grid-connected systems using PQ variations

Mihai Ciobotaru[(1)] Remus Teodorescu[(2)] Pedro Rodriguez[(3)] Adrian Timbus[(4)] Frede Blaabjerg[(5)]

[(1) (2) (4) (5)] Institute of Energy Technology, Aalborg University
Pontoppidanstraede 101, 9220 Aalborg
DENMARK
Tel: +45-9635-9252, Fax: +45-4142-7949
[(1)] **mpc@iet.aau.dk** [(2)] ret@iet.aau.dk [(4)] avt@iet.aau.dk [(5)] fbl@iet.aau.dk

[(3)] Department of Electrical Engineering
Technical University of Catalonia,
SPAIN
+34 (93) 739 8036
[(3)] prodriguez@ee.upc.edu

Abstract- **This paper presents an online grid impedance estimation method for single-phase grid-connected systems, such as photovoltaic systems, small wind turbines, fuel-cells power systems. The method is based on producing a small perturbation on the output of the power converter that is in the form of periodical variations of active and reactive power (PQ variations). The main idea is to make the power converter working in two operation points in order to solve the equation of the equivalent grid impedance. During the perturbation, measurements of voltage and current are performed and signal processing algorithms are used in order to estimate the value of the grid impedance. The online grid impedance estimation method can be used for compliance with the anti-islanding standard requirements (IEEE1574, IEEE929 and VDE0126) and for adaptive control of the grid-connected converters. The proposed method is embedded in the existing power converter control. The selected results validate the effectiveness of the proposed method.**

Keywords- **Grid impedance estimation, Distributed generation, Grid-connected systems, Islanding detection, Adaptive control.**

I. INTRODUCTION

The increased penetration of the electrical grid with Distributed Power Generation Systems (DPGS) based on alternative sources such as photovoltaics (PVs), fuel cells and wind has been enabled by inverter technology developments [1]. The evolution of the recommended guidelines and standards has streamed manufacturing and shaped inverter design and control [2], [3]. However, this necessitates continuous harmonization of standards at international level [4]. Integrating extra functions into the operation of the inverter such as harmonic filtering and distortion elimination have added another progress dimension [5], [6].

In order to comply with certain stringent standard requirements for islanding detection such as the German standard VDE0126 for grid-connected PV systems, it is important to estimate the impedance of the distribution line (grid). The standard requirement is to isolate the supply within 5 s after an impedance change of 1 ohm. Therefore, the PV inverters should make use of an online measurement technique in order to meet these regulation requirements. Moreover, the estimation of the grid impedance can also be used in order to increase the stability of the current controller by adjusting its parameters online. If the variation is mainly resistive then the damping of the line filter is significant and makes the PV inverter control more stable. If the variation is mainly inductive, then the bandwidth of the controller decreases [15]. Also, in this case, due to the additional inductance of the grid, the tuning order of the line filter becomes lower and the filter will not fulfill the initial design purpose. Therefore, besides the standard requirement the knowledge about the grid impedance value is an added feature for the PV inverter [13].

The objective of the paper is to propose an online grid impedance estimation method suitable for single-phase grid-connected systems. The method relies on the variations of active and reactive power.

The paper is organized as follows. First, the known impedance estimation techniques are summarized. Secondly, two applications requiring on-line grid impedance estimation are presented. Next, the proposed grid impedance estimation method based on PQ variations is described. Finally, selected results are presented to validate the effectiveness of the proposed method.

II. GRID IMPEDANCE ESTIMATION TECHNIQUES

According to [13] different techniques, as presented in [7], [8], [9], [10], [11] and [12] can be used for line impedance measurements. It is noticeable that, usually, these methods use special hardware devices. Once the inputs are acquired by voltage and current measurement, the processing part follows, typically involving large mathematical calculations in order to obtain the impedance value.

The state of the art divides the measuring solutions into two major categories: the passive and the active methods.

The passive method uses the non characteristic signals (line voltages and currents) that are already present in the system. This method depends on the existing background distortion of the voltage [16] and, in numerous cases, the distortion has neither the amplitude nor the repetition rate to be properly measured. This will not be interesting for implementing it in a PV inverter.

1-4244-0655-2/07/$20.00©2007 IEEE

Active methods make use of deliberately "disturbing" the power supply network followed by acquisition and signal processing [7], [8], [9] and [11]. The way of "disturbing" the network can vary, therefore, active methods are also divided into two major categories: transient methods and steady-state methods, as briefly described in the following.

A. *Transient Active Methods*

It is worth mentioning that the transient methods are well suited for obtaining fast results, due to the limited time of the disturbing effect on the network. Quickly, by this technique, the impedance measuring device generates a transient current in the network (e.g., a resistive short circuit), and then measures the grid voltage and current at two different time instants, before and after the impulse occurrence. The impulse will bring in a large harmonic spectrum that afterwards should be analyzed. The results obtained show the network response over a large frequency domain, making this method well suited in applications where the impedance must be known at different frequencies. However, this method may involve high performance in A/D acquisition devices and must also use special numerical techniques to eliminate noise and random errors [17]. These requirements are difficult to achieve on a non dedicated harmonic analyzer platform like a PV inverter, even if a DSP controller is used.

