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Methods of high voltage generation by cascading amplifiers

Abstract. The purpose of this study was to create a new model of a high-voltage measuring amplifier that would include several stages of operational amplifiers to increase the operating voltage range by sequentially "virtual" connecting the output voltages of each stage. The research methodology included the use of cascaded amplifier coupling, an additive error correction scheme, as well as modelling and computational studies to optimise the design of high-voltage operational amplifiers. The study results showed that the use of high-voltage operational amplifiers RA94 provides high stability and accuracy of the output signal even under variable loads. The cascaded connection of the amplifiers helped to expand the frequency range and increase the operating voltage, which increased their efficiency. The use of an additive error correction scheme significantly reduced signal distortion, improving its quality. Modelling and computational studies optimised the design of the amplifiers, which contributed to the achievement of high technical characteristics. By combining these methods, a reliable system with improved parameters was created. The amplifiers have shown promise for a wide range of industrial and scientific applications. They can operate in difficult conditions with high accuracy. The study confirmed the importance of integrating modern technologies into the development of electronic systems. Computational studies of a new model of a high-voltage measuring amplifier demonstrate that the use of several stages of operational amplifiers together with an additive error correction scheme can significantly expand the frequency range of the amplifier and increase the operating voltage range, which leads to improved measurement quality

Keywords: high-voltage measuring device; resistance; range; calibrator; electronics

INTRODUCTION

The study of high-voltage operational amplifiers (OA) is extremely relevant in modern conditions, when the requirements for the accuracy, reliability, and stability of electronic systems used in industrial and scientific fields are growing. High-voltage amplifiers play an important role in a wide range of applications, including energy, process automation, medical engineering, scientific experiments, and other critical areas. Therefore, the development and optimisation of amplifiers with improved performance is extremely important to ensure efficient operation of such systems and meet modern needs for high-tech equipment. In modern science and technology, there is an urgent need to generate high voltage in a wide frequency range. However, the existing element base and ready-made solutions

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do not always allow building high-voltage amplifiers using classical methods. This is especially important for the use of high-voltage amplifiers in metrological certification and calibration of thermoelectric converters, where accuracy and reliability are critical parameters. Therefore, it is necessary to review similar studies and applications to find optimal approaches and solutions to solve this problem.

A problematic issue in the field of designing high-voltage amplifiers is ensuring stable operation when generating high voltages with minimal signal losses and distortion (Panov & Tymchuk, 2023). The study by S. Sahoo *et al*. (2022) presented an optimised hybrid operational transconductance amplifier (OTA) that used adaptive offset source degeneration technology for high-frequency applications. This technology reduces crystal area and power consumption, while improving the linearity of the amplifier, which is important for generating high voltages with minimal losses. The use of a memristor also increases the gain per bandwidth, which allows the amplifier to work more efficiently at high frequencies, but the issue of stability at significant voltages remains relevant.

J. Bohler *et al*. (2022) investigated the problem of high voltage generation in power electronic converters and emphasised that in order to achieve ultra-high bandwidth, it is necessary to solve the problem of stability of amplifiers when working with high voltages. The researchers noted that modern amplifiers must be able to operate at very high frequencies and maintain signal stability under high voltage conditions, which is a problem for many industrial systems. In this context, J. Park *et al.* (2020) presented a solution for a cascade Ka-band CMOS power amplifier using inter-stage matching networks. An important aspect of this study is the linearisation of the amplifier due to the introduction of matching networks between stages, which allows working at high frequencies with an optimal voltage level. A. Davidson & H. Krishnaswamy (2024) focused on the problem of increasing the output power when generating high voltages, suggesting the use of a cascade-stacked architecture. This provides a higher output voltage while remaining within the standard power domain. This solution is effective for reducing the impact of overload on the amplifier and maintaining high voltage stability. I. Petricli *et al*. (2021) investigated a cascade amplifier for the 110-170 GHz band, where achieving high bandwidth was possible by compromising the original matching network. This creates stability problems when generating high voltages at very high frequencies, which can limit the efficiency of systems.

