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Models of disturbances in power networks for testing frequency methods used in measurements of power quality

Streszczenie. *W artykule przedstawiono systematykę zakłóceń, pojawiających się w sieci elektroenergetycznej związanych z niskoczęstotliwościowymi zaburzeniami przewodzonymi, do których należą zakłócenia związane z jakością energii elektrycznej. Zaprezentowano również propozycję bazy sygnałów testowych będących pomocnych w badaniach nowych, alternatywnych do DFT, metod częstotliwościowych przetwarzania sygnałów, koniecznych do obliczeń niektórych parametrów jakości energii elektrycznej. (**Modele zakłóceń w sieci elektroenergetycznej z uwzględnieniem pomiarów jakości energii**).*

Abstract. This article presents the systematics of disturbances occurring in power networks, connected with low frequency conducted disturbances including disturbances related to the quality of electrical power. It also provides a proposal of test signals basis that may be useful in testing new, alternative frequency methods of signal processing, necessary for calculation of some parameters of power quality.

Słowa kluczowe: jakość energii elektrycznej, systematyka zakłóceń, modele testowe zakłóceń.
Keywords: Power quality, systematics of disturbances, testing models of disturbances.

Introduction

Recently, the increased development of measuring tools for test and analysis of electrical power quality has been observed. The tools include both measuring equipment and methods of signal analysis. In such measuring systems, time analysis (e.g. for calculation of voltage deviations) and frequency analysis (e.g. for calculation of THD parameter) are used as main analyses. Most frequency analyses use discrete Fourier transform (DFT). However, that analysis provides incorrect results for testing e.g. transient overvoltages. Therefore, as an alternative to DFT, scientists search for other analyses that could guarantee proper measurement of such types of disturbances.

Adaptation of various methods of signal analysis for the purpose of calculating power quality parameters requires determination of the basis for test signals that shall make it possible to thoroughly test the suitability of the new method. In practice, the method uses several signals which model the most frequent disturbances in power network [1], [2]. This article presents the complex systematics of disturbances occurring in power networks and the proposal of signals that model these disturbances and that may be helpful in testing frequency methods. The classification of disturbances with regard to correlation of their occurrence with the power frequency is also proposed.

Classification of disturbances in power networks

The problems of power quality mostly concern galvanic-induced low frequency disturbances. There are many classifications and systematics of disturbances [3]. Fig. 1 classifies disturbances with regard to their character, as: sustained (e.g. long-term voltage increase) or transient (e.g. voltage dip).

Time of low frequency disturbances spans from several or several dozens microseconds (transient disturbances) to times above single seconds or minutes (sustained disturbances). Occurrence of fast transients in power network triggers the risk of instability of thyristor-controlled systems (inverters), whereas occurrence of long sustained disturbances can damage input circuits due to high disturbance power.

Frequency methods in disturbances measurements

Detection and parametrisation of disturbances presented in fig. 1 is made using the combination of time and frequency methods (at present, works aiming at application of time and frequency methods have also been conducted [3], [4]). Determination of parts of disturbance parameters imposes the use of frequency methods. Such disturbances are constituted by harmonics and interharmonics. The most frequent method is the DFT method (especially its FFT computational variation), yet, due to its faults, other methods (e.g. Prony's transform which proves very useful in testing interharmonics [5]) are now examined.
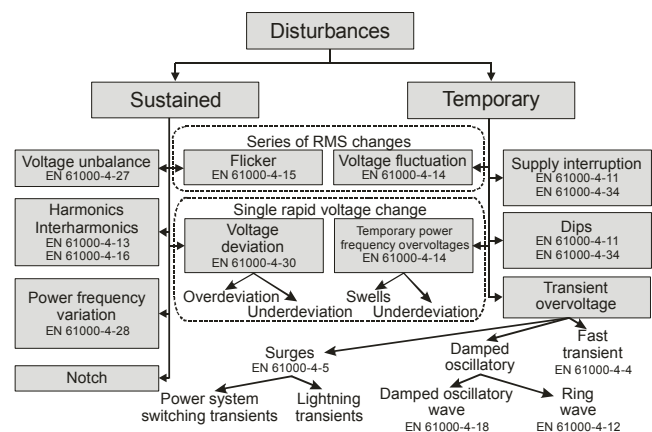

Fig. 1. Classification of disturbances in power networks.

