STABILITY ANALYSIS OF ANTI-ISLANDING PROTECTION BASED IN POSITIVE FEEDBACK TECHNIQUE

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***Abstract* – This paper develops a stability analysis of a local Islanding Detection Algorithm (IDA) based in positive feedback technique that has no Non Detection Zone (NDZ). The stability analysis is developed with the Nyquist stability criterion. It is demonstrated that the parameters of the IDA can be easily tuned using the extended Nyquist criterion at the key operating conditions. Finally, experimental results are presented to support the analysis carried out.**

***Keywords* - Anti-islanding, Distributed Generation (DG), Stability Analysis**

I. INTRODUCTION

The electric energy demand is growing constantly in the last decades. The forecast of the electric energy demand in the world in 2030 is twice the consumption in 2003 [1]. There are many options to attend this demand, among them is highlighted the use of distributed generation (DG). The appealing factors of DG are [2]: (i) DG units are closer to costumers so that the distribution and transmission losses and costs are reduced or even avoided; (ii) it is easier to find sites for small generators and; (iii) the liberalization of the electricity market contributes to create opportunities for new enterprising in the power generation sector.

It is important to mention that distribution systems have been for decades designed considering the power and currents flowing from substations to the load. Therefore, the integration of DG's in traditional distribution systems results in issues and obstacles in aspects as protection, stability, energy market structure, etc. The condition called Islanding is among these obstacles.

Islanding is a condition in which a section of the network including the DG is disconnected from the main grid and during the period of disconnection, the DG continues to supply active and reactive power to local load with reasonable normal voltage and frequency. Fig. 1 shows a scenario with an islanding condition.

Unintended islanding is a concern because it may result in energy-quality issues, interference to grid-protection devices, damage to power generation and utility as a result an unsynchronized re-closure, as well as personal safety hazards [3].

The *Std* IEEE 1547 [4] is a series of standards that gives specifications and technical requirements for the interconnection of distributed generators with aggregate capacity of 10 MW or less. The section 4.4 of *Std* IEEE 1547 points that the DG interconnection system shall detect the island and ceases to energize the section islanded within two seconds after the formation of the island. Therefore, a DG must have a device or equipment that detects the islading condition within the time limits specified.

The Non Detection Zone (NDZ) is a performance index to evaluate Anti-Islanding schemes. The NDZ defines a region in ΔP and ΔQ space where the IDA fails, where ΔP and ΔQ are the active and reactive power mismatch between DG and local load (consumers), respectively [5]. So, a small or empty NDZ is desirable.

The islanding detection techniques can be classified in two groups: remote techniques and local techniques.

The remote techniques detect the opening of contacts at the point of disconnection and transmit that signal to all DG that could support the respective island zone.

Usually, remote techniques do not have NDZ, but as they are based on communication between the grid and DG's, these techniques tend to be expensive compared to the local techniques [6].

