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Analysis of power system stabilizer Pareto optimisation when taking into account the uncertainty of power system mathematical model parameters

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Abstract: The paper presents analysis of optimisation results of power system stabilizer (PSS) parameters when taking into account the uncertainty of mathematical model parameters of the power system (PS) elements. The Pareto optimisation was used for optimisation of the system stabilizer parameters. Parameters of five stabilizers of PSS3B type were determined in optimisation process with use of a genetic algorithm with tournament selection. The results obtained were assessed from the point of view of selecting the criterion function. The analysis of influence of the parameter uncertainty on the quality of the results obtained was performed.

Key words: power system stabilizer, Pareto optimisation, parameter uncertainty

1. Introduction

Nowadays the number of new types of electric sources of higher and higher power increases in the power system (PS). They are mostly renewable sources (for instance wind power plants) which influence the power system (voltage and angular) stability. Hence, investigations on the system stability from this point of view become necessary. The investigation results can be used for estimation of the PS stability margin as well as for design of new structures of regulation systems, including power system stabilizers (PSSs), operating in PS.

The performing of appropriate analyses is connected with the necessity of determining the reliable parameters of mathematical models used for computer modelling of the investigated system. Different kinds of mathematical models of the system elements, in particular the generating unit elements, are used for computations [4, 6]. For estimation of their parameters there are often used the waveforms recorded during the transient states of the object modelled. In that case, the problem of parameter estimation is brought to minimisation of the objective function determined by the difference between the true waveforms at particular time instants and the simulation waveforms resulting from the generating unit element model.

The modelling errors arise during the parameter estimation of the mathematical model. They are caused by:

- errors resulting from non-adequacy of the model (simplifications used in mathematical description),
- errors resulting from minimisation of the objective function (non-adequacy of the objective function, ineffectiveness of the optimisation method used),
- numerical errors.

The modelling errors arisen in the estimation process influence unfavourably the quality of the system stability analysis. That problem can be solved, among others, by taking into account the uncertainty of the model parameters in the system stability analyses.

The paper presents a method for design of PSSs which takes into consideration the uncertainty of the mathematical model parameters of PS elements. The multicriteria optimisation (optimisation in Pareto sense) [2, 3, 5] was used for tuning the PSS parameters. In the optimisation process there were determined the parameters of five PSS3B stabilizers [8]. The number of the parameters optimised was equal to 30 (five stabilizers, six parameters for each one). The genetic algorithm with selection by the tournament method was used for optimisation.

The results obtained from the optimisation were assessed from the point of view of selecting the objective function. The analysis of the influence of the parameter uncertainty on the quality of the results obtained was performed.

2. Mathematical model of PS

Exemplary calculations concerning PPS parameter optimisation were carried out for a selected fragment of the Polish PS (PPS). The fragment analysed contained 277 nodes, in that 122 generating nodes, 59 real energy sources (traditional large power system plants, heat and power plants and distributed sources) as well as 63 equivalent sources being the equivalent of the PPS non-analysed part and 155 load nodes connected through the power network with transmission lines of 400, 220 and 110 kV. The simplified diagram of the system analysed is shown in Figure 1. In the figure there are marked connections of the generating units equipped with the optimised PSSs (G1-G5). Moreover, there are marked lines in which there were modelled short-circuits during investigations (lines L1 and L2).

In the calculations made, the generating units of the system power plants were represented by a sixth-order synchronous generator model of GENROU type which was equipped with the EXAC1 electromachine excitation system and driven by a steam turbine of IEEEG1 model. In order to limit the number of variables, there was assumed a simplified model of generating units representing the equivalent part of PPS in the form of a second order generator of GENCLS model. In the same way there were modelled the generating units of distributed, non-wind sources. Besides, it was assumed that all wind power plants working in the selected fragment of the system were equipped with asynchronous induction generators controlled by a change of resistance in the rotor circuit (generator of GENWRI model, controlled rotor resistance of EXWTG1 model and wind turbine of WNDTRB model).

