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The use of PSS2A system stabilisers to damp electromechanical swings in medium voltage networks with distributed energy sources

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Abstract: In this paper, the design issue of effective damping of electromechanical swings in a medium voltage network with distributed generation by the use of a PSS2A type power system stabiliser is described. This stabiliser was installed in the generating unit with the highest rated power. Time constants of correction blocks, as well as the main gain, were determined by analyzing a single-machine system, generating unit – infinite bus. The time constants were calculated on the basis of the frequency-phase transfer functions both of the electromagnetic moment to the voltage regulator reference voltage and of the generator voltage to the voltage regulator reference voltage, under the assumption of an infinite and real value of the generating unit inertia time constant for various initial generator loads. The main stabiliser gain was calculated by analyzing the position, on the complex plane, of eigenvalues of the state matrix of the single-machine system, linearised around a steady operating point, at the changed value of this gain.

Key words: electromechanical swings, distributed generation, medium-voltage network power system stabilisers, power system design

1. Introduction

For several years, dynamic growth in the number of distributed electricity sources, including renewable energy sources, can be observed. Generating units or groups of units (such as wind farms) with a capacity of the order of megawatts are typically connected to the power system (PS) at high voltage substations. Smaller units can be connected to the network at medium voltage stations [1–3].

One of the methods of improving the operating conditions of sources may be the use of systems stabilizing the operation of small generating units, including power system stabilisers (PSSs) installed in excitation systems of selected synchronic generators [1, 2, 4–6].

The first part of this paper (Sections 2 and 3) presents the theoretical basis of one of the methods for selecting the settings of the dual input power system stabiliser PSS2A. Section 3 introduces, among other things, the newly derived relationships which show that the frequency-phase transfer functions, generator electromagnetic torque to the voltage regulator reference voltage and the generator voltage to the reference voltage are in some cases close to each other. When determining the time constants of the stabiliser corrector, these transfer functions can then be used interchangeably, with a preference for the latter, which is much easier to measure. The second part of the paper (Sections 4 and 5) presents a design for the practical use of the determined dependencies.

2. The use of PSS2A stabilisers for damping electromechanical swings

Currently, dual input (rotor angular speed ω and generator real power P) PSS2A stabilisers are preferred. With the right selection of their parameters, they can damp swings in complex power systems well [7–11]. The general structure of the PSS2A stabiliser is shown in Fig. 1.

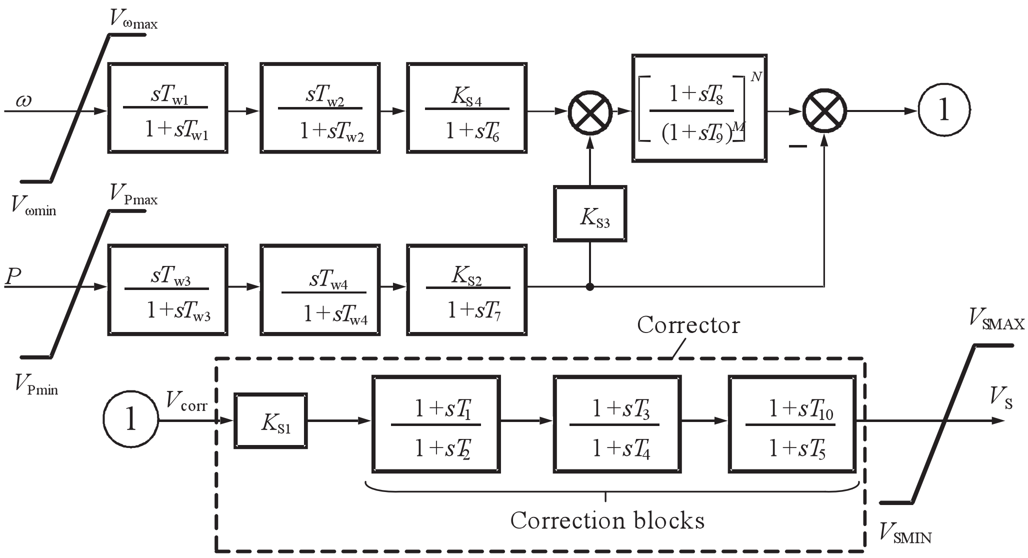

Fig. 1. Structural diagram of the dual input PSS2A stabiliser

At the input of the corrector of the PSS2A stabiliser (Fig. 1) there is obtained a signal V_{corr}, which is free from torsional disturbances and close to a signal angular speed deviation $\Delta\omega$ [5–8]. The V_{corr} signal can be used to form correction blocks and an appropriate output signal of the

PSS. The operator transfer function of the PSS corrector results from the separation of the electromagnetic torque components of the generator in the generating unit. These are shown in Fig. 2. The electromagnetic torque ΔT_e (Fig. 2) has two components depending on the change in the angular speed of the rotor $\Delta\omega(s)$:

– component $\Delta T_{e\delta}(s)$, related to the generator load angle change $\Delta\delta(s)$ and to the transfer function $G_{T\delta}(s)$,
– component $\Delta T_{eS}(s)$, related to the operation of the PSS corrector through the voltage regulator and excitation system, and to the transfer function $G_{T\omega}(s) = G_{TV}(s) \cdot G_{SC}(s)$.