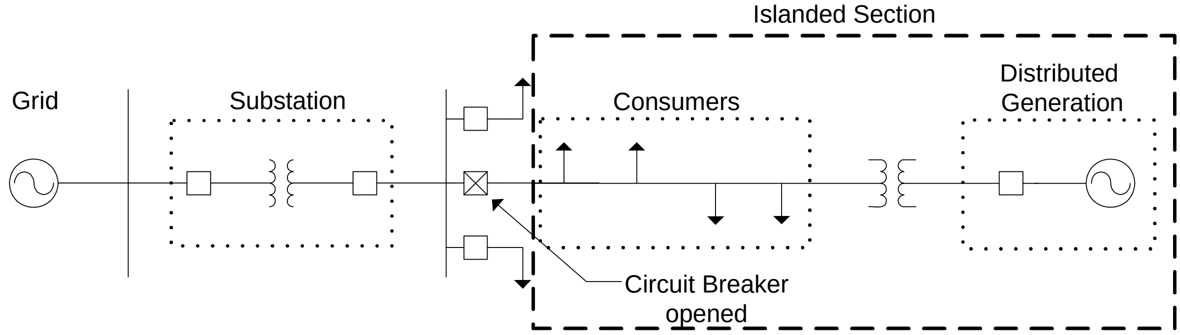


Fig. 1 Scenario with an islanded section

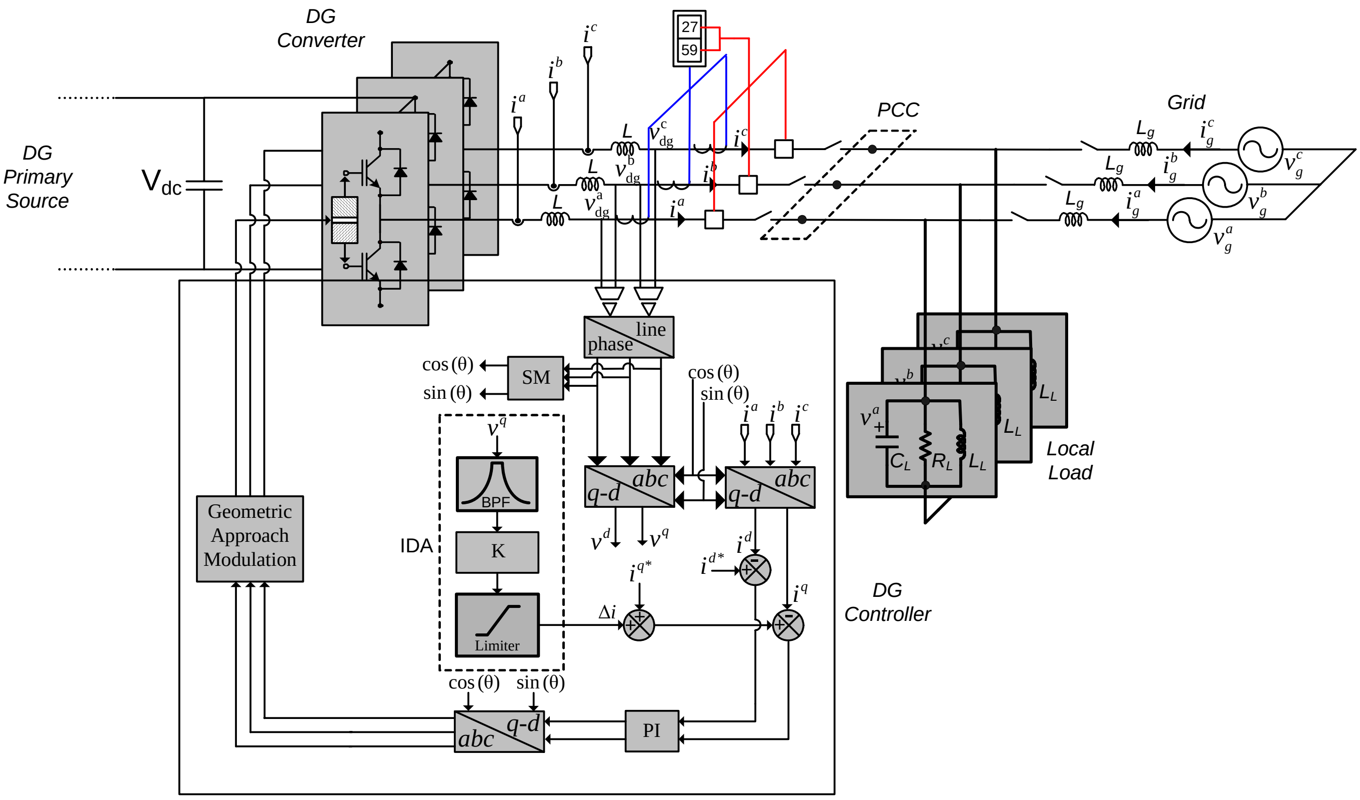


Fig. 2 Block Diagram of a DG with the Islanding Detection Algorithm (IDA) connected in a distribution system

The local techniques are based on the information available at DG site. Normally, these measurements are available as part of DG control system, so additional sensors and components are not required. Therefore, the local techniques implementation has low costs. The disadvantages of local techniques are the NDZ and the power quality degradation with the current harmonics injection [6-8].

