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Monitoring of operational parameters of interconnected power systems

***Abstract**. One approach to the detection of the threat to Interconnected power systems' stability in the form of oscillatory instability is presented. The instability threat can be detected in real time by contemporary monitoring of subsystems and the use of the proper data processing procedures.*

Streszczenie.** Przedstawiono procedurę wykrywania zagrożeń niestabilności złożonych systemów elektroenergetycznych. Oscylacje o małej częstotliwości związane z oscylacjami występującymi w grupach generatorów mogą prowadzić do niestabilności systemu. Pokazano, że tendencja do niestabilności może być wykrywana w czasie rzeczywistym przez odpowiednie monitorowanie systemu. **(Monitorowanie parametrów operacyjnych systemów elektroenergetycznych)

Keywords: Interconnected power system's operational condition parameters, monitoring, low-frequency oscillations, oscillatory instability.
Słowa kluczowe: System elektroenergetyczny, monitoring, drgania niskoczęstotliwościowe , niestabilność oscylacyjna.

Introduction

It is known that low-frequency oscillations of Interconnected Power System (IPS) operational condition parameters can lead to the IPS oscillatory instability [1,2]. Such oscillations are associated with the antiphased oscillations with IPS's eigenfrequencies of corresponding generators' groups. Information about a danger 's emergency of the IPS oscillatory instability is very important for the IPS dispatch staff.

Some features of proposed approach

The IPS oscillatory instability is connected with the increase of amplitudes of low-frequency components of the operational condition parameters' oscillations that leads to the increase of amplitudes of the resultant oscillations to the unallowable values.

The spectral analysis methods' usage is proper in the cases of the stationary random processes. As to the IPSs' processes they are considered as stationary only on certain time intervals. That causes some restrictions concerning the usage of the spectral analysis methods in solving the problems connected with analysis of the IPS's processes.

The proposed approach to detection of the threat of a IPS oscillatory instability takes into consideration the study results which are given in [3-5], and is based on the use of the synchronized measurements of IPS operational condition parameters relating to controlled IPS's cutsets.
The main purpose consists in the detection of the low-frequencies oscillations' components and in the evaluation (in the real time) of their contributions to the resultant oscillations of IPS operational condition parameters.

Next parts contain the examples of synthesized test signals' description and the results of signals' analysis by using two methods of data processing.

Synthesized test signal

The synthesized test signals should contain the low-frequency components the contributions of which to the resultant oscillations lead to the increase of oscillations' amplitude of the complex signal. Moreover, the amplitudes and the frequencies of certain components should be variable, and white noise (*WN*) should be present in each synthesized signal. To test the resolving ability of different analysis' methods the frequencies of the low-frequency components of test signals should be very close. The test signal as well as the provided by Phasor Measurement Units (PMUs) results of synchronized measurements of IPS operational condition parameters should be given in the data sample form.

On the basis of given requirements 3 low-frequency components (0.05 Hz, 0.09 Hz and 1.2 Hz), the main frequency's component (50 Hz), two high-frequency components (150 Hz and 250 Hz), and *WN* were loaded to the composition of the synthesized test signal. This signal was represented by a data sample. The frequency of the signals sampling was 200 Hz. The amplitude of the main component (50 Hz) was invariable on the periods [0, 10.0] sec. and [10.5, 20] sec., but on the interval (10.0, 10.5) this amplitude changed according to expression

$A(t)=1+0.5\sin(2\pi(t-10))$.

It should be noted that in further the amplitudes of all signal components are reduced to the amplitude of the main component (50 Hz) and are presented as relative units (r.u.). The amplitudes' change pending 20 sec. are shown in Fig. 1.

