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Multi-criteria optimization of the parameters of PSS3B system stabilizers operating in an extended power system with the use of a genetic algorithm

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In the paper, the application of multi-criteria optimization of the parameters of PSS3B system stabilizers to damping electromechanical swings in an extended power system (PS) is presented. The calculations of the power system stabilizer (PSS) parameters were divided into two stages. In the first stage, single-machine systems, generating unit – infinite bus, of generating units critical for the angular stability of the PS were analyzed. Time constants and preliminary values of the PSS gains were calculated. In the second stage, the main one, the main gains on which the effectiveness of operation of PSSs depends the most were calculated by multi-criteria optimization of the extended PS. The calculations were carried out in several variants: for two-dimensional objective functions and the six-dimensional objective function. In multi-criteria optimization, the solution is not one set of PSS parameters, but a set of sets of these parameters, i.e. a set of compromises that were determined for each analyzed case. Additionally, for the six-dimensional compromise set, projections of this set on the planes connected with the quantities of individual generating units and the boundary of these projections on these planes were determined. A genetic algorithm adapted to multi-criteria issues was used to minimize the multivariate objective function. Sample calculations were made for the model of the National (Polish) Power System taking into account 57 selected generating units operating in high and extra high voltage networks (220 and 400 kV). The presented calculations show that the applied multi-criteria optimization of the PSS3B stabilizer parameters allows effectively damping electromechanical swings without worsening the voltage waveforms of generating units in the extended PS.

Key words: power system, power system stabilizers, polyoptimization, transient states, electromechanical swings, angular stability

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1. Introduction

The power system (PS) is a large nonlinear dynamical system used for the generation, transmission and distribution of electricity. In an extended power system, disturbances in the operation of individual generating units may adversely affect the operation of other units. In the PS, there may appear, among others, electromechanical swings, that is slowly changing swings of rotors of synchronous generators which can also be observed in the waveforms of instantaneous power in generators and transmission lines [5, 7, 8, 16]. In unfavorable cases, these swings may result in the loss of angular stability of generating units and, consequently, their emergency shutdown. Widely used, fast, static excitation systems of synchronous generators contribute to increase in the unfavorable effects of such swings in the extended PS.

In some generating units, electromechanical swings can be weakly damped, or even increase, which may lead to the loss of angular stability of the entire PS. Therefore, it is necessary to locate the generating units which are most endangered (critical) from the point of view of possible loss of the PS angular stability [19]. These units also have the greatest influence on the angular stability of the PS. In these units, particular care must be taken to ensure that various measures for improving the angular stability work properly.

One of the methods of damping electromechanical swings, and thus also improving the angular stability of PS, is the use of appropriately selected power system stabilizers (PSS for short). Power system stabilizers included in the excitation systems are to damp electromechanical swings by creating an additional damping component of the electromagnetic moment of synchronous generators [6, 20, 21]. The use of PSSs may, however, deteriorate other waveforms, mainly voltage waveforms in individual PS nodes [15].

The problem of using PSSs appropriately selected for an extended PS can be reduced to the issue of minimizing a certain objective function, describing the behavior of the PS in selected transient states, when taking into account the favorable and unfavorable effects of operation of these PSSs. The analysis of such an issue requires the simultaneous consideration of many, often contradictory criteria related to the operation of the PS.

This problem can be solved by using multi-criteria optimization (polyoptimization, Pareto optimization) [3, 13, 15, 16, 23], in which several criteria which can be presented in the form of a vector being an objective function are simultaneously minimized. Many methods, including genetic algorithms [4, 14, 22], can be used to numerically solve the multi-criteria optimization problem. The use of a genetic algorithm for multi-criteria optimization does not require significant modifications, compared to the algorithm used in single-criteria problems.

2. Application of the genetic algorithm to multi-criteria optimization

Assuming that the objective function in which nq components (single criteria) are taken into account, each of which is a function of n variables (in the considered case, parameters of the PSSs operating in the PS), is minimized, the genetic algorithm adaptation function (equal to the vector objective function), in the general case, takes the form:

$$\mathbf{f} = \begin{bmatrix} f_1(\mathbf{x}) \\ f_2(\mathbf{x}) \\ \vdots \\ f_i(\mathbf{x}) \\ \vdots \\ f_{nq}(\mathbf{x}) \end{bmatrix} = \begin{bmatrix} f_1(x_1, \cdots, x_j, \cdots, x_n) \\ f_2(x_1, \cdots, x_j, \cdots, x_n) \\ \vdots \\ f_i(x_1, \cdots, x_j, \cdots, x_n) \\ \vdots \\ f_{nq}(x_1, \cdots, x_j, \cdots, x_n) \end{bmatrix}, \tag{1}$$

where: $\mathbf{f}$ – objective function, $\mathbf{x}$ – vector of control variables, f_i – value of the i-th component function for the set of parameters $\mathbf{x} = \{x_1, \cdots, x_j, \cdots, x_n\}$, $\mathbf{X}$ – control space (domain of the objective function, determined by the permissible values of the PSSs parameters), nq – number of the optimized component functions, n – number of the optimized variables.

The solution to such a defined minimization problem is not one optimal set of independent variables, but a set of sets $\widetilde{\mathbf{x}} = \left\{\widetilde{x}_1, \cdots, \widetilde{x}_j, \cdots, \widetilde{x}_n\right\} \in \mathbf{X}$ in which each of the elements is optimal in multi-criteria optimization. The set of the objective function values corresponding to the optimal parameters $\widetilde{\mathbf{x}}$ is called the compromise set (Pareto-optimal front). The set of compromises $\boldsymbol{\Lambda}$ includes all such points of the objective space $\widetilde{\mathbf{f}} = \left\{\widetilde{f}_1, \widetilde{f}_2, \cdots, \widetilde{f}_{nq}\right\} \in \mathbf{F}$, where: $\mathbf{F}$ – objective space, i.e. the area of possible values of the vector objective function (adaptation) $\mathbf{f}$, and the symbol $\widetilde{\cdot}$ denotes the optimal value in multi-criteria optimization, for which there is no direction of simultaneous improvement. The direction of the simultaneous improvement is such a change of the optimized variables $\mathbf{x}$, which results in the simultaneous improvement of all the components of the objective function f_i. The above definition, when minimizing the objective function, can be written as follows:

$$\begin{bmatrix} \widetilde{f}_1(\widetilde{\mathbf{x}}) \\ \widetilde{f}_2(\widetilde{\mathbf{x}}) \\ \vdots \\ \widetilde{f}_i(\widetilde{\mathbf{x}}) \\ \vdots \\ \widetilde{f}_{nq}(\widetilde{\mathbf{x}}) \end{bmatrix} = \widetilde{\mathbf{f}} \in \boldsymbol{\Lambda} \;\Leftrightarrow\; \sim \exists(\mathbf{x} \in \mathbf{X} \wedge \mathbf{x} \neq \widetilde{\mathbf{x}}) \begin{cases} \widetilde{f}_1(\widetilde{\mathbf{x}}) \geqslant f_1(\mathbf{x}) \\ \widetilde{f}_2(\widetilde{\mathbf{x}}) \geqslant f_2(\mathbf{x}) \\ \vdots \\ \widetilde{f}_i(\widetilde{\mathbf{x}}) \geqslant f_i(\mathbf{x}) \\ \vdots \\ \widetilde{f}_{nq}(\widetilde{\mathbf{x}}) \geqslant f_{nq}(\mathbf{x}) \end{cases}, \tag{2}$$

where: symbol $\sim\exists$ means, does not exist, $\mathbf{\Lambda}$ – set of compromises, $\widetilde{f_i}$ – value of the i-th component function belonging to the set of compromises.

