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PARAMETRICAL METHOD OF LOW-FREQUENCY HARMONICS SUPPRESSION IN RECTIFIER'S OUTPUT VOLTAGE UNDER SUPPLY VOLTAGE UNBALANCES (MATHEMATICAL MODEL, STUDY AND INDUSTRIAL APPLICATION)

This paper deals with using an original and pure electronic method for low-frequency harmonic suppression with wide industrial realization and application, in place of the usually heavy inductive, low-frequency harmonic filters. One of the main applications was made for small land power supply units of onboard complexes in ground-based air navigation when preflight ground check-service is made. The transport management at thousands of small provincial airports in the former country is still unfortunate. The same situation is in Northern and central Central Asia, Northern Caucasian and Trans-Caucasian Mountains, oriented to small civil and agricultural services airports, etc. Everywhere the phase and line voltage amplitude unbalance can reach between 10-15% at the settlement's power tiny transformer or generator and there are thousands and thousands of such local «airports» [1, 6]. This paper has been editing by a native speaker, Ms. Rachel Alcorn — our sincere thanks.

Key words: *noise, adaptive methods, telemetry canals.*

Introduction. Voltage disturbance is the most common type of power quality (PQ) degradation phenomenon [11–13]. Among the various types of voltage disturbances, voltage variation and unbalance occur frequently because of different regular switching loads in the supply network [14–15]. The presence of nonlinear loads across the power system network also degrades the PQ. Thereby, slight changes in the convertors voltage or load make the operating parameters change. Applying varying voltages (or their angles), or simultaneous variation of both of them to a three-phase bridge AC-DC convertor can cause the variation of side-operating parameters. In this case, it is necessary to study the operating performance under variable conditions. This paper presents the performance analysis of a three-phase bridge AC-DC convertor system for voltage variations using an experimental case study. In order to study the performance variations of a three-phase AC-DC convertor system for voltage variations. Voltage unbalance has been interpreted and expressed mathematically as a voltage unbalance factor (VUF) in a number of ways [16]. The VUF as expressed by the IEC (International Electro technical Commission) is

$$VUF = (V_N / V_P) * 100\ \%$$

where V_N and V_P are magnitudes of negative and positive sequence voltage components.

As discussed, there will be infinite possibilities of voltage combinations that will satisfy a VUF. This can be reduced to a unique case by considering the complex nature of the sequence components which is the complex voltage unbalance factor (CVUF) defined as the ratio of the negative sequence voltage phasor to the positive sequence voltage phasor, and it is expressed as $CVUF = K_V \angle V$, where K_V is the ratio of magnitudes negative sequence voltage to the positive sequence voltage and $\theta_V = (\theta_N - \theta_P)$ is the phase angle by which the negative sequence component leads the positive sequence component.

For most AC-DC convertor systems, it is quite difficult to measure the individual phase voltages, as the neutral point is often not externally available. Since all calculations are computed on a per-phase basis, to calculate the voltage unbalance factor (K_V), a definite relationship must exist between the magnitudes of the K_V computed using line and phase voltage values. Voltage variations and unbalance can be classified into balanced over voltage (BOV), balanced under voltage (BUV), unbalanced over voltage (UBOV), unbalanced under voltage (UBUV) and unbalanced equal voltage (UBEV); and by making use of the upper limit of voltage variations, the ambiguity among voltage combinations that lead to the calculation of CVUF can be greatly reduced.

This paper deals with an original and pure electronic method with its wide industrial realization and application for suppression rectifier's low-frequency harmonics due to the different types of the voltage unbalances mentioned above.

Body. The transportation management at thousands of small provincial airports is still unfortunate in Northern and central Siberia oil fields service, Ural, Turkey, Central Asia, Northern Caucasian and Transcaucasia Mountains, oriented to small airports or of distant agricultural services, etc.

Their converters often are fed through the weak three-phase airfield network, or from the settlement's autonomous diesel generator with a limited power supply. Besides, there are some random-fluctuation regimes that lead to a rising asymmetry (unbalance) of phases and lines' voltage amplitudes in the feeding network.

