

Calculated studies of the vibrational properties of the mode parameter of the electric power system containing asynchronous turbogenerators by their frequency characteristics

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Abstract. The article presents the results of a study of the oscillatory properties of the operating parameter of electric power systems during joint operation of synchronous and asynchronous turbine generators at the station and the influence of the proportional ratios of their powers on the oscillatory properties based on their amplitude-frequency characteristics.

1 Introduction

Low-frequency fluctuations of operating parameters in the range of 0.1-3.0 Hz are one of the main problems of reliability and functioning of power systems all over the world. This is due to the fact that the presence of such fluctuations can significantly reduce the permissible flows in the system and, as a result, worsen the economy while ensuring the required level of reliability [1-5].

The conducted studies of the modes of power systems show the expediency of the layout of power plants with a mixed composition of synchronous and asynchronous generators, which improves the operating conditions of synchronous generators, since the reactive power available by them will be used. As studies show, in this case, the stability level of the synchronous turbine generator (STG) increases, its reliability and the technical and economic indicators of the station and the system as a whole improve. Also, the widespread introduction of static sources of reactive power will make it possible to create long-distance AC transmission lines with a station at the starting end, entirely consisting of an asynchronous turbine generator (ATG). Based on the results of previous studies, it is known that the indisputable advantages of the proposed power transmission are: the absence of the problem of dynamic stability in its traditional sense, practically unlimited length, the ability to take off power at any point in the line. The modes of modern power systems, the observed trend and new technical means for the generation and distribution of reactive power solve the problem of covering the reactive power of asynchronous generators and open up prospects for the creation of long-

distance and ultra-long-distance AC power transmissions.

The studies were carried out according to the simplified Park-Gorev equations in the d-q coordinate system, by the method of small oscillations.

As you know, in the study of weakly damped free vibrations or forced vibrations under the action of periodic disturbing forces (asynchronous movement or a sharply variable periodic load), periodic solutions of the original equations are sought.

In the study of small oscillations, periodic solutions of linearized differential equations written in operator form are sought. One of the common methods for studying the dynamic properties of EPS - the frequency method - is also based on the operator form of linearized equations, in which the properties of the system in transient processes are determined based on the frequency characteristics of the operating parameters of the system.

2 The mathematical statement of the problem

The computational studies of the vibrational properties of the EPS were carried out according to the schematic diagram shown in Fig. 1.

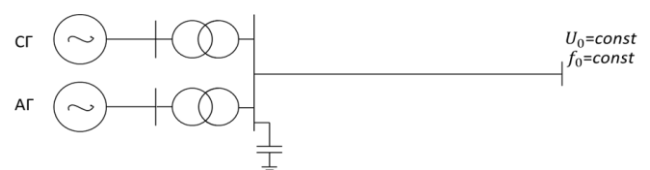


Fig. 1. Scheme of joint work of STG and ATG

When STG and ATG work together at one station, the active power of the generators at the starting end of the transmission line in the initial mode is determined by the ratios:

$$\begin{aligned} P_L &= P_S + P_A - P_I \\ P_S &= (1-K) (P_L - P_I) \\ P_A &= K(P_L - P_I) \end{aligned}$$

Where: P_L - transmitted active power at the beginning of the line;

P_S, P_A - active power of synchronous and asynchronous generators, respectively;

K – power ratio between STG and ATG.

When studying the oscillatory properties of the equations of transient processes of the stator of the STG and ATG, the static elements of the system are simplified by eliminating the transformer e. d. s and emf slip, active resistances of the stator of generators are also not taken into account [6-14].

The components of the voltage of the buses of infinite power (BWM) in this case can be determined by the total angle of power transmission:

$$\begin{aligned} U_{d0} &= U_o \sin \delta_o \\ U_{q0} &= U_o \cos \delta_o \end{aligned}$$

Where: $\delta_o = \delta_g + \delta_s$

In this case, the balance equation for the component currents is as follows:

$$\begin{aligned} i_{dl} &= i_{dcg} + i_{dag} - i_{dc} \\ i_{ql} &= i_{qcg} + i_{qag} - i_{qc} \end{aligned}$$

Where i_{dc}, i_{qc} - components of the power line charging power currents.