The genetic algorithm [4, 14, 22] used for minimization was adapted to the defined multi-criteria problem. There was applied the algorithm based on real number encoding. In the process of initialization, a random initial population of α individuals was generated. For the selection, a modified tournament method [12] was used, in which a tournament group was drawn α-times from the entire population and the fittest individual was selected from it for a new population. The selection of the best individual in each drawn tournament group was sequential for each optimized function f_i. Therefore, each component function f_i was a criterion for α/nq tournaments. Such a selection method required the size of the population α to be an integer multiple of the number of the optimized criteria nq.

The arithmetic crossover [11] was used in the genetic algorithm. For two parent individuals selected for crossover $\{x_1^{<o1>}, \cdots, x_j^{<o1>}, \cdots, x_n^{<o1>}\} \in \mathbf{X}^{<o1>}$ and $\{x_1^{<o2>}, \cdots, x_j^{<o2>}, \cdots, x_n^{<o2>}\} \in \mathbf{X}^{<o2>}$, two off springs $\{x_1^{<d1>}, \cdots, x_j^{<d1>}, \cdots, x_n^{<d1>}\} \in \mathbf{X}^{<d1>}$ and $\{x_1^{<d2>}, \cdots, x_j^{<d2>}, \cdots, x_n^{<d2>}\} \in \mathbf{X}^{<d2>}$ were generated according to the relationship:

$$\begin{cases} x_j^{<d1>} = x_j^{<o1>} + \gamma(x_j^{<o2>} - x_j^{<o1>}), \\ x_j^{<d2>} = x_j^{<o2>} + x_j^{<o1>} - x_j^{<d1>}, \end{cases} \tag{3}$$

where: γ is a random number from the interval $\langle 0,\ 1\rangle$.

To change the values of particular individuals, the uniform mutation [11] was used. It was modified in such a way that the value of an individual was changed by a random number of normal distribution ξ, around the value of the mutating individual. Moreover, in the mutation algorithm, the control of exceeding the permissible area of a given parameter, taken from the boundary mutation method [11] was applied, according to the relationship:

$$\begin{cases} x_j^{<d1>} = x_{j\mathrm{u}} \;\Leftarrow\; x_j^{<p1>}(1+\xi) \geqslant x_{j\mathrm{u}}\,, \\ x_j^{<d1>} = x_j^{<p1>}(1+\xi) \;\Leftarrow\; x_{j\mathrm{u}} > x_j^{<p1>}(1+\xi) > x_{j\mathrm{d}}\,, \\ x_j^{<d1>} = x_{j\mathrm{d}} \;\Leftarrow\; x_j^{<p1>}(1+\xi) \leqslant x_{j\mathrm{d}}\,, \end{cases} \tag{4}$$

where: $x_j^{<d1>}$ – variable after mutation, $x_j^{<p1>}$ – variable before mutation, ξ – random number with normal distribution, $x_{j\mathrm{d}}$ – lower permissible value of the mutating parameter, $x_{j\mathrm{u}}$ – upper permissible value of the mutating parameter.

Due to the multi-objective optimization problem, deriving the result of the genetic algorithm is a complex process. In the case under consideration, there is no one optimal solution, so it is necessary to check the condition of optimality for each individual from all generations. Thus, for the so assumed structure of the genetic algorithm, the algorithm of searching for a set of compromises is a two-stage process. In the first stage, the genetic algorithm searches for solutions "suspected" of belonging to a set of compromises in the objective space. Then, in the second stage, the condition (2) is checked for each individual and the set of compromises $\mathbf{\Lambda}$ is determined.

3. PSS3B system stabilizers, the method of preliminary parameter determination

PSS3B dual-input power system stabilizers [15, 18], which have two input signals, proportional to the instantaneous (active) power and to the generator angular speed deviation, and a simple structure shown in Fig. 1 are widely used in PS. In each control channel, there are: a derivative element described by transfer function $\dfrac{sT}{1+sT}$ for elimination of a constant component, a correction coefficient of type $\dfrac{1}{1+sT}$ and a gain. Limiting the stabilizer output signal to the range $V_{SMAX} \div V_{SMIN}$ is used to eliminate a significant influence of the stabilizer on the voltage control channel (preventing excessive forcing or reversing of the field voltage).

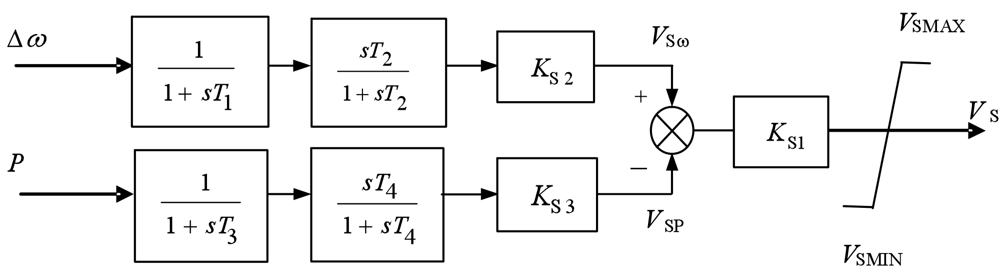

Figure 1: Structural diagram of the dual-input stabilizer PSS3B

During optimization investigations of power system stabilizers with one input signal and dual-input stabilizers PSS2A, the time constants of their correction elements are selected in such a way that the electromagnetic torque component of the generator, controlled by the PSS, has a character of damping torque, and thus it is proportional to the angular speed deviation of the generator [1, 2, 5, 10, 15, 16]. Such optimization of the stabilizer parameters is carried out by compensating the phase angle (argument) of the torque-voltage transfer function (generator electromagnetic torque to the voltage regulator reference voltage) of the system $G_{\mathrm{TV}}\,(s = \mathrm{j}2\pi f) = \dfrac{\Delta T_{\mathrm{e}}}{\Delta V_{\mathrm{ref}}}\,(s = \mathrm{j}2\pi f)$, by the phase angle of the transfer function of the PSS corrector in the frequency range of electromechanical swings [15].

The simple structure of the PSS3B system stabilizer does not allow for the fulfillment of the appropriate compensation condition [15], therefore the parameters of the PSS3B stabilizer must be selected in a different way. In this paper, it is proposed to determine the optimal (polyoptimal) parameters of the PSS3B system stabilizers operating in an extended, multi-machine PS in two stages of calculations, which, among others, is presented in Section 4.

4. Polyoptimization of PSS3B parameters operating in the extended PS

Due to the complexity of phenomena occurring in the power system, the process of optimizing the parameters of power system stabilizers should take into account many criteria related to the damping of electromechanical swings and the limitation of voltage changes in individual generating units during various disturbances of the steady state [15].

Another, worse solution is the optimization of the parameters of PSSs, leading to the minimization of one appropriately defined (e.g. additive or multiplicative) objective function associated with the waveforms in the multi-machine PS [15]. The objective function which is to be minimized in this case must contain various components related to the optimized criteria. One of the basic problems in determining such an objective function is the appropriate selection of the weight coefficients corresponding to the individual components of the function (related, among others, to the waveforms of the instantaneous power and voltage at different points of the PS). There are many ways to determine these coefficients [15]. Additionally, the analysis is complicated by the fact that there are contradictory criteria in the objective function (assumed in this way): the criterion of minimizing changes in the instantaneous power and the criterion of minimizing changes in the terminal voltage of individual generators [15]. The assumed values of the weight coefficients of the objective function significantly affect the final optimization results [15, 17].

