A grid impedance estimation based on injected power variations and mathematical morphology

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***Abstract*—This paper proposes a method for estimating grid impedance suitable for applications where distributed generators are connected to the grid through single-phase inverters. The method is based on variations of the active and reactive power injected into the power grid by the inverter. The impedance is calculated by means of measurements of current and voltage at the Point of Common Coupling (PCC). To enhance the method's performance, a Half-Cicle Fourirer (HCF) filter is applied to the measurement voltage and current. As the inverter's control system is carried out on synchronous dq reference frames, a orthogonal signal generator (OSG) is applied in conjuction with the a Park transformation to generate the synchronous variables. These dq currents are prone to impulsive interference. Therefore, it is suggested the implementation of a morphological filter for mitigation it. The results show the effectiveness of the method.**

***Keywords* – Impedance Estimation, Mathematical Morphology, Fourier Algorithm, Inverter.**

I. Introduction

The increasing penetration of renewable and distributed generation (DG) sources in the power distribution system demands greater robustness from the systems, like inverters, interfacing the power grid. Such inverters must be able to ensure effective control of the flux of energy without causing system instability. Towards this purpose, the control of power converters turned to be a key element in the expansion of Distributed Generation Systems (DGS). The control of inverter must ensure suitable operation of DGS in the presence of harmonic distortions, and limit the harmonic levels of the current injected by the converter. In addition, it must also work to avoid potential resonance risks between the converter and the electrical grid. In this task, estimation and monitoring of the grid impedance constitutes important tools for tuning the parameter1s controllers of the converters connected to the grid in order to meet performance requirements and stability against disturbances and variations of load [1], [2].

The grid impedance variation can bring the instability or deterioration in the quality of energy injected by the inverter in high or low frequency bands of the control system. In high band frequencies, the resonance effect between the LCL filter and the grid must be addressed [3]–[5]. In low-frequencies, the grid variation can impact on the total harmonic distortion (THD) of the injected current [6].

The sudden increase of the impedance estimated at the PCC can indicate an islanding condition of the inverter. In this condition, it is recommended a quick disconnection of the inverter from the grid to avoid risks to the maintenance operators as well as damages to equipment [7].

In this scenario, grid impedance estimation methods stand out as alternatives to adaptive control of grid-connected inverters in conformity with the protection requirements ruled in standards such as IEEE1574, IEEE929 and VDE0126 [8].

It can be found in literature various estimation methods for estimating grid impedance. Given the unpredictability of incoming and outgoing loads in the system, such techniques should obtain the necessary information by grid measurements through the point of common coupling (PCC). There is a predominance of the use of invasive techniques, which rely on disturbing signals that are injected into the grid in a control manner. Despite of the injected disturbance, the invasive methods have predetermined features in terms of repeatability and magnitude, which allow greater precision to the grid impedance estimate at different conditions of grid.

In order to minimize the impacts on the power quality, a method based on variations of active and reactive power is presented in [9]. In this reference, the measured voltages and currents at the PCC between a three-phase converter and the grid are transformed into synchronous dq variables. These variables are used to compute the grid resistance (R) and grid inductance (L) through the interleaved variation of the reference currents (i_d^* and i_q^*) adopted by the inverter's control, without significant disturbances injected into the power grid. Despite of its easiness of implementation, this approach becomes highly inaccurate with harmonic distortion presented in the voltage grid.

It was noted that the method's performance of the method relies heavily on the accuracy and quickness of the current and voltage phasors estimation. Therefore, it is necessary to use auxiliary structures to filter out undesirable distortions from the measured signals. One interesting option, which is suggested in the presented paper is the use of the Half-Cycle

Fourier (HCF) algorithm. This is a filter capable of filtering odd harmonics from the processed signal. It is advantageous over the full-cycle Fourier version due to its shorter length window which makes the filter1s response faster. The drawback is its inability of coping with DC and even harmonics. But those interference distortions are not so common in the grid. Another proposal of this paper is the use of a mathematical morphological (MM) filter to the dq currents. These filters can be adapted to filter out distortions affecting DC signals such the ones as the dq currents. These morphological filters are nonlinear filters whose responses are faster than those ones obtained by linear operations [10]. Finally, the proposal in [9] is here adapted to single-phase systems with the use of an orthogonal signal generator (OSG).

