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INVESTIGATION OF CHARACTERISTICS OF PRECISION AMPLIFIERES

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A review of the principles construction of existing high voltage measuring amplifiers (HVMA) was carried out. Their frequency range was investigated. It is proposed to use a circuit of additively connected operational amplifiers with virtual power to achieve the limiting frequencies of 400 kHz and a voltage of 500V. Several models of the circuit in the circuit simulator were investigated. It was found that to compensate for the phase shift of the output signal it is necessary to use boosting capacitances and a circuit with independent feedback. References 11, figures 5, table 3.
***Key words**:* reproduction, metrological equipment, electricity, measure power amplifiers, calibrator, computer simulation.

Introduction. It has been established that in order to ensure reliable operation of electrical equipment and electric energy metering devices the quality of electric energy (EE) must comply with DSTU EN 50160: 2014 and GOST 13109-97 taking into account DSTU IEC 61000-4-30: 2008. In accordance with these standards restrictions on distortion of the sinusoidal voltage curve, harmonic levels, interharmonics and high frequency (HF) of signals are established. The presence of high frequency harmonics are one of the causes of the distortion of EE quality caused by the nonlinear load on the power grid and the standing increase in the number of semiconductor transducers and their power [1]. Thus, the task of controlling the quality of the EE and reducing the distorting factors arises before the energy industry.

The check of quality of EE is carried out by devices of measuring the quality indices (DMQI) of EE. Moreover, the DMQI should be adjusted and verified in accordance with DSTU IEC 61000-4-7: 2012. However, there is some inconsistency between DSTU IEC 61000-4-7: 2012 and DSTU EN 50160: 2014 and DSTU IEC 61000-4-30: 2008. It consists in the fact that the DMQI according to DSTU IEC 61000-4-7: 2012 must measure signals up to 9 kHz. At present, DSTU EN 50160: 2014 restricts the frequency of signals to 148.5 kHz and DSTU IEC 61000-4-30 sets the spectra of transients of voltages and currents of electric networks that contain harmonics with frequencies up to 10 MHz.

In the electric power industry, the use of pulse converters which cause significant distortion of voltages and currents in the power grid, is growing rapidly. The spectrum of noise generated by pulsed transducers all the time expands to high and ultrahigh frequencies, due to the increase in the efficiency of transducers at high frequencies. This problem is partially solved by filtration of higher harmonics on the verge of balancing affiliation of enterprises that generate higher harmonics. Control of the effectiveness of the use of filters is impossible without control of harmonics in the extended frequency range and calibrators to check DMQI. In developed countries, analyzers of harmonic and devices for calibrating them in a limited range of frequencies and voltages are produced. For example, calibrator of the Fluke 6105 / 6100B of the American Fluke Corporation reproduces an AC frequency of up to 9 kHz with an amplitude of 200 V, and a calibrator of the German ZERA GmbH up to 400 KHz with an amplitude of 100 V.

The first step in solving this problem is the creation of HVMA as the output cascades of portable and stationary calibrators, with a frequency range up to 400 kHz, output voltage up to 500 V rms (RMS) to provide organizations of the SE "UKRMETRTESTSTANDART" and the Ministry of Energy of Ukraine.

The purpose of the work – analysis of the principles of construction of high-voltage, broadband measuring amplifiers and research of their computer, physical models for the development of HVMA for portable and stationary calibrators and metrological applications, with operating frequency ranges up to 400 kHz and output voltages from 0 to 500 V.

