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POWER SYSTEMS AND POWER ELECTRONICS

# The performance of passive methods of detecting island operation implemented in PV inverters during selected disturbances in distribution power grids

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**Abstract.** Distributed generation is an issue intensively studied in recent years. It concerns, among others protection systems of distributed generation units connected to electric power grids. The main goal of this paper is to present the issue of functional reliability of selected passive loss of mains (LoM) protection systems, i.e. methods of detecting island operation in distribution power grids, which are implemented in PV inverters installed in sample MV and LV grids, typical for Polish conditions. First, different methods of detecting island operation have been distinguished and shortly characterized. Some problems concerning their action have also been presented. Then commonly used passive methods of island grid operation detection have been described. Next sample distribution grid has been presented and chosen disturbances modelled in the grid to test mentioned passive methods have been defined. For each of the determined type of disturbance the dynamic simulation has been carried out, as well as voltage and frequency plots for two selected RES nodes have been recorded and observed. All considered passive methods of island grid operation detection have been implemented in a Matlab/Simulink environment. Models of RoCoF, U/OVP and U/OFP algorithms have been presented in diagrams. Then, results of carried out extensive studies have been shown in tables and discussed. The results are a consequence of a realized research project concerning electric grids in rural areas. Summary, final conclusions, and future research possibilities constitute the last part of the paper. The conclusions are mainly concentrated on evaluation of action of passive methods of island operation detection as well as possibility of using the methods in Polish conditions, particularly in rural distribution grids.

**Key words:** distribution power grid, distributed generation, island operation detecting; passive methods, PV inverters, functional reliability.

## 1. Introduction

Some important aspect of electric power system reliability is functional reliability of components, which create the system. It is particularly important for different types of protection systems. Two main aspects concerning correct protections operation are distinguished [1]: dependability and security. Notion of dependability "relates to the degree of certainty that a protection system will operate correctly". In turn, notion of security "relates to the degree of certainty that a protection system will not operate incorrectly".

Distributed generation (DG) is an issue, which has been intensively studied in recent years. The paper [2] presents various key technologies of distributed energy generation, which were developed under the research projects coordinated by Institute of Fluid-Flow Machinery at Polish Academy of Sciences, i.e. Combined Heat and Power (CHP) units for residential houses and for municipalities, as well as "energy plus" technologies for other buildings.

In turn, methodology to determine the optimum location and size of multi-type DG in an electric distribution grid was presented in the paper [3]. The PSO algorithm and differential evolution were applied to solve this problem.

The paper [4] is devoted to the issue of integration of distributed energy sources (DES) with electric power grid. To connect various DESs to supplying grid power electronic converters are often used. In this paper possibilities of application of the power electronic converters to ensure ancillary services resulting from power grid characteristics are analyzed.

A tutorial overview of the most important issues concerning the use of power electronic systems in the context of Smart Power Grids was presented in the publication [5].

In the case when DG units are connected to distribution power grids, the issues concerning Loss of Mains (LoM) protections become crucial. These issues will be presented in this work. The LoM protections are very important from the point of view of correct functioning of distribution power grids in different configurations and states of their operation. In island mode operation it can be the intended (intentional) island operation and unintended (unintentional) island operation.

Polish legal regulations do not allow unintentional island mode operation to be performed as a long lasting state. This state could lead to conditions in which not only the electrical infrastructure may be damaged but also electric shock hazard may appear [6–8]. Due to these reasons many anti-islanding methods have been developed and implemented in DESs. It is possible to distinguish three method groups of detecting island operation [7–9]: active methods, communication-based methods, and passive methods.

Active methods are based on the observation of the disturbance intentionally created and introduced into the grid. Many

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different methods of this type have been developed so far. These algorithms are based on frequency, voltage, impedance and phase measurements. The most popular methods of this type are [9–11]: impedance measurement, detection of impedance at specific frequency, slide mode frequency shift, active frequency drift, and sandia frequency/voltage shift.

Communication based methods are methods that require signals which are sent to inverters by Distribution System Operators (DSOs). These methods could be easily implemented in Smart Grids but would be expensive to implement on the existing extensive distribution grids [12].

Passive methods of detecting island operation mode base on observation of electrical energy quality parameters in Point of Common Coupling (PCC). The most popular methods of this type are [9, 13, 14]: Under/Over Voltage Protection (U/OVP), Under/Over Frequency Protection (U/OFP), Rate of Change of Frequency (RoCoF), Voltage Vector Shift (VVS or VS), and Rate of Change of Power (RoCoP).

According to Polish Grid Codes for every DSO, it is necessary to equip every DES with U/OVP, U/OFP (settings of described protections are presented in Table 1) and LoM protection. It is not specified what method of detection of LoM is required.

Table 1
Default settings of protection systems for low voltage distribution power grids [9, 15]

| Relay function | | Settings | | |
|---|---|---|---|---|
| $U_{LN}$ | $U<$ | 0.8 $U_n$ | 184 V | $<$100 ms |
| | $U>$ | 1.1 $U_n$ | 253 V | $<$100 ms |
| | $U\gg$ | 1.15 $U_n$ | 264 V | $<$100 ms |
| $U_{LL}$ | $U<$ | 0.8 $U_n$ | 320 V | $<$100 ms |
| | $U>$ | 1.1 $U_n$ | 440 V | $<$100 ms |
| | $U\gg$ | 1.15 $U_n$ | 460 V | $<$100 ms |
| $f<$ | | 47.5 Hz | | $<$100 ms |
| $f>$ | | 51.5 Hz | | $<$100 ms |
| LoM | | – | | $<$5 s |

Note: The $U>$ protection system reacts to 10 – minute average voltage value (rms averaging), which is calculated continuously, based on consecutive measurements performed each 3 s, i.e. with overlapping sliding measuring window

In case of generating plants up to and including Type B (this type of generating units is defined in Commission Regulation (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators) connected in parallel with LV distribution grid, respective requirements on selective passive protection systems are presented in Table 2.

We would like to mention, that sets of requirements for type A power-generating modules, including micro-installations have been recently published on the web pages of Polish distribution system operators (e.g. see [16]). Type A power-generating modules were defined in [16], as the ones of power capacity from 0.8 kW up to 200 kW. Requirements related to the settings of particular protection systems for type A power-generating modules are presented in Table 3.