This paper is structured as follows. The second section describes the fundamentals of the method for grid impedance estimation to singe-phase systems here proposed. In the third section, the scope of application in which the technique is be evaluated is outlined. In the fourth section, it is described the proposed method along with the explanation about the MM filter. In the fifth section, the results are presented. Finally, the conclusions are drawn in the last section.

II. IMPEDANCE ESTIMATION METHOD

Consider a generic single-phase DGS, represented in a simplified form by the diagram shown in Fig. 1. In this figure, v_{pcc} and i_{pcc} represent the voltages and currents of phase at PCC and v_g, the grid voltages. The grid impedance is represented by a resistance R and an inductance L.

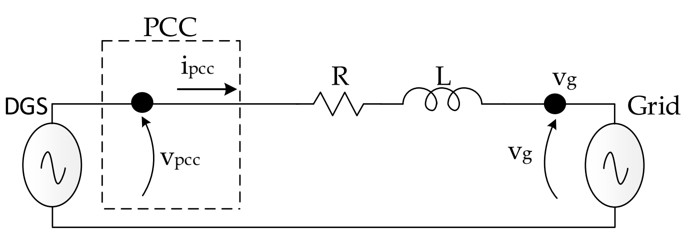

Fig. 1: Simplified single-phase diagram for an DGS.

Based on Figure1 and neglecting the effects of magnetic coupling between phases, the voltage, current and impedance may be related in accordance with (1).

$$v_{pcc} = Ri_{pcc} + L\frac{di_{pcc}}{dt} + v_g \tag{1}$$

The impedance estimation method proposed here is based on variations of active and reactive power references imposed by the inverter's control system. Typically the d current is proportional to the active power and the q current to the reactive power. PI controllers are used to control such currents. In three-phase systems, the $dqcurrents$ are directly obtained the phase currents through the Park transformation. However, in the case of single-phase systems, there is a need of producing quadrature $\alpha\beta$ signals from the single current and voltage sinusoidal signals. In this paper, it is suggested the use of orthogonal signal generator [11], defined as:

$$G(S) = \frac{\omega - s}{\omega + s} \tag{2}$$

From OSG, obtain an orthogonal voltage system as equations (3) and (4). For this, it adopts $v_\alpha = v_{i_{pcc}}$ e $v_\beta = G(S)v_\alpha$.

$$v_\alpha = Ri_\alpha + L\frac{di_\alpha}{dt} + v_{g_\alpha} \tag{3}$$

$$v_\beta = Ri_\beta + L\frac{di_\beta}{dt} + v_{g_\beta}, \tag{4}$$

The equations (3) and (4) can be described in dq coordinates, accordingly to (5) and (6)

$$v_d = Ri_d - L\omega_0 i_q + L\frac{di_d}{dt} + v_{dg} \tag{5}$$

$$v_q = Ri_q + L\omega_0 i_d - L\frac{di_q}{dt} + v_{qg}, \tag{6}$$

where (v_d, v_q) and (i_d, i_q) voltages and currents at the PCC in the synchronous axes dq and (v_{dg}, v_{qg}), the grid voltages in dq. The fundamental frequency of the mains voltage is represented by ω_0. It should be noted that for the steady-state the terms of the derivatives in dq in these equations become null. The grid impedance estimation method proposed here is based on the variations of the voltages and synchronous currents dq at the PCC, imposed by the control of the inverter through the variations of the references currentes (Δi_d^* e Δi_q^*).