The solution to this problem can be the use of multi-criteria optimization. It makes it possible to simultaneously take into account different and contradictory criteria [13, 17]. In multi-criteria optimization, there is a general vector criterion (1), which in the analyzed case for one operating state of the power system and one disturbance can be presented in the form [15, 16]:

$$\mathbf{f} = \begin{bmatrix} \displaystyle\int \Delta P(t)^{(1)}\,\mathrm{d}t \approx \sum_{i=1}^{n} \Delta P_{i1} \\ \vdots \\ \displaystyle\int \Delta P(t)^{(k)}\,\mathrm{d}t \approx \sum_{i=1}^{n} \Delta P_{ik} \\ \vdots \\ \displaystyle\int \Delta P(t)^{(N_i)}\,\mathrm{d}t \approx \sum_{i=1}^{n} \Delta P_{iN_i} \\ \displaystyle\int \Delta V_{\mathrm{T}}(t)^{(1)}\,\mathrm{d}t \approx \sum_{i=1}^{n} \Delta V_{\mathrm{T}i1} \\ \vdots \\ \displaystyle\int \Delta V_{\mathrm{T}}(t)^{(k)}\,\mathrm{d}t \approx \sum_{i=1}^{n} \Delta V_{\mathrm{T}ik} \\ \vdots \\ \displaystyle\int \Delta V_{\mathrm{T}}(t)^{(N_i)}\,\mathrm{d}t \approx \sum_{i=1}^{n} \Delta V_{\mathrm{T}iN_i} \end{bmatrix}, \tag{5}$$

where: ΔP_{ik}, $\Delta V_{\mathrm{T}ik}$ – deviations from the steady values of active power (instantaneous) and generator voltage of the k-th generating unit in the subsequent i-th time instants, $k = 1 \ldots N_i$, N_i – number of the PS generating units (to which power system stabilizers are introduced), dimension of the function f: $nq = 2N_i$.

In order to improve the process of calculating the optimal parameters of the PSS3B system stabilizers, the calculation process was divided into two stages. In the initial stage I, each of the generating units into which power system stabilizers were introduced was analyzed separately, assuming that they operated in single-machine systems of generating unit – infinite bus type. The aim of this stage was to calculate the time constants of the power system stabilizers, the value of which had a smaller influence on the angular stability of the PS, and the initial values of the basic gains (K_{S2} and K_{S3}). At this stage, single-criterion optimization was used for the calculations, because the single-machine system is a simple system, and the correctness of the obtained optimization results can be easily assessed. In the main stage II, by means of multi-criteria optimization related to the multi-machine system, only the gains K_{S2} and K_{S3} were calculated, on which the effectiveness of electromechanical swing damping depends the most. Due to such a division of the calculations, in stage II, the size of the control space $\mathbf{X}$ was significantly reduced during polyoptimization, i.e. the number of simultaneously optimized parameters of the power system stabilizers and thus the time of optimization calculations were significantly reduced.

In stage I, the optimization of the parameters of individual power system stabilizers operating in subsequent generating units in the single machine system was performed by minimizing the deviations of the selected control quantities, such as: generator active power P and generator terminal voltage V_{T}, from their steady values for a typical disturbance in the form of a transient symmetrical short-circuit in the transmission line, which could be brought to the minimization of the indicator determined in the form [15]:

$$f_1(\mathbf{x}_1) = \sum_{i=1}^{n} \left[(w_{\mathrm{p}}|\Delta P_i(\mathbf{x}_1)|)^2 + (w_{\mathrm{V}}|\Delta V_{\mathrm{T}i}(\mathbf{x}_1)|)^2 \right], \tag{6}$$

where: $\mathbf{x}_1$ – vector of the optimized parameters of one power system stabilizer, ΔP_i, $\Delta V_{\mathrm{T}i}$ – active power and voltage deviations of the generator under consideration in successive i-th time instants, w_{P}, w_{V} – weight coefficients.

The optimization calculations were carried out for the following load conditions and typical values of transmission line impedance:

- rated state of the synchronous generator, associated with the initial load $P_0 = 0.85$, $Q_0 = 0.5$ (in relative units),
- $Z_{\mathrm{e}} = R_{\mathrm{e}} + \mathrm{j}X_{\mathrm{e}} = 0 + \mathrm{j}0.3$,
- $Z_{\mathrm{e}} = R_{\mathrm{e}} + \mathrm{j}X_{\mathrm{e}} = 0 + \mathrm{j}0.6$ (in relative units).

In the calculations of stage I (referring to single-machine systems), two significantly different values of the equivalent reactance of the PS were taken into account, assuming that the individual real, equivalent values of these reactances in the multi-machine PS ("seen" from the point of view of individual generating units) were in the range 0.3–0.6 (in relative units). Moreover, it was assumed, for simplification, that the equivalent resistance was equal to 0.

The following values of the weight coefficients were assumed in formula (6): $w_{\mathrm{p}} = 1$, $w_{\mathrm{V}} = 4$. These values resulted from the analysis of the components defining the objective function (6). The relatively large values of w_{V} were assumed due to the need to ensure satisfactory control waveforms of the generator terminal voltage.

In stage I, the following parameters of the power system stabilizers were calculated: time constants T_1, T_2, T_3, T_4 and the initial values of gains K_{S2} and K_{S3}. In the second stage of calculations, the initial values of gains were the basis for assuming the control space, i.e. the ranges in which polyoptimal solutions were sought. The following typical parameter values were assumed as constants: $K_{\mathrm{S1}} = 1$, $V_{\mathrm{SMAX}} = 0.2$, $V_{\mathrm{SMIN}} = -0.066$ for all the power system stabilizers operating in the analyzed PS.

The calculations in stage II were carried out in several variants, relating to various forms of the multivariate objective function for multi-criteria optimization.

5. Description of the analyzed power system and sample optimization calculations

5.1. Description of the power system model

Exemplary calculations were carried out for the Polish Power System (PPS) model. It is a nonlinear model developed in the Matlab/Simulink program environment, including 49 selected generating units operating in high and highest voltage networks and 8 equivalent generating units representing the impact of power systems of the neighboring countries [19] (Fig. 2).

The following models of the generating unit components were taken into account in the PPS model [19]: the GENROU model of a synchronous generator [18], the model of a static [15, 19] or electromachine [15, 19] excitation system operating in the Polish Power System, the model of a steam turbine IEEEG1 [18, 19] or a water turbine HYGOV [18, 19] and, optionally, the model of a power system stabilizer PSS3B [18, 19]. The equivalent generating units were described by the simplified model of a synchronous generator GENCLS [18], neglecting the influence of the excitation system, the turbine, and the power system stabilizer. The above names of synchronous generator models and turbine models are taken from the IEEE standard. On the other hand, it is difficult to assign the appropriate models from this standard to the excitation systems operating in the PPS. They are described in the monograph [15] and in the paper [19].

For the investigated PS, the generating units critical for angular stability were determined: ROG411 (6 units with the rated apparent power 426 MV·A – $S_{\mathrm{N}} = 6 \cdot 426$ MV·A and the rated voltage $V_{\mathrm{TN}} = 400$ kV), KRA214 ($S_{\mathrm{N}} = 2 \cdot 252.8$ MV·A, $V_{\mathrm{TN}} = 220$ kV) and ZRC415 ($S_{\mathrm{N}} = 4 \cdot 209$ MV·A, $V_{\mathrm{TN}} = 400$ kV) based on the criteria presented in [19]. These criteria are determined on the basis of participation factors and correlation coefficients depending on the electromechanical eigenvalues (especially with the largest real parts) and the right and left side eigenvectors of the state matrix associated with them. The electromechanical eigenvalues were calculated on the basis of the analysis of the instantaneous power waveforms of individual synchronous generators at introduction of appropriate disturbances in subsequent generating units [19]. The critical units are marked in bold and underlined in Fig. 2.

