FAILURE ANALYSIS OF INVERTER BASED ANTI-ISLANDING SYSTEMS IN PHOTOVOLTAIC ISLANDING EVENTS

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ABSTRACT

Given that the conclusion of field tests was that islanding events have to do somehow with the transient behaviour of the inverters and their interaction with the loads connected to the network, two different analyses have been carried out, considering both passive methods and Sandia Frequency Shift Islanding Detection Method (SFS). The aim of these analyses is to understand the reasons for the failures of protection systems embedded in inverters, in order to be able to develop improved detection methods.

The analyses follow two different approaches.

The first one is focused on the inverter behaviour, taking into account several aspects, such as association with different kind and number of inverters, constants used in SFS, quality factor or islanding detection with presence of motors among the loads.

The second approach takes into account their integration into a large network, studying SFS performance in presence of active and reactive power balance between generation and active loads in the network and including the simulation of the interaction among inverters with different anti-islanding configurations, different sites and power control parameterization.

The results show that setting of inverter parameters (power control loops, SFS parameters and PLL system) in addition to load characteristics out of the DSO control (resistive or constant power loads, presence of asynchronous motors) could make the islanding detection system inoperative.

INTRODUCTION

In CIRED 2011, Iberdrola presented the experience on problems of islanding behaviour detected in medium and high voltage networks of Iberdrola, including field tests in PV plants. Those field tests proved that islanding events are possible even when the balance of active and reactive power is not perfect, when several inverters, either of the same brand or different brands, were involved.

Since voltage characteristics in the island were within normal limits, it was also clear that it was not possible to detect islanding behaviour with traditional protections settings. Moreover, active methods without coordination between brands, proved to be ineffective.

Other conclusions were that laboratory tests did not represent field situations and that the situation will get worse when the necessary requirements to preserve transmission system stability, (fault ride through capabilities and frequency insensitivity) are applied.

Starting from this point, the project PROINVER −with participation of inverter, protection relay and communication system manufacturers, as well as laboratories and research centres− was launched in 2011. The purpose of this project was to develop new protection systems, either implemented in the inverters or based in relays and communications, to overcome the limitations of present systems, in addition to a laboratory test representative of field conditions.

However, the first step had to be, necessarily, to understand the reasons for the failures of protection systems embedded in inverters, since the conclusion of field tests was that islanding events have to do somehow with the transient behaviour of the inverters and their interaction with the loads connected to the network.

To this aim, two different analyses have been carried out, considering both passive methods and Sandia Frequency Shift Islanding Detection Method (SFS):

1. Sensibility analysis of the constants used in SFS. Association with different kind and number of inverters, equivalent quality factor in the point of common coupling, and presence of active loads (electric motors), have been assessed to identify how detection time is affected.
2. Modelling of a real network. It includes simulation of the interaction among inverters with different anti-islanding configurations and power control parameterizations. Performance of SFS has been studied and assessed in presence of active and reactive power balance between generation and loads in the network.

INVERTER SENSITIVITY ANALISIS

During the first stage of this work, a sensitivity analysis for the different parameters or causes that could affect the anti-islanding detection method has been carried out. This analysis has been done through simulation by determining the detection time measured from the time when the islanding situation starts to the time when this situation is detected, usually when the frequency goes out of the established interval (50 ±1Hz).

The first analysis tries to determine the influence of different K constants used for determining the chopping factor typical of SFS methods, according to equation 1 [1] and Fig.1,

$$cf = \frac{2t_z}{T} = cf_0 + K(f_a - f_{line}) \qquad (1)$$

for different quality RLC (Fig.2) load factors, Q, given by equation 2 at fundamental frequency, f_1. The capacitor C is selected for the resonance frequency of this load be equal to f_0.

$$Q = \frac{R}{L2\pi f_1}\ ;\ C = \frac{Q\, f_1}{2\pi R\, f_0^2} \qquad (2)$$

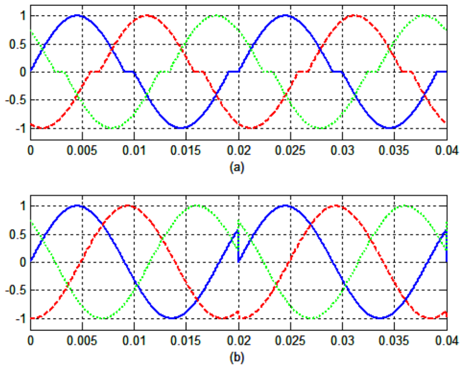
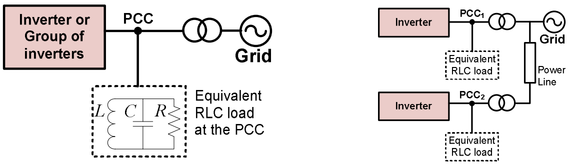


Fig. 1. Two ways of implement the SFS method (*cf*=0.1): (a) type A defined in [1], and (b) type B used in [3].