Table 2
Recommended settings of protection systems for generating plants up to and including Type B connected in parallel with LV distribution grid; elaborated on the basis of [14]

| Relay function | Threshold | Operating time |
|---|---|---|
| $U<$ a) | (0.2–1.0) $U_n$ | (0.1–100) s |
| $U\ll$ a) | (0.2–1.0) $U_n$ | (0.1–5) s |
| $U>$ a) | (1.0–1.2) $U_n$ | (0.1–100) s |
| $U\gg$ a) | (1.0–1.3) $U_n$ | (0.1–5) s |
| $U>$(10-minute avg.) b) | (1.0–1.15) $U_n$ | $\leq$3 s |
| $f<$ | (47.0–50.0) Hz | (0.1–100) s |
| $f\ll$ | (47.0–50.0) Hz | (0.1–5) s |
| $f>$ | (50.0–52.0) Hz | (0.1–100) s |
| $f\gg$ | (50.0–52.0) Hz | (0.1–5) s |

Notes: a) The voltage trip values are "true r.m.s." values or the values of fundamental component. b) The voltage trip values are "true r.m.s." values. The U> protection system reacts to 10 – minute average voltage value (rms averaging), which is calculated continuously, based on consecutive measurements performed each 3s, i.e. with overlapping sliding measuring window. $U_n$ is a nominal voltage

Table 3
Settings of protection systems for type A power-generating modules; based on [16]

| Protection function | Minimum operation time | Maximum disconnection rate | Trip value |
|---|---|---|---|
| $U<(U_{LN}, U_{LL})$ | 1.2 s | 1.5 s | 0.85 $U_n$ |
| $U>(U_{LN}, U_{LL})$ a) | – | 3 s | 1.10 $U_n$ |
| $U\gg(U_{LN}, U_{LL})$ | 0.1 s | 0.2 s | 1.15 $U_n$ |
| $f<$ | 0.3 s | 0.5 s | 47.5 Hz |
| $f>$ | 0.3 s | 0.5 s | 52 Hz |
| LoM – RoCoF | – | 0.5 s | 2.5 Hz/s |
| LoM – active b) | – | 5 s | – |

Notes: a) 10-minute average value, according to EN 50160, b) use of protection systems utilizing methods associated with injection of pulses to electric distribution grids is not allowed;
$U_n$ is a nominal voltage, respectively phase to ground or phase to phase voltage

It is worth underlining that apart from passive methods of detecting power islands presented in Table 2 the following methods are commonly used to detect these islands according to [14]:

- RoCoF tripping,
- Voltage Vector shift,
- active methods tested with a resonant circuit (ones "*which pass a resonant circuit test for PV inverters according to EN 62116*" (see [17])),
- switch to a narrow frequency band (to increase sensitivity of the DES interface protection relay – "*to enable activation of the restrictive frequency window*"),
- transfer trip (intertripping) method.

The subject of this paper is important from a theoretical and practical point of view. Many journal and conference papers have been published on this subject, among others [18–20]. In a paper by Shang, Shi and Dong, an islanding method is proposed in ungrounded power distribution systems based on an asymmetric (single-phase) tripping of feeder circuit breakers. Additionally, a paper by Merlin, dos Santos and Grilo Pavani [19] describes the essential aspects concerning training an artificial neural network used for islanding detection of synchronous distributed generators. The impact of both the active power imbalance and load variation on the vector shift (VS) method, via simulation tests in the laboratory conditions, has been presented in [20].

However, the passive anti-islanding protections could fail when the balance between generation and demand in the power island takes place, but it does not deteriorate the power quality. The novel methods of passive detection of islanding such as combination of Q-f droop, RoCoF function and frequency checking [21], rate of change of Voltage Unbalance (RoCoVU) weighted by the RoCoF or RoCoQ [22] are still being invented. What is more, the hybrids of active and passive anti-islanding protections are being developed in order to reduce the negative effects of active detection methods with the maintenance of its fast response [23].

Another innovative approach is to carry out the measurement of electrical quantities in traditional anti-islanding protections and relate the tripping time with magnitude of the disturbance [24].

The use of unconventional circuit breakers installed in a distribution system, which open asymmetrically in order to obtain easy to detect negative sequence voltage with certain duration is described in [25].

Some of the new methods of islanding detection are designed for synchronous generators. In [26] authors present the graphical method of adjusting frequency-based method of islanding detection, maximizing the performance of detection and minimizing false operation. The correct and fast operation of anti-islanding methods can be obtained by observing frequency and voltage deviations simultaneously [27, 28].

In order to obtain faster and more reliable algorithms for islanding detection it is possible to use artificial intelligence (AI) methods. The example of that algorithm is presented in [29, 30]. The threshold for the RoCoF and RoCoP in the proposed method is based on the result of fuzzy logic algorithm action.

In [31] the impact of the voltage and frequency regulation systems on detection of power island was investigated. It was done by the determination of the non-detection zone of the passive protective system located at generator unit both in steady as well as in dynamic states. The study showed that, if the dynamics of power regulation systems is slow enough in comparison to the dynamics of voltage and frequency, then the area of non-detection zone could be decreased when regulation systems are added.

Many detailed issues concerning LoM protections were described in [32]. In particular, the used types of LoM protections, i.e. RoCoF, VS, and Intertripping, as well as recommended settings of these protections for different types of generating units connected to distribution grids in Great Britain (GB) were discussed. Moreover, the necessity of raising the RoCoF protection settings caused by change of energy generation mix and system inertia decrease in GB was taken into account. Limitations in possibility to use VS protections in the case of small power stations due to the inadvertent operation of the protections were also considered. Additionally, several problems, which island operation can cause were presented there. As it was noted, functional unreliability of LoM protections can have an influence on electric distribution grids operation. Two different cases can be specified in this situation: failure of LoM protections and LoM mal-operation [32]. In the case of failure of LoM protections, operation related problems and safety related problems faced by the Distribution System Operators, operational personnel and customers were described in [32]. In turn, in the case of inadvertent operation of LoM protections, causes of such operations as well as impact of such operations on electric distribution grids and generating units operation were presented there.

It is worth to consider the second aspect of the LoM protections operation. It turns out that the RoCoF protections and the VS protections are differently susceptible to different types of power system disturbances. The RoCoF protection is sensitive to changes of generation and load in remote locations, and it is less sensitive to other disturbances and faults in power system. However, this observation can prove not true in the future with regard to system inertia decrease. In turn, the VS protection is sensitive to faults which appear in transmission or distribution grids, and in customer installations [32]. It justifies, in opinion of the authors of this paper, the sense of continuous research on functional reliability of LoM protections in distribution grids, which are specific for particular countries.

Many of the works presented earlier confront the detecting methods with LoM event only. The main contribution of this paper is to evaluate and confront the classic passive anti-islanding protections, which are implemented in PV inverters, with various disturbances appearing in sample distribution grid, typical for Polish conditions. In this way the paper refers to the issue of inadvertent operation of the LoM protection systems in a practical way.