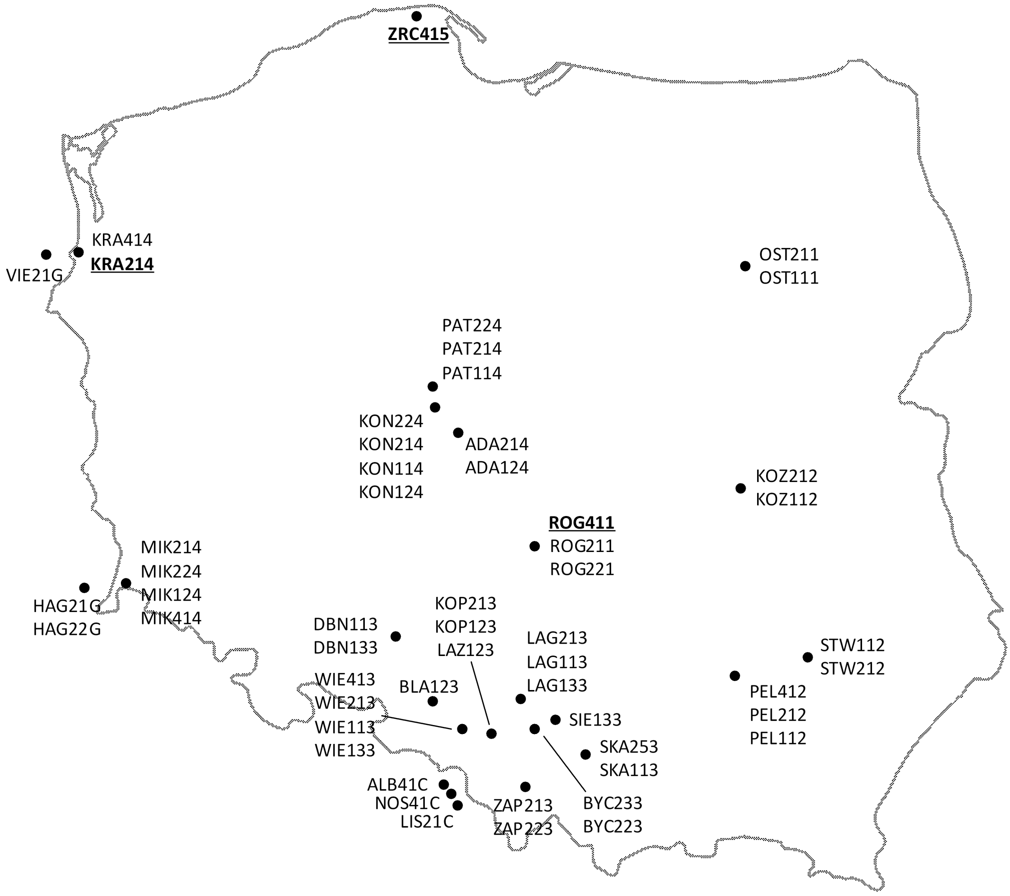

Figure 2: Generating units included in the Polish Power System model

5.2. Optimization calculations of the parameters of system stabilizers – stage I

In the first stage of the calculations, the time constants of the system stabilizers and the initial values of the gains in the critical units of the analyzed PS were determined by minimizing the single objective function (quality index) (6), determined each time for these units. The minimization of the quality index was performed using the Newton gradient algorithm with limitations from the Optimization Toolbox of the Matlab program [9]. This algorithm makes it possible to determine upper and lower limits, ensuring the physical sense of the optimized parameters.

The calculation results of the optimized parameters of the power system stabilizers are presented in Table 1.

Table 1: Calculation results of the PSS3B system stabilizer parameters (stage I)

Generating unit	K_{S2}	K_{S3}	T_1	T_2	T_3	T_4
	–	–	s	s	s	s
ROG411	17.5	0.521	0.097	4.94	0.026	4.905
KRA214	20.0	0.444	0.010	5.00	0.019	5.000
ZRC415	20.0	0.334	0.100	5.00	0.100	0.147

5.3. Variant calculations of the parameters of power system stabilizers for multi-criteria optimization – stage II

In the case of optimization of the parameters of the PSSs installed in a complex PS, many criteria can be included in the objective function. Two variants were selected in the presented research.

In the first variant, the parameters of a single PSS were polyoptimized, when taking into account in the objective function the waveforms of the generating unit with this PSS. Consequently, the control space and the objective space were two-dimensional.

The first analyzed case was the polyoptimization of the power system stabilizer in the generating unit ROG411. The optimized vector objective function was of the form:

$$\mathbf{f}^{<\mathrm{ROG}>} = \begin{bmatrix} f_1\left(K_{\mathrm{S2}}^{<\mathrm{ROG}>}, K_{\mathrm{S3}}^{<\mathrm{ROG}>}\right) \\ f_2\left(K_{\mathrm{S2}}^{<\mathrm{ROG}>}, K_{\mathrm{S3}}^{<\mathrm{ROG}>}\right) \end{bmatrix} = \begin{bmatrix} f_{\mathrm{P}}^{<\mathrm{ROG}>} \\ f_{\mathrm{V}}^{<\mathrm{ROG}>} \end{bmatrix} = \begin{bmatrix} \sum\limits_{i=1}^{n} \Delta P_i^{<\mathrm{ROG}>} \\ \sum\limits_{i=1}^{n} \Delta V_{\mathrm{T}i}^{<\mathrm{ROG}>} \end{bmatrix}, \tag{7}$$

where: $K_{\mathrm{S2}}^{<\mathrm{ROG}>}$, $K_{\mathrm{S3}}^{<\mathrm{ROG}>}$ – optimized parameters of the power system stabilizer, $\Delta P_i^{<\mathrm{ROG}>}$, $\Delta V_{\mathrm{T}i}^{<\mathrm{ROG}>}$ – deviations of the active (instantaneous) power and voltage of the ROG411 generating unit generator in the successive i-th time instants. A disturbance in the form of a symmetrical short-circuit in the transmission line located close to the ROG411 generating unit, with a short-circuit time of 0.1 s, was assumed. Such a disturbance was also assumed for other calculations presented in this subsection.

The optimization results, i.e. the compromise set, the objective function component values determined during polyoptimization of the objective function (7) and the PSS parameters corresponding to the compromise set, are shown in Fig. 3. Additionally, in Fig. 3, two marginal points of the compromise set are marked, i.e. point A, for which the lowest value of the component f_{P} in (7) was obtained and point B, for which the lowest value of f_{V} was obtained.

The next analyzed case was the polyoptimization of the power system stabilizer for the generating unit KRA214. The optimized vector objective function was of

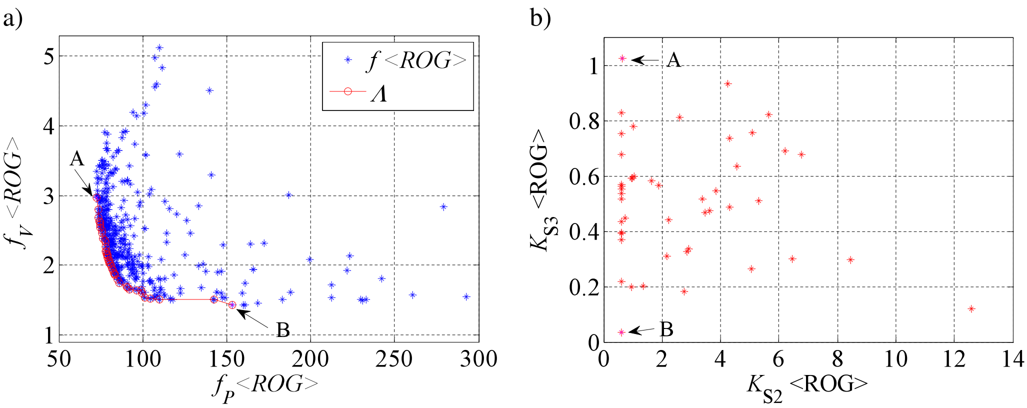

Figure 3: Values of the components of the objective function ($\mathbf{f}^{\text{<ROG>}}$) and the set of compromises $\mathbf{\Lambda}$ (a) and the optimized power stabilizer parameters K_{S2} and K_{S3} corresponding to the compromise set (b) for polyoptimization of PSS in the generating unit ROG411