Variations in the values of i_d^* and i_q^* imposed on the inverter control system are carried out at two specific instants (t_1 and t_2) in order to intercalated change the voltages and currents in the PAC. It is also possible to rewrite (5) e (6) for instants of time t_1 e t_2 respectively. Hence, for $t = t_1$:

$$v_{d_1} = Ri_{d_1} - L\omega_0 i_{q_1} + v_{dg_1} \tag{7}$$

$$v_{q_1} = Ri_{q_1} + L\omega_0 i_{d_1} + v_{qg_1} \tag{8}$$

For $t = t_2$:

$$v_{d_2} = Ri_{d_2} - L\omega_0 i_{q_2} + v_{dg_2} \tag{9}$$

$$v_{q_2} = Ri_{q_2} + L\omega_0 i_{d_2} + v_{qg_2} \tag{10}$$

The described method proposes the estimation of R and L through the variation of voltages and current at the PCC between two operation points (t_1 and t_2), assuming there are no changes in the value of v_g.Hence, as there are no changes Δv_{dg} and Δv_{qg}, the variations of voltages and currents at the PCC can be written as (12) and (13).

$$\Delta v_{dg} = v_{dg_2} - v_{dg_1} = 0 \quad ; \quad \Delta v_{qg} = v_{qg_2} - v_{qg_1} = 0 \tag{11}$$

$$\Delta v_d = v_{d_2} - v_{d_1} \quad ; \quad \Delta v_q = v_{q_2} - v_{q_1} \tag{12}$$

$$\Delta i_d = i_{d_2} - i_{d_1} \quad ; \quad \Delta i_q = i_{q_2} - i_{q_1} \tag{13}$$

Based on (5),(6),(12), (13) can be rewritten (14) and (15).

$$\Delta v_d = R\Delta i_d - L\omega_0 \Delta i_q, \tag{14}$$

$$\Delta v_q = R\Delta i_q + L\omega_0 \Delta i_d. \tag{15}$$

It is demonstrated in [9] that due the dynamics of the PLL (*Phase Locked Loop*), the variation Δv_q introduces an error in estimation of the grid impedance. Δv_d is considered in grid impedance estimation. To determine the resistance R, one imposes variation only in i_d accordingly to (16).

$$\left\{ \begin{array}{l} \Delta i_d = (i_{d1} - i_{d2}) \neq 0 \\ \Delta i_q = (i_{q1} - i_{q2}) = 0 \end{array} \right\}, \tag{16}$$

and to determine the L, only i_q is varied, accordingly (17).

$$\left\{ \begin{array}{l} \Delta i_d = (i_{d1} - i_{d2}) = 0 \\ \Delta i_q = (i_{q1} - i_{q2}) \neq 0 \end{array} \right\}, \tag{17}$$

It is observed that the value of R obtained from the variation of the current i_d at PCC retaining i_q constant, while the value of L is obtained in the reverse order. Thus, based on the requirements set forth above, one obtains (18) and (19).

$$R = \frac{\Delta v_d}{\Delta i_d}, \tag{18}$$

$$L = \frac{-\Delta v_d}{\omega_0 \Delta i_q}. \tag{19}$$

III. PROPOSED METHOD

The algorithm proposed in this paper is is outlined in Fig. 2. It is observed that the grid impedance estimation is performed with the aid of a HCF filter, and the use of a MM filter. The HCF algorithm is widely used in power system relaying applications such as fundamental component estimation due to its computational efficiency. This strategy eliminates the distortion present in the voltage and current signals caused by odd harmonics. Once these harmonics are rejected, it is possible to visualize the variations in the currents i_d, i_q and in the voltage v_d obtained at the PCC. It is important that the range of these variations is greater than a minimum level to meet the minimum sensitivity levels of the current and voltage measurement sensors and greater non-significant variations of minor grid events. This level is represented by ξ in Fig. 2 and its value is obtained ad-hoc. Emphasizes that dq currents are prone to impulsive interference during the Park transformation. Therefore, it is suggested the use of a morphological filter for mitigation it. this filter, nonlinear filters whose response is faster than those ones obtained by linear operations Costa:2014. In the following, it is discussed the MM filter incorporated used to improve the method proposed.