Ye at al [9] have shown a local technique that has no significant impact on THD performance and NDZ. This technique is based on positive feedback control that drives away the limits of voltage or frequency when the utility section, where the DG is operating, is islanded.

Islanding detection techniques with positive feedback loop should be stable when the utility is present and unstable when the grid is not present. Therefore, a discerning stability analysis in these techniques should be carried out to ensure the right fulfillment of islanding detection equipment. So far, this analysis has not been reported in the literature.

This paper proposes a stability analysis of the scenario shown in Fig. 2 in the following conditions: (i) DG without the IDA when the grid is present; (ii) DG without the IDA when the grid is not present; (iii) DG with the IDA when the grid is present and; (iv) DG with the IDA when the grid is not present.

The remainder part of this paper is organized as follow: Section II describes the DG unity, the local load, the equivalent grid and the islanding detection algorithm. Section III analyses the stability for the four conditions. Section IV shows the experimental results.

II. SYSTEM DESCRIPTION

The circuit where the stability analysis is performed is shown in Fig. 2. The DG system, the local load, the equivalent grid and the Islanding Detection Algorithm are described in this section.

A. DG System

For the purpose of this study, the DG is considered to be connected to the grid by means of a three-phase PWM converter, Fig. 2, where DC bus is constant and the output filter is comprise by an inductor L. This simplification is valid because, usually the power-conditioning systems include a regulated DC source and the reactance of the output filter plus the interconnection transformer is strongly inductive. The DG control method as well as the DC/AC converter topology are described in [10].

The synchronization method with the grid (SM in Fig. 2) is based in a passive band-pass filter with low cut-off frequency that will be described in the next section.

B. Synchronisation Method

There are a number of methods to synchronize the PWM converter with the grid [11-12]. Here, a simple method based in two band-pass filter is used, as shown in Fig. 3. In [13], the author proposes a method based on low-pass filters. However, it has found experimentally that this method is quite sensitive to DC components present in the measured voltages. Considering that is very hard to take out entirely the DC level in the measurements in an experimental setup, the low-pass filters have been replaced by second order band-pass filters (BPF) with cut-off frequency of 5 Hz. In addition, a low-pass filter on the norm of the voltage to remove the undesired 120 Hz component resulted of the voltage unbalance is included.

Finally, a rotation matrix R is used to compensate the phase lag of the FPB filters given by

$$\mathrm{R}(\Delta\theta) = \begin{bmatrix} \cos(\Delta\theta) & -\sin(\Delta\theta) \\ \sin(\Delta\theta) & \cos(\Delta\theta) \end{bmatrix} \tag{1}$$

where $\Delta\theta$ is the phase lag of the FPB in the grid frequency. In the present case, $\Delta\theta = 84.23$ rad/s .

As the response time of the SM is very large compared with the time periods analyzed in this paper, the SM dynamic is not considered in the IDA stability analysis.

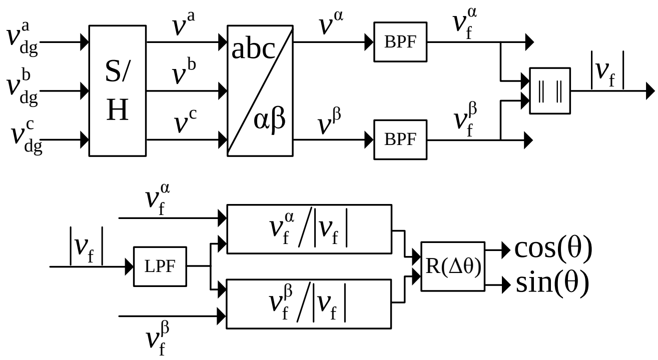


Fig. 3 Block diagram of the synchronization method (SM)

C. Local Load and Grid

The *Std* IEEE 1547.1 [14] specifies a test procedure for islanding detection equipment. The test circuit defined in this procedure is shown in Fig. 4.