Transfer functions:

$$G_{T\delta}(s) = \frac{\Delta T_e(s)}{\Delta\delta(s)}, \qquad G_{TV}(s) = \frac{\Delta T_e(s)}{\Delta V_{\mathrm{ref}}(s)}, \tag{1}$$

(where V_{ref} is the voltage regulator reference voltage) are determined under the conditions of switching off the PSS.

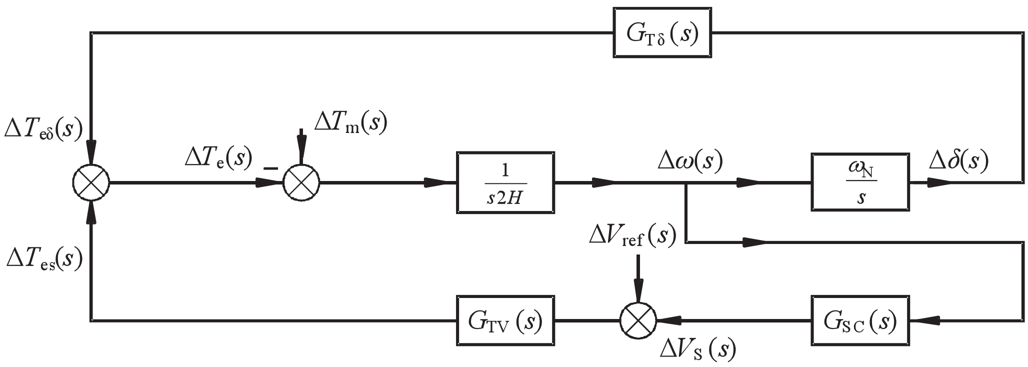

Fig. 2. Block diagram of electromagnetic torque components of the synchronous generator, H, ω_N – inertia time constant, rated angular speed of the generator

The PSS should control the additional electromagnetic torque damping component, proportional to the rotor speed deviation [7–14]:

$$\Delta T_{eS}(s) = D \cdot \Delta\omega(s) = G_{TV}(s) \cdot G_{SC}(s) \cdot \Delta\omega, \tag{2}$$

where: D is the damping coefficient of the generator, $G_{SC}(s)$ is the transfer function of the corrector of the PSS.

The PSS corrector transfer function, resulting from Eqs. (1)–(2), can be realized by introducing several, most often three, correction blocks and the gain K_{S1}.

Calculations of the basic parameters of the PSS can be carried out in two stages. In the first step, time constants of the PSS corrector are calculated by approximating the frequency characteristics of the phase angle of the transfer function G_{TV} by the phase angle of the PSS corrector transfer function. The time constants of the PSS corrector should meet the following compensation condition in the frequency range of electromechanical swings:

$$\arg\{G_{SC}(j2\pi f)\} + \arg\{G_{TV}(j2\pi f)\} = 0. \tag{3}$$

In the second stage of calculations, the value of the main gain K_{S1} of the PSS is determined. The gain calculation is made by analyzing the position of the eigenvalues of the state matrix of the linearised system, when changing the value of K_{S1}. Introducing the PSS to the system with a properly selected gain K_{S1} should shift the electromechanical eigenvalues to the left on the complex plane. It should be noted, however, that an incorrect selection of the gain may lead to a shift of other eigenvalues to the right.

3. Alternative method of determining the parameters of the PSS2A

As presented above, the time constants of the PSS2A stabiliser corrector can be calculated by approximating the frequency characteristics of the phase angle of the transfer function G_{TV} by the phase angle of the PSS corrector transfer function, when assuming an infinitely large value of the inertia time constant of the synchronous generator. The transfer function G_{TV} can be determined by having a reliable model of the generating unit and a set of real parameters for this model. When determining the parameters of the PSS corrector, models and parameters of the generator and its excitation system are decisive. Monograph [15] presents effective methods of estimating the parameters of the models of the above-mentioned elements of the generating unit. However, these reliable parameters of the models are not always available when determining the parameters of the PSS, for example when starting new generating units or after their repairs.

However, other easily measurable measurement signals, such a generator stator voltage or current, can be used to obtain a good effect in determining the time constants of the stabiliser correction blocks. This will be explained later in this section.