A. Mathematical Morphology

The application of mathematical morphology (MM) theory in signal processing dates back to the 1980's [12]. Its two most basic operations are the dilation and the erosion. The dilation operation, denoted by $\oplus$ of a discrete-time domain $y[n]$ by a structuring element (SE) $g[n]$ is written as:

$$y[n] \oplus g[n] = \max_k \{y[n+k] + g[k]\}, \tag{20}$$

where max returns the maximum of a given set. The other basic operation of the mathematical morphology, erosion, denoted by $\ominus$, has the effect of erode the processed signal. For a structuring element $g[n]$, the erosion is expressed by:

$$y[n] \ominus g[n] = \min_k \{y[n+k] - g[k]\}, \tag{21}$$

Two other operations originate from the dilation and erosion. The first is the opening, denoted by $\circ$ and defined by:

$$y[n] \circ g[n] = (y[n] \ominus g[n]) \oplus g[n]. \tag{22}$$

The second is the closing, $\bullet$, provided by:

$$y[n] \bullet g[n] = (y[n] \oplus g[n]) \ominus g[n]. \tag{23}$$

These operators are used to define an applied filter.

1) Applied morphological filter: The morphological filter employed in this paper acts on the i_d and i_q currents, which are constants in steady-state conditions. To provide generality in the analyse, let us assume that y_f stands for the dq currents to be processed by the SE $g[n]$. The MM filter is given as [13]:

$$y_f[n] = (y[n] \circ g[n] \bullet g[n] + y[n] \bullet g[n] \circ g[n])/2. \tag{24}$$

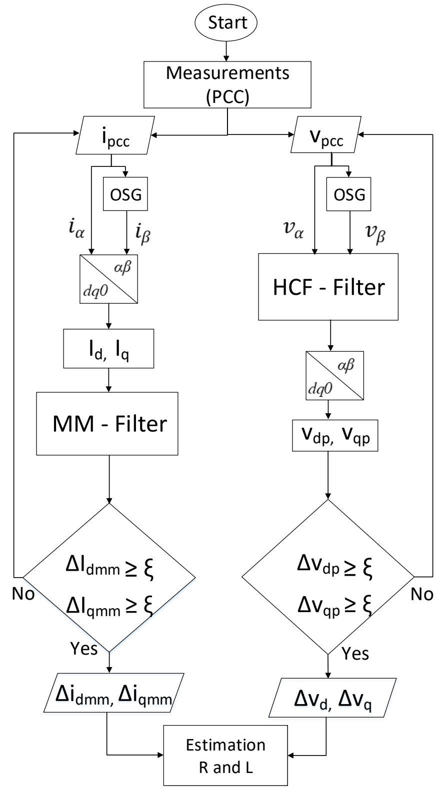

Fig. 2: Proposed algorithm method.

This filter was applied to remove impulsive noise from reference power signals to wind DGs wireless transmitted by a central operator. The flatness of the SE explains the filter performance for DC signals and its realization has been carried out accordingly to [10]. A sliding window is adopted over the signal whose length is equal to the flat SE.

IV. SCOPE OF APPLICATION

For evaluation of the technique, it was simulated a GDS of 2KW in the MATLAB/Simulink environment. Fig.3 shows the diagram for the simulated GDS. Where, v_{pcc} and i_{pcc} are the instantaneous voltage and current at the PCC transformed into reference dq reference frames. The power grid is modeled by a single-phase source connected in series with the grid impedance, represented by L and R. i_{dmm} and i_{qmm} are the synchronous currents filtered by the MM filter and v_{dp} is v_d filtered by the HCF-Filter. Table I summarizes the main system's parameters.

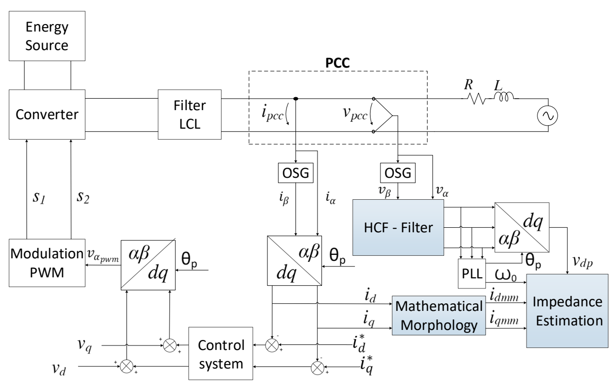

Fig. 3: Single-phase DGS.

TABLE I: System Parameters.

