DISTRIBUTED ENERGY RESOURCES PROTECTION REQUIREMENTS IN FUTURE DISTRIBUTION GRIDS

Hannu Laaksonen, Sinisa Zubic*, Juha Ylinen

ABB Oy Finland, *ABB Corporate Research Center Cracow

ABSTRACT

One of the key protection functionalities in the future active distribution networks will be reliable detection of islanding. Non-detection zone (NDZ) near a power balance situation and maloperation due to other network events have been the major challenges with traditional passive islanding detection methods like voltage, frequency, rate-of-change-of-frequency, voltage vector shift (VVS). However, in the new grid codes for distributed energy resources (DERs), for example the use of voltage, frequency, rate-of-change-of-frequency for defining DER unit fault-ride-through (FRT) becomes more common. Also when the number of DER units in distribution networks increases in the future, the possibility of achieving power balance in the distribution network will also increase. Therefore, the risk of distribution system segments operating in the NDZ of the traditional passive islanding detection methods will increase, too. In addition, some new grid codes state that islanding detection should not be based only on communication based transfer trip. Due to these issues proper co-ordination between traditional passive islanding detection methods and DER unit FRT / grid code requirements becomes very challenging in the future and new islanding detection schemes are needed.

In this paper the new requirements for distribution network protection and islanding detection related to development of new DER unit grid code requirements will be presented. In the future active management of distribution networks can also simultaneously affect to protection settings or principles if for instance network topology is changed. Therefore, protection adaptation and DER grid code compatibility may be required increasingly in future distribution networks during normal grid-connected and intended island (microgrid) operation. This paper presents potential future grid-code compatible protection schemes i) combined scheme - high-speed communication based transfer trip + VVS, ii) multi-criteria based scheme. With new methods no selectivity issues between islanding detection and DER unit FRT / grid code requirements will exist. In addition, risk of false islanding detections due to other network disturbances will be negligible. Active network management (ANM) functionality could be also used to continuously control the reactive power unbalance over circuit-breaker in order to ensure reliable islanding detection (no NDZ) with VVS alone or as part of the combined scheme. This reactive power unbalance control to ensure reliable islanding detection could be one part of future ANM scheme which would be able to fulfil multiple MV network management targets simultaneously. More details related to this ANM scheme and new combined islanding detection scheme research and development in Sundom Smart Grid (smart grid pilot in Vaasa, Finland) will be also presented in the final paper.

1. INTRODUCTION

In following, at first some of the new DG unit grid code requirements are presented and after that possible effects of new grid code requirements on future islanding detection schemes will be discussed. These new grid codes may require totally new protection functions, modification of existing protection functions (like frequency and voltage), co-ordination of islanding detection functions and grid code active power/frequency (P/f) or reactive power/voltage (Q/U) -control requirements as well as co-ordination of existing protection principles and settings with grid code requirements to have selective and grid code compatible, future-proof protection schemes.

1.1 DG Unit Grid Code Requirements to Support Utility Grid Stability

Previously DG units were usually required to be disconnected during faults, but due to constantly increasing number of DG units connected into the distribution networks this is not feasible anymore because it would lead to loss of large amount of generation after voltage or frequency disturbances. Therefore, it has become important to require utility grid stability supporting functionalities also from
these units by local grid codes. Currently almost all countries have their own specific grid codes.

1.1.1 Frequency Stability Support Related Grid Code Requirements. Grid codes require FRT capability from DG units regarding \( f \) and \( df/dt \) as well as frequency support. In Fig. 1a some grid code frequency FRT requirements for DG units are presented. In Europe, in ENTSO-E NC RfG [1] for DG units (Type A and larger, DG units > 0.8 kW connected to voltage levels below 110 kV) it has been stated that, regarding to frequency ranges, a DG unit shall be capable of staying connected to the network and operating within the frequency ranges and time periods specified in Fig. 1b (some differences between different synchronous areas). In addition, in NC RfG [1] it is also stated that the DG unit (Type A and larger) shall be capable of reducing active power during over-frequencies (\( P/f \)-drop, Fig. 1b). There are also requirements in [1] regarding to operation and active power control during under-frequencies for larger DG units (Type C and larger). For example the DG unit shall be capable of increasing the active power output during under-frequencies (\( P/f \)-droop) starting from point between 49.5 Hz and 49.8 Hz with a droop in a range of 2–12 % (Fig. 1b) [1].