For modelling a synchronous generator working in the PS a GENROU [15] model is often used. In the GENROU model one can separate: electromagnetic state equations, algebraic constraint equations, motion equations [15] and output equations (in relative units for $\omega = 1$):

$$T_e = V_d I_d + V_q I_q\,, \qquad V_T = \sqrt{V_d^2 + V_q^2}\,, \tag{4}$$

where V_d, V_q, I_d, I_q, are the stator voltages and currents in the d and q axes, V_T is the stator voltage of the generator (terminal voltage).

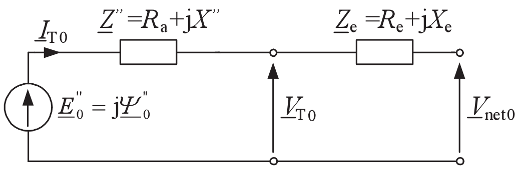

Fig. 3. The equivalent circuit of the synchronous generator stator and infinite bus

For a generator operating in a single machine system with an infinite bus, the following dependencies, resulting from Fig. 3, hold for the steady state:

$$\underline{E}''_0 = j\underline{\Psi}''_0 = \Psi''_{d0} + j\Psi''_{q0} = \underline{Z}''\underline{I}_{T0} + \underline{V}_{T0} = (R_a + jX'')\left(I_{q0} - jI_{d0}\right) + V_{q0} - jV_{d0}\,, \tag{5a}$$

$$\underline{V}_{T0} = V_{q0} - jV_{d0} = \underline{Z}_e\underline{I}_{T0} + \underline{V}_{\mathrm{net}0} = (R_e + jX_e)\left(I_{q0} - jI_{d0}\right) + V_{\mathrm{net}q0} - jV_{\mathrm{net}d0}\,, \tag{5b}$$

$$\Psi''_{d0} = V_{q0} + R_a I_{q0} + X I''_{d0}\,, \qquad \Psi''_{q0} = -V_{d0} - R_a I_{d0} + X I''_{q0}\,, \tag{5c}$$

$$V_{q0} = R_e I_{q0} + X_e I_{d0} + V_{\text{net}q0}\,, \qquad V_{d0} = R_e I_{d0} - X_e I_{q0} + V_{\text{net}d0}\,, \tag{5d}$$

where: R_a, X'' is the resistance and subtransient reactance of the generator, $\underline{Z}_e$ is the PS equivalent impedance, $\underline{E}''_0, \underline{\Psi}''_0, \underline{V}_{T0}, \underline{I}_{T0}, \underline{V}_{\text{net0}}$ is the phasors of: the voltage behind the generator subtransient reactance, the subtransient flux linkage, the stator generator voltage, the stator generator current, the infinite bus voltages; the index "0" denotes the values in the steady state.

When analyzing electromechanical transient states index "0" can be omitted in Eq. (5).

Since there are problems with the precise measurement or calculation of the electromagnetic torque, such an output quantity related to the transfer function G_{TV}, whose phase angle is used in determining the correction blocks of the PSS2A stabiliser, replacing it with the transfer function G_{VV} can be considered [9, 12, 16–18].

The transfer functions G_{TV} and G_{VV} can be presented as follows:

$$\begin{aligned} G_{TV}(s) &= \frac{\Delta T_e}{\Delta E_{fd}}(s)\frac{\Delta E_{fd}}{\Delta V_{\text{ref}}}(s) = G_{TE}(s)G_{EV}(s), \\ G_{VV}(s) &= \frac{\Delta V_T}{\Delta E_{fd}}(s)\frac{\Delta E_{fd}}{\Delta V_{\text{ref}}}(s) = G_{VE}(s)G_{EV}(s). \end{aligned} \tag{6}$$

It can be seen from the above dependencies that the possible differences in the transfer functions (6) are decisively influenced by the first transfer function components, depending on the model and parameters of the generator and equivalent PS. However, the transfer function G_{EV}, which depends on the model and parameters of the excitation system, does not affect these differences.