Grid Line Voltage (rms)	230 V	Inductance Filter L_1	20 mH
Grid Inductance (L)	5 mH	Inductance Filter L_2	0.05 uH
Grid Resistance (R)	2 Ω	Capacitor Filter	5 uF
Link DC(inverter)	400 V	Resistance Filter	10 Ω
Grid Frequency	60 Hz	Switching Frequency	18 kHz

The simulations propose to evaluate the behavior of the method on presence of voltage harmonics odd order 5ª an 11ª, the features on systems with non-linear loads connected to grid. Through the programmable single-phase voltage source, mains voltage harmonics with $0,05\angle 0°$ p.u obtaining THD of 7.13%. This value is within the limits established by the IEEE standards 519-2014 for individual and total distortion.

V. RESULTS

In order to evaluate the proposed grid impedance estimation method and to highlight the influence of its auxiliary structures (HCF and MM filters) on the reduction of the error for the grid resistance (R_{est}) and inductance (L_{est}), three simulation scenarios have been devised in Matlab/Simulink environment. The grid is submitted to harmonics. In the first one, the grid impedance is computed without the addition of the HCF and the MM filter. In the second scenario, the method is tested using the HCF Filter. In the last scenario, the MM filter is also added to the impedance estimator.

The results aims to access the method efficiency with regards to the estimation time (Δt_e) and to the error (%) produced in the computation of the grid impedance. The time (Δt_e) is determined by the difference between the instant that the variations in I_d or I_q are imposed and the instant in which the impedance estimation is performed by the algorithm.

A. 1º Scenario: Impedance estimation without any filters

In this section, the results have been obtained without the HCF and MM filter. Fig. 4 illustrates how the estimation is carried out for the inductance L_{est}. It shows the i_d current, obtained after processing the measured current through the OSG and Park transformation. This measurement is very oscillatory due to the harmonic distortions presented in the grid voltage. At a given moment, a step variation is forced to i_q and after a time period of $\Delta t_e = 0.0178s$, the estimation for L_{est} is completed. The error for this estimation is 38.2%. Similarly to the previous figure, Fig. 5 demonstrates the calculation performed for the resistance R_{est} from the imposed steppe at i_q. The time for R_{est} is $\Delta t_e = 0.0201s$ with error of 60%.

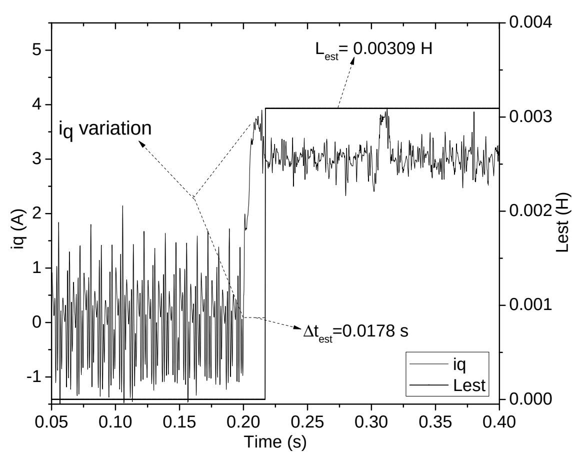

Fig. 4: Estimation of L by the variation of i_q.

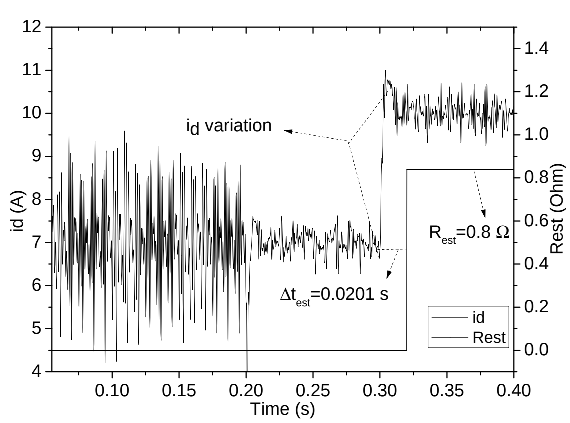

Fig. 5: Estimation of R for the i_d.