![Frequency FRT Requirement for DG Units](image1)

FIGURE 1: a) different frequency FRT requirements for DG units. [1], [2], [3], [4], [5], [6], b) frequency FRT (Nordic area) and support requirements for DG units (Type A and larger) [1].

In ENTSO-E NC RfG [1] it is stated for DG units (Type A and larger), regarding to their ROCOF or \( df/dt \) withstand capability, that a DG unit shall be capable of staying connected to the network and operating at rates of change of frequency up to a value defined by the TSO. For example in [7] the required ROCOF withstand capability has been set up to 2.5 Hz/s and in Australia (Western Power / South West Interconnected Network) 4 Hz/s ROCOF ride-through capability [4] is required. In current Finnish grid code, VJV2013 / Fingrid (TSO), a generator unit ROCOF ride-through requirement is 2 Hz/s for 1.25 s. Generator unit can be disconnected if ROCOF is over 2 Hz/s, except during undervoltage situations defined by LVVRT curve. In [8] a study was performed to identify possible limitations of the generators to meet ROCOF values of up to 2 Hz/s. It was stated in [8] that a 2 Hz/s ROCOF value may not be achievable with most of the present generators depending on the power factor (leading/lagging) and duration of the event.

1.1.2 Voltage Stability Support Related Grid Code Requirements. Grid codes can also require FRT capability from DG units regarding \( U \) and voltage support. In ENTSO-E NC RfG [1], in Europe, for Type B and larger DG units it has been stated that with regard to FRT capability of DG units each TSO should define a voltage-against-time-profile (low-voltage-ride-through, LVVRT curve) as shown in Fig. 2a). In [7] also additional voltage support by reactive current injection during faults is required from MV network connected converter- / doubly-fed-induction-generator (DFIG) -based DG units and the requirement applies to all kinds of faults (1-, 2- and 3-phase). In [7] it is also stated that synchronous generator-based MV network connected DG units naturally provide a voltage support during faults, which is considered to be sufficient and there are no further requirements for synchronous generators regarding to this voltage support scheme. In [11] it has been also pointed out that in certain configurations reactive current injection as required in German grid code [12] may lead to instabilities as well as voltage and power oscillations and suggest that these issues should be taken into account in the forthcoming ENTSO-E NC RfG. The directional reactive power undervoltage (\( Q->&U< \) -protection is required in German grid code [12] from MV network connected DG units to prevent even larger voltage drops during faults. \( Q->&U< \) -protection must trip the DG unit, which is required to ride through the faults, from the network after 0.5 s if all three line-to-line voltages at the network connection point are below 85% from nominal and if the DG unit
simultaneously draws inductive reactive power from the network [13].

In Europe, in ENTSO-E NC for demand connection (DC) [14] it has also been stated that all transmission connected distribution networks shall fulfil requirements related to reactive power exchange and control.

1.2 Grid code requirements and islanding detection schemes

Traditionally techniques proposed for islanding detection have been divided into two categories: 1) communication-based, like transfer trip schemes and 2) local detection-based, active and passive methods. Local methods have also usually been dependent from the DG unit type, unlike the communication-based methods. More recently also hybrid and combined islanding detection methods have been proposed and are used in some countries. The major challenges with distributed generation (DG) traditional passive islanding detection methods like frequency (f), rate-of-change-of-frequency (ROCOF, df/dt), voltage (U) or voltage vector shift (VVS) have been NDZ near a power balance situation and nuisance tripping / maloperation due to other network events like, for example, utility grid fault, parallel MV feeder fault or capacitor connection (Fig. 3).

In the future, the use of f, U and ROCOF (df/dt) for defining DG units’ fault-ride-through (FRT) requirements in the new grid codes will increase (Fig. 4). DG unit grid code requirements like the P/f- or Q/U-control may also stabilize island if operation time delays are not coordinated with U, f, df/dt or VVS (Fig. 4). In general, it is expected that when the number of DG units increases and power balance situations can happen more frequently, the high-speed communication based transfer trip schemes will be increasingly used as a primary islanding detection method. However, in Europe in ENTSO-E grid code Requirements for Generators (RfG) [1] it has been stated that islanding detection should not be based only on network operator’s switchgear position signals (Fig. 4). Based on above, in the future, the use of only the traditional local parameters like f, df/dt and U for reliable and selective, e.g. with auto-reclosing schemes, islanding detection becomes more difficult than it is today and new islanding detection schemes are needed. Also, as presented in [15] and [16], centralized active network management functionality (CANM) at MV level could continuously control the reactive power unbalance \( Q_{\text{unb}} \) over circuit-breakers which could potentially create an island (Fig. 4), so that the operation point would constantly remain outside the NDZ of the VVS algorithm (or some other passive islanding detection method).