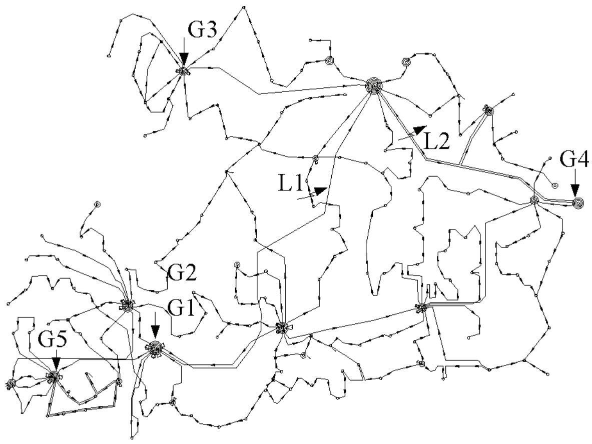

Fig. 1. Simplified diagram of the PS fragment analysed

Commonly used, two-input power system stabilizers of PSS3B type of structure shown in Figure 2 were assumed to stabilize the system. For such a type of stabilizers the input signals are proportional to instantaneous power $p(t)$ and generator speed deviation $\Delta\omega(t)$. The PSS parameters are: inertial element time constant T_1, differential element time constant T_2 and gain K_1 in the speed deviation channel as well as inertial element time constant T_3, differential element time constant T_4 and gain K_2 in the power channel.

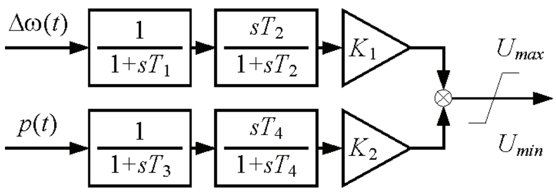

Fig. 2. Structural diagram of PSS3B stabilizer

In the calculations carried out, symmetrical three-phase short-circuits in lines L1 (110 kV) and L2 (220 kV) of duration time equal to 150 ms were assumed to be disturbances in the system operation. The generating units G1-G5, in which PSSs were installed, are connected to the 220 kV transmission lines. Due to it, for a short-circuit in the line L1 the changes of appropriate quantities during disturbances in those units are much less than those for a short-circuit in the line L2.

3. Multi-criteria optimisation

3.1. Multi-criteria objective function

Due to comlexity of phenomena occurring in the power system, the process of PSS optimisation should take into account many criteria associated with the damping of electromechanical swings and the limiting of voltage changes in particular generating units during different disturbances of the steady state [7-9]. Therefore the objective function being minimised has to contain different components connected with the optimised criteria. That function can be given in the form:

$$Q = \sum_{j=1}^{M} \sum_{i=1}^{N} \left\{ w_p{}^{(j,i)} \int \Delta p(t)^{(j,i)} \mathrm{d}t + w_u{}^{(j,i)} \int \Delta u(t)^{(j,i)} \mathrm{d}t \right\}, \tag{1}$$

where: $\Delta p(t)^{(j,i)}$, $\Delta u(t)^{(j,i)}$ – deviations of the instantaneous power and terminal voltage of the i-th generator for the j-th disturbance, $w_p{}^{(j,i)}$, $w_u{}^{(j,i)}$ – weight coefficients, N – number of the generating units, $M = L \cdot K$, K – number of the system load states considered, L – number of the steady state disturbances considered.

It is best to take into account in the objective function (1) such disturbances which can be most threatening to the system stability. They are, for instance, short-circuits in the transmission lines close to the generating units whose participation factors for electromechanical eigenvalues (of the linearised system model) responsible for the less damped modes are highest [7, 8].

One of the basic problems when determining the objective function (1) is appropriate selection of the weight coefficients corresponding to particular components of that function. Additionally, the analysis is complicated by the fact that in the so assumed objective function there are criteria contradictory to each other: criterion of minimisation of the instantaneous power changes and criterion of the terminal voltage changes of particular generators [8]. The assumed values of those weight coefficients influence significantly the final results of optimisation.