For the linearised model of the system, Eq. (4) can be transformed to the form:

$$\Delta T_e = I_{d0}\Delta V_d + V_{d0}\Delta I_d + I_{q0}\Delta V_q + V_{q0}\Delta I_q\,, \qquad \Delta V_T = \left(V_{d0}\Delta V_d + V_{q0}\Delta V_q\right)/V_{T0}\,. \tag{7}$$

As a consequence, the following dependencies hold:

$$G_{TE}(s) = \frac{\Delta T_e}{\Delta E_{fd}}(s) = I_{d0}\frac{\Delta V_d}{\Delta E_{fd}}(s) + V_{d0}\frac{\Delta I_d}{\Delta E_{fd}}(s) + I_{q0}\frac{\Delta V_q}{\Delta E_{fd}}(s) + V_{q0}\frac{\Delta I_q}{\Delta E_{fd}}(s), \tag{8a}$$

$$G_{VE}(s) = \frac{\Delta V_T}{\Delta E_{fd}}(s) = \frac{V_{d0}}{V_{T0}}\frac{\Delta V_d}{\Delta E_{fd}}(s) + \frac{V_{q0}}{V_{T0}}\frac{\Delta V_q}{\Delta E_{fd}}(s). \tag{8b}$$

Further considerations can be started with the analysis of the system: generating unit – infinite bus when introducing the following simplifications:

– assuming zero values of the generator stator resistance $R_a = 0$ and the PS equivalent resistance $R_e = 0$,
– assuming a linear magnetisation characteristic of the generator.

As a consequence of the above assumptions, when analyzing transient states for the system linearised at the operating point, Eqs. (5c) and (5d) can be transformed into the form:

$$\Delta\Psi''_d = \Delta V_q + X''\Delta I_d\,, \qquad \Delta\Psi''_q = -\Delta V_d + X''\Delta I_q\,, \tag{9a}$$

$$\Delta V_q = X_e\Delta I_d + \Delta V_{\text{net}q}\,, \qquad \Delta V_d = -X_e\Delta I_q + \Delta V_{\text{net}d}\,. \tag{9b}$$

For the infinite bus, the change in the field voltage does not affect the network voltage, so it follows from the relationships (9b) that:

$$\begin{aligned}
\frac{\Delta V_{\mathrm{net}d}}{\Delta E_{fd}}(s) = 0 = \frac{\Delta V_d}{\Delta E_{fd}}(s) + X_e \frac{\Delta I_q}{\Delta E_{fd}}(s), \\
\frac{\Delta V_{\mathrm{net}q}}{\Delta E_{fd}}(s) = 0 = \frac{\Delta V_q}{\Delta E_{fd}}(s) - X_e \frac{\Delta I_d}{\Delta E_{fd}}(s).
\end{aligned} \tag{10a}$$

Whereas, under the simplifying assumptions made, from the equations describing the GENROU model it follows that the change in the field voltage (in the generator d axis) does not affect the flux Ψ_q'', which leads to the relationships:

$$\begin{aligned}
&\frac{\Delta \Psi_q}{\Delta E_{fd}}(s) = 0 = -\frac{\Delta V_d}{\Delta E_{fd}}(s) + X \frac{\Delta I_q}{\Delta E_{fd}}(s) = (X_e + X)\frac{\Delta I_q}{\Delta E_{fd}}(s), \\
&\frac{\Delta I_q}{\Delta E_{fd}}(s) = \frac{\Delta V_d}{\Delta E_{fd}}(s) = 0.
\end{aligned} \tag{10b}$$

Consequently, it follows from Eqs. (8) and (10) that:

$$\begin{aligned}
&G_{TE}(s) = V_{d0}\frac{\Delta I_d}{\Delta E_{fd}}(s) + I_{q0}\frac{\Delta V_q}{\Delta E_{fd}}(s) = \left(\frac{V_{d0}}{X_e} + I_{q0}\right)\frac{\Delta V_q}{\Delta E_{fd}}(s), \\
&G_{VE}(s) = \frac{V_{q0}}{V_{T0}}\frac{\Delta V_q}{\Delta E_{fd}}(s).
\end{aligned} \tag{11}$$

It can be seen from Eqs. (11) that under the made simplifying assumptions, the transfer functions $G_{TE}(s)$ and $G_{VE}(s)$ and, as a result of the dependencies (6), also the transfer functions $G_{TV}(s)$ and $G_{VV}(s)$, have the same phase angles.

When the simplifying assumptions are not met, the phase angles of the above transfer functions in the frequency range of electromechanical swings are only approximately equal to each other.

The frequency-phase characteristic of the transfer function G_{VV} can be determined by measuring the difference in phase angles between the generator stator voltage and the test signal V_{test}, when a sinusoidal signal with a variable frequency is introduced parallel to the regulator reference voltage V_{ref} [12].

4. Example calculation results for the single-machine system

In the investigations presented in this paper, a single-machine system, generating unit – infinite bus, was analyzed first. A design model of the system with a general model of the generating unit was developed from scratch by the authors in the Matlab-Simulink program environment.

The state equations and the output equations of the system were obtained by combining the state equations and the output equations of:

- the synchronous generator with rated power $S_N = 3.75$ MV·A, represented by the GENROU model, connected to the infinite bus,

– the static excitation system with the voltage regulator, operating in the Polish PS [15],
– the steam turbine and its governor, represented by the IEEEG1 model [15, 19],
– and, as an option, the PSS2A stabiliser.

