NDZ of an anti-islanding protection with ROCOF threshold

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ABSTRACT

Using the rate of change of frequency (ROCOF) to detect undesired islanding in distribution networks is already done in a few countries of Europe and is considered a possibility in some others. The ROCOF is known to improve islanding detection, however the benefit of using it is not well understood from the theoretical viewpoint and it remains difficult today to quantify its practical effect. We focus on the frequent situation where potential islands are powered by inverters, then, based on simulations, this paper investigates the benefit of using the ROCOF by studying its effect on the Non-Detection Zone (NDZ) of the anti-islanding protection.

INTRODUCTION

Unwanted islanding is defined as a situation where a part of the network remains energized by local generators after losing its main power supply. It may occur in particular after the opening of a protection on a feeder in a distribution grid. It is generally assumed that the worst-case conditions correspond to the case with both active and reactive powers nearly exactly balanced in the considered subnetwork; in such a case, almost no current is exchanged with the upstream power grid. The opening of the feeder may not be a disruptive event and the islanding may be difficult to detect.

Three important trends are currently reviving research activities on the topic of unwanted islanding. First, distributed generation is increasing steadily, which favors the occurrence of situations where the generation and consumption of active power inside a distribution feeder are nearly equal. Second, due to concerns for system stability, DSOs in Europe tend to enlarge the frequency thresholds that are set in the anti-islanding protections of wind and PV generators. Third, recent European grid codes also require the implementation on distributed generators of new control mechanisms [1] (similar, for instance, to the primary frequency control of conventional generators) that may have a detrimental effect on the efficiency of anti-islanding protections [2][3]. In this context, the improvement of anti-islanding protection is a major concern.

Many solutions to detect and eliminate unwanted islanding have been proposed across the literature. They may be classified within three groups:

- Passive methods, only based on local measurements made at generator-level, and that are generally the least expensive.
- Active methods, involving the injection of small perturbations at the generator output, that are generally more efficient than passive methods but might deteriorate stability and power quality [4].
- Communication-based methods, which would be the perfect solution if they were not (currently) so costly, especially for small-scale generation.

As a consequence, passive methods seem to be a good solution for DSOs as far as small-scale generators are concerned. Among them, protections based on ROCOF thresholds are one of the most frequent as they are already used in several countries, including UK, Ireland, Italy and Japan. The core idea of ROCOF protection is to take advantage of the low inertia of an islanded grid. As few large electrical machines are usually connected to distributions grids, the global inertia is quite low in comparison to the transmission grid and the frequency is expected to change quickly after any power imbalance event, making the ROCOF a good indicator to detect islanding. But it also means a certain level of power imbalance is required to reach the thresholds.

Situations with islanding remaining undetected are said to “belong to the Non-Detection Zone (NDZ)”. The NDZ is generally defined in terms of the values of active and reactive power imbalance before the event, and it is often admitted that the size of the NDZ is a good indicator of the efficiency of the protection algorithm: the smaller the NDZ, the better the protection. Surprisingly, although ROCOF protections are more common nowadays, we are not aware of any previous research aiming at assessing the complete NDZ associated with these protections. This paper aims at bridging this gap by computing the NDZ for different loads, and protection algorithms, and to analyse the simulation results. The surfaces of these NDZ are also computed as they are an indicator of the efficiency of the detection.

DESCRIPTION OF THE MODELS

The studied system is described on Fig. 1, and is simulated on Matlab/Simulink with an RMS model.

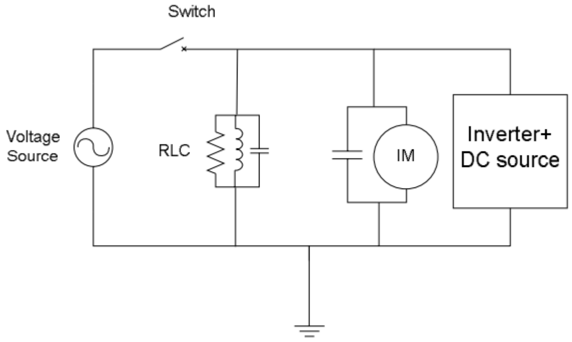

Fig. 1. Distribution system simulated.