The solution to that problem can be application of multi-criteria optimisation (polyoptimisation, optimisation in Pareto sense). The Pareto optimisation enables taking into account different and contradictory criteria simultaneously [2, 3, 5, 10]. In the multi-criteria optimisation there is the so-called vector criterion (instead of one objective function) which for one PS operating conditions and one disturbance can be given in the form:

$$Q = \begin{cases} Q_1 \\ Q_2 \\ \vdots \\ Q_m \end{cases} = \begin{cases} \int \Delta p(t)^{(1)} \mathrm{d}t \\ \vdots \\ \int \Delta p(t)^{(N)} \mathrm{d}t \\ \int \Delta u(t)^{(1)} \mathrm{d}t \\ \vdots \\ \int \Delta u(t)^{(N)} \mathrm{d}t \end{cases} \tag{2}$$

In the case of selection of PSS parameters, Pareto optimisation result is a set of optimal solutions, the so-called compromise set (in the case of classical optimisation, the solution is one set of searched parameters of the optimised stabilizers). The optimal solutions $\{\tilde{Q}_1, \tilde{Q}_2, \cdots, \tilde{Q}_m\}$ fulfilling the relation (3) belong to the compromise set $\mathbf{\Lambda}$, where m determines the number of criteria optimised in the objective space $\mathbf{Q}$.

$$\left\{\tilde{Q}_1, \tilde{Q}_2, \cdots, \tilde{Q}_m\right\} \in \mathbf{\Lambda} \Leftrightarrow \neg\exists \left\{Q_1, Q_2, \cdots, Q_m\right\} \in \mathbf{Q} \tag{3}$$

where

$$\begin{Bmatrix} Q_i \le \tilde{Q}_i & \text{for each} & i \in \langle 1, 2, \cdots, m\rangle \\ Q_i < \tilde{Q}_i & \text{for at least one} & i \in \langle 1, 2, \cdots, m\rangle \end{Bmatrix},$$

where the symbol $\neg\exists$ denotes does not exist.

An important problem in the optimisation process is possibility of assessing the obtained solution from the point of view of the influence of a disturbing factor such as, for instance, changes of the system operating conditions or the uncertainty of the system mathematical model parameters. Assessment of the solutions and possible comparison with other solutions is usually performed by analysis of the investigated factor influence on the factor (objective function) value assumed for optimisation. Such assessment can be made for both classical one-criterion and Pareto optimisation.

3.2. Genetic algorithm in Pareto optimisation

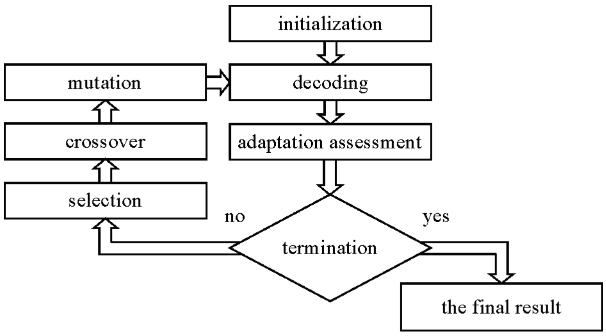

Fig. 3. Genetic algorithm structure

Numerical algorithms are used for classical and Pareto optimisation. They enable calculations of a single or vector objective function and its minimisation. There can be distinguished algorithms for searching local extrema (for instance gradient methods) and global algorithms (for instance genetic and hybrid algorithms) [1]. In the investigations presented there was used a genetic algorithm of structure shown in Figure 3 adapted to optimise many criteria simultaneously.

Adaptation of the genetic algorithm to multi-criteria optimisation consisted in modification of the selection method. In calculations there was applied tournament selection of m simultaneous tournaments (where m is the number of the optimised criteria). The modified tournament method structure is shown in Figure 4.

In the investigations presented there was performed the Pareto optimisation for two vector objective functions. In the first case, there was analysed the two criteria objective function, in the second case – the three criteria one. More complex functions (more criteria than 3) are not analysed in the paper, because of limited possibilities of clear graphical presentation of results.