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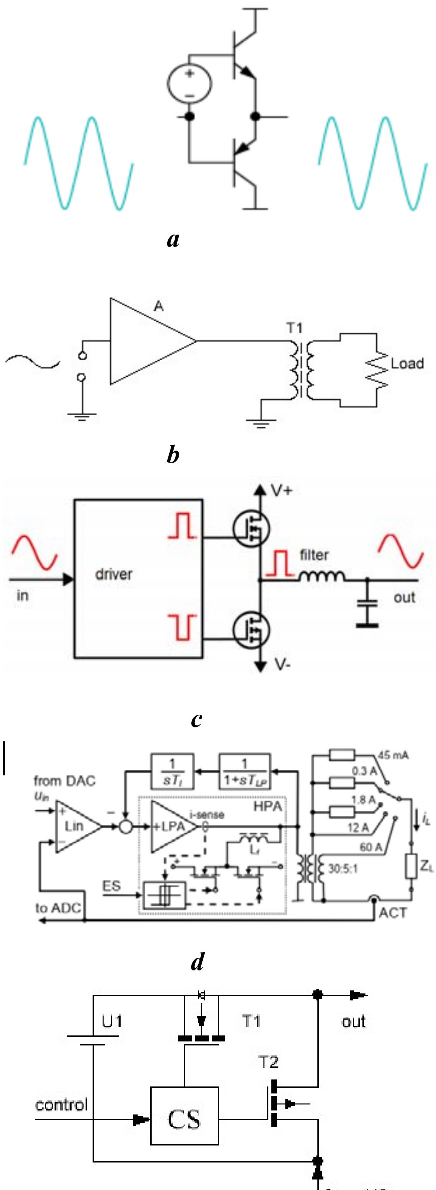

Fig. 1

Analysis of the principles of construction of HVMA, content and research results. Studies [2] have shown that the metrological characteristics of the calibrators are largely determined by the design of the output amplifiers and their work regimes were established. Most of them works in the AB [3], D [4] or hybrid [5] modes and often contain output transformers [6]. Based on these studies and works [3 – 6], a review and analysis of technical solutions for the construction of HVMA was made.

Amplifiers operating in AB mode (Fig. 1, *a*) have a number of advantages such as linearity, time stability, low total harmonic distortion (THD). Output circuits can be built on bipolar (BPT), bipolar isolated gate (IGBT), field-isolated gate (MOSFET) transistors. The frequency characteristics of the amplifier on the BPT especially such as the upper of broadband amplification frequency of HVMA f_h in the region of the HF are determined by the transfer coefficient of the transistor h_{FE} which decreases with the increase in the frequency of the input signal. High-voltage transistors used in the construction of transformerless HVMA are low-frequency (f_h <3 MHz) and allow the upper limit amplification to be about 100-150 kHz. The amplifiers based on MOSFETs are somewhat improved HVMA with BPT. But in the general case, the MOSFETs do not have advantages over bipolar transistors due to the speed and frequency properties. Also, the limiting frequency as in the BPT decreases with the rise of the drain-source voltage.

The amplifiers based on IGBTs are a kind of the above discussed. The amplifiers based on IGBTs are a kind of the above discussed. The use of low-voltage transistors which are more high-frequency does not solve the problem as to obtain the output voltage equal to the network it is necessary to apply an raising voltage transformer (VT) T1, see Fig. 1, *b*.

The broadband frequencies VT with a core of electrotechnical steel or permalloy are limited to frequencies of about 10 - 30 kHz and on amorphous - 200-300 kHz. At the same time, the VT contributes a loss which worsens the efficiency of the amplifier which for the mode of AB does not exceed 72% (is a significant disadvantage of this type of amplifier) limits the lower frequency of amplification of HVMA f_l and increases weight and size of device.

Amplifiers operating in D mode (Fig. 1, *c*) have several advantages over the previous ones. Due to the fact that the output transistors work in key mode their main advantage is high efficiency (up to 90%) much smaller weight and dimensions at equal output power. Their disadvantages are higher THD and noise level due to the transformation of the input signal into pulse-width modulated (PWM).

Due to the interfacing of clock and working frequencies in the amplifier the possibility of a "pulse crushing" effect occurs when more than one pulse is formed during the clock cycle. It makes difficult to form a signal in the load which completely repeats the entering signal. These features lead to an increase in the distortion of the restored signal and cause the clock frequency to be chosen tens times higher than the upper limit frequency of the amplified wave range. Output circuits are usually built on IGBT or MOSFET. Thus, the achievable switching frequency for these transistors is 200 kHz and the maximum reproducible qualitative signal will be in the range of up to 20 kHz. And the present source filter which is required for suppressing the carrier frequency introduces a significant phase shift to the output signal.

