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## Acknowledgments

## Keywords

<<Distributed power>>, <<Excitation system>>, <<Active damping>>, <<Estimation technique>>.

## Abstract

The penetration of the distributed power generation systems (DPGSs) based on renewable sources (PV, WT) is strongly dependent on the quality of the power injected to the utility grid. However, the grid impedance variation, mainly caused by grid faults somewhere in the electric network, can degrade the power quality and even damage some sensitive loads connected at the point of the common coupling (PCC). This paper presents detection-estimation method of the grid impedance variation. This estimation tehnique aims to improve the dynamic of the distributed generation (DG) interfacing inverter control and to take the decision of either keep the DG connected, or disconnect it from the utility grid. The proposed method is based on a fast and easy grid fault detection method. A virtual damping resistance is used to drive the system to the resonance in order to extract the grid impedance parameters, both resistive and inductive parts, using resonant filter frequency determination. Theoretical analysis and simulation results are presented to validate the proposed method.

## Introduction

Distributed power generation systems (DPGSs) are emerging as a possibility of integrating renewable power sources such as wind and photovoltaic into the electrical network. These prime movers are usually operating in grid-connected mode injecting the maximum power to the grid, i.e. they are connected to the utility grid through an inverter to exchange the power between the grid and the system. One of the major challenges in such system is the islanding operation due to a blackout or the occurence of a predefined disturbances such as a long grid voltage sag and frequency variations. Many islanding detection methods are proposed in the literature [1], [2], [3]. Many of them are based on the grid impedance variation,which can lead to a poor power quality at the point of the commun coupling (PCC) by shifting the voltage and attemps the system stability by shifting the resonance frequency [4], [5]. Indeed, the effects of grid impedance variation are related to the resonance frequency variation of the system, which can be divided into two main categories according to the frequency range, as follows:
- Low frequency range: The increase of the grid impedance leads to a decrease in the resonance frequency, so it can be less than 10 times the grid frequency, this leads to the resonance phenomenon, especially when supplying nonlinear loads, since $5^{th}$, $7^{th}$ and $11^{th}$ current harmonics in these loads may

coincide with the resonance frequency and introduce severe problems [4], [5].
- High frequency range: if the half of the switching frequency is lower than the resonance one, the capacitor becomes useless and the LCL-filter behaves like the sum of the converter-side and grid-side inductances, hence causing unpredictable current waveform [4], [5].
Thus, one solution is to estimate the grid impedance once it changes [6] and to introduce the new parameters in the system control strategy in order to keep the system stable. This will allow to improve the PWM-voltage source inverter (VSI) output power quality and to disconnect the DPGS when the grid impedance variation exceeds the limits.
Several methods have been proposed in the literature to calculate the grid impedance. They can be classified into three categories:
1) Grid impedance estimation method based on control loop variations, which include the new resistive and inductivevalues into the control strategy in order to improve its performance [7].
2) Grid impedance estimation methods based on using extra devices dedicated for this purpose [8].
3) Methods based on the injection of harmonic signal into the grid, and then mathematically analys the output response to determine the new grid impedance parameters [9], [10] and [11].

The method described in this paper can be considered inside the last category method since it is based on the filter resonance excitation: it is seemly to say the injection of a harmonic signal with the proper resonance frequency of the LCL-filter. The method consists on an active damping with a virtual resistance implemented in the control system strategy. The virtual resistance helps to improve the output power quality in grid healthy mode (no grid impedance variation) and to drive the system near the resonance in case of grid impedance variations for inductance estimation purposes.
This paper is organized as follows. The system control strategy is being described in the second section. The proposed improved grid impedance estimation is presented and discussed in the third section describing the different algorithm steps. Finally, in the last section simulation results are given.


## Modelling of the current-controlled voltage source inverter

Inverters are often used in distributed power systems to interface prime movers with the utility grid. Passive filters are also used to eliminate the switching frequencies harmonics, LCL-filters are widely used due to its efficiency.