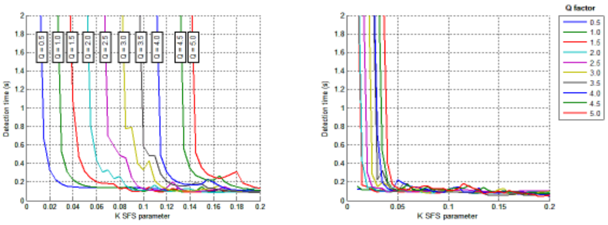
This analysis has been done using an average model for the inverter, assuming the systems shown in Fig.2, where the inverter or group of inverters supply the 100% of the power demanded by the load. It is also considered that the resonant frequency of the RLC are $f_0 = f_1$=50Hz. This situation has been considered because it has been described as the worst case for SFS islanding detection method [2].



(a) (b)

Fig. 2. Systems under study: (a) One PCC system, (b) Two PCC system

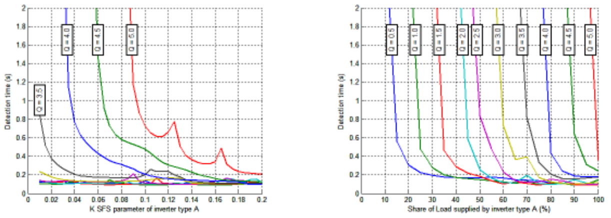
The detection times obtained by a set of simulations are shown in Fig.3 when a single inverter is supplying the 100% of the load connected at the PCC. In this figure one can see that there is a dependence of this time on the constant *K* and factor *Q*, that is not easy to determine, and also this time depends highly on the type of inverter being considered. But, at the same time, it could be concluded that for having detection problems in the proposed system, the factor *Q* has to be quite high, up to 4, that it is very difficult to achieve in real systems.



(a) (b)

Fig. 3. Detection time for a single inverter and different Q factors, when varying the parameter K: (a) inverter type A, (b) inverter type B.

As a second stage of our analysis a group of two inverters has been considered instead of a single inverter. The results are shown in Fig.4 for two cases. These simulations allow concluding that the detection time (and the operation of the anti-islanding protection) not only depends on the inverter itself but also on other inverters that could be connected to the same PCC, or even in other PCC.



(a) (b)

Fig. 4. Detection time for a two-inverter system and different *Q* factors: (a) inverter type A (varying *K*) with an inverter type B (*K*=0.05) supplying each inverter the 50% of the load power, (b) inverter type A (*K*=0.15) with an inverter without anti-islanding when varying the share of the load being supplied by each inverter.

The above results have been validated through a simulation model including a solar panel, a 6-pulse three-phase inverter controlled by current, a LCL filter, a phase lock loop (PLL) for frequency measurement, a RLC load, a LV-HV transformer and a grid model. This model has permitted to evaluate the influence of other parameters of the system, like the filter *L* and *C* values or the PLL constants. As a result, the filter parameters and the proportional constant of the PLL have shown a weak influence in the detection time. However, the integral constant K_i of the PLL has a significant influence, as shown in Table I.

Table I. Influence of the K_i constant of the PLL in the detection time (s). K_p is fixed to 1.

K_i	120	400	640	720	800	880	960	1200
Time (s)	>3	1.09	0.75	0.69	0.63	0.57	0.53	0.43

This simulation model has been also used to study a multi-inverter scenario. If all the inverters have the same SFS anti-islanding system with equal value of *K*, their behaviour faced with an islanding situation is similar than the expected for a single inverter. However, the presence of one inverter without SFS system or with an inadequate value of *K* can cause all the inverters located in the same or even in different PCCs to fail faced with an islanding situation.

Another interesting conclusion is obtained when substituting a part of the load connected to the photovoltaic plant by an asynchronous motor. A commercial 11 kW squirrel-cage motor has been used for this simulation. A RLC load is also connected in parallel to keep the same quality factor and a correct balance of active and reactive power (they have been adjusted to a maximum unbalance of 2%). Fig. 5 shows the frequency variation for the same inverter with SFS constant *K*=0.01 and the same quality factor of 2.5. The frequency limits match up with the established performance interval. Fig. 5a corresponds to a pure RLC load and Fig. 5b includes a motor. It can be observed that the presence of the motor causes the anti-islanding system to fail while the system performs well with RLC loads. It can be also observed that the way the frequency varies after the beginning of the islanding situation is different in both situations, as it moves forward the same direction with RLC loads (following the positive-feedback concept of SFS) while it fluctuates around the reference value when a motor is connected.

