Journal of Cybernetics and Informatics

published by

Slovak Society for Cybernetics and Informatics

Volume 14, 2014

http://www.kasr.elf.stuba.sk/sski/casopis/

ISSN: 1336-4774

Journal of Cybernetics and Informatics 14 (2014)
http://www.kasr.elf.stuba.sk/sski/casopis/

DETERMINATION OF POLISH POWER SYSTEM ANGULAR STABILITY FACTORS BASED ON INSTANTANEOUS POWER DISTURBANCE WAVEFORMS

Pruski, P, Paszek, S.
Silesian University of Technology, Faculty of Electrical Engineering
piotr.pruski(stefan.paszek)@polsl.pl

Abstract
The paper presents investigation results concerning the accuracy analysis of calculating the defined stability factors of the Polish Power System on the basis of power system state matrix eigenvalues associated with electromechanical phenomena. The eigenvalues were calculated by analysis of the disturbance waveforms of the instantaneous power when taking into account introduction of a disturbance to different units. There were analysed the power swing waveforms occurring after introducing the disturbance in the form of a rectangular impulse of different height to the voltage regulation system of generators in generating units of different powers.

Keywords
power system, electromechanical eigenvalues, transient states, reconstruction of waveforms

1 INTRODUCTION

There occur various transient phenomena of different character and time horizon in a power system (PS) which is a very complex physical system. Depending on the phenomena and quantities describing the PS operating condition, the following kinds of the PS stability can be distinguished [1]:

- angular stability,
- voltage stability,
- frequency stability.

The angular stability is associated with maintaining synchronism of all synchronous generators working in PS generating units. Loss of synchronism of synchronous generators is identified with loss of the PS angular stability [2]. The angular stability is directly connected with electromechanical phenomena such as, among others, electromechanical swings.

Maintaining the angular stability of a power system is one of the most important aspects of its work. Stability factors calculated on a basis of the PS state matrix eigenvalues can be used for assessing the PS angular stability [3]. The eigenvalues can be calculated from the PS state equations, however, the calculation results then depend on the values of the system state matrix elements; they also – indirectly – depend on the assumed system models and their uncertain parameters [4]. The eigenvalues can also be calculated with good accuracy from analysis of the actual disturbance waveforms occurring in the PS after various disturbances [5].

The goal of the paper is to determine the stability factors of the Polish Power System (PPS) with use of the eigenvalues calculated on a basis of the analysis of instantaneous power disturbance waveforms in PPS generating units.

2 LINEARISED MODEL OF A POWER SYSTEM

The power system model linearised around the working point is described by the state and output equations [6]:

$$\Delta\dot{\boldsymbol{X}} = \boldsymbol{A}\Delta\boldsymbol{X} + \boldsymbol{B}\Delta\boldsymbol{U}\ , \tag{1}$$

$$\Delta\boldsymbol{Y} = \boldsymbol{C}\Delta\boldsymbol{X} + \boldsymbol{D}\Delta\boldsymbol{U}, \tag{2}$$

where: $\Delta\boldsymbol{X}$, $\Delta\boldsymbol{U}$, $\Delta\boldsymbol{Y}$ - deviations of the vectors of: state variables, inputs and output variables, respectively. The waveforms of input quantities of the linearised system model can be calculated directly by integrating the state equation, or by using the eigenvalues and eigenvectors of the state matrix $\boldsymbol{A}$ [6].

Assuming only single eigenvalues of the state matrix, the vector of state variables and the vector of output quantities can be described by [6]:

$$\Delta \boldsymbol{X}(t)=\int_0^t \boldsymbol{V}\mathrm{e}^{\boldsymbol{\Lambda}(t-\tau)}\boldsymbol{W}^{\mathrm{T}}\boldsymbol{B}\boldsymbol{u}(\tau)\mathrm{d}\tau=\int_0^t \mathrm{e}^{\boldsymbol{A}(t-\tau)}\boldsymbol{B}\boldsymbol{u}(\tau)\mathrm{d}\tau, \tag{3}$$

$$\Delta \boldsymbol{Y}(t)=\int_0^t \boldsymbol{C}\boldsymbol{V}\mathrm{e}^{\boldsymbol{\Lambda}(t-\tau)}\boldsymbol{W}^{\mathrm{T}}\boldsymbol{B}\boldsymbol{u}(\tau)\mathrm{d}\tau+\boldsymbol{D}\boldsymbol{u}(t)=\int_0^t \boldsymbol{C}\mathrm{e}^{\boldsymbol{A}(t-\tau)}\boldsymbol{B}\boldsymbol{u}(\tau)\mathrm{d}\tau+\boldsymbol{D}\boldsymbol{u}(t), \tag{4}$$

where: $\boldsymbol{V}$, $\boldsymbol{W}$ – right- and left-side modal matrices whose columns are right- and left-side normalised ($\boldsymbol{W}_h^{\mathrm{T}}\boldsymbol{V}_h=1$) eigenvectors of the state matrix, respectively, $\boldsymbol{\Lambda}$ – diagonal matrix in which the eigenvalues of the state matrix are placed on the main diagonal.