Considering that the continuous DC voltage is kept constant by a prime source side converter and the grid model is an inductive + resistive branch in series with an ideal voltage source noted $V_g$ [6]. In grid connection mode, the distributed generation acts as a current source and the voltage is imposed by the grid, so the strategy of connected system control is based on controlling only the grid side current as shown in Fig. 1.



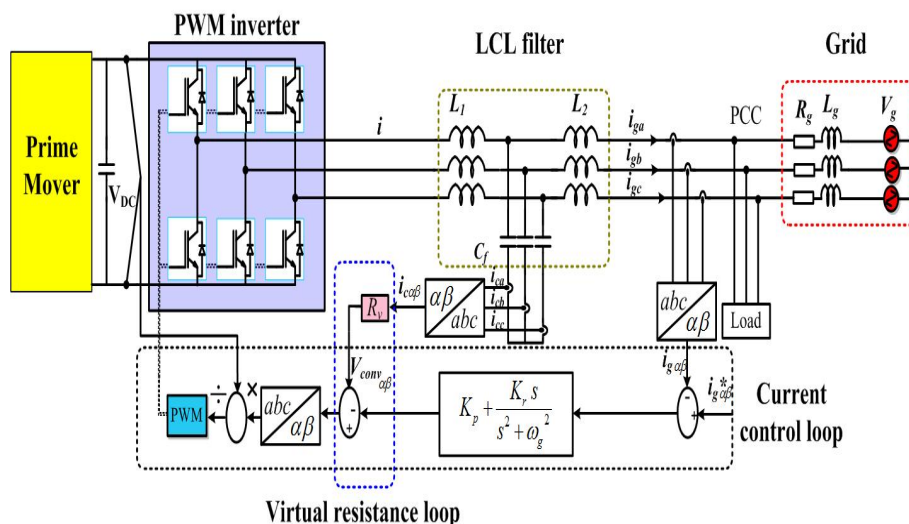Fig. 1 : Power stage and control of the DPGS connected to the grid


The grid side current $i_g$ is chosen as a control variable in order to reduce the sensors number since the grid fault detection method is based on the difference calculation between two consecutive grid current measurements [6].
The transfer function of the VSI closed loop output voltage $V_{conv}$ to the grid current $i_g$ can be expressed

as an admitance as follows.

$$\frac{I_g}{V_{conv}} = \frac{1}{L_1 s} \frac{Z_{LC}^2}{(s^2 + \omega_{res}^2)} \tag{1}$$

where $s$ is the Laplace operator, $\omega_{res}$ is the filter resonance frequency and $Z_{LC}$ is the gain of the grid-side current sensor and their resonant zeros in the converter-side current sensor.
Being

$$Z_{LC} = \frac{1}{(L_2 + L_g)C_f} \tag{2}$$

$$\omega_{res} = \sqrt{\frac{L_1 + L_2 + L_g}{L_1 C_f (L_2 + L_g)}} \tag{3}$$

Noteworthy that the high order LCL-filter can provoke system instabilities [12] which needs the integration of damping elements, so that the active damping is the adopted solution and it is carried out by the implementing of a virtual resistance in the control strategy. Indeed, the virtual resistance is carried out by sensing the filter- capacitor current and multiplying it by a gain noted here $R_v$ [13]. The output of this gain will be subtracted from the converter reference $V_{conv}^*$.
It is worthwhile to use a Proportional+Resonant controller(P+R) to regulate the grid current as it produces an infinite gain at the selected resonant frequency (grid frequency) for the steady-state error elimination at this frequency, in this work the grid frequency is supposed to be constant (50 Hz), in case of various grid frequency, a non ideal resonant controller should be adopted [14]. The transfer function of an ideal P+R controller is given by (4).