The below subsections describe the simulated performance of common passive LoM protections mentioned in [15], which are installed in PV inverters. Summary and presentation of final conclusions will be included at the end of the paper.

## 2. Passive methods detecting island operation

The commonly used passive methods detecting island mode operation have been presented below.

**2.1. Rate of Change of Frequency.** The RoCoF relay detects a change of frequency over time, i.e. if frequency keeps changing for several time periods the relay will operate to trip DES. The RoCoF is often approximated in practice by the formula [33]:

$$\frac{df}{dt} = \frac{f_n - f_{n-3}}{T_{3n}}. \tag{1}$$

where: $f_n$ – frequency measured in $n$ (current) cycle, $f_{n-3}$ – frequency measured in $n$–3 cycle, $T_{3n}$ – duration of three cycles (60 ms)

The RoCoF value is calculated in moving 60 ms windows (in 50 Hz electric power system), because the PV inverter compares two measured frequencies: the current measured one and the frequency measured three cycles earlier. To ensure that the change is stable and not transient it is required that two consecutive calculations of the frequency change value be above the previously set threshold [33, 34].

The concepts of the RoCoP and the RoCoF are similar. The RoCoP algorithm measures the derivative of power generated (instead of frequency) by DES [9, 13]. The threshold of islanding protections should be reliant also on the conditions in the grid. The number of motors and oscillatory loads influences the behavior of the grid in case of islanding, which is the reason to adjust the protection systems [35].

**2.2. Voltage Vector Shift.** The VVS relays detect a change in load impedance to the generator by detecting the change in the voltage angle (measured in all three phases). The VVS can also be used to trip the DES [33].

If the voltage angle changes rapidly it could be a sign that an island event took place. The angle difference is calculated as a difference between angles in zero-crossing time of the present and the previous cycle. Each cycle has two zero-crossing moments per phase. In total it gives six results after one cycle. If five of the mentioned six results are above the setting threshold a trip signal is generated. This should make the algorithm resistant to unbalanced faults (which is an advantage to this solution). The described protection is supposed to operate in approximately 30 ms [33].

**2.3. Under/Over Voltage Protection**, **Under/Over Frequency Protection.** Table 1 presents settings of U/OVP and U/OFP which are given by DSOs. The boundary delay of protection trip is equal to 5 cycles (100 ms) but the required time to cut off the DES from the distribution system is equal to 200 ms. The additional 100 ms is time for the inverter to cut off the generating unit from the distribution power grid.

The paper is mainly dedicated for analyzing the reaction of passive anti-islanding methods on none islanding events.

## 3. Distribution grid test case

The test grid was designed and implemented in a PowerFactory environment. The test system consists of three levels of voltages (see scheme in Fig. 1): 110 kV, 15 kV and 0.4 kV. The system used is a 27-bus system. The high voltage (HV) is also

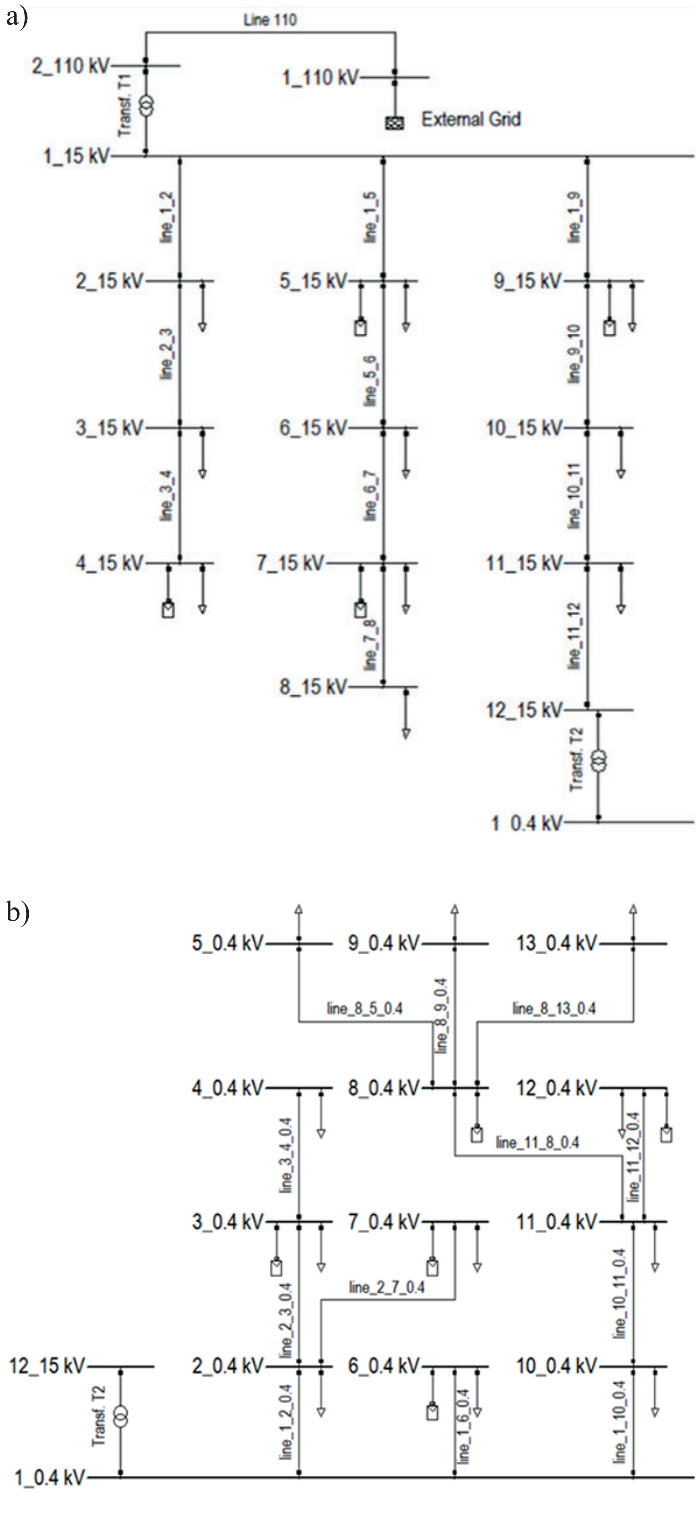


Fig. 1. HV, MV and LV section diagram of the test grid (a – HV and MV section, b – LV section)

included in the test grid model, but it plays a marginal role in further studies. The test grid consists of 2 high voltage (HV) nodes, 12 medium voltage (MV) nodes and 13 low voltage (LV) nodes. Mainly, this model is planned to carry out research in LV and MV grids.

