Evaluation of Voltage Phase Fluctuations in Power Networks with Rapid Variable Loads

A. Lipsky *
Dept. of Electrical and Electronic Engineering
Ariel University, Israel

Y. Hemo
IEC

N.Miteva
Dept. of Electrical and Electronic Engineering
Ariel University, Israel

Abstract*— This paper presents a method for calculation of the voltage phase fluctuations in power networks due to the operation of the electrical energy consumers with rapid variable nature of the active and reactive power consumption. The operation of these power consumers leads to the simultaneous occurrence of the voltage frequency and voltage phase fluctuations in the power system load nodes. The voltage frequency fluctuations appear because of mechanical transients in power station "generator – turbine" blocks of energy system. Voltage phase fluctuations are associated with variations of the value of the transverse component of the voltage drop on the equivalent power system impedance, in relation to a concrete power system node. Considering the processes of power consumption value variations caused by above mentioned consumers as random processes with known parameters and types of correlation functions of consumers' load diagrams, are obtained expressions which give the possibility to assess the variances of the corresponding voltage phase fluctuation graphs in the analysed power system node. The carried out calculations allow defining the conditions that depend on the permissible calculation accuracy, when it can neglect the influence of the voltage frequency variations in the power system under assessing the voltage phase fluctuation values in the power system node, where rapid variable consumers are connected. The analysis of the calculation results allows also revealing the basic parameters of the power spectrum of rapid variable power consumption graphs of users. These parameters have a practical influence on the values of the error assessments for voltage phase value fluctuations at power system nodes.

***Keywords*—Voltage phases variations, voltage frequency variations, power systems, rapid variable loads.**

I. INTRODUCTION

Some of the mighty power consumers such as electric arc furnaces (EAF), rolling mills (RM), welding machines, etc. have rapidly varying loads graphs [1, 2, etc.]. The main frequency of power consumption variations for power networks with EAF is not larger than 1 Hz, for networks with RM frequency of these variations is about 0.1 Hz and less [3, 4]. The considered loads consume from the power network varying reactive and active powers. Rapid variations of the reactive power consumption lead, as known, to the voltage fluctuations in the power networks and to flicker. These processes are identified by the relevant standards, for example, EN 50160 [5].

Active power consumption variations mainly effect on the voltage phase fluctuations at the power network nodes, where rapid variable consumers are connected. These voltage phase fluctuations caused by changes in the magnitude of the transverse component of the voltage drop on the power network equivalent impedance, which is the external impedance for power system node with rapid variable loads [6]. Active power consumption variations also lead to the appearance of larger or smaller voltage frequency fluctuations in the power networks. These voltage frequency fluctuations occur due to mechanical transients in "generator – turbine" blocks of electrical system power plants [7]. Thus, the operation of electricity consumers with rapid variable load leads to simultaneous fluctuations of the voltage phase and the voltage frequency at power network node, where these power users are connected.

Voltage frequency and voltage phase fluctuations are not defined and not standardized by relevant electric power quality standards, for example, [5 and others]. Nevertheless, the presence of voltage phase and voltage frequency fluctuations can adversely affect the efficiency and performance of various types of electrical equipment connected to the same power network load nodes where discussed consumers are connected. For example, there are problems for the measurements associated with the voltage period measurement in power network, which lead to the time measurement errors [8, 9, etc.].

The fluctuations of voltage period duration can lead to the following: to errors in estimation of losses in dielectrics when spectral analysis techniques are used [10], to errors in evaluation of the average and the RMS periodic signal values [11], to additional errors for electric power meters, etc.

Voltage period duration fluctuations lead to the incorrect operation of control devices, of various protection devices and systems [12] and so on. To take in account and to reduce the negative effects of the presence of voltage phase and frequency fluctuations in power system load nodes it is necessary to estimate correctly the magnitude of these fluctuations in each concrete case. Thus, there is a problem to estimate the magnitude of the voltage phase fluctuations in power systems load nodes, caused by the effect of rapid variable loads on power networks, taking into account the simultaneous presence of voltage phase and voltage frequency fluctuations.