$$TF_{(P+R)} = K_p + \frac{K_r s}{(s^2 + \omega_g^2)} \tag{4}$$

where $K_p$ is the proportional gain which controls the system dynamic and $K_r$ is the resonant gain allowing the elimination of the steady-state error.
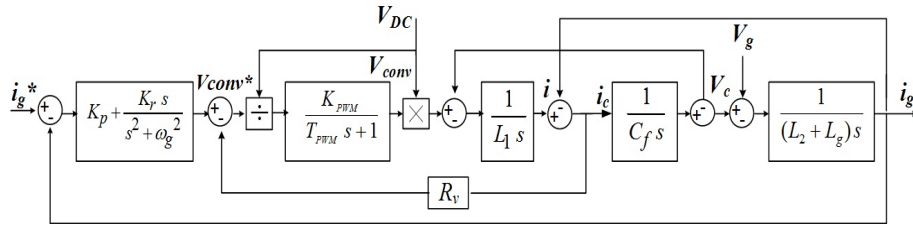


Fig. 2 : Block diagram of the closed loop transfer function.

Fig. 2 shows the block diagram of the closed loop control strategy, including the PWM effect $K_{PWM}$ is the gain of the inverter and $T_{PWM}$ the control delay. The resistive grid impedance part is neglected for calculation simplifications reason. The closed loop transfer function can be expressed as follows:

$$\frac{i_g}{i_g^*} = \frac{z_0 s^2 + z_1 s + z_2}{a_0 s^6 + a_1 s^5 + a_2 s^4 + a_3 s^3 + a_4 s^2 + a_5 s + a_6} \tag{5}$$

Being
$z_0 = K_p$
$z_1 = K_r$
$z_2 = K_p \omega_g^2$
$a_0 = T_{PWM}(L_g + L_2)L_1 C_f$
$a_1 = (L_g + L_2)L_1 C_f$
$a_2 = R_v(L_g + L_2)C_f + \omega_g^2 T_{PWM}(L_g + L_2)L_1 C_f + T_{PWM}(L_g + L_2 + L_1)$
$a_3 = \omega_g^2(L_g + L_2)L_1 C_f + (L_g + L_2 + L_1)$
$a_4 = \omega_g^2(R_v(L_g + L_2)C_f + T_{PWM}(L_g + L_2 + L_1)) + K_p$
$a_5 = \omega_g^2(L_g + L_2 + L_1) + K_r$
$a_4 = K_p \omega_g^2$

# Proposed method principle

The proposed method in this paper is based on LCL-filter resonance excitation. The excitation of the filter is ensured by varying the virtual resistance value after a detection of a grid impedance variation. The steps are followed:
- Improve the system stability by expanding the system stability margin especially in case of no impedance variation.
- Reduce the resonance effect near the low frequency range.
- Give the possibility of the system control reconfiguration by varying $R_v$ in order to keep the system stable even after an impedance variation due to the ability of this virtual resistance as it is a software component.

The filter resonance excitation is reached by decreasing gradually the damping effect. Then, the resonance frequency, which depends on the grid impedance, is determined [6], [12]. And finally, the grid inductance value is extracted. The resistive grid impedance part can be deduced from the grid impedance value.

## Grid impedance variation detection

In order to detect a grid impedance variation, the method uses temporal redundancies of grid current measurements [15]. Theoretical developments are given in [16], where its efficiency in fault detection and isolation of faulty sensor in electrical drives (FDI) was proven. Its principle consists on the calculation of the difference between two consecutive current measurements.

In healthy conditions, i.e with no grid impedance variation, the residual $Res_{igk}$ is lower than a calculated threshold, with a very small sampling time, $T_a$. As the grid impedance varies, this residual increases significantly. Its waveform presents a spike that defines the instant of the fault. The residual expressions are given by (6) and (7).

$$Res_{i_{gk}} = r_k + r_{k-1} + r_{k-2} \tag{6}$$

$$r_k = |i_{gk} - 2i_{gk-1} + i_{gk-2}| \tag{7}$$

where $i_{gk}$, $i_{gk-1}$ and $i_{gk-2}$ are the grid side measured current at the consecutive times $kT_a$, $(k-1)T_a$, $(k-2)T_a$ respectively. The threshold expression is given by (8) where more analytical development is performed in [15], [16]. The parameters used for the threshold expression are given in Table 1.