The linearized equations of the EPS elements, taking into account the simplification, have the form:

$$\begin{aligned} \Delta U_{dg} &= -\Delta \psi_q \\ \Delta U_{qg} &= \Delta \psi_d \\ \Delta \psi_d &= G(P) \Delta U_f - X_d(P) \Delta i_d \\ \Delta \psi_q &= -X_q(P) \Delta i_q \\ T_{js} P^2 \Delta \delta &= -\psi_d \Delta i_q - i_q \Delta \psi_d + \psi_q \Delta i_d + i_d \psi_q \end{aligned}$$

$$\begin{aligned} \Delta U_{dg} &= -\Delta \psi_{qAG} \\ \Delta U_{qg} &= \Delta \psi_{dAG} \\ \Delta \psi_{dAG} &= X_m \Delta i_{dr} - X_S \Delta i_{dAG} \\ \Delta \psi_{qAG} &= X_m \Delta i_{dr} - X_S \Delta i_{qAG} \\ P \Delta \psi_{dr} &= -S_{AG} \Delta \psi_{ar} - \Delta S_{AG} - R_r \Delta i_{dr} \\ P \Delta \psi_{qr} &= S_{AG} \Delta \psi_{ar} + \Delta S_{AG} - R_r \Delta i_{qr} \\ \Delta \psi_{dr} &= X_r \Delta i_{dr} - X_m \Delta i_{dAG} \\ \Delta \psi_{qr} &= X_r \Delta i_{qr} - X_m \Delta i_{dAG} \\ T_{jAG} p \Delta S_{AG} + X_m i_{qAG} \Delta i_{dr} - X_m i_{dAG} \Delta i_{qr} - X_m i_{qr} \Delta i_{dAG} \\ &\quad + X_m i_{dr} \Delta i_{qAG} = 0 \\ \Delta U_{dg} &= U_o \cos \delta_o \Delta \delta - X_l \Delta i_{ql} + R_l \Delta i_{dl} \\ \Delta U_{qg} &= -U_o \sin \delta_o \Delta \delta - X_l \Delta i_{dl} + R_l \Delta i_{ql} \\ \Delta i_{dl} &= \Delta i_{dcg} + \Delta i_{dag} - \Delta i_{dc} \\ \Delta i_{ql} &= \Delta i_{qcg} + \Delta i_{qag} - \Delta i_{qc} \end{aligned}$$

$$\begin{aligned} \Delta U_{dg} &= X_{s3} \Delta i_{qc} \\ \Delta U_{qg} &= -X_{c3} \Delta i_{dc} \end{aligned}$$

In the above equations, it is denoted: $U_d, U_q, \psi_{dc}, \psi_{qc}, \psi_{dA}, \psi_{qA}$ - longitudinal and transverse components of voltage and stator flux links of synchronous and asynchronous generators;

T_{jc}, T_{jAG} -inertial machine constants; δ, S_{AG} - the load angle of the synchronous generator and the slip of the asynchronous generator, taken positive in the generator mode.

Where: $G(p), X_d(p)$ and $X_q(p)$ - respectively, the operator conductivity and the operator resistance along the STG axes, taking into account three damping windings.

Transforming the above equations and including here the ARV s.d STG equations, we obtain:

$$\begin{aligned} \Delta U_{dg} &= X_q(P) \Delta i_{qcg} \\ \Delta U_{qg} &= G(P) \Delta U_f X_d(P) \Delta i_{dcg} \\ P^2 \Delta \delta - (\psi_q + i_q X_d(P)) \Delta i_d + (\psi_d + i_d X_q(P)) \Delta i_q \\ &\quad + i_q G(P) \Delta U_f = 0 \\ \Delta U_{dg} + X_m/X_r \Delta \psi_{qr} + (X_m^2/X_r - X_S) \Delta i_{qag} &= 0 \\ \Delta U_{qg} - X_m/X_r \Delta \psi_{dr} - (X_m^2/X_r - X_S) \Delta i_{dag} &= 0 \\ (R_r/X_r + P) \Delta \psi_{dr} + \psi_{qr} \Delta S_{AG} + S_{AG} \Delta \psi_{qr} + R_r X_m / \\ X_r \Delta i_{dag} &= 0 \\ (R_r/X_r + P) \Delta \psi_{qr} - \psi_{dr} \Delta S_{AG} - S_{AG} \Delta \psi_{dr} + R_r X_m / X_r \Delta i_{qag} \\ &= 0 \\ T_{jAG} P \Delta S_{AG} - (X_m \psi_{qr} / X_r) \Delta i_{dag} + (X_m \psi_{dr} / X_r) \Delta i_{qag} \\ &\quad + (X_m i_{qAG} / X_r) \Delta \psi_{dr} \\ &\quad - (X_m i_{dAG} / X_r) \Delta \psi_{qr} = 0 \\ (X_l / X_{s3} - 1) \Delta U_{dg} + R_l / X_{s3} \Delta U_{qg} + R_l \Delta i_{dcg} - X_l \Delta i_{qcg} \\ &\quad + R_l \Delta i_{dag} X_l \Delta i_{qag} U_o \cos \delta_o \Delta \delta = 0 \\ -R_l / X_{s3} \Delta U_{dg} + (X_l / X_{c3} - 1) \Delta U_{qg} + X_l \Delta i_{dcg} + R_l \Delta i_{qcg} \\ &\quad + R_l \Delta i_{qag} + X_{dag} \Delta i_{dag} - U_o \sin \delta_o \Delta \delta = 0 \\ \Delta U_f &= \Sigma W_{APB}(P) / (1 + PT_\theta) \Delta P \end{aligned}$$