the form:

$$\mathbf{f}^{\text{<KRA>}} = \begin{bmatrix} f_1\left(K_{\text{S2}}^{\text{<KRA>}}, K_{\text{S3}}^{\text{<KRA>}}\right) \\ f_2\left(K_{\text{S2}}^{\text{<KRA>}}, K_{\text{S3}}^{\text{<KRA>}}\right) \end{bmatrix} = \begin{bmatrix} f_{\text{P}}^{\text{<KRA>}} \\ f_{\text{V}}^{\text{<KRA>}} \end{bmatrix} = \begin{bmatrix} \sum\limits_{i=1}^{n} \Delta P_i^{\text{<KRA>}} \\ \sum\limits_{i=1}^{n} \Delta V_{\text{T}i}^{\text{<KRA>}} \end{bmatrix}, \tag{8}$$

where: $K_{\text{S2}}^{\text{<KRA>}}$, $K_{\text{S3}}^{\text{<KRA>}}$ – optimized parameters of the power system stabilizer, $\Delta P_i^{\text{<KRA>}}$, $\Delta V_{\text{T}i}^{\text{<KRA>}}$ – deviations of the active (instantaneous) power and voltage of the KRA214 generating unit generator in the successive i-th time instants.

The optimization results (compromise set with A and B marginal points marked) for the objective function (8) and the PSS parameters corresponding to the compromise set are shown in Fig. 4. In Fig. 4 (and in Fig. 5), for the sake of clarity, the points related to the calculated values of the components of the objective function are omitted. They are marked in blue in Fig. 3.

The last analyzed case for the two-dimensional objective and control spaces was polyoptimization of the power system stabilizer in the generating unit ZRC415. The optimized vector objective function was of the form:

$$\mathbf{f}^{\text{<ZRC>}} = \begin{bmatrix} f_1\left(K_{\text{S2}}^{\text{<ZRC>}}, K_{\text{S3}}^{\text{<ZRC>}}\right) \\ f_2\left(K_{\text{S2}}^{\text{<ZRC>}}, K_{\text{S3}}^{\text{<ZRC>}}\right) \end{bmatrix} = \begin{bmatrix} f_{\text{P}}^{\text{<ZRC>}} \\ f_{\text{V}}^{\text{<ZRC>}} \end{bmatrix} = \begin{bmatrix} \sum\limits_{i=1}^{n} \Delta P_i^{\text{<ZRC>}} \\ \sum\limits_{i=1}^{n} \Delta V_{\text{T}i}^{\text{<ZRC>}} \end{bmatrix}, \tag{9}$$

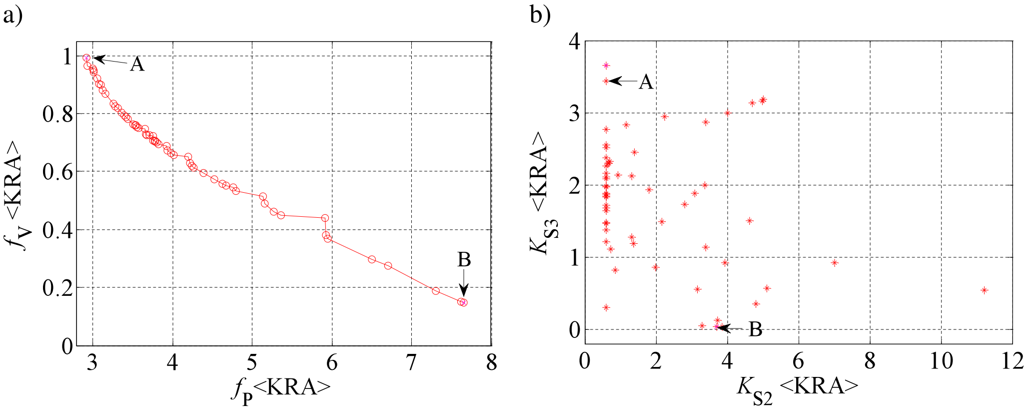

Figure 4: The compromise set (a) and optimized power stabilizer parameters corresponding to the compromise set (b) for polyoptimization of PSS in the KRA214 generating unit

where: $K_{S2}^{<ZRC>}$, $K_{S3}^{<ZRC>}$ – optimized parameters of the power system stabilizer, $\Delta P_i^{<ZRC>}$, $\Delta V_{Ti}^{<ZRC>}$ – deviations of the active (instantaneous) power and voltage of the ZRC415 generating unit generator in the successive i-th time instants.

The optimization results (compromise set with A and B marginal points marked) for the objective function (9) and the PSS parameters corresponding to the compromise set are shown in Fig. 5.

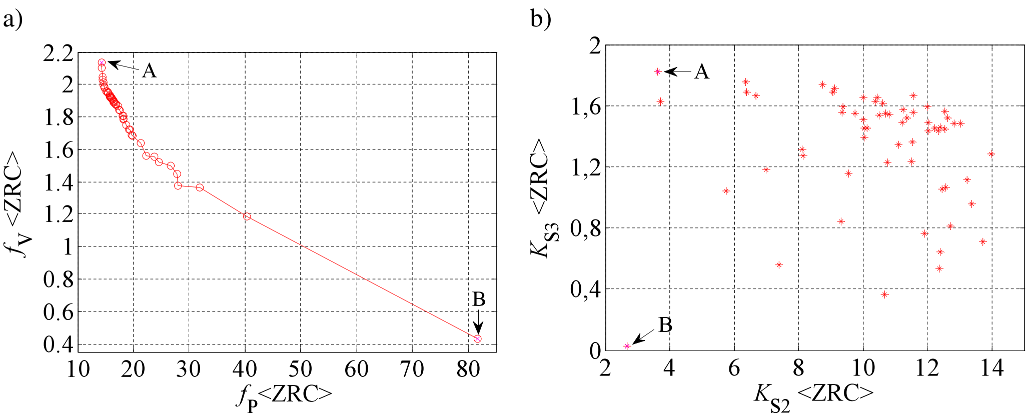

Figure 5: The compromise set (a) and optimized power stabilizer parameters corresponding to the compromise set (b) for polyoptimization of PSS in the ZRC415 generating unit

The values of the optimal gains of the system stabilizers at the compromise set marginal points A and B for the three generating units are presented in Table 2.

Table 2: Calculation results of the gains of the PSS3B system stabilizers (polyoptimization of the two-dimensional objective function)

Generating unit	K_{S2}		K_{S3}	
	–		–	
	point of the compromise set			
	A	B	A	B
ROG411	0.6449	0.6000	1.0257	0.0335
KRA214	0.6000	3.6928	3.6566	0.0300
ZRC415	3.6368	2.6630	1.8248	0.0300

Selected waveforms in the three generating units for the marginal points of the compromise set (according to Table 1) are shown in Figs. 6–8.