$$\varepsilon = 3\omega^2 T_a^2 I_m \tag{8}$$

$$I_m = \frac{V_{PCC_m} - V_{g_m}}{|Z_g|} \tag{9}$$

**Table 1** : **Threshold Parameters**

| Symbol | Definition |
|---|---|
| $\tau_s(\omega = \frac{2\pi}{\tau_s})$ | System time constant |
| $V_{PCC_m}$ | Maximum voltage at PCC |
| $V_{gm}$ | Maximum grid voltage |

## Grid impedance estimation

As proven in [4], [6], the system resonance frequency depends on the grid impedance, especially on the inductive part of the grid impedance. The resonance frequency is expressed as follows:

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{L_1 + L_2 + L_g}{L_1 C_f(L_2 + L_g)}} \tag{10}$$

Fig. 3 shows that an increase in the grid inductance leads to the decrease of the resonance frequency and inversely a decrease in the grid inductance moves up the resonance frequency.
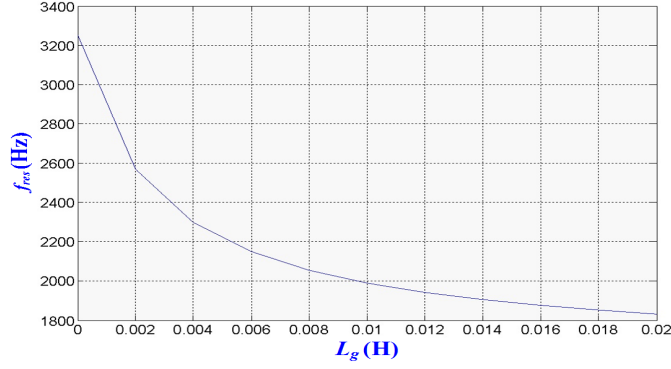
Fig. 3 : Resonance frequency variation versus $L_g(H)$

The inductive part of the grid impedance can be deduced from the resonance frequency by applying the Fast Fourier transformation (FFT). Consequently, the grid inductance can be deduced as follows :

$$\widehat{L_g} = \frac{(L_1 + L_2) - (4\pi^2 L_1 L_2 C_f f_{res}^2)}{(4\pi^2 L_1 C_f f_{res}^2 - 1)} \tag{11}$$

Instead of increasing the proportional gain until reaching the resonance, the proposed method consists on taking a high proportional gain at the beginning, and then reducing the virtual resistance so that we drive the system poles to the left half plane to reach the resonance. Note that a system in resonance is an unstable system but an unstable system can be in a resonance state.

Fig. 4 presents the proposed method algorithm, where a high P+R controller parameters are designed. The virtual resistance is evaluated by resolving the Routh criteria equation whereas the residual based on current measurement is continuously calculated. When its value becomes higher than a predefined threshold, i.e. to say when a grid fault is detected, the system is driven near the resonance to perform a new calculation of $L_g$ parameter value by decreasing the resistance value gradually to move the system poles toward the right half plane until detecting the resonance. Once the resonance is detected, the system control keeps the new virtual impedance value and the FFT is applied in order to determine the new inductive grid impedance value from the relation expressed in (11).

Since $L_g$ has been estimated from the resonance frequency and the residual measurements, the grid impedance resistive value, $R_g$, is deduced from (9) as follows:

$$\widehat{R_g} = \sqrt{\frac{9\omega^4 T_a^4}{\varepsilon^2}(V_{PCC_m} - V_{g_m})^2 - (\omega L_g)^2} \tag{12}$$
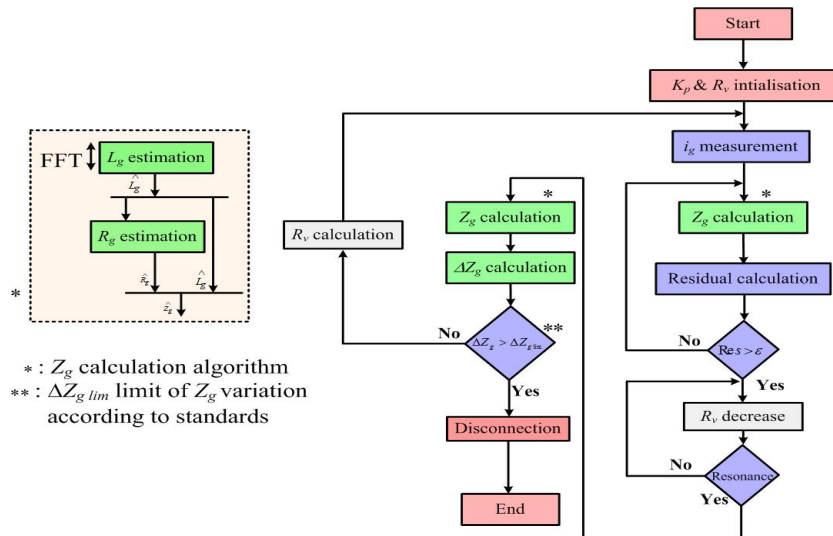


Fig. 4 : Proposed method algorithm

Indeed, the grid impedance variation detection and estimation need the integration of the new parameters to keep the system stable. In this way, we propose to solve the Routh criteria equations to calculate the new resistance value that allows the placement of the new variable system poles into the stable region. The grid impedance variation leads to a change of the system poles location, hence causing the system instability, so that even after the resonance excitation the virtual resistance cannot take again its initial value because it may introduce system instability. As a solution, $R_v$ should have a new value allowing the location of the new system poles in the left half plane. From the transfer function mentioned in (5), the Routh criteria array can be designed as follows:

$$
\begin{array}{c|cccc}
S^6 & a_0 & a_2 & a_4 & a_6 \\
S^5 & a_1 & \mathsf{a_3} & a_5 & 0 \\
S^4 & b_1 & b_2 & b_3 & 0 \\
S^3 & c_1 & c_2 & 0 & 0 \\
S^2 & d_1 & d_2 & 0 & 0 \\
S^1 & e_1 & 0 & 0 & 0 \\
S^0 & f_1 & 0 & 0 & 0
\end{array}
$$

$$
\begin{aligned}
b_1 &= \frac{a_1 a_2 - a_0 a_3}{a_1} & c_1 &= \frac{b_1 a_3 - a_1 b_2}{b_1} & d_1 &= \frac{c_1 b_2 - b_1 c_2}{c_1} \\
b_2 &= \frac{a_1 a_4 - a_0 a_5}{a_1} & c_2 &= \frac{b_1 a_5 - a_1 b_3}{b_1} = a_5 & d_2 &= \frac{c_1 b_3}{c_1} = b_3 \\
b_3 &= \frac{a_1 a_6}{a_1} = a_6 & e_1 &= \frac{d_1 c_1 - d_2 c_1}{d_1} & f_1 &= \frac{e_1 d_2}{e_1} = d_2
\end{aligned}
$$

In order to ensure the system stability, the necessary and sufficient conditions that ensure the roots of equation stay in the left half plane are:
- All coefficients of equation are positive.
- All terms in the first column of the array have positive signs.
In our case, all system parameters are known except $R_v$, so that all system coefficients are positive and the terms in the first column of the Routh array are all positive, except those depending on $R_v$.
Solving of Routh criteria equations will give a condition on $R_v$ to ensure the system stability:
For the first condition all the system poles are positive even those depending on $R_v$, which are $a_2$ and $a_4$.
To achieve the second condition and having all first column coefficients positive the following equations should be solved

$$b_1 a_3 - a_1 b_2 > 0 \tag{13}$$
$$c_1 b_2 - b_1 c_2 > 0 \tag{14}$$
$$d_1 c_2 - d_2 c_1 > 0 \tag{15}$$

