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Dynamic Stability Enhancement Through the Application of Stabilizers of Electromechanical Oscillations

SUMMARY

Power system dynamic stability is one of key issues system engineers face. Oscillations that regularly occur in the system, limit the transmission capability of the network. The need to study the stability of power systems has been increasingly growing along with the development of power systems and their grouping into large interconnections. The focus of this paper is determining the dynamic stability of a synchronous generator, and thus the power system, by applying the general theory of stability of dynamic systems. Furthermore, the procedure for the initial adjustment of the parameters of a conventional (IEEE3 type PSS1A) stabilizer of electromechanical oscillations is briefly described based on the frequency response analysis of a linear generator model also known as the Heffron-Phillips generator model.

KEY WORDS

dynamic stability, electromechanical oscillations, stabilizers

1. INTRODUCTION

Power system dynamic stability is one of key issues system engineers face as the electricity supply chain is inherently non-linear, interconnected and can be affected by various disturbances [1]. Oscillations that regularly occur in the system, limit the transmission capability of the network. Due to the continuous increase in the integration of renewable energy sources (RES), power systems nowadays operate close to the limits of dynamic stability. The notion of dynamic stability of the power system is related to the problem of low-frequency (in the order of 0,2 - 3 Hz) electromechanical oscillations that occur due to small operating disturbances in the system and arise from the physical properties of synchronous generators [2]. Insufficiently damped electromechanical oscillations, or more precisely, power fluctuations, limit the transmission of electricity. If these oscillations are not damped at all, the protection system is activated and the generator is separated from the network. The failure of one generator can often cause considerable disturbances to the remaining generators in the system and the consequent loss of synchronism can lead to the breakdown of the entire system. In worst-case scenario, this can result in the breakdown of the entire power system. Complex mathematical problems regarding the operation of a power system are solved by different heuristic algorithms. Perhaps one of the most popular solutions in this field is the application of particle swarm optimization (PSO) [3][4][5][6][7][8][9]. However, methods such as simulated annealing (SA)[10], differential evolution (DE)[11], artificial bee colony (ABC)[12][13][14], Tabu search (TS)[15] and the genetic algorithm (GA)[16][17] are also being used. These algorithms were developed by observing the social behavior of living creatures and eventually became models applied in optimization methods. Efficient damping of electromechanical oscillations can be achieved by implementing electromechanical oscillation stabilizers in digital synchronous generator excitation control systems. Power system stabilizers (PSSs) are incorporated into the system in order to provide the damping torque necessary to suppress oscillations and are used to improve system reliability [18]. The adoption of PSSs started along with the very development of the power system [3] and has been explored by numerous research studies [19]. These studies analyzed various techniques for tuning PSS parameters. Some focused on robust control [20][21][22], others on optimization methods [23]. In more recent times, modules of artificial intelligence (AI) also found their way to system stability issues through the application of fuzzy [24][25] and neuro-fuzzy logic [26][27]. The majority of these approaches focus on angular speed deviation ($\Delta\omega$). Some techniques that use this approach suffer from computational complexity, require a significant amount of memory or are non-adaptive to changing operating conditions and different system configurations [3].

The focus of this paper is determining the dynamic stability of a synchronous generator, and thus the power system, by applying the general theory of stability of dynamic systems. Furthermore, the procedure for the initial adjustment of the parameters of a conventional (IEEE3 type PSS1A) stabilizer of electromechanical oscillations is briefly described based on the frequency response analysis of a linear generator model also known as the Heffron-Phillips generator model. The paper is organized as follows. After the introduction and a literature review of the subject matter in section 1, section 2 describes the dynamic stability of a synchronous generator. In section 3, the possibilities for improving the dynamic stability using electromechanical oscillation stabilizers are presented and elaborated. Section 4 concludes the paper.

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2. DYNAMIC STABILITY OF A SYNCHRONOUS GENERATOR

The need to study the stability of power systems has been increasingly growing along with the development of power systems and their grouping into large interconnections. Today, as we witness a surge of renewable energy sources (RES), system stability issues seem to be more important than ever. Power system stability is defined as »the ability of a system to remain in its initial state after a disturbance or to assume a new equilibrium state, given that the system state variables remain within the limits that ensure system integrity« [20]. Depending on the observed physical quantity, the stability of the power system can be divided into three types: angular, frequency and voltage. Angular stability refers to the ability of synchronous generators in the power system to remain in synchrony after a disturbance. Depending on the magnitude of the disturbance, it can be divided into (1) stability during large disturbances (transient stability) and (2) stability during small disturbances (dynamic stability). Although large disturbances such as short circuits and outages of large generating units posed as the greatest threat to the power system in recent decades, more and more attention is paid to the system's behavior during small disturbances that result in low-frequency electromechanical oscillations, i.e. oscillations of characteristic synchronous generator variables.

