

Article

Implementation of the Improved Active Frequency Drift Anti-Islanding Method into the Three-Phase AC/DC Converter with the LCL Grid Filter

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Abstract: The article presents a modified standard Active Frequency Drift (AFD) method used to detect unintentional island operation in converters generating electricity from renewable energy sources to the power grid. The primary aim of each of the island operation detection methods is the possibility of shortening the energising of a separate part of the power grid. The proposed method eliminates fragments of the reference current signal when it reaches a constant value for a particular time. This part of the signal is replaced with the hyperbolic sine function. It allows reducing the value of Total Harmonic Distortions (THD) while maintaining the same effectiveness of island operation detection. The article contains a detailed description of the newly proposed type of disturbance generation. The proposed solution is verified by conducting simulation and laboratory tests. The possibility of shortening the island operation detection time is proven by increasing the maximum distortion introduced into the current without exceeding the permissible THD limit for converters connected to the power grid.



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Keywords: anti-islanding detection; renewable energy source; energy quality; active frequency drift; three-phase converter; predictive control

1. Introduction

Global ecological trends cause the industry's dynamic development in obtaining electricity from Renewable Energy Sources (RES) [1,2]. In various parts of the world, changes in the immediate environment are noticeable, and there are more wind turbines or photovoltaic panels. The growing interest in the subject is caused by the political and economic situation [3]. In highly developed countries, electricity consumers are encouraged to become electricity producers by co-financing the construction of home mini-power plants. Due to their profitability, there are also large-scale investments (larger power plants). Such a rapid and dynamic development of the electricity production market from renewable sources forces the manufacturers of voltage converters to apply additional safeguards. They are obliged to implement islanding detection algorithms [4–6]. The voltage converter operates in the unintentional islanding operation when electric power from a renewable energy source is fed into the separated part of the power grid. This separate grid part contains a voltage converter and electric energy consumers (Figure 1b).

The problem occurs when the amount of electricity produced by the RES matches the demand by electric energy consumers connected to it (e.g., households) [7–10]. Among the possible reasons for the islanding of part of the power grid, the following reasons can be indicated [11]:

1. Opening of the power switch as a result of faults in the power grid.
2. Accidental opening of the power switch during regular power grid operation.
3. A deliberate shutdown of the power grid to service the power infrastructure.
4. As a result of human error.

5. As a result of the action of the forces of nature.

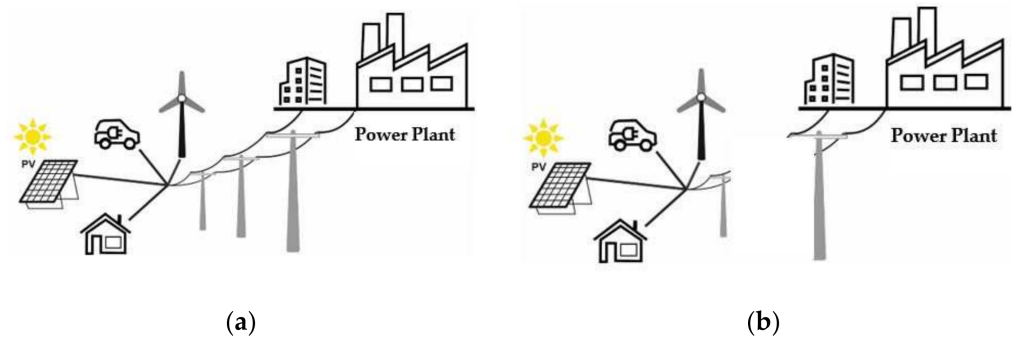


Figure 1. Examples of power grid configuration: (a) without islanded part of the grid, (b) with islanded part of the grid.

Regardless of the reason for the islanding of a part of the power grid containing the electric source and loads, the following undesirable effects may occur:

1. The presence of a severe threat to health and/or the life of power line workers.
2. Damage to load inside the island area.
3. Damage to power grid equipment and infrastructure as a result of insufficient short-circuit power of the energy source.
4. Damage to the converter coupling the RES with the power grid.

Anti-islanding detection is used to prevent this type of situation. In the literature, these methods are classified into passive, active and based on power line communication [12–14]. The first group, called passive methods, is based on the power grid’s nominal limits of voltage and frequency parameters. The main principle is to use elements detecting too high or too low voltage and/or frequency in the power grid, or to calculate the rate of the change of the grid parameters [15–17]. Nevertheless, the electrical parameters in an islanded part of the power grid depend on the power balance between the electrical source and the loads. Maintaining the power grid parameters within the tolerance limits is possible with a low probability. In this case, no islanding detection will occur, and the grid will be energised. When such disconnection occurs, it is perilous to carry out service works on power lines, and power line workers, unaware of the risk, try to reach the conductive parts of the power infrastructure. To eliminate the Non-Detection Zone (NDZ) [18], the authors of many publications have proposed various solutions to introduce some disturbance to the current generated to the power grid [19,20]. The introduction of disturbing signals to the set signals of the converter grid currents forces an inevitable change of the selected parameter. Such activities aimed at detecting island phenomena are classified as active methods.

The parameters ultimately to be changed are the frequency and/or RMS (Root Mean Square) voltage in a separate part of the supply network. The distortion of the current generated to the grid causes the injection of additional components with higher frequencies, apart from the fundamental harmonic of the current, into the grid. As active power is related to the first harmonic, additional components in the current spectrum increase the proportion of reactive power. The NDZ depends on the active and reactive energy balance produced and absorbed by devices (local loads) in islanded part of the supply network. The following equation describes the correlation between the local load parameters and the voltage and frequency in the islanded part of the network [21].

$$\begin{aligned} P_{load} &= 3(U_{GridRMS}^2/R) \\ Q_{load} &= 3(U_{GridRMS}^2/(2\pi fL) - U_{GridRMS}^2 2\pi fC) \end{aligned} \quad (1)$$

When an islanded part of the supply network appears, its substitute parameters R , L and C are considered as constant—see parallel RLC block in Figure 3. Suppose the active and reactive power generated in the converter differs from the load demand for power at

rated voltage parameters ($P_{inv} \neq P_{load}$ and $Q_{inv} \neq Q_{load}$). Then, according to Equation (1), the voltage RMS and frequency f values of $U_{GridRMS}$ must change (Figure 2).