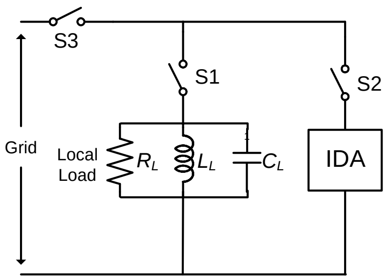


Fig. 4 Unintentional islanding test configuration

The capacitance C_L and inductance L_L are to be calculated using the followings equations:

$$C_L = \frac{PQ_f}{2\pi f v^2} \tag{2}$$

$$L_L = \frac{v^2}{2\pi f P Q_f} \tag{3}$$

where

P - active output power per phase of the DG (W)

f - grid frequency (Hz)

v - phase nominal voltage across each phase of the *RLC* load (V)

Q_f - quality factor of the parallel (*RLC*) resonant load and it is given by

$$Q_f = R_L \sqrt{\frac{C_L}{L_L}} \tag{4}$$

The resistance R_L is calculated as

$$R_L = \frac{v_p^2}{P} \tag{5}$$

where v_p phase voltage of Point of Common Coupling (PCC). The local load parameters must be obtained for $Q_f = 1 \pm 0.05$.

The substation feeder and the grid of Fig. 1 are represented as an infinite bus with an equivalent inductance L_g, as shown in Fig. 2. The *Std* IEEE 1547 establishes that the minimum short-circuit current in the PCC where the DG is connected is

$$I_{ccmin} = 20 I_n \tag{6}$$

where I_n is DG rated current of one phase.

Therefore, the maximum of L_g is given by

$$L_{gmax} = \frac{v_p}{I_{ccmin} 2\pi f} \tag{7}$$

Usually, there is a power transformer between the PCC and the DG that elevates the output DG voltage. So, it is convenient to reflect the L_{gmax} to low-voltage side of the transformer, that is:

$$L_{gmax}^L = \frac{1}{\alpha^2} L_{gmax} \tag{8}$$

where α is the voltage transformation ratio.

D. Islanding Detection Algorithm (IDA)

The active Islanding Detection Algorithm (IDA) block diagram is shown in Fig. 2. In this system, the voltages in *abc* stationary frame are measured and transformed to *q-d* synchronous frame resulting in the components u^q and u^d . The component u^q is filtered by a second order band-pass filter (BPF) and then it is multiplied by a gain K. This signal passes through a saturation limiter resulting in Δi , that is added to a current reference i^{q*} .

By modeling the non-linear saturation as a describing function, it is possible to define the frequency and the amplitude to analyze the behavior of a possible limit cycle associate with the IDA, which can be useful for the over/under voltage relays coordination.

The mechanism of the IDA can be explained considering the positive feedback loop. When the DG output voltage is increasing, the IDA will command the DG output active power to be increased. Due to the load characteristic, the DG output voltage also will increase to balance the active power. As a result, the DG output voltage will increase until the defined voltage limits and then, the islanding can be detected by the over/under voltage relays.

III. STABILITY ANALYSIS OF THE SYSTEM WITH THE ISLANDING DETECTION ALGORITHM

In order to investigate the impact of Islanding Detection Algorithm in the DG control system, a stability analysis is carried out in this section. Firstly, a complete model in *q-d* synchronous frame is described. Then, a reduced model is derived.

A. Dynamic Models

Fig. 5 shows the three-phase dynamic model *q-d* synchronous frame of Fig. 2. It is possible to see couplings between *q* and *d* frames which, initially, will be neglected. As a result, the circuit of Fig. 6 can be obtained. Later, this simplification will be verified experimentally. For the stability analysis, the circuit of Fig.6 will be represented by block diagram of Fig.7. Note in this block diagram that the current loop controllers as well as the IDA are included.