It is worth mentioning that node 1_110 is slack bus. It was modeled as the External Grid block with the short-circuit power equal to 1500 MVA.

The medium voltage part of the test grid is the typical 15 kV grid with Renewable Energy Sources (RESs) connected to it (to nodes: 4_15, 5_15, 7_15, 9_15). The load is moderately high, but the voltage is in the correct range.

The low voltage part of the test system works on the typical Polish conditions 0.4 kV. On LV side of the model five RESs are connected to nodes: 3_0.4, 6_0.4, 7_0.4, 8_0.4, 12_0.4. The calculated voltage in the low voltage section of the model is low, which is often the state in rural grids (note: the voltages in all nodes of analyzed LV grid were in the range ±10% of $U_n$, but the lowest voltage value was close to the lower limit of permissible voltage).

Electric parameters of the HV, MV and LV lines have been presented in Table 4. Data on powers generated and received in the particular nodes of the test grid have been shown in Table 5. In turn, parameters of transformers installed in the test system have been presented in Table 6.

Table 4
Parameters of lines of the test system

| Line Name | Node 1 | Node 2 | $R_L$ [Ω] | $X_L$ [Ω] | $B_L$ [μS] |
|---|---|---|---|---|---|
| line_110 | 1_110 | 2_110 | 3.0 | 4.5 | 1224 |
| line_1_2 | 1_15 | 2_15 | 0.2086 | 0.1005 | 97.38 |
| line_2_3 | 2_15 | 3_15 | 0.2044 | 0.0829 | 70.37 |
| line_3_4 | 3_15 | 4_15 | 0.2427 | 0.0984 | 83.56 |
| line_1_5 | 1_15 | 5_15 | 0.2920 | 0.1407 | 136.34 |
| line_5_6 | 5_15 | 6_15 | 0.3321 | 0.1347 | 114.35 |
| line_6_7 | 6_15 | 7_15 | 0.1788 | 0.0725 | 61.57 |
| line_7_8 | 7_15 | 8_15 | 0.2810 | 0.1140 | 96.76 |
| line_1_9 | 1_15 | 9_15 | 0.1672 | 0.0973 | 103.67 |
| line_9_10 | 9_15 | 10_15 | 0.1672 | 0.0973 | 103.67 |
| line_10_11 | 10_15 | 11_15 | 0.1672 | 0.0973 | 103.67 |
| line_11_12 | 11_15 | 12_15 | 0.2086 | 0.1005 | 97.38 |
| line_1_2_0.4 | 1_0.4 | 2_0.4 | 0.0253 | 0.0059 | 2.51 |
| line_2_3_0.4 | 2_0.4 | 3_0.4 | 0.0221 | 0.0029 | 1.25 |
| line_2_7_0.4 | 2_0.4 | 7_0.4 | 0.0335 | 0.0119 | 0.15 |
| line_3_4_0.4 | 3_0.4 | 4_0.4 | 0.0295 | 0.0144 | 0.20 |
| line_1_6_0.4 | 1_0.4 | 6_0.4 | 0.0443 | 0.0059 | 2.51 |
| line_1_10_0.4 | 1_0.4 | 10_0.4 | 0.0618 | 0.0221 | 5.66 |
| line_10_11_0.4 | 10_0.4 | 11_0.4 | 0.0379 | 0.0088 | 3.77 |
| line_11_8_0.4 | 11_0.4 | 8_0.4 | 0.0759 | 0.0177 | 7.55 |
| line_11_12_0.4 | 11_0.4 | 12_0.4 | 0.0886 | 0.0118 | 5.03 |
| line_8_9_0.4 | 8_0.4 | 9_0.4 | 0.0443 | 0.0059 | 2.51 |
| line_8_5_0.4 | 8_0.4 | 5_0.4 | 0.0886 | 0.0118 | 5.03 |
| line_8_13_0.4 | 8_0.4 | 13_0.4 | 0.0414 | 0.0202 | 0.28 |

where: $R_L$ is a line resistance, $X_L$ is a line reactance, $B_L$ is a line susceptance

Table 5
Data on powers generated and received in the particular nodes of the test system

| Node name | $P_{gen}$ [kW] | $Q_{gen}$ [kvar] | $P_{load}$ [kW] | $Q_{load}$ [kvar] |
|---|---|---|---|---|
| 1_15 | 0 | 0 | 0 | 0 |
| 2_15 | 0 | 0 | 1000 | 300 |
| 3_15 | 0 | 0 | 2000 | 400 |
| 4_15 | 200 | 0 | 3000 | 600 |
| 5_15 | 240 | 0 | 1050 | 210 |
| 6_15 | 0 | 0 | 1100 | 220 |
| 7_15 | 250 | 0 | 1300 | 260 |
| 8_15 | 0 | 0 | 1100 | 220 |
| 9_15 | 500 | 0 | 2000 | 400 |
| 10_15 | 0 | 0 | 1400 | 280 |
| 11_15 | 0 | 0 | 1200 | 240 |
| 12_15 | 0 | 0 | 0 | 0 |
| 1_0.4 | 0 | 0 | 0 | 0 |
| 2_0.4 | 0 | 0 | 20 | 10 |
| 3_0.4 | 5 | 0 | 30 | 0 |
| 4_0.4 | 0 | 0 | 20 | 50 |
| 5_0.4 | 0 | 0 | 30 | 0 |
| 6_0.4 | 60 | 0 | 85 | 20 |
| 7_0.4 | 35 | 0 | 60 | 0 |
| 8_0.4 | 20 | 0 | 0 | 0 |
| 9_0.4 | 0 | 0 | 10 | 0 |
| 10_0.4 | 0 | 0 | 40 | 10 |
| 11_0.4 | 0 | 0 | 10 | 0 |
| 12_0.4 | 40 | 0 | 10 | 0 |
| 13_0.4 | 0 | 0 | 20 | 0 |

where: $P_{gen}$ is an active generated power, $Q_{gen}$ is a reactive generated power, $P_{load}$ is an active received power, $Q_{load}$ is a reactive received power

Note: All powers generated and received in particular nodes are three-phase powers

Table 6
Parameters of transformers installed in the test system

| Name | $U_{1r}$ [kV] | $U_{2r}$ [kV] | $S_{rT}$ [kVA] | $u_{kr}$ [%] | Node 1 | Node 2 |
|---|---|---|---|---|---|---|
| Transf. T1 | 115 | 15.75 | 32000 | 16 | 2_110 | 1_15 |
| Transf. T2 | 15.75 | 0.4 | 400 | 4.5 | 12_15 | 1_0.4 |

where: $U_{1r}$ is a high voltage side nominal voltage, $U_{2r}$ is a low voltage side nominal voltage, $S_{rT}$ is a nominal apparent power, $u_{kr}$ is a short-circuit voltage.