Hybrid amplifiers (Fig. 1, *d*) use several amplifying channels which switch depending on the magnitude of the instantaneous signal value. The first of the LPA channels (used at low instantaneous signal values) always operates in the AB mode and the other HPA channel works in D mode (used at high instantaneous signal values). They have smaller weight and dimensions, greater efficiency than the HVMA with a mode of operation AB and a smaller THD than amplifiers with operating mode D. However, they do not give a win at high frequency and are mainly used in current channels with transformers [5].

In [7] the high-voltage digital-to-analog converter (HVDAC) was proposed for accurate reproduction of sinusoidal voltage and use in metrology in particular in portable calibrators. Formation of the output voltage is done directly via high-voltage digital-to-analog conversion by feeding codes to its inputs. The converter has several advantages: high accuracy of reproduction of complex signals, absence of an amplifier, no low-frequency output transformer, small weight and dimensions. It reproduces network voltages and spectrum in 40 harmonics. The voltage discrete at the output of the HVDAC is formed by the reference voltage source and the key cell consisting of the switching circuit (driver) CS output transistors N-channel and P-channel MOSFETs (Fig. 1, *e*). Unfortunately, the bandwidth of the voltage in the P-channel is much more limited than the N-channel of the device due to semiconductor physics and is currently 500 V and 1200 V. This fact does not allow you to get the voltage specified in the beginning. The maximum frequency characteristics are determined by the switching frequency of the transistors. In accordance with the Nyquist sampling theorem [8] in order to be able to restore the output signal without distortion the sampling frequency F_s should be at least twice the highest frequency of the processed signal $F_{\max}$:

$$F_s = 2 \cdot F_{\max} \,. \tag{1}$$

Proceeding from it, we have the maximum reproducible achievable frequency $F_{\max}$ limited by the switching frequency of MOSFETs twice less than he mentioned above, which is 50 – 100 kHz.

In [2] it is noted that high-voltage operational amplifiers (HVOA) can be used as HVMA. These include operational amplifiers (OA) that allow a full range of more than 50 V at unipolar supply (± 25 V at bipolar). Having studied the proposals of HVOA from global manufacturers, it was possible to establish that such devices are offered only by Texas Instruments and Apex Microtechnology. Texas Instruments produces an HVOA with a maximum supply voltage of ± 50 V, which allows an output AC voltage of 32.27 Vrms. Apex Microtechnology manufactures a HVOA of industrial use [9] with a maximum power supply of ± 1250 V and is a leader in the industry. Using these components can significantly reduce the number of elements in the scheme and reduce the time spent on development and testing. However, an HVOP with a Power Bandwidth of 500 kHz has a supply voltage of ± 225 V, with an output voltage of ± 215 V or 152.48 Vrms.

A studied of computer models of known HVMA circuits [3-7, 9, 10], as a result of which the most promising circuit [10] was selected in terms of stability of phase-frequency characteristics, breadth of frequency and dynamic range for further research and practical use.

So, there is a need to get the output voltage higher than the voltage supply of a separate HVOA. It can be done by using successively additively included operational amplifiers series with additive connection (OASAC) with virtual supply (OASACVS) [10]. For this purpose, the middle point of the bipolar supply of each following OA is connected to the output of the previous one. As a result, the supply middle point of the following OA hasn't got any galvanic connection to the general grounding bus. There are several OASACVS schemes. The scheme with interconnected feedback was supposed to be universal for different types of calibrators. Its advantages: the input impedance does not depend on the number of OA and set by the input resistor. This allows you to set its value in the desired range and get a high input resistance value. At the expense of the serially connected feedback (FB) resistors, the diffused by them the power and consumed by the amplifier is not significant and is determined by the output load. The general amplification factor is equal to the sum of amplification factors of separate OA and the output voltage when operating on alternating current voltage is equal to the geometric sum of each OA. The disadvantage is that the output voltage module OASAC is less than the sum of the output voltage modules of each OA in the presence of phase shifts in them. Therefore, it is desirable to select the OP with the highest voltage supply, the maximum slew rate of the signal to reduce their amount.