B. *Steady-State Active Methods*

Steady-state methods typically inject a periodically known distortion into the grid and then make the analyses in the steady-state period. One of these techniques proposes the development of a dedicated inverter topology [11] and by measuring the phase difference between supply and inverter voltage the computation of line impedance. Another technique, which is easy to implement [18], repetitively connects a capacitive load to the network and measures the difference in phase shift of the voltage to the current.

The technique proposed in [13] is a steady-state technique that injects a non characteristic harmonic current into the grid and records the voltage change response. Results are processed by means of a Fourier analysis at the particular injected harmonic. In this way, the method has the entire control of the injected current. Thus, the calculation resumes only at the specific Fourier terms that give the final result. It is worth mentioning that the same technique can be used to obtain the frequency characteristic of the grid impedance, if the method repeats the measurements at different frequencies [19].

III. APPLICATIONS SUITED FOR GRID IMPEDANCE ESTIMATION

Two applications requiring on-line grid impedance estimation are briefly presented in the following.

A. *Anti-islanding method using grid impedance estimation*

The islanding problem is defined as a continuation of operation of a grid-connected converter after the grid has been turned off. As shown in Fig. 1, the grid-connected inverter can actually continue to run especially if there is a resonant RLC local load (where the resonant frequency is close to the line frequency value and the value of the resistor R matches with the inverter output power). This worst case scenario poses serious safety problems.

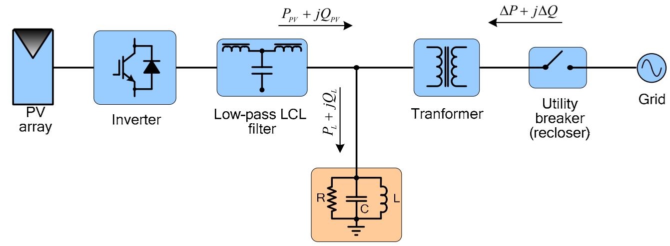


Figure 1. Islanding operation phenomenon

The German standard VDE0126 for PV inverters requires the detection of the increase of grid impedance within a determined time (1 ohm jump in the grid impedance has to be detected in 5 seconds). Therefore, the on-line grid impedance estimation is well suited for this particular standard requirement.

B. *Adaptive control for grid converters based on grid impedance estimation*

The grid impedance also has impact on the control of the grid converters. A large variation on the grid impedance highly decreases the stability and the performance of the current controller. As mentioned, the knowledge of the grid impedance is important for safe operation of a grid connected converter. The performance of the converter also depends on the grid impedance (Z_g) and the voltage at the Point of Common Coupling (V_{PCC}) which in most of the cases is distorted due to other nonlinear loads connected to PCC. See Fig. 2.

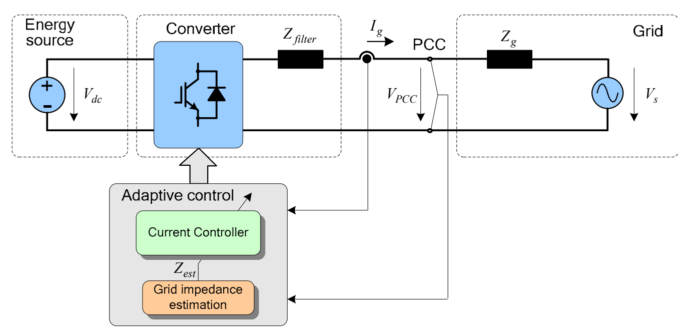


Figure 2. Adaptive control of the grid-connected inverter

The current controller parameters are tuned in accordance with the output filter impedance of the converter Z_{filter} and some assumed value of the grid impedance Z_g. A linear current controller for AC reference tracking with zero steady state error (zero phase shift and zero amplitude error) can be constructed either by transforming the control system into an equivalent DC system and using a DC controller or by using an AC controller (e.g. the proportional resonant controller). In both cases the stability of the controllers depends upon the grid impedance value as the grid impedance is a serial addition to the output filter of the converter. If the variation is mainly inductive, then the bandwidth of the controller decreases as it can be noticed from Fig. 3. In order to alleviate this problem, the gain scheduling method can be used for adjusting online the current controller parameters, as presented in Fig. 4.

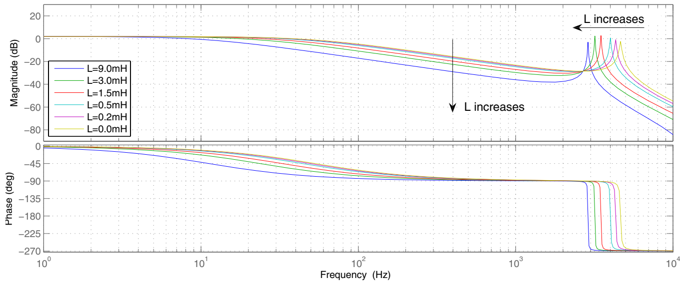


Figure 3. Bode plot of plant for different values of the grid inductance L in case of using an LCL filter