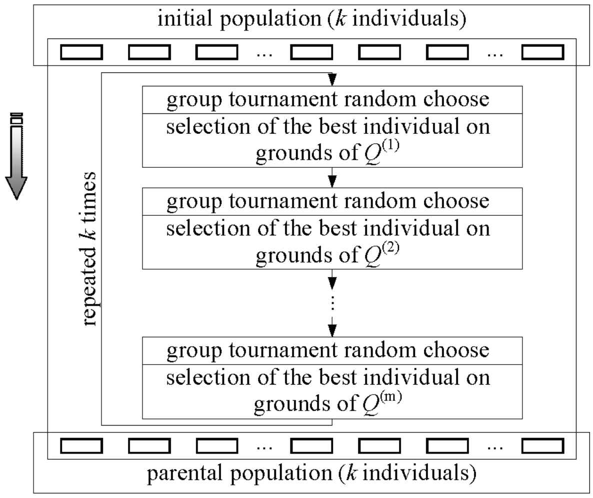

Fig. 4. Modified tournament selection structure

For both objective functions analysed there were assumed the following parameters of the genetic algorithm: population of 16 individuals ($k = 16$), crossover probability equal to 0.9, mutation probability equal to 0.05, tournament group of 4 individuals. The genetic algorithm was stopped after 40 generations, and the final result was determined by verifying the condition (3) for all individuals in all generations.

4. Example of PSS pareto optimisation

For the system considered the simplest case of the Pareto optimisation is two criteria optimisation according to the relationship:

$$Q = \begin{cases} Q_1 \\ Q_2 \end{cases} = \begin{cases} \sum_{i=1}^{5} \int \Delta p(t)^{(i)} \mathrm{d}t \\ \sum_{i=1}^{5} \int \Delta u(t)^{(i)} \mathrm{d}t \end{cases} \tag{4}$$

where each criterion is an additive function determining: the degree of damping the instantaneous power swings and the degree of voltage changes of all analysed generators for one concrete disturbance.

As a result of optimisation for disturbances in the form of short-circuit in lines L1 and L2, there were determined two different compromise sets which create 15 and 6 optimal Pareto solutions Λ, respectively. They are presented in Figures 5 and 6. Moreover, in these figures there are shown the points determined during the optimisation process.

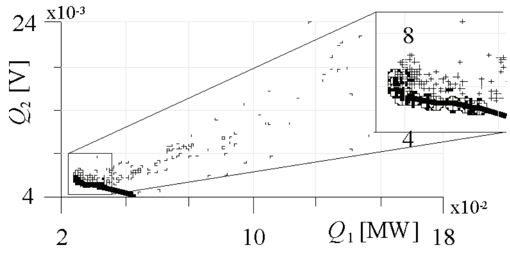

Fig. 5. Set of optimal Pareto solutions for short-circuit in line L1 (110 kV) when optimising criterion (4)

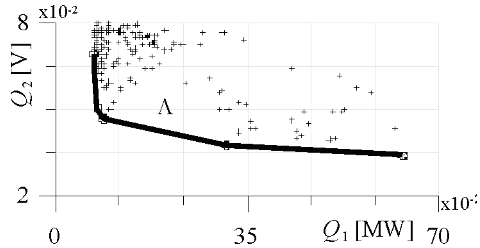

Fig. 6. Set of optimal Pareto solutions for short-circuit in line L2 (220 kV) when optimising criterion (4)

The second case considered is optimisation of the three criteria objective function. The criteria assumed for investigations were related to the instantaneous power changes of one selected generator, voltage changes of this generator as well as a sum of power and voltage changes (given in relative units) of the other generators.