Frequency methods allow to detect and parameterise other relatively long disturbances. Depending on the calculation accuracy required, some of these disturbances, e.g. variability of power frequency, can be determined with the use of other simple or complex algorithms [6]. Simple disturbances, such as voltage deviations or power stoppage, are calculated mainly on the basis of tracing the temporary RMS voltage value, which is why the frequency methods are not applied here.

In case of complex disturbances, such as notch-type disturbances or transient overvoltages, frequency analysis provides additional data (e.g. information about the frequency of disturbance oscillation in case of damped oscillatory waves overvoltages), in comparison to time analysis.

In case of disturbances connected with flicker, i.e. a special phenomenon of series of RMS changes, determination of short-term and long-term flicker coefficient (P_{st} and P_{lt}, respectively) is made on the basis of special computational methods described in standard [21].

Disturbances correlated or not correlated with fundamental harmonic of power waveform

Disturbances that should be parameterised in frequency analysis can be divided into two subgroups. The division accounts for their correlation with fundamental frequency of waveform:

- disturbances not correlated with power network,
- disturbances correlated with power network.

The first group comprises asynchronous disturbances whose character and frequency of occurrence do not depend on fundamental frequency of the disturbed power waveform. These mostly comprise very short transient overvoltages. Such disturbances are related to the capacitors banks switching, active protection or atmospheric discharge.

The second group is made of disturbances that modify the spectrum in correlation with fundamental component. These disturbances include:

- harmonics and interharmonics (and subharmonics in particular),
- notch-type disturbances,
- power frequency variations.

Harmonics, interharmonics and subharmonics are generated by non-linear loads that can rapidly change the uptake of power within time that is shorter than one sinusoidal cycle of supply voltage. Deformed current causes deformed voltage losses on network impedances that are proportional both to the current value and harmonic frequency.

Harmonic voltage according to [15] is sinusoidal voltage whose frequency equals total multiplicity of the fundamental frequency of supply voltage.

Interharmonic voltages are sinusoidal voltages with the frequency between harmonics [15].

Interharmonics are generated by static frequency inverters, cycloconverters used for powering low-speed motors. Some induction motors with irregular port generate several harmonic frequencies of angular frequency.

Subharmonics are special cases of inteharmonics with lower frequencies than the values of fundamental harmonic.

Notch-type disturbances, comprising short voltage drops - voltage collapses [7], - occur mainly during commutation of thyristors in bridge rectifiers.

Modulation of power frequency results from the significant increase of generator's load. Frequency variations (frequency gets lower with the increase in power) are compensated by activation of available reserves of generated power. If the frequency is still falling, successive power drops are perpetrated, and in case of frequency falling to ca. 47.5 Hz, the generator is switched out of the system and operates in isolation [7].

Electronic devices should be able to resist frequency variations of ±4 % lasting up to 10 minutes. Frequency drop affects increase in working temperature of transformers with saturated cores. Additionally, higher and uneven harmonics are generated in transformer's current.

General guidelines for testing measuring systems of electrical power quality

Basic parameters of test signals for testing measuring systems of power quality have been presented in standard [24]. The standard also covers the scope of modification of individual quality parameters of electrical power and waveform parameters on the basis of which the estimation of their effect on the accuracy of measuring system can be calculated.

Below, for information purposes, it has been presented the procedure of testing measuring systems of power quality indicators. The successive steps of the procedure are presented in fig. 2. Table 1 provides important definitions of values used in [24].