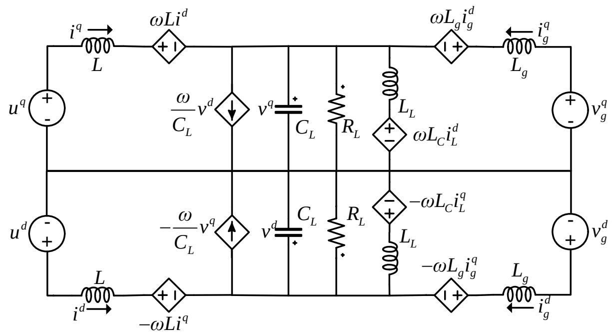


Fig. 5 Complete Three-Phase Dynamic Model

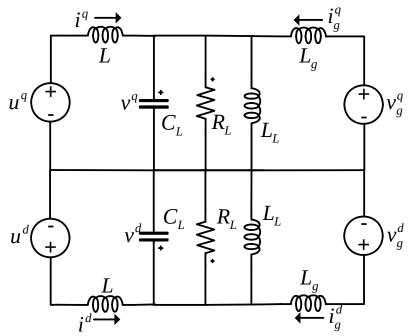


Fig. 6 Simplified Three-Phase Dynamic Model

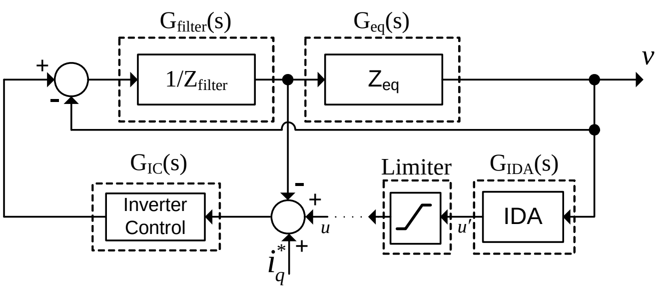


Fig. 7 Block Diagram of the considered system

The transfer functions of Fig. 7 are given by

$$G_{filter}(s) = \frac{1}{Ls} \tag{9}$$

$$G_{eq}(s) = \frac{[(L_L^{-1} + L_{gmax}^{L}{}^{-1})^{-1} R_L]s}{(R_L C_L L_L)s^2 + [(L_L^{-1} + L_{gmax}^{L}{}^{-1})^{-1}]s + R_L} \tag{10}$$

$$G_{IDA}(s) = K\frac{\frac{\omega_0}{Q}s}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} \tag{11}$$

$$G_{IC}(s) = K_{INV}\frac{K_P s + K_I}{s} \tag{12}$$

where

ω_0 - BPF cut-off frequency

Q - BPF quality factor

K_{INV} - Inverter gain

K_P - Proportional gain of currents controllers

K_I - Integral gain of currents controllers

When the grid is not present, the value of L_{gmax}^{L} in (10) should be considered infinite.

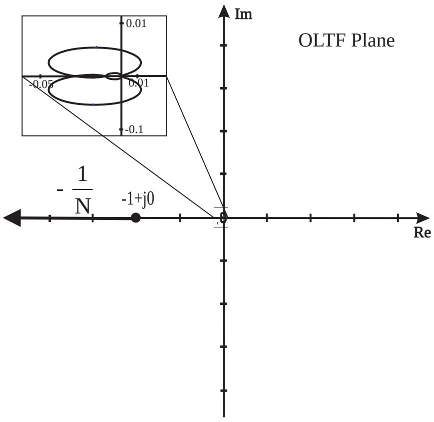
B. Stability Analysis

In order to design the Islanding Detection Algorithm parameters ω_0 and K as well as the limit of the saturation non-linearity, the extended Nyquist criterion will be used. The open loop transfer function of interest of block diagram of Fig. 7 is:

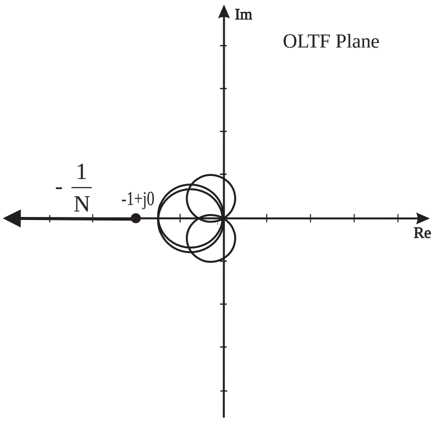
$$\text{OLTF} = -\frac{G_{filter}G_{eq}G_{IC}}{1 + G_{filter}(G_{IC} + G_{eq})}G_{IDA} = G_I G_{IDA} \tag{13}$$