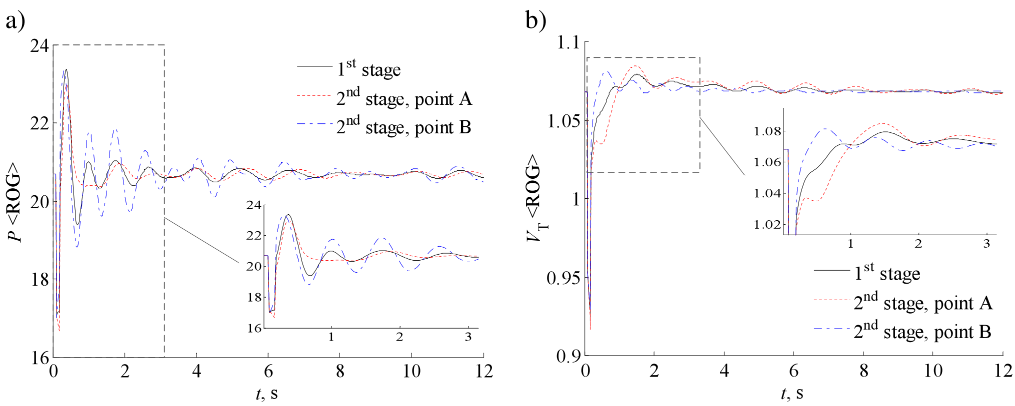

Figure 6: Waveforms of instantaneous power (a) and voltage (b) of the ROG411 generating unit for PSS parameters at the compromise set marginal points A and B

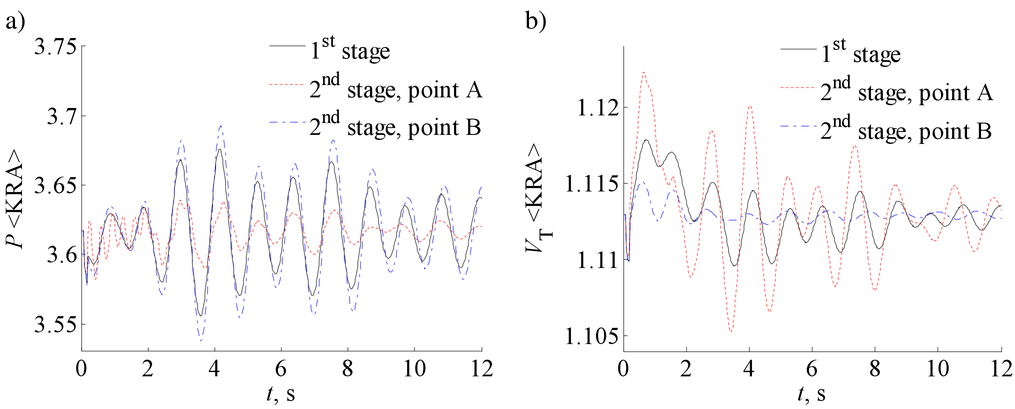

Figure 7: Waveforms of instantaneous power (a) and voltage (b) of the KRA214 generating unit for PSS parameters at the compromise set marginal points A and B

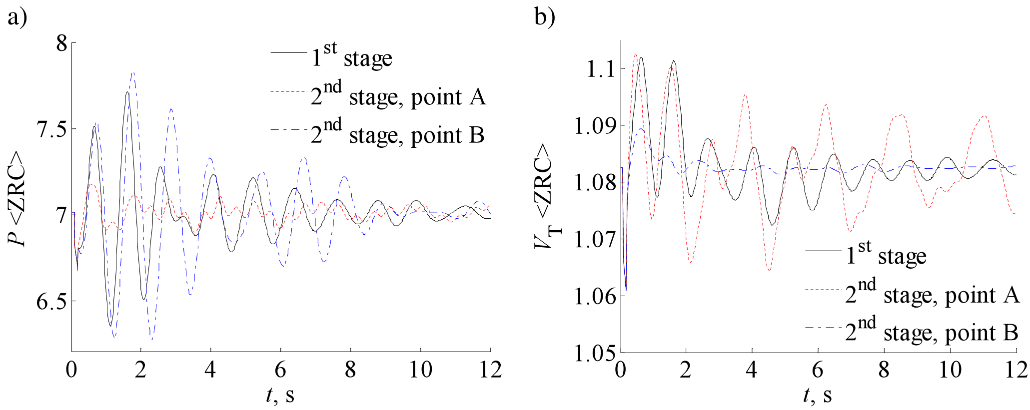

Figure 8: Waveforms of instantaneous power (a) and voltage (b) of the ZRC415 generating unit for PSS parameters at the compromise set marginal points A and B

In the second variant of the calculations, the parameters of the power system stabilizers in the three generating units were simultaneously polyoptimized, when taking into account in the objective function the waveforms in these units. In this case, the control space and the objective space were six-dimensional. The optimized vector objective function was of the form:

$$\mathbf{f} = \begin{bmatrix} f_1\left(K_{\mathrm{S2}}^{\text{<ROG>}}, K_{\mathrm{S3}}^{\text{<ROG>}}\right) \\ f_2\left(K_{\mathrm{S2}}^{\text{<ROG>}}, K_{\mathrm{S3}}^{\text{<ROG>}}\right) \\ f_3\left(K_{\mathrm{S2}}^{\text{<KRA>}}, K_{\mathrm{S3}}^{\text{<KRA>}}\right) \\ f_4\left(K_{\mathrm{S2}}^{\text{<KRA>}}, K_{\mathrm{S3}}^{\text{<KRA>}}\right) \\ f_5\left(K_{\mathrm{S2}}^{\text{<ZRC>}}, K_{\mathrm{S3}}^{\text{<ZRC>}}\right) \\ f_6\left(K_{\mathrm{S2}}^{\text{<ZRC>}}, K_{\mathrm{S3}}^{\text{<ZRC>}}\right) \end{bmatrix} = \begin{bmatrix} f_{\mathrm{P}}^{\text{<ROG>}} \\ f_{\mathrm{V}}^{\text{<ROG>}} \\ f_{\mathrm{P}}^{\text{<KRA>}} \\ f_{\mathrm{V}}^{\text{<KRA>}} \\ f_{\mathrm{P}}^{\text{<ZRC>}} \\ f_{\mathrm{V}}^{\text{<ZRC>}} \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n} \Delta P_i^{\text{<ROG>}} \\ \sum_{i=1}^{n} \Delta V_{\mathrm{T}i}^{\text{<ROG>}} \\ \sum_{i=1}^{n} \Delta P_i^{\text{<KRA>}} \\ \sum_{i=1}^{n} \Delta V_{\mathrm{T}i}^{\text{<KRA>}} \\ \sum_{i=1}^{n} \Delta P_i^{\text{<ZRC>}} \\ \sum_{i=1}^{n} \Delta V_{\mathrm{T}i}^{\text{<ZRC>}} \end{bmatrix}. \tag{10}$$

The result of polyoptimization of the objective function (10), due to the dimensions of the objective and control space, can be graphically presented as projections of the six-dimensional space onto planes determined by the appropriate pairs of the components of the objective function (e.g., for the generating unit ROG411, it is the plane $f^{<\mathrm{ROG}>}$ determined by $f_{\mathrm{P}}^{<\mathrm{ROG}>}$ and $f_{\mathrm{V}}^{<\mathrm{ROG}>}$). For the analyzed case, such projections are shown in Fig. 9.