The analysis was performed for two generating units G3 and G5. The form of the objective function for the generating unit G3 is given by the relationship (5), and for the generating unit G5 – by the relationship (6). The appropriate sets of the optimal Pareto solutions are shown in Figures 7-10.

$$\begin{cases} Q_1 \\ Q_2 \\ Q_3 \end{cases} = \begin{cases} \int \Delta p(t)^{(3)} \mathrm{d}t \\ \int \Delta u(t)^{(3)} \mathrm{d}t \\ \sum\limits_{i=1,2,4,5} \int \Delta p(t)^{(i)} \mathrm{d}t + \sum\limits_{i=1,2,4,5} \int \Delta u(t)^{(i)} \mathrm{d}t \end{cases} \tag{5}$$

$$\begin{cases} Q_1 \\ Q_2 \\ Q_3 \end{cases} = \begin{cases} \int \Delta p(t)^{(5)} \mathrm{d}t \\ \int \Delta u(t)^{(5)} \mathrm{d}t \\ \sum\limits_{i=1,2,3,4} \int \Delta p(t)^{(i)} \mathrm{d}t + \sum\limits_{i=1,2,3,4} \int \Delta u(t)^{(i)} \mathrm{d}t \end{cases} \tag{6}$$

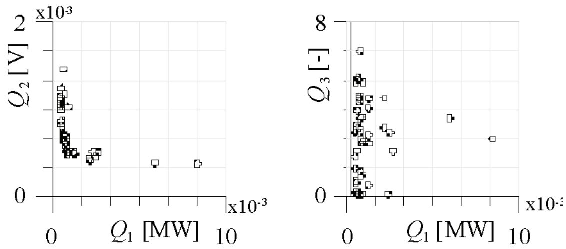

Fig. 7. Set of optimal Pareto solutions for short-circuit in line L1 (110 kV) when optimising criterion (5)

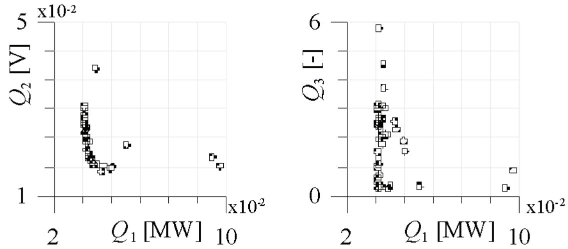

Fig. 8. Set of optimal Pareto solutions for short-circuit in line L2 (220 kV) when optimising criterion (5)

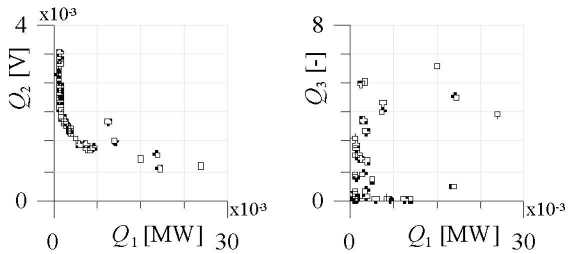

Fig. 9. Set of optimal Pareto solutions for short-circuit in line L1 (110 kV) when optimising criterion (6)

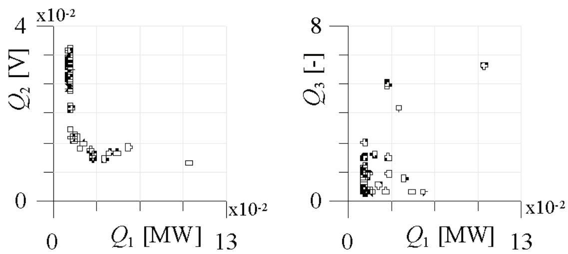

Fig. 10. Set of optimal Pareto solutions for short-circuit in line L2 (220 kV) when optimising criterion (6)

5. Influence of PS parameter uncertainty on optimisation results

The optimal solution (adjustment of the control system parameters, in the considered case the PSS parameters) determined on the basis of numerical (simulation) methods, is not usually optimal in a real system. The errors of representing a real control object by a model assumed for calculations are one of the basic reasons for it. The representation errors are due to, among others, the simplified assumptions taken (for instance, neglecting the regulation object nonlinearity) and inaccuracy (uncertainty) of determining the regulation object mathematical model parameters.