Note that the converter connected to the grid, which is represented by the transfer function G_I, is designed to be stable for all grid impedance when the grid is present[15,16]. That is, the denominator of G_I is Hurwitz stable at all operating conditions. Furthermore, the IDA, represented by the transfer function G_{IDA}, is also designed to be stable. Therefore, the number of rotations of the considered open loop transfer function (13) about the -1+j0 is equal to the number of right closed loops poles, that is the number of unstable poles with the IDA included loop. Due to the presence of the saturation non-linearity, the intersection of the OLTF locus with the negative inverse of the describing function (-1/N) of the limiter represents a possible limit cycle [17]. Small perturbation on the intersection point revels that the limit cycle is stable for *K*>0. In addition, its frequency and amplitude can be adjusted by the IDA filter gain and saturation limit value of the limiter. In this way, it is possible to coordinate the operation of the under/voltage relays (27 and 509 of Fig. 2) to detect the islanding condition.

The Nyquist plot of Fig. 8a represents the operation with the DG connected to the grid while Fig. 8b demonstrates that a stable operation is also possible even if the grid is not connected, characterizing in this way a possible unintentional islanding operation. On the other hand, Fig. 9 demonstrates that by adding the IDA, with the parameters shown in Table I, it is possible to have a stable operation if the grid is present and have an unstable operation whenever the DG operates in islanded section. The parameters of the system are given in TABLE II and they follow the guidelines described in section II.

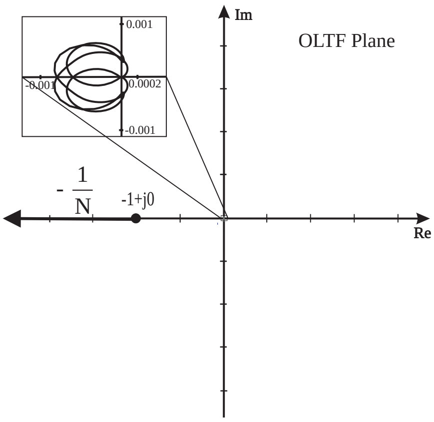


(a) With grid present



(b) Without Grid (islanded)

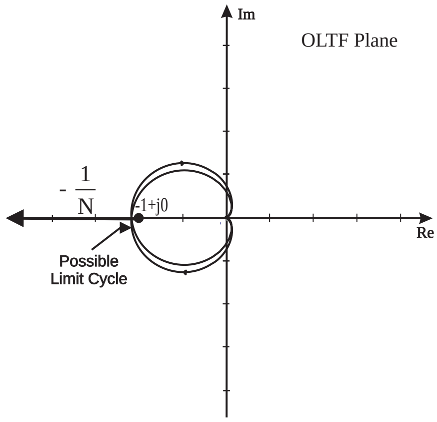
Fig.8 Nyquist Diagrams without the IDA.



(a) With Grid Present

TABLE I

IDA Parameters	
Parameter	**Value**
ω_0	62.83 [rad/s]
Q	0.5
K	1.5
S (Saturation Limit)	0.3 [p.u.]



(b) Without Grid (islanded)

Fig. 9 Nyquist Diagrams with the IDA.

In the following section the experimental results are presented to validate the stability analysis of this section.

TABLE II

Platform Parameters			
Parameter	**Value**	**Parameter**	**Value**
L	1.125 [mH]	L_{gmax}^{L}	19.15 [μH]
C_L	551.2 [μF]	$v_g^a = v_g^b = v_g^c$	24.5 [V_{rms}]
L_L	130 [mH]	ω_0	62.83 [rad/s]
R_L	4.812 [Ω]	Q	0.5
K_P	0.411	K_{INV}	55
K_I	411		

IV. EXPERIMENTAL RESULTS

In order to validate the above analysis, experimental results of the system of Fig. 2 have been performed. The converter is a three-phase two-leg per phase operating from a 55V DC bus, output current about 1.6A and the switching frequency of 10 kHz. The IDA parameters are given in TABLE I and the others parameters of the experimental platform are given in TABLE II.

Fig. 10 represents the DG operation without IDA connected to the grid. In the time when the grid current is zero, the DG is islanded with the local load. It is demonstrated that a stable operation is also possible even if the grid is not connected, characterizing in this way an unintentional islanding operation. Furthermore, it can be noted a quality energy degradation when the DG is islanded with the local load.