First, the phase angles of the transfer functions G_{TV} and G_{VV} were calculated in the frequency range of electromechanical swings. They are presented in Fig. 4 in various variants. Figs. 4(a) and 4(b) show the phase angles of transfer functions G_{TV} and G_{VV} for the system without the previous simplifications, for $H = \infty$ and $H = 3.6$ s (actual value) and two extremely different generator initial loads (very small load and rated load).

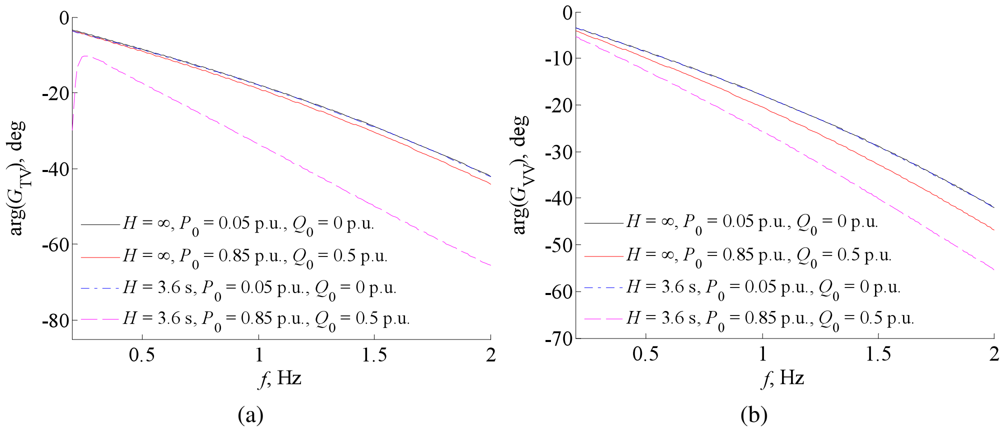

Fig. 4. Frequency-phase characteristics of for the system without simplifications for $H = \infty$ and $H = 3.6$ s transfer functions G_{TV} (a) and G_{VV} (b)

The following conclusions can be drawn from the calculations:

– The phase angles of the transfer functions G_{TV} and G_{VV} for the simplified model of the system for $H = \infty$ are equal to each other for different initial load values (these results are not shown in the figure).
– The phase angles of the transfer functions G_{TV} and G_{VV} for the system without and with simplifications for $H = \infty$ differ only slightly and depend to a small extent on the initial load.
– The phase angles of the transfer functions G_{TV} and G_{VV} for $H = \infty$ and the real value $H = 3.6$ s also slightly differ only for a very small initial generator load. However, for an increased load, that is rated load, these differences are already large.
– To determine the time constants of the PSS2A stabiliser correction blocks, all the characteristics shown in Fig. 4 can be used, except for the characteristics relating to the rated load and $H = 3.6$ s.
– The selection of the phase characteristic G_{VV} determined for the actual value of the generating unit inertia time constant for a small initial generator load (e.g. $P_0 = 0.05$, $Q_0 = 0$) seems, however, the most advantageous from the point of view of the possibility of accurate measurement of the appropriate quantities.

In connection with the above conclusions and taking into account the compensation condition (3), the phase characteristic of the transfer function G_{VV} determined for the actual value of the generating unit inertia time constant and the small initial generator load $P_0 = 0.05$, $Q_0 = 0$ was approximated when calculating the time constants of the PSS2A stabiliser correction blocks. The approximated phase characteristic of the transfer function G_{VV} and its approximation by the phase angle of the transfer function of the PSS corrector G_{SC} in the frequency range of electromechanical swings are shown in Fig. 5a(a). For the optimisation calculations related to the minimisation of the compensation error from condition (3), the Newton gradient algorithm with constraints from the Matlab program was used [20].

Next, the stabiliser gain K_{S1} was determined by analysing the position of the eigenvalues λ_h of the state matrix of the system linearised at the operating point, determined by the rated initial generator load ($P_0 = 0.85$, $Q_0 = 0.5$). The value of the gain K_{S1} was changed (in the range from 0 to 10 with step 1) and the eigenvalues of the state matrix were calculated (Fig. 5b). There was selected the value $K_{S1} = 5$ for which the absolute value of the real part of the electromechanical eigenvalues (related to electromechanical swings) [10–21] was sufficiently large, without a significant shift to the right of other eigenvalues on the complex plane, which corresponds to, amongst others, no significant worsening of the generator stator voltage control waveforms.