## 4. Chosen disturbances modelled in the test system

The chosen disturbances planned for simulation in the test grid are presented in Table 7.

For each of the disturbances presented in Table 7, variants of the dynamic simulation were carried out and the voltage and frequency plot was saved for two RES nodes for each voltage level; for one node close to the transformer and one node far from it. Additionally, voltages and frequencies in all busbars were also saved. Figure 2 shows the exemplary records of frequencies and voltages in nodes. The results are presented for nodes in LV and MV sections of the test grid. The fault occurs in LV busbars and has significantly greater impact on the LV section than on the MV part of the grid. During the disturbance the voltage in bus 04_15 kV drops to 0.9 pu whereas in 06_0.4 kV it is very unstable. Similar conclusions could be drawn in frequency records. In the MV section frequency is stable but in LV one high frequency oscillations can be observed.

Table 7
Disturbances chosen to test passive methods of detection of islanding operation

| Type of disturbance | Details about disturbance | Time duration | The location |
|---|---|---|---|
| Voltage Dip [a)] | 80% $U_n$ | 200 ms | 1_110 kV |
| | | 700 ms | |
| | | 1000 ms | |
| | | 2000 ms | |
| | 50% $U_n$ | 200 ms | 1_110 kV |
| | | 700 ms | |
| | | 1000 ms | |
| | | 2000 ms | |
| | 30% $U_n$ | 200 ms | 1_110 kV |
| | | 500 ms | |
| | | 1000 ms | |
| | | 2000 ms | |

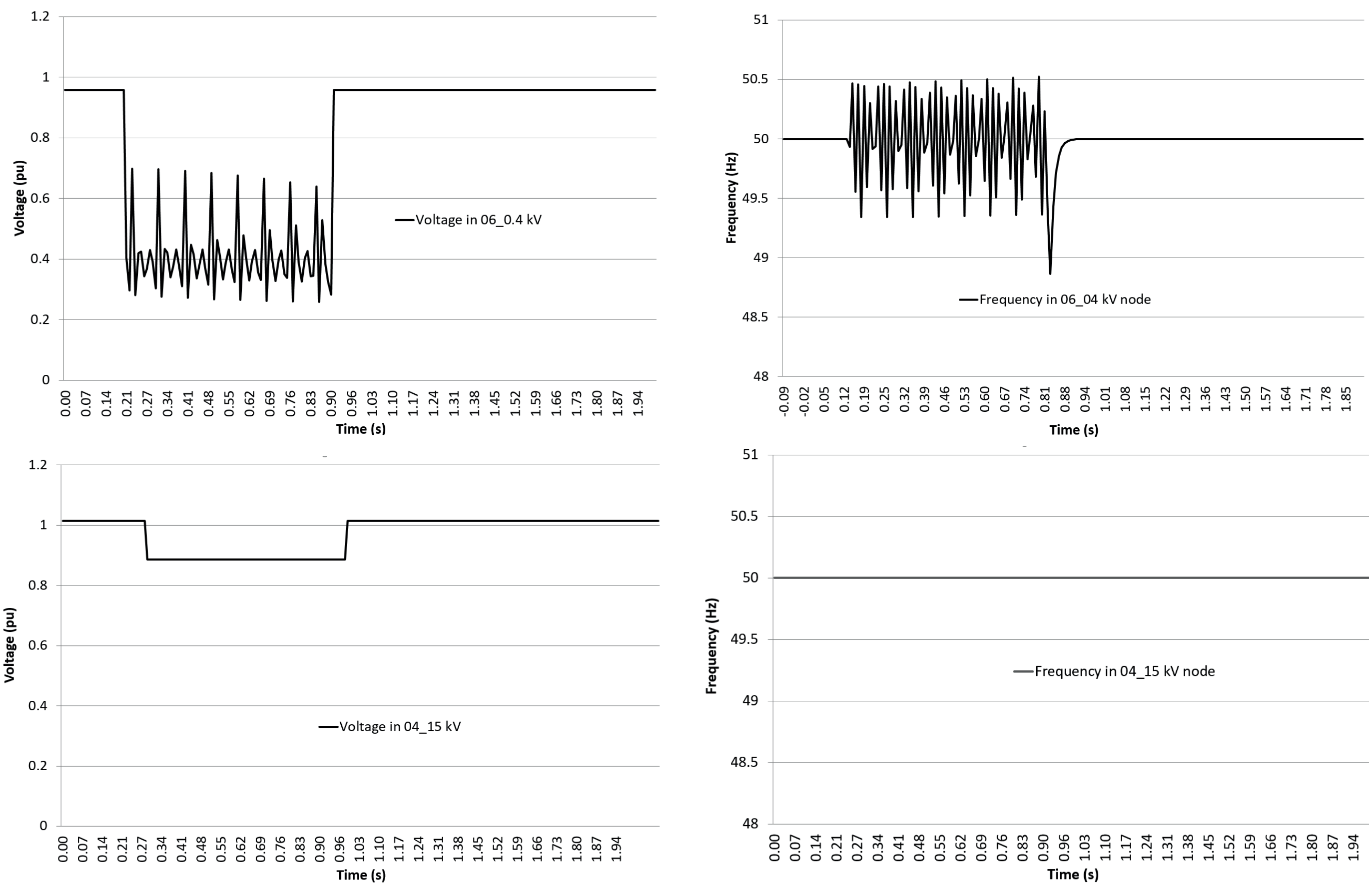


Fig. 2. The example plots of voltage and frequency in selected nodes of the test system. Simulation variant – fault in node 1_0.4 kV lasting 700 ms.

Table 7

| Type of disturbance | Details about disturbance | Time duration | The location |
|---|---|---|---|
| Fault | Three-phase | 100 ms | 1_110 kV |
| | | 200 ms | |
| | | 500 ms | |
| | | 200 ms | 1_15 kV |
| | | 400 ms | |
| | | 400 ms | 12_15 kV |
| | | 10 ms [b)] | 1_0.4 kV |
| | | 20 ms [c)] | |
| | | 200 ms [c)] | |
| | | 700 ms [c)] | |
| | | 10 ms [b)] | 13_0.4 kV |
| | | 500 ms [c)] | |
| LoM | Three-phase | 4000 ms | HV/MV transformer |
| | | 4000 ms | MV/LV transformer |

Notes: a) the voltage dips are modelled as three-phase and rectangular ones, b) the faults are cleared by fuses, c) the faults are cleared by circuit breakers

The second step of the analysis was the implementation of passive methods to check proper detection of island operations in Matlab/Simulink environment. The algorithms taken into consideration were: RoCoF, VVS, U/OVP and U/OFP. Models of RoCoF, U/OVP and U/OFP algorithms were implemented in Simulink. VVS algorithm behavior was coded in Matlab. The full string of actions, which were taken to obtain the final results, are presented in Fig. 3.