The production in the distribution system is only composed of a single (aggregated) inverter-based generator representing e.g. PV panels or wind generators with synchronous machines. Then, different mixes of the following two types of loads are used: a linear (constant impedance) load, and an induction motor. The impedance is a parallel RLC load, which is a classic load in islanding studies; one of its parameter is the quality factor q_f, defined by (1). It is an important parameter characterizing the load. It can be seen as the rate of reactive power in the grid relatively to the real power.

$$q_f = \frac{\sqrt{Q_L Q_C}}{P} \qquad (1)$$

The induction motor drives a load with a resistive torque which is a function of the rotation speed, represented on Fig. 2, and the reduced inertia of the motor is H=0.1s. Both reduced inertia and resistive torque are the same as in the model from the project IDE4L [5]. A capacitance is set in parallel to the induction machine in order to compensate the reactive power absorbed by the motor while in a nominal state.

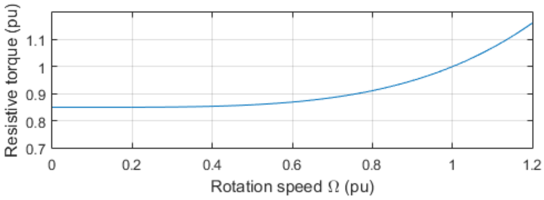

Fig. 2: Resistive torque of the induction machine.

At the beginning of the simulation, the system is powered by the substation, which is modeled by a voltage source. Then we open the switch, and we study the evolution of voltage and frequency.

ROCOF COMPUTATION AND PROTECTION LIMITS

From the theoretical viewpoint, the ROCOF is simply the time derivative of frequency. In practice however, computing the time derivative of a signal is not a trivial operation: if the numerical derivation is performed over a too short time frame, the ROCOF calculation might be subject to an unacceptable level of noise and disturbances. It is thus important to compute the numerical derivative over a long enough time frame, or to use filters. In this paper, we define the ROCOF_T as the derivative of the frequency computed over a sliding window of duration T, see (2). In this study, we will use two different integration periods T in order to compare their effects: 200ms and 500ms. This topic is crucial: if the ROCOF is too much averaged, then the anti-islanding protection will not be efficient; and if it is not averaged enough, then the protection will potentially trip unduly on random disturbances of the grid, such as phase jumps.

$$ROCOF_T(t) = \frac{f(t) - f(t-T)}{T} \qquad (1)$$

In the UK, the ROCOF threshold used is 1Hz/s. In this study, we will use a threshold of 0.5Hz/s, which seems to be more a suitable value for continental Europe as the inertia is higher in the continent than in UK and the ROCOF is smaller under normal operating conditions, allowing *a priori* to set smaller thresholds.

We set the under/over voltage (UOV) limits to 0.85-1.15pu and we study two different under/over frequency (UOF) thresholds:

- 49.5-50.5Hz, which are currently used in the European network on a number of protection relays for small-scale generators, but are no longer allowed by several DSOs in Europe because of concerns on grid stability.
- 47.5-50.6Hz, which are an example of new limits allowed by some DSOs.

NDZ COMPUTATION: METHODOLOGY

The NDZ is defined in the (ΔP,ΔQ) plane with $\Delta P = P_{load} - P_{prod}$ and $\Delta Q = Q_{load} - Q_{prod}$. In order to approximately compute the shape of the NDZ, we sample the (ΔP,ΔQ)-plane; each point in this plane corresponds to a different initial condition for the simulation. More precisely, for each sampled value of (ΔP,ΔQ), we modify the parameters of the RLC load while keeping constant the quality factor q_f, — and without changing any other of the system parameters.