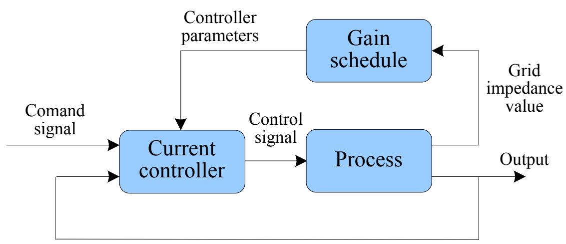


Figure 4. Gain scheduling method

IV. GRID IMPEDANCE ESTIMATION - METHOD DESCRIPTION

The method relies on the variation of active and reactive power of the grid-connected converter. The principle of the variation of active and reactive power is presented in Fig. 5. A PQ control strategy is required in order to implement this method for a single-phase grid-connected system, as presented in [14].

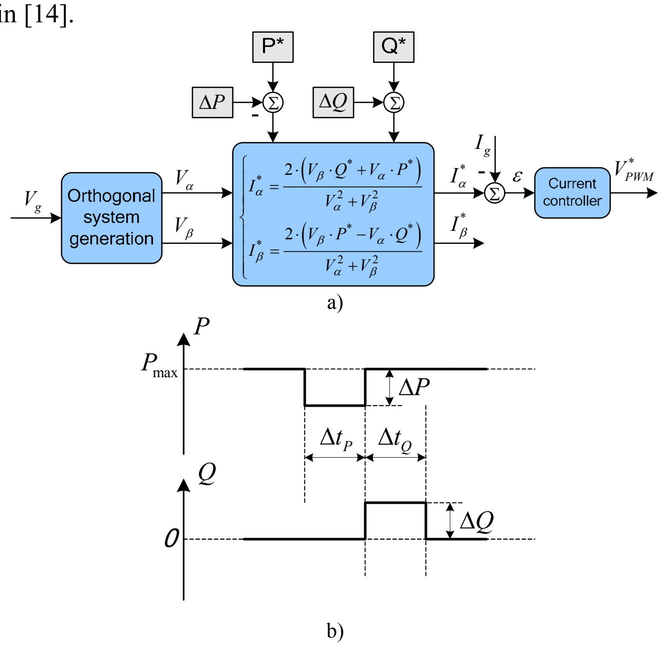


Figure 5. The principle for the variation of active (P) and reactive (Q) power

The PQ control structure is depicted in Fig. 5a. The Orthogonal System Generation (OSG) block is required in order to implement a PQ control in single-phase systems. The orthogonal voltage system is generated by a Second Order Generalized Integrator (SOGI) structure, as shown in [20]. For three-phase systems, this is not longer required, being replaced by the Clarke transformation block (*abc-αβ*).

The accuracy of this method depends of the PQ variation values (ΔP – variation value of active power P and ΔQ – variation value of reactive power Q) and the duration of the perturbation (ΔtP – variation period of active power P and ΔtQ – variation period of reactive power Q), as shown in Fig. 5b.

The PQ control principle is based on the relations presented in (1) and (2) according to [14].

$$\begin{cases} P = \frac{1}{2}\left(V_\alpha \cdot I_\alpha + V_\beta \cdot I_\beta\right) \\ Q = \frac{1}{2}\left(V_\beta \cdot I_\alpha - V_\alpha \cdot I_\beta\right) \end{cases} \tag{1}$$

$$\begin{cases} I_\alpha^* = \dfrac{2\cdot\left(V_\beta \cdot Q^* + V_\alpha \cdot P^*\right)}{V_\alpha^2 + V_\beta^2} \\ I_\beta^* = \dfrac{2\cdot\left(V_\beta \cdot P^* - V_\alpha \cdot Q^*\right)}{V_\alpha^2 + V_\beta^2} \end{cases} \tag{2}$$

Fig. 6 shows the principle of how the method using PQ variations works. The estimation of the grid impedance using PQ variations is explained in the following.

$$\overline{V}_{PCC} = \overline{I}_g \cdot \overline{Z}_g + \overline{V}_s \tag{3}$$

The equation of the grid voltage measured at the Point of Common Coupling (V_{PCC}) is given in (3), where I_g represents the current injected into the grid by the grid-connected converter, Z_g is the grid impedance and V_s represents the voltage source of the grid. The difficulty in the estimation of Z_g using (3) is that the voltage source of the grid (V_s) is immeasurable. Therefore, the main idea is to make the power converter working in two operation points (1 and 2), as presented in Fig. 6, in order to avoid the unknown variable V_s from (3).