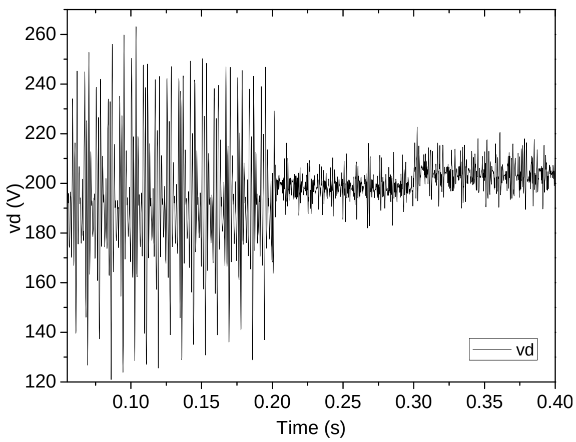

Fig. 6: Variation of v_d at the PCC.

B. 2º Scenario: Impedance estimator with the HCF filter

In this scenario, the results have been obtained by incorporating the HCF filter to the grid voltages at the PCC. Figs. 7 and 8 show the currents i_q and i_d still with significant amount of distortion. In spite of these distortions, the usage of the extractor based on HCF filter cleans the harmonic distortions from the grid voltages. This results in a stable estimation for v_d, as depicted in Fig. 9. Consequently, the variations for v_d are more easily detected. This, in turn, leads to a more accurate estimation of the inductance and resistance. In Fig. 7 and 8, it is shown that the time for estimation of L_{est} is $0.0243s$ and for estimation of R_{est} is 0.0213. Although these times are slightly greater than the ones obtained in the first scenario, the error for L_{est} is 8,2% and for *Rest* is 13,25%, which are quite less than the errors reached in the previous situation.

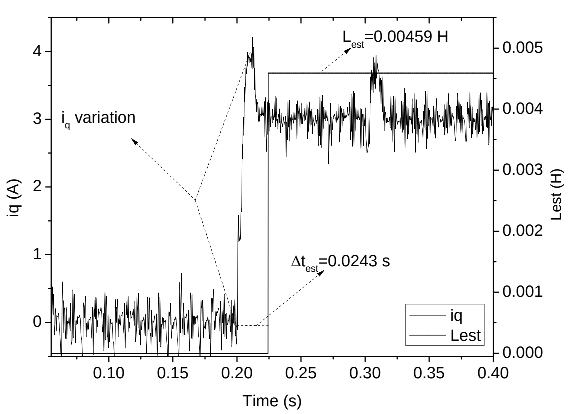

Fig. 7: Estimation of L by the variation of i_q.

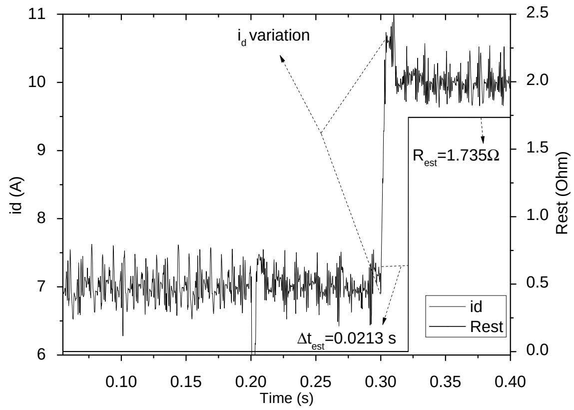

Fig. 8: Estimation of R for the variation of i_d.

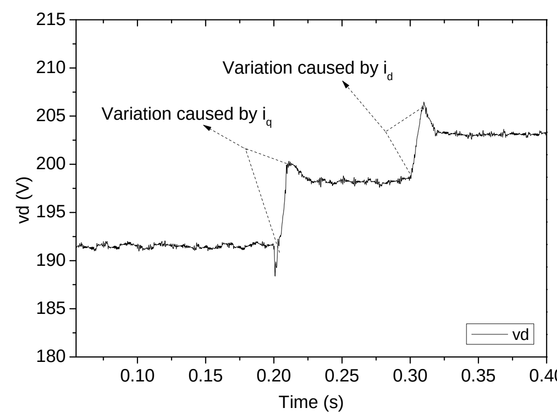

Fig. 9: Variation of v_d at the PCC.

