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Assessment of Polish Power System angular stability based on analysis of different disturbance waveforms

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Abstract. The paper presents investigation results concerning assessment of the Polish Power System (PPS) angular stability based on power system state matrix eigenvalues associated with electromechanical phenomena, when using the angular stability factors calculated on the basis of these eigenvalues. The eigenvalues were calculated by analysis of the disturbance waveforms of the instantaneous power, angular speed and power angle of synchronous generators in PPS generating units when taking into account introduction of a disturbance to different units. There was assumed a disturbance in the form of a rectangular pulse introduced to the voltage regulation system of a generating unit. There was also analysed the effect of the duration of the introduced test disturbance on the calculation results of the eigenvalue influencing the measurement waveforms of the instantaneous power of generating unit no 5 in Rybnik Power Plant. The method for eigenvalue calculations used in the investigations consists in approximation of the disturbance waveforms in particular generating units with the use of the waveforms being a superposition of the modal components associated with the searched eigenvalues. The hybrid optimisation algorithm being a serial combination of the genetic and gradient algorithms was used for computations.

Key words: power system, eigenvalues associated with electromechanical phenomena, angular stability.

1. Introduction

The angular stability of a power system (PS) is associated with the rotation of the rotors of PS generating units. Maintaining the PS angular stability is the necessary condition for the correct operation of the PS. The loss of this stability can be the cause of serious and extensive system failures, which can result in power stoppage for a large number of recipients.

The assessment of the PS angular stability can be made on the basis of the system state matrix eigenvalues associated with electromechanical phenomena, when using the angular stability factors calculated based on these eigenvalues [1, 2].

The eigenvalues can be calculated from the assumed PS mathematical model state equations, however, the calculation results then depend on the values of the PS state matrix elements. These results also depend indirectly on the assumed PS elements models and their parameters [3]. The parameters are usually not known with a satisfactory accuracy [4].

The eigenvalues can also be calculated with a good accuracy from the analysis of the actual disturbance waveforms occurring in the PS after various disturbances [5]. In this case, calculation results are not affected by the assumed PS model and its parameters, but only by the real, current system performance [6].

The goals of the paper are:

- to determine the stability factors of the Polish Power System (PPS) with use of the eigenvalues calculated on the basis of the analysis of the instantaneous power, angular speed and power angle simulated disturbance waveforms in PPS generating units,
- to analyse the impact of the duration of the introduced test disturbance on the calculation results of the eigenvalue influencing the measurement waveforms of the instantaneous power of generating unit no 5 in Rybnik Power Plant.

2. The linearised power system model

The PS mathematical model linearised around the steady operating point is described by the state equation and output equation [1, 7–9]:

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

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

where $\Delta\boldsymbol{X}$, $\Delta\boldsymbol{U}$, $\Delta\boldsymbol{Y}$ – deviations of the vectors of the: state variables, input variables and output variables, respectively. The elements of the $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$ and $\boldsymbol{D}$ matrices are calculated for the steady operating point of the PS.

The transient waveforms of output quantities of the linearised PS model can be calculated directly by integrating the state equation (1), or by using the eigenvalues and eigenvectors of the state matrix $\boldsymbol{A}$ [1, 6, 7]. Assuming only single eigenvalues of the matrix $\boldsymbol{A}$, the vector of the state variables and the vector of the output variables can be described by [1, 8]:

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

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

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

The waveform of the given output variable 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 $\Delta U_j(t) = \Delta U \delta(t)$, the i-th output value (at $\boldsymbol{D} = \boldsymbol{0}$ and assuming only single eigenvalues) is [1, 6, 7]:

$$\Delta Y_i = \sum_{h=1}^{n} F_{ih}\mathrm{e}^{\lambda_h t}, \tag{5}$$

$$F_{ih} = \boldsymbol{C}_i \boldsymbol{V}_h \boldsymbol{W}_h^{\mathrm{T}} \boldsymbol{B}_j \Delta U, \tag{6}$$

where $\lambda_h = \alpha_h + j\nu_h$ – 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. The values λ_h and F_{ih} can be real or complex.