N.L.K. Nguyen *et al*. (2022) proposed an approach to improving amplifier performance by using network feedback, which allows efficient generation of two peaks at the extreme frequencies of the amplifier's band response. This technology improves gain over a wide bandwidth, but remains a problematic issue of upper limit frequency stability when operating at high voltages. N. Shailesh *et al*. (2021) also emphasised that distributed amplifiers are the optimal choice for generating high voltages in broadband systems. However, their power consumption and design complexity can be problematic factors in high-voltage environments, especially when it is necessary to ensure stable performance over a large frequency band. The study by H. Mosalam *et al*. (2021) proposed an integrated approach to optimising input, output, and inter-stage broadband matching networks that can simultaneously increase output power and improve performance over the entire operating frequency range. This approach is key to solving stability problems when generating high voltages, providing better amplifier performance over a wide frequency range.

In general, most current research in the field of high-voltage amplifiers focuses on the problems of stability and energy efficiency in the generation of high voltages. Although significant progress has been made in optimising amplifiers for high-frequency operation, the problem of overload resistance and ensuring stable operation under high voltage conditions remains. In the research on power electronic converters and broadband amplifiers, several aspects can be noted that were neglected by the authors. The issue of stability and reliability of amplifier components during long-term use at high frequencies and power was practically not considered. This is an important point, because the service life of devices in such conditions can significantly affect their overall performance.

The purpose of the study was to develop an innovative model of a high-voltage measuring amplifier. The objectives of the study included: creating an architecture that uses several stages of operational amplifiers to extend the operating voltage range; conducting modelling and computational studies to determine the optimal parameters of the devices; implementing a method that minimises distortion of the output signal and improves its quality.

MATERIALS AND METHODS

One of the key components of the study was high-voltage operational amplifiers of the PA94 model. The choice of this amplifier was not accidental, as it has a number of technical advantages that ensure high accuracy and stability of the output voltage. The PA94 amplifier was capable of working with capacitive loads and transmitting both direct and pulsed currents. This versatility allowed using the amplifiers in various conditions, in particular, under variable loads that require high stability of the output signal. In addition, signal generators and calibrators with an integrated automatic output voltage adjustment system were used to create the amplifiers. These devices have played a key role in maintaining the stability of the output signal, which is extremely important in the context of metrological certification and other industrial applications.

The main method used in the study was the cascade connection of several amplifiers. This method helped to significantly expand the frequency range of amplifiers and increase the operating voltage interval. To improve the accuracy of the amplifiers and reduce errors, an additive error correction scheme was used. In addition to practical experiments, modelling and computational studies were also actively used in the study. This allowed optimising the design of the amplifiers and identify the best parameters for their operation. Due to the use of specialised software, it was possible to perform various calculations and analyse various variants of schemes, which greatly simplified the design process. Modelling helped to identify the most efficient options for connecting and configuring amplifiers, which increased their efficiency and reliability. The voltage at the output of the stages was calculated using equations (1, 2):

$$Vout_n = Vout_{n-1} \times K_n, \tag{1}$$

$$K_n = 1 + \frac{R_{fb2_n}}{R_{fb1_n}}, \tag{2}$$

where: n – number of the amplifier stage; $Vout_{n-1}$ – voltage supplied to the non-inverting input of the corresponding amplifier; K_n – feedback divider coefficient.

Conversion equation for input voltage (3):

$$V_{out} = V_{in} \times \prod_{i=1}^{n} K_i. \tag{3}$$

When selecting the conversion factor for each stage, it should be noted that the output voltage of an individual stage should not exceed the sum of the input voltage and power supply voltage values (4, 5):

$$V_n \times K_n < Vcc_n + V_n, \tag{4}$$

$$K_n < \frac{V_{cc_n} + V_n}{V_n}. \tag{5}$$

Thus, the output voltage at each stage was calculated by the equation (6):

$$U_n = U_{n-1} \times K_n, \tag{6}$$

where: n – number of the amplifier stage; U_{n-1} – voltage applied to the non-inverting input of the operational amplifier; K_n – gain divider coefficient determined by the equation (7):

$$K_n = 1 + \frac{R_{7n}}{R_{8n}}, \tag{7}$$

where: R_{7n} – resistance of the signal gain setting resistor; R_{8n} – resistance of the signal gain setting resistor.