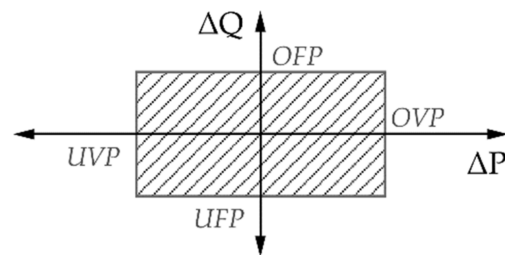


Figure 2. Example of NDZ zone based on monitoring grid's frequency and voltage parameters.

Because we can influence the generated active and reactive power from the converter side, we can shift the operating point lying inside the NDZ zone toward its external borders. When this point is on the border of the NDZ zone area, the appropriate protection against voltage and/or frequency limits will be activated by over/under voltage protection (OVP/UVP) or over/under frequency protection (OFP/UFP). In this way, unintentional islanding operations will be detected.

One of the solutions developed to detect unintentional islanding uses the introduction of additional harmonics to the generated current. Then, based on the presence of these harmonics in the voltage, the impedances for particular frequencies are calculated. The disadvantage of this method is the sensitivity to the parameters of the load in the occurred island. Additional problems may be caused by non-linear control methods of the converter, which are characterised by a variable switching frequency, which may affect the results of the calculated impedances [22,23]. The second example of an active island detection method is a positive feedback method that changes the phase angle of the generated current as a function of frequency. These methods change the frequency in the island part of the power grid to the maximum or minimum frequency value limit. Popular among the literature is the Active Frequency Drift (AFD) method, which uses a unique form of the generated current waveform where, for a fraction of the time of the supply voltage period, the current is 0 [24,25]. However, when there is no island operation, this method reduces the amount of energy fed to the grid and significantly lowers the quality of the generated current (more significant harmonic distortion). The solution to this problem is the use of methods that cause periodic generation of disturbances, which does not eliminate the problem of reducing the amount of energy supplied to the grid during the normal operating state of the power grid [26].

Therefore, an improvement of the detection of the islanding mode in the AFD method can be made. The amount of active energy transferred in detection standby mode can be increased. In addition, it is possible to keep the detection time short and improve the spectrum of the generated current. The authors developed an improved AFD method, which introduces a new type of disturbance to the sinusoidal waveform of the converter current signal. The distorted current signal waveform in the standard AFD method can be divided in the time domain into two parts. The first part contains a sinusoidal waveform with a slightly higher frequency than the network's nominal frequency. As a result, during one period of the mains voltage, the set signal of the mains current of the converter reaches the end of its period slightly earlier than the mains voltage (Figure 4b). The second part of the current waveform is when it goes to zero at the end of its period and is held at zero until the line voltage becomes zero. The proposed method novelty replaces the period when the set current maintains the value zero with the course of the hyperbolic sine function. The article contains a detailed description of the implementation of the proposed solution. The authors present the results of laboratory and simulation tests. The newly proposed type (shape) of the introduced disturbance improves the THD₄₀ coefficient while maintaining the same time of the introduced disturbance. The THD₄₀ is defined as the root mean square

value of the first 40 harmonics of the signal, divided by the RMS value of its fundamental signal [27].

$$\text{THD}_{40} = \text{sqrt}(I_2^2 + I_3^2 + I_4^2 + \dots + I_{40}^2)/I_1 \dots 100\% \quad (2)$$

A detailed description of the AFD methods, standard and proposed, can be found in the following chapters.

2. Description of Three-Phase Standard AFD Method

The original rules of distorting the generated power grid current using the AFD method were related to single-phase systems [28]. However, to switch to the three-phase supply system, it was necessary to slightly modify the control system in which the current distortion is calculated [25]. One of the most important physical quantities in the control system presented in Figure 3 is the phase angle ϑ_{eu} signal of the voltage vector of the supply network.

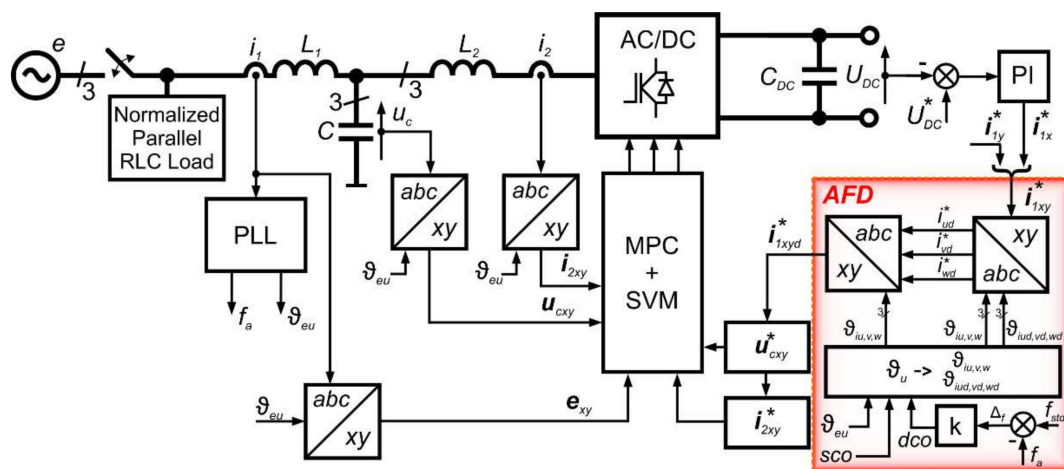


Figure 3. Block diagram of the voltage converter control system with implemented an anti-islanding function.