In Eqs. (3) and (4) there were used the following relationships connecting matrices $\boldsymbol{V}$, $\boldsymbol{W}$, $\boldsymbol{A}$ and $\boldsymbol{\Lambda}$:

$$\boldsymbol{\Lambda}=\boldsymbol{W}^{\mathrm{T}}\boldsymbol{A}\boldsymbol{V}, \tag{5}$$

$$e^{\boldsymbol{A}t}=\boldsymbol{V}e^{\boldsymbol{W}^{\mathrm{T}}\boldsymbol{A}\boldsymbol{V}t}\boldsymbol{W}^{\mathrm{T}}. \tag{6}$$

The waveform of the given output value is a superposition of the modal components which depend on the eigenvalues and eigenvectors of the state matrix. For example, in the case of a disturbance being a Dirac pulse of the j-th input value:

$$\Delta U_j(t)=\Delta U\delta(t), \tag{7}$$

the i-th output value (at $\boldsymbol{D}=\boldsymbol{0}$ and assuming only single eigenvalues) is [7]:

$$\Delta Y_i=\sum_{h=1}^{n} F_{ih}e^{\lambda_h t}, \tag{8}$$

$$F_{ih}=\boldsymbol{C}_i\boldsymbol{V}_h\boldsymbol{W}_h^{\mathrm{T}}\boldsymbol{B}_j\Delta U, \tag{9}$$

where: $\lambda_h=\alpha_h+\mathrm{j}\nu_h$ – h-th eigenvalue of the state matrix, F_{ih} – participation factor of the h-th eigenvalue in the i-th output waveform, $\boldsymbol{C}_i$ – i-th row of $\boldsymbol{C}$ matrix, $\boldsymbol{V}_h$ - h-th right-side eigenvector of the state matrix, $\boldsymbol{W}_h$ – h-th left-side eigenvector of the state matrix, $\boldsymbol{B}_j$ – j-th column of $\boldsymbol{B}$ matrix, n – dimension of the state matrix $\boldsymbol{A}$. The values λ_h and F_{ih} can be real or complex.

In case of the waveforms of instantaneous power swings in PS, the eigenvalues associated with motion of generating units rotors, called *electromechanical eigenvalues* in the paper, are of decisive significance. They are complex conjugate eigenvalues with imaginary parts, which correspond to the frequency range (0.1-2 Hz), hence their imaginary parts fall into the range (0.63-12.6 rad/s). The electromechanical eigenvalues intervene in different ways in the instantaneous power waveforms of particular generating units, which is related to the different values of their participation factors.

3 EXEMPLARY CALCULATIONS

Calculations were carried out for the Polish Power System (PPS) model (Fig. 1) in which there were taken into account 49 selected generating units working in high and highest voltage networks as well as 8 equivalent generating units representing influence of PSs of neighbouring countries.

The method for calculations of electromechanical eigenvalues used in investigations consists in approximation of instantaneous power waveforms in particular generating units with use of the expression (8). The electromechanical eigenvalues and participation factors of specific modal components are the unknown parameters of this approximation. In the approximation process, these parameters are iteratively selected to minimize the value of the objective function defined as a mean square error between the approximated and approximating waveform:

$$\varepsilon_{\mathrm{w}}(\boldsymbol{\lambda},\boldsymbol{F})=\sum_{i=1}^{N}\left(P_{i(\mathrm{m})}-P_{i(\mathrm{a})}(\boldsymbol{\lambda},\boldsymbol{F})\right)^2, \tag{10}$$

where: $\boldsymbol{\lambda}$ is the vector of electromechanical eigenvalues, $\boldsymbol{F}$ is the vector of participation factors, N – number of samples, the index m denotes the approximated waveform, while the index a denotes the approximating waveform of the instantaneous power P, calculated from the searched eigenvalues and participation factors.