In the present work, these equations are implemented and solved in real-time, hence giving the new virtual resistance value allowing the system stability after the grid impedance variation.
As a first step of the proposed control algorithm the grid impedance is supposed to be null ($Z_g = 0$), so that all calculation was giving the following condition on $R_v$:

$$27.44\Omega < R_v < 254\Omega \tag{16}$$

**Table 2** : **Simulation parameters**

| $P_n$ | $V_g$ | $f_{PWM}$ | $L_1$ | $C_f$ | $L_2$ | $K_p$ | $K_r$ |
|-------|-------|-----------|-------|-------|-------|-------|-------|
| $4kW$ | $230V$ | $10kHz$ | $6mH$ | $4\mu F$ | $2mH$ | $29$ | $7000$ |

## Simulation results

Simulations were carried out by using co-simulation between PSIM and MATLAB softwares. The afore-mentioned method described for detection and estimation of grid impedance variation is tested on a $4kW$ three phase inverter as described in Fig. 5. The system parameters used in simulations are shown in Table 2.
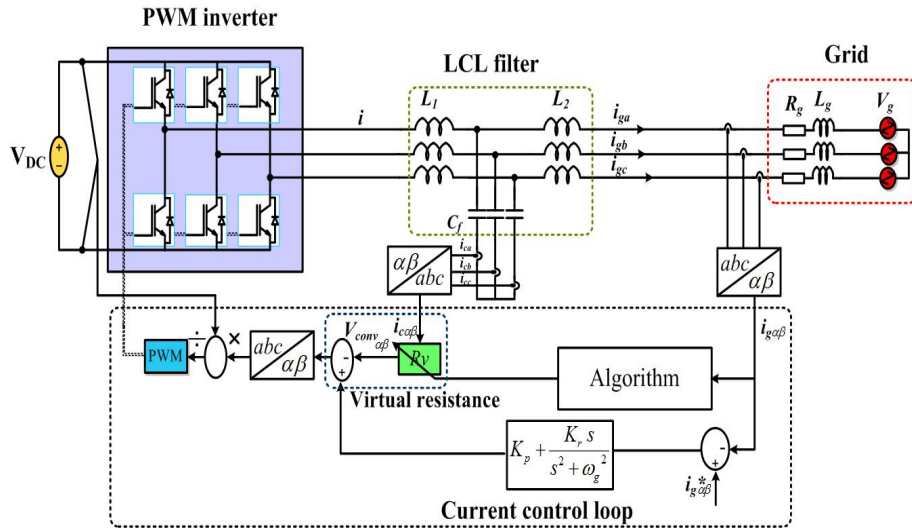
Fig. 5 : System under simulation



(a) $R_v = 27\Omega$
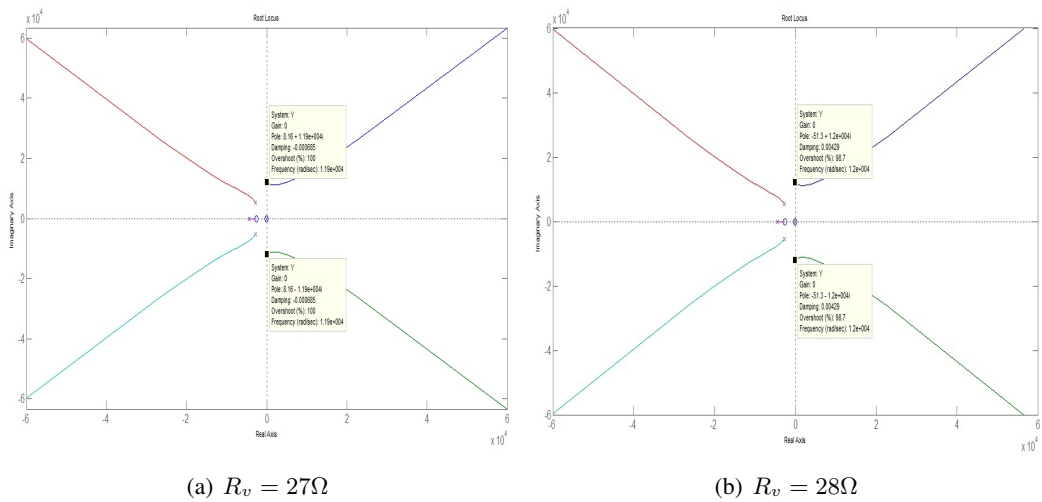
(b) $R_v = 28\Omega$