2.1.ELECTROMECHANICAL OSCILLATIONS EXAMPLE

The occurrence of electromechanical oscillations is easiest to understand on the example of changing the operating point of the generator shown in Figure 1.

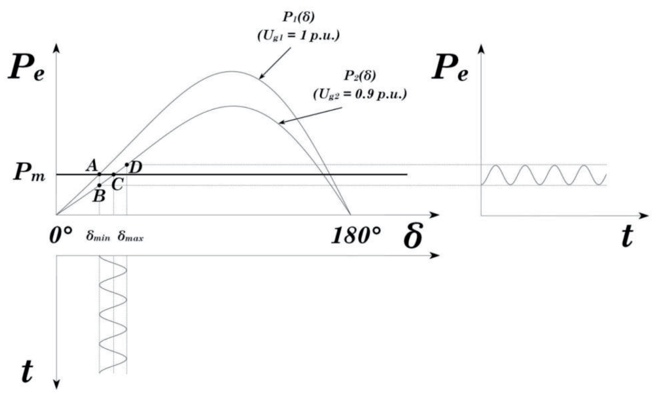

Figure 1 Occurrence of electromechanical oscillations

By abruptly changing the voltage reference value U_g with 1 p.u. at 0,9 p.u., the generator switches from characteristic $P_1(\delta)$ to characteristic $P_2(\delta)$. Due to the inertia of the rotor, load angle (δ) cannot be changed immediately, so the output electric power (P_e) falls to a value corresponding to point B. Since at point B the input mechanical power (P_m) is greater than the electrical one, the acceleration force accelerates the machine which causes the electric power and the load angle to increase. At point C, the electrical and mechanical power are of equal value ($P_e = P_m$), but the rotational speed is higher than synchronous ($\omega > \omega_s$) which is why the generator will not steady in the equilibrium position, but will rather continue to increase the output electrical power. As the electrical power increases, the (negative) amount of acceleration power increases. At point D, the machine has a synchronous speed ($\omega = \omega_s$) and a maximum negative acceleration, which is why it starts to slow down and the load angle decreases. At point C, the electrical and mechanical power are equal ($P_e = P_m$), but the speed is less than synchronous ($\omega < \omega_s$), so the generator will not steady in the equilibrium position, but will accelerate to point B, reducing the output electrical power. The described process then starts from the beginning and over time it is attenuated after which the generator assumes an equilibrium state at point D ($P_e = P_m$).

2.2. DYNAMIC STABILITY ANALYSIS OF A SYNCHRONOUS GENERATOR

The equation of moment balance on the axis of a synchronous machine in the generator mode is expressed by (2.1) [28]:

$$J\frac{d\omega_m}{dt} = M_m - M_e - D_m\Delta\omega_m \tag{2.1}$$

Where: J – sum of inertia moments of the drive machine and synchronous generator [kgm^2], ω_m – mechanical speed of rotor rotation expressed in mechanical work [rad/s], M_m – mechanical torque of the propulsion machine [Nm], M_e – electromagnetic moment of synchronous generator [Nm], D_m – coefficient that considers the influence of the damping winding during transients [Nms] and $\Delta\omega_m$ – change in mechanical speed of rotor rotation [rad/s]. The mechanical speed of rotation of the rotor can be expressed as:

$$\omega_m = \omega_{sm} + \Delta\omega_m = \omega_{sm} + \frac{d\delta_m}{dt} \tag{2.2}$$

Where: ω_{sm} – synchronous speed [rad/s] and δ_m – rotor angle of the synchronous generator [rad]. By including expression (2.2) in expression (2.1) the following equation is obtained:

$$J\frac{d}{dt}\left(\omega_{sm} + \frac{d\delta_m}{dt}\right) = M_m - M_e - D_m\Delta\omega_m \tag{2.3}$$

Since the synchronous speed is constant, expression (2.3) can be written as:

$$J\frac{d^2\delta_m}{dt^2} = M_m - M_e - D_m\frac{d\delta_m}{dt} \tag{2.4}$$

If the left and right equations in expression (2.4) are multiplied by the synchronous rotational speed ω_{sm}, the following equation is obtained:

$$J\omega_{sm}\frac{d^2\delta_m}{dt^2} = M_m\omega_{sm} - M_e\omega_{sm} - D_m\omega_{sm}\frac{d\delta_m}{dt} \tag{2.5}$$

Furthermore, considering the fact that the product of the torque and the speed of rotation are equal to the force, expression (2.5) can be written as:

$$J\omega_{sm}\frac{d^2\delta_m}{dt^2} = P_m - P_e - D_m\omega_{sm}\frac{d\delta_m}{dt} \tag{2.6}$$