In [10] investigated OASACVS in the ranges from 0 to 30 MHz to 30 V, 0 to 1 MHz to 100 V, 0 to 0.1 MHz to 1000 V. In order to create a HVMA run in ranges: up to 400 kHz, output voltage U_{out} 0 - 500 Vrms , it is necessary to conduct research and selection of HVAC circuits in the given ranges.

To solve the problem, obtaining the output voltage U_{out} 500 V RMS and frequency up to 400 kHz it is necessary to choose the optimal HVOP, their number N_{op} and research the computer model of implementation in the circuit simulator NI Multisim [11]. The indicated criteria suit to OP 98 or RA85 (different type of package). Its characteristics are given in Table 1.

Table 1

Model	Gain Bandwidth Product, MHz	Power Bandwidth, kHz	Slew Rate, V/µS	Supply Voltage, V	Output Voltage, U_{op} V	Output Current, A
PA85 (PA98)	100	500	1000	±225	±215	0,2

Necessary number of HVOPs rounded up to a larger whole number:

$$N_{op} \approx \frac{U_{out}}{U_{op}} = \frac{500 \cdot \sqrt{2}}{215} \approx 4\,. \tag{2}$$

Accordingly, the investigated principle scheme with interconnected feedback bundles on four OA A1 - A4 is shown in Fig. 2, where: C1 – C3 are the capacitive component of isolated DC power V1 – V8, resistors: R1 is the input, R2 – R5 are the feedback (FB), R6 – R9 are the current limiters, R10 – R13 are the supporting, XFG1 is the generator, XSC1 is the oscilloscope, XBP1 is the meter of phase-frequency characteristic (PFC), XMM1 is the RMS voltmeter. Using the generator XFG1 the amplitude and frequency of the input signal were set. The output signal was observed by the oscilloscope XSC1. The measurement of the PFC was carried out by the XBP1 device and the RSM voltage was measured by the XMM1 voltmeter, C_f is the boosting capacity.

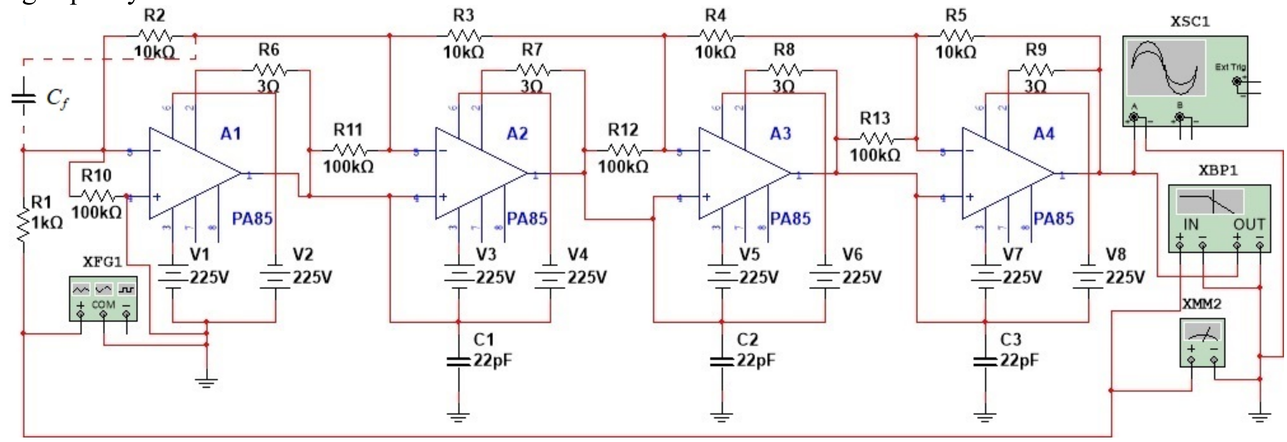

Fig. 2

The overall gain of the amplifier (Fig. 2) according to [10] will be:

$$k = \sum_{2}^{N_{op}+1} r_i / r_1, \tag{3}$$

where r_i is the resistance of resistors FB, r_1 is the resistance of the input resistor.