Here the first three equations describe the transient process in synchronous, the next five - in asynchronous generators, the rest - in the line, as well as in the ARV system, and its transfer function is represented in the form: $W_p(P) = \Delta U_f / \Delta P = (K_{OP} + PK_{1P} / (1 + PT_1) + P^2 K_{2P} / (1 + PT_2)) / (1 + PT_\theta)$.

where P - mode parameter (U, I, f, δ and etc)

T_θ, T_1, T_2 -time constants, respectively, of the STG pathogen, differentiating and doubly differentiating ARV elements;

K_{OP}, K_{1P}, K_{2P} -amplification factors, respectively, by deviation (ΔP) the first (pP) and the second (p²P) derivatives of the controlled parameter P . Obtaining the characteristic equation of the system under study in the form of a polynomial in p by expanding the determinant, or, which is the same, excluding all unknowns from the system of equations one by one, presents special difficulties [15-20].

From the point of view of using computer programs, it is most desirable to represent the characteristic equation in the form of a determinant, the order of which is equal to the number of equations in the system. This representation of the characteristic equation allows the use of the frequency method.

The presented system of equations makes it possible to investigate the oscillatory properties of the system under

consideration when regulating the emf of the STG as a function of various operating parameters (respectively, in terms of voltage and stator current, total angle of power transmission) STG and (in terms of stator current and slip) ATG and other dynamic characteristics of the system. The characteristic determinant of the system of equations for the total angle of STG power transmission has the form:

$$F(P) = W_{\delta}(P)/(1 + PT_{\theta})$$

where: $F(P)$ - transfer functions of the ARV system, reflecting the regulation of e . with STG according to the total angle of power transmission (δ).

Denoting the characteristic determinant of the system under study through the operator expression $A_{ij}(p)$:

$$D(P) = [A_{ij}(P)]$$

where $A_{ij}(p)$ – elements of the characteristic determinant depending on the parameters of the EPS mode.

To find the expression of the transfer function of the ARV along the transmission angle channel (δ), the characteristic equation has the form:

$$D(P) = H(P)D_1(P) - D_2(P) = 0$$

$$\Delta U_f / \Delta \delta = Y(P)$$

where: $D_1(P)$, $D_2(P)$ – minors of the characteristic determinant.

$Y(P)$ - a complex expression that includes transfer functions and parameters of all other elements - external in relation to the ARV system under consideration and the values characterizing its initial steady state.

The structural diagram of the studied EPS is a closed circuit consisting of ARV elements and an external circuit in relation to the ARV.

$W_{EX}(j\omega) = \Delta \delta / \Delta U_f = 1/Y(j\omega)$; -external frequency response.

The physical explanation of the frequency characteristics of the external system and ARV can be given using the structural diagram shown in Fig. 2, obtained by opening the closed system at the ARV input

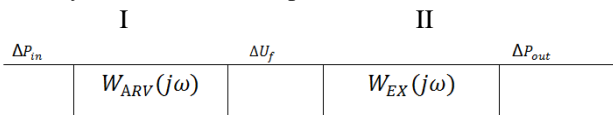


Fig. 2. Open circuit of the elements of the studied EPS.