In the case of the transient waveforms of the instantaneous power, angular speed and power angle of generators of generating units in the PS, the system state matrix eigenvalues associated with electromechanical phenomena, called *electromechanical eigenvalues* in the paper, are of decisive significance. They are complex conjugate eigenvalues whose imaginary parts correspond to the frequency range (0.1–2 Hz), hence their imaginary parts fall into the range (0.63–12.6 rad/s). These eigenvalues intervene in different ways in the transient waveforms of particular generating units, which is related to the different values of their participation factors [1, 6, 7].

3. The method for calculations of electromechanical eigenvalues

For calculations there were used the transient waveforms of the deviations of generating unit output variables which occurred after the purposeful introducing of a small disturbance to the PS. The assumed disturbance is a rectangular pulse of the voltage regulator reference voltage in one of generating units. The system response to an input in the form of a short rectangular pulse with a suitably selected height and length is close to that to a Dirac pulse [1, 6, 7]. The amplitude of the output variable deviation waveforms in the case of a short rectangular pulse is approximately proportional to the surface area of the pulse [1, 6].

The method for calculations of electromechanical eigenvalues used in investigations consists in approximation of the output variable deviation waveforms of particular generating units with the use of expression (5). 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 minimise the value of the objective function defined as a mean square error between the approximated and approximating waveform:

$$\varepsilon_{\mathrm{w}}(\boldsymbol{\lambda}, \boldsymbol{F}) = \sum_{k=1}^{N} \left(\Delta W_{k(\mathrm{m})} - \Delta W_{k(\mathrm{a})}(\boldsymbol{\lambda}, \boldsymbol{F})\right)^2, \tag{7}$$

where $\boldsymbol{\lambda}$ – vector of electromechanical eigenvalues, $\boldsymbol{F}$ – vector of participation factors, ΔW – waveform of the deviations of the quantity analysed, k – current number of the waveform sample, N – number of samples, the index m denotes the approximated waveform, while the index a – the approximating waveform, calculated from the searched eigenvalues and participation factors with the use of expression (5). The objective function (7) is minimised by a hybrid algorithm [10–12] which is a serial combination of a genetic algorithm [12–14] with a gradient algorithm [12, 13].

The eigenvalues with small participation factor modules in particular waveform are neglected in calculations based on this waveform. From the made calculations it follows that only the modal components associated with electromechanical eigenvalues intervene significantly (after decaying the strongly damped modal components) in the waveforms of the instantaneous power deviations ΔP. In the waveforms of angular speed deviations $\Delta\omega$ also the modal components associated with other electromechanical eigenvalues intervene significantly but the influence of electromechanical eigenvalues is also significant. The influence of electromechanical eigenvalues on the waveforms of power angle deviations $\Delta\delta$ is relatively inconsiderable. Moreover, the steady values of the waveforms $\Delta\delta$ after the disturbance differ from the initial values of these waveforms before the disturbance. Based on the investigations performed, it can be stated that to make the correct approximation of the waveform $\Delta\omega$ possible, one should (in the case of a pulse disturbance) take into account one equivalent oscillatory modal component of a relatively low frequency which represents the influence of the neglected modal components on this waveform. Whereas for the waveform $\Delta\delta$ one should take into account two equivalent modal components: oscillatory (as for the waveform $\Delta\omega$) and aperiodic. The parameters of the equivalent modal components are also arguments of the objective function (7) and are optimised.

To eliminate the effect of the fast decaying modal components associated with the real and complex eigenvalues, which are not electromechanical eigenvalues, it is convenient to start the waveform analysis after a certain time t_{p} after the disturbance occurrence [6].

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 larger than a certain assumed limit, the results were rejected. The assumed final result of the calculations of real and imaginary parts of the particular eigenvalues on the basis of that waveform were the arithmetic means from the real and imaginary parts, respectively, of the eigenvalues obtained from the not rejected results of the repeated calculations [1, 6, 7].