Then the RMS simulation yields the evolution of voltage, frequency and ROCOF from the initial conditions to the final steady-state, e.g. Fig. 3 for which only the ROCOF threshold is exceeded. Then we can estimate whether they are inside or outside the thresholds; see green and red points on Fig. 4. Finally, knowing the exact frequency and voltage values reached by these points, we can compute a more precise estimation of the NDZ limits by using linear interpolation; see black and cyan (blue) curves.

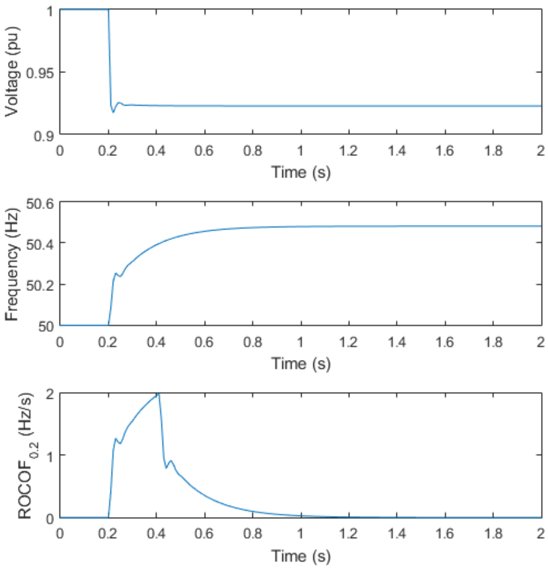

Fig. 3: Time evolution of voltage, frequency and ROCOF$_{0.2}$ after the opening of the switch at t=0.2, with ΔP=0.117pu, ΔQ=3e-3pu and for a load with 70% RLC (Q_f=0.5) and 30% IM (H=0.1s).

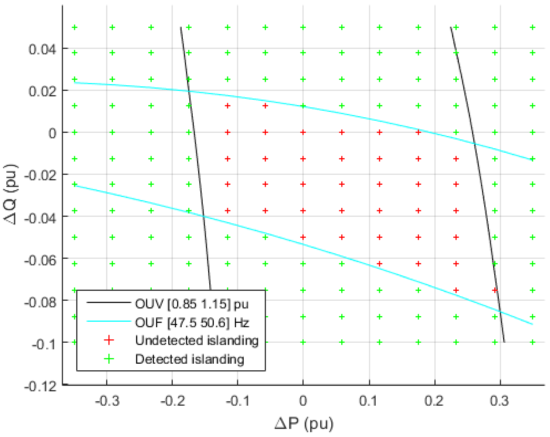

Fig. 4: Grid pattern used for the NDZ computation, with UOV and UOF limits and a load composition of 70% RLC, 30% IM.

NDZ COMPUTATION: RESULTS & ANALYSIS

We computed the NDZ for two types of loads: 100% RLC or 70% RLC and 30% induction machines (IM). To get more precise limits on the NDZ associated to ROCOF, more points have been computed around ΔQ=0.

NDZ with RLC loads

The NDZ is plotted for two different values of the quality factor, namely q_f=0.5, see Fig. 5, and q_f=2, see Fig. 6, the latter being a more pessimistic than the first for islanding detection. Indeed, a larger value of the quality factor implies that the energy exchanged between the inductance and the capacitance will be larger and will more easily dominate any reactive power imbalance, reducing the frequency variation. Although the two figures look rather similar, note the difference of range on the y-axis (range of ΔQ).

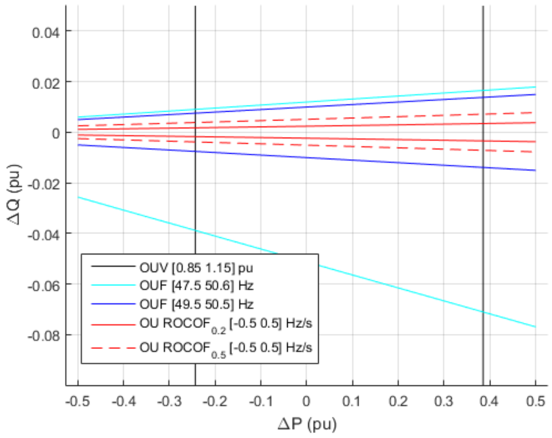

Fig. 5: NDZ with RLC load, q_f=0.5.