2. FUTURE-PROOF ISLANDING DETECTION SCHEMES

New and forthcoming grid codes increasingly require fault-ride-through capabilities as well as
utility grid supporting functionalities from distributed generators. However, these grid code requirements have been made mainly from transmission network stability point of view and less attention has been paid on potential effects on islanding detection and protection of distribution networks. Therefore, conflicts for example between traditional passive islanding detection methods, like voltage vector shift, and new grid code requirements may exist. Due to this and issues mentioned in the Section 1 new, grid code compatible islanding detection schemes (Fig. 5) are needed. In next sections 5 islanding detection scenarios are analysed and a summary is presented in Fig.6b.

2.1 Passive Islanding Detection with Advanced Voltage Vector Shift (VVS) Algorithm

In order to improve the reliability of voltage vector shift based islanding detection an advanced VVS algorithm has been developed. More detailed description can be found in [21]. This new algorithm can use all three phase voltages or a positive sequence voltage for the vector shift detection and should not cause nuisance tripping of DG units due to other network disturbances. The developed algorithm takes simultaneously into account the behaviour of voltage and frequency, adapts to steady-state frequency variations and has time-dependent correlation checks between phase voltages (when all three phase voltage are used). The algorithm can adaptively correct the measured vector shift angle based on the steady-state frequency variations, which makes the algorithm immune to steady-state frequency variations. The vector shift algorithm is blocked, when any of the measured voltages drop below or increase above the threshold values.

In [24] the effects of two different VVS determinations were studied and it was also stated that when VVS is used alone, the possibility of maloperation of VVS in removing 3-phase faults should be taken into account by long enough internal blocking (for example 100-200 ms) after voltage has risen above undervoltage blocking limit (0.3 pu). In addition, the start/operate of VVS should be again possible 100-200 ms after internal undervoltage blocking removal [24].

Although the proposed vector shift algorithm guarantees fast and reliable islanding detection in nearly all operational conditions when the DG unit is running in parallel with the utility grid supply, certain cases may still cause maloperations. If the power unbalance before islanding is very small and the detected vector shift angle is therefore small, the function may not operate. This means that the vector shift algorithm, like many traditional passive islanding detection methods, still has NDZ near a power balance situation (Scenario 1 in Fig 6b). Therefore, other combined or local passive methods for detecting the islanding without NDZ should be further developed. VVS is still used for islanding detection in many countries, although Germany and...
Denmark have forbidden its use due to its sensitivity to nuisance tripping.

**FIGURE 5: Grid code compatible islanding detection schemes**

### 2.2 Reliable Passive Islanding Detection with Active Network Management

In [15], [16] it has been proposed that centralized active network management functionalities (CANM), like voltage control or losses minimization, at the MV level could include a scheme in the future, which confirms the reliable operation of the passive islanding detection method in real time and possibly also has additional functionalities, like adaptive islanding detection, adaptive auto-reclosing open-time settings and the minimization of the DNO reactive power costs.

The proposed scheme continuously controls the reactive power unbalance $Q_{unb}$ so that the operation point remains constantly outside the NDZ of the used islanding detection method (Fig. 6a), like for example VVS (Section 2.1) and therefore high-speed communication based transfer trip would not be needed (Scenario 2 in Fig.6b). The proposed scheme was simulated with different DG unit configurations as well as by taking the effect of recent grid code requirements into account, especially $P/f$ -droop control of DG units.

The power unbalance $P_{unb}$ and $Q_{unb}$ monitoring can be performed either by centrally based on MV feeder measurements or independently by each MV feeder IED. When, for example, a MV feeder IED measures the reactive power unbalance $Q_{unb}$ change from one stage to another, it sends a signal to CANM functions at MV level about registering the change and also required actions (Fig. 6a). For instance three levels (high, medium, low) for $Q_{unb}$ level could be used. In general, CANM scheme must communicate with controllable distributed energy resources, like DG units, in order to maintain reactive power unbalance $Q_{unb}$ at or above the required level.

If multiple protection zones are used in the same MV feeder the power flow i.e. power unbalance through each CB should be taken into account in the centralized algorithm (Fig. 6a). Change of network topology e.g. from radial to meshed could also in some cases lead the reduced network losses, but before possible change it should be checked that also condition from reliable islanding detection point of view can be fulfilled after the topology change.