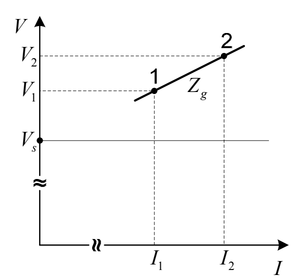


Figure 6. Power converter working in two operation points

It is assumed that the grid impedance is linear between these two nearby working points. In (4), the equations of the grid voltage in these two working points are presented. V_1 and V_2 represent the V_{PCC} for the working points 1 and 2. By subtracting V_2 from V_1 (5), the unknown variable V_s is avoided.

$$\begin{cases} \overline{V}_1 = \overline{I}_1 \cdot \overline{Z}_g + \overline{V}_s \\ \overline{V}_2 = \overline{I}_2 \cdot \overline{Z}_g + \overline{V}_s \end{cases} \tag{4}$$

$$\overline{V}_1 - \overline{V}_2 = \overline{Z}_g \left(\overline{I}_1 - \overline{I}_2 \right) \tag{5}$$

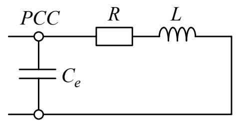


Figure 7. Equivalent grid impedance

Fig. 7 shows the equivalent grid impedance, where R and L are the resistive and the inductive part of the grid impedance. At the fundamental frequency the influence of EMI capacitance C_e over the grid impedance can be neglected: Thus, the relation of the grid impedance Z_g can be written as shown in (6).

$$\overline{Z}_g = R + j \cdot \omega L = \frac{\overline{V}_1 - \overline{V}_2}{\overline{I}_1 - \overline{I}_2} \tag{6}$$

Furthermore, the expressions of the resistance R and inductance L are given in (7) and (8).

The ΔV_q from (8) is considered equal to 0, as the orthogonal voltage system is created artificially for a single-phase system.

$$\begin{cases} R = \mathrm{Re}\left(\dfrac{\overline{V}_1 - \overline{V}_2}{\overline{I}_1 - \overline{I}_2} \right) \\ L = \dfrac{1}{\omega} \cdot \mathrm{Im}\left(\dfrac{\overline{V}_1 - \overline{V}_2}{\overline{I}_1 - \overline{I}_2} \right) \end{cases} \tag{7}$$

$$\begin{cases} R = \dfrac{\Delta V_d \cdot \Delta I_d + \Delta V_q \cdot \Delta I_q}{\Delta I_d^2 + \Delta I_q^2} \\ L = \dfrac{\Delta V_q \cdot \Delta I_d - \Delta V_d \cdot \Delta I_q}{\left[\Delta I_d^2 + \Delta I_q^2 \right] \cdot \omega} \end{cases} \tag{8}$$

As it can be seen from (8), the calculation algorithm for the grid impedance is less complicated in contrast with some of the known used algorithms based on more advanced mathematics such as DFT method [13], Prony extrapolation [7].

V. RESULTS

A single-stage grid-connected PV inverter (1.5 kW power range) has been modeled in order to analyze the proposed method performances, as depicted in Fig. 8. The system has been modeled using MATLAB/Simulink. The plant including the LCL filter and the grid impedance has been developed using Simulink transfer functions as shown in Fig. 9. The voltage source inverter (VSI) is controlled using a unipolar PWM to place the harmonics on the high frequency side making them easier to filter. The parameters of the LCL filter are: L_1 = 1426 μH, C_f = 2.2 μF, L_2 = 713 μH. The EMI capacitance C_e is equal to 1uF. The switching frequency of the inverter is 10 kHz. For higher power, the LCL filter needs to be redesigned.

The Proportional Resonant (PR) plus Harmonic Compensator (HC) current controller, as defined in [15], has been used to control the grid current.

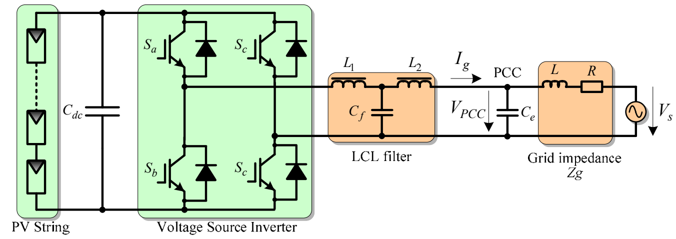


Figure 8. The voltage source PV inverter connected to the grid through an LCL filter

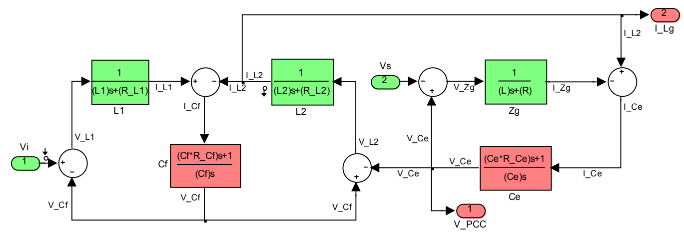


Figure 9. LCL filter and grid impedance modeling

The following parameters were used for the PQ variations: ΔP=100 W (6.6 % of nominal P), ΔQ=100 var, ΔtP=ΔtQ= 60 ms.

A resonant filter has been used (to filter the V_d, I_d, and I_q) in order to get accurate values for the R and L according to (8). The Bode plot and the step response of the resonant filter are presented in Fig. 10a and Fig. 10b. The resonant filter has been designed for a very good filtering without affecting to much the dynamics.