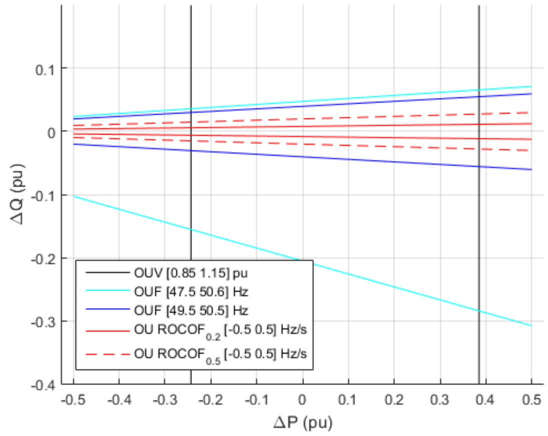

Fig. 6: NDZ with RLC load, q_f=2.

The previous figures lead us to the following observations.

1) First, we can see that the shapes of frequency and ROCOF limits are very similar: they both are straight lines crossing the point (ΔP=-1pu, ΔQ=0) with different slopes. Also, these lines are more or less horizontal, showing that whether the frequency and ROCOF limits are exceeded is mostly characterized by the reactive power imbalance ΔQ.
2) The NDZ associated to ROCOF limits are smaller than the one associated to frequency limits, even the most narrow [49.5 50.5] Hz. So, for an RLC load, the objective of improving islanding detection is well achieved by ROCOF thresholds.
3) The NDZ with an integration period T= 0.5 is quite larger than with T=0.2, so the way the ROCOF is computed is crucial: changing the value of the integration period changes significantly the results.

Table 1: Ratio between NDZ surfaces.

	S_{NDZ}/S_{ref}			
	100%RLC q_f=0.5	100%RLC q_f=2	70% RLC, 30% IM q_f=0.5, H=0.1s	70% RLC, 30% IM q_f=0.5, H=0.5s
OUV+OUF [47.5 50.6] Hz	100 %	100 %	100 %	100 %
OUV+OUF [49.5 50.5] Hz	32 %	32 %	31 %	31 %
OUV+OU $ROCOF_{0.2}$ [-0.5 0.5] Hz/s	7.6 %	6.4 %	4.2 %	1.3 %
OUV+OU $ROCOF_{0.5}$ [-0.5 0.5] Hz/s	16 %	16 %	15 %	7.6 %

4) The quality factor does not change the shapes of NDZ, but directly impacts its width on the ΔQ axis. This phenomenon seems to be proportional: from Fig. 5 to Fig. 6, the quality factor is multiplied by 4, and so is the scale of the NDZ on the ΔQ axis, and so is the NDZ surface. This may indicate that a grid with a higher proportion of reactive power relatively to the real power (e.g. with many underground cables, along with enough inductive elements to balance the reactive power generation of the cables), is more likely to become an unwanted island.

NDZ with 70% RLC and 30% IM

With the IM, we computed the NDZ for two different inertias: H=0.1s, see Fig. 7, and H=0.5s, see Fig. 8. As the curves shapes are more subtle, five times more points for each line and column have been computed.

Note on Fig. 7 and Fig. 8: The red lines denoting the ROCOF threshold cross each other, meaning that some points on the left and right sides exceed both ROCOF thresholds, negative and positive —e.g. ΔP>0.2pu and ΔQ~-0.02pu on Fig. 7. It is the consequence of a frequency perturbation just after the opening of the switch, leading to a ROCOF perturbation exceeding both limits.