The product $J\omega_{sm}$ in expression (2.6) is called the angular momentum and is denoted by M. However, the amount of angular momentum can differ significantly from one machine to another because it primarily depends on the size of the machine itself, so it is more practical to express the angular momentum through inertia, H. Machines of the same type (e.g. steam turbo-generators) have similar inertia constant values regardless of their size [20]. The inertia constant is defined by the expression:

$$H = \frac{W_k}{S_n} = \frac{\frac{1}{2}J\omega_{sm}^2}{S_n} \tag{2.7}$$

Where: H – inertia constant [s], W_k – kinetic energy of the rotor at synchronous speed [J] and S_n – nominal apparent power of the synchronous generator [VA]. The relationship between the angular momentum and the inertia constant is defined by the expression:

$$M = J\omega_{sm} = \frac{2HS_n}{\omega_{sm}} \tag{2.8}$$

By including expression (2.8) in expression (2.6) the following equation is obtained:

$$\frac{2H}{\omega_{sm}} S_n \frac{d^2\delta_m}{dt^2} = P_m - P_e - D_m\omega_{sm}\frac{d\delta_m}{dt} \tag{2.9}$$

It is often desirable to express the synchronous speed in electrical rad/s and the angle of the rotor in electrical work, because then the angle of the rotor corresponds to the load angle of the generator. Therefore, expression (2.9) can be written as:

$$\frac{2H}{\frac{\omega_s}{p}} S_n \frac{d^2\left(\frac{\delta}{p}\right)}{dt^2} = P_m - P_e - D_m\frac{\omega_s}{p}\frac{d\delta}{dt} \tag{2.10}$$

or abbreviated as:

$$\frac{2H}{\omega_s} S_n \frac{d^2\delta}{dt^2} = P_m - P_e - D\frac{d\delta}{dt} \tag{2.11}$$

Where: ω_s – synchronous speed expressed in electrical [rad/s], p – number of pole pairs of a synchronous generator, δ – load angle of the synchronous generator expressed in electrical [rad] and – o general damping coefficient [Nm]. If left and right sides of the equation in expression (2.11) are divided by the nominal apparent power of the generator, the following expression is obtained:

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e - D\frac{d\delta}{dt} \tag{2.12}$$

Expression (2.12), in which all quantities are expressed in unit values (hereinafter p.u.), is called the oscillation equation and represents the basis for the analysis of transient and dynamic stability. The oscillation equation is a nonlinear differential equation of the second order, so it can be written in the form of a system of two differential equations of the first order:

$$\begin{aligned} 2H\frac{d\Delta\omega}{dt} &= P_m - P_e - D\Delta\omega \\ \frac{d\delta}{dt} &= \omega_s\Delta\omega \end{aligned} \tag{2.13}$$

2.3. LINEARIZATION OF THE OSCILLATION EQUATION

As stated earlier, the oscillation equation is a nonlinear differential equation. The reason for this is the highly nonlinear dependence of the output electric power on the load angle, which is given by the expression:

$$P_e = \frac{E_q U_g}{x_d}\sin\delta + \frac{U_g^2}{2}\frac{x_d - x_q}{x_d x_q}\sin(2\delta) \tag{2.14}$$

That is, in the case of a machine with a round rotor (for which), by the expression:

$$P_e = \frac{E_q U_g}{x_d}\sin\delta \tag{2.15}$$

Where: E_q – induced electromotive force in the armature of the synchronous generator [p.u.], U_g – voltage at the terminals of the synchronous generator [p.u.], x_d – actance of the synchronous generator in the longitudinal axis [p.u.] and x_q – reactance of the synchronous generator in the transverse axis [p.u.]. For the purposes of dynamic stability analysis, it's possible to linearize the output characteristic of the synchronous generator, i.e. to approximate it with the tangent at the operating point (P_{e0}, δ_0) as shown in Figure 2.

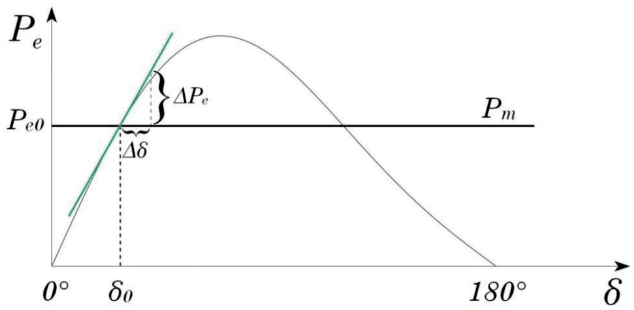

Figure 2 Linearization of the output characteristic of a synchronous generator

By linearizing the output characteristic of the synchronous generator in the vicinity of the operating point (P_{e0}, δ_0), the expression is obtained:

$$\Delta P_e = \left.\frac{\partial P_e}{\partial\delta}\right|_{\delta=\delta_0}\Delta\delta \tag{2.16}$$