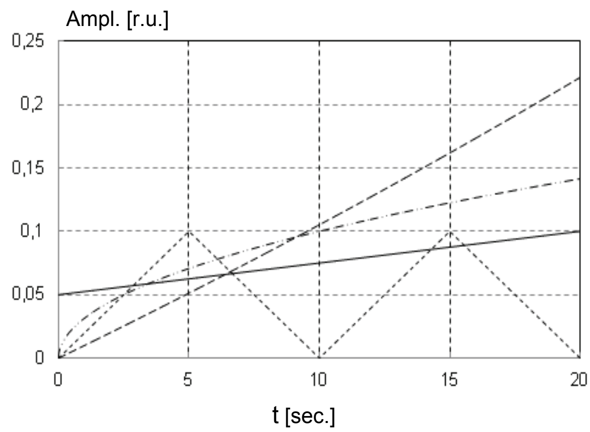

Fig. 1. Change of signal components' amplitudes (0.05 Hz - solid line, 0.09 Hz - dashed line, 1.2 Hz - chain line, 150 Hz and 250 Hz - dotted line).

The maximum level of *WN* does not exceed 5% from the amplitude of 50 Hz component. The frequency of the main component (50 Hz) is changed (linearly) from 50 to 49 Hz pending 20 sec. To ensure the monitoring continuity a sliding watch window was used. The least necessary width of this window was determined for each of the methods under consideration, taking into account their features.

The Prony's method usage

The Prony's method does not belong to the methods of spectral analysis, but it enables to calculate the spectral density of signal's energy. For this purpose a signal is presented as a data series and a certain deterministic exponential model is used.

In general, if there is a data sample that includes N complex data values $x[1]$, $x[2]$,…, $x[N]$, the Prony's method enables to evaluate the sequence $\{x[n]\}$ using the model (1)

$$(1)\quad \{\hat{x}[n]\} = \sum_{k=1}^{k=r} A_k \exp[(\alpha_k + j2\pi f_k)(n-1)\tau + j\varphi_k],$$

where: $1\leq n\leq N$, r is the order of the complex exponents' model, τ is the samples' interval [sec.], A_k, α_k – the amplitude and damping coefficient [sec.$^{-1}$] of the k^{th} complex component correspondingly, f_k, φ_k – the frequency [Hz] and initial phase [radian] of the k^{th} sinusoid correspondingly.

In the test signal the data sample is formed by the real equidistant (according to time) values, that is why the model is presented in the form (2)

$$(2)\quad \{\hat{x}[n]\} = \sum_{k=1}^{k=r/2} 2A_k \exp[\alpha_k (n-1)\tau]\cos[2\pi f_k (n-1)\tau + \varphi_k].$$

To approximate the data sample the modified least squares Prony's method (this enabled to speed up the calculations). Because the problem of low-frequency components' detection from the test signal was putted, the high-frequency components (150 Hz and 250 Hz) were filtered with cutoff filter (the cutoff frequency was equal to 60 Hz).

While data samples processing the watch window width as well as the watch window shift was equal to 1 sec. at first.

As a result of the test sample processing 4 components which frequencies are close to the frequency of the main test signal component were detected. That is in addition to the main component also 3 secondary (false) components (the calculated "phantoms") were detected.

Pay attention to the fact that in the watch window there was detected the signal's component with the frequency is equal to 0.063 Hz and the amplitude is equal to 0.121 r.u. at the 2nd second instead of the signal's component with the frequency is equal to 0.05 Hz. There was not detected some more "traces" which testify for presence in the test sample the component with the frequency that is close to 0.05 Hz. Another test signal's component (0.09 Hz) was detected as from the 3rd second. Within first 8 second in the test sample there were also "detected" the false components ("trash"). Twin extension of the watch window's width (the window's shift remained stable) influenced little on the results of the test sample's analysis. The amplitudes' change of two test signal's components (1.2 Hz and 0.09 Hz) are presented in Fig. 2).

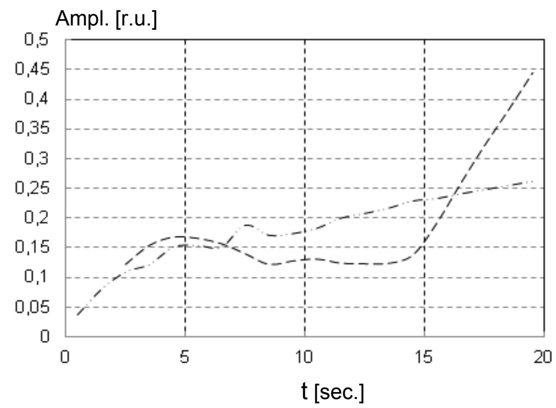

Fig. 2. Change of signal components' amplitudes (1.2 Hz - chain line, 0.09 Hz - dashed line; the window's width is equal to 2 sec., the window's shift is equal to 1 sec.).