C. 3º Scenario: Impedance estimation using HCF and MM

In this scenario, the results have been obtained by incorporating the MM filter before the transformed current i_q and i_d. This strategy eliminates the distortion in the currents caused by the harmonics presented in voltages at PCC, as shown by Figs. 10 and 11. The influence of the MM filter on the results of the method can be clearly inferred by the errors found in the inductance (L_{est}) and resistance (R_{est}), which are 0.2% and 0.3%, respectively. The times Δt_e reached to the estimation of L_{est} and R_{est} are $0.0243s$ and $0.0214s$, respectively. Although a slight increase in Δt_e is noticeable, a significant reduction in the error (%) is obtained. Hence, it is possible to state that this approach is advantageous over the previous scenarios. The SE used by the MM filter has a window length of 10 samples (0.03 % of a fundamental cycle). As the MM operators applied in this filter are based on simple operations, with size of SE, it is possible to ensure low computational effort.

Table II summarizes the results. It is clear that the proposed method really enhances the standard method proposed in [9].

TABLE II: Summary of results

Scenario	**error (%)** L	Δt_e **(s)**	**error (%)** R	Δt_e **(s)**
1º	38.2	0.0178	60	0.0201
2º	8.2	0.0243	13.25	0.0213
3º	0.2	0.0243	0.30	0.0214

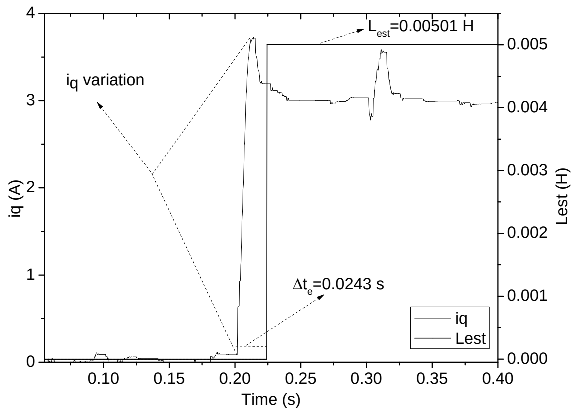

Fig. 10: Estimation of L by the variation of i_q.

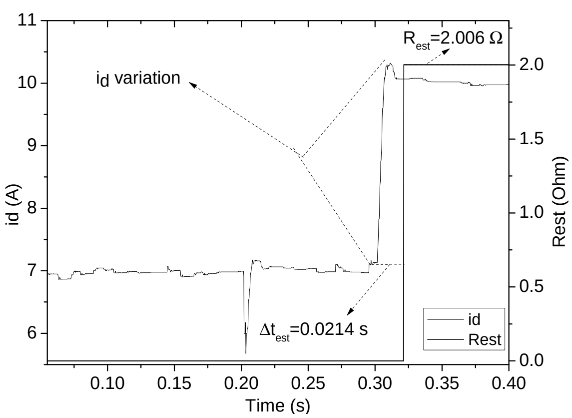

Fig. 11: Estimation of R for the variation of i_d.

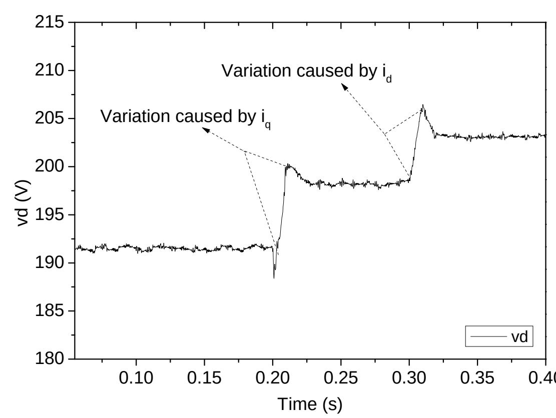

Fig. 12: Variation of v_d at the PCC.

VI. Conclusion

This paper has presented a proposal for improving a method of grid impedance estimation based on current variations injected by a single-phase grid-connected inverter. The enhancement relies on the use of a Fourier and a morphological filters. The Fourier filter is applied only to the voltages as it imposes excessive delays on the currents. The developed algorithm rejects odd harmonics presented in the voltage and current signals. The pre-filtering current signals i_d and i_q with the morphological filter reduces the impedance error estimation.

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