The generally recognized upper limit for running any motor or generator with unbalanced voltages is usually around 5% — Table 1, (10%

[10]). However, the allowable nameplate power of an electrical machine must be de-rated according to the following table for voltage unbalances 1% and greater [9] (extrapolated from the curve www.epri.com: «Power Plant Electrical Reference Series», Volume 6 Motors):

Table 1

Motors output as a function of unbalance in the supplied voltage

Voltage Unbalance	Output De-Rating
1%	98%
2%	96%
3%	92%
4%	85%
5%	76%

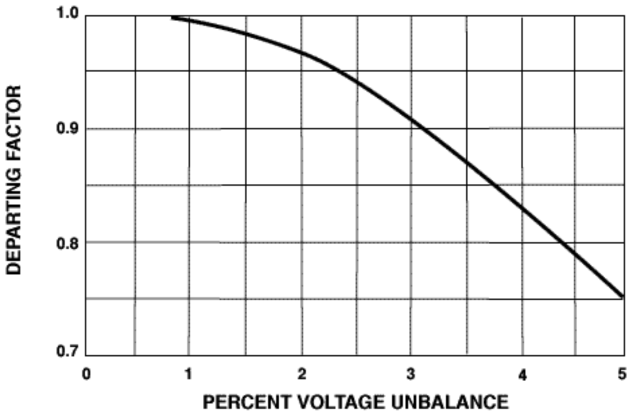

Fig. 1. *Motors output as a function of unbalance in the supplied voltage*

Phase voltage unbalance should be less than one percent for proper motor operation. If any three phase unit (a motor, rectifier, transformer etc) must be operated with a phase unbalance of greater than one percent, then the unit should be de-rated according to the presented table. A unit should not be operated at all where phase unbalance is greater than five percent. (http://cipco.apogee.net/mnd/mspupha.asp).

From the other point of view, it is known that under such voltage unbalance conditions (even up to 10%, for distant wilderness places) the low-frequency harmonic components appear in the rectifier load voltage and current output spectrums. They penetrate into the onboard network electrical motors or electronic devices, dramatically decreasing their output power and this may cause a reason for auto-oscillations or other undesirable processes [1–9, 11] only because of ineffective filtering of their low-frequency harmonics. In addition, these harmonics may become a source of interference for the airport's other ground service apparatuses.

Therefore, the problem of low-frequency harmonic suppression is very important, but the practical realization of low frequency filters (in particularly the inductive ones) clashes with the problem of the mobile rectifier's overall mass and dimensions, a converter's stability under certain conditions, its efficiency and other difficulties.

There are many well-known ways to improve the filtration efficiency of a thyristor voltage rectifier (TVR). One of these ways is the transition to multi-pulse rectifiers (3, 6, 12, 18, 24, etc.). The pulse frequency of such rectifiers is equal to $f * N$, where N is the pulses-number of the rectified voltage (3, 6, 12, 18, 24, etc.) and $\boldsymbol{f}$ is the frequency of the supply voltage. When the asymmetry of phase voltage amplitude has taken place, the influence of low frequency harmonic components are increased significantly in these rectifiers — usually by frequency $2f$ Hz pulsations appear in the rectifier's output voltage — about 10% of its maximum value (proportional to the level of the phase or line voltage amplitude unbalance). These pulsations can make the spectrum of output voltage harmonics even worse than the spectrum of 2- or 3- pulse rectifiers. The application of passive or resonant filters results in a considerable increase of the mobile rectifier's weight and size. Moreover as the onboard apparatuses work with sharply variable loads, there are output voltage fluctuations and possible voltage surge and overloads in these rectifier filters. Therefore, the passive and resonant filters are rarely applied for suppressing and smoothing the low-frequency harmonics in the ground service thyristor voltage rectifiers at small airports.

This paper outlines an untraditional [2, 3, 8], but a pure electronic approach to the suppression of low-frequency harmonics without the use of any additional low-pass filters with heavy inductors or big capacitors.

There is a rapidly growing interest in these so-called parametric methods for suppressing harmonics in the rectified voltage. They are simple for technical realization and efficient in practice. For the effective work on the parametric methods, it is necessary to find and technically understand the connection between the asymmetry characterizing main parameters and the level of the generated-additionally low-frequency harmonics.

Theoretically the rectifier semiconductor valve system can be described by the nonlinear, non-homogeneous (dissimilar) differential equations with periodically and discretely changing coefficients and perturbing functions by changing their amplitude and frequency:

$$
\begin{aligned}
&a_{11*}y_1' + a_{12*}y_2' + \ldots + a_{1n*}y_n' = f_1(t,\omega) + b_{11*}y_1 + b_{12*}y_2 + \ldots + b_{1n*}y_n,\\
&a_{21*}y_1' + a_{22*}y_2' + \ldots + a_{2n*}y_n' = f_2(t,\omega) + b_{21*}y_1 + b_{22*}y_2 + \ldots + b_{2n*}y_n,\\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\
&a_{n1*}y_1' + a_{n2*}y_2' + \ldots + a_{nn*}y_n' = f_n(t,\omega) + b_{n1*}y_1 + b_{n2*}y_2 + \ldots + b_{nn*}y_n,
\end{aligned} \tag{1}
$$

or in matrix form $[A].s[Y] = F(t, \omega) + [B]\cdot[Y]$.