This signal is calculated in the Phase-Locked Loop block (PLL). It is used to convert the three-phase signals into a vector placed on a plane of the rotating reference frame aligned with power grid voltage vector (and vice versa). Moreover, it is used in the block that distorts the set current vector i_{1xy}^* of the AC/DC converter. In a separate part of the diagram marked AFD, based on information about the phase voltage vector angle ϑ_{eu} , phase angles $\vartheta_{iu,v,w}$ of the grid current waveforms i_1 are generated.

$$\begin{aligned}\vartheta_{iu}(t) &= \vartheta_{eu}(t) \\ \vartheta_{iv}(t) &= \vartheta_{eu}(t) - 2\pi/3 \\ \vartheta_{iw}(t) &= \vartheta_{eu}(t) + 2\pi/3\end{aligned}\tag{3}$$

It is assumed that the range of changes of the angles $\theta_{iu,v,w}$ is normalised within the limits of 0.2π . The calculation of phase angles used to generate the distorted waveforms for the anti-islanding function requires additional input parameters: the static coefficient (*sco*) and dynamic coefficient (*dco*). The *sco* parameter is equivalent to the chopping fraction (*cf*) in the original description of the AFD method. It is a coefficient related to the time the grid current waveform remains at the value 0 (see Figure 4b) in a static state, i.e., no island operation occurs. The static coefficient is assumed to be constant. On the other hand, the value of the dynamic coefficient depends on the product of the gain k , and the difference between the rated value of the grid frequency f_{rtd} and the actual value of the grid voltage frequency f_a .

$$dco = k \cdot (f_{rtd} - f_a) \quad (4)$$

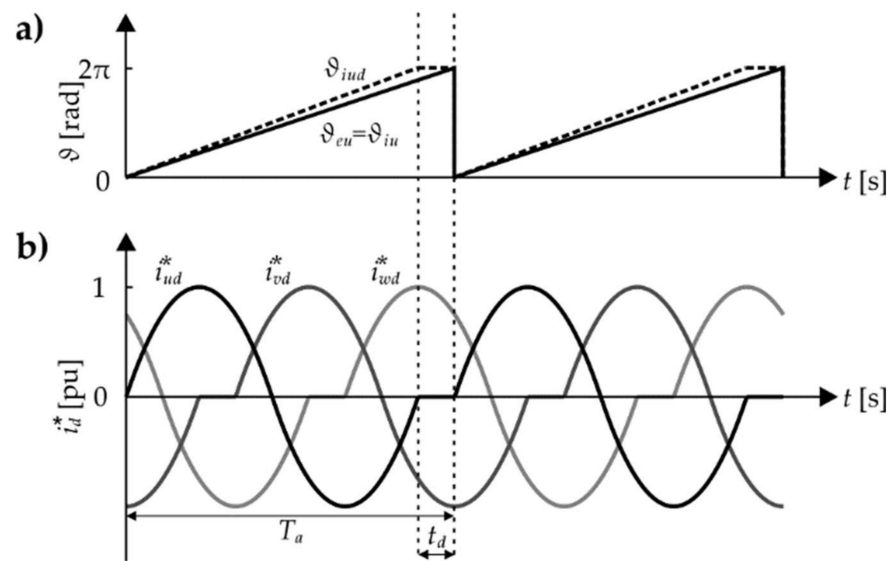


Figure 4. Waveforms in the standard AFD method: (a) phase angles, (b) distorted phase currents.

Thus, the frequency f_{acc} of the accelerated sinusoidal part of the waveform in Figure 4b is equal:

$$f_{acc} = f_a + sco + dco. \quad (5)$$

The auxiliary angles $\vartheta_{iud, vd, wd}$ used to generate the set signals of the distorted grid currents $i_{1ud, vd, wd}$ in the discrete form were calculated using Equation (6) for each of the phases, respectively.

$$\begin{aligned} \vartheta_{iud}(t) &= 0 & \text{for } \vartheta_{iu}(t) &= 0 \\ \vartheta_{iud}(t) &= \vartheta_{iud}(t - T_s) + 2\pi f_{acc} T_s & \text{for } \vartheta_{iu}(t) < 2\pi \end{aligned} \quad (6)$$

Then, the signals of the distorted set currents in the natural three-phase system i_{ud}^* , i_{vd}^* , i_{wd}^* were calculated considering the set values of the i_{1xy}^* vector.

$$\begin{aligned} i_{ud}^*(t) &= i_{1x}^* \cdot \sin(\vartheta_{iud}(t)) + i_{1y}^* \cdot \cos(\vartheta_{iud}(t)) \\ i_{vd}^*(t) &= i_{1x}^* \cdot \sin(\vartheta_{ivd}(t)) + i_{1y}^* \cdot \cos(\vartheta_{ivd}(t)) \\ i_{wd}^*(t) &= i_{1x}^* \cdot \sin(\vartheta_{iwd}(t)) + i_{1y}^* \cdot \cos(\vartheta_{iwd}(t)) \end{aligned} \quad (7)$$

The distorted waveforms of the setpoint currents i_{ud}^* , i_{vd}^* , i_{wd}^* were converted into a rotating reference frame xy aligned with the network voltage vector.

$$\begin{aligned} i_{1xd}^* &= 2/3(i_{ud}^* \cdot \sin(\vartheta_{iu}) + i_{vd}^* \cdot \sin(\vartheta_{iv}) + i_{wd}^* \cdot \sin(\vartheta_{iw})) \\ i_{1yd}^* &= 2/3(i_{ud}^* \cdot \cos(\vartheta_{iu}) + i_{vd}^* \cdot \cos(\vartheta_{iv}) + i_{wd}^* \cdot \cos(\vartheta_{iw})) \end{aligned} \quad (8)$$

The vector i_{1xyd}^* determined according to the above equations is the set value at the input of the predictive grid current control system.

