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Peculiar Properties of Voltage Phase Fluctuation Calculations at Power Networks with Rapid Variable Loads

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Abstract–**This report presents the results of investigations of active power variation influences on such parameter values of transients as voltage frequency at power supply networks and voltage phase at the same network. It was analyzed the main types of theoretical transfer functions and experimental ones for equivalent power system with thermoelectric power stations. Analyzed transfer functions correspond to mane types of regulators which are used for frequency regulation at power systems. Active power variations are represented as random processes with known parameters. The results of calculations have revealed that on the condition that peak-to-peak value of active power fluctuations in power networks no more than 0.1% of active power of equivalent power system generator, it is possible to neglect the influence of frequency fluctuations on voltage phase variations.**

Index Terms–**Active power variations, power system transients, frequency fluctuations, voltage phase variations.**

I. Introduction

Consumers with rapid variable operational mode of load such as rolling mils (RM), electric arc furnaces (EAF) and similar ones are characterized by rapid variable consumption modes of active and reactive powers. In common case it leads to appearance of electromagnetic and electromechanical transients in power supply networks of such consumers and power supply systems as a hole. These transients are characterized by fluctuation of voltage module and voltage phase or frequency in power supply networks, where the similar consumers are connected [1].

In many cases power equipment of such consumers and their control systems are connected to different points of their power supply network. For example, ac/dc converters of power electric drive of rolling mills, and its automation and control systems are connected to different bas bar or transformers of their power supply network [2]. This gives possibility in some cases to reduce negative influence of electric power quality deterioration in power supply networks, which is stipulated by power circuits of the equipment, on its automation and control systems. For example, it gives possibility to avoid harmonic instability of electric drives converters of rolling mills. But in this case two parts of the same equipment are connected to two different points of the same power supply network with different variable voltage phases. To avoid this problem it is necessary to know these phase variations, i.e. it is necessary to calculate this phase variations for automatic correction of phase shift. For this purpose transient processes have to be calculated in such power supply networks.

On the base of well known equation $\omega = d\varphi / dt$, it is possible to analyze voltage phase fluctuations or its frequency variations at any point of power supply network. Hereinafter we will consider at frequency variations.

II. Evaluation of Calculation Errors

Such error evaluates for power networks with rolling mills and electric arc furnaces may be carried out because of block diagram, which is depicted on Fig.1. In addition to general assumptions, which are usually used for analysis of dynamic conditions under small perturbations [1], let us to take into consideration the following:

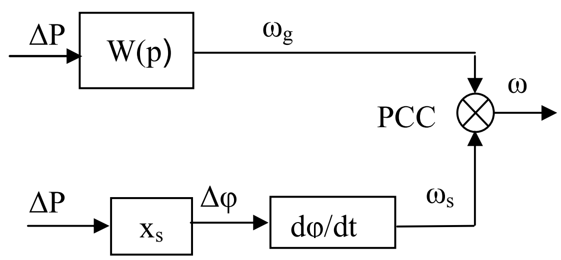

Fig. 1 Functional block diagram for error evaluation

1. The investigated transients are characterized by small parameter variations of operation mode. That is why all calculations can be carried out because of linearized differential equations of power system elements.
2. The power system is reduced to one equivalent generating block: generator - turbine. It is characterized by transfer function:

$$W(p) = \omega(p) / \Delta P_l(p) \,, \qquad (1)$$

where ΔP_l is load variation.

Processes of load variations of above mentioned consumers are random ones. With allowance for this, determine frequency variations which depend on rotor speed of equivalent generator, $D_{\omega.g}$, frequency variations, which are determined by voltage phase variations, caused by transversal component of voltage drop, $D_{\omega S}$, and total frequency in PCC - D_{ω}. Take into consideration also, that processes ω_g and ω_S are not correlated, because processes $\Delta\varphi(t)$ and his first derivation are not correlated, it is possible to write [3]:

$$D_{\omega} = D_{\omega S} + D_{\omega g} \tag{2}$$

Define error of frequency fluctuation calculations as

$$\Delta = \left[\sqrt{1 + \frac{D_{\omega g}}{D_{\omega S}}} - 1 \right] 100\% \tag{3}$$

In common case $D_{\omega.g}$ value is defined by following equation [3]:

$$D_{\omega g} = \frac{1}{S_{S.C.}^{2}} \int_{-\infty}^{+\infty} \left| W(j\omega) \right|^{2} G_{\Delta P}(\omega) d\omega, \tag{4}$$

Here $W(j\omega)$ is the transfer function "active power variations – voltage frequency" of a power system, $G_{\Delta P}(\omega)$ is power spectrum of consumed active power variations $\Delta P_l(t)$ of rapid variable load.

