POTENTIAL RISK FOR POWER SYSTEM STABILITY OF MASSIVE USE OF ESCALATING FREQUENCY SHIFT ISLANDING DETECTION METHOD

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ABSTRACT

Many methods may be used to avoid unwanted islanding situations on distribution networks. Among all of them, one shows potential to protect against islanding risks, without non-detection area and even in the presence of numerous inverters, provided that its parameters are properly adjusted in relation to the load and network characteristics and harmonized between generators : the escalating frequency shift. This method operates by amplifying frequency increases or decreases of an islanded feeder through reactive power absorption, respectively injection, with a positive loop on frequency.
However, this method has two drawbacks: it might be inefficient in some load cases (in particular industrial loads) and, due to its destabilizing nature, if implemented massively on a power system the escalating frequency shift may impair the overall stability of this system.
As some standards and technical specifications around the world, and in particular in Europe, authorize this type of islanding detection method, a question arises on the overall use of such type of method in the current European power system.
The paper also shows that more generally efficient islanding detection methods on the distribution system often feature a drawback for overall power system stability and that a trade-off will be necessary to take into account requirements of power system stability while maintaining sufficient efficiency of islanding detection.

INTRODUCTION

Detection of unwanted islanding situations on MV networks is a challenge for Distribution Networks Operators (DNOs) as islanding situations may have adverse consequences such as:

- out-of-phase reclosing of circuit breakers with potential damages to equipments.
- delay in operation of fast reclosers and deterioration in the quality of supply.
- impairment of operation of protections due to the loss of Neutral at the HV/MV substation and the loss of the short circuit power of the main network.
- potential hazard for maintenance staff.

DNOs use interface protections on decentralized generators connected to distribution networks in order to preserve safety and power quality of the distribution networks and to prevent decentralized generators from feeding into islanded feeders.

Most Interface protections in the world use frequency and voltage thresholds (min/max) surveillance as a basis to detect faulty (and islanding) situations. In addition other specific means are implemented to increase the efficiency of protections. These specific means may be quite different among countries and so far, no standard provides a universally recognized way to protect MV and LV feeders from unwanted islanding situations.

We will first review some of the methods mostly used and give the pros and cons of each of them. Then, we will focus on the escalating frequency shift method.

VOLTAGE AND FREQUENCY EVOLUTION DURING AN ISLAND

Today, most decentralized generators connected to the distribution networks are current sources controlled to supply a given active power P and a given reactive power Q. They are not controlled to maintain frequency nor voltage at set values as are power plants connected to the transmission system (the new Q(U) local voltage control as well as the P(f) reduction of active power in case of high frequency required by ENTSOE will modify this behaviour but not the conclusions of this paper. We do not take them into account in order not to complicate the reasoning). As a consequence of these P and Q settings, when a feeder is islanded, initial unbalances ΔP and ΔQ between respectively active power and reactive power produced and consumed on the islanded feeder come to zero and frequency and voltage on the feeder have to adapt to compensate for this change in balances of active and reactive powers. The higher the initial unbalances ΔP and ΔQ, the larger the frequency and/or voltage deviations from nominal values on the islanded feeder.

In the following the example of a simplified feeder made of a single generator with a RLC parallel load is taken.

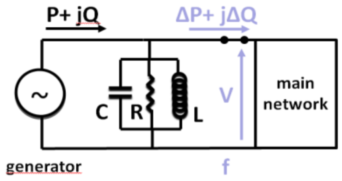

Fig 1: simplified model for an islanded feeder

In case of islanding situation, frequency and voltage adapt to reach the following values:

$$V_{balance} = \sqrt{RP} \qquad (1)$$

$$\omega_{balance} = \frac{1}{\sqrt{LC}}\left(-\frac{Q}{2qP} + \sqrt{1 + \left(\frac{Q}{2qP}\right)^2}\right) \qquad (2)$$

Where q is the quality factor of the RLC load: $q = R\sqrt{\frac{C}{L}}$

In that particular load case, voltage depends only on the balance of active power and frequency depends on the tan φ of the generator. With real life loads, the link between frequency and voltage on the one hand and generator tan φ and active power balance on the other hand is complex but a dependency of frequency on generator tan φ remains (at various degrees according to the loads). If present, inertia (e.g. motors) only plays a role during transients. Again, evolution of frequency and voltage is different on islanded distribution feeders and on transmission networks. On the latter frequency is controlled via the inertia of synchronous generators by adjusting their active power and voltage is controlled via the high reactance/resistance ratio of transmission lines by adjusting the reactive power of these generators.