The equations (1) are the generalized mathematical model of the semiconductor valve converter in which the models of a semiconductor valve and its control system are taken into consideration. Thus, this model allows us to investigate the semiconductor valve converters at any interval of the discreteness. However, its application for analyzing the harmonic composition of the rectified voltage takes a lot of time to calculate, as it is necessary to determine the conditions of the valves at each interval of the discreteness that is bound with the joint decision of the control system and electromagnetic process equations in the converter itself

$$A^T Z_B A i = A^T E_B \,, \tag{2}$$

where T — the matrix transposition symbol; A, Z_B and E_B — the matrix of the connections, resistances and electromotive forces branches matrixes; and i — the connection current matrix in accordance with the graph of the diagram. The problem is simplified considerably if the angle of bias $\Delta\alpha$ showing the switching point's bias in asymmetric modes is brought relative to the switching points of the symmetric modes (fig. 2) in the model. In this case it isn't necessary to conduct the work to find the switch-on/off moments of the valves at each interval of the discreteness or to solve the equation in full volume, but it may limit the mathematical model of the rectifier describing the voltage envelope. In this case, the equation of the mathematical model, for example, bridge thyristor rectifier for the continuous current mode can be written in the following way: $|\alpha_I| \geq (\Delta\alpha_{ib}) : \alpha_I < 60$ electric degrees from natural switching points. Thus, the non-symmetrical three-phase voltages can be written in the following way:

$$\begin{aligned} u_1(t) &= U_1 \sin(\omega t + \pi/6); \\ u_2(t) &= U_2 \sin(\omega t + \pi/2); \\ u_3(t) &= U_3 \sin(\omega t + 5\pi/6), \end{aligned} \tag{3}$$

where $U_{1m} = 1$, $U_{2m} > U_{1m}$, $U_{3m} = U_{1m}$. Then the equations of the output voltage envelope in the interval of the discreteness $\lambda = 2\pi / m$, corresponding to the symmetric mode taking into account $\Delta\alpha ib$ for the asymmetric modes, will be the following:

$$u_{\lambda 1}(t) = \left[u_3(t) - u_2(t)\right] \times$$
$$\times \begin{bmatrix} \left(\alpha_r + |\Delta\alpha_{1b}|\right)/\omega + \left[u_1(t) - u_2(t)\right] & \lambda_1/\omega \\ 0 & \left(\alpha_r + |\Delta\alpha_{1b}|\right)/\omega \end{bmatrix}, \tag{4.1}$$

$$u_{\lambda 2}(t) = \left[u_1(t) - u_2(t)\right] \times$$
$$\times \begin{bmatrix} \left(\lambda_1 + \alpha_r + |\Delta\alpha_{2b}|\right)/\omega + \left[u_1(t) - u_3(t)\right] & \lambda_2/\omega \\ \lambda_1/\omega & \left(\lambda_1 + \alpha_r + |\Delta\alpha_{2b}|\right)/\omega \end{bmatrix}, \tag{4.2}$$

$$u_{\lambda 3}(t)=\left[u_1(t)-u_3(t)\right]\times$$
$$\times\begin{bmatrix}\left(\lambda_2+\alpha_r+\left|\Delta\alpha_{3b}\right|\right)/\omega+\left[u_2(t)-u_3(t)\right] & \lambda_3/\omega \\ \lambda_2/\omega & \left(\lambda_2+\alpha_r+\left|\Delta\alpha_{3b}\right|\right)/\omega\end{bmatrix}, \tag{4.3}$$

$$u_{\lambda 4}(t)=\left[u_2(t)-u_3(t)\right]\times$$
$$\times\begin{bmatrix}\left(\lambda_3+\alpha_r+\left|\Delta\alpha_{4b}\right|\right)/\omega+\left[u_2(t)-u_1(t)\right] & \lambda_4/\omega \\ \lambda_3/\omega & \left(\lambda_3+\alpha_r+\left|\Delta\alpha_{4b}\right|\right)/\omega\end{bmatrix}, \tag{4.4}$$