Due to the problematic possibility of correct calculation of voltage frequency fluctuations in the electrical system load nodes where are connected a large number of different electric power stations, within the framework of the analyzed problem the great practical importance has the determination of the conditions which allow to neglect the magnitudes of the voltage frequency fluctuations under the evaluation of the voltage phase fluctuation magnitudes.

II. CHARACTERISTICS OF MODE PARAMETER VARIATION PROCESSES IN POWER NETWORKS WITH RAPID VARIABLE LOADS

Under theoretical analysis of the static stability processes at power system load nodes (Fig. 1, point B) with powerful rapid variable loads, which are external to the load node under consideration, the power system is represented as a generalized power system with a generalized or equivalent unit "generator - turbine" G (Fig. 1) and an equivalent impedance in relation to the considered power system load nodes z_{eq} (Fig. 1) [7].

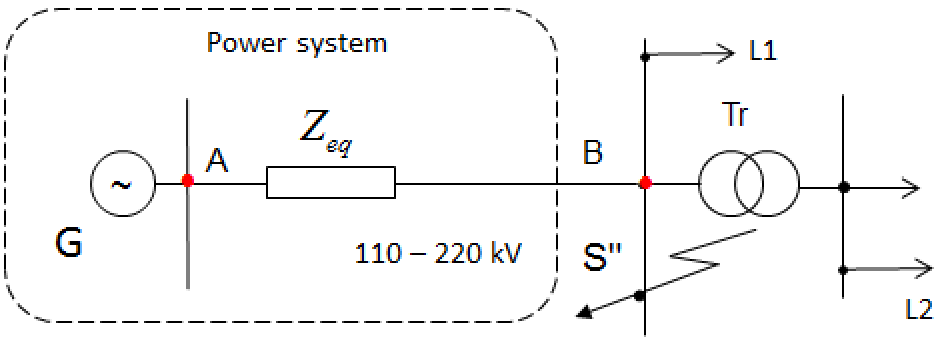

Fig. 1 Scheme for evaluation of voltage frequency and voltage phase at a power system particular point.

In Fig. 1 S'' is a sub-transient short-circuit power at the point B of the power system, Tr is a power load transformer, L1 and L2 are electricity consumers in the power network with rapid variable load, A is a point of clamps location for equivalent "turbine – generator" block. And even in such simplified scheme the calculation of the voltage frequency fluctuations at the point B in the scheme (Fig.1) presents some difficulties due to the lack and (or) the ambiguity of the initial information about the parameters of the equivalent "generator - turbine" unit and its control systems, as well as about the equivalent power network run between generator clamps at the point A and the power system point B under consideration. Therefore, it is advisable to determine the conditions under which the magnitudes of the voltage frequency fluctuations caused by mechanical transients, can be neglected in comparison with the magnitudes of the voltage frequency fluctuations at a specific network point (point B), caused by the voltage phase fluctuations. A formal comparison of the voltage phase and frequency fluctuations can be done on the basis of the known equation $\Omega(t) = \frac{d\varphi(t)}{dt}$ [13].

III. EVALUATION OF VOLTAGE FREQUENCY FLUCTUATIONS AT POINT B (FIG. 1)

Consider the case (Fig. 1) when an equivalent generating unit operates on a system with constant voltage, i.e., the voltage at the point A remains unchanged when the load under consideration operates. Further, we will consider the power system consisting of thermal power stations. It is known that during sudden load changes in power systems with mixed-generating units these changes are perceived mainly by thermal power stations [14].

In practice, there are different voltage frequency and power control systems of different “turbine - generator" blocks. Consider the power system, reduced to one equivalent "turbine - generator" unit without intermediate superheating, and equipped with a turbine speed control system.