Fig. 6 : Healthy mode system poles location for two diffrent $R_v$ values

Fig. 6(a) and Fig. 6(b) show the efficiency of the Routh criteria method in the design of the resistance and they depict the system poles location in both case respecting and unrespecting condition.
Fig. 6(a) depicts two poles cited in the right half plane, which leads to system instability when the virtual resistance does not respect the condition (16), while the Fig. 6(b) shows the same two poles cited in the left half plane, hence introducing the system stability for $R_v$ value chosen in manner to respect the condition.
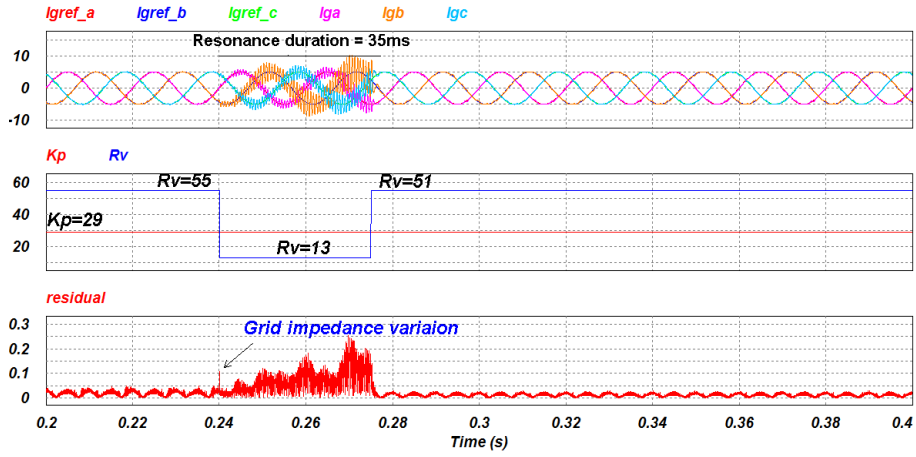
Fig. 7 : Resonance excitation due to $Z_g$ variation ($Z_{g_{Lg=0=>Lg=2mH}}$)



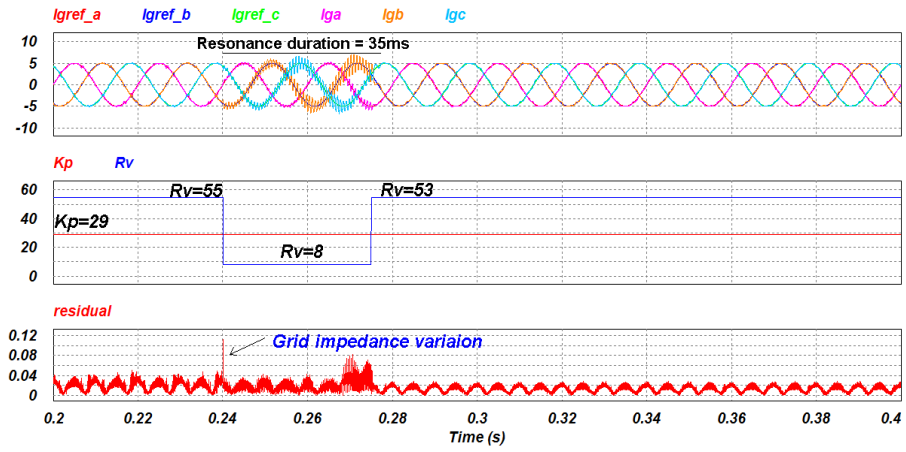Fig. 8 : Resonance excitation after $Z_g$ variation ($Z_{g_{Lg=0=>Lg=4mH}}$)

The grid inductance $L_g$ is set to zero ($0mH$) and the grid resistance $R_g$ is evaluated by respecting the relation $R_g = \frac{X_g}{0.13}$ as the work is performed in low voltage conditions [19]. The variation of the grid impedance Zg is simulated by inserting variable fault impedance $Z_d = R_d + j\omega L_d$, controlled by a switching gate block.