ANM improves islanding detection in terms of reliability by eliminating NDZ, but security issue remains since VVS maloperations due to other network disturbances are still possible (Fig.6b). For this reason scenarios 1 and 2 from Fig.6b are not considered as grid code compatible.

### 2.3 Grid Code Compatible Combined Islanding Detection Method

Future-proof combined islanding detection schemes (e.g. high-speed communication based transfer trip, like IEC 61850-based GOOSE or R-GOOSE message & fault detection/direction + VVS) using VVS with sensitive setting (for example $2^\circ$) and without under-/overvoltage blocking are presented in Fig. 4. Due to sensitive setting used in combined scheme (scenario 3 in Fig. 6b) smaller NDZ can be achieved and risk of maloperation due to other network events is small because combined criteria is used. In addition, as stated in Section 2.2 ANM functionality at MV level could also be used to control the reactive power unbalance $Q_{unb}$ continuously in order to ensure islanding detection of the passive method (like VVS with sensitive settings) in the combined
scheme without NDZ (scenario 4 in Fig. 6b) [20], [24]. Both of these schemes are acceptable as future-proof ID schemes, since there is no nuisance tripping (maloperation).

FIGURE 6: a) integration of a new algorithm as part of future active MV network management functionalities to continuously ensure reliable islanding detection even with traditional passive methods, b) 5 scenarios where future-proof, grid code compatible combined islanding detection schemes are scenarios 3, 4 and 5

2.4 Multi-Criteria based Passive Islanding Detection Method

Due to above mentioned issues and challenges (NDZ and nuisance tripping, maloperations) with traditional passive islanding detection methods, a new multi-criteria-based islanding detection algorithm based on multiple simulations has been proposed and developed in [25], [26], [27].

In the future, also intentional utilization of island operation of certain distribution network sections/zones i.e. microgrid operation will become more and more common. Therefore, to enable and guarantee the stability after transition to island operation, islanding and the change of DG unit control parameters or principles must be performed very fast, for instance, in less than 100 ms. This means that a very rapid islanding detection is required. However, this sensitivity depends from many factors like for instance from the DG units’ type, size, inertia, load dynamics, microgrid size and voltage level, line length and $R/X$-ratio etc.

In addition, the detection of islanding situation with a trip time of less than 100-150 ms may be required in the future to be able to disconnect the DG units during auto-reclosing open time (e.g. 200-400 ms). To minimize NDZ of traditional passive islanding detection methods, more sensitive settings could be applied, but it also increases the risk of nuisance tripping of the DG units. Therefore, it is not a realistic option because the new grid codes with different FRT requirements want to minimize the risk of simultaneous nuisance tripping of multiple DG units. Also, no matter how sensitive settings are applied, traditional passive methods cannot detect islanding near a power balance very fast (e.g. in 75-100 ms), because they are based on parameters which measure dynamic changes such as frequency and ROCOF. Therefore, other parameters need to be utilized which are also independent from the DG unit type and applied control principles.

Due to above mentioned issues a new multi-criteria-based islanding detection algorithm has been proposed in [25] and [26]. Based on PSCAD simulations the new islanding detection algorithm is able, based on local measurements, to detect very fast and selectively islanding situations in a perfect power balance without NDZ. The new
multi-criteria algorithm measures the changing natural response of the network due to islanding based on a change in the voltage total harmonic distortion (THD) of all the phase components $\Delta U_{THD_{15a}}$, $\Delta U_{THD_{15b}}$, $\Delta U_{THD_{15c}}$ and a change in the voltage unbalance $\Delta VU$ as well as utilizes intelligently the available fault detection information which ensures a rapid and reliable islanding detection (Fig. 7). With the new islanding detection algorithm no nuisance tripping is likely to occur due to other network events or disturbances and it is not dependent on the DG unit type [25].

In [27] enhanced multi-criteria-based passive islanding detection scheme is presented. Multi-criteria based islanding detection is in [27] also based on measuring the change of voltage unbalance and voltage total harmonic distortion of all phase-to-phase voltages, but in [27] these values are also multiplied by voltage sequence components dependent value. In this enhanced scheme [27], the islanding verification logic is also further improved so that it can separate real islanding (healthy island i.e. no fault in the islanded part of the network) case from all the other network disturbances more reliably including also cases where islanding happens after fault in HV or MV network. In addition, the effect of recent grid code requirements as well as change in voltage positive sequence angle has been considered and taken into account in the proposed islanding detection scheme with improved islanding verification logic. The performances of the algorithm are summarized in scenario 5 in Fig. 6b.