The objective function can also be written, based on expression (8), as:

$$\varepsilon_{\mathrm{w}}(\boldsymbol{\lambda},\boldsymbol{F})=\sum_{i=1}^{N}\left(P_{i(\mathrm{m})}-\sum_{h=1}^{n}F_{ih}e^{\lambda_h t}\right)^2. \tag{11}$$

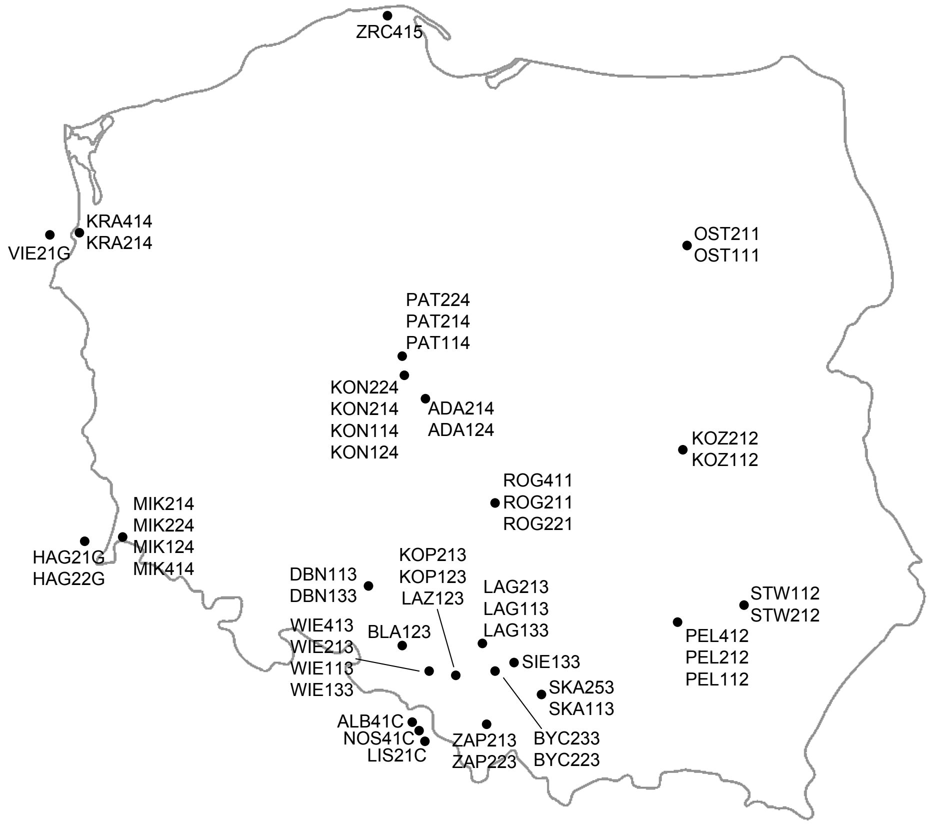

Fig.1 Generating units included in the PPS model

The eigenvalues with small participation factor moduli in particular waveform are neglected in calculations based on this waveform. The objective function (10) or (11) is minimized by a hybrid algorithm which is a serial combination of a genetic algorithm (Fig. 2a) with a gradient algorithm (Fig. 2b). The results of the genetic algorithm are the starting point of the gradient algorithm. The genetic algorithm seeks the global minimum of the objective function in the given interval of the parameters being determined. The starting point is sampled from the search interval, so it is not necessary to define it precisely. However, the algorithm is slowly convergent. The gradient algorithm is more quickly convergent, but it seeks the local minimum of the objective function, due to which the initial parameter values must be carefully selected to obtain correct results. The serial combination of genetic and gradient algorithms eliminates their basic disadvantages [7, 8].

For the purpose of calculations, the input data (approximated during the calculation) is the measured instantaneous power waveforms, but in order to verify the calculation method, the instantaneous power waveforms obtained from simulations with use of the PS model are employed. The eigenvalues and participation factors calculated from the assumed structure and parameters of the model are assumed to be the reference point [7].

Due to the existence of the objective function local minima in which the optimisation algorithm may freeze, the eigenvalues were calculated repeatedly based on the same waveform. If the objective function values were higher than a certain assumed limit, the results were rejected. The adopted final result of the calculations of real and imaginary parts of the particular eigenvalues were the arithmetic means from the real and imaginary parts, respectively, of the eigenvalues obtained from the results not rejected in further calculations.

The analysed PS model was worked out in Matlab-Simulink environment. It consists of 57 models of generating units as well as the model of the network and loads.

The calculations presented in this paper consider the following models: a synchronous generator GENROU [7], a static [7] or electromachine excitation system operating in the PPS, a steam turbine IEEEG1 [7] or water turbine HYGOV and, optionally, a power system stabilizer [9] (type PSS3B [7]). For the equivalent generating units representing influence of power systems of the neighbouring countries there was used the simplified model of a synchronous generator.