The equation for converting the input voltage of a high-voltage non-inverting broadband cascade amplifier has the form (8):

$$U_{out} = U_{in} \times \prod_{i=1}^{n} K_i, \tag{8}$$

where: U_{out} – output voltage of a high-voltage non-inverting broadband cascade amplifier; U_{in} – input voltage of a high-voltage non-inverting broadband cascade amplifier; K_i – gain divider factor.

When selecting a coefficient on each stage, the condition must be observed that the output voltage cannot be greater than the sum of the input voltage and the supply voltage 1.

$$U_{n-1} \times K_n < U_{nsup} \times U_{n-1}, \tag{9}$$

$$K_n < \frac{(U_{nsup} + U_{n-1})}{U_{n-1}}, \tag{10}$$

where: K_n – gain divider factor; U_{n-1} – voltage coming from the output of the previous stage to the non-inverting input of the operational amplifier 4 of the current stage; U_{nsup} – operating range of the supply voltage source 1 of the current stage.

The operating range of the supply voltage 1 is given by the equation (11):

$$U_{sup} = U_{+} - U_{-}, \tag{11}$$

where: U_+ – absolute value of the voltage of the positive supply voltage 1; U_- – absolute value of the voltage of the negative supply voltage 1, and must not exceed the passport values.

For bipolar power supply, the absolute value of the output signal amplitude cannot exceed the value of the supply voltage range of 1 U_v. The operating amplifier voltage level was determined by equations (12, 13):

$$U_{оп+_n} = (U_{sup+_n} - U_n) \times \left(\frac{R_5}{R_6} + 1\right)^{-1} - U_{tr}, \tag{12}$$

$$U_{op-_n} = (U_{sup} - U_n) \times \left(\frac{R_5}{R_6} + 1\right)^{-1} - U_{tr}, \tag{13}$$

where: U_{op+_n}, U_{op-_n} – relative value of the operational amplifier supply voltage 4; U_{sup+_n}, U_{sup-_n} – absolute value of the supply voltage 1; U_n – operational amplifier output voltage 4; R_5 – resistance of the operating voltage setting resistor 5; R_6 – resistance of the operating voltage setting resistor 6; U_{tr} – junction voltage of the transistor repeater.

Output signal on the first stage (U_{out1}) was formed according to equation (14):

$$U_{out1} = U_{in} \times K, \tag{14}$$

where: U_{in} – signal sent to the non-inverting input of the operational amplifier 4.

Equation (15) determined the gain divider coefficient:

$$K = 1 + \frac{R_7}{R_8} -, \tag{15}$$

where: R_7 – resistance of the resistor setting the signal gain 7; R_8 – resistance of the resistor setting the signal gain 8.

The output signal of the first stage was sent to the non-inverting input of the amplifier 4 of the next stage and formed the output signal according to equation (16):

$$U_n = U_{n-1} \times K_n, \tag{16}$$

where: n – cascade number; U_{n-1} – output signal of the previous stage.

The gain divider coefficient of the current stage was determined by the equation (17):

$$K_n = 1 + \frac{R_{7n}}{R_{8n}}, \tag{17}$$

where: R_{7n} – resistance of the resistor setting the signal gain 7; R_{8n} – resistance of the resistor setting the signal gain 8.

Overall, the study was based on cutting-edge technologies in high-voltage electronics and engineering modelling.

RESULTS

High-voltage measuring amplifiers (HVMA), also known as voltage dividers, are important electrical devices used to accurately measure high voltages, usually exceeding 1 kV. The main function of these devices is to reduce the voltage to a level that is safe and convenient for measuring with standard instruments such as voltmeters or oscilloscopes. The principle of operation of voltage amplifiers is based on the separation of voltage between the components of the device, such as resistors or capacitors connected in series. On one of these components, some of the voltage is removed, which is then measured. The resulting voltage is proportional to the total input voltage. There are several types of high-voltage amplifiers, including resistive, capacitor, and combined. Resistive amplifiers consist of a series of resistors connected in series and are used to measure both DC and AC voltage. They are characterised by high accuracy, but can heat up when operating at high voltages, which can affect the measurement accuracy.