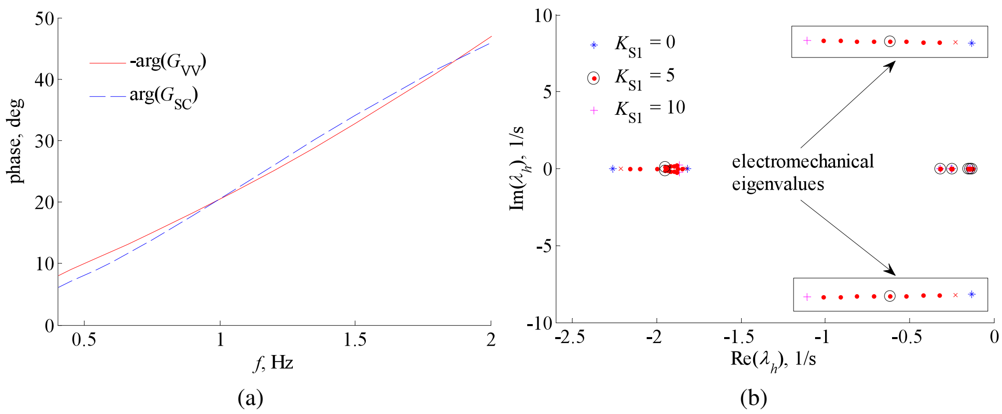

Fig. 5. Determination of the time constants of the PSS corrector by approximating the phase characteristics of the transfer function G_{VV} by the phase angle of the corrector G_{SC} (a); location of the eigenvalues of the system state matrix (rated load) when changing gain K_{S1}, selection of the value of gain K_{S1} (b)

The proposed choice of the stabiliser gain K_{S1} is somewhat arbitrary, but when performed by an experienced researcher, the result is usually satisfactory.

The calculated ($K_{S1} = 5, T_1 = 0.076$ s, $T_2 = 0.015$ s, $T_3 = 0.076$ s, $T_4 = 0.015$ s, $T_{10} = 0.076$ s and $T_5 = 0.161$ s, respectively) and assumed parameters of the PSS as well as the nonlinear model of the system were taken into account in the simulation calculations relating to the step change (by +5% in relation to the steady-state) of the voltage regulator reference voltage. Figure 6 shows the waveforms of the generator active power and voltage in the system with and without the PSS.

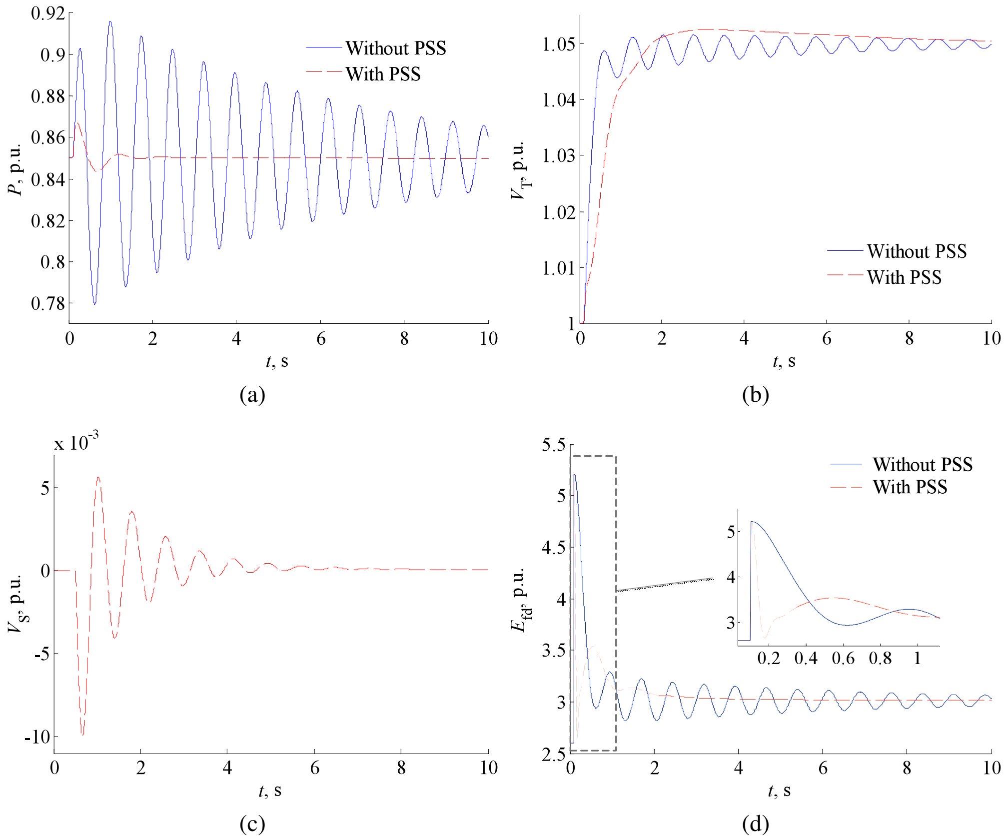

Fig. 6. The waveforms of active power (a); voltage of the generator (b); the stabilizer output signal (c) and excitation voltage (d) in the system with and without the PSS

The simulation results presented in Fig. 6 show that the introduction of the PSS with the parameters determined in the way discussed above significantly increases the damping of generator power swings while worsening the generator voltage control waveforms only slightly and the output signal of the power system stabiliser does not reach the limits.