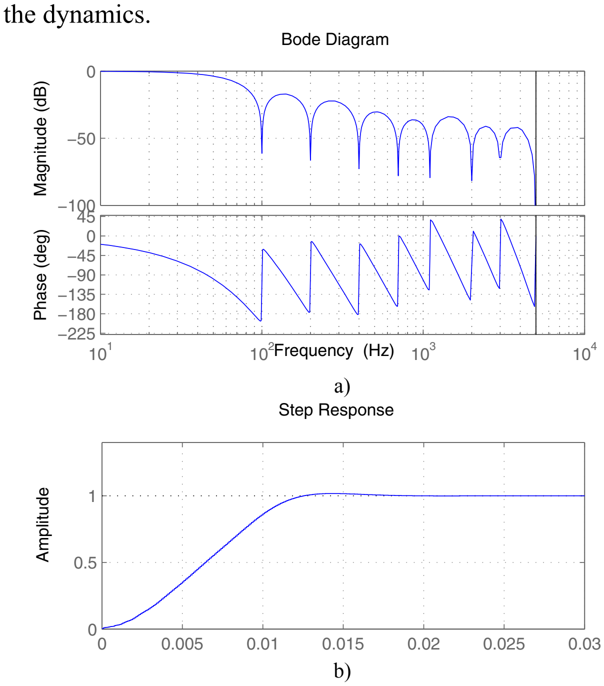
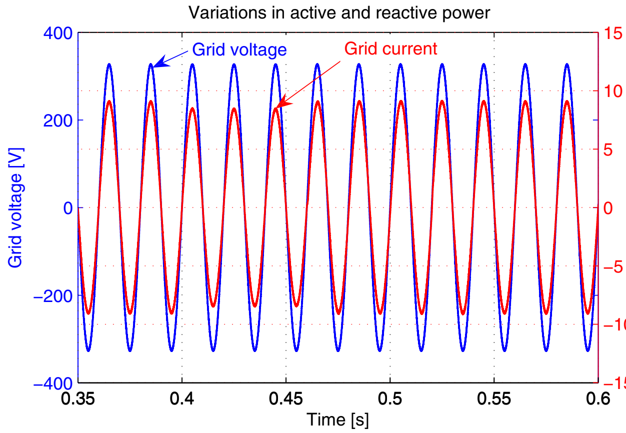


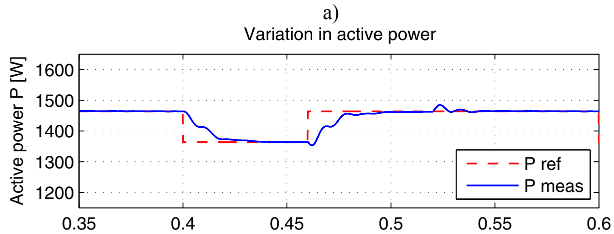
Figure 10. Resonant filter: a) Bode plot and b) Step response

In the following, selected results are presented to validate the proposed method.

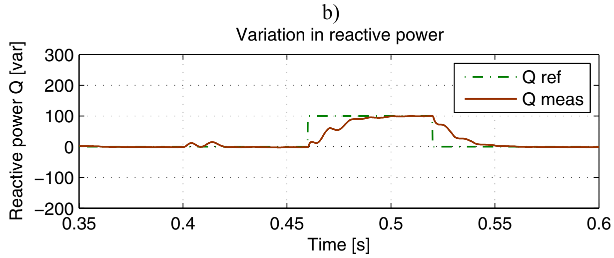
The first set of results is obtained for a simultaneous resistive step of 0.1 ohm and an inductive step of 100 uH, in the case of a grid voltage THD equal to 0% (Fig. 11).



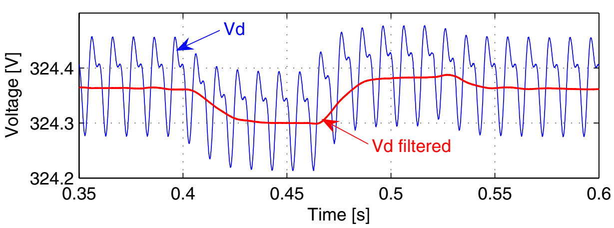
a)



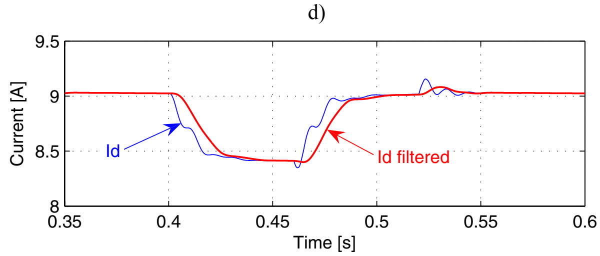
b)



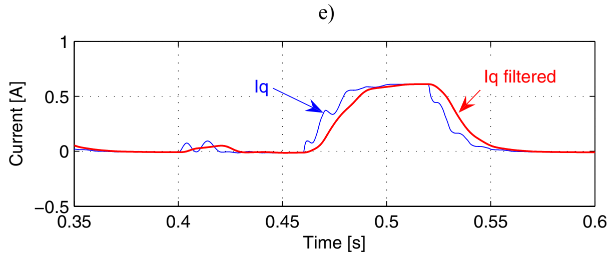
c)