3. Description of the Proposed Method

The proposed Active Frequency Drift Hyperbolic Sine method (AFDhs) is based on the same block diagram of the converter control system as the standard AFD method (Figure 3). The main difference is in the block of generating the grid current distortion. The sinusoidal part is proposed to be computed from the angle signal calculated according to Equations (6)–(8) using f_{acc} calculated in Equation (9).

$$f_{acc} = f_a + (sco + dco)/2 \quad (9)$$

The comparison of Equations (5) and (9) shows that the AFDhs method increases the frequency of the sinusoidal part of the waveform by twice the value of the sum of the static and dynamic coefficients. When we apply the same disturbance time t_d to compare the methods, we can see that the set current signal reaches zero at the beginning of the period t_d in Figure 4b, illustrating the standard AFD method. On the other hand, in the proposed method (Figure 5b), at the beginning of the period t_d , the value of the converter current signal is different from zero.

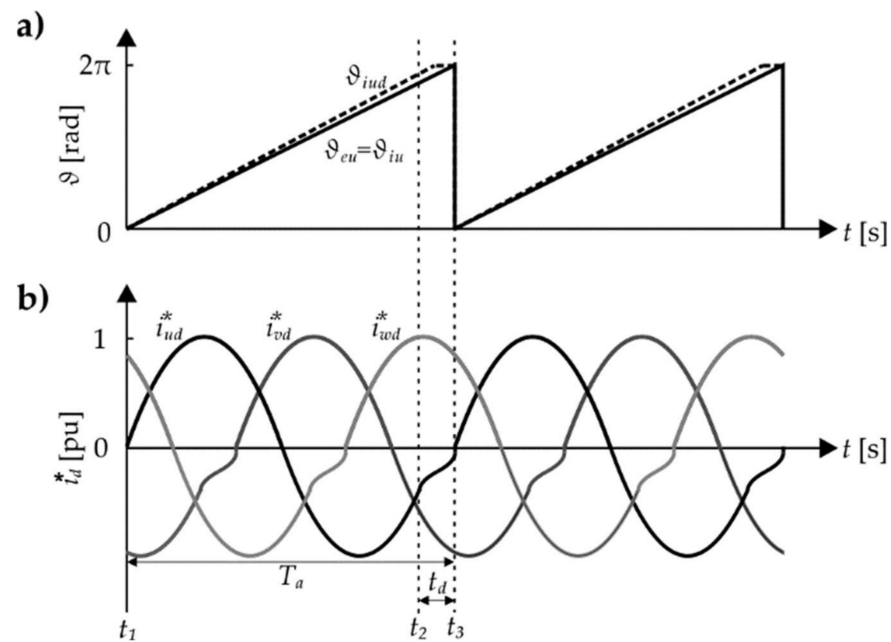


Figure 5. Waveforms in the AFDhs method: (a) phase angles, (b) distorted phase currents.

As mentioned earlier, at time t_2 (Figure 5b), the sinusoidal waveform did not reach the value of 0. It should be emphasised that the phase angle ϑ_{iu} at this point did not reach the value of 2π (Figure 5a). The moment t_2 , when the sinusoidal part of the waveform should be finished, depends on the value of the angle ϑ_{iu} . It has been proposed that the moment of time t_2 is when the angle ϑ_{iu} reaches the following value:

$$\vartheta_{iu} = 2\pi - \pi f_a / (f_a + (sco + dco)) \quad (10)$$

When the phase angle signal satisfies Equation (10), the last value of the set current signal $i_{ud}(t_2)$ is stored. The hyperbolic sine function requires an argument x . Its argument varies linearly from $-x$ to x over time from t_2 to t_3 . The $\sinh$ function for both arguments $-x$ and x is not the same as the value of $i_{ud}^*(t_2)$. Thus, it is required to scale the value of the $\sinh$ function at time t_2 by the factor m to maintain the continuity of the generated waveform i_{ud}^* .

$$m = -i_{ud}(t_2) / \sinh(x) \quad (11)$$

Necessary for further calculations is the value of the $i_{ud}^*(t_2)$ signal and the number of iterations of the control algorithm n that will be performed in the time range from t_2 to t_3 . The number n was related to the time between iterations of the algorithm (in a real digital system, it is the sampling time T_s) and was defined as follows:

$$n = (2\pi - \vartheta_{iu}(t_2)) / (2\pi \cdot T_s) \cdot (1/f_a) \quad (12)$$

Summarising the above, the waveform of the i_{ud}^* signal is the result of the following function:

$$\begin{aligned} i_{ud}^*(t) &= i_{1x}^* \cdot \sin(\vartheta_{iud}(t)) + i_{1y}^* \cdot \cos(\vartheta_{iud}(t)) & \text{for } t_1 \leq t \leq t_2 \\ i_{ud}^*(t) &= m \cdot (\sinh(-x + x_{step}(t)) / 2 + \sinh(-x) / 2) & \text{for } t_2 < t < t_3 \\ x_{step}(t) &= 0 & \text{for } t_1 \leq t \leq t_2 \\ x_{step}(t) &= x_{step}(t - T_s) + 2x/n & \text{for } t_2 < t < t_3 \end{aligned} \quad (13)$$

Quantity $x_{step}(t)$ increments the domain of the $\sinh$ function. It increases, in accordance with the equations above, and causes a transition from $-x$ to x in the domain of the $\sinh$ function at the time between t_2 and t_3 in n steps.

4. Simulation and Experimental Verification

The method of determining the sinusoidal part of the waveforms of both methods is based on different signals of phase angles ϑ_{iud} . The AFD method uses the angle calculated from Equations (5) and (6), while the AFDhs method also calculates phase angle from Equation (6), but uses f_{acc} calculated in Equation (9). They show that the difference between the voltage phase angle ϑ_{eu} and the distorted current angle ϑ_{iud} in the AFD method is twice as significant as in the AFDhs method. Primarily, the sinusoidal part defines the first harmonic of the current i_{ud}^* and determines the phase shift angle with respect to the grid voltage e_u . This part also directly affects the ability of the algorithm to detect an island state [13,15]. The comparison of the proposed method with the standard method should base on the same f_{acc} value. The result is that the distortion time t_d in the AFDhs method must be twice as long.