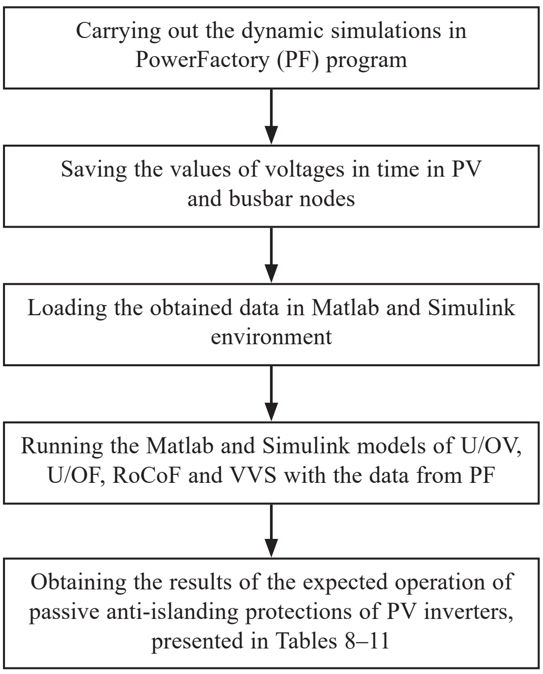


Fig. 3. The actions taken in order to obtain the results of passive anti-islanding protection systems

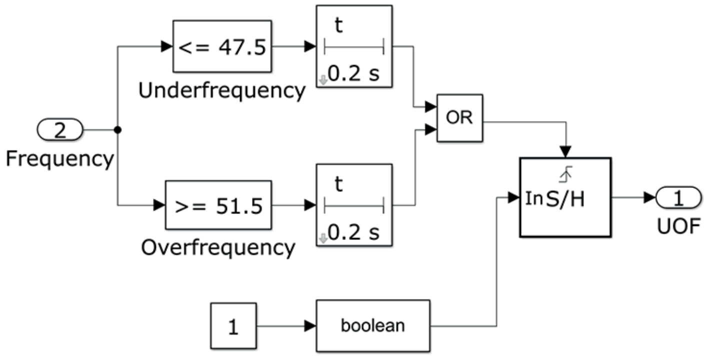


Fig. 4. U/OFP model in Simulink environment

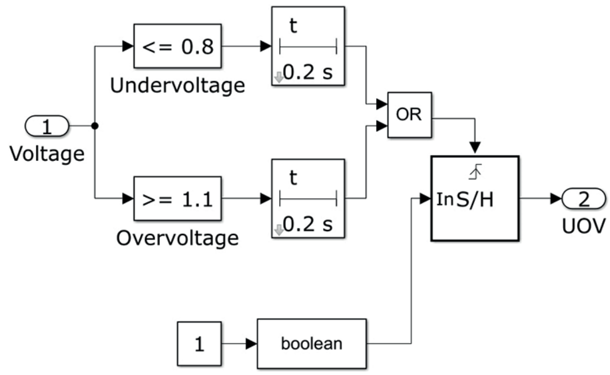


Fig. 5. U/OVP model in Simulink environment

The under/over frequency protection Simulink model is presented in Fig. 4. The thresholds for that model are 47.5 Hz and 51.5 Hz. The delay is equal to 0.2 s.

In turn, the under/over voltage protection Simulink model is presented in Fig. 5. The thresholds are 0.8 pu and 1.1 pu. The delay is also equal to 0.2 s.

The RoCoF protection Simulink model is presented in Fig. 6. The threshold was set to different values. The RoCoF algorithm was tested with values: 0.2 Hz/s, 0.5 Hz/s, 2 Hz/s (both positive and negative ones). There is no delay set in this model.

The VVS protection system model was written in Matlab. Its role was to check the above described VVS condition of zero-crossing time and to compare it with the threshold. The threshold was set to different values: 12°, 9°, 6° between two cycles (both positive and negative). In time domain mentioned

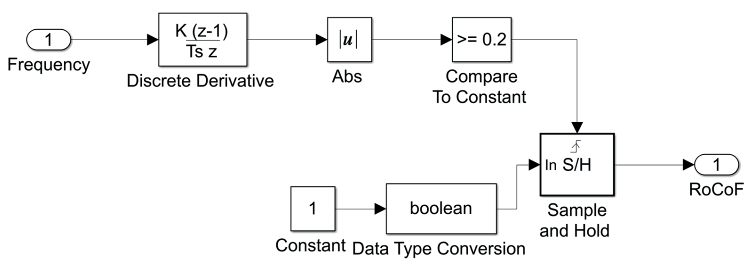


Fig. 6. RoCoF model in Simulink environment

angles are 0.66 ms, 0.5 ms and 0.33 ms. There is no delay set in the model.

The calculations have been carried out for the resolution-factor of data equal to 0.001 s. The maximum error of state equations was equal to 0.1%. The investigations were conducted in RMS mode, according to the algorithm used by PowerFactory program.

## 5. Results of carried out studies

The results of the carried-out simulations are presented in Tables 8–11. They present the simulated behavior of mentioned anti-islanding protection system models during defined disturbances. The response time of protection system (or no response time information) is given for each location of the PV inverters in the test grid.

During voltage dips only U/OV protections respond to the disturbance. When the duration of the voltage dip is equal to 200 ms then time of the event is too short, thus protection does not work. When the time is longer than 200 ms, the voltage dip magnitude does not matter, U/OV protection will trigger at the same time (Table 8). In such cases, PV inverters would be switched off. U/OF, RoCoF, and VVS protection systems do not react to voltage dips at all (Tables 9–11).

The results of the simulation of anti-islanding protections during faults in busbars of the test case are different for every protection system. The U/OV protection for faults lasting not longer than 200 ms does not switch off the PV inverter. For longer faults protection trips out the PV inverters at the same time because the same time delay (200 ms) is set. When fault occurs in a HV or MV section then all inverters are tripped out. When the fault occurs in a LV section then only some inverters installed in the LV part of the grid are tripped out in time 210 ms (Table 8).

The U/OF protection systems respond to the fault disturbance to trip out the PV inverters when the fault lasting at least 200 ms occurs in a HV section. During some faults in a MV section only the inverters installed in the LV section trip out in 210 ms, but when the fault is in the LV section it does not trip any inverter in the grid (Table 9).