In addition, the following expression is obtained:

$$\Delta P_e = \left[\frac{E_q U_g}{x_d}\cos\delta_0 + U_g^2\frac{x_d - x_q}{x_d x_q}\cos(2\delta_0)\right]\Delta\delta \tag{2.17}$$

Where: ΔP_e – change in electrical power of the synchronous generator [p.u.], δ_0 – he amount of the load angle of the synchronous generator at the operating point where the linearization was performed [rad] and Δδ – change of load angle of synchronous generator [rad]. The term assigned to the change of the load angle in expression (2.17) is called the coefficient of power (moment) of synchronization and is denoted by k_{sP}. Therefore, expression (2.17) can be written as:

$$\Delta P_e = k_{sP}\Delta\delta \tag{2.18}$$

It was said earlier that the oscillation equation can be written in the form of a system (2.13). In the case of small disturbances where there are small deviations of the load angle during the first oscillation, the system (2.13) can be written as:

$$\begin{aligned} 2H\frac{d\Delta\omega}{dt} &= (P_{m0} + \Delta P_m) - (P_{e0} + \Delta P_e) - D\Delta\omega \\ \frac{d}{dt}(\delta_0 + \Delta\delta) &= \omega_s\Delta\omega \end{aligned} \tag{2.19}$$

Where: P_{m0} – input mechanical power at the initial operating point [p.u.], ΔP_m – change of input mechanical power [p.u.], P_{e0} – electrical power of the synchronous generator at the initial operating point [p.u.], ΔP_e – change of electric power of the synchronous generator [p.u.], δ_0 –

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load angle of the synchronous generator at the initial operating point [rad] and Δδ – change of load angle of the synchronous generator [rad]. Since before the disturbance, the synchronous generator was in an equilibrium state in which $P_e = P_m$ (2.19), the following expression is obtained:

$$2H\frac{d\Delta\omega}{dt} = \Delta P_m - \Delta P_e - D\Delta\omega$$
$$\frac{d\Delta\delta}{dt} = \omega_s\Delta\omega \qquad (2.20)$$

That is:

$$2H\frac{d\Delta\omega}{dt} = \Delta P_m - k_{sP}\Delta\delta - D\Delta\omega$$
$$\frac{d\Delta\delta}{dt} = \omega_s\Delta\omega \qquad (2.21)$$

System (2.21) represents the oscillation equation which, for the purposes of analyzing the dynamic stability of a synchronous generator, is linearized in the vicinity of the operating point in which the generator was located before the disturbance, i.e. the transient. In Figure 3, the basic model of the linearized oscillation equation is presented.

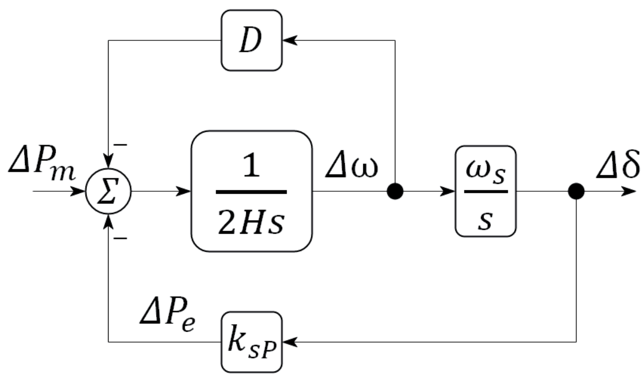

Figure 3 Basic model of the linearized oscillation equation

2.4. MODEL OF THE OSCILLATION EQUATION IN THE STATE SPACE

The analysis of the stability of complex dynamic systems, such as the electric power system, starts from the system model in state space. The model of a dynamic system in state space is described by a system of equations:

$$\dot{x} = Ax + Bu$$
$$y = Cx \qquad (2.22)$$

Where: – derivation vector of system state variables, x – vector of system state variables, u – vector of system input variables, y – vector of system output variables, A – system matrix, B – management distribution matrix and C – output matrix. The linearized oscillation equation of the synchronous generator written in the form of system (2.21) can be represented in the state space by a system of matrix equations:

$$\frac{d}{dt}\begin{bmatrix}\Delta\omega\\ \Delta\delta\end{bmatrix} = \begin{bmatrix}-\frac{D}{2H} & -\frac{k_{sP}}{2H}\\ \omega_s & 0\end{bmatrix}\begin{bmatrix}\Delta\omega\\ \Delta\delta\end{bmatrix} + \begin{bmatrix}\frac{1}{2H} & 0\\ 0 & 0\end{bmatrix}\begin{bmatrix}\Delta P_m\\ 0\end{bmatrix}$$
$$\begin{bmatrix}\Delta\delta\\ 0\end{bmatrix} = \begin{bmatrix}0 & 1\end{bmatrix}\begin{bmatrix}\Delta\omega\\ \Delta\delta\end{bmatrix} \qquad (2.23)$$