Also known

$$k = U_{out} / U_{in}\,, \tag{4}$$

where U_{in} is the input voltage. When R1=R2=…R5=r =r_i the resistance values of resistors FB:

$$r = \frac{U_{out} \cdot r_1}{U_{in} \cdot N_{op}}\,. \tag{5}$$

For the input sinusoidal voltage of equal to 12.73 V RMS and the output is 500 V, the input resistance R1 = 1 kΩ applying (5) we have the following value of resistors FB 9.82 kΩ which was rounded to the standard value of 10 kΩ.

Table 2

№	C_f, pF	φ , deg.	
		41,7 kHz	400 kHz
1	No	179,746	177,559
2	10	179,897	179,009
3	15	179,953	179,730
4	18	179,983	179,837
5	20	179,953	Oscillations

The work of the scheme was investigated at different frequencies and amplitudes of the input signal. The analysis of the scheme shows that the amplifier introduces a phase shift of 2.441 degrees at 400 kHz, which is extremely a lot for metrological purposes. As a result of the scheme's analysis it was found that the largest phase shift is caused by the first stage of the circuit. It was decided to try compensating the lagging phase shift by means of forcing capacitor C_f (isn't shown in Fig. 2) bypassing the input resistor R1. The obtained data are given in Table 2.

As a result of the research the optimum value of the forcing capacitance is 18 pF was established. Further increase of capacitance leads to reduce the effect of compensation at frequencies of tens of kHz and causes excitation at frequencies of hundreds of kHz. Unfortunately, the final phase shift at 0,163° at 400 kHz is not acceptable for stationary calibrators and metrological equipment. In addition, with this value of the boosting capacity the circuit has insufficient stability when the calculated input voltage is applied with maximum frequency and can only work with a smooth increase in the input voltage. However, given its low power consumption, it is advisable to use it in portable calibrators, because they require a precision for the reproduction of the phase shift voltage much less than in the stationary. The use of a Cf capacity of 10 pF will result in a phase shift of less than 1 ° and will provide a stable work of the circuit.

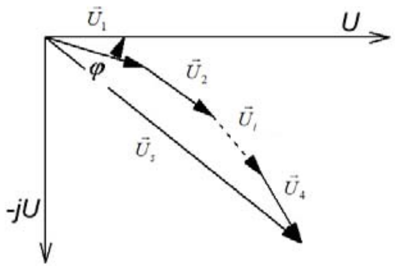

Fig. 3

Fig. 3 shows how the direction of the directional vector $\vec{U}_s$ voltage of the successive HVMA changes with respect to the input voltage vector. The output voltage vector consists of the sum of voltage vectors $\vec{U}_1, \vec{U}_2 - \vec{U}_i$ after each cascade. In the case of an increase in cascades of the amplifier to n in order to increase its output voltage the phase shift angle of the vector of the output voltage in relation to the input voltage vector can reach several tens of degrees. It's due to the summation of the phase shifts φ_i and each of the successively included cascades of the amplifier and is inadmissible for the creation of precision HVMA. On a complex plane, the vector of the output voltage will be:

$$U_s = \sum_{i=1}^{n} U_i e^{j\varphi_i}. \tag{6}$$

If all amplifiers are the same, namely $U_i = U$, $\varphi = i\varphi$, then

$$U_s = Ue^{j\varphi} \sum_{i=0}^{n-1} e^{ji\varphi}. \tag{7}$$

As can be seen from (7), the total phase shift angle of the signal vector at the output of the amplifier (Fig. 2) in relation to the vector of input signal depends on the number of stages and can reach the value at which self-oscillation occurs. The authors decided to investigate the OASACVS scheme with independent feedback [10] for each of the virtually connected OA (Fig. 4), the vector of the output signal which is described by the formula

$$U_s = nUe^{j\varphi}, \tag{8}$$

where φ is the phase shift angle of each of the vectors of the output signals of the amplifier stages. Since the adjustment of the angle of each stage of the amplifier does not affect the phase shift angle of the other stages, it can be reduced to zero, so the self-excitation does not depend on the number of stages, as follows from formula (7).