3. DEVELOPMENT OF COMBINED ISLANDING DETECTION SCHEME IN SUNDOM SMART GRID

Sundom Smart Grid (SSG) in Vaasa, Finland (Fig. 8) is a smart grid pilot of ABB Oy, Vaasan Sähkö (local DSO), Elisa (previously Anvia) and University of Vaasa (http://ses.jrc.ec.europa.eu/sundom-smart-grid-ssg). Until recently, new grid automation solutions have been installed in SSG to enable more accurate earth-fault detection and localization in compensated mixed (overhead, OH-line & cable) distribution grids. Today SSG serves as Finnish Innovation Cell in a 3-year ERA-Net Smart Grids Plus project called DeCAS (Demonstration of coordinated ancillary services covering different voltage levels and the integration in future markets) [29] which started 2016 (Fig. 8). In SSG IEEE 1588 time-synchronized, IEC 61850-9-2 SV based, measurement data from multiple points is collected and stored in servers (Fig. 8) to enable research and development of future ANM, protection and islanding detection functionalities (Fig. 9) [30], [31].

In DeCAS -project, combined islanding detection schemes (Fig. 9, scenario 4) for both MV and LV network connected DG units will be further studied and developed [31]. The focus is on such scheme (Fig. 9) which utilizes reactive power unbalance control based Qflow & U-management based ANM scheme. Qflow & U -scheme is able to fulfill multiple targets simultaneously (not only islanding detection without NDZ). The purpose is also, as part of the combined islanding detection scheme, that the fault location could be taken intelligently into account by fault detection/direction information from primary and secondary substations so that depending on the fault location, DG units inside

![FIGURE 7: a) Principle of the multi-criteria-based algorithm for islanding detection in distribution networks [25] and b) Example simulation results about voltage THD, voltage unbalance, frequency and voltage behavior after islanding at t=10.0 s with shown study network [28].](image)
FIGURE 8: Sundom Smart Grid in which ANM and islanding detection schemes presented in Fig. 14 will be investigated [31]

FIGURE 9: a) Proposed future-proof, grid code compatible combined islanding detection scheme, b) grid code compatible ANM scheme able to fulfill multiple targets simultaneously [30] and c) Dependencies between network status, future-proof protection, islanding detection and ANM functionalities as well as issues related to intended islanding (microgrid operation) prioritization [31]
faulted network section will be disconnected (faulty island) and DG units outside faulted section would not be unnecessarily disconnected. The DG units outside the faulted section could then be used for improving local or system-wide grid resiliency through FRT, P.f- or Q/U -control or intentional island operation depending on the fault location, power balance situation etc. before fault; prioritization as well as allowance of intended island operation (Fig.9). Realization of future-proof and grid code compatible schemes requires studies regarding dependencies between protection, islanding detection and active network management (ANM) functionalities [31].

4. CONCLUSIONS

This paper presented several islanding detection algorithms and three future-proof islanding detection schemes i) VVS + transfer trip, ii) VVS + transfer trip + ANM and iii) multi-criteria based scheme. With these new schemes selectivity issues between islanding detection and DG unit FRT / grid code requirements do not exist (no maloperations). Also risk of false islanding detections due to other network disturbances is negligible. ANM functionality which continuously controls the reactive power unbalance over circuit-breaker could be used to ensure reliable islanding detection. Currently, as part of ERA-Net Smart Grids Plus DeCAS-project (http://www.decas-project.eu/), this kind of ANM scheme which is able to fulfill multiple MV network management targets simultaneously is investigated in Sundom Smart Grid (Vaasa, Finland) together with combined islanding detection scheme in co-operation between ABB Oy and University of Vaasa. In the project scheme ii) is considered since the multi-criteria based algorithm was not implemented in IED’s at the moment of project launching.

REFERENCES

[5] ActewAGL, Technical performance requirements for the connection of large scale embedded generators to ActewAGL’s network, Australia, July 2013
[14] ENTSO-E, ENTSO-E Network Code on Demand Connection (NC DC), December 2012,
Available at: https://www.entsoe.eu/major-projects/network-code-development/Pages/default.aspx


[17] Technical standard CEI 0-16, Technical conditions for electricity distribution grid connection with a nominal voltage of greater than 1 kV, Italy, December 2012