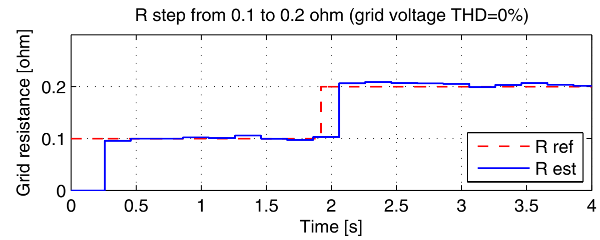
d)



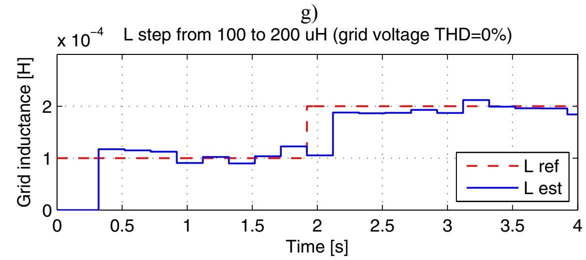
e)



f)



g)

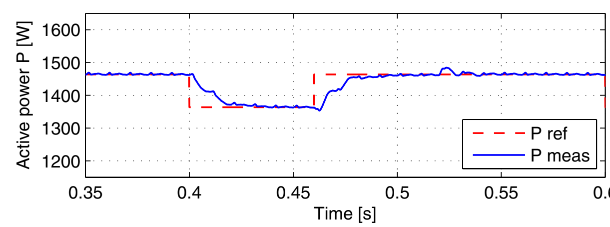


h)

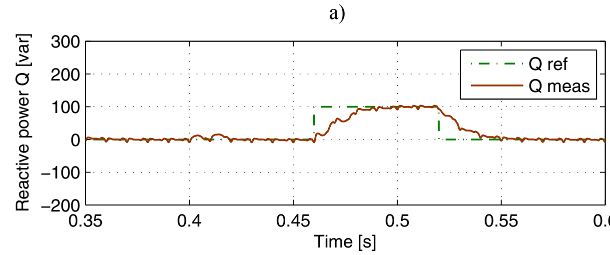
Figure 11. Simultaneous *R* and *L* steps (*R* step from 0.1 to 0.2 ohm and *L* step from 100 to 200uH, grid voltage THD = 0%)

Fig. 11a shows the behavior of the grid voltage (V_{PCC}) and the grid current (I_g) under PQ variations. The references and the measured values of the active and reactive power are shown in Fig. 11b and Fig.11c. The filtered values of V_d, I_d, and I_q, as shown in Fig. 11d, Fig. 11e and Fig. 11f, are used for solving (8). The estimated values of the resistive and inductive part (*R est* and *L est*) of the grid impedance are presented in Fig. 11g and Fig. 11h.

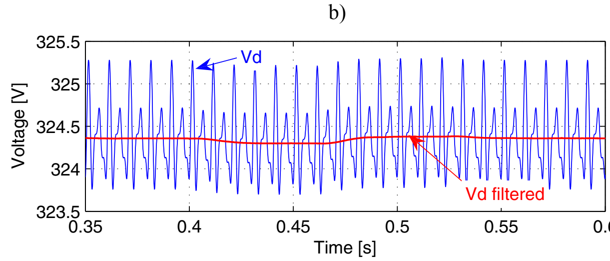
The second set of results is obtained for a simultaneous resistive step of 0.1 ohm and an inductive step of 100 uH, in the case of a grid voltage THD equal to 2.5% (Fig. 12). This is just to show that the harmonics have a minimal impact on the obtained results using the proposed method.



a)



b)



c)