The RoCoF protection during short circuit events in a HV section trips out all the inverters in 60 ms. When the fault occurs in a MV section, then the inverters installed in a LV section trip out at the same time. In this case interesting results occur in the MV inverters protections, which make those inverters switch off from the grid when the fault lasts 200 ms for the 0.5 Hz/s and 0.2 Hz/s thresholds but not when it is longer (400 ms). When the threshold is 2 Hz/s the protections do not trip out. This is because of frequency oscillations after fault clearance. The RoCoF protection response is then equal to 240 ms. When the fault occurs in a LV section only LV inverters trip out in time 60 ms (Tables 10 and 11). It concerns only faults in node 1_0.4 kV. In the case of short-lasting faults (10 ms, 20 ms) it refers to selected nodes – locations of protections, while for long-lasting faults (200 ms, 700 ms) to all considered locations.

Table 8
The behavior of U/OV protection system during different disturbances

| Type of disturbance | Details about disturbance | Time duration of disturbance | The location of disturbance | Location of U/OV protection: | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 1_15 kV | 4_15 kV | 5_15 kV | 1_0.4 kV | 6_0.4 kV | 8_0.4 kV |
| Voltage Dip | 80% $U_n$ | 200 ms | 1_110 kV | No | No | No | No | No | No |
| | | 700 ms, 1 s, 2 s | | 210 ms | 210 ms | 210 ms | 210 ms | 210 ms | 210 ms |
| | 50% $U_n$ | 200 ms | 1_110 kV | No | No | No | No | No | No |
| | | 700 ms, 1 s, 2 s | | 210 ms | 210 ms | 210 ms | 210 ms | 210 ms | 210 ms |
| | 30% $U_n$ | 200 ms | 1_110 kV | No | No | No | No | No | No |
| | | 500 ms, 1 s, 2 s | | 210 ms | 210 ms | 210 ms | 210 ms | 210 ms | 210 ms |
| Fault | Three-phase | 100 ms, 200 ms | 1_110 kV | No | No | No | No | No | No |
| | | 500 ms | | 210 ms | 210 ms | 210 ms | 210 ms | 210 ms | 210 ms |
| | | 200 ms | 1_15 kV | No | No | No | No | No | No |
| | | 400 ms | | 210 ms | 210 ms | 210 ms | 210 ms | 210 ms | 210 ms |
| | | 400 ms | 12_15 kV | 210 ms | 210 ms | 210 ms | 210 ms | 210 ms | 210 ms |
| | | 10 ms, 20 ms, 200 ms | 1_0.4 kV | No | No | No | No | No | No |
| | | 700 ms | | No | No | No | 210 ms | 210 ms | 210 ms |
| | | 10 ms | 13_0.4 kV | No | No | No | No | No | No |
| | | 500 ms | | No | No | No | No | No | 210 ms |
| Loss of Mains | Three-phase | 4000 ms | only LV grid | No | No | No | 210 ms | 210 ms | 210 ms |
| | | | LV and MV grid | 210 ms | 210 ms | 210 ms | 210 ms | 210 ms | 210 ms |

Note: No – no response time information

Table 9
The behavior of U/OF protection system during different disturbances

| Type of disturbance | Details about disturbance | Time duration of disturbance | The location of disturbance | Inverter location U/OF protection: | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 1_15 kV | 4_15 kV | 5_15 kV | 1_0.4 kV | 6_0.4 kV | 8_0.4 kV |
| Voltage Dip | 80% $U_n$ | 200 ms, 700 ms, 1 s, 2 s | 1_110 kV | No | No | No | No | No | No |
| | 50% $U_n$ | 200 ms, 700 ms, 1 s, 2 s | 1_110 kV | No | No | No | No | No | No |
| | 30% $U_n$ | 200 ms, 500 ms, 1 s, 2 s | 1_110 kV | No | No | No | No | No | No |
| Fault | Three-phase | 100 ms | 1_110 kV | No | No | No | No | No | No |
| | | 200 ms, 500 ms | | 210 ms | 210 ms | 210 ms | 210 ms | 210 ms | 210 ms |
| | | 200 ms, 400 ms | 1_15 kV | No | No | No | 210 ms | 210 ms | 210 ms |
| | | 400 ms | 12_15 kV | No | No | No | No | No | No |
| | | 10 ms, 20 ms, 200 ms, 700 ms | 1_0.4 kV | No | No | No | No | No | No |
| | | 10 ms, 500 ms | 13_0.4 kV | No | No | No | No | No | No |
| Loss of Mains | Three-phase | 4000 ms | only LV grid | No | No | No | 210 ms | 210 ms | 210 ms |
| | | | LV and MV grid | 210 ms | 210 ms | 210 ms | 210 ms | 210 ms | 210 ms |

Table 10
The behavior of RoCoF and VVS protection systems installed in MV test grid during different disturbances

| Type of disturbance | Details about disturbance | Time duration of disturbance | The location of disturbance | Inverter location: 1_15 kV, 4_15 kV, 5_15 kV | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | RoCoF | | | VVS | | |
| | | | | 2 Hz/s | 0.5 Hz/s | 0.2 Hz/s | 12° | 9° | 6° |
| Voltage Dip | 80% $U_n$ | 200 ms | 1_110 kV | No | No | No | No | No | No |
| | 50% $U_n$ | 700 ms | | No | No | No | No | No | No |
| | 30% $U_n$ | 1 s, 2 s | | No | No | No | No | No | No |
| Fault | Three-phase | 100 ms | 1_110 kV | 60 ms | 60 ms | 60 ms | 60 ms | 60 ms | 60 ms |
| | | 200 ms, 500 ms | | 60 ms | 60 ms | 60 ms | 110 ms | 110 ms | 110 ms |
| | | 200 ms | 1_15 kV | No | 240 ms | 240 ms | No | No | No |
| | | 400 ms | | No | No | No | No | No | No |
| | | 400 ms | 12_15 kV | No | No | No | No | No | No |
| | | 10 ms, 20 ms, 200 ms, 700 ms | 1_0.4 kV | No | No | No | No | No | No |
| | | 10 ms, 500 ms | 13_0.4 kV | No | No | No | No | No | No |
| Loss of Mains | Three-phase | 4000 ms | only LV grid | No | No | No | No | No | No |
| | | | LV and MV grid | 60 ms | 60 ms | 60 ms | 60 ms | 60 ms | 60 ms |

The VVS protections trip out MV inverters in time 60 ms or 110 ms only when fault occurs in a HV section (Table 10). The VVS protections installed in a LV section trip out in case of each fault in node 1_0.4 kV in time 60 ms or 110 ms (Table 11). The analyzed angles (12º, 9º, 6º) do not matter in the considered cases. In the case of short-lasting faults (10 ms, 20 ms) in node 1_0.4 kV it refers to selected nodes – locations of protections, while for long-lasting faults (200 ms, 700 ms) to all considered locations. In turn, in the case of faults in node 13_0.4 kV protections are not tripped out.