BRIEF REVIEW OF VARIOUS TYPES OF ISLANDING DETECTION METHODS

Passive methods

These methods encompass all methods that consist in monitoring operating parameters of the network at the point of connection of the generator (such as phase-phase voltage U, phase-earth voltage V, frequency f, dV/dt, df/dt, harmonics rates,...) and disconnect the generator as soon as a pre-defined threshold has been crossed and the given parameter is not any more in the authorized operating range.

As mentioned earlier voltage and frequency thresholds surveillance are the most common interface protections and are quite efficient at detecting islands as long as these thresholds are close enough to nominal values.

Other passive methods like harmonic rate surveillance are more difficult to implement as the choice of a threshold may prove difficult to be made (only voltage and frequency are permanently controlled on a network and thus supposed to remain close to predefined values).

In any case, passive methods have the drawback to always feature what is called a “non-detection area”, this is ranges of initial unbalances [ΔP, ΔQ] (centered around [0,0]) for which voltage and/or frequency will not vary enough after islanding to have frequency, voltage, df/dt, ... defined thresholds being crossed and the islanding situation detected. The narrower the thresholds around the nominal values, the lesser the probability to have an initial unbalance that leads to an islanding situation and the smaller the non-detection area.

Transfer trip

Transfer trip uses direct communication between HV/MV substations and distributed generators connected to MV and LV feeders supplied by this substation. When the circuit-breaker of the feeder head opens due to a fault, a disconnection order is immediately sent to the interface protections of generators connected to this feeder.

Whereas this solution is already used commonly for large generators (typically a few MW or more) its cost for smaller generators, especially connected in LV, is potentially prohibitive to obtain a fast and reliable trip of generators (in about 100 ms) needed for instance when feeders are equipped with fast reclosing systems.

PLC

The idea is to use power line to transmit ripple control signals from the HV/MV substation to generators and command disconnection in case an island is detected. PLC (power line communication) is still experimental in MV networks. First tests have shown a limited signal range. In LV, transmission of the signal is correct but crossing MV/LV substation remains a challenge. In the present state of the art, this solution is not mature enough.

Active methods with periodic action

These methods use electrical perturbations injected periodically and observe the response of the system. Such methods can be for instance:

- impedance measurement: a current peak is injected periodically, voltage response is observed and the impedance of the network is calculated (it is higher in case of islanding situation).
- active frequency drift: the wave form of the current is regularly altered to try to push the frequency higher.
- periodic cycles comprising each a step of reactive power injection followed by a step of reactive power absorption and measurement of the rate of change of frequency (ROCOF): in case of islanding situation, the frequency varies sharply at each step.
- periodic current phase jumps and surveillance of voltage jump: in case of islanding situation the voltage follows the current.

These methods are efficient in case only a few generators are connected to a feeder. In the presence of many :

- either the actions of the various inverters connected to a feeder are not coordinated (which is the usual case) and each of these perturbations gets diluted and loses its effect, or rather the opposite, may in some cases cause spurious tripping of generators.
- or the actions of the various inverters connected to a feeder are coordinated (how this could be done remains to be clarified) and power quality would be impaired.

So these active methods with periodic action are not appropriate to detect islands on feeders equipped with many generators.

Active methods with “escalating” action

These methods monitor parameters of the network (typically frequency or voltage) and start acting only when the chosen parameter varies from its nominal value in order to amplify that variation, push the parameter outside of allowed limits and force disconnection.

There are basically two main options: try to amplify voltage deviations or try to amplify frequency deviations by absorbing/supplying active and/or reactive power.

Playing on active power is not practical as, for economic reasons, decentralized generation usually operates at full available active power leaving no margin nor possibility for permanent active power adjustments.

Playing on reactive power requires a reserve in reactive power which is easier to obtain through an appropriate design of the generator. Acting on reactive power will impact voltage and frequency in a way that depends on load characteristics (see above "VOLTAGE AND FREQUENCY EVOLUTION DURING AN ISLAND"). As frequency thresholds of interface protections are usually narrower (e.g. in France a few % around nominal values) than voltage thresholds (e.g. in France 15 to 20 % around nominal values) and reactive power has an impact on frequency on an islanded feeder, acting on reactive power with a positive loop on frequency is an interesting option.