The disadvantages of this scheme are that the input impedance of the high-voltage amplifier decreases, which is equal parallel connection all of R1.i that is it decreases n times. Currents through the input resistors of each OP will be the same if identical HVOP. This will increase the total power that should be diffused on the circuit board where the HVMA is located, which is not critical to stationary equipment. Where the resistors R1.i have the same value and the resistors R2.i, R3.i, R4.i, R5.i have the same value for unification and the creation of uniformly distributed mounting reactivity. Capacitors C1.i shunt resistors R1.i and create a phase forward shift which should compensate reduction of the amplitude-frequency characteristic of each the OA.

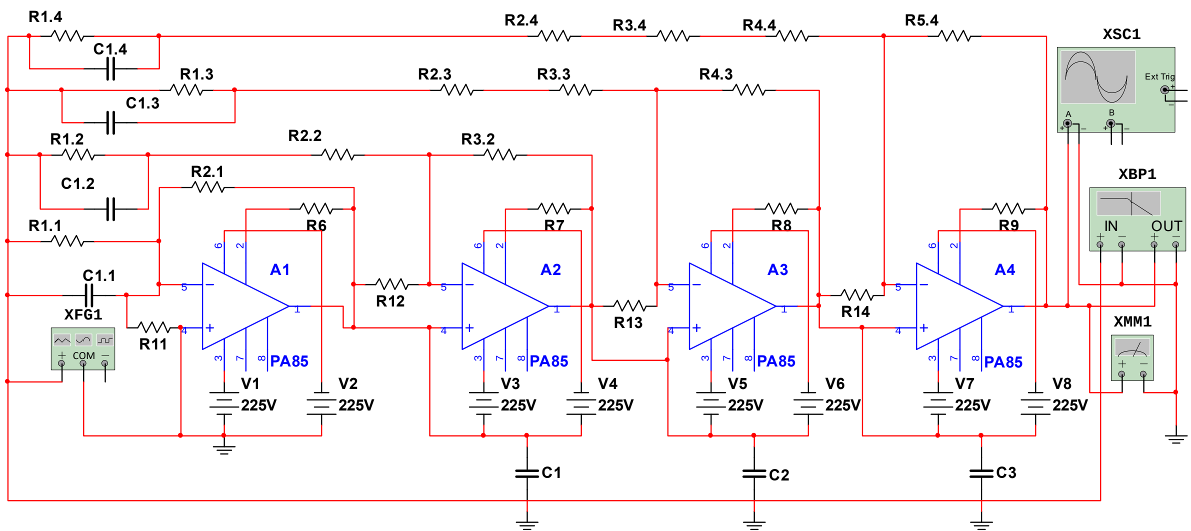

Fig. 4

Table 3

№	C1.i, pF	φ , deg	
		41,75 kHz	400 kHz
1	No	179,637	176,500
2	10	179,787	177,956
3	20	179,937	179,397
4	22	179,998	179,973
5	25	signal distortion	

Titles, functions and values of the elements in Fig. 4 coincide with Fig. 2. The values of resistors R1.i are 1 kΩ, the values of resistors R2.i, R3.i, R4.i, R5.i are 10 kΩ. The values of the capacitor C1 changed in accordance with Table 3. There are presents the results of investigations of the effect of the forcing capacitor vessels on the phase shift of the signal. During the research of the OASACVS scheme with independent feedback it was found that the compensation of the phase shift is more efficiently, the optimal value of the forming capacities is 22 pF. Its further increase leads to a distortion of the signal throughout the frequency range. The final phase shift equal 0.027 ° at 400 kHz is acceptable for precision equipment. The scheme is not subject to oscillations at any permissible values of the input signal and the load resistance in the frequency range of 0 – 400 kHz. Given its increased power consumption, recommended to use it in a stationary calibrator and metrological installation, where the requirements for the accuracy of the reproduction phase shift voltage are much tougher than the portable ones.