The procedure starts with defining tested value whose accuracy of measurement should not decrease in the function of declared input voltage U_{din} variations and variations in other parameters of test signal ("scope of variations in values affecting the measurement"). The notion of "scope of variations in values affecting the measurement" has been defined in [24] with the purpose to estimate the maximum value of changes in other parameters at which the result of measurement of the tested parameters should not exceed the permissible values determined by the measurement uncertainty.

Tables 2 and 3 present measurement uncertainty values for individual parameters and ranges of value variations affecting the measurement.

Table 1 Important definitions [24].

Designation	Parameter	Definition
U_N	Rated voltage	As per standard [24]: 115 V, 230 V, 400 V
U_c	Declared supply voltage	Declared supply voltage U_c is normally the nominal voltage U_N of the system. If by agreement between the supplier and the customer a voltage different from the nominal voltage is applied to the terminal, then this voltage is the declared supply voltage U_c.
U_m		Component with the frequency of f_m of measured supply voltage
U_{din}	Declared input voltage	Value obtained from the declared supply voltage by a transducer ratio.

Table 2 Range of influence quantities in 50 Hz systems for class A performance [24]

Parameter	Measurement uncertainty	Range of variation
Frequency	± 10 mHz	42.5 Hz – 57.5 Hz
Voltage magnitude	± 0.1 % U_{din}	10 % - 200 % U_{din}
Flicker	EN 61000-4-15	0 – 20 P_{st}
Harmonics	EN 61000-4-7, class I	200 % values as in EN 61000-2-4 class 3
Interharmonics	EN 61000-4-7, class I	200 % values as in EN 61000-2-4 class 3
Transients	-	6 kV peak
Fast transients	-	4 kV peak

The second stage consists in selecting 5 equally spaced values of the tested parameter within the range of variations affecting the measurements, taking into account limit values, e.g. when testing the RMS voltage, the values of 10 %, 45 %, 80 %, 115 % and 150 % U_{din} are selected.

Next, keeping the conditions of other parameters in the so-called test condition 1 (table 4), the accuracy of RMS value measurement is evaluated for the 5 values mentioned above.

After evaluation, the measurement conditions are worsened by increasing the part of other parameters in the tested signal (test condition 2) and the measurement uncertainty is redetermined for the tested value.

Finally, the same procedure is carried out for state 3, which is the worst of all states.

The result of measurement of tested parameters during the abovementioned tests should be included in the uncertainty range given in tables 2 and 3.

Accuracy of harmonics measurement for class A:

- $U_m \geq 1\%$ U_N equals: 5 % U_m,
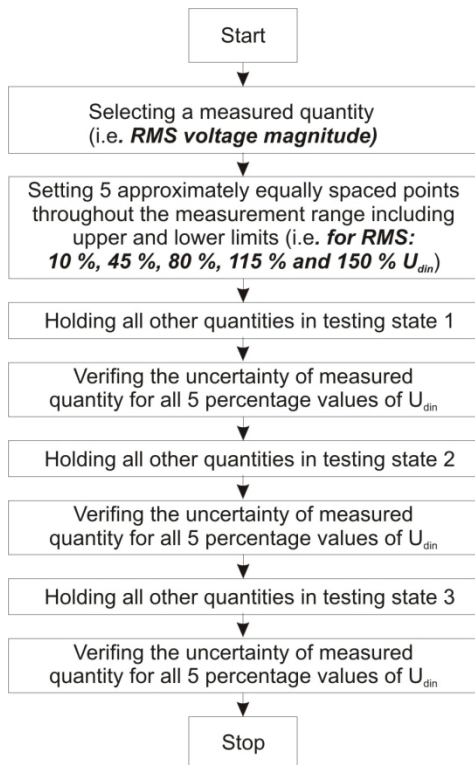- $U_m < 1\%$ U_N equals: 0.05% U_N.

Fig. 2. Testing procedure of power quality measuring systems according to [24].