We focus on this latter method in the rest of the paper.

ESCALATING FREQUENCY SHIFT

This method has basically the same principle as the Sandia Frequency shift method [1]. In generators, it can formally be implemented in two ways :

- for inverters, a current phase angle is introduced in the PLL

$$\theta_{frequency\ \ shift} = -\frac{\pi}{2}\, k\,(f - f_o) \qquad (3)$$

  where f_o is the reference frequency (50 Hz in Europe), f the measured frequency and k is an amplification coefficient.
- for any generator, the reactive power setpoint of the generator is defined as a function of the measured frequency :

$$\Delta Q_{supplied\ \ by\ the\ generator} = -\,k'\,(f - f_o) \qquad (4)$$

In both cases, there is injection of reactive power if the frequency is lower than the reference frequency and absorption of reactive power if the frequency is higher than the reference frequency.

As we will see now, the efficiency of the method depends on the value of the coefficient k (or k') in relation to the characteristics of the network.

Close to the nominal frequency f_o, the behaviour of the network with regard to reactive power absorption as a function of the frequency can be linearized :

$$\Delta Q_{absorbed\ \ by\ the\ network} = -k_{network}\,(f - f_o) \qquad (5)$$

A schematic illustration of the proper, and improper, operation of the frequency shift is given in the following schemes and the associated comments.

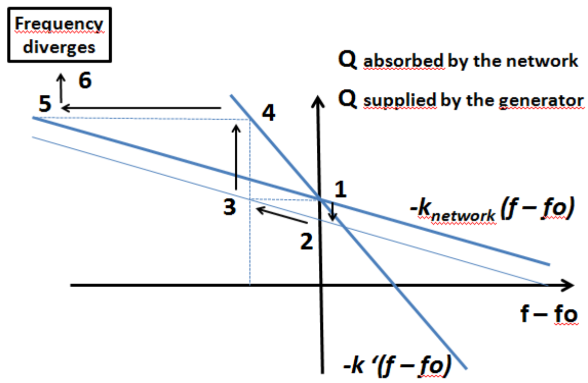

Fig 2: escalating frequency shift with proper parameter

1 : initial state. $Q_{produced} = Q_{consumed}$
2 : perturbation : in that example, the reactive power consumption decreases due to a variation of a load
3 : the frequency adapts fast (electromagnetism laws) to re-establish the balance in reactive power
4 : the frequency shift regulation of the generator sees the frequency deviation and commands a variation in the reactive power produced (this takes some time)
5 : frequency moves again to re-establish the balance in reactive power
6 : and so on … frequency diverges.

If the coefficient k' is too low, the frequency shift will not diverge but find a balance point that may be within the allowed frequency range of the interface protection.

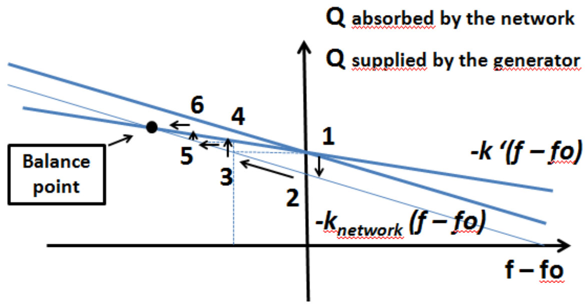

Fig 3: escalating frequency shift with improper parameter

As a conclusion the frequency shift is efficient, even starting form a minimal frequency deviation, provided that its parameters are properly adjusted.

In the case of many inverters, they must have similar parameters to provide a homogeneous behaviour and maintain the efficiency of the islanding detection [2].

ESTIMATE OF REQUIRED PARAMETERS FOR THE FREQUENCY SHIFT

This chapter provides a tentative estimate of the frequency shift parameters necessary for the island detection to be efficient.