Where the system matrix has a special significance in the stability analysis:

$$A = \begin{bmatrix}-\frac{D}{2H} & -\frac{k_{sP}}{2H}\\ \omega_s & 0\end{bmatrix} \qquad (2.24)$$

Namely, the characteristic polynomial of system *A(λ)* according to [28] is obtained, with the knowledge of the matrix of system *A*, according to the expression:

$$A(\lambda) = \det(A - \lambda I) \qquad (2.25)$$

Where: *I* denotes the unit matrix. By further elaboration of the expression (2.25) we get:

$$A(\lambda) = \lambda^2 + \frac{D}{2H}\lambda + \frac{\omega_s k_{sP}}{2H} \qquad (2.26)$$

Furthermore, by solving the equation *A(λ)* = 0, the so-called eigenvalues of the system are obtained. Since this equation is a characterized by a second-order polynomial, two eigenvalues are obtained:

$$\lambda_{1,2} = -\frac{D}{4H} \pm \sqrt{\frac{D^2}{16H^2} - \frac{\omega_s k_{sP}}{2H}} \qquad (2.27)$$

As in reality for a synchronous generator operating in an electric power system it is true that in expression (2.27) the subtractor under the root is larger than the subtractor, the eigenvalues are conjugate complex quantities. Conjugate complex pairs of eigenvalues are generally indicators of the inherent oscillatory behavior of the system [29]. Therefore, a synchronous generator in a power system can be considered an oscillating system in which, during transients, there is an interaction or exchange of energy between the rotor of the unit and the rest of the power system.

2.5. INFLUENCE OF EIGENVALUE CHARACTER ON DYNAMIC STABILITY

Eigenvalues generally take the form of:

$$\lambda_i = \sigma_i + j\omega_i \; ; \; i = 1, 2, \ldots, n \qquad (2.28)$$

Real part of the eigenvalue represents the attenuation, while the imaginary part represents the oscillation frequency of the system. A dynamic system is stable if the real parts of all its eigenvalues are less than zero [29]:

$$Re\{\lambda_i\} < 0 \; ; \; \forall i \in \mathbb{N} \qquad (2.29)$$

If the above is applied to a synchronous generator in a power system whose typical values are given by expression (2.27), it is obvious that the dynamic stability of the generator is conditioned by a positive value

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of the damping coefficient D, or the stability of the positive damping moment. Interestingly, the synchronous generator begins to lose stability only at the moment of changing the sign of the real part of the eigenvalues. Therefore, the points to which it applies are the following:

$$Re\{\lambda_i\} = 0 \;\; ; \;\; \forall i \in \mathbb{N} \tag{2.30}$$

Together, these numbers form the limit of dynamic stability. In Figures 4-6, possible responses of the synchronous generator depending on the character of the eigenvalues are shown.