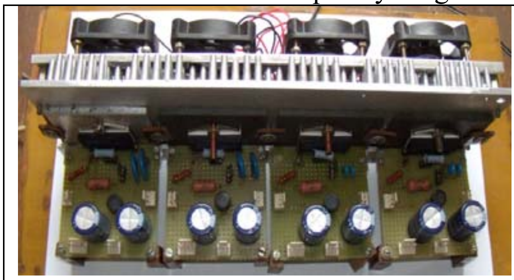

Fig. 5

Based on the research of the computer model of the amplifier with independent feedback, its physical model was created and studied. Tests of the physical model were performed in the same frequency and dynamic ranges.

The obtained characteristics of the physical model fully confirmed the results of computer model research. The photo of the experimental sample OASACVS created according to the scheme of the computer model of the HVMA (Fig. 4), is shown in Fig. 5. An attempt to increase the number of stages in computer and physical models causes distortion and oscillations of the output signal of the amplifier. Thus, the optimal number of amplifier stages with independent feedback was found.

Conclusions.

1. For the first time, using computer simulation the number of amplification stages and values of capacitances of boosting capacitors are optimized, which do not lead to self-oscillation of the circuit and distortion of the sinusoidal signal in the whole range of frequencies and loads of the amplifier.

2. For the first time, the adequacy of the computer model of the amplifier was confirmed by experimental studies of its physical model, which allows to avoid further material costs and time spent on the creation and study of physical models of such devices.

3. According to the results of theoretical and experimental studies conducted in the work, for the first time in world practice created a broadband, high voltage measuring amplifier used in voltage calibrators, with operating frequency ranges 0 - 400 kHz, output voltages 0 - 500 V and phase shift angle 1º and 0.027º, respectively.

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УДК 621.317

ИССЛЕДОВАНИЕ ХАРАКТЕРИСТИК ПРЕЦЕЗИОННЫХ УСИЛИТЕЛЕЙ

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Проведен обзор принципов построения существующих высоковольтных измерительных усилителей, дана оценка их предельной частоты работы в высокочастотной области. Предложено использовать схему последовательно аддитивно включенных операционных усилителей с виртуальным питанием для достижения предельной частоты в 400 кГц и напряжения 500 В. Исследовано несколько моделей схемы в схемном симуляторе, установлено, что для компенсации фазового сдвига выходного сигнала необходимо применять форсирующие емкости и схему с независимыми обратными связями. Библ. 11, рис. 5, табл. 3.

Ключевые слова: воспроизведение, метрологическое обеспечение, электроэнергия, измерительные усилители, калибратор, компьютерная модель.

ДОСЛІДЖЕННЯ ХАРАКТЕРИСТИК ПРЕЦІЗІЙНИХ ПІДСИЛЮВАЧІВ

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Проведено огляд принципів побудови існуючих високовольтних вимірювальних підсилювачів, досліджено їхній частотний діапазон. Запропоновано використовувати схему послідовно адитивно включених операційних підсилювачів з віртуальним живленням задля досягнення граничної частоти в 400 кГц та напруги 500 В. Досліджено декілька моделей схеми в схемному симуляторі, встановлено, що задля компенсації фазового зсуву вихідного сигналу необхідно застосовувати форсуючі ємності та схему з незалежними зворотними зв'язками. Бібл. 11, рис. 5, табл. 3.

Ключові слова*:* відтворення, метрологічне забезпечення, електроенергія, вимірювальні підсилювачі, калібратор, комп'ютерне моделювання.

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