Then, it is recommended to limit the influence of the model representation inaccuracy at the stage of optimisation of regulator parameters, in the considered case – of PSS parameters. This limitation can be made in two ways. Firstly, by making the system mathematical model more accurate (for instance, by careful estimation of its parameters), which is not always possible to be realised for technical reasons. Secondly, by making the optimised stabilizers robust to the influence of unfavourable factors. The second solution is usually realised by replacing the classical stabilizers with the robust ones whose parameters are determined, for instance, basing on the artificial neuron network theory. Such a solution can be troublesome also for technical reasons (for instance, due to the cost of a device realising the robust control algorithm). The other solution is selection of the tuning of classical stabilizers so that their robustness is increased. It is made by assessment of the influence of unfavourable factors on optimal solutions and choice of the most robust solutions for realisation. This method transfers technical problems from the realisation field (accurate measurement of parameters, realisation of a complex control algorithm) to the field of theoretical analysis (optimisation with taking into account unfavourable factors).

One of the methods for assessing the influence of unfavourable factors on the optimal solutions is determination of the optimised criterion changes under influence of these factors for the assessed solution [5]. After performing assessment for many solutions, the selection of the most robust solution is possible. Such a method is troublesome for one criterion optimisation due to the lack of alternative solutions. However, it is not a problem for optimisation in Pareto sense, since its result is a set of alternative optimal solutions [5].

In the presented investigations such assessment was made through investigating the influence of PS mathematical model parameter changes on the optimised criteria values. The PS mathematical model parameter changes assumed for analysis correspond to the assumed uncertainty of determining these parameters by numerical estimation [4, 6]. It was assumed in calculations that the probability of changes of all transmission line parameters (line reactances and resistances) as well as all generating unit parameters (time constants, gains and so on) equals 0.6. The new values of the parameters being changed were determined according to the relationship:

$$X = X_0 + \Delta x_{\%}\,, \tag{6}$$

where: X – changed parameter value; X_0 – initial value of the changed parameter (the value for which PSSs were optimised); $\Delta x_{\%}$ – random value of the parameter change of the normal distribution from the range $\pm 25\%$.

The influence of PS parameter changes on the criteria values was assessed using the relative change factor of the criterion value determined for particular k-th optimal solutions from the relationship:

$$\Delta Q_{1,2,3}{}^{(k)} = \frac{Q_{1,2,3}{}^{(k)} - \tilde{Q}_{1,2,3}{}^{(k)}}{\tilde{Q}_{1,2,3}{}^{(k)}} \tag{7}$$

According to the formula (7), there were determined 50 values of the change factor ΔQ ($n = 50$ random changes of PS parameters) for each optimal point. In consequence of it, in order to assess the concrete optimal solution, there was calculated the change factor ΔQ value which reached 10, 50 and 90% of the all results. Figure 11 shows graphical interpretation of these values.

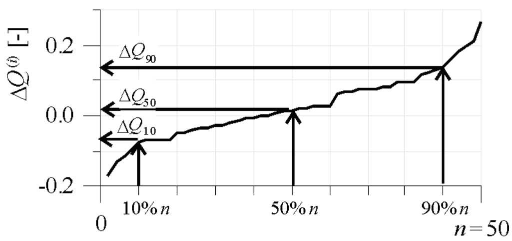

Fig. 11. Graphical interpretation of factors ΔQ

The factors for particular optimal solutions determined from formula (7) are presented in Figures 12-15.

From the factor values shown, it follows that there exist such optimal solutions (PSSs tuning) for which the PS analysed is more robust to changes of the PS parameters – in Figures 12-15 the areas in which the values of factors ΔQ_{10}, ΔQ_{50} and ΔQ_{90} are close to each other.