With suitable for practical calculation accuracy, the process of the frequency variation Ω in the power system with thermal power stations depends on variations of active power consumption, ΔP, is characterized by the following transfer function [15]:

$$W(p)=\frac{\Omega(p)}{\Delta P(p)}=\frac{1}{T_j p + A}; \qquad (1)$$

$$A = K_L + \frac{1}{S_t}.$$

Here T_j is the mechanical inertia time constant of the equivalent "turbine - generator" unit, K_L is the load regulating effect coefficient on active power, S_t is the offset value of control system performance, which characterizes the slope of the static characteristic of the turbine control mechanism. Considering the process of load active power consumption variations as a stationary normal random process, one can determine the variance of the voltage frequency fluctuations due to mechanical transients in the "generator - turbine" unit in the discussed system as:

$$D_{\Omega.G}=2\int_0^{+\infty}\left|W(j\omega)\right|^2\cdot G_{\Delta P}(\omega)d\omega \qquad (2)$$

where $G_{\Delta P}(\omega)$ is the power spectrum of the process of load active power consumption variations, $|W(j\omega)|$ is the module of the frequency transfer function corresponding to the operator transfer function (1).

In many cases, the power spectrum of the active power consumption of discussed load types can be approximated by the following expression [16]:

$$G_{\Delta P}(\omega)=\frac{2\sigma_{\Delta P}^2\alpha}{\pi}\cdot\frac{\alpha^2+\omega_0^2}{\left(\alpha^2+\omega^2+\omega_0^2\right)^2-4\omega_0^2\omega^2}, \qquad (3)$$

which corresponds to the following correlation function [17].

$$K(\tau)=\sigma_{\Delta P}^2 e^{-\alpha|\tau|}\left(\cos\omega_0\tau+\frac{\alpha}{\omega_0}\sin\omega_0|\tau|\right). \qquad (4)$$

Here α and ω_0 are the damping coefficient of the correlation function and its main frequency of variations, respectively.

IV. EVALUATION OF VOLTAGE PHASE VARIATIONS AT POINT B (FIG. 1)

The magnitude of the angle between the voltages at A and B points (Fig.1) in the high-voltage power networks taking into account the features of their network parameters can be estimated as [7]:

$$\Delta\varphi(t)\approx\frac{\Delta P_L(t)X''}{U_B^2}=\frac{\Delta P_L(t)}{S''} \qquad (5)$$

where S'' is the sub-transient short-circuit power at the B point in the Fig. 1, X'' is power system sub-transient reactance corresponding to this power.

Taking into account the last equation, the power spectrum of the voltage phase variations at B point (Fig. 1) is represented as:

$$G_\varphi(\omega)=\frac{1}{\left(S''\right)^2}G_{\Delta P}(\omega) \qquad (6)$$

Considering that $\Omega(t)=\frac{d\varphi(t)}{dt}$, the power spectrum of voltage frequency fluctuations due to voltage phase fluctuations is defined as follows [17]:

$$G_{\Omega\varphi}(\omega)=\frac{1}{\left(S^{"}\right)^2}\omega^2 G_{\Delta P}(\omega) \tag{7}$$

Taking into consideration the equation (3) the variance of voltage frequency fluctuations at the B point of the discussed scheme, caused by voltage phases fluctuations, can be estimated as

$$D_{\Omega.\varphi}=\frac{\sigma^2_{\Delta P}}{\left(S^{"}\right)^2}\int_{-\infty}^{+\infty}\omega^2 G^*_{\Delta P}(\omega)d\omega=\frac{\sigma^2_{\Delta P}}{\left(S^{"}\right)^2}\left(\alpha^2+\omega_0^2\right), \tag{8}$$

where $\sigma^2_{\Delta P}$ and $G^*_{\Delta P}(\omega)$ are the variance of load active power consumption fluctuations and the normalized power spectrum of this process.