Since there are only several modal components of significant amplitude in the output waveforms of a single generating unit, it is necessary to analyse the output waveforms of different generating units occurring at various places of disturbance input [1, 6].

4. Exemplary calculations based on simulated waveforms

In order to verify the calculation method accuracy, the disturbance waveforms of generating unit output variables obtained from simulations with the use of the PPS model were employed. In this model there were taken into account 49 selected generating units working in high and highest voltage networks as well as 8 equivalent generating units representing the influence of PSs of neighbouring countries. The analysed PPS model was worked out in Matlab-Simulink environment [1]. It consists of 57 models of generating units as well as the model of the network and loads [1, 6, 7]. The generating units included in this model are shown in Fig. 1.

The following models of the PPS generating units components were assumed for the calculations: a synchronous generator GENROU [12, 15], a static [12] or electromachine [11, 12, 15] excitation system working in the PPS, a steam turbine IEEEG1 [11, 12, 15] or water turbine HYGOV [12, 15] and, optionally, a power system stabilizer PSS3B [10, 12, 15]. For the equivalent generating units there was used the simplified model of a synchronous generator GENCLS [15]. In this case the effects of the excitation system, turbine, and power system stabilizer were neglected.

The electromechanical eigenvalues (as well as the other eigenvalues) of the PS state matrix can be calculated directly on the basis of the structure and parameters of the PS model in program Matlab-Simulink. These electromechanical eigenvalues are called *original eigenvalues* further in the paper. Comparison of the eigenvalues calculated based on minimisation of the objective function (7) and the original eigenvalues is assumed as a measure of the calculation accuracy [6, 7]. The state matrix of the analysed PPS model has 56 electromechanical eigenvalues. They were sorted in ascending order according to their real parts and numbered from λ_1 to λ_{56}. The selected original eigenvalues are presented in Table 1.

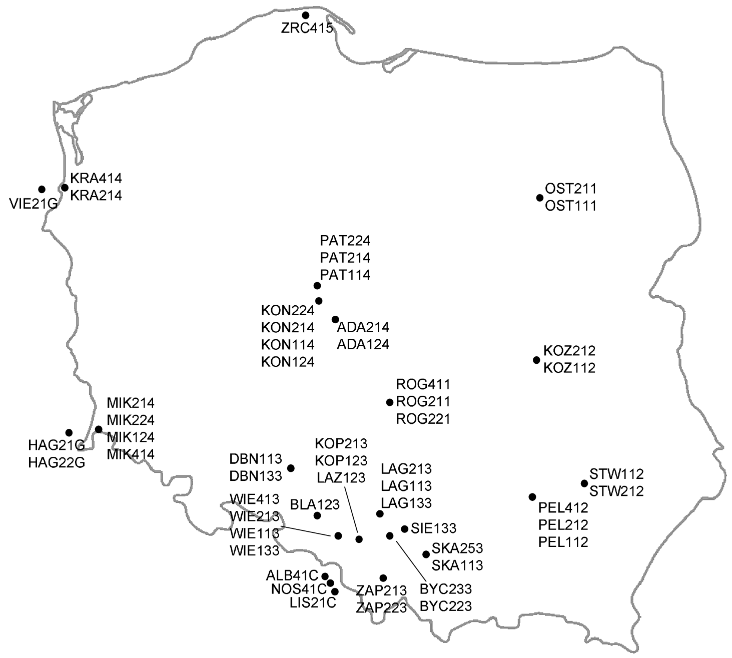


Fig. 1. Generating units included in the Polish Power System model (Ref. 1)