$$u_{\lambda 5}(t)=\left[u_2(t)-u_1(t)\right]\times$$
$$\times\begin{bmatrix}\left(\lambda_4+\alpha_r+\left|\Delta\alpha_{5b}\right|\right)/\omega+\left[u_3(t)-u_1(t)\right] & \lambda_5/\omega \\ \lambda_4/\omega & \left(\lambda_4+\alpha_r+\left|\Delta\alpha_{5b}\right|\right)/\omega\end{bmatrix}, \tag{4.5}$$

$$u_{\lambda 6}(t)=\left[u_3(t)-u_1(t)\right]\times$$
$$\times\begin{bmatrix}\left(\lambda_5+\alpha_r+\left|\Delta\alpha_{6b}\right|\right)/\omega+\left[u_3(t)-u_2(t)\right] & \lambda_6/\omega \\ \lambda_5/\omega & \left(\lambda_5+\alpha_r+\left|\Delta\alpha_{6b}\right|\right)/\omega\end{bmatrix}. \tag{4.6}$$

The advantages of these equations (4.1–4.6) are that both α_r and $\Delta\alpha_{ib}$ enter in each interval of the discreteness. On the one hand, α_r defines the degree of asymmetry of the output voltage curve; on the other hand, it defines the asymmetry of the control angles which appear.

Additionally, the equations (2) follow the idea that by means of α_r changing at each interval of the discreteness, this may compensate for the influence of $\Delta\alpha_{ib}$ and fix the same values of α_r at the intervals when the low-frequency pulse components will be:

$$\Delta\alpha_{ib}=30^\circ-arcctg\left(\left(U_{i+1}/U_i\right)-\sin 120^\circ\right)\Big/\sin 120^\circ. \tag{5}$$

Thus, the equation (2) makes us think that if it may be receiving the information about current value of $\Delta\alpha_{ib}$ in each interval of the discreteness, then by means of bringing the correction in the control angles, it may influence the output voltage spectrum structure as far as possible.

The way of practically carrying out the given algorithm consists of the following steps. First, the crossing point of the phase voltage across zero and natural switching point in each interval of the discreteness is measured, and then the control angle correction in the same interval according to received results is formulized.

The block diagram of the implemented method and voltage diagrams show the efficiency of the correction as presented in fig. 2 and fig. 3a, 3b, respectively.

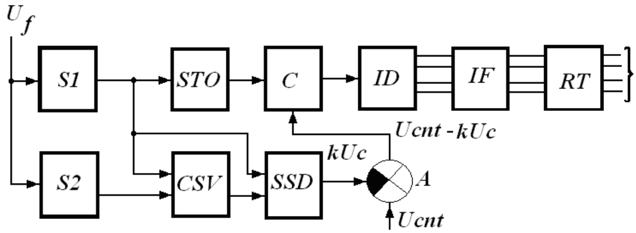

***Fig. 2.** The block diagram of the realized method*

*S*1 — the First Synchronizer to synchronize the work of the Converter of the Slot to the Voltage (CSV) in each interval of the discreteness; *S*2 — the Second Synchronizer interrupting the work of CSV in the natural switching points (when equal to the line voltages). The time-slot between the synchronous pulses *S*1 and *S*2 is proportional to the measured voltage. In the capacity of CSV usually a Saw-Tooth Oscillator (STO) is used, the start of which is synchronized with *S*1 while the ending is synchronized with *S*2.

CSV output voltage is sent to the input of the Selection and Storage Device (SSD). The pulses with the output of S1 simultaneously enter the controlling input of SSD after each interval of the discreteness. These pulses allow the instantaneous value of the voltage corresponding to the ending of the interval between the moments of the synchronous pulses *S*1 and *S*2 in SSD to be recorded. The voltage kU_c enters one of the Adder's (A) inputs with the SSD output, another input, the controlling voltage U_{cnt}, is presented.

There is algebraic summation U_{cnt} and kU_c in the Adder and its sum $U_{\sum} = U_{cnt} - kU_c$ enters the Comparator block (C) with the adder's output. The Comparator block sets the corrected control angle, gives the signal throw Impulse Distributor (ID) and Impulse Former (IF) for switching the Rectifier's Thyristor (RT) off at the proper instant of the current period. Next period (in 60 el. degrees) the process is repeated and corrected signal feeds the next value etc.