Loss of mains event causes tripping of PV inverters. During this disturbance all the methods of detecting islanding mode of operation work properly. Protection systems can selectively switch off PV inverters. Faster would be RoCoF and VVS protections with comparable time of 60 ms. Then U/OV and U/OF protections work with tripping times close to 210 ms.

Table 11
The behavior of RoCoF and VVS protection systems installed in LV test grid during different disturbances

| Type of disturbance | Details about disturbance | Time duration of disturbance | The location of disturbance | Inverter location: 1_0.4 kV, 6_0.4 kV, 8_0.4 kV | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | RoCoF | | | VVS | | |
| | | | | 2 Hz/s | 0.5 Hz/s | 0.2 Hz/s | 12° | 9° | 6° |
| Voltage Dip | 80% $U_n$ | 200 ms | 1_110 kV | No | No | No | No | No | No |
| | 50% $U_n$ | 700 ms | | No | No | No | No | No | No |
| | 30% $U_n$ | 1 s, 2 s | | No | No | No | No | No | No |
| Fault | Three-phase | 100 ms | 1_110 kV | 60 ms | 60 ms | 60 ms | 60 ms | 60 ms | 60 ms |
| | | 200 ms, 500 ms | | 60 ms | 60 ms | 60 ms | 110 ms | 110 ms | 110 ms |
| | | 200 ms, 400 ms | 1_15 kV | 60 ms | 60 ms | 60 ms | 110 ms | 110 ms | 110 ms |
| | | 400 ms | 12_15 kV | 60 ms | 60 ms | 60 ms | 60 ms | 60 ms | 60 ms |
| | | 10 ms | 1_0.4 kV | (6_0.4 only) 60 ms | (6_0.4 only) 60 ms | (6_0.4 only) 60 ms | (6_0.4 only) 60 ms | (6_0.4 only) 60 ms | (6_0.4 only) 60 ms |
| | | 20 ms | | (6_0.4 and 8_0.4) 60 ms | (6_0.4 and 8_0.4) 60 ms | (6_0.4 and 8_0.4) 60 ms | (6_0.4 and 8_0.4) 60 ms | (6_0.4 and 8_0.4) 60 ms | (6_0.4 and 8_0.4) 60 ms |
| | | 200 ms, 700 ms | | 60 ms | 60 ms | 60 ms | 110 ms | 110 ms | 110 ms |
| | | 10 ms, 500 ms | 13_0.4 | No | No | No | No | No | No |
| Loss of Mains | Three-phase | 4000 ms | only LV grid | 60 ms | 60 ms | 60 ms | 60 ms | 60 ms | 60 ms |
| | | | LV and MV grid | 60 ms | 60 ms | 60 ms | 60 ms | 60 ms | 60 ms |

## 6. Summary and conclusion

The performance of passive methods of detecting island operation implemented in PV inverters during selected disturbances in distribution power grids has been presented in the paper. The following issues concerning the subject of this paper: short characteristics of different methods detecting island operation, description of commonly used passive methods of island grid operation detection, presentation of sample distribution grid and chosen disturbances modelled in the grid to test mentioned passive methods, models of RoCoF, U/OVP and U/OFP algorithms implemented in Simulink environment, results of carried out studies shown in plots and tables, including observations have been described.

Based on information included in this paper as well as information presented in other literature sources, the following observations and conclusions can be formulated:

- PV inverters can be equipped with many algorithms of detection of island grid operation. We can distinguish three groups of those methods: passive methods, active methods, communications-based methods.
- The developed sample distribution grid and simulation models allow for simulating behavior of considered passive anti-islanding protection systems during defined disturbances in the grid and drawing respective conclusions.
- During long lasting voltage dips only U/OV protections respond to the disturbance. U/OF, RoCoF, and VVS protection systems do not react to voltage dips at all.
- The results of the simulations of action of anti-islanding protections during faults in nodes of the sample grid are different for every protection system and are described above in detail.
- Special attention has been paid to operation of the RoCoF protection and the VVS protection. The RoCoF protections trip out all the inverters in 60 ms during short circuit events in a HV section. In turn, when the fault occurs in a MV section, then the inverters installed in a LV section trip out. Location of disturbance does not matter. Interesting results occur in the MV inverters protections, which make those inverters switch off from the grid when the fault (only in node 1_15 kV at the beginning of circuit) lasts 200 ms for the 0.5 Hz/s and 0.2 Hz/s thresholds but not when it is longer. When the threshold is 2 Hz/s the protections do not trip out. When the fault occurs in a LV section only LV inverters trip out. Location of disturbance and its duration matter. For short-lasting faults (10 ms, 20 ms) in node 1_0.4 kV it refers to selected nodes – locations of protections, while for long-lasting faults (200 ms, 700 ms) to all considered locations. In turn, in the case of faults in node 13_0.4 kV protections are not tripped out. In case of the VVS protections MV inverters trip out only when fault occurs in a HV section. The VVS protections installed in a LV section trip out in case of each fault in the grid (fault at the end of LV circuit is exception to this rule). Similarly, as in case of the RoCoF protection, location of disturbance and its dura-

tion matter. The analyzed angles (12º, 9º, 6º) do not matter in the considered cases during studies. As it can be seen, inadvertent operation of the RoCoF protection and the VVS protection in many short circuit events can be observed. During carried out simulation studies these protections interpreted three-phase fault as a LoM state. Operating time of the RoCoF protections was usually shorter than operating time of the VVS protections.

- During LoM disturbances all the considered passive methods of island grid operation detection work properly, i.e. cause tripping of PV inverters. Protection systems can selectively switch off the inverters. The RoCoF and VVS protections would activate first, then the U/OVP and U/OFP would act.
- The obtained simulation results are very important for distribution grids in Polish conditions. The rapid development of PV installations in Polish rural areas, where electrical energy quality is low, could lead to the problems of incorrect passive anti-islanding protection systems performance. Before connecting large groups of inverters to DES the analysis of power quality should be taken into consideration. If disturbances such as voltage dips happen very often the DES would switch off from the grid often as well. As it was shown, faults may also involve inadvertent operation of anti-islanding protection systems.

The future research on foreseen changes concerning distribution grids, i.e. change of natural inertia value related to increase of DESs number and connected with them converters in the context of correctness of LoM protections functioning, as well as perhaps necessity of introducing artificial inertia to grids by means of the converters are planned.

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