On the other hand, Fig. 11 demonstrates that by adding the IDA it is possible to have a stable operation if the grid is present and have an unstable operation whenever the DG operates in islanded section, substantiating the stability analysis of section III. Note that after the grid is disconnected, there is an oscilation in the PCC voltage that has been defined by the describing function of the saturation limiter to have amplitude of 7V and frequency of 12 Hz. Furthermore, note that the simplified three-phase dynamic model described in section II is valid for the stability analysis of the system shown in Fig. 2.

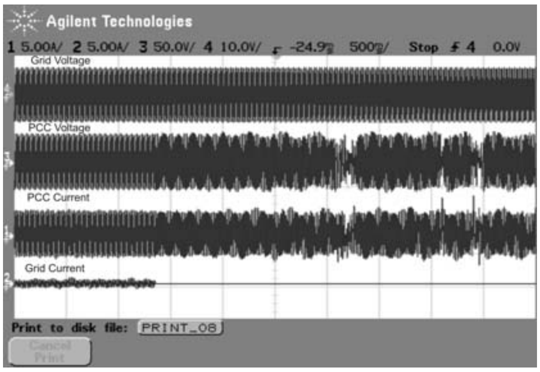
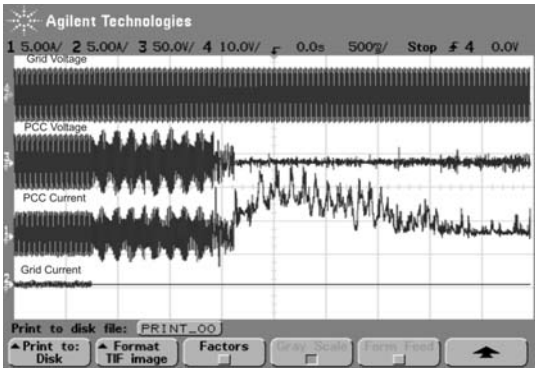
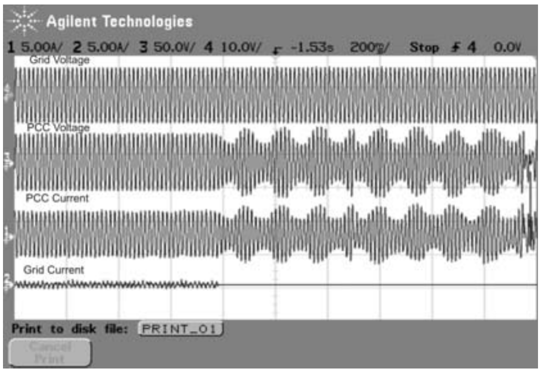


Fig. 10 Experimental results without IDA - Grid Voltage, PCC Voltage, PCC Current and Grid Current when the grid is disconnected (islanded). Horizontal scale: Time (500ms/div). Vertical scale: Voltage (20V/div) and Current (2A/div)



(a) Grid Voltage, PCC Voltage, PCC Current and Grid Current when the grid is disconnected (islanded). Horizontal scale: Time (500ms/div). Vertical scale: Voltage (20V/div) and Current (2A/div)



(b) Grid Voltage, PCC Voltage, PCC Current and Grid Current when the grid is disconnected (islanded). Horizontal scale: Time (200ms/div). Vertical scale: Voltage (20V/div) and Current (2A/div)

Fig. 11 Experimental results with the IDA .

V. CONCLUSIONS

This paper develops a stability analysis of a local Islanding Detection Algorithm (IDA) based in positive feedback technique that has no Non Detection Zone (NDZ). Its main attributes are (i) low costs; (ii) low THD impact (iii) A complete and reduced three-phase dynamic model of the system has been derived. It is demonstrated that the reduced three-phase dynamic model is valid for the stability analysis of the IDA. It demonstrated that a stable operation is possible even if the grid is not connected. Furthermore, by adding the Islanding Detection Algorithm it is possible to have a stable operation if the grid is present and have an unstable operation whenever the DG operates in islanded section. Experimental results support the prediction carried out.

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