The assumed disturbance is a square pulse of the voltage regulator reference voltage in one of generating units. The system response to an input in the form of a short square pulse with a suitably selected height and length is close to that to a Dirac pulse.

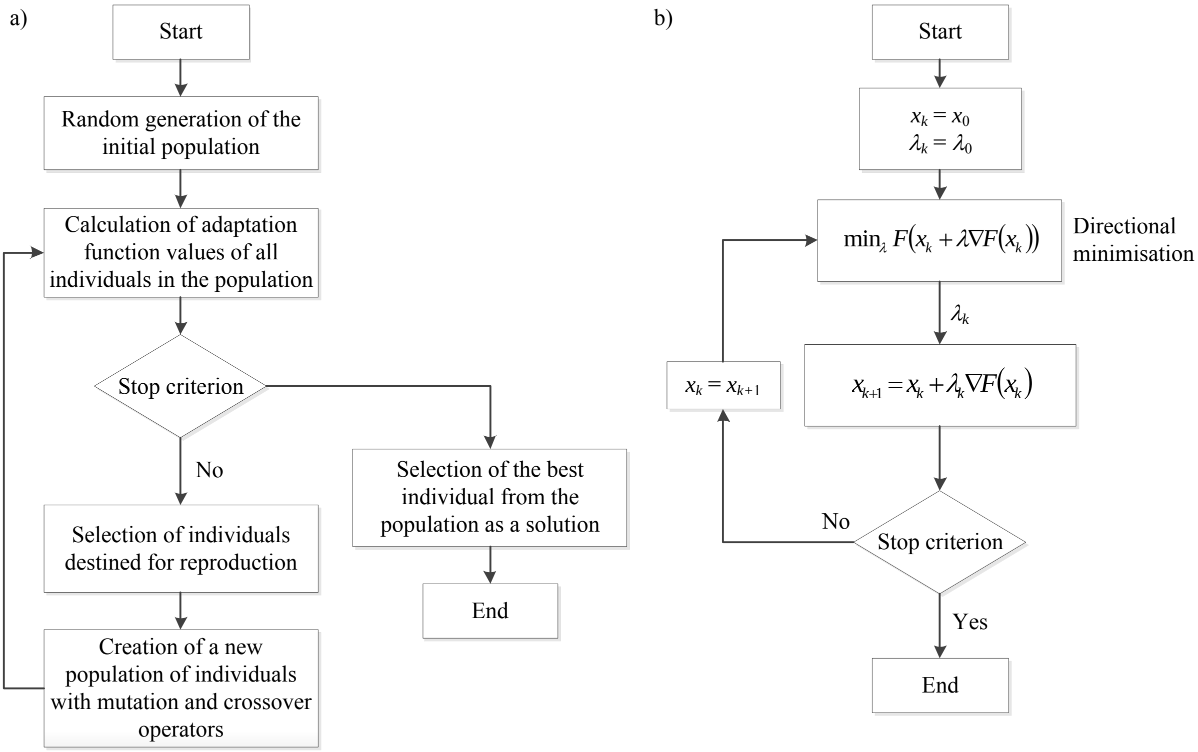

Fig. 2. Flowcharts of algorithms: genetic (a) and gradient (b)

The right selection of the height and length of the rectangular pulse of the voltage regulator reference voltage is an important factor which determines the accuracy of calculations. The amplitude of instantaneous power swings must be sufficiently high to allow separating these swings from the recorded waveforms of phase currents and voltages in individual system nodes. The amplitude increases with the increase in the pulse surface of the voltage regulator reference voltage, which can be expressed as:

$$\Delta P \approx k \Delta V_{\mathrm{ref}} t_{\mathrm{imp}} , \tag{12}$$

where: ΔP – amplitude of the instantaneous power swing waveform, ΔV_{ref} – height of the square pulse of the voltage regulator reference voltage, t_{imp} – pulse length, k – proportionality gain. The pulse height ΔV_{ref}, however, must be limited to avoid a significant impact of nonlinearity and limits on the instantaneous power waveforms. The square pulse duration t_{imp} must also be limited, since its significant lengthening results in increasing differences in the system responses to the square and Dirac pulse, which can decrease the accuracy of determining electromechanical eigenvalues [7].

Since there are only several modal components of significant amplitude in the instantaneous power waveform of a single generating unit, it is necessary to analyse the instantaneous power waveforms of different generating units occurring at various place of disturbance input.