Contrary to the literature cited earlier, the islanding detection problem analysis uses a two-level AC/DC converter coupled with the grid through the LCL filter. The transistors are controlled by the SVM predictive method (Space Vector Modulation). The method used was described in detail by the authors of [29]. It is a non-linear method [30] belonging to the group of methods with a Continuous Control Set of output voltage vectors based on Model Predictive Control (CCS-MPC). The simulation tests reflected the discrete nature of the microcontroller-based converter. These tests were performed in the Matlab/Simulink environment. Similar to the laboratory tests, they were performed following the scheme in Figure 3. The most critical parameters of the analysed circuit are presented in Table 1.

Table 1. System parameters for the simulation and laboratory tests.

Parameter	Value
Parallel RLC load (values per phase)	$R = 32 \text{ } (\Omega)$
	$L = 100 \text{ (mH)}$
	$C = 100 \text{ } (\mu\text{F})$
	$Q_f = 1 \text{ (-)}$
Normal frequency range	$49.5 < f_a < 50.5 \text{ (Hz)}$
Normal voltage phase range	$207 < U_{GridRMS} < 253 \text{ (V)}$
Nominal grid parameters	$230/400 \text{ (V)}, 50 \text{ (Hz)}$
DC link voltage	640 (V)
Grid side inductance L_1	1.83 (mH)
Converter side inductance L_2	4.57 (mH)
Grid filter capacitance C	$10 \text{ } (\mu\text{F})$
Sampling time T_s	$200 \text{ } (\mu\text{s})$
Modulation frequency	5 (kHz)

The waveforms of set grid current i_{ud}^* were generated using the simulation model for the standard AFD method (Figure 6a) and the proposed AFDhs method (Figure 7a).

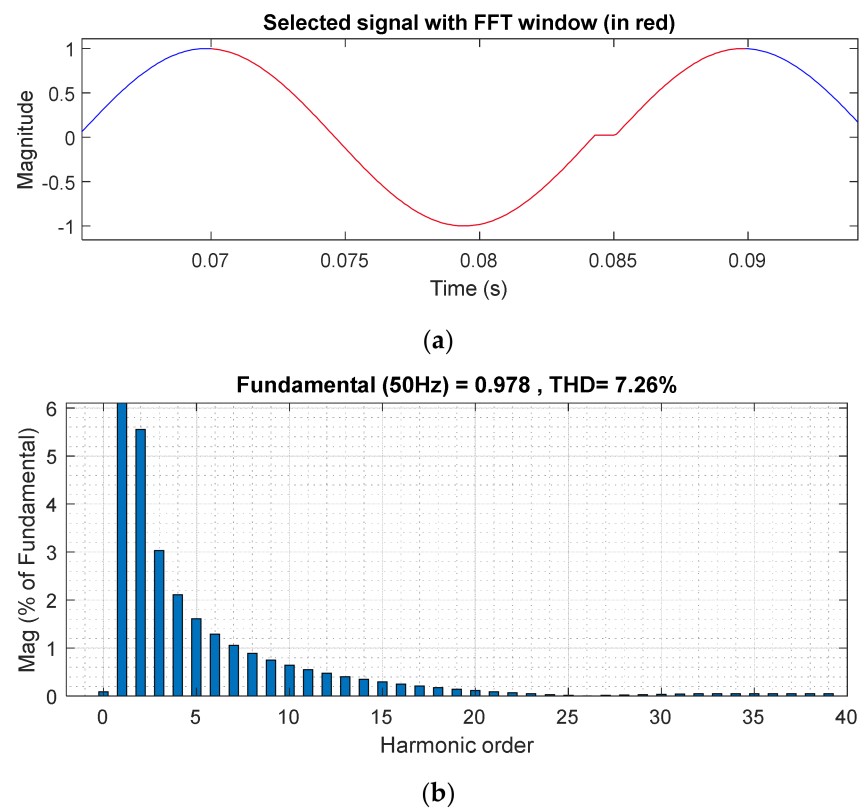


Figure 6. The result of the simulation of the AFD method ($f_{acc} = 2$): (a) waveforms of the set converter current signal on the AC side, (b) harmonic analysis of the waveform shown in (a).