III. Main types of power system transfer functions

Let us to consider some existing theoretical and experimental types of power-frequency transfer functions for power systems [4, 5].

We will analyze transfer functions of power systems based on the linear equations of rotor rotation of equivalent generator and the linear equations of load dynamic characteristics. Take into consideration power systems, consisting only of thermal power stations, because rapid variable loads in power systems with the mixed types of power stations perceive first of all by thermal power stations [1].

Analyze theoretical model of power system which consist equivalent generator with its equivalent load.

The generator has automatic control system of turbine speed with proportional feedback. Taking into consideration simplified dependence load value on voltage frequency and presence of hot standby for generator, it is possible to represent power system block diagram as [5]:

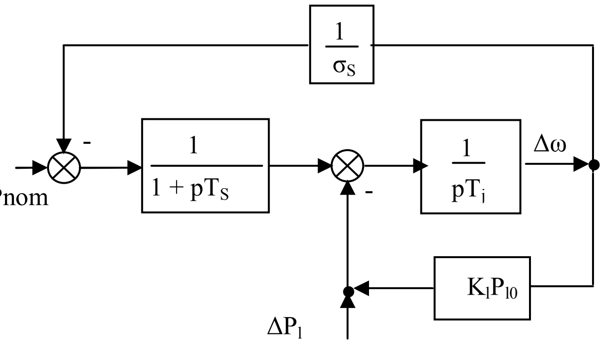

Fig 2. Block diagram of frequency regulation for simplified power system

The transfer function of such system is [5]

$$W(p) = \frac{\sigma_S (1+}{p^2 T_j T_S \sigma_S + p\left(T_j \sigma_S + T_S \sigma_S K_l P_{l.0}\right)} \rightarrow$$
$$\rightarrow \frac{+pT)}{+P_{nom} + \sigma_S K_l P}. \tag{5}$$

Here σ_S is slope factor of power system static characteristic, T_j is time constant of power system mechanical inertia, T_S is time constant of drive mechanism of speed automatic control of turbine, load effect coefficient versus frequency, P_{nom} and $P_{l.0}$ are rated powers of turbine and generator.

The more detailed conception of theoretical model of power system consists of thermoelectric power station without intermediate steam superheat and with automatic control system of frequency according to its instantaneous deviation and with speed control system. The block diagram of such system is present on Fig. 3 [4.5].

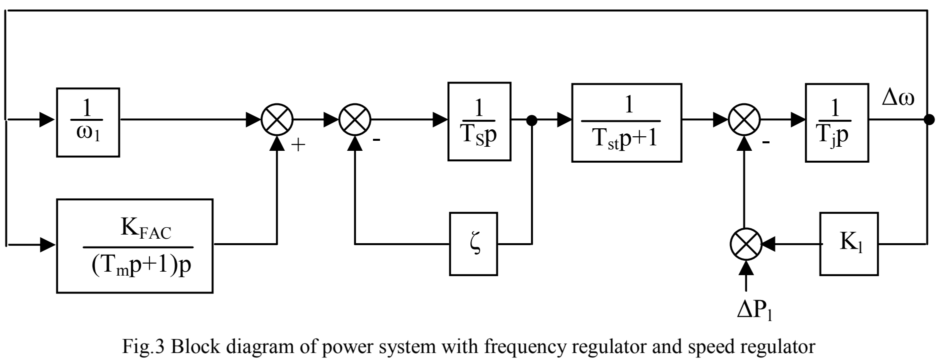

Fig.3 Block diagram of power system with frequency regulator and speed regulator

The transfer function of such system may be written as [5]:

$$W(p)=\frac{\omega_1\left(1+pT_S\right)\left(1+pT_{st}\right)(1+}{\omega_1 p\left(K_l+pT_j\right)\left(\xi+pT_S\right)\left(1+pT_{st}\right)}\rightarrow \qquad (6)$$

$$\rightarrow\frac{+pT_m)\left(1+pT_m\right)}{\left(1+pT_m\right)+p\left(1+pT_m\right)+\omega_1 K_{FAC}},$$

Where T_{st} is time constant of steam space, T_m is time constant of motor of automatic control system of frequency, ε is feedback factor of equivalent turbine regulator, $1/\omega_1$ is transfer constant of regulator metering section, K_{FAC} is gain constant of automatic control system of frequency.