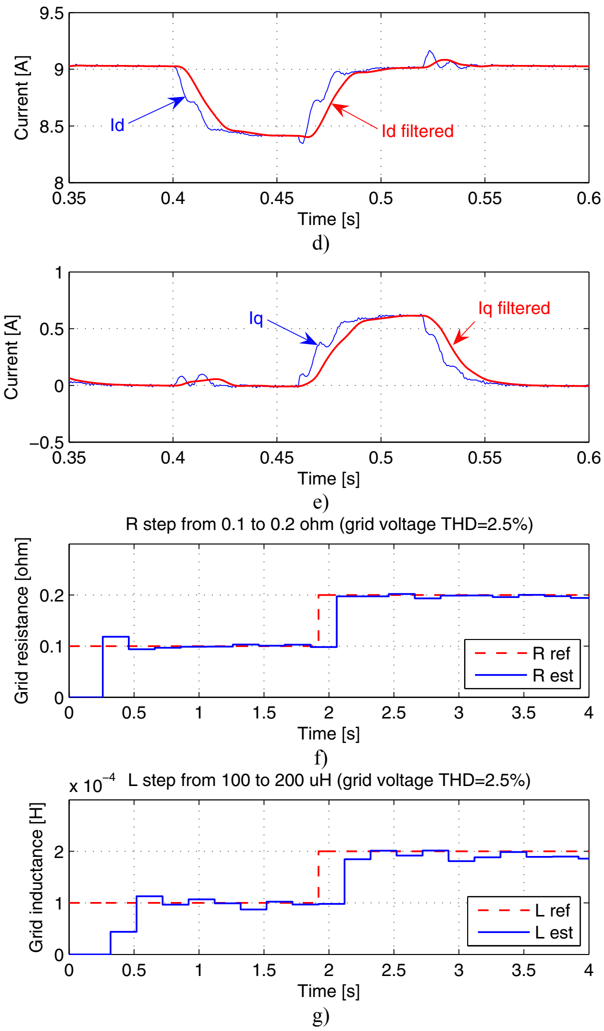


Figure 12. Simultaneous R and L steps (R step from 0.1 to 0.2 ohm and L step from 100 to 200uH, grid voltage THD = 2.5%)

Fig. 12a and Fig.12b show the references and the measured values of the active and reactive power. The filtered values of V_d, I_d, and I_q, as shown in Fig. 12c, Fig. 12d and Fig. 12e, are used for solving (8). Comparing the estimated values of the resistive and inductive part (*R est* and *L est*) of the grid impedance (comparing Fig. 11g with Fig. 12f, and Fig 11h with Fig 12g), similar results are obtained.

The results presented in Fig. 11 and Fig 12 are obtained using small values of the resistive and inductive part of the grid impedance. This can be the case when the grid converter is connected to the grid without an AC isolation transformer.

Fig. 13 shows the results for the case when the grid converter is connected to the grid through an AC transformer. For this particular case, the following test has been performed:
- simultaneous R and L steps (R step from 1 to 2 ohm and L step from 2.5 to 5mH, grid voltage THD = 2.5%).

For the compliance with the German standard VDE0126, a resistive step of 1ohm has been performed in the both cases, with (L=100uH) and without (L=2.5mH) an AC isolation transformer. As it can be seen from Fig. 14, the proposed method using PQ variations successfully fulfill the requirement of the standard VDE0126.

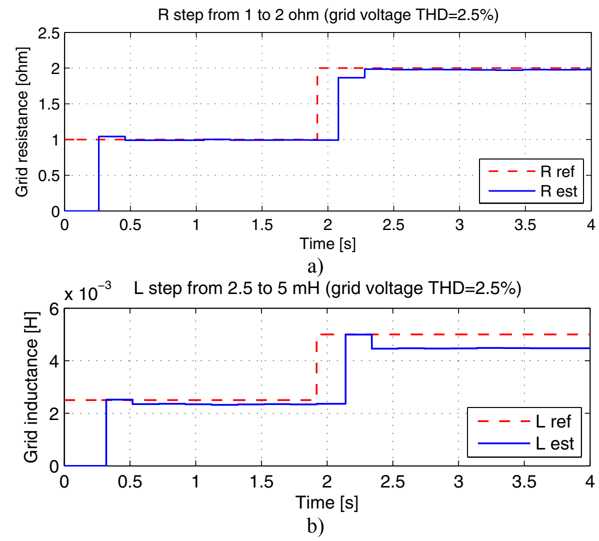


Figure 13. Simultaneous R and L steps (R step from 1 to 2 ohm and L step from 2.5 to 5mH, grid voltage THD = 2.5%)

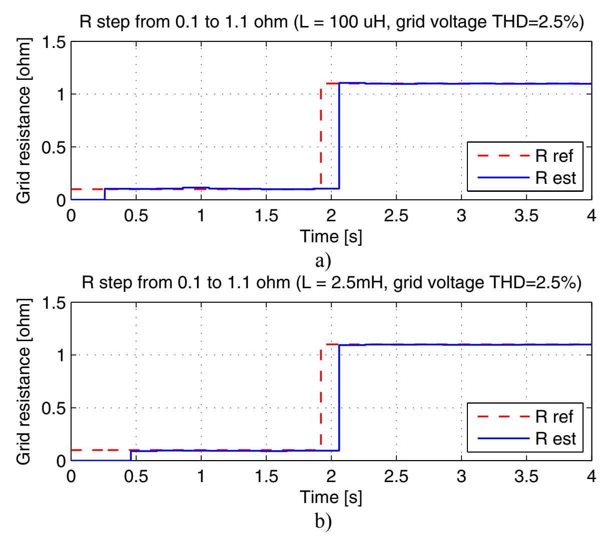


Figure 14. Resistive step of 1ohm (R step from 0.1 to 1.1 ohm, grid voltage THD = 2.5%): a) L=100uH and b) L=2.5mH

VI. CONCLUSIONS

The grid impedance estimation using PQ variations is well suited for both, anti-islanding standard requirements such as the German standard VDE0126 and adaptive control for grid converters due to the fact that the output power of the inverter is less disturbed compare to known active methods.

Moreover, the calculation algorithm for the grid impedance is less complicated in contrast with some of the known used algorithms based on more advanced mathematics such as DFT method, Prony extrapolation. Also, the PQ variation method proved to be robust under harmonics conditions.

However, the implementation of the proposed method necessitates the usage of the PQ control for a single-phase system which can be troublesome in the case of using an inappropriate orthogonal system generation method.