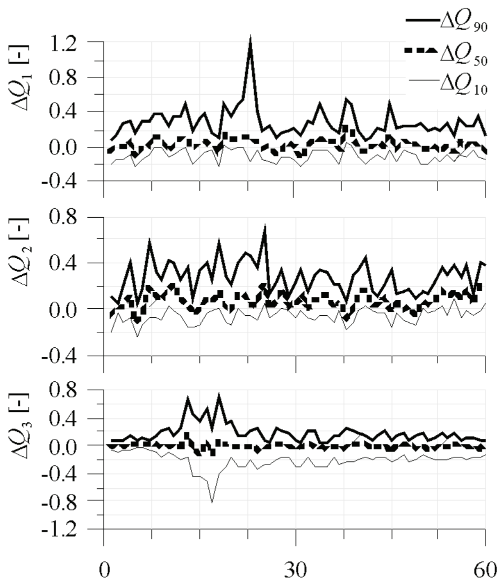

Fig. 12. Change factors of the Pareto optimal solution criteria for short-circuit in line L1 (110 kV) when optimising criterion (5)

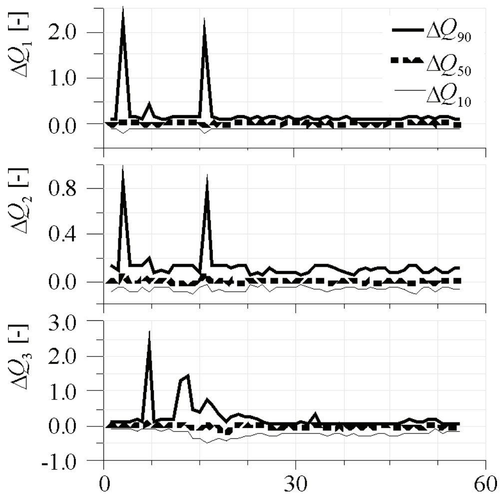

Fig. 13. Change factors of the Pareto optimal solution criteria for short-circuit in line L2 (220 kV) when optimising criterion (5)

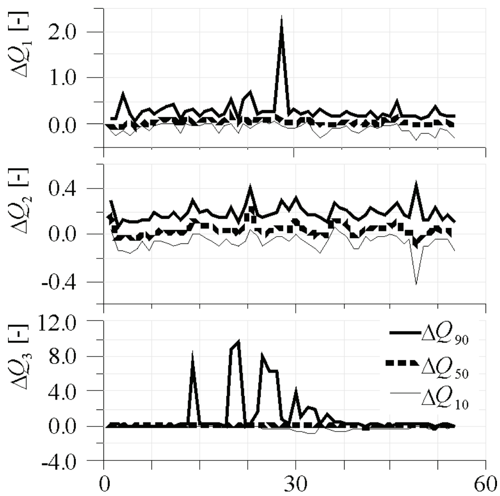

Fig. 14. Change factors of the Pareto optimal solution criteria for short-circuit in line L1 (110 kV) when optimising criterion (6)

Figures 16 and 17 present exemplary waveforms of the instantaneous power and terminal voltage of the generator G3 for the system without PSSs and with PSSs of the parameters optimised according to the criterion (5). These waveforms were determined for the PS of initial parameters (for which PSSs were optimised – Fig. 16) and those of changed parameters (Fig. 17) for a disturbance in the form of a short-circuit in the line L2 (220 kV). For both sets of PS parameters there were determined the waveforms when using "robust" and "non-robust" stabilizers. From the waveforms presented it can be seen that the stabilizers "robust" to the PS parameter changes damp the electromechanical swings well without worsening the generator voltage regulation waveforms for different parameters of the system analysed. The "non-robust" stabilizers damp the power swings in the system of changed parameters (Fig. 17) much worse.

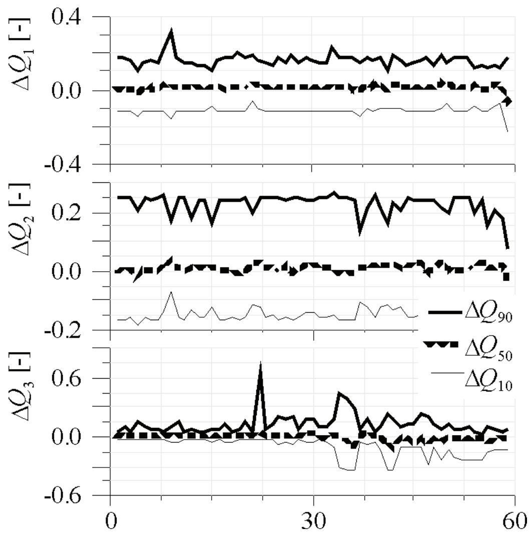

Fig. 15. Change factors of the Pareto optimal solution criteria for short-circuit in line L2 (220 kV) when optimising criterion (6)