The standard deviation of the voltage frequency variations due to voltage phase variations can be estimated as follows:

$$\Delta\Omega_{\varphi}=\frac{\sigma_{\Delta P}}{S^{"}}\sqrt{\left(\alpha^2+\omega_0^2\right)}. \tag{9}$$

V. THE ERROR CAUSED BY NOT TAKING INTO ACCOUNT THE MECHANICAL TRANSIENTS

Processes of voltage frequency variations in the power system Ω_G, caused by mechanical transients, and variations of formal frequency due to voltage phase fluctuations, caused by changes in active power consumption, are uncorrelated, since it is not correlated process and its first derivative. [17] Therefore, the variance of the resulting voltage frequency fluctuations at the point B of the power network (Fig.1) can be estimated as follows:

$$D_{\Omega}=D_{\Omega.G}+D_{\Omega.\varphi} \tag{10}$$

where $D_{\Omega.G}$ and $D_{\Delta.\varphi}$ are the variances of voltage frequency variation process due to mechanical transients and voltage frequency variation process due to voltage phase fluctuations.

The error caused by not taking into account the voltage frequency fluctuations under evaluation of voltage phase fluctuations can be estimated as:

$$\Delta^2=\frac{D_{\omega.G}}{D_{\omega.S}} \tag{11}$$

Based on the above expressions after some transformations it can be written:

$$\Delta^2=\left(\frac{S^{"}}{P_{gen.eq}}\right)^2\cdot\frac{4\alpha}{\pi}\cdot\int^{+\infty}\frac{1}{A^2+\omega^2T_J^2}\cdot\frac{1}{\left(\alpha^2+\omega^2+\omega_0^2\right)^2-4\omega_0^2\omega^2}d\omega \tag{12}$$

Or, based on the allowable magnitude of the error caused by not taking into account the mechanical transients, we can estimate the maximum possible relations $P_{gen.eq}/S^{"}$ in which the calculation error will be no more than allowed error

$$\Delta_{all}\ :\ \frac{4\alpha}{\pi\cdot\Delta^2_{all}}\cdot\int_0^{+\infty}\frac{1}{A^2+\omega^2T_J^2}\cdot\frac{1}{\left(\alpha^2+\omega^2+\omega_0^2\right)^2-4\omega_0^2\omega^2}d\omega\le\frac{P^2_{gen.eq}}{\left(S^{"}\right)^2} \tag{13}$$

In accordance with the expression (13) calculations were carried out for different types of power consumers with rapid variable load modes, including the two most powerful groups of different type consumers: metallurgical rolling mill "1150" and the 200-ton electric arc furnaces. Some results of the calculations are shown below. In these calculations the magnitude of the mechanical time constants is equal to 5, 10, 15 seconds, the load regulating effect coefficient is assumed to be 2, the offset value of control system performance is equal to 0.1 [15]. Some obtained calculation results are shown on Figs. 2 - 5.

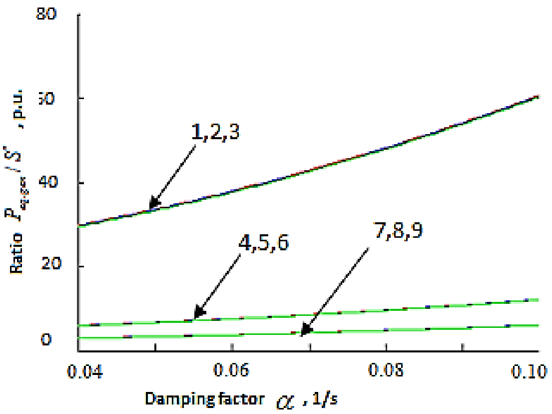

Fig. 2 Permissible ratio $P_{gen.eq} / S''$ *for rolling mills when* ω_0 *=0.15, 1/s*

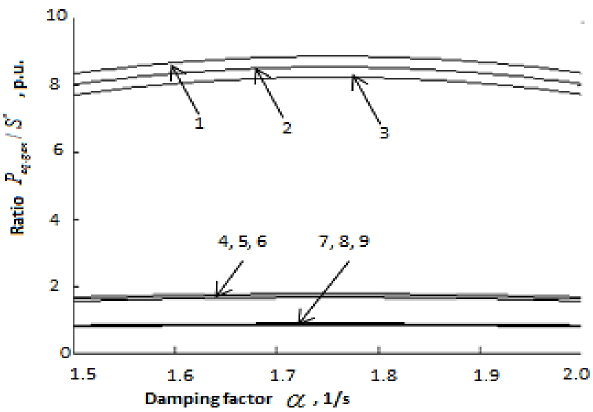

Fig. 3 Permissible ratio $P_{gen.eq} / S''$ *for rolling mills when* ω_0 *=1.75, 1/s*