Thus, in one period 6 correcting signals are formed which set corrected control angles accordingly. The value of correcting signal (voltage) U_c is defined in each synchronizing time period in the following way: as $\Delta t_c = \Delta\alpha_{ib}/\omega$, the amplitude dependence and Δt are changing linearly, then $U_c = tg\varphi\Delta t$, where φ — is the tilt angle of the CSV output voltage (saw-tooth voltage in our case). In one turn, $\Delta t = t_{s2} - t_{s1}$ is the time interval between two synchronous signals from *S*2 and *S*1. And t_{s1} can be decomposed into two components, one of which is constant and corresponds to the symmetric mode t_{s1h}, but another changes depending on the asymmetry of the supply voltages — Δt_{s1}. Therefore: $t_{s1} = t_{s1h} + \Delta t_{s1}$ and after substituting this expression into the equation U_c the following expression was received

$$U_c = tg\varphi\left(t_{s2} - t_{s1h}\right) + tg\varphi\Delta t_{s1} = U_{ch} + \Delta U_c, \tag{6}$$

where U_{ch} — the constant component, which corresponds to the symmetric mode.

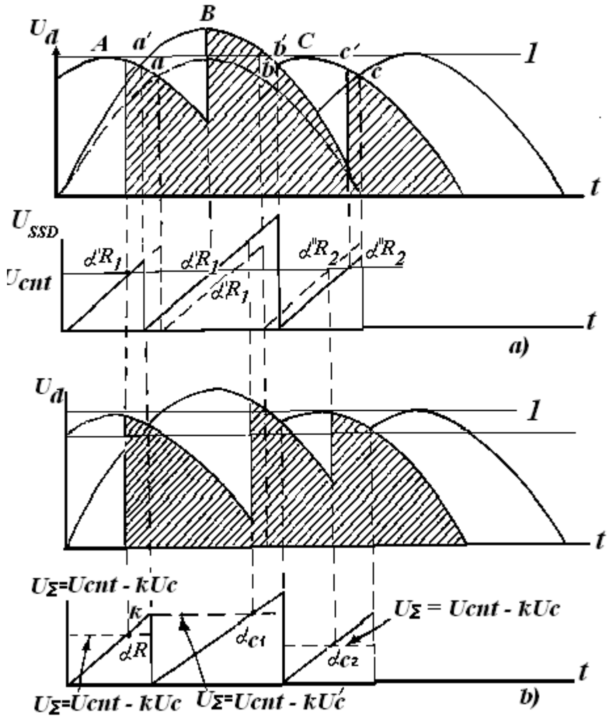

Fig. 3. *Correction efficiency shown in the voltage diagrams*

It may be compensated with entering a bias voltage in the control voltage U_{cnt} in the adder A. ΔU_c is the variable component of the correction voltage which is proportional to the supply voltage phase increment of the amplitude changing. Thus, it can be considered as proportionality $U \equiv \Delta U$. The coefficient k is defined as the ratio $\Delta\alpha_{ic}/\Delta\alpha_{ib}$, where $\Delta\alpha_{ic}$ — the angle increment in asymmetry. The system provides the full compensation of the switching moments changing (the control angles), that is, the constancy of the control angle in linearly scanning voltages of CSV and equal increasing speed of this voltages ($k = 1$) the method allows changing k in any intervals to promote better correction and therefore better the smoothing of the output voltage.

The worst nonsymmetrical feeding case happens when phases A and C are 12% lower than phase B. The results of comparing the converter output DC voltage spectrogram for the two cases — with and without the application of the electronic method mentioned above of low-frequency harmonic suppression in output DC voltage — are presented in Table 2.

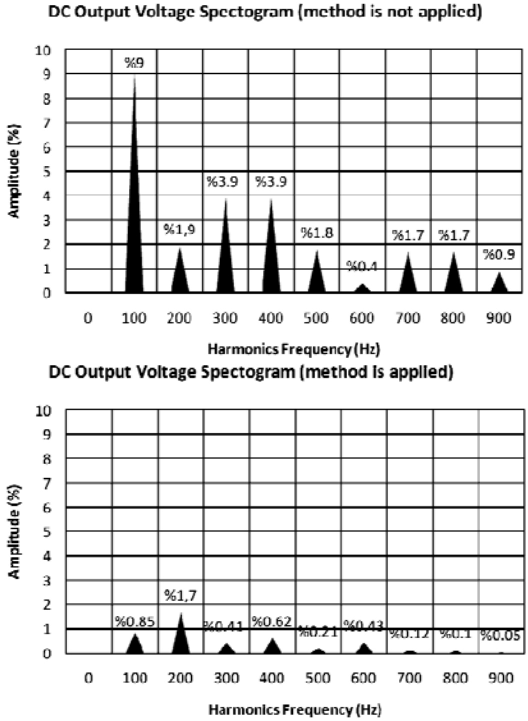

Fig. 4. *Nonsymmetrical feeding of the converter (A and C phases are 10% lower): the DC output voltage spectrograms*