REFERENCES

[1] F. Blaabjerg, Z. Chen, and S.B. Kjaer, "Power electronics as efficient interface in dispersed power generation systems", *IEEE Trans. on Power Electronics,* Vol. 19, No. 5, September 2004, pp. 1184-1194.

[2] *IEEE Standard 929-2000:* IEEE Recommended practice for utility interface of photovoltaic (PV) systems.

[3] *IEEE Standard 1547-2003:* IEEE Standard for interconnecting distributed resources with electric power systems.

[4] A. Woyte, K. De Brabandere, D.V. Dommelen, R. Belmans, and J. Nijs, "International harmonization of grid connection guidelines: adequate requirements for the prevention of unintentional islanding", *Progress in Photovoltaics: Research and Applications 2003,* Vol. 11, pp. 407-424.

[5] T.F. Wu, H.S. Nien, C.L. Shen and T.M. Chen, "A single-phase inverter system for PV power injection and active power filtering with non-linear inductor consideration", *IEEE Trans. on Industry Applications,* Vol. 41, No. 4, July/August 2005, pp. 1075-1083.

[6] T.F. Wu, C.L. Shen, C.H. Chang, J. Chiu, "1~3W grid-connection PV power inverter with partial active power filter", *IEEE Trans. on Aerospace and Electronic Systems,* Vol. 39, No. 2, April 2003, pp. 635-646.

[7] Sumner, M.; Palethorpe, B.; Thomas, D.; Zanchetta, P.; Di Piazza, M.C., "Estimation of power supply harmonic impedance using a controlled voltage disturbance," Power Electronics Specialists Conference, 2001. PESC. 2001 IEEE 32nd Annual, vol.2, pp. 522-527.

[8] Di Piazza, M.C.; Zanchetta, P.; Sumner, M.; Thomas, D.W.P., "Estimation of load impedance in a power system," Harmonics and Quality of Power, 2000. Proceedings. Ninth International Conference on, vol.2, pp. 520-525.

[9] Sumner, M.; Palethorpe, B.; Thomas, D.W.P.; Zanchetta, P.; Di Piazza, M.C., "A technique for power supply harmonic impedance estimation using a controlled voltage disturbance," Power Electronics, IEEE Transactions on , vol.17, no.2, pp. 207-215.

[10] Rhode, J.P.; Kelley, A.W.; Baran, M.E., "Line impedance measurement: a nondisruptive wideband technique," Industry Applications Conference, 1995. Thirtieth IAS Annual Meeting, IAS '95., Conference Record of the 1995 IEEE , vol.3, pp. 2233-2240.

[11] Ishigure, N.; Matsui, K.; Ueda, F., "Development of an on-line impedance meter to measure the impedance of a distribution line," Industrial Electronics, 2001. Proceedings. ISIE 2001. IEEE International Symposium on, vol.1, pp. 549-554.

[12] Tsukamoto, M.; Ogawa, S.; Natsuda, Y.; Minowa, Y.; Nishimura, S., "Advanced technology to identify harmonics characteristics and results of measuring," Harmonics and Quality of Power, 2000. Proceedings. Ninth International Conference on, vol.1, pp., 341-346.

[13] Asiminoaei, L.; Teodorescu, R.; Blaabjerg, F.; Borup, U., "Implementation and Test of an Online Embedded Grid Impedance Estimation Technique for PV Inverters," Industrial Electronics, IEEE Transactions on , vol.52, no.4, pp. 1136- 1144.

[14] Georgakis, D.; Papathanassiou, S.; Hatziargyriou, N.; Engler, A.; Hardt, C., "Operation of a prototype microgrid system based on micro-sources quipped with fast-acting power electronics interfaces," Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual , vol.4, pp. 2521- 2526.

[15] M. Liserre, R. Teodorescu, and F. Blaabjerg, "Stability of grid-connected PV inverters with large grid impedance variation," in Proc. IEEE PESC'04, 2004, pp. 4773–4779.

[16] K. O. H. Pedersen, A. H. Nielsen, and N. K. Poulsen, "Short-circuit impedance measurement," Proc. IEE—Generation, Transmission, Distrib., vol. 150, no. 2, pp. 169–174.

[17] B. Palethorpe, M. Sumner, and D. W. P. Thomas, "Power system impedance measurement using a power electronic converter," in Proc. Harmonics and Quality of Power Conf., vol. 1, 2000, pp. 208–213.

[18] K. Klaus-Wilhelm, "Process and Device for Impedance Measuring in AC Networks as Well as Process and Device for Prevention of Separate Networks," German Patent DE19504271 C1/1996.

[19] J.P. Rhode; A.W. Kelley and M.E. Baran, "Complete characterization of utilization-voltage power system impedance using wideband measurement," IEEE Trans. Ind. Appl., vol. 33, no. 6, pp. 1472–1479, Nov./Dec. 1997.

[20] M. Ciobotaru, R. Teodorescu and F. Blaabjerg, "A new single-phase PLL structure based on second order generalized integrator", in Record of IEEE PESC 2006, Jeju, Korea, p. 1511-1516.