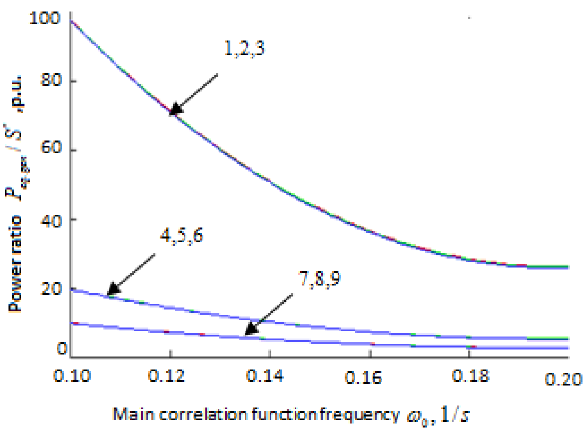

Fig. 4 Permissible ratio $P_{gen.eq} / S''$ *for rolling mills when* ω_0 *=0.07, 1/s*

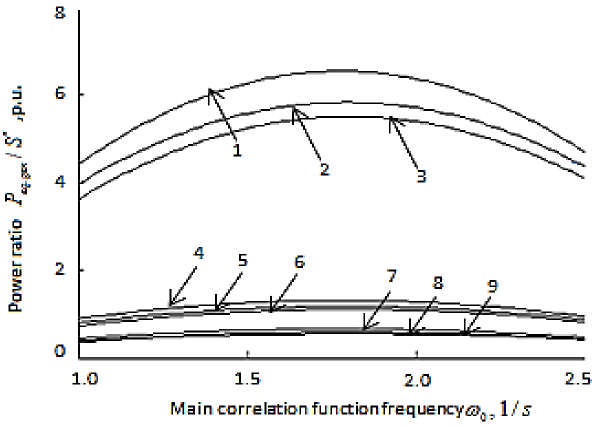

Fig. 5 Permissible ratio $P_{gen.eq}/S^{''}$ for rolling mills when ω_0 =2.0, 1/s

The results shown in Figs. 2 - 5 were obtained for the following initial data:

$1-\Delta_{all}=0.01,\ T_j=5s;\ 2-\Delta_{all}=0.01,\ T_j=10s;\ 3-\Delta_{all}=0.01,\ T_j=15s;\ 4-\Delta_{all}=0.05,\ T_j=5s;$
$5-\Delta_{all}=0.05,\ T_j=10s;\ \Delta_{all}=0.05,\ T_j=15s;\ 7-\Delta_{all}=0.1,\ T_j=5s;\ 8-\Delta_{all}=0.1,\ T_j=10s;\ 9-\Delta_{all}=0.1,\ T_j=15s$

As can see from the above graphs, the errors caused by the neglecting of voltage frequency variations in power network under evaluation of the voltage phase fluctuations for the above considered parameters is practically independent of the value of the standard deviation of the active power consumption variations.

In power networks with EAF the time constants magnitudes of system mechanical inertia in considered range of their values do not affect the calculation results at any approved calculation accuracy. In power networks with RM this is observed when adopted calculation accuracy is of 5% or less.

The parameters α and ω_0 of power spectrum of the active load process variations affect differently on the admissibility of neglecting the voltage frequency fluctuations. For example, as shown on Fig. 2, for the power networks with rolling mills when the permissible calculation error is 1%, the effect of the correlation function damping factor is considerable. A slight influence of this parameter is observed for power systems with rolling mills when the allowed error is 5% or more, and for power networks with EAF (Fig. 3) for all values of the permissible calculation accuracies. Essentially the same effect has the parameter ω_0 (Fig. 3, 5).