In the case of Prony's method usage the obtained results only testify about certain restrictions as to the components' detection in the low-frequency part of the spectrum of oscillations, but do not testify against such usage. For example, the usage of Prony's method for other test signal (the test signal N. 2) enables to detect (with different watch window's width) the low-frequency components (1,8 and 1,9 Hz). The test signal N. 2 is presented by following expression

$x(t)=0.19\sin(2\pi\cdot 1t+4\pi/7)+0.27\sin(2\pi\cdot 1.2t+\pi/5)+$
$+0.3(e^{0.004t}-1)\times\sin(2\pi\cdot(1.8+t/3600)t+3\pi/8)+0.5(e^{0.004t}-1)\times$
$\times\sin(2\pi\cdot(1.9-t/3600)t+\pi/3)+0.2\sin(2\pi\cdot 49.7t+\pi/3)+$
$+\sin(2\pi\cdot 50t)+0.25\sin(2\pi\cdot 50.2t+\pi/4)+WN.$

Change of these signal components' amplitudes are shown in Fig. 3.

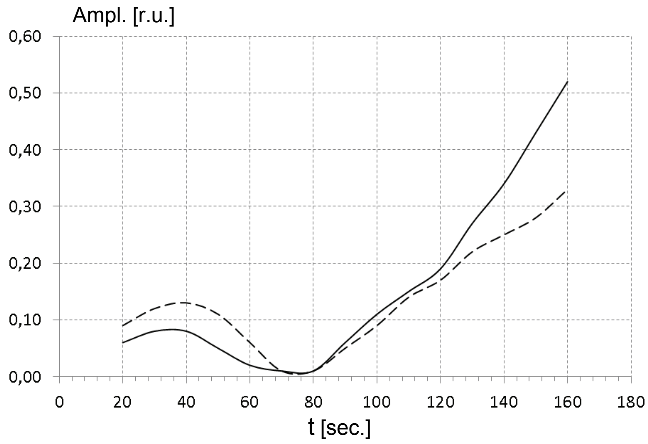

Fig. 3. Change of signal components' amplitudes (1.8 Hz - solid line, 1.9 Hz - dashed line).

The Hilbert-Huang's transform usage

The Hilbert-Huang's transform [6] is available for the non-stationary processes' analysis. Inherently, this transformation comes to splitting the signal into empiric modes with the further application of Hilbert-Huang's transform to them.

The Hilbert-Huang's transform compared, for example, to the Prony's method, enables to ensure high performance of the corresponding calculating procedures. But its application has also one important disadvantage, because the transform accuracy according to the frequency f_p [Hz] depends on the watch window's width t_B [sec.]: $f_p\approx(t_B)^{-1}$. So, in order to detect the component which frequency is equal to 0.09 Hz, the watch window's width should be no less than 11.1sec., and to detect the component which frequency is equal to 0.05 Hz, the watch window's width should be no less than 20 sec. For example, in the case of the watch window width is equal to 10 sec., the detection of the component which frequency is equal to 1.2 Hz must be ensured. Also there is a capability of the component's detection even its frequency is equal to 0.09 Hz, because 10 sec. (the watch window's width) is close to 11,1… sec. But the hope relating to the detection of the component which frequency is equal to 0.05 Hz is unreal. Such preliminary considerations are confirmed with the main results of the test sample's analysis given in Table 1 (some part of information belongs to the columns "Trash" is absent in Table 1).

Predictably, the test signal's component which frequency is equal to 0.05 Hz was not detected, while the component with the frequency close to 1.2 Hz was detected confidently although with some inaccuracy according to the frequency, that is induced, first of all, by the change of the frequency of the main signal's component (from 50 to 49 Hz). Pay attention to the fact that in the 4th watch window (8th second corresponds to the center of this window) the signal's component which frequency is equal to 1.053 Hz and the amplitude is equal to 0.081 r.u. is detected (these data present in "Trash" columns in Tabl. 3; and they are marked out with bold type). It is obviously that the mentioned data "belong" to the signal's component which frequency is equal to 1.2 Hz and this component was not detected in the previous watch window (the 7th second corresponds to the center of this window).