Table 1
Selected original eigenvalues of the PPS model

λ_1	$-1.3099\pm$j11.1792	λ_4	$-1.2123\pm$j9.4372	λ_7	$-1.1669\pm$j10.1882
λ_{10}	$-1.0867\pm$j10.9129	λ_{13}	$-1.0559\pm$j10.3520	λ_{16}	$-1.0449\pm$j10.2168
λ_{19}	$-0.9956\pm$j9.7503	λ_{22}	$-0.9896\pm$j10.3399	λ_{25}	$-0.9591\pm$j10.1540
λ_{28}	$-0.8749\pm$j9.9664	λ_{31}	$-0.8524\pm$j9.5702	λ_{34}	$-0.8136\pm$j9.6312
λ_{36}	$-0.7765\pm$j9.1363	λ_{39}	$-0.7368\pm$j9.6011	λ_{40}	$-0.6723\pm$j8.6222
λ_{44}	$-0.5713\pm$j8.5011	λ_{48}	$-0.4165\pm$j8.0932	λ_{49}	$-0.1710\pm$j4.9780

4.1. Analysis of the impact of output quantity selection on the participation factors. As it is apparent from formula (2), when assuming $\boldsymbol{D} = \boldsymbol{0}$, the values of the vector $\Delta\boldsymbol{Y}$ are dependent on the values of the vector $\Delta\boldsymbol{X}$ of the state variables and the matrix $\boldsymbol{C}$. The waveforms of the i-th output variable are obtained by multiplying the i-th row of the matrix $\boldsymbol{C}$ and the vector $\Delta\boldsymbol{X}$. From formula (5) it follows that the participation factor F_{ih} depends on the values of the elements in successive rows of the matrix $\boldsymbol{C}$. Then the participation factors of the eigenvalues are different in the disturbance waveforms of particular output quantities of the PS.

As an instance, in Table 2 there are given the relative absolute values of the participation factors $|F|_{pu}$ of selected electromechanical eigenvalues in the waveforms of the deviations of instantaneous power ΔP, angular speed $\Delta\omega$ and power angle $\Delta\delta$ of the generating unit ROG211 when introducing a disturbance to the unit ROG411 (in relation to the largest absolute values of the participation factors of electromechanical eigenvalues in these waveforms).

Table 2
Participation factors of electromechanical eigenvalues in the waveforms of generating unit ROG211

	Waveform		
	ΔP	$\Delta\omega$	$\Delta\delta$
$\lvert F_{28}\rvert_{pu}$	1	1	1
$\lvert F_{39}\rvert_{pu}$	0.2191	0.2281	0.2369
$\lvert F_{40}\rvert_{pu}$	0.1042	0.1214	0.1404
$\lvert F_{48}\rvert_{pu}$	0.3400	0.4244	0.5240
$\lvert F_{49}\rvert_{pu}$	0.0486	0.1038	0.2086

From Table 2 it follows that the relative absolute values of the participation factors of particular electromechanical eigenvalues in the analysed waveforms differ significantly. A similar situation occurs in the case of the waveforms of the other generating units of the analysed model of the PPS. Based on the investigations performed, it can be stated that the eigenvalues can be usually calculated with a satisfactory accuracy based on the waveforms whose absolute values of the participation factors are larger than 0.3.

4.2. Calculations of electromechanical eigenvalues. In Table 3 there are given the absolute errors $\Delta\lambda$ of calculations of selected electromechanical eigenvalues on the basis of the disturbance waveforms ΔP, $\Delta\omega$ and $\Delta\delta$ of particular generating units of the PPS model. The eigenvalues were, in general, calculated based on the waveforms of different generating units. The arithmetic means of the calculation errors are listed in the table.

From Table 3 it follows that almost all the eigenvalues were calculated with the satisfactory accuracy. The accuracies of calculations based on the waveforms of all the analysed quantities were close to each other. The eigenvalues λ_{50} and $\lambda_{52} - \lambda_{55}$ were not calculated on the basis of the disturbance waveforms since the modal components associated with them did not influence the output variable waveforms of any of the PPS generating units strongly enough.

Figure 2 shows the exemplary simulation disturbance waveforms of the deviations of the instantaneous power ΔP, angular speed $\Delta\omega$ and power angle $\Delta\delta$ of the generator in unit ROG211 in the case of the pulse disturbance in unit ROG411 as well as the bands of the approximating waveforms corresponding to the non-rejected calculation results. The band of the approximating waveforms determines the range of the waveforms changes in which "there are" all approximating waveforms corresponding to particular calculation results.