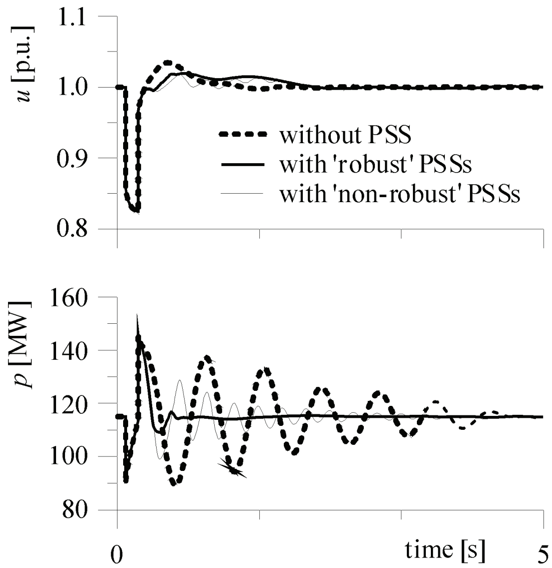

Fig. 16. Waveforms of voltage and instantaneous power of generator G3 for short-circuit in line L2 (220 kV) in the system of initial parameters

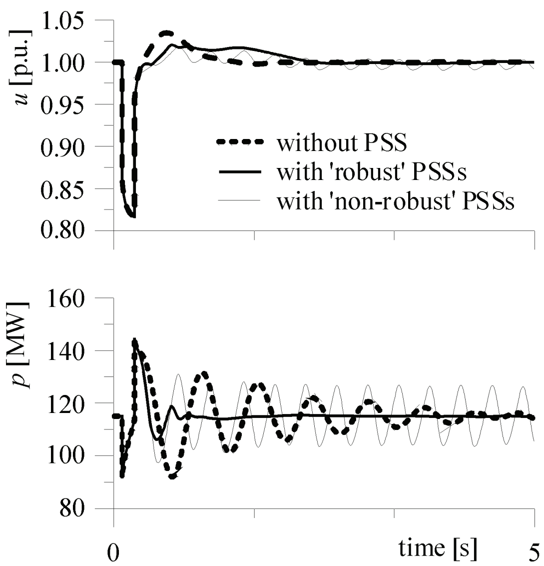

Fig. 17. Waveforms of voltage and instantaneous power of generator G3 for short-circuit in line L2 (220 kV) in the system of changed parameters

6. Summary

On the basis of the analyses performed, the following general conclusions can be drawn:

- The used Pareto optimisation of PSS parameters enabled efficient damping of electromechanical swings without worsening the terminal voltage regulation waveforms in the PS analysed.
- Application of multi-criteria methods allows taking into account in the PSSs parameter optimisation process many (in the presented investigations 2 and 3 criteria), sometimes contradictory requirements (criteria) without loss of ability to achieve an optimal solution.
- The genetic algorithm used makes it possible to fast determine optimal tuning of many PSSs simultaneously.
- The system operating conditions and the assumed optimisation criterion are the main factor influencing the optimised stabilizers robustness to changes of parameter values and system configuration (Figs. 14-17).
- There exists possibility of selection of PSSs tuning so that their sensitivity to PS parameter changes is decreased. To do it, there should be taken into account such stabilizer parameter changes to which little changes of factors $\Delta Q_{1,2,3}^{(i)}$ of Figures 12-15 correspond.

The analysis results of the influence of the PS mathematical model parameter uncertainty on the optimal solution presented in the paper can be the basis for developing the method for selecting PSSs parameters increasing the robustness of the stabilizers optimised. However, it requires further investigations dealing with, among others, the choice of disturbances which can especially threaten the system stability and including them in the vector objective function.

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