Table 1. Test sample analysis's results obtained in the case of the Hilbert-Huang's transform usage (the watch window's width is 10 sec., the window's shift is 1 sec.)

Time	Frequencies						Trash	
	$50 \rightarrow 49$		1,2		0,09			
	Rev. freq.	Ampl.	Rev. freq.	Ampl.	Rev. freq.	Ampl.	Rev. freq.	Ampl.
5	49.773	1	0.950	0.061	-	-	3.000	0.056
6	49.700	1	1.087	0.052	0.092	0.043	3.894	0.029
7	49.664	1	-	-	0.092	0.036	2.541	0.062
8	49.600	1	1.282	0.086	-	-	**1.053**	**0.081**
9	49.536	1	1.243	0.081	-	-	3.199	0.068
10	49.500	1	1.199	0.093	-	-	0.188	0.072
11	49.436	1	1.432	0.102	-	-	0.150	0.061
12	49.400	1	1.277	0.105	0.092	0.024	0.191	0.063
13	49.365	1	1.282	0.110	0.100	0.060	0.192	0.045
14	49.300	1	1.347	0.118	0.092	0.063	1.050	0.109
15	49.246	1	1.351	0.119	-	-	1.044	0.125

As to detection of the component which frequency is equal to 0.09 Hz, the presence of it in the test signal was detected in 5 out of 11 sliding watch windows. This can be considered as not bad result, taking into account the fact that the watch window's width was equal to 10 sec.

It should be noticed that in the case of watch window width equals to 2 sec. the test signal's component which frequency is equal to 1.2 Hz was also detected in 13 out of 19 windows (Fig. 4), although with some inaccuracy (the calculated values of the frequency were in their majority at the level of 1.42 Hz).

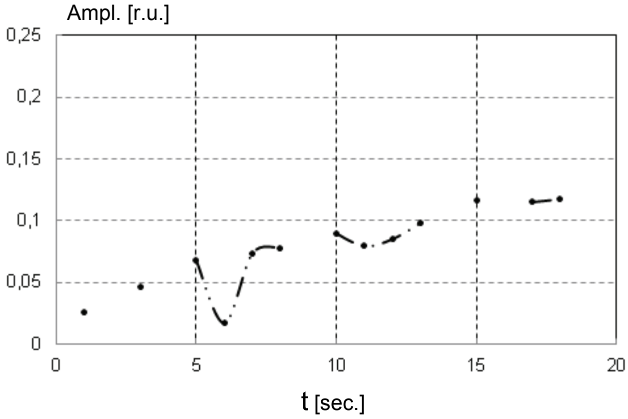

Fig. 4. Change of signal component's amplitude (1.2 Hz - chain line; the window's width is equal to 2 sec., the window's shift is equal to 1 sec.).

Conclusions

The results of the accomplished research show that in order to solve in the real time the problem of the detection of the threat to IPSs' stability in the form of oscillatory instability it is reasonably to use in the IPSs' contemporary monitoring systems (Wide Area Measurement Systems) some sequence of the data processing procedures. First of all, the data provided by PMUs should be filtered, the low-frequency components of the IPS operational condition parameters' oscillations should be detected, these components' "energy contributions" to the resultant oscillations should be evaluated in the real time.

Test results of different methods' application to the synthesized multicomponent signals' analysis show that not all methods successfully cope with formulated problem of the low-frequency components' detection because serious restrictions concerning data samples processing exist.

The simultaneous independent application of tuned data processing procedures which realize the most preferable (from the viewpoint of the mentioned problem's solving) methods enables to increase the detection's reliability of the threat to IPSs' stability in the form of oscillatory instability.

The mentioned procedures' fulfillment in the real time (within each sliding watch window) is connected with a considerable amount of calculating operations therefore the corresponding processor's computing power should be provided.

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