Table 1 presents the results of the modal analysis of instantaneous power waveforms after introducing a disturbance to chosen generating units. For analysis, for each place of disturbance input, there were selected instantaneous power waveforms in which there occurred power swings of significant amplitudes. The following denotations are used in Table 1: P_0 – generating unitactive power in steady state, $\overline{\Delta P}$ – relative amplitude of instantaneous power swings (calculated as a quotient of the instantaneous power swing amplitude ΔP and the generating unit active power in steady state P_0 – Fig. 3), λ – selected eigenvalues influencing the instantaneous power waveforms significantly (original eigenvalues are given in brackets), $|\overline{F}|$ – modules of the participation factors (relative values referred to the largest absolute value of the participation factor in a given waveform). The state matrix of the analysed PPS model has 56 electromechanical eigenvalues. They were sorted in increasing order according to the real parts and numerated from λ_1 to λ_{56}.

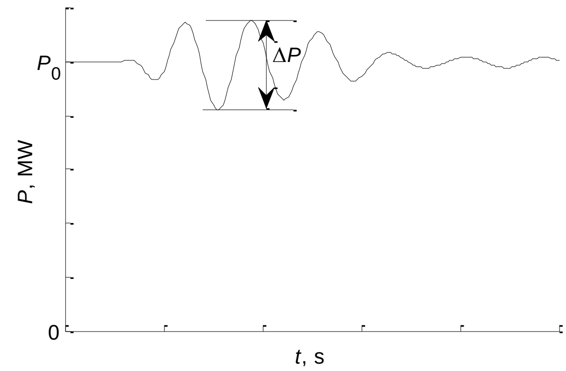

Fig.3 The way of calculating the relative amplitude of instantaneous power swings $\overline{\Delta P}$

Tab.1 Results of modal analysis of instantaneous power waveforms for selected places of disturbance input

Place of disturbance input	Place of occurence of power swings	P_0	$\overline{\Delta P}$	λ	$\lvert F \rvert$
		MW	p.u.	1/s	p.u.
KOZ212	KOZ212	1140.1	0.1097	λ_{29} (-0.8716±j9.5518)	0.1665
				λ_{31} (-0.8524±j9.5702)	1
				λ_{37} (-0.7670±j8.5753)	0.2556
				λ_{46} (-0.4788±j7.6653)	0.3189
				λ_{49} (-0.1710±j4.9780)	0.1328
	KOZ112	382.1	0.0757	λ_{29} (-0.8716±j9.5518)	0.1702
				λ_{31} (-0.8524±j9.5702)	1
				λ_{37} (-0.7670±j8.5753)	0.2889
				λ_{38} (-0.4165±j8.0932)	0.1661
				λ_{46} (-0.4788±j7.6653)	0.2711
	STW122	172.6	0.0557	λ_{37} (-0.7670±j8.5753)	1
				λ_{38} (-0.4165±j8.0932)	0.2334
				λ_{40} (-0.6723±j8.6222)	0.1538
				λ_{42} (-0.6372±j8.3382)	0.2820
				λ_{46} (-0.4788±j7.6653)	0.5316
	STW112	117.8	0.0518	λ_{29} (-0.8716±j9.5518)	0.9508
				λ_{31} (-0.8524±j9.5702)	1
				λ_{38} (-0.4165±j8.0932)	0.2053
				λ_{46} (-0.4788±j7.6653)	0.2176
	ZRC415	701.3	0.0491	λ_{37} (-0.7670±j8.5753)	0.1681
				λ_{42} (-0.6372±j8.3382)	0.1680
				λ_{46} (-0.4788±j7.6653)	0.1670
				λ_{47} (-0.4488±j6.6540)	1
				λ_{49} (-0.1710±j4.9780)	0.9524
DBN113	DBN113	335.8	0.2058	λ_{32} (-0.8499±j9.6756)	1
				λ_{40} (-0.6723±j8.6222)	0.1274
				λ_{41} (-0.6417±j8.8039)	0.5788
				λ_{43} (-0.5910±j8.5763)	0.4981
				λ_{44} (-0.5713±j8.5011)	0.1664
	DBN133	335.8	0.0656	λ_{32} (-0.8499±j9.6756)	1
				λ_{41} (-0.6417±j8.8039)	0.3671
				λ_{43} (-0.5910±j8.5763)	0.3454
				λ_{44} (-0.5713±j8.5011)	0.1186

From Table 1 it follows that the disturbance in the generating unit KOZ212 (of large apparent power of generator) caused large power swings both in that unit and several other ones. Namely, the large power swings occurred not only in the generating unit KOZ212 located in the close neighbourhood of the generating unit KOZ212, but also in the generating units STW122, STW112 and ZRC415 located in a significant distance from the generating unit KOZ212 (Fig. 1). There are five modal components of significant amplitudes in the instantaneous power waveform of the unit KOZ212. There are four from among those modal components in the instantaneous power waveform of the unit KOZ112, and proportions of their amplitudes are similar as those in case of the instantaneous power waveform of the unit KOZ212. In the instantaneous power waveform of the unit KOZ112 there is also one modal component not occurring in the instantaneous power waveform of the unit