5. Multi-machine system – influence of the PSS on distributed energy

Since the PS consists of many generators interconnected with the power network, the electromechanical swings occurring in the PS may be less damped by the PSS with parameters selected for a single machine system (even if this selection is optimal [10, 11]). Therefore, it is necessary to verify the settings of the PSS. Such verification can be performed by simulation methods.

Nowadays, due to the steady increase in the number of generating units with a capacity of several megawatts (including renewable energy sources), electromechanical swings may also appear in medium voltage networks. One of solutions is the use of one PSS installed in the generating unit with the highest power in a given part of the power network, that is in the medium-voltage network supplied from one transformer. In order to verify the made hypothesis and check the correctness of selection of the PSS parameters presented in the first part of the paper, the medium voltage network with the structure shown in Fig. 7, constituting a part of the Polish Power System, was considered.

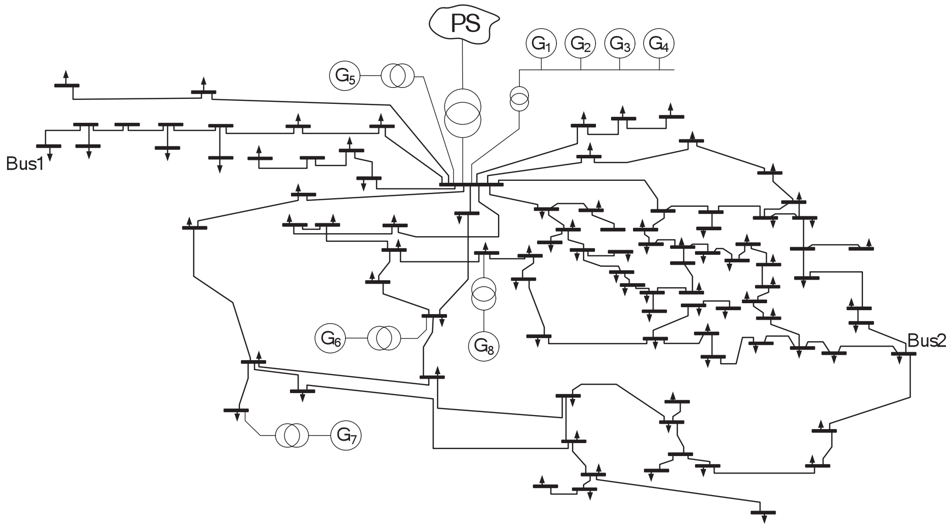

Fig. 7. Simplified diagram of the analysed medium voltage network

Several generating sources were installed in the network with a rated voltage of 15 kV. The hybrid wind-gas power plant with a total capacity of 6 MW is the generation source with the highest power output. The power plant consists of three wind power plants (G_1, G_2 and G_3 in Fig 7) with a unit capacity of 1 MW with double-fed asynchronous generators [4] and one generating unit with a rated capacity of 3 MW (G_4) consisting of a synchronous generator and a steam turbine powered by a biomass boiler. In addition, four small hydropower plants, one with a capacity of 1 MW (G_5) and three with a capacity of 0.5 MW (G_6, G_7 and G_8), are connected to the network.

In this case, the PSLF program was used for simulation investigations. The data necessary to develop a mathematical model (line lengths and cross-sections, transformer parameters) were obtained from the Polish Distribution Network Operator. Mathematical models of turbines, generators, and excitation systems, including the GENROU mathematical model of the synchronous generator, the model of the static excitation system operating in the Polish PS [15], and the models of asynchronous generators installed in wind turbines, were assumed in accordance with the standards of the IEEE Committee [22].

The simulation investigations were carried out by modelling the transient states caused by sudden shutdown of the generation of all three wind turbines being part of the wind-gas hybrid power plant. It was assumed that the shutdown of wind turbines was caused by exceeding the permissible wind speed.

The waveforms of selected quantities obtained by computer simulation are presented in Fig. 8. The results presented show the waveforms of instantaneous powers and terminal voltages of individual generating units in two cases, for the system with the PSS2A stabiliser installed in the source G_4 and that without the PSS.