Table 3 Permissible values of individual harmonics for EMC class 3 [16].

Line h	Value	Line	Value	Line	Value
5	8	3	6	2	3
7	7	9	2.5	4	1.5
11	5	15	2	6	1
13	4.5	21	1.75	8	1
17	4	>21	1	10	1
19	4			>10	1
23	3.5				
25	3.5				
>25	5 + sqrt(11/h)				

Models of test signals for testing devices sensitivity to disturbances that are not correlated with fundamental frequency of waveform

Disturbances that are not correlated with fundamental frequency of waveform are mostly connected with transient disturbances in the form of transient overvoltages (fig. 1). To model the disturbances, the parameters and shapes of disturbances, given in appropriate standards for electromagnetic compatibility [17], [18], [19], [22], and tests of power quality measuring systems can be used.

Transient type of disturbances models are presented in figs. 3 - 7. In Fig. 3, the test signal imitating fast transients related to load switch (stoppage of power in induction-type receivers, oscillating transmitter contacts) is shown [17]. Fig. 4 presents the model of voltage surge resulting from atmospheric discharge (signal 1.2/50 µs [13], [14], [18]). Disturbances of attenuated sinusoids type (ring wave), occurring very frequently in real power networks, have been modelled in figs. 5 [19] and 6 [22]. The models are of similar shape with the main difference marking the frequency of

attenuated sinusoids as 100 kHz for the first and 1 MHz for the second one.

Table 4. States for testing uncertainty for class A performance [24]

Parameter	Test condition 1	Test condition 2	Test condition 3
Frequency	$F_{nom} \pm 0.5$ Hz	$F_{nom} - 1$ Hz $\pm$ 0.5 Hz	$F_{nom} + 1$ Hz $\pm$ 0.5 Hz
Voltage magnitude	$U_{din} \pm 1\%$	Determined by flicker, unbalance, harmonics, interharmonics (below)	Determined by flicker, unbalance, harmonics, interharmonics (below)
Harmonics	0 % to 3 % U_{din}	10 % $\pm$ 3 % U_{din} 3 at 0º 5 % $\pm$ 3 % U_{din} 5 at 0º 5 % $\pm$ 3 % U_{din} 29 at 0º	10 % $\pm$ 3 % U_{din} 7 at 180º 5 % $\pm$ 3 % U_{din} 13 at 0º 5 % $\pm$ 3 % U_{din} 25 at 0º
Interharmonics	0 % to 0.5 % U_{din}	1 % $\pm$ 0.5 % U_{din} at 7.5 f_{nom}	1 % $\pm$ 0.5 % U_{din} at 3.5 f_{nom}

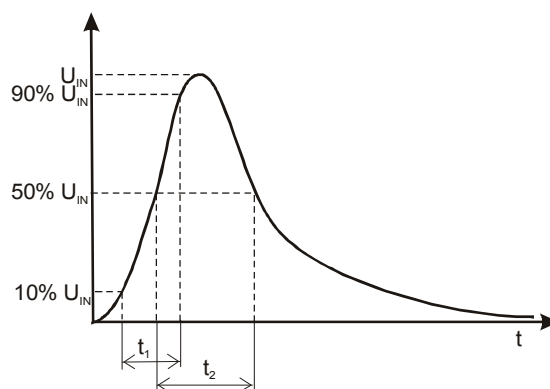

Fig. 3. Model of disturbance signal with fast transients. U_{in} = 0.25 - 4kV, t_1 = 5 ns, t_2=50 ns.
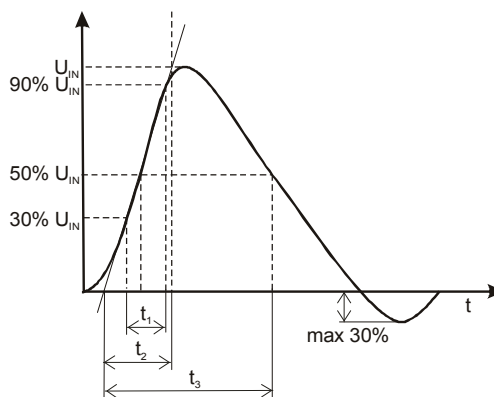