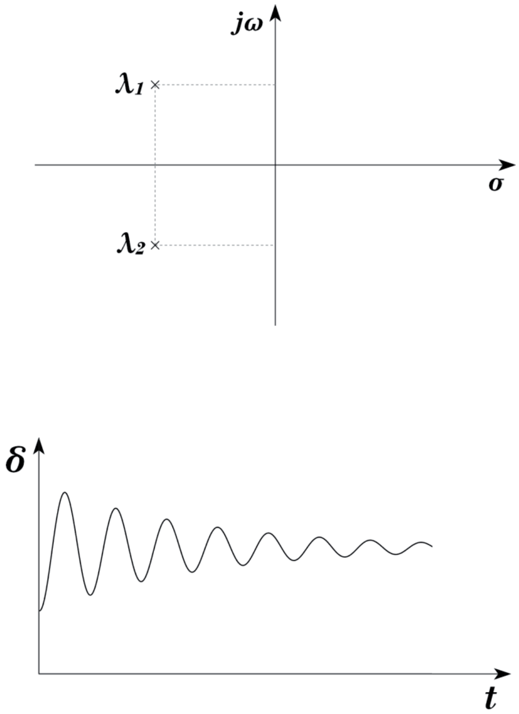

Figure 4 Re{λ1,2} < 0, The synchronous generator is stable

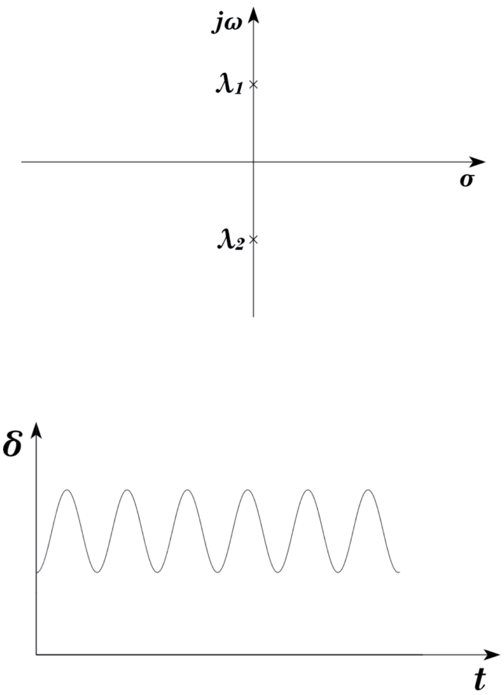

Figure 5 Re{λ1,2} = 0, The synchronous generator is at its stability limit

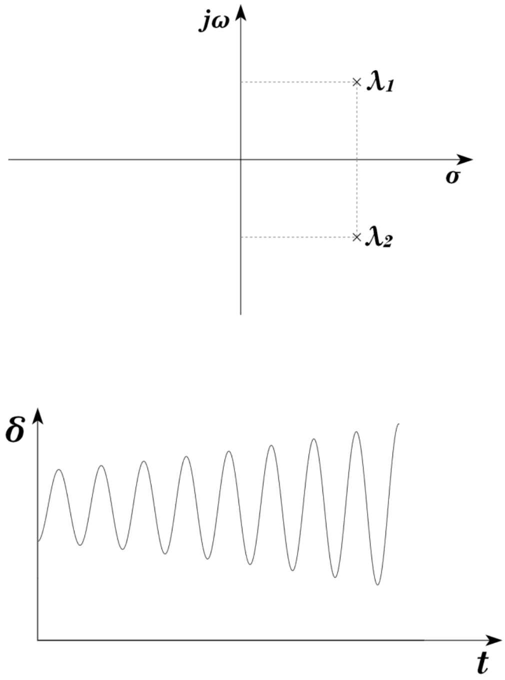

Figure 6 Re{λ1,2} > 0, The synchronous generator is oscillatory unstable

3. IMPROVING DYNAMIC STABILITY THROUGH THE USE OF ELECTROMECHANICAL OSCILLATION STABILIZERS

In the past, the problem of damping electromechanical oscillations was solved by installing a larger number of damping windings in the pole shoes or the rotor body, depending on the type of machine. In 1969, de Mello and Concordia proposed the introduction of an additional control circuit in the excitation systems of synchronous generators with the aim of damping electromechanical oscillations [30]. This additional control circuit was later called the Power System Stabilizer. The role of the stabilizer is to recognize the occurrence of electromechanical oscillations and acting through an automatic voltage regulator in an artificial way to create an additional component of damping torque on the rotor which is in phase with the change of speed. Nowadays, the stabilizer of electromechanical oscillations is an indispensable part of digital excitation control systems [31].

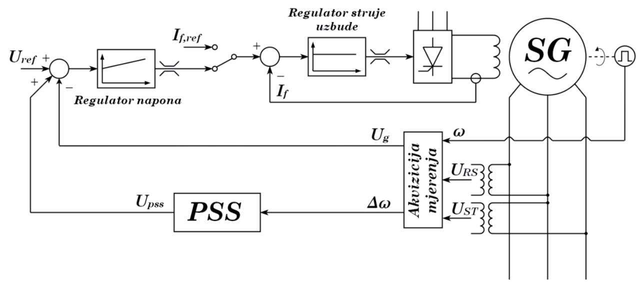

Figure 7 Classical excitation control circuit structure with PSS

3.1. STRUCTURE OF A CONVENTIONAL STABILIZER OF ELECTROMECHANICAL OSCILLATIONS

From the control theory point of view, stabilizers of electromechanical oscillations are linear elements. The structure of a conventional (IEEE type PSS1A) stabilizer is described by a transfer function:

$$G_{pss}(s) = K_{pss}\frac{T_f s}{1 + T_f s}\frac{1 + T_1 s}{1 + T_2 s}\frac{1 + T_3 s}{1 + T_4 s} \qquad (3.1)$$

From the transfer function of the stabilizer it can be seen that it consists of: K_{pss} high-pass filter, time constant T_f and phase compensators. Among the mentioned members of the transfer function of the stabilizer, phase compensators play a crucial role. This is due to the fact that a necessary condition for the correct operation of the stabilizer is that the artificially created damping torque component is in phase with the change of speed. Therefore, it is necessary to compensate for the phase delay introduced by other components in the excitation system (e.g. PI voltage regulator). The mentioned phase delay compensation is achieved by phase compensators. In addition to phase compensators, an important role is played by a high-pass filter that must remove DC signals in order for the stabilizer to operate only during transient states of the system.