VI. CONCLUSIONS

1. The limit ratio values of $P_{gen.eq}/S^{''}$ were obtained for the power system load nodes with rapid variable loads, in which it cannot be taken into account the mechanical transients in "turbine-generator" blocks of energy system power stations for the evaluation of voltage phase fluctuations in these nodes.

2. From the carried out researches follows that in many cases, the characteristics of the power system mechanical inertia do not affect the calculation accuracies, and therefore there is no need to define the time constant of the power system mechanical inertia.

3. The permissible $P_{gen.eq}/S^{''}$ values, for which it cannot be taken into account the mechanical transients in "turbine-generator" blocks of power stations under the evaluation of voltage phase fluctuations, are determined only by the parameters of the normalized correlation function of the active power consumption graphs.

REFERENCES

[1] G. A. Orcajo, J. D. Rodríguez, P. G. Ardura, J. M. Cano, J. G. Norniella, R. T. Llera, D. R. Cifrián, "Dynamic Estimation of Electrical Demand in Hot Rolling Mills", *IEEE Transaction on industry application*, vol. 52, Issue 3, pp. 1-9, May-June 2016.

[2] R.V.Mineev, A.P.Mihneev, Y.L Ryzhnev. *The load graphs of electric arc furnaces*, PH Energy, Moscow, Russia, 1977,p. 120.

[3] A.S. Karandaev, V.R.Khramshin, R.R.Khramshin, I.I. Barankova, "Conceptual area of development of power saving thyristor electric drives on rolling mills", *2nd International Conference on Industrial Engineering* (*ICIE-2016*), pp. 277-283, May 19-20, 2016, Chelyabinsk, Russia, available in http://www.sciencedirect.com/science/article/pii/S1877705816315910

[4] G. A. Orcajo, J. D. Rodríguez, P. G. Ardura et al., "Dinamic estimation of electrical demand in hot rolling mills", *Industry ApplicationsSociety Annual Meeting*, pp. 1-9, Oct.18-22, 2015 , Addison,TX,USA

[5] *Voltage characteristics of electricity supplied by public electricity networks*, EN 50160, p. 34, 2010.

[6] V.I . Idelchik, Power *electrical networks and systems*, Energoatomisdat, 1989, p. 592.

[7] V.A. Venikov, *Electromechanical transient in power systems*, 4th edition, Moscow,Russia, 1985, p.596. https://wwwhome.ewi.utwente.nl/~ptdeboer/misc/mains.html,

[8] http://www.ni.com/product-documentation/4801/en/

[9] Y. Minzhong, L. Shaoyu, W. Zhuo, Y. Zhang, "Error analysis for dielectric loss factor measurement based on harmonic analysis", *Proceedings of 2001 International Symposium on Electric Insulating materials* (*ISEIM 2001*), Nov.22-22, 2001, pp. 2-25.

[10] G. E.Mog, E.P. Ribeiro, "Mean and RMS calculation for sampled periodic signal with non-integer number of samples per period applied to ac energy system", available in http://www.eletrica.ufpr.br/edu/artigos/CIl22-012_final_gerson.pdf

[11] .A. Mesrobian, D. Rowe, "The impact of variable operating frequencies and distortion on electrical power monitoring and protection systems", *Industry Applications Society, 38th Annual Petroleum and Chemical Industry Conference*, 1991, pp. 119-122, Toronto, Canada.

[12] I.S. Gonorovsky, *Radio technical circuits and signals*, , Ltd Drofa, 2006, p.719

[13] L.D. Sterninson, *Transient phenomena at frequency and power regulation in power systems* PH Energy, Moscow, Russia, 1975, p.216.

[14] Sovalov V.A et al., Experimental investigations of power system modes, Energoatomisdat, 1985, p.448.

[15] A.M. Lipsky, V.E. Tulainov, R.A. Igwuilo, *Characteristics of power quality indices in power networks*, "Modeling, Simulation & Control A: General Physics (Matter & Waves), Electrical & Electronic Engineering, V 61, n. 1-3, 1995, pp. 19-27.

[16] A.V. Bulinskiy, A.N. Shiryaev, *The theory of random processes*, PH "Fizmatlit", 2005, p.408.