KOZ212. In the instantaneous power waveforms of the units STW122, STW112 and ZRC415 there occur some of the components occurring in the instantaneous power waveform of the unit KOZ212 and the modal components not occurring in that waveform. However, it can be noted that those modal components which also occur in the instantaneous power waveform of the unit KOZ212 are dominant in the instantaneous power waveforms of the units STW122 and STW112. In case of the instantaneous power waveform of the unit ZRC415 there is a deviation from that rule, since the modal component of the largest amplitude in that waveform does not occur in the instantaneous power waveform of the unit KOZ212. However, the modal component of the second largest amplitude occurs in the instantaneous power waveform of the unit KOZ212. The disturbance in the unit DBN113 of small generator rated apparent power caused power swings of significant amplitude only in that unit and in the unit DBN133 neighbouring with DBN113. In the instantaneous power waveform of the unit DBN133 there does not occur one of the modal components occurring in the instantaneous power waveform of the unit DBN113. None additional modal components occur in it, either. Proportions of the amplitudes of the modal components in the instantaneous power waveforms of the units DBN113 and DBN133 differ significantly.

Table 2 presents electromechanical eigenvalues λ calculated directly by a program Matlab-Simulink on a basis of the PPS model (called *original eigenvalues* in the paper) and absolute errors $\Delta\lambda$ of calculating those eigenvalues on a basis of the instantaneous power waveforms.

Tab.2 Original eigenvalues and absolute errors of calculations of these eigenvalues

h	1	2	3	4	5
λ_h, 1/s	-1.3099±j11.1792	-1.2866±j11.5541	-1.2768±j10.1287	-1.2123±j9.4372	-1.1925±j10.9116
$\Delta\lambda_h$, 1/s	-0.0377∓j0.3307	0.0746∓j0.0033	-0.0106∓j0.0649	0.0284±j0.1082	0.0859∓j0.1185
h	6	7	8	9	10
λ_h, 1/s	-1.1670±j10.8599	-1.1669±j10.1882	-1.1405±j10.6099	-1.0939±j9.8686	-1.0867±j10.9129
$\Delta\lambda_h$, 1/s	-0.0495±j0.0872	0.0215∓j0.1457	0.0420±j0.1233	0.0358±j0.1090	0.0022∓j0.2474
h	11	12	13	14	15
λ_h, 1/s	-1.0627±j10.3843	-1.0615±j10.2550	-1.0559±j10.3520	-1.0520±j10.3293	-1.0477±j10.0241
$\Delta\lambda_h$, 1/s	-0.0328±j0.0576	0.0600±j0.0474	-0.0115±j0.0876	0.0676∓j0.1348	-0.0061±j0.0214
h	16	17	18	19	20
λ_h, 1/s	-1.0449±j10.2168	-1.0231±j9.6776	-1.0087±j10.2941	-0.9956±j9.7503	-0.9937±j10.3461
$\Delta\lambda_h$, 1/s	-0.0328±j0.0254	-0.0110±j0.1274	-0.0389∓j0.1256	-0.0035∓j0.1107	0.0582±j0.0746
h	21	22	23	24	25
λ_h, 1/s	-0.9925±j10.1970	-0.9896±j10.3399	-0.9891±j10.3132	-0.9843±j9.1122	-0.9591±j10.1540
$\Delta\lambda_h$, 1/s	-0.0163±j0.1737	0.0440±j0.1682	0.0120±j0.0465	0.0769∓j0.0399	-0.0595∓j0.0466
h	26	27	28	29	30
λ_h, 1/s	-0.9005±j9.5251	-0.8831±j9.4212	-0.8749±j9.9664	-0.8716±j9.5518	-0.8660±j9.8514
$\Delta\lambda_h$, 1/s	-0.0687±j0.1609	0.0844∓j0.1723	0.0471∓j0.1695	-0.0111±j0.0301	-0.0440∓j0.0883
h	31	32	33	34	35
λ_h, 1/s	-0.8524±j9.5702	-0.8499±j9.6756	-0.8226±j9.1135	-0.8136±j9.6312	-0.7888±j8.5214
$\Delta\lambda_h$, 1/s	0.0186∓j0.1181	0.0220±j0.1535	0.0179±j0.0287	-0.0813±j0.0925	0.0139∓j0.0320
h	36	37	38	39	40
λ_h, 1/s	-0.7765±j9.1363	-0.7670±j8.5753	-0.7501±j9.0125	-0.7368±j9.6011	-0.6723±j8.6222
$\Delta\lambda_h$, 1/s	-0.0086±j0.0195	-0.0054±j0.0942	-0.0751∓j0.0168	-0.0383±j0.2604	0.0731∓j0.0028
h	41	42	43	44	45
λ_h, 1/s	-0.6417±j8.8039	-0.6372±j8.3382	-0.5910±j8.5763	-0.5713±j8.5011	-0.4955±j7.3005
$\Delta\lambda_h$, 1/s	-0.1158∓j0.0635	0.0646±j0.0754	-0.0595∓j0.8201	-0.0818∓j0.0409	0.0293∓j0.2115
h	46	47	48	49	50
λ_h, 1/s	-0.4788±j7.6653	-0.4488±j6.6540	-0.4165±j8.0932	-0.1710±j4.9780	-0.0884±j7.7781
$\Delta\lambda_h$, 1/s	0.0691±j0.1107	-0.0277±j0.0088	0.0138±j0.0976	-0.0340±j0.1444	-
h	51	52	53	54	55
λ_h, 1/s	-0.0835±j5.6278	-0.0826±j6.9521	-0.0744±j5.5362	-0.0671±j9.3707	-0.0568±j3.4772
$\Delta\lambda_h$, 1/s	-0.0745±j0.4093	-	-	-	-
h	56				
λ_h, 1/s	-0,0457±j4.0116				
$\Delta\lambda_h$, 1/s	0.0272∓j0.0939				