Simplified RLC load

Typical frequency range of interface protection goes down to 47,5 Hz, this is f_o – 5%. Equation (2) shows on the simplified RLC model that to move frequency by 5% from nominal frequency, one must have $\frac{Q}{2qP} = 5\%$ this is $\frac{Q}{P} = 10\%q$. The quality factor q can also be written $q = \sqrt{\frac{Q_L Q_C}{P^2}}$ where Q_L, Q_C and P are respectively the inductive, the capacitive and the active powers consumed by the load. On a real feeder, tan φ = 1 is already a very high level of inductive power level consumption. For an island to occur, we would need $Q_L = Q_C$ this is $q = 1$ with tan φ = 1. So, for an islanded RLC load of quality factor = 1, to move frequency by 5% from the nominal frequency Q = 10% P is needed.

Real loads

In the paragraph "ESCALATING FREQUENCY SHIFT" we showed that the frequency shift is efficient if :

$$\left|\frac{\partial Q}{\partial f}_{frequency \quad shift}\right| > \left|\frac{\partial Q}{\partial f}_{network}\right|$$

[7] gives typical values for the behavior of various loads. This allows to compute (calculation not detailed here) the link between Q variations and f variations on an islanded system. A value of -6 for $(dQ_{network}/Q_{network})/(df/f)$ results as a maximum for residential and commercial loads on distribution feeders. A cos φ = 0,85 is also taken, this is tan φ = 0,6. This means that for 1% of variation of frequency the reactive power consumed by a load will vary by at most 6%, this is $\Delta Q \leq 6\%.Q = 6\%.\tan\varphi.P = 6\%.0,6.P = 3,6\%$ of the active power P consumed by the load. So, for the frequency shift to be efficient, it would need to supply reactive power of more than 3,6%.P per % of variation of frequency. If a 5% frequency reduction is needed to activate interface protections, reactive power to the amount of 5%.3,6 = 18% P would be needed.

For industrial loads the coefficient $(dQ_{network}/Q_{network})/(df/f)$ found is 40 to 80 which results in a need of 120% P to 240% P to get a 5% frequency variation which is not feasible. This suggests that the frequency shift may not be efficient for industrial loads.

The above calculations are only indicative and aimed at getting orders of magnitude.

ESCALATING FREQUENCY SHIFT IMPACT ON THE POWER SYSTEM

In case the escalating frequency shift would be installed in mass on decentralized generators, all inverters would react in the same way and simultaneously either inject or absorb reactive power. A question arising is the potential impact on the stability of the power system due to these massive and fast injections/absorptions of reactive power.

To find the answer, simulations were performed with a real power system (French island) modeled with EUROSTAG. The load is 210 MW and peak PV generation capacity is 64 MW (~ 30%). PV generators do not take part to frequency nor voltage regulation.

Escalating frequency shift is modeled through a law $Q_{injected} = k'(f_o - f)$ with $f_o = 50$ Hz. k' is defined as follows : k' = 1 means an injection of 1% of reactive power (compared to apparent power of the PV plant) for a frequency variation of 1 % (500 mHz). We tested the following values for k' = 0.5, 1, 2, 5. For instance, for k' = 5, for a frequency deviation of 2,5 Hz, or 5% of 50 Hz, injection or absorption of reactive power is 5 x 5% = 25% of apparent power. This latter value is envelope of the value found in the paragraph "ESTIMATE OF REQUIRED PARAMETERS FOR THE FREQUENCY SHIFT" for the reactive power that may be needed for the frequency shift to be efficient for residential and commercial loads.

The figure below illustrates the frequency behavior when 50% of PV uses escalating frequency shift and a 28 MW generator is lost. Different values of k' were simulated : k' = 0, 0.5, 1, 2 and 5.

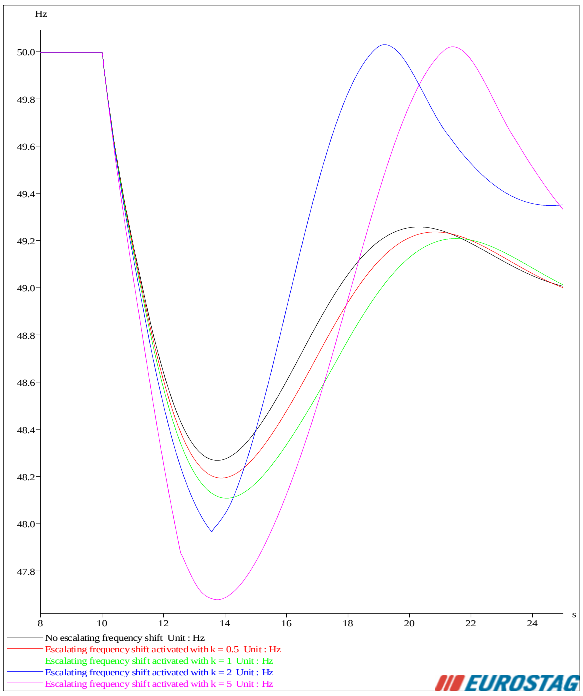

Fig 4: example of impact of frequency shift on a 210 MW power system in case of loss of a power plant