3.2. HEFFRON-PHILLIPS SYNCHRONOUS GENERATOR MODEL

The initial adjustment of the parameters of the electromechanical oscillation stabilizer is performed before commissioning and based on the analysis of frequency responses of the linear model of the synchronous generator (also known as the Heffron-Phillips model of the generator). The mentioned model is extremely precise in the environment of a certain operating point for which it was made [32]. In addition, it requires knowing only basic parameters of the synchronous generator which makes it suitable for synthesis of stabilizers and control circuits in general. The Heffron-Phillips generator model is shown in Figure 8.

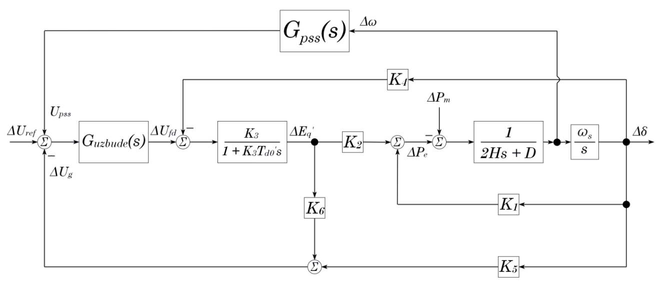

Figure 8 Heffron-Phillips model of the synchronous generator

3.3. DETERMINATION OF THE TIME CONSTANT OF A HIGH-PASS FILTER

It is not necessary to explicitly determine the cut-off frequency, i.e. the time constant of the high-pass filter, as the values of the filter time constant between 1 and 20 seconds fully meet the set requirements. The amplitude-frequency characteristic of the high-pass filter is shown in Figure 9.

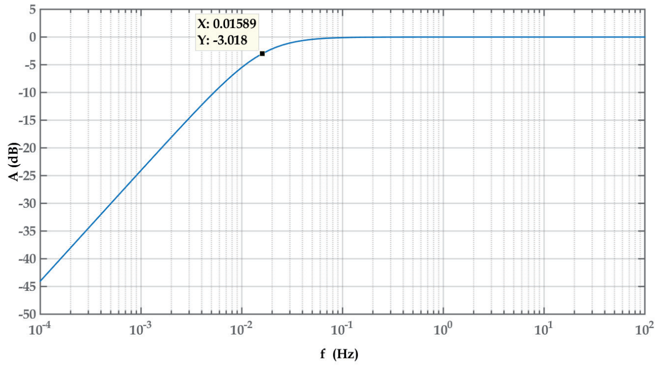

Figure 9 Amplitude-frequency characteristic of high-pass filter

3.4. DETERMINATION OF TIME CONSTANTS OF BLOCKS FOR PHASE COMPENSATION

As mentioned earlier, the elements in the excitation system introduce a certain phase delay into the stabilizing signal generated by the electromechanical oscillation stabilizer. In Figure 10, the phase-frequency characteristic of an excitation system is shown. At the frequency of electromechanical oscillations, which in this example is 1,94 Hz, the excitation system introduces a phase delay in the amount of 126,5°.

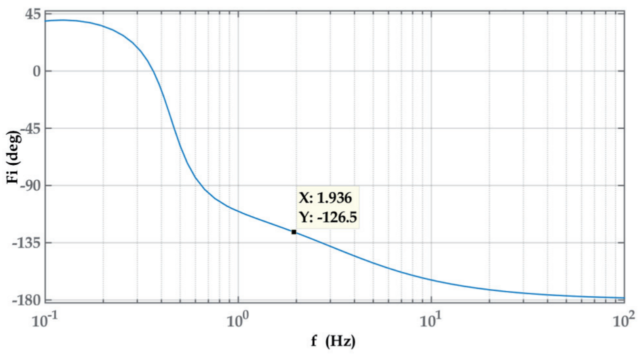

Figure 10 Phase-frequency characteristic of the excitation system before compensation

With correctly set phase compensation blocks, the phase delay at the frequency of electromechanical oscillations is almost 0 °, which allows the creation of »pure« damping torque on the rotor, which is in phase with the change of speed. The phase-frequency characteristic of the excitation system after compensation is shown in Figure 11.

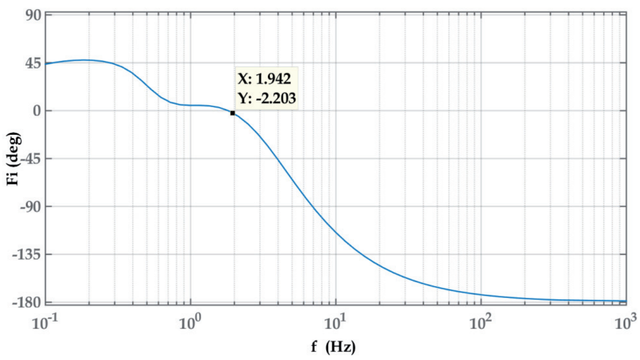

Figure 11 Phase-frequency characteristic of the excitation system after compensation

3.5. SIMULATION OF SYNCHRONOUS GENERATOR WITH AND WITHOUT AN ELECTROMECHANICAL OSCILLATION STABILIZER

In Figures 12-15, the responses of the characteristic variables of the synchronous generator during the abrupt change of the reference value of the active power from 0,5 p.u. to 0,6 p.u. and for cases with the electromechanical oscillation stabilizer turned off and on are shown.