Where: $W_{ARV}(j\omega) = \Delta U_f / \Delta P_{in}$ - frequency response of ARV.

$W_{EX}(j\omega) = \Delta P_{out} / \Delta U_f$ - external system frequency response.

$W_{time}(j\omega) = W_{ARV}(j\omega)W_{EX}(j\omega) = \Delta P_{out} / \Delta P_{in}$ - frequency response of an open system. A periodic signal is applied to the input of link I: $\Delta P_{in}(j\omega) = |\Delta P_{in}|e^{j\omega t + \nu}$

Output signal: $\Delta U_f(j\omega) = |\Delta P_{in}|e^{j\omega t + \nu}$ undergoes amplitude and phase changes. The phase shift between the V_{ARV} output and input signals is a function of frequency. The output signal of link I is fed to the excitation winding of the STG of the external system - link II, where the input signal also undergoes an amplitude and phase change. Phase shift between output ΔP_{out} and input ΔP_{in} signals:

$$F(j\omega) = V_{ARV}(j\omega) + \varphi_{rot}(j\omega)$$

where: $\varphi_{rot}(j\omega) = \varphi_{rot.sg}(j\omega) + \varphi_{rot.ag}(j\omega)$ – phase shift in a link II.

Thus, the open-circuit frequency response of the system under study has the form:

$$W_{time}(j\omega) = W_{ARV}(j\omega)W_{EX}(j\omega) = [(K_{OP} + j\omega K_{1P} / (1 + j\omega T_{1}) - \omega^2 K_{2P} / (1 + j\omega T_{2})) / (1 + j\omega T_{\theta})] W_{EX}(j\omega) = A e^{jF\omega}$$

Below are the results of computational studies of the amplitude-frequency characteristics of the total power transmission angle of EPS when the composition of the station changes from the traditional layout ($K = 0$) to the complete replacement of all STGs with ATGs ($K = 1$), each time increasing by 20% (**Fig. 3**).

In the proposed plant layouts, the required reactive power for the ATG is generated by jointly operating STGs and partially by the transmission line, i.e. there is no need to install additional reactive power sources.

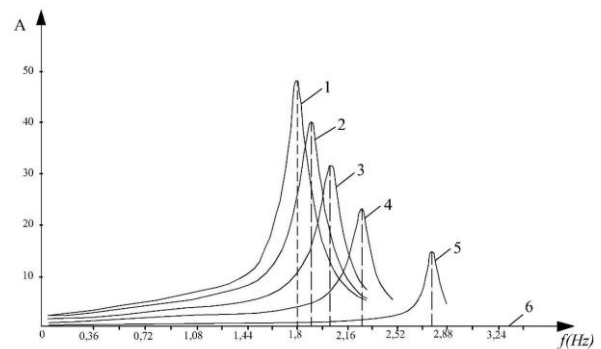


Fig. 3. Amplitude-frequency characteristics of EPS, in the presence of ATG in percentage ratios. 1-0 %; 2-20%; 3-40%; 4-60%; 5-80%; 6-100%;

As can be seen from the characteristics, with an increase in the share of ATG in the transmission of power through the power transmission line while maintaining the unchanged installed power of the station, the damping of electromechanical vibrations increases, and with a complete replacement of the STG with ATG, electromechanical vibrations are almost absent.

The increase in vibration damping due to the ATG is explained, firstly, by the influence of the damping properties of the ATG, and secondly, by an increase in the reactive power generated by the jointly operating STGs and, accordingly, their EMF [21-23].

From the obtained amplitude-frequency characteristics, it should be noted that with the introduction of ATG at the station, the resonant frequency shifts upward, for example, the resonance frequency value at $K = 1$ is approximately two times greater than at $K = 0$.

Such a shift of the resonant frequency of the EPS operating parameters from the possible frequency bandwidth allows preventing system accidents caused by low-frequency weakly damped oscillations.

3 Conclusions

Thus, the joint layout of the station from STG and ATG not only improves the operating and technical and economic indicators of the power plant, but also creates a natural damping of fluctuations in operating parameters, and this layout also improves the stability of the STG, the advantage

is manifested especially in transient modes, operating in parallel. STG and ATG act as a self-regulated system of fluctuations of the mode parameters, localized within the station buses, and the EPS will have a greater attenuation than a system containing only STG.

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