For more clarity, in healthy mode, the grid impedance variation is null ($Z_d = 0$) so the total grid impedance is null. Then, as the switch gate is opened, at the fault instant, the grid impedance varies to take the $Z_d$ value. Fig. 7 and Fig. 8 present the grid current evolution when the virtual resistance decreased following a grid fault appearance and presents a peak at the instant of fault, i.e at $0.24s$.

In Fig. 7, the total grid inductance is equal to $L_g = 2mH$. However, in Fig. 8, the grid inductance increases to $L_g = 4mH$. The acquisition time for simulation is chosen equal to $5\mu s$ and the residual signal lasts $4T_a = 20\mu s$ as explained in [20].

After detecting the grid impedance variation, i.e, when a residual peak appears and exceeds the threshold as demonstrated in the second section, the virtual resistance decreases gradually until reaching the resonance and then a Fast Fourier Transformation (FFT) can be done in order to determine the resonance frequency $f_{res}$.

The resonance state duration is the time between the resonance start time and the detection time which finish when the FFT got the result, then $R_v$ takes the new calculated value and the system returns to its stability state.
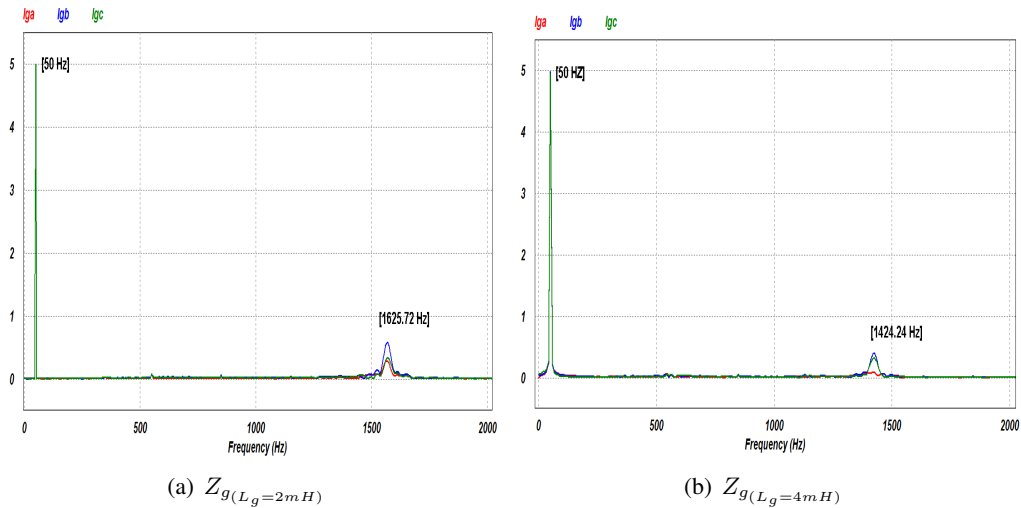
(a) $Z_{g(L_g=2mH)}$  (b) $Z_{g(L_g=4mH)}$

Fig. 9 : Spectral analysis of the grid current after resonance excitation for two $Z_g$ values

Fig. 9(a) and Fig. 9(b) show the measured grid current FFT for two grid impedance values. In both figures two spectral peak was appeared where the first is related to the fondamentale frequency $50Hz$ and the second shows the effect of the resonance excitation when the resonance frequency appeared according to the grid impedance value.

## Conclusion

A novel grid impedance estimation method based on an LCL-filter resonance excitation has been presented. The grid impedance variation detection method is based on consecutive grid-side current measurements. An adaptive virtual resistance control loop devoted to both damp the system in order to improve the distributed generation output power quality and to change it in order to excite the resonance while ensuring the system stability was proposed. The proposed method is a proper solution for both grid impedance estimation and system control reconfiguration. The system reconfiguration is carried out by introducing the new parameters into the mathematical algorithm in order to improve the system stability when a heavy grid fault occurs.

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