Fig. 4. Model of disturbance signal with surges (atmospheric discharge) U_{in} = 0.25 – 4 kV, t_1 = 0.71 µs, t_2=1.2 µs, t_3=50 µs.
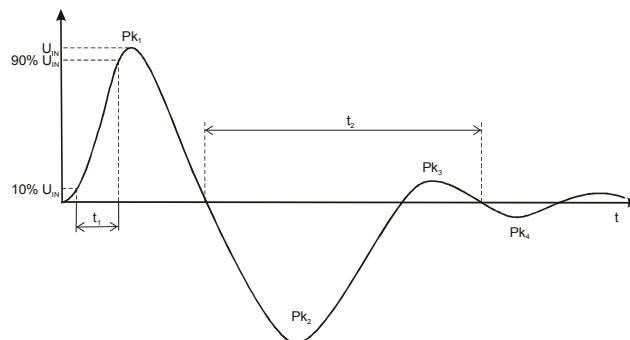

Fig. 5. Model of disturbance signal with attenuated oscillation forms. U_{in} = 0.25 – 4 kV, t_1 = 0.5 µs, t_2=10 µs, Pk_2= 110 %– 40 % Pk_1.
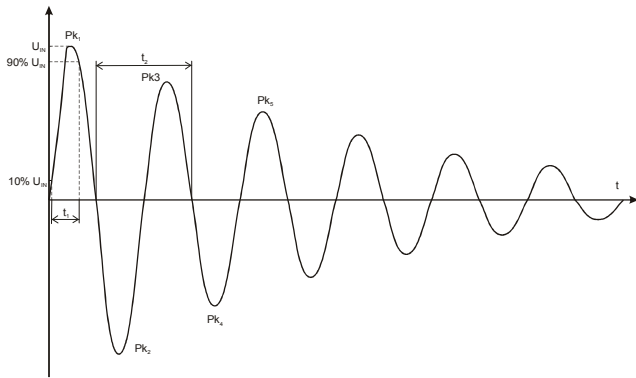
Fig. 6. Model of disturbance signal with attenuated sinusoidal forms (ring wave). U_{in} = 0.25 – 2 kV, t_1 = 75 ns, t_2=1 µs, Pk_5 > 50 % Pk_1, Pk_{10} < 50 % Pk_1.

Application of time analyses allows to determine time parameters that define e.g. rise rate of the edge t_1 or time after which the disturbance reaches half of its value t_2. Frequency analysis permits determination of the disturbance character as oscillatory or non-oscillatory.

Fig. 7 presents the way of adding the abovementioned disturbances to fundamental component of waveform. Parameters have been obtained from [17].
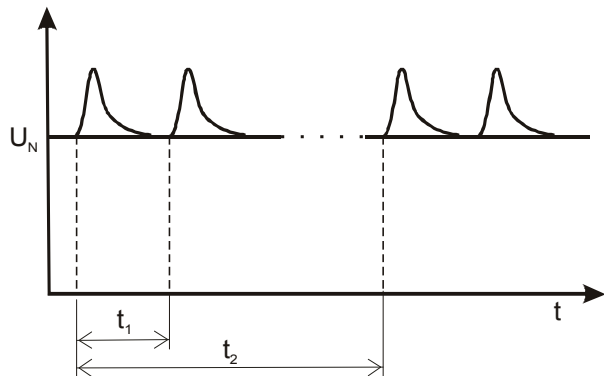

Fig. 7. Way of arranging the transient overvoltage models in signals with fundamental component. t_1 = 0.75 ms, t_2 = 300 ms.

Models of test signals for testing devices sensitivity to disturbances correlated with power network.