Table 3
Absolute errors of calculations of selected electromechanical eigenvalues on the basis of simulated waveforms

ΔP waveforms					
$\Delta\lambda_1$	$-0.0377\mp$j0.3307	$\Delta\lambda_4$	0.0284$\pm$j0.1082	$\Delta\lambda_7$	0.0215j0.1457
$\Delta\lambda_{10}$	0.0022$\mp$j0.2474	$\Delta\lambda_{13}$	$-0.0115\pm$j0.0876	$\Delta\lambda_{16}$	$-0.0328\pm$j0.0254
$\Delta\lambda_{19}$	$-0.0035\mp$j0.1107	$\Delta\lambda_{22}$	0.0440$\pm$j0.1682	$\Delta\lambda_{25}$	$-0.0595\mp$j0.0466
$\Delta\lambda_{28}$	0.0471$\mp$j0.1695	$\Delta\lambda_{31}$	0.0186$\mp$j0.1181	$\Delta\lambda_{34}$	$-0.0813\pm$j0.0925
$\Delta\lambda_{36}$	$-0.0086\pm$j0.0195	$\Delta\lambda_{39}$	$-0.0383\pm$j0.2604	$\Delta\lambda_{40}$	0.0731$\mp$j0.0028
$\Delta\lambda_{44}$	$-0.0818\mp$j0.0409	$\Delta\lambda_{48}$	0.0138$\pm$j0.0976	$\Delta\lambda_{49}$	$-0.0064\pm$j0.1107
$\Delta\omega$ waveforms					
$\Delta\lambda_1$	$-0.0180\pm$j0.1097	$\Delta\lambda_4$	0.0306$\mp$j0.0261	$\Delta\lambda_7$	0.0499$\mp$j0.2280
$\Delta\lambda_{10}$	$-0.0514\mp$j0.0224	$\Delta\lambda_{13}$	0.0710$\mp$j0.0704	$\Delta\lambda_{16}$	$-0.0243\pm$j0.0441
$\Delta\lambda_{19}$	$-0.0411\mp$j0.0204	$\Delta\lambda_{22}$	$-0.0591\mp$j0.1633	$\Delta\lambda_{25}$	0.0812$\pm$j0.1638
$\Delta\lambda_{28}$	$-0.0565\pm$j0.0984	$\Delta\lambda_{31}$	$-0.0286\pm$j0.1886	$\Delta\lambda_{34}$	0.0793$\mp$j0.1466
$\Delta\lambda_{36}$	$-0.0454\pm$j0.1293	$\Delta\lambda_{39}$	0.0466$\pm$j0.0483	$\Delta\lambda_{40}$	$-0.0200\mp$j0.1869
$\Delta\lambda_{44}$	$-0.0886\pm$j0.0152	$\Delta\lambda_{48}$	$-0.0668\mp$j0.0862	$\Delta\lambda_{49}$	0.0022$\pm$j0.0043
$\Delta\delta$ waveforms					
$\Delta\lambda_1$	0.0189$\pm$j0.0660	$\Delta\lambda_4$	$-0.0414\mp$j0.4193	$\Delta\lambda_7$	0.0069$\mp$j0.0657
$\Delta\lambda_{10}$	0.0889$\pm$j0.2448	$\Delta\lambda_{13}$	0.0444$\mp$j0.0309	$\Delta\lambda_{16}$	$-0.0492\pm$j0.1047
$\Delta\lambda_{19}$	$-0.0520\mp$j0.0127	$\Delta\lambda_{22}$	0.0581$\pm$j0.1297	$\Delta\lambda_{25}$	$-0.0486\pm$j0.0969
$\Delta\lambda_{28}$	$-0.0723\pm$j0.0638	$\Delta\lambda_{31}$	$-0.0499\pm$j0.1687	$\Delta\lambda_{34}$	$-0.0305\mp$j0.1138
$\Delta\lambda_{36}$	$-0.0515\pm$j0.1381	$\Delta\lambda_{39}$	$-0.0382\mp$j0.0275	$\Delta\lambda_{40}$	0.0414$\mp$j0.0825
$\Delta\lambda_{44}$	$-0.0974\pm$j0.0710	$\Delta\lambda_{48}$	0.0293$\mp$j0.0858	$\Delta\lambda_{49}$	0.0032$\mp$j0.0048