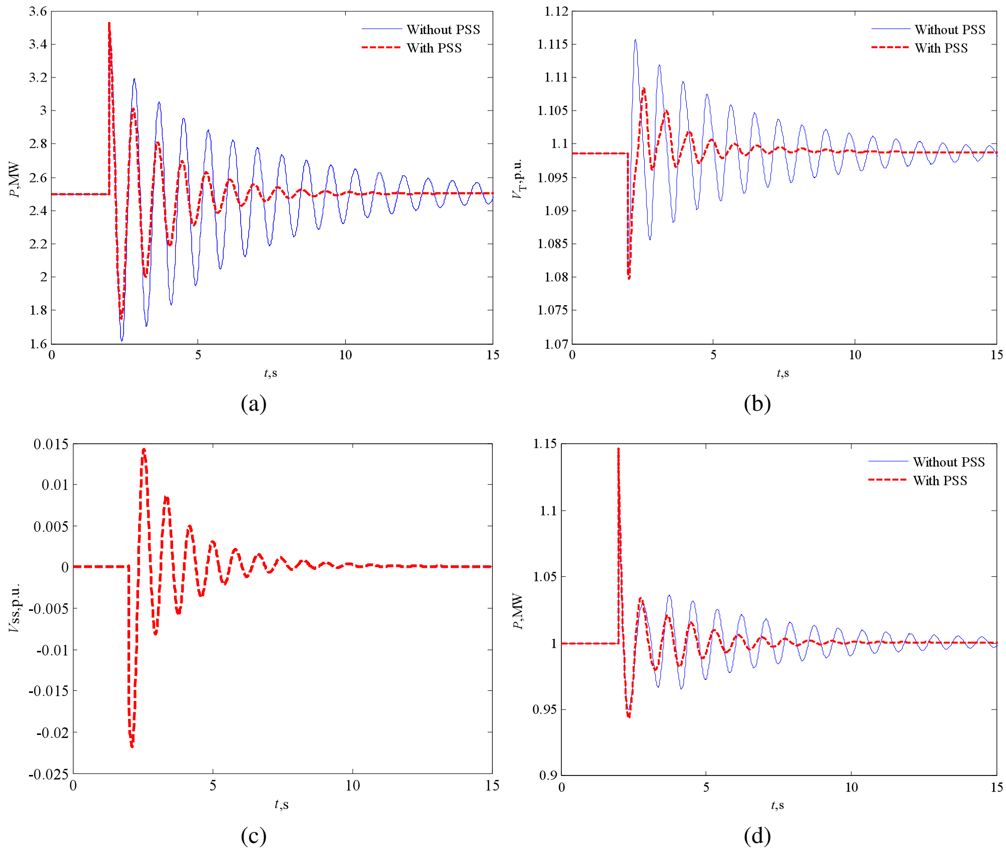

Fig. 8. The waveforms of instantaneous power (a); voltage (b); the PSS output signal (c) of the generator G_4 as well as instantaneous power of the generator G_5 (d)

6. Conclusions

The following detailed conclusions can be drawn from the calculations carried out:

– On the basis of the theoretical analysis relating to the electromagnetic torque components of a synchronous generator, the determination of time constants of the correction blocks of the PSS2A stabiliser can be performed by approximating the frequency-phase transfer function of the electromagnetic torque to the voltage regulator reference voltage G_{TV} (determined for the linearised model of the system, when assuming the infinite value of the time constant of inertia H) by the phase angle of the PSS corrector transfer function in the frequency range of electromechanical swings.

– It follows from the investigations conducted that in the above calculations, the phase transfer function G_{TV} can be replaced by the phase transfer function G_{VV} (transfer function of the generator voltage to the voltage regulator reference voltage), which is easier to determine for the infinite and real value of the generating unit inertia constant. These characteristics differ only slightly for different load conditions at $H = \infty$.
– However, the selection of the G_{VV} phase characteristic determined for the actual value of the generating unit inertia time constant at a low initial generator load seems to be the most advantageous from the point of view of the possibility of accurate measurement of appropriate quantities.
– By analysing the position of eigenvalues of the state matrix of a single-machine system linearised around a steady operating point, when changing the value of gain K_{S1}, the value of this gain can be determined.
– The PSS with appropriately selected parameters dampens power swings well and at the same time improves the voltage control waveforms in a single machine system, generating unit – infinite bus.
– In the medium voltage network considered with distributed generation, the use of one PSS installed in the generating unit with the highest rated power allowed for effective damping of electromechanical instantaneous power swings in all the generating units connected to this network. The voltage control waveforms in various places of the PS are also satisfactory and well-damped. Good damping of electromechanical swings was obtained without modifying the stabiliser settings, which were determined for the system, generating unit – infinite bus.

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