The model of disturbances for testing the response of the tool to the content of individual harmonics has been demonstrated in fig. 8. In the model, successive harmonics are added to the fundamental harmonic whose effective value is maintained at the constant, rated level for the entire time of measurements. The model is based on [20].

Measurement of interharmonics is conducted on the basis of the model as in fig. 8, taking into account the frequencies and levels of individual interharmonics as in table 5.
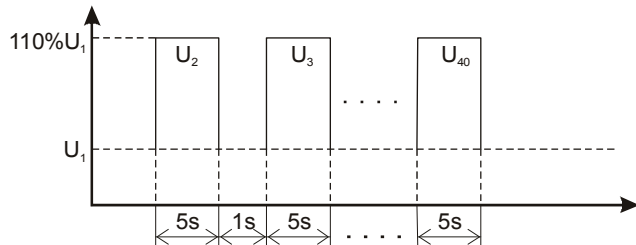

Fig. 8. Model of disturbance signal for testing harmonics.

Table 5 Table of interharmonic and subharmonic frequencies [24].

Frequency range	Frequency hopping
From 0.33 x f_1 to 2 x f_1	0.1 x f_1
From 2 x f_1 to 10 x f_1	0.2 x f_1
From 10 x f_1 to 20 x f_1	0.2 x f_1
From 20 x f_1 to 40 x f_1	0.5 x f_1

The measurement of method reaction to the presence of harmonics and interharmonics of various frequencies can be presented by means of a model with subharmonics, harmonics and interharmonics (table 6). In theory, other, more complex combination can also be used [8].

Table 6. Model of complex test signal for measuring harmonics, subharmonics and interharmonics.

frequency	amplitude	Phase [deg]
0	1 p.u.	-
20	0.1 p.u.	0
21	0.1 p.u.	30
25	0.25 p.u.	0
49	0.5 p.u	30
50	1 p.u.	0
51	0.5 p.u.	30
100	0.1 p.u.	0
1950	0.1 p.u.	30
1999	0.1 p.u.	0
2000	0.1 p.u.	30

The signal is constructed in such a way as to specify whether the resolution of spectrum can be kept at the level of 1 Hz at subharmonic frequencies, fundamental component and 40 harmonic frequency. Then, white noise with the amplitude of 5 % [9] should be added to the above signal.

Generally, the methods of testing frequency methods possibilities, given in literature, and especially Prony's method, are not so demanding as it has been presented before. For example, the simulation of arc furnace offering power of 80 MW is based on the signal with such components as 25 Hz, 50 Hz and 350 Hz [9], [10]. Modelling of currents drawn by the industrial converter with input frequency of 40 Hz uses 5, 7, 17, 19, 25, 35 and 41 harmonic [9].

The model of sustained disturbances, notch type, has been presented in fig. 9. The analysis of these disturbances uses time methods enabling determination of time parameters, such as rising time t_r, falling time t_f and lasting time t_n. The frequency analysis is also used here due to the characteristic content of disturbance spectrum and its effect on the THD (Total Harmonic Distortion) parameter.
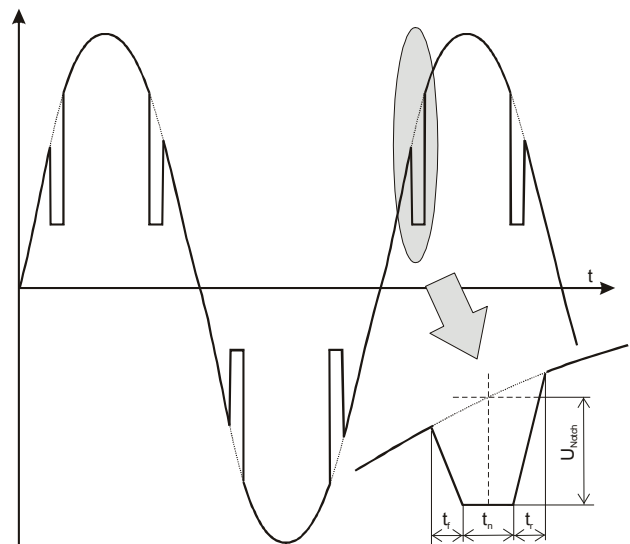

Fig. 9. Model of notch-type disturbance signal. , t_f = 1 µs, t_r = 1 µs, t_n = 200 µs, ΔU_{notch} = 30 V.