The obtained result confirms and illustrates the affirmation found in literature about the influence of the presence of motors among loads in the failure of anti-islanding systems [4]. Further studies have to be done to determine how to avoid this interaction that could exist when active loads (motors) are present in the proximity of inverters.

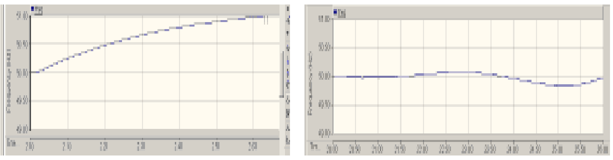

(a) (b)

Fig. 5. Frequency variation during an islanding situation (K=0.01, Q=2.5): (a) with RLC load, (b) with a combined RLC and motor load.

NETWORK INTEGRATION

Modelling

The static PV generator model used comprises the following elements:

- An ideal DC source representing a generic static generation system (e.g. PV system).
- A voltage source inverter (VSI) linking the static DC stage with the AC system.
- An AC low pass filter to limit high frequency harmonics generated by the inverter.
- The inverter control system affecting its dynamic performance.

The inverter control scheme follows the typical power control with an external PI control loop to regulate PQ power and an inner decoupled anti-windup PI current loop in the dq synchronous frame (Fig. 6). The space angle and frequency of the voltage vector at the PCC are detected with a PLL.

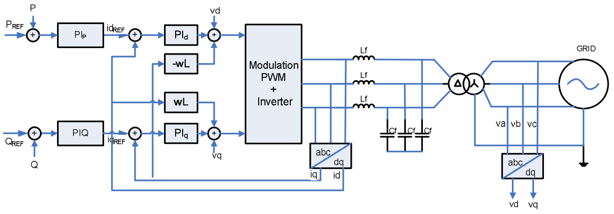


Fig. 6. Inverter control scheme.

The anti-islanding active frequency drifting method SFS was originally developed for a single-phase inverter and has been extended to three phase DGs that utilize PLL. In order to implement the SFS positive feedback anti-islanding active method the frequency deviation is used as feedback signal to compute the DG current phase angle θ_{SFS} or chopping fraction according to the following expression:

$$\theta = \frac{\pi}{2} cf \qquad (3)$$

where *cf* is the chopping fraction given by equation (1)

In three-phase systems a phase angle transformation is applied in the PQ controller in order to compute the modified current references to force frequency shift and thus frequency instability:

$$\begin{bmatrix} i'_{dREF} \\ i'_{qREF} \end{bmatrix} = \begin{bmatrix} \cos\theta_{SFS} & -\sin\theta_{SFS} \\ \sin\theta_{SFS} & \cos\theta_{SFS} \end{bmatrix} \begin{bmatrix} i_{dREF} \\ i_{qREF} \end{bmatrix} \qquad (4)$$

Results

In the simulations, the inverters are operated at unity power factor and the disconnection from the main grid occurs at the instant of 1 s. The results presented refer to a particular identified scenario where the islanding detection becomes more difficult by the active SFS method. Several simulations have been run, varying different factors that may affect the reliability of the islanding detection, described below.

High gains on the outer power loop, especially in the Q control loop to inject no reactive power (Q_{REF}=0) degrades the performance of SFS method, as shown in Fig. 7 (P control loop gains remain fixed). This effect is due to the cancellation of the reactive power injection in which active frequency drifting anti-islanding methods are based [1]. As a consequence, larger SFS gains would be required for faster and successful islanding detection. This is shown in Fig. 8, where a strong PQ power control loop is acting.

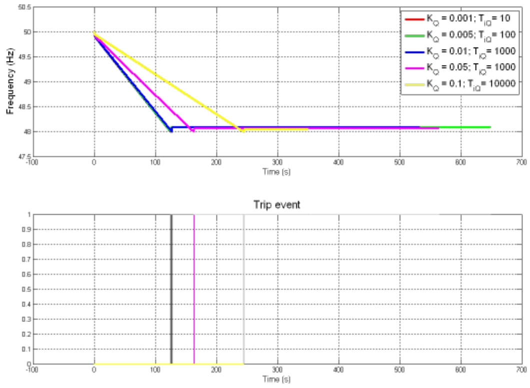


Fig. 7 Frequency deviation with different PQ control loop gains.