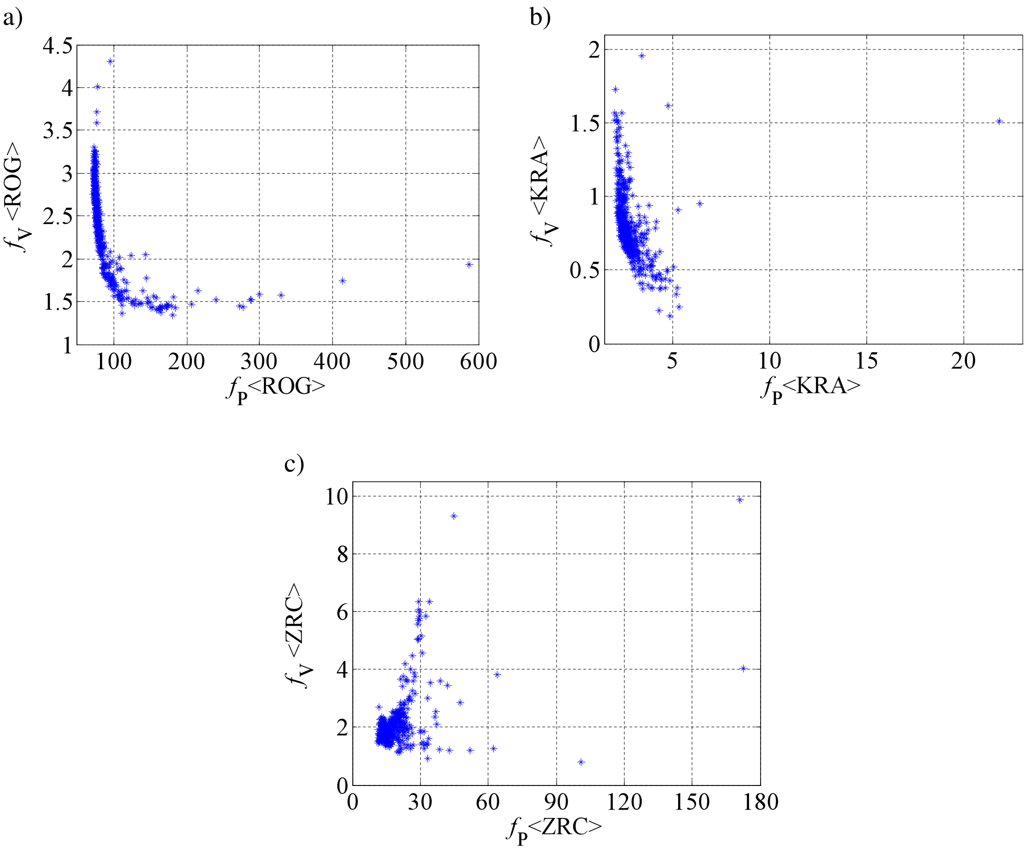

Figure 9: Projections of the six-dimensional set of compromises on the planes

Comparison of the compromise sets determined for the two-dimensional objective functions ((7)–(9)) with the optimization results of the six-dimensional objective function (10) is interesting from the point of view of the evaluation of the obtained optimization results. For this purpose, the boundaries of the projections of the six-dimensional compromise set on the corresponding two-dimensional objective spaces $\overline{\mathbf{\Lambda}^{<6>}}$ were additionally determined. The comparison results (two-dimensional compromise sets, projections of the six-dimensional compromise set and their boundaries are presented in Figs. 10–12.

Moreover, the marginal points of the boundaries of the projections of the six-dimensional set of compromises on the appropriate two-dimensional spaces were determined. In Figs. 10–12, these points are marked with letters C and D.

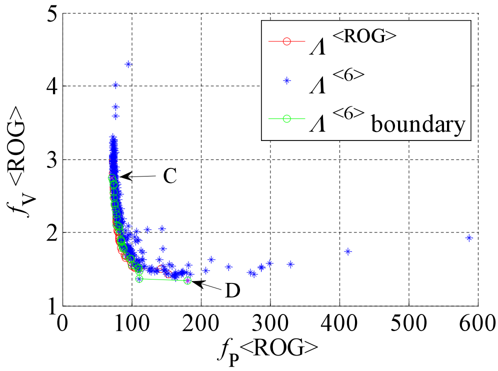

Figure 10: Comparison of the six-dimensional set of compromises $\mathbf{\Lambda}^{<6>}$ and its two-dimensional boundary $\overline{\mathbf{\Lambda}^{<6>}}$ with the two-dimensional set of compromises $\mathbf{\Lambda}^{<ROG>}$ on the plane $f^{<ROG>}$

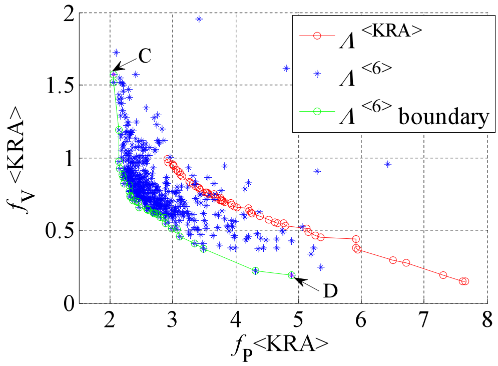

Figure 11: Comparison of the six-dimensional set of compromises $\mathbf{\Lambda}^{<6>}$ and its two-dimensional boundary $\overline{\mathbf{\Lambda}^{<6>}}$ with the two-dimensional set of compromises $\mathbf{\Lambda}^{<KRA>}$ on the plane $f^{<KRA>}$

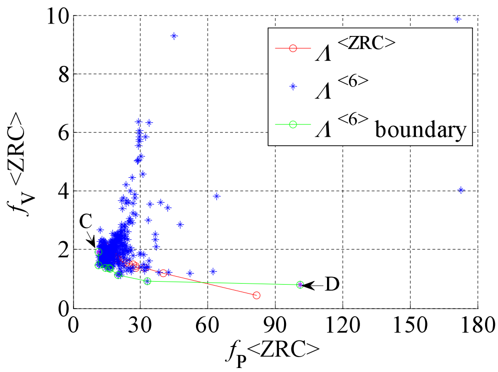

Figure 12: Comparison of the six-dimensional set of compromises $\mathbf{\Lambda}^{<6>}$ and its two-dimensional boundary $\overline{\mathbf{\Lambda}^{<6>}}$ with the two-dimensional set of compromises $\mathbf{\Lambda}^{<ZRC>}$ on the plane $f^{<ZRC>}$

The values of the corresponding gains are given in Table 3. The instantaneous power and voltage waveforms in the analyzed PS generating units corresponding to these points are presented in Figs. 13–15.

Table 3: Calculation results of the gains of the PSS3B system stabilizers (polyoptimization of the two-dimensional objective function)

Projection area	Generating unit	K_{S2}		K_{S3}	
		-		-	
		point of the compromise set			
		C	D	C	D
$f^{<ROG>}$	ROG411	4.0438	9.0716	0.8870	0.0300
	KRA214	14.663	11.477	1.3992	1.6235
	ZRC415	6.0572	79.096	0.2913	4.000
$f^{<KRA>}$	ROG411	10.302	14.662	0.8735	0.6884
	KRA214	80.000	6.4255	2.637	0.0300
	ZRC415	12.438	1.5667	1.589	3.4812
$f^{<ZRC>}$	ROG411	28.563	28.225	2.0254	0.4075
	KRA214	17.186	19.816	2.3877	1.6118
	ZRC415	18.108	5.2259	1.9310	0.0300

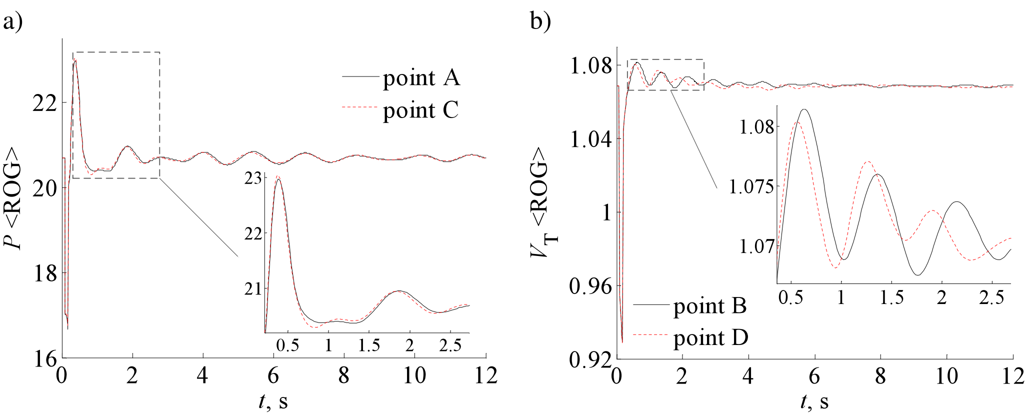

Figure 13: Voltage and instantaneous power waveforms of the ROG411 generating unit for the PSS parameters at the compromise set marginal points: A and C (a), B and D (b) from Figs. 3 and 10