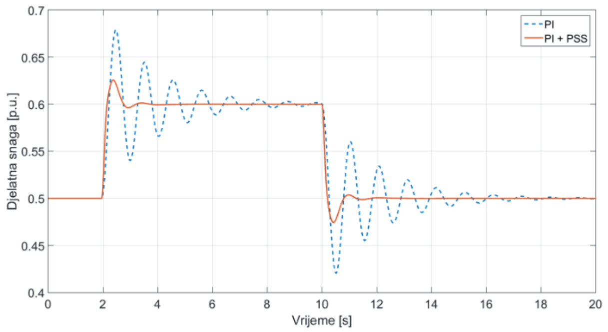

Figure 12 Active power response (Pe)

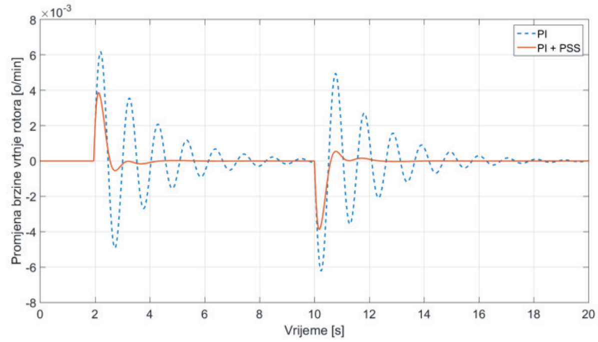

Figure 14 Load angle change (Δn)

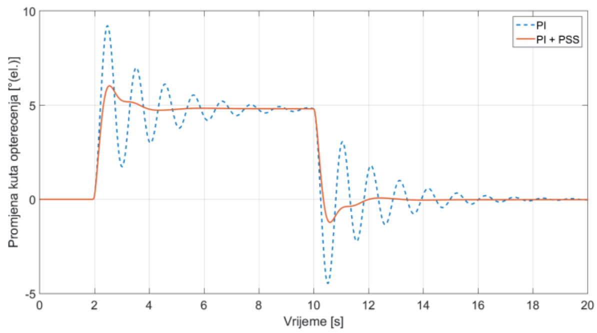

Figure 13 Change of rotation speed (Δδ)

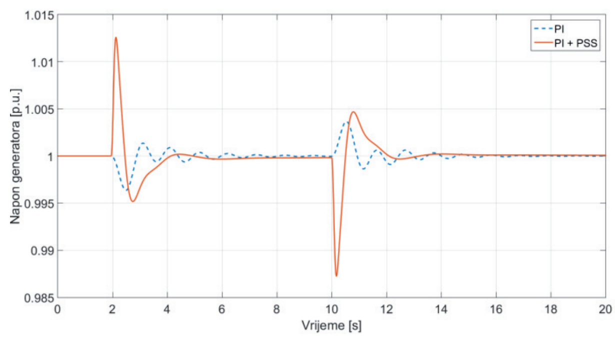

Figure 15 Voltage response (U_g)

4. CONCLUSION

The reliability of power supply is of paramount importance not only for the economy, but for the wellbeing of the entire society. The power system consists of countless elements that deliver electric energy in real time. Due to its gravity and size, it's vulnerable to a number of disturbances during its operation. In recent years, this problem is even more emphasized due to the increasing share of renewables. This paper deals with the problem of dynamic stability of synchronous generators in a power system. The literature review presented in the introduction segment revealed the existence of numerous techniques being applied for enhancing the dynamic stability of the power system. The notion of dynamic stability is related to the problem of low-frequency electromechanical oscillations that occur due to small driving disturbances and arise from the physical properties of synchronous generators. Namely, the eigenvalues of a synchronous generator occur in conjugate complex pairs, which indicate the oscillatory nature of the synchronous generator during network operation. The character of the eigenvalues determines the behavior of the synchronous generator after an operational disturbance. It is found that a synchronous generator is stable if the real parts of the eigenvalues are less than zero and that the generator begins to lose stability at the moment of a transition of eigenvalues from the left to the right side of the complex plane.

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(Footnotes)

1 Statements expressed in the paper are author's own opinions, they are not binding for the company/institution in which author is employed nor they necessarily coincide with the official company/institution's positions.