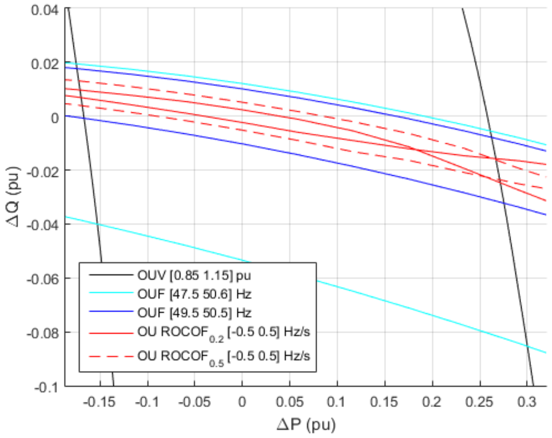

Fig. 7: NDZ with 70% RLC load (q_f=0.5) and 30% IM (H=0.1s).

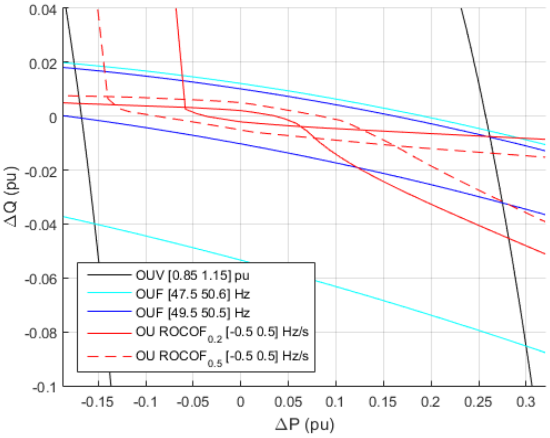

Fig. 8: NDZ with 70% RLC load (q_f=0.5) and 30% IM (H=0.5s).

Based on the upper figure, we lead the following analysis:

1) First, the analysis 2) and 3) done for RLC loads remain true with IM.
2) The IM changes a little the shape of OUV&OUF limits but does not have much impact on the total surface of the NDZ.
3) In our configuration, the IM does have an impact on OU ROCOF limits, and seems to reduce the associated NDZ.
4) A higher inertia seems to reduce the NDZ surface associated to ROCOF limit, *which is the opposite of what might be expected*. The *a priori* on inertia is that it reduces the ROCOF, which is based on the equation of motion of a synchronous machine from which we can deduce (3) — the upper bar standing for per unit variable. However, in our system we do not have any synchronous machine, but induction machine and an inverter based generator, so we have totally different behaviour, including for frequency.

$$\frac{d\bar{f}}{dt} = \frac{\overline{P_{prod}} - \overline{P_{load}}}{2H\bar{f}} \qquad (3)$$

In order to compare the efficiency of different frequency/ROCOF threshold, we computed their NDZ surface and the ratio between them, see Table 1. The reference surface S_{ref}, is the surface of the NDZ of OUV+OUF [47.5 50.6] Hz limits. The NDZ surface figures are coherent with the previous analyses: the ROCOF thresholds reduce the NDZ and the integration time constant of ROCOF is very important: a smaller value decreases the NDZ — although it might also increase nuisance trips.

CONCLUSION

Using a simple model, we plotted the NDZ of several protection thresholds—including ROCOF—for different loads to get an estimation of the efficiency of these settings and algorithms. For every case study, we found that the NDZ of ROCOF thresholds is smaller than the NDZ of narrow frequency thresholds, which confirms that ROCOF improve islanding detection. The NDZ surface reduction using ROCOF is meaningful, although the exact value cannot be precisely estimated as it is directly dependent on the way the ROCOF is computed. The latter observation emphasizes the need to well design the frequency and ROCOF computations within the relay protection: making it both fast and reliable remains the core challenge of ROCOF-based protections.

Furthermore it has also been observed that “standard” way of reasoning based on grid inertia might lead to wrong results as they are based on only synchronous generators in the grid. Actually, in our simulations, increasing inertia by adding an induction machine reduced the NDZ instead of expanding it.

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