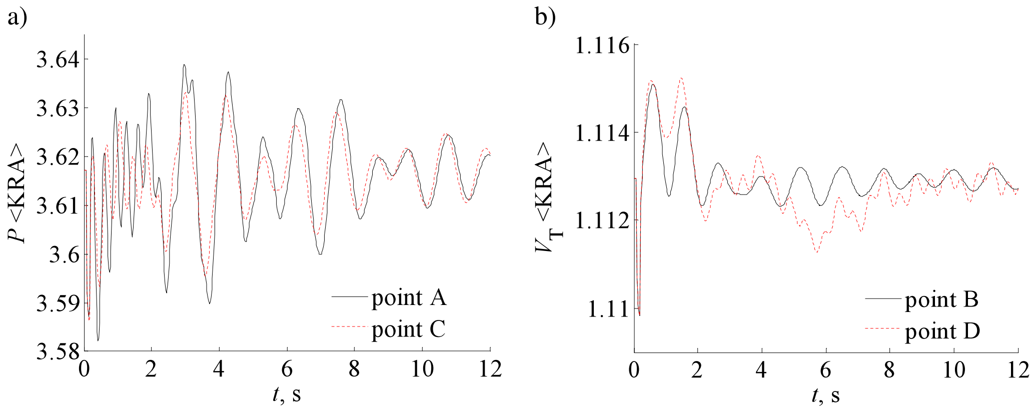

Figure 14: Voltage and instantaneous power waveforms of the KRA214 generating unit for the PSS parameters at the compromise set marginal points: A and C (a), B and D (b) from Figs. 4 and 11

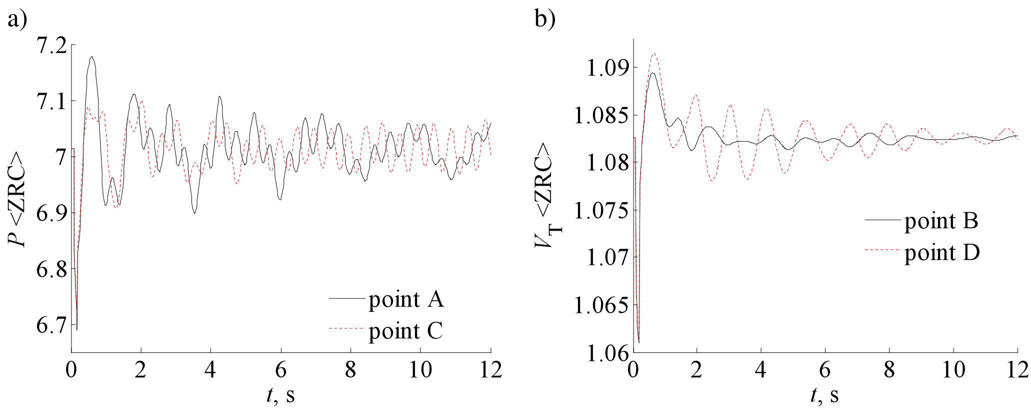

Figure 15: Voltage and instantaneous power waveforms of the ZRC415 generating unit for the PSS parameters at the compromise set marginal points: A and C (a), B and D (b) from Figs. 5 and 12

6. Summary and conclusions

In the paper, the application of multi-criteria optimization of the parameters of PSS3B system stabilizers to damping electromechanical swings in an extended power system is presented. For the sake of simplicity, the calculations were divided into two stages. In the first stage, the generating units critical for the angular stability of the PS were analyzed separately. The time constants and the initial values of the gains of the power system stabilizers were calculated by analyzing single-machine systems (generating unit – infinite bus), for these units and minimizing the objective function (6). In the main second stage, by means of multi-criteria optimization related to the extended PS, there were calculated only the gains K_{S2} and K_{S3}, on which the effectiveness of PSSs operation depends the most, thus the size of the control space during polyoptimization was limited. In the second stage, the calculations were carried out in several variants: for the two-dimensional objective functions (determined by the instantaneous power and voltage waveforms for the three critical generating units at the three-phase transient short-circuit in the selected transmission line) and for the six-dimensional objective function (determined by the instantaneous power and voltage waveforms in these three critical generating units). In multi-criteria optimization, the solution is not a single set of variables, i.e. the parameters of power system stabilizers, but a set of sets of these parameters, i.e. a set of compromises that have been determined for each analyzed case. In the investigations, for the six-dimensional compromise set, projections of this set on the planes related to the sizes of individual generating units and the boundary of these projections on these planes were determined additionally.

Based on the performed analyzes and the presented calculation results, the following conclusions can be drawn:

- Despite their simple structure, power system stabilizers can damp electromechanical swings well in an extended power system without significant worsening the voltage waveforms in generating units. However, it is necessary to correctly determine their parameters.
- By analyzing single-machine systems, generating unit – infinite bus (taking into account generating units critical for angular stability), it is possible to determine a set of PSS parameters for which the analyzed waveforms of instantaneous power and nodal voltages in a multi-machine PS are satisfactory (Figs. 6–8).
- By using multi-criteria optimization of the parameters of power system stabilizers, the waveforms of instantaneous power and voltages in generating units can be further improved.
- The use of multi-criteria methods in the optimization process allows taking into account many (in the presented research 2 or 6 criteria), sometimes contradictory requirements, without losing the ability to achieve an optimal solution.
- The criteria related to voltage deviations are rather contradictory to the criteria related to instantaneous power waveforms, i.e. electromechanical swings. When power swings are well damped, significant voltage deviations usually occur (the waveforms related to point A in Figs. 6–8) and vice versa (the waveforms related to point B in Figs. 6–8). By analyzing the determined compromise set shown in Figs. 4a and 5a, the almost linear relationship

between the voltage criteria f_V and the power criteria f_P can be seen. When one of the criteria is corrected, the other deteriorates proportionally. However, there may be a situation (as in Fig. 3) when in the compromise set there are ranges for which large changes in the criterion $f_P^{\text{<ROG>}}$ occur at only slight changes in the criterion $f_V^{\text{<ROG>}}$ and vice versa. Thus, it is possible to find the controls (values of power system stabilizer parameters) for which the damping of electromechanical swings improves significantly at only slight deterioration of the voltage waveforms.

- For correctly performed polyoptimization, it is possible to choose such a solution for which all criteria are satisfied to a satisfactory degree. It is also possible to choose a solution that better meets the criteria which, in the case under consideration, are more important than the others.
- Polyoptimization, in terms of the mathematical methods used, is more difficult than optimization. It requires the use of more complex tools. Above all, however, it makes it difficult to interpret the results. However, it allows obtaining better results, i.e. selecting the system stabilizers which damp the waveforms better.
- It can be assumed that increase in the dimension of the objective function allows obtaining better results. This is confirmed by the comparisons of the two- and six-dimensional compromise sets (Figs. 10–12). These figures show that some points of the six-dimensional compromise set projection are to the left and below the two-dimensional compromise set. These points therefore improve both criteria at the same time. This is confirmed by the waveforms obtained for these marginal points, e.g. the power waveform for point C in Fig. 14a is better damped than that for point A, and the voltage waveform for point D in Fig. 15b has smaller deviations from the steady value than that for point C.
- The modified genetic algorithm used allows determining the parameters of many power system stabilizers simultaneously.

Further research may take into account the influence of the uncertainty of extended PS mathematical model parameters on polyoptimal parameters of power system stabilizers by, among others, formulating appropriate deformation factors [16].

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