From Table 2 it follows that almost all eigenvalues were calculated with the satisfactory accuracy. The exception is the real part of the eigenvalue λ_{41} and imaginary parts of the eigenvalues λ_{43} and λ_{51}which were calculated with the worse accuracy. The eigenvalues λ_{50} and λ_{52} - λ_{55} were not calculated on a basis of the instantaneous power waveforms since the modal components associated with them did not influence the instantaneous power waveforms of any of the PPS generating units strongly enough.

For instance, Fig. 4 shows the instantaneous power disturbance waveforms of the generating unit KOZ212 (Kozienice power plant) when introducing a disturbance to that unit.

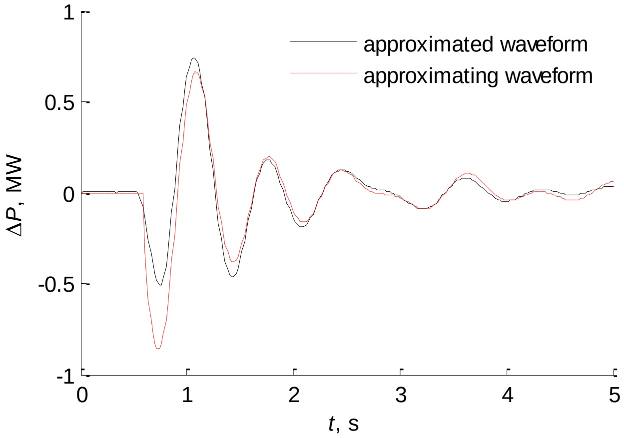

Fig. 4 Instantaneous power disturbance waveforms of the generating unit KOZ212

From Fig. 4 it follows that the quality of approximating the instantaneous power waveforms with the hybrid algorithm is worse in the time range of about 0.5 s after occurrence of the disturbance, which is caused by the influence of strongly damped modal components not associated with the electromechanical eigenvalues. In order to eliminate the influence of those modal components, the analysis of the waveform is started after 0.5 s since the disturbance occurrence [10].

The following stability factors were used for assessing the PPS angular stability [3]:

$$W_1 = \max(\alpha_h), \quad W_2 = \max(\xi_h) = \max\left(\frac{\alpha_h}{\sqrt{\alpha_h^2 + \nu_h^2}}\right), \quad W_3 = \min(\eta_h) = \min\left(\ln\left(2\pi\frac{-\alpha_h}{\nu_h}\right)\right). \tag{13}$$

Only real part of this electromechanical eigenvalue which is connected with the least damped modal components of electromechanical quantities decides on the value of the factor W_1. The value of the factor W_2 is determined by the maximal relative damping factor of electromechanical eigenvalues $\xi_h = \frac{\alpha_h}{\sqrt{\alpha_h^2 + \nu_h^2}}$ which is also influenced by the imaginary part of the electromechanical eigenvalue (associated with the frequency of electromechanical swings). The factor W_3 is related to the logarithmic decrement for damping swings $\eta_h = \ln\left(2\pi\frac{-\alpha_h}{\nu_h}\right)$ and is undetermined for unstable systems.