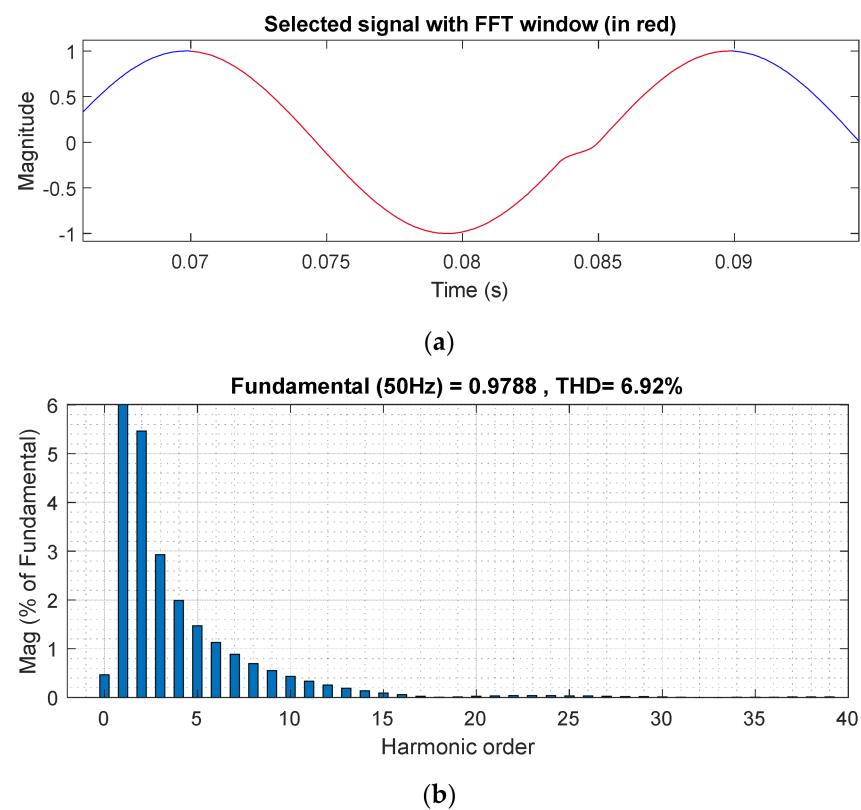
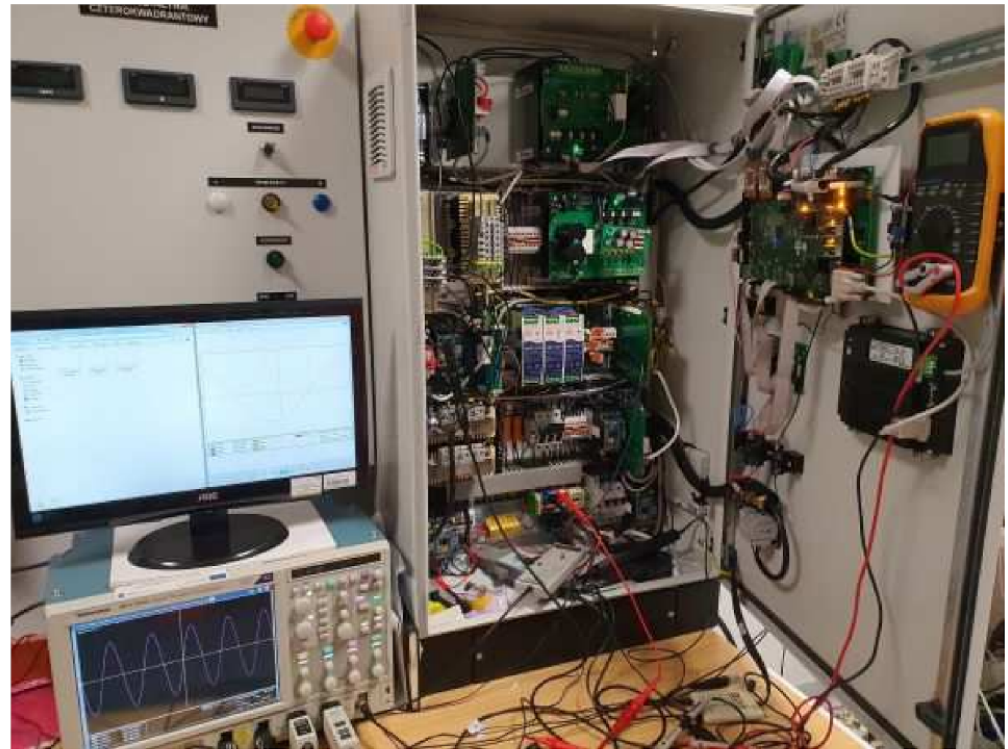


Figure 7. The result of the simulation of the AFDhs method ($f_{acc} = 2$, $x = 2$): (a) waveforms of the set converter current signal on the AC side, (b) harmonic analysis of the waveform shown in (a).

Subsequently, laboratory tests were performed. The control algorithm was created in C++ and loaded into microprocessor Analog Devices ADSP-21369. The microprocessor is supposed to gather all signals from the voltage and current transducers, and compute the duty cycles for each phase. The generation of gate pulses for the transistors in a two-level AC/DC converter was executed in Spartan XC3S400 FPGA. The tested system (Figure 8) was powered by an arbitrary power source California MX30-3Pi. The presented time courses were recorded on Tektronix DPO7054C oscilloscope and Yokogawa WT1800 power analyser. A set of photos showing the components of the laboratory circuit is presented below.



(a)



(b)

Figure 8. Elements of the laboratory examination circuit: (a) two-level AC/DC voltage converter with an LCL filter, (b) parallel RLC load.

Contrary to the simulation studies, the ability of the algorithms to detect the islanding operation was tested. The oscilloscope trigger point was tied to the opening time of the main contactor contacts. It was marked on the oscillograms with a vertical line with the symbol t_0 . The threshold of anti-islanding protection chosen for this study was $49 < f < 51$ (Hz).

5. Discussion

The simulation results are presented in Figures 6 and 7. Their comparison allows us to obtain the following conclusions:

1. The AFD method was characterised by a 4.91%-higher THD₄₀ coefficient of the generated current waveform compared to the harmonic distortion of generated current in the AFDhs method.
2. The spectrum of the current signal in the AFDhs method had a different distribution of individual components. In the AFD method, the amplitudes of successive harmonics (from 1 to 26) decreased. The first local minimum amplitude had the 26th harmonic. The harmonic amplitudes 26–40 grew higher. However, in the AFDhs method, the first local minimum was on the 18th harmonic. Higher-order harmonics (18–40) had lower amplitudes compared to the signal spectrum of the AFD method.
3. The AFDhs method generated a distorted current with a slightly higher RMS value.

The tests performed in the laboratory (results in Figures 9–11) show that the current generated by the AFDhs method, in the grid-connected mode, had a lower value of the THD₄₀ coefficient. Regarding the generated current harmonic distortion, without the activated islanding detection function (Figure 9), the methods were characterised by successive THD₄₀ values higher by 57.25% and 47.4%, respectively, for the AFD and AFDhs methods.