Fig. 4 shows functional diagram of theoretical model of power system with control system of frequency and power regulator and without intermediate steam superheat, i.e. $T_{st} = T_m = 0$ [5].

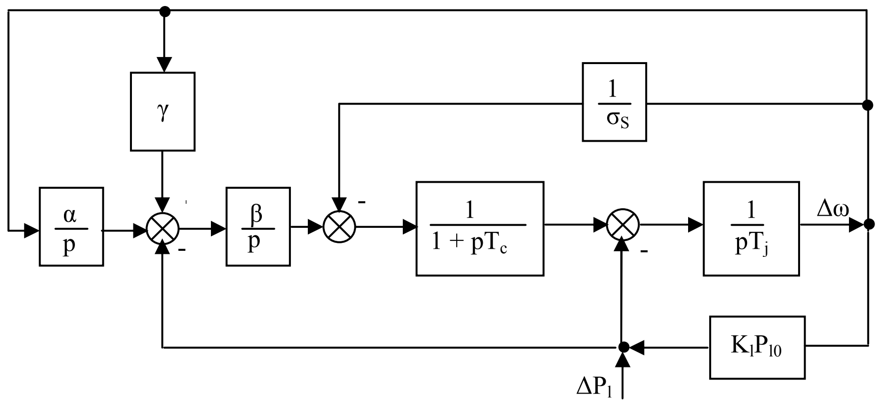

Fig. 4. Block diagram of power system with power regulator

Its transfer function is [4, 5]

$$W(p)=\frac{T_S p^3+p^2+}{T_j T_S p^4+\left(T_j+K_l T_S\right)p^3+\left(\dfrac{1}{\omega_1}+K_S\right)p^2}\rightarrow$$

$$\rightarrow\frac{+\beta p}{+\beta\left(\gamma+K_S\right)p+\delta}, \qquad (7)$$

where α, β and γ are special system parameters.

The simplest theoretical transfer function of power system under consideration may be represented as follows [1, 4, 5]:

$$W(p)=\frac{1}{T_j p+P_{l.0}K_l} \qquad (8)$$

Experimental investigations have shown, that transfer function of power system may be approximated by the equation [4]

$$W(p)=\frac{1}{B_n}\frac{1+bp}{\left(1+T_1 p\right)\left(1+T_2 p\right)}, \qquad (9)$$

under aperiodic nature of transients, and

$$W(p)=\frac{1}{B_n}\frac{1+bp}{1+T_3 p+T_4 p^2}, \qquad (10)$$

under oscillation nature of transients, where B_n, b, T_1, T_2, T_3, T_4 are parameters, which are determined as a result of experiments.

IV. CALCULATION RESULTS

The equations (2)÷(9) give possibility to carry out all necessary calculations. The calculations were carried out according to real average parameters of different types of power systems. Thus, for example, for the system, which is shown on Fig. 2, it was used following data: K_l = 2, 3; σ_S = 0.1; T_S = 0.5 sec; T_j = 10 and 20 sec; P_{nom} = 1.0; $P_{l.0}$ = 1.0. Power spectrum of active power variations is approximated by following equation [6]:

$$G_{\Delta P}(\omega)=\frac{2\sigma_{\Delta P}^2\alpha}{\pi}\frac{\alpha^2+\omega^2}{\left(\omega^2+\alpha^2+\omega_0^2\right)^2-4\omega_0^2\omega^2}. \qquad (11)$$

Here α and ω_0 are parameters of power spectrum, $\sigma_{\Delta P}^2$ is dispersion of active power variation process. For rolling mill it was taken into consideration α = 0.064 sec^{-1} and ω_0 = 0.13 sec^{-1}; for electric arc furnace α = 2.3 sec^{-1} and ω_0 = 2.0 sec^{-1} [6].

For diagram Fig. 3 it was used K_{FAC} = 3; ε = 1; T_m = T_{st} = 0.25 sec; T_j = 10 sec, T_S = 0.5 sec, K_l = 2; ω_1 = 0.05. For diagram Fig. 4 in additional it was taken into consideration $\gamma = 10$, $\beta = 9.1$, $\delta = 1$ [1, 4, 5]. Parameters of experimental transfer functions are as follows: $B_n = 3$; $b = 15$; $T_1 = 1$ sec, $T_2 = 200$ sec for equation (8) and $B_n = 1.85$; $b = 160$; $T_1 = 144$ sec, $T_2 = 8100$ sec [4].