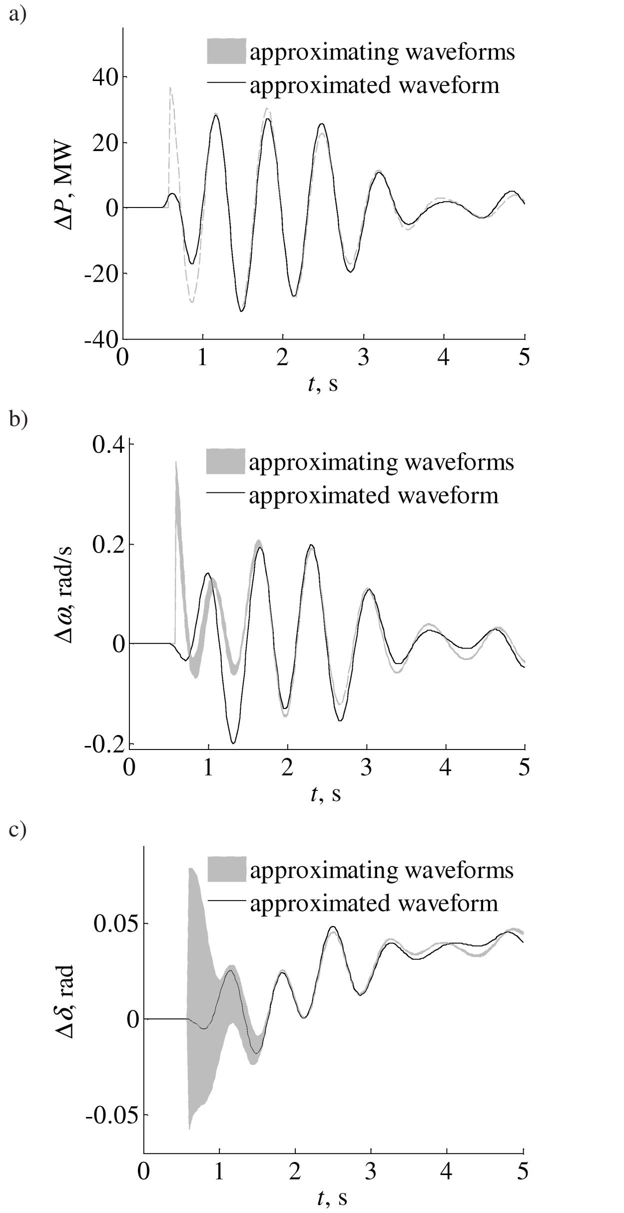


Fig. 2. Exemplary disturbance waveforms of the deviations of: instantaneous power ΔP (a), angular speed $\Delta\omega$ (b) and power angle $\Delta\delta$ (c) of generating unit ROG211

From Fig. 2 it follows that the approximation quality of the disturbance waveforms is satisfactory in the time interval after decay of strongly damped modal components which do not influence the calculation results.

4.3. Calculations of stability factors. The following stability factors were used for assessing the PPS angular stability [2]:

$$W_1 = \max(\alpha_h), \tag{8}$$

$$W_2 = \max(\xi_h) = \max\left(\frac{\alpha_h}{\sqrt{\alpha_h^2 + v_h^2}}\right), \tag{9}$$

$$W_3 = \min(\eta_h) = \min\left(\ln\left(2\pi\frac{-\alpha_h}{v_h}\right)\right). \tag{10}$$

The values of the stability factors determined on the basis of original eigenvalues and eigenvalues calculated on the basis of ΔP, $\Delta\omega$ and $\Delta\delta$ waveforms are compared in Table 4.