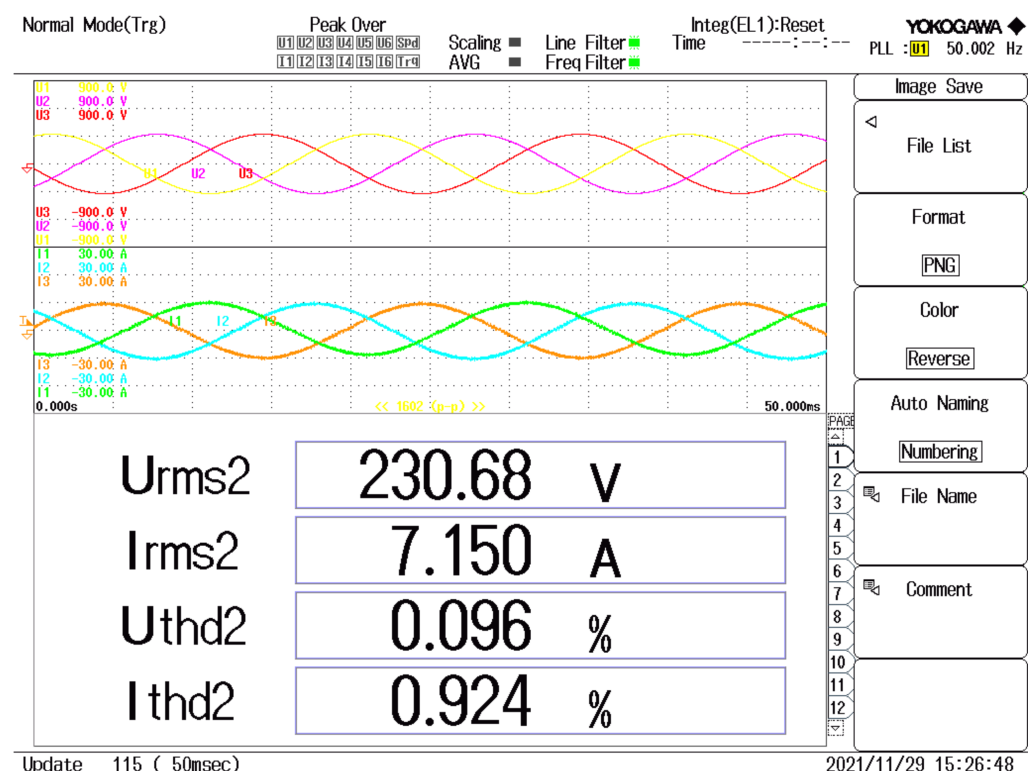
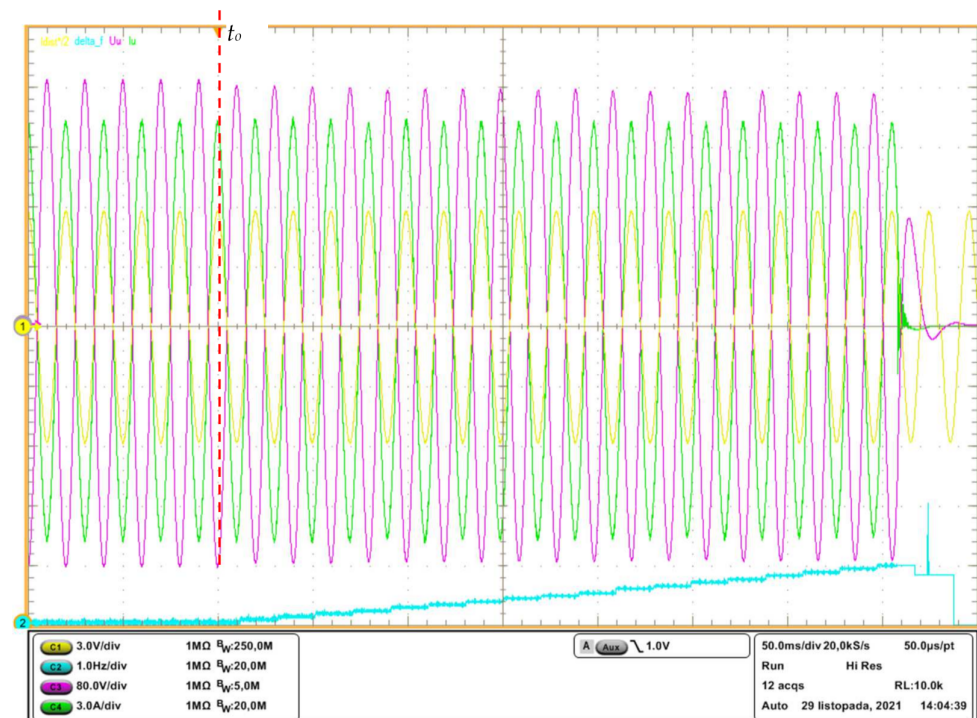


Figure 9. The network voltage and current THD₄₀ values measured by the power analyser in normal operation without implementing the anti-islanding method.

Figures 6b and 7b show the spectra of the set current signals. The proposed method was characterised by a more advantageous spectrum of the generated current, a reduced number of disturbances in the form of higher harmonics introduced to the supply network,

the same efficiency in terms of island detection time and a slightly larger amount of active energy transferred in the grid-connected mode.