The values of stability factors (13) determined on a basis of original and calculated by means of the hybrid algorithm eigenvalues are compared in Table 3. There are given the absolute errors of calculating the stability factors by means of the hybrid algorithm.

Tab.3 Calculation results of stability factors

	Calculated based on original eigenvalues	Calculated based on calculated eigenvalues	Error
W_1	-0.1710	-0.2050	-0.0340
W_2	-0.0343	-0.0400	-0.0057
W_3	-1.5335	-1.3805	0.1530

4 SUMMARY

The investigations performed allow to draw the following conclusions:

– It is possible to determine electromechanical eigenvalues, and based on them to calculate PPS stability factors, on a basis of the analysis of the instantaneous power waveforms in disturbance states. The higher participation of modal components associated with the calculated eigenvalues in the instantaneous power waveform is, the more accurate calculations of eigenvalues based on that waveform are. The larger modal component participation factor module, the greater influence of the eigenvalue associated with this modal component on the instantaneous power waveform shape, hence on the value of the objective function minimised by the optimisation algorithm.

– Use of the hybrid algorithm being a series connection of genetic and gradient algorithms allows eliminating the basic weaknesses of those both algorithms. Use of a genetic algorithm at the first stage of approximation eliminates the need of precise determination of the starting point, which allows obtaining good results in spite of the wide range of solution search.

– Repeated calculations of eigenvalues with the hybrid algorithm, at different starting points sampled at each calculation from the seek range, eliminates the problem of algorithm freezing at local minima of the objective function. The calculation accuracy is increased by comparing the eigenvalues calculated from the instantaneous power waveforms of various generating units.

– From the investigations performed it follows that the eigenvalue λ_{49} is of decisive significance for the PPS angular stability. That eigenvalue has the largest (of the smallest absolute value) real part from among the eigen-values interfering in a significant way in the instantaneous power waveforms of generating units working in PPS. The eigenvalue λ_{49} has the largest values of the participation factor module in the instantaneous power waveforms of the generating units ZRC415 and KON124. It has also large values of the participation factor modules in the instantaneous power waveforms of, among others, the generating units PAT114, ADA214, KON214, KON224 and PEL412.

– The calculation error of the stability factor W_2 appeared to be the smallest one (considering its module). A little greater is the calculation error of the stability factor W_2. The largest is the calculation error of the stability factor W_3 .

5 REFERENCES

[1] IEEE TF Report: Proposed terms and definitions for power system stability. IEEE Trans. Power Apparatus and Systems, vol. PAS-101, July 1982, pp. 1894-1897.

[2] Machowski J., Białek J., Bumby J.: Power System Dynamics. Stability and Control. John Wiley & Sons, Chichester, New York, 2008.

[3] Paszek, S., Nocoń, A.: The method for determining angular stability factors based on power waveforms. AT&P Journal Plus2, Power System Modeling and Control, Bratislava, Slovak Republic 2008, pp. 71-74.

[4] Cetinkaya, H.B., Ozturk, S., Alboyaci, B.: Eigenvalues Obtained with Two Simulation Packages (SIMPOW and PSAT) and Effects of Machine Parameters on Eigenvalues, Electrotechnical Conference, 2004. MELECON 2004. Proceedings of the 12th IEEE Mediterranean, Vol. 3, pp. 943 – 946.

[5] Saitoh, H., Miura, K., Ishioka, O., Sato, H., Toyoda, J.: On-line modal analysis based on synchronized measurement technology. Power System Technology, 2002. Proceedings. PowerCon 2002. International Conference on, vol. 2, pp. 817 – 822.

[6] Kudła, J., Paszek, S.: Reduced-order transfer function in Power System (in Polish). 18-th International Conference on Fundamentals of Electrotechnics and Circuit Theory, SPETO'95,vol. 2, pp. 299-304.

[7] Paszek, S., Pruski, P.: Assessment of the power system angular stability based on analysis of selected disturbance states. Acta Energetica, nr 02/2011, pp. 44-53.

[8] Nocoń, A., Paszek, S.: Polyoptimisation of synchronous generator voltage regulator (in Polish). Monografia. Wydawnictwo Politechniki Śląskiej. Gliwice 2008.

[9] Veselý, V., Quang T. N.: Robust power systemstabilizer via networked control system. Journal of Electrical Engineering, Vol. 62, No. 5, 2011, pp. 286-291.

[10] Paszek, S., Pruski, P.: Determination of electromechanical eigenvalues of power system state matrix based on instantaneous power disturbance waveforms (in Polish). Zeszyty Naukowe Politechniki Śląskiej „Elektryka", Gliwice 2010, zeszyt 3, rok LVI, pp. 59-73.