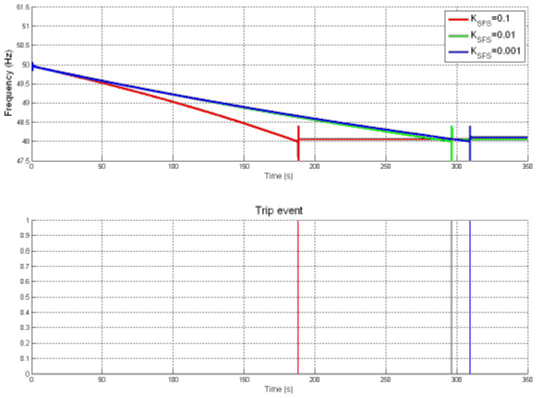


Fig. 8. Frequency deviation with different SFS gains.

Loads with dynamic voltage dependence seem to have the effect of accelerating or decelerating the frequency destabilization depending on the percentages and the type of dependence.

Up to a certain percentage (10-15 %), constant PQ power loads have an adverse effect as previously stated, although a larger increment in constant power loads affects positively islanding detection [2]. This result is confirmed when dynamic loads are replaced directly by asynchronous motors with the same rate of power and the same PQ control (Fig. 9).

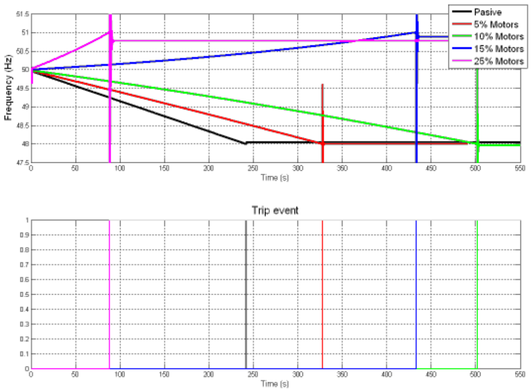


Fig. 9 Frequency deviation with different percentages of asynchronous motors.

Under certain conditions there is no simultaneous disconnection of generators; the disconnection of the first generator due to its anti-islanding system delays the disconnection of the second one. In order to analyze this effect the SFS method is implemented with different frequency relay trigger delays (Fig. 10).

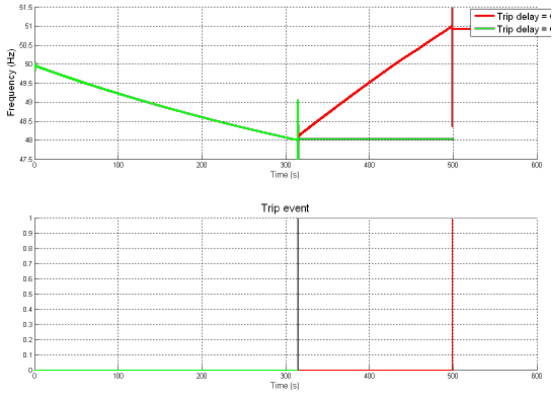


Fig. 10. Frequency deviation depending on trigger event delays.

Longer trigger delay times cause a new power mismatch between generation and load in the islanded network after the disconnection of first generator, changing the frequency drifting direction and therefore delaying the actuation of the anti-islanding system of the second generator.

The presence of more generators with different trigger delays could even lead to a better match between generation and load, causing the system to be within a non-detection zone (NDZ), making the islanding situation more likely.

CONCLUSIONS

Several simulations have been run, to determine the causes of islanding situations detected in MV networks. In this analysis different factors that may affect the reliability of the islanding detection have been studied, concluding that the detection time –and, consequently, the operation or not of the anti-islanding protection− depends on several factors:

- The inverter itself, that may have active detection or not, and the way to implement the detection method.
- Other inverters that could be connected to the same point of the network, or even in other points.
- The presence of active loads, as motors, analysing the failures of anti-islanding systems that perform well with RLC loads.

Even having the same detection method, for instance SFS, there can be important differences between inverters. Firstly because the constant K of the SFS method has a significant influence. Another aspect that may degrade the performance of SFS method is the reactive power control loop.

When several inverters are connected to the same network and all of them have the same SFS anti-islanding system with equal value of K, their behaviour faced with an islanding situation is similar than the expected for a single inverter. However, the presence of inverters without SFS system or with an inadequate value of K can cause all the inverters located in the same network to fail faced with an islanding situation. Moreover, the presence of generators with different trigger delays could increase the probability of islanding.

Finally, the way the frequency varies after the beginning of the islanding situation with motors is different from the behaviour with RLC, standardized for laboratory tests, since the dynamic voltage dependence seems to have the effect of accelerating or decelerating the frequency destabilization.

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