The Fig.5 below depicts results of calculation using aforementioned equations:

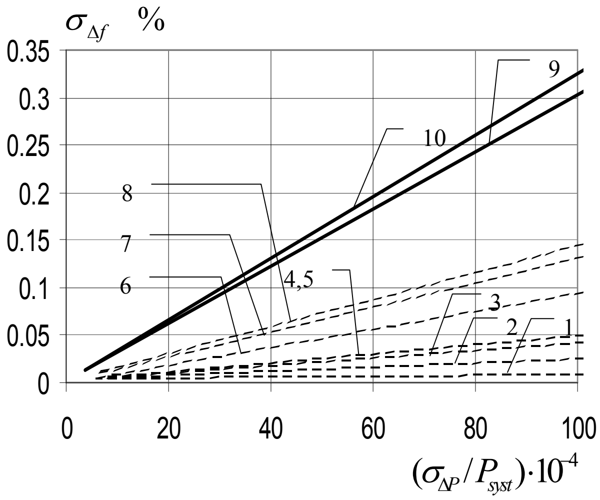

Fig. 5. Frequency fluctuation

Dotted lines in the Fig.5 present frequency fluctuation which are produced by operation of electric arc furnace; solid line is used for rolling mill characterictics. Following graphs present several types of power system transfer functions:

- 1 – equation (7)
- 2 – equation (5)
- 3, 4, 8 – equation (6)
- 5 – equation (9)
- 6,7 – equation (10)
- 9, 10 – equation (8)

For graphs 5, 7, 10 Tj = 10 sec, for graphs 6, 7 Tj = 20 sec.

The analysis of the results of calculations allows concluding, for example, that electric arc furnace influences on voltage phase fluctuations in its power supply systems in a smaller degree in comparison with rolling mills. Frequency band, in which the fluctuations of active power, consumed by electric arc furnace, are concentrated, is higher in a comparison with similar frequency band of rolling mills. Therefore fluctuations of active power consumption of electric arc furnace are not so largely affect on the equivalent generator of a power system.

The errors of calculations of voltage phase fluctuations in power network for example of 110 kV with rolling mills, which are connected with the help of 110/10 kV transformer, are larger.

In 10 kV network, which is connected to above mentioned point of common coupling (PCC) of 110 kV, phase fluctuations are significant larger, than in the network of 110 kV. Increase of a short-circuit power under the same values of rapid variable load, brings about increasing an errors of voltage phase calculations in PCC power network, stipulated by neglecting of frequency fluctuations.

The magnitudes of phase fluctuations in power systems depend on types of the used frequency regulators and the simulation method of equivalent generator of a power system. In all cases under simulation of the equivalent generator of a power system by the simplest type with automatic control systems of frequency according to its values, the calculated phase fluctuations are the greatest. Using the assumption about an acceptability of 5% error of engineering calculations, in the most hard case of 110 kV networks it is possible to neglect frequency oscillations in power systems under calculations of voltage phase fluctuations provided that $\sigma_{\Delta P}/P_{syst.} \leq 0.001$. As a rule, it exists in high-power power supply systems.

V. References

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VI. Biographies

Anatoly M. Lipsky (M'1995) received the M.Sc. degree from the Kharkov Polytechnic Institute, Ukraine, in 1970, and Ph.D. and D.Sc. degrees from the Ivanov Power University and the Novosibirsk Electro technical University, Russia, in 1976 and 1989 respectively. Since 1977 till 1998 he worked as an Associate Professor and Full Professor at Priazovsky State Technical University, Ukraine. Now he works as a Full Professor at Ariel University Center of Samaria, Israel. Some areas of his scientific interests are as follows: measurement and analysis of EPQI random processes, simulation of power networks with adjustable EPQI levels, reactive power in power networks with different voltage and current distortions.

Elena Rosentul received the M.Sc. degree from the Leningrad Polytechnic Institute. Her employment experience included the Lenenergo Electrical Company, Leningrad, the industrial automation and communication companies in the USSR and Israel, and Electrical and Electronics Department of the Ariel University Center of Samaria, Israel. Her special fields of interest include power networks analysis and optimization and high voltage transient effects.