There are many models for testing method reaction to variation of fundamental frequency of the waveform [6], [8], [11], [23]. In general, the tests are conducted on the basis of two models: 1st - with hopping frequency variations and

2nd - with constant frequency variations. Usually, the range of variations does not exceed ±2 Hz to 2.5 Hz (above these values, the generator gets switched out of the system). Fig. 10 presents the model with hopping frequency variations and fig. 11 show the model with constant variations.

The frequency variability in linear model is expressed in equation (1) [12].

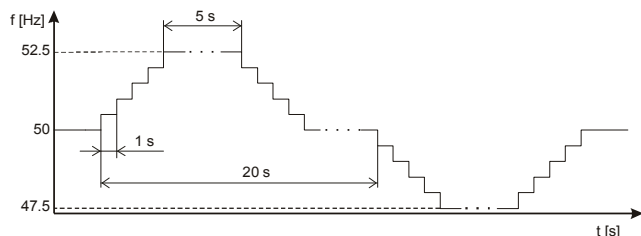$$(1) \qquad f(t) = 50 + \sin(2\pi t) + 0.5\sin(12\pi t)$$

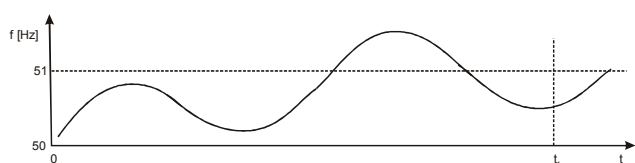Fig. 10. Model of signal with frequency hopping.

Fig. 11. Model of signal with constant frequency change $t_1 = 0.3$ s.

Suggested testing procedure

To illustrate the way of testing frequency methods by means of the proposed test signals, the testing procedure has been suggested below. The procedure should be composed of the following elements:
- disturbances not correlated with power network:
o testing method response to the series of fast transients (fig. 3),
o testing method response to the series of voltage surges (fig. 4),
o testing method response to a series of attenuated oscillations (fig. 5),
o testing method response to a series of attenuated sinusoids (fig. 6),
- disturbances correlated with power network:
o testing method response to the presence of harmonics (fig. 8),
o testing method response to the presence of interharmonics and subharmonics (fig. 8, table 5),
o testing method response to the presence of the harmonics, interharmonics and subharmonics combination (table 6),
o testing method response to the presence of the harmonics, interharmonics and subharmonics combination with noise (table 6),
o testing method response to the presence of notch-type disturbances (fig. 9),
o testing method response to the variations of fundamental frequency (fig. 10, fig. 11).

For the first group of disturbances the method should provide precise results for oscillation-type disturbances. In case of surges and fast transients the spectrum should be broadband, with no local extremes.

Results of testing the test signals of the second group of disturbances (correlated with the network) shall provide discreet spectrum with precisely determined components. In case of noise, detection of components can be lower.

The notch-type disturbance spectrum should be broadband with local extremes.

Summary

This article presented the systematics of disturbances occurring in electrical power network, connected with low frequency conducted disturbances. It also focused on the systematics in the light of disturbances correlation with fundamental frequency of the waveform. Such classification of disturbances made it possible to propose the basis for testing signals that might be useful in testing application of new frequency methods of signal processing in measurements of power quality. Models have been constructed on the basis of parameters of real disturbances occurring in power networks and of models of test signals used for testing electromagnetic compatibility, type 61000-4-x.

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