(a)

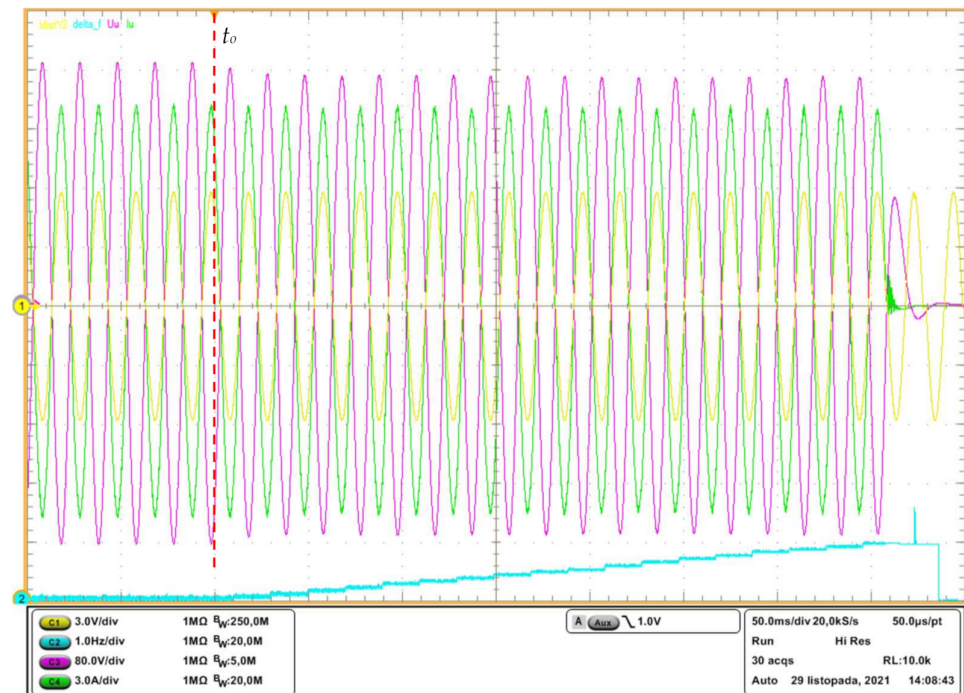
U_{rms2}	230.67	V
I_{rms2}	7.185	A
U_{thd2}	0.089	%
I_{thd2}	1.453	%

(b)

Figure 10. Island operation state detection by the AFD method ($sco = 0.5$, $dco = 2$): (a) waveforms of the grid voltage (magenta), grid current (green), 0.5*reference grid current (yellow) and frequency delta $f_a - f_{rtd}$ (blue). (b) The network voltage and current THD₄₀ values measured by the power analyser in normal operation (grid-connected).

Figures 10 and 11 show the oscillograms containing the waveforms of the grid voltage (magenta), grid current (green), reference grid current (yellow) and frequency delta $f_a - f_{rtd}$ (blue). The opening time of the grid contactor contacts, which disconnects the power supply from the voltage converter and the local load, is marked with the black dashed line. Before the contacts of the grid contactor are opened, the current fed into the network is slightly distorted. In the AFD method in standby mode, the THD₄₀ coefficient was 1.362% for the AFDhs method, while the generated current without active anti-islanding protection had a THD₄₀ of 0.924%. At the moment of disconnecting from the power grid, the frequency value increased due to the operation of algorithms protecting against unintentional islanding operation. Along with the increase of the distortion time related to the frequency delta, the value of the $U_{GridRMS}$ voltage in the separated circuit slightly decreased during the detection process, despite the constant value of the reference current (yellow wave). The lower value of the voltage in the islanded network results from the current control mode of

the converter [29]. The voltage in the network is not a regulated quantity. The parameters of the local load do not change during island operation state detection. Increasing the proportion of the deformed part of the generated current waveform causes a reduction in the output of active power. Thus, according to Equation (1), a voltage drop in the network occurs. When the active power decreases, the share of reactive power increases, which, referring to Equation (1), causes the frequency to change.



(a)

Urms2	230.68	V
Irms2	7.195	A
Uthd2	0.093	%
Ithd2	1.362	%

(b)

Figure 11. Island operation state detection by the AFDhs method ($sco = 1$, $dco = 2$, $x = 2.5$): (a) waveforms of the grid voltage (magenta), grid current (green), $0.5 \times$ reference grid current (yellow) and frequency delta $f_a - f_{rtd}$ (blue). (b) The network voltage and current THD₄₀ values measured by the power analyzer in normal operation (grid-connected).

In the assumptions for the research, it was decided to keep the same distortion time t_d for both compared methods. This assumption was to ensure the same proportion of active and reactive power transferred to the supply network during the operation of the converter with the connected power grid. After implementing a new type of disturbance, the converter mains current had a better spectrum than when using the distortion of the standard AFD method. The detection time for both methods was very similar. The standard AFD method and the proposed AFDhs detected the island operating state in approximately 360 ms.

It is worth noting that the generated current was smooth. The ripples of the current associated with switching transistors were invisible. High current quality is ensured by the

applied predictive-SVM control method, which perfectly mimics the set current despite using an LCL filter. This method effectively suppresses the resonance harmonics related to the inductances and capacitance of the converter input filter. It perfectly reproduces the complicated shape of the set current resulting from applying the anti-islanding algorithm. Using the predictive-SVM method is an additional advantage of the presented article, as it is an innovative approach to test anti-islanding methods. Earlier publications on islanding operation have presented results in circuits with a voltage converter connected to the network through a more straightforward and much less effective L-type filter.

6. Conclusions

Based on the results of the tests it can be concluded that the goals set for the new method in the introduction were achieved. Laboratory tests confirmed that it is possible to maintain the unintentional islanding detection efficiency of the standard AFD method using the proposed AFDhs method. The modified method generates the sinusoidal part of the set current waveform i_1^* with a frequency closer to the mains voltage frequency than the standard method. Therefore, it increases the share of the first harmonic of the current, i.e., in the standby mode, more active power is fed into the network. However, two goals were achieved due to the more favourable current spectrum. First, it improved the overall quality of the voltage in the network. Second, it reduced the THD₄₀ factor for the same disturbance time, which allowed us to achieve the maximum allowable THD₄₀ value of the current generated to the network when injecting more disturbance (longer time t_d). Thus, the proposed method allows increasing the current distortion to shorten the island detection time while meeting the requirements of the maximum current THD for voltage converters connected to the power grid.

In the future, research will focus on developing new island detection methods, combining the minimization of introduced disturbances and observing the sensitivity of the phase synchronization loops to these disturbances.

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