Table 4
Calculation results of the stability factors

Calculated on a basis of	W_1	W_2	W_3
Original eigenvalues	−0.1710	−0.0343	−1.5335
ΔP waveforms	−0.1773	−0.0348	−1.5189
ΔP waveforms – error, %	3.717	1.460	−0.946
$\Delta\omega$ waveforms	−0.1687	−0.0339	−1.5474
$\Delta\omega$ waveforms – error, %	−1.296	−1.380	0.907
$\Delta\delta$ waveforms	−0.1678	−0.0337	−1.5512
$\Delta\delta$ waveforms – error, %	−1.855	−1.759	1.159

From Table 4 it follows that particular stability factors were calculated with the satisfactory accuracy on the basis of all the analysed output quantities of the PPS. The calculation accuracy of the eigenvalue λ_{49} influenced the calculation accuracy of all the stability factors decisively. This eigenvalue has the largest (the smallest, regarding the absolute value) real part from among the eigenvalues interfering in a significant way in the disturbance waveforms of generating units working in PPS. So it proved to be decisive for the PPS angular stability. The relative calculation errors of the stability factor W_3 were the smallest ones (regarding the absolute value).

5. Exemplary calculations based on measured waveforms

In this subsection there is presented the comparison of the calculation results of the PPS electromechanical eigenvalues for different duration t_{imp} of the step disturbance of the voltage regulator reference voltage. There were taken into account the instantaneous power measurement waveforms of unit no 5 (WIE213 in Fig. 1) in Rybnik Power Plant.

The measurement waveforms recorded at the power plant were heavily disturbed. The presence of disturbances was due to the measurement environment properties. One of the causes of the disturbances was the strong electromagnetic field generated by rotating machines, transformers, and electrical devices (including high-current circuits and reactors). Power electronic inverters were another cause of the disturbances [6].

The filtering of the measurement waveforms was made with a third order digital Butterworth low pass filter with the cut-off frequency equal to 20 Hz [16]. There was used the zero phase filtering [16]. It allowed eliminating the phase delays and distortions of the signals introduced by the filter [7].

In the case of calculating the PPS electromechanical eigenvalues based on the measurement waveforms, the complete estimation of the calculation accuracy was not possible due to the lack of access to accurate and reliable enough calculation results of these eigenvalues obtained with the use of other methods [7]. Therefore this section presents the calculation results only, without assessment of their accuracy. The instantaneous power waveforms recorded in unit no 5 in Rybnik Power Plant contain only one significant modal component associated with the electromechanical eigenvalue λ_{23} of the PPS model.

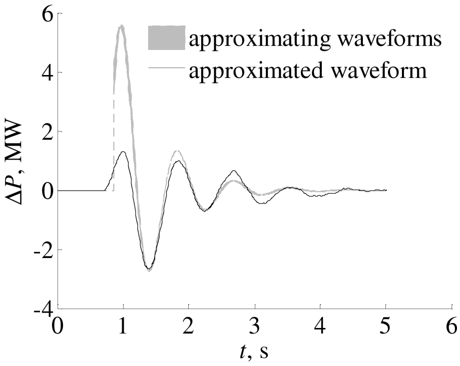
In Table 5 there are listed the results of calculations of the eigenvalues based on the measured instantaneous power waveforms in the case of different durations t_{imp} of the step disturbance.