The higher k', the deeper the frequency dip :

- without frequency shift the frequency reaches at the lowest 48,3 Hz (black curve).
- for a value of k' = 1 the frequency dip is accentuated by 200 mHz to 48,1 Hz (yellow curve).
- for values of k' ≥ 2, the frequency crosses 48 Hz and load shedding occurs (blue curves).

The reason for this amplification of frequency dips is that reactive power injection (induced by the frequency dip) causes an increase in voltage locally and as a consequence an increase in the load (whose active power consumption typically increases with voltage). The unbalance between production and generation is accentuated. The other way around, when frequency goes up again, the frequency shift helps the frequency increase by reducing the voltage and thus the load.

We conclude that, if massively installed, the escalating frequency shift islanding detection method may reduce the stability of the power system.

REGULATORY ENVIRONMENT

Various standards and specifications in the world authorize the use of the escalating frequency shift. We can for instance mention :

- *USA* : UL 1741 [3] requires to test anti-islanding detection methods with the oscillating circuit test : using a test bench similar to the one given in Fig.1, the RLC paramaters are adjusted so that, while the feeder is connected to the main network, the RLC load consumes close to 100% of the active and reactive power produced by the inverter (with a given quality factor). Then the feeder is separated from the main network and the inverter must detect alone, and in a given time, that it is connected to an islanded feeder (even if its production is quasi balanced with the load and frequency and voltage have not moved much at the separation from the main network). The frequency shift is one of the methods that pass this test.
- *Germany* : VDE AR-N 4105 2011-08 [4] requires for Low Voltage inverters the use of the oscillating circuit test, but with a different quality factor for the RLC load and a different detection time than in the USA.
- *Japan* : the standard JEM 1498 [5] defines the frequency shift as the islanding detection method for Low Voltage generators with some adaptations : e.g. there are two k' coefficients, a small one for small frequency variations, and a large one when the frequency variation has reached a certain level.
- *France* : the specification ERDF-NOI-RES_13E [6] allows the use of the oscillating circuit test for LV connected inverters.

ACTUAL USE OF ESCALATING FREQUENCY SHIFT IN EUROPE

As seen in the previous paragraph, standards and technical specifications currently in force in some European countries (to our knowledge, at least Germany and France) authorize the use of the escalating frequency shift. However no official record tracks which islanding detection methods have actually been implemented in decentralized producers on distribution networks.

Besides, it should be noted that this islanding detection method might compete for reactive power available in generators with the developing local voltage regulation Q(U), making its use possibly more difficult in the future.

DISCREPANCY BETWEEN DESTABILIZING EFFECTS FOR ISLANDING DETECTION AND POWER SYSTEM REQUIREMENTS

It should be noted that the escalating frequency shift is not the only efficient anti-islanding method that contradicts overall power system stability requirements.

Voltage and frequency thresholds surveillance is also efficient at detecting quickly most islands especially when authorized frequency range is narrow (for instance [49,5-50,5 Hz] in France). However narrow frequency margins for local interface protections contradict the need to avoid massive decentralized generation loss in case of system incident with significant frequency variations.

Likewise immediate disconnection of decentralized generation on a voltage dip may allow avoiding islanding situations but contradicts the need for the power system to avoid worsening a simple voltage dip into a voltage collapse after a short circuit.

A trade-off will be necessary to take into account requirements of power system stability while maintaining sufficient efficiency of islanding detection.

CONCLUSION

This paper showed that though the escalating frequency shift is potentially an efficient anti-islanding method (with possible restriction for industrial loads), its massive use may impair the stability of the power system. This islanding detection is authorized in some European countries and a question that may be raised is how much of it is actually implemented in Europe, if any.

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