Table 2

Voltage unbalances influence on low harmonic amplitudes (mainly 100 Hz)

Unbalance Case 10%	100Hz	200Hz	300Hz	400Hz	500Hz	600Hz
1. The method is not applied	9.2%	1.9%	3.9%	3.9%	1.8%	0.22%
2. The method is applied	0.85%	1.7%	0.41%	0.62%	0.21%	0.43%
Output de-rating (times) 1/2	10.82↓	1.11↓	9.5↓	6.3↓	8.6↓	0.51↑

Not wanting to overburden the paper with comments to the other unbalance cases (5% and 7.5%) DC output voltage spectrogram's photo results, it is best to confine the final remarks about these two cases: the percentage of 100Hz harmonic and output de-rating (times) are **1.27**% (**3.61**) for 5%, and **2.53**% (**7.2**) for 7.5% unbalance cases, respectively. All these results confirm the efficiency of the method proposed and allow us to reject the use of the usually heavy inductive low-frequency-harmonic filters.

The thorough studies of the DC converter model, [7] and laboratory experiments have shown (table 2) the sensitivity and the almost linear proportionality between the phase-, voltage-amplitude unbalances and the low harmonic of the converter output voltage (100Hz amplitudes before and after applying the method). The other harmonics up to 600Hz are not too sensitive to the applied voltage unbalance and are usually suppressed by little traditional RLC filters.

Conclusion. The ground power supplies must completely correspond to the characteristics of the onboard power supplies during the ground service and maintenance of aircrafts' onboard complexes. If low-frequency harmonics appear in the output of the ground power supplies, it means that there is an amplitude asymmetry of the feeding voltages and their suppression is bound with well-known difficulties. Therefore, it is important to solve this question. This paper presented the simple mathematical model of the m-phase rectifier and its output voltage curves taking into account the real instant value of asymmetry in each interval of the discreteness. In addition, the description of the correction arrangement way is given, which allows the rectifier output voltage smoothing considerably increasing or, in other words, the ability of suppressing the converter's low-frequency voltage harmonics. It simultaneously raises the speed of the control system and the possibility of forming the necessary rectifier output characteristics.

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У статті розглядається використання оригінального і чисто електронного методу низькочастотного зниження рівня гармонік для широкої промислової реалізації та застосування в якості індуктивних низькочастотних фільтрів гармонік. Одним з основних застосувань методу було здійснено для невеликих блоків живлення бортових комплексів наземного базування повітряної навігації при проведенні передпольотної наземної перевірки та обслуговування. Управління транспортом у великій кількості невеликих провінційних аеропортів проводилося невдало. Та ж ситуація спостерігається в північній і центральній частині Середньої Азії, Північного Кавказу і Закавказьких гір, які орієнтовані на невеликі аеропорти цивільних і сільськогосподарських послуг і т.д. Скрізь в локальних аеропортах дисбаланс фази і амплітуди напруги в лініях може досягати 10-15% при включенні живлення невеликого трансформатора поселення або генератора [1, 6]. Висловлюємо подяку за редагування статті пані Рейчел Алкорн.

Ключові слова: *шум, адаптивні методи, телеметричний канал зв'язку.*

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ЗАСТОСУВАННЯ ДИВІДІРІАЛЬНОГО ТА МУЛЬТИГРАЛЬНОГО ЧИСЛЕНЬ В ДОСЛІДЖЕННІ ЕКОНОМІКИ СІЛЬСЬКОГО ГОСПОДАРСТВА УКРАЇНИ

У статті наведено основні поняття дивідіріального та мультигрального числень, розглянуто виробничу функцію зі змінними коефіцієнтами еластичності. Розроблено математичні моделі виробничих функцій для дослідження економіки сільського господарства України.

Ключові слова: *дивідіріальне числення, мультигральне числення, виробнича функція, коефіцієнт еластичності, ВВП сільського господарства, основні засоби, оборотні активи.*

Вступ. Застосування економіко — математичного моделювання відіграє велику роль при дослідженні й прогнозуванні економічних систем різного рівня. Оскільки на результат виробництва має вплив