Table 5
Calculation results of eigenvalue λ_{23} on the basis of the measured instantaneous power waveforms

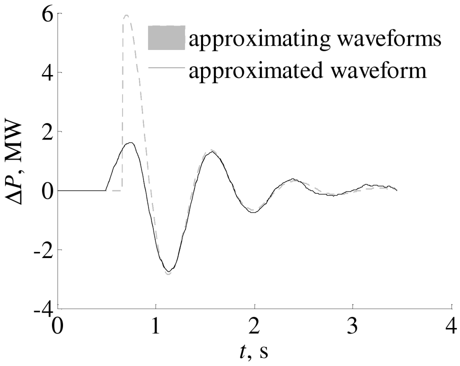
	$t_{\mathrm{imp}} = 290$ ms	$t_{\mathrm{imp}} = 343$ ms	$t_{\mathrm{imp}} = 420$ ms
λ_{23}	$-1.6471\pm$j7.2801	$-1.7153\pm$j7.3482	$-1.6878\pm$j7.1326

From Table 5 it follows that in all the cases the calculation results of the eigenvalues were close in spite of the relatively large differences between the durations of the pulses.

a)



b)



c)

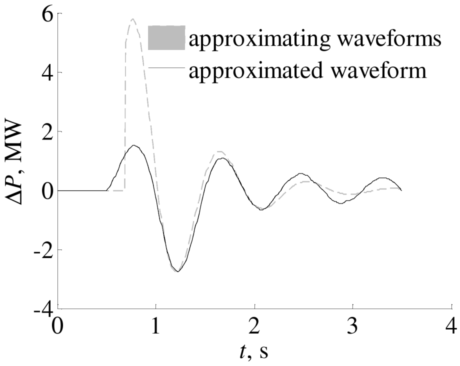


Fig. 3. Measured instantaneous power deviation waveforms of unit no 5 in Rybnik Power Plant for duration of the step disturbance: $t_{\mathrm{imp}} = 290$ ms (a), $t_{\mathrm{imp}} = 343$ ms (b) and $t_{\mathrm{imp}} = 420$ ms (c)

Figure 3 shows the measured instantaneous power deviation waveforms of unit no 5 in Rybnik Power Plant as well as the bands of the approximating waveforms corresponding to the non-rejected calculation results.

From Fig. 3 it follows that the approximation quality of the instantaneous power deviation measurement waveforms is also satisfactory in the time interval after decay of strongly damped modal components. This quality was best for $t_{\mathrm{imp}} = 343$ ms. In all the cases the bands of the approximating waveforms were very narrow. The amplitude of power swings was smallest for $t_{\mathrm{imp}} = 290$ ms, but it was comparable also for the other values of the pulse duration.

6. Concluding remarks

The investigations performed allow drawing the following conclusions:

- The investigations performed for the PPS model showed that it was possible to determine electromechanical eigenvalues with the good accuracy based on the analysis of the waveforms of the instantaneous power, angular speed and power angle after introducing a pulse disturbance in the voltage regulation system of one of generating units. The method used for calculations of eigenvalues on the basis of these waveforms works well in the case of large PSs.
- The averaging of calculation results of successive eigenvalues on the basis of the analysis of the waveforms of different generating units allowed increasing the calculation accuracy. In the cases when the calculation result of the eigenvalue on the basis of one waveform differed significantly from the calculation results of that eigenvalue on the basis of other waveforms, such a result was rejected.
- The accuracy of approximation of simulation waveforms proved to be generally better than that of approximation of measurement waveforms which was influenced by the measurement errors. However, the accuracy of approximation of measurement waveforms was also satisfactory.
- The stability factor W_3 proved to be most robust to calculation errors of eigenvalues. In the case of particular output quantities of the PPS, the relative calculation error of that factor was the smallest one considering the absolute value.
- The zero phase filtering method with the use of a digital Butterworth filter allowed for good filtering of the noised measurement waveforms without delaying and significantly distorting them.
- The calculation results of the eigenvalues on the basis of the measurement waveforms of instantaneous power recorded at different pulse duration t_{imp} were close to each other. However, as it follows from the simulation investigations performed, the appropriate selection of the time t_{imp} is often an important factor influencing the calculation accuracy of eigenvalues. This time has to be short enough so that the system response to a rectangular pulse was close to the response to a Dirac pulse. On the other hand, it has to be long enough so that the waveforms of the PPS output quantities had sufficiently large values of amplitudes.

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