Capacitor amplifiers consist of series-connected capacitors and are commonly used to measure high-frequency variable voltages. They have less impact on the frequency characteristics of the measuring system, but their calibration may be more difficult. Combined amplifiers combine resistive and capacitor elements, which facilitates optimal measurement characteristics under various operating conditions. The key characteristics of amplifiers are the division factor, rated voltage, frequency response, and measurement error. These parameters determine the accuracy and reliability of the amplifiers, and their ability to adapt to different operating conditions. The application of high-voltage measuring amplifiers is extremely wide. They are used in energy, scientific research, electrical equipment testing, and other industries where high voltage measurement is required. These devices help to safely and accurately measure high voltages, which ensures reliable operation of electronic equipment and increases the safety of measurements.

Operational amplifiers were originally designed to perform mathematical operations where the voltage level determined numerical values, signs, and frequency. Over time, they have become multifunctional devices with a wide range of applications. High-voltage operational amplifiers typically contained amplification circuits where the output voltage exceeded the operating voltage level of the existing element base (Asha & Dahiya, 2022). These amplifiers consisted of complex multi-transistor configurations that provided a high voltage gain (up to 106) and an operating frequency range from 0 to fmax. In modern models of amplifiers, the value of f_{max} could reach several GHz (Sedov, 2017). High-voltage amplifiers are widely used in dielectric spectroscopy, where it is important to provide not only a high output voltage (hundreds of volts), but also to maintain its stability and quickly change its value. This makes them indispensable in diagnostic equipment for insulation and dielectrics in industrial environments (power supplies, welding equipment, control systems for electric drives, valves, solenoids and other actuators), and in laboratories. In addition, such amplifiers have found application in military and aerospace technologies (vibration compensation systems, sonar, electrostatic levitation devices) and in medical equipment (ultrasound diagnostic devices, magnetic resonance imaging, microscopes and analysers) (Medyanyi, 2017).

AC voltage calibrators had limitations in terms of operating frequency range, output level, and stabilisation accuracy. The main sources of errors were shifts in the zero voltage level at the outputs of the stages and voltage losses in the communication lines between them (Liu *et al.*, 2016). For most calibrators, the frequency range usually did not exceed 100 kHz, and high-frequency calibrators had a limited output signal level (30 V), which made it difficult to conduct comprehensive verification of devices in this frequency range. The output voltage stabilisation error for calibrators with a frequency range of up to 100 kHz was ±(0.002-0.05) %, and for devices operating in the range of up to 100 MHz, – ±(0.1-1) % (Roberts, 2007).

Measuring operational amplifiers are often used in measuring and testing equipment due to their high-precision characteristics (Sedov, 2017), although they do not provide high power output. A high-voltage measuring amplifier is a specialised version of an operational amplifier, based on which not only amplifier circuits are developed, but also automatic control systems. Various circuit solutions are used to increase the operating voltage range and reduce stabilisation errors. The most common in 2024 are high-voltage amplifiers from Fluke and operational amplifiers from Apex Microtechnology (2024), used in modern calibrators with integrated power amplifiers (Dovhal, 2023).

The amplifiers developed by Apex Microtechnology have unique characteristics such as a wide range of supply voltages, high output currents, low quiescent currents, minimal internal losses, and high linearity (class AB) (Zhu *et al.*, 2020). However, non-specialised operational amplifiers are not capable of providing an output voltage that exceeds the supply voltage. The study presents a new high-voltage amplifier circuit that uses multiple operational amplifier stages to extend the operating voltage range of the device. The study examined a model of a 3-stage high-voltage measuring amplifier (HVMA) built on the basis of the PA94 operational amplifier from Apex Microtechnology.

W.G.K. Ihlenfeld (2005) described the transformer converter as a simple and reliable solution for generating high voltage. This solution provided stable operation and high reliability, but had limitations in generating signals in the wide frequency band and constant voltage signals. Transformer converters were well suited for certain low-frequency applications, but did not provide the necessary flexibility for broadband or constant signals, making them unsuitable for some demanding metrological applications. H. Pan *et al.* (2019) investigated the use of operational amplifier cascades and optocouplers. This solution met the needs for generating constant voltage signals. However, it had low accuracy and a narrow frequency band, which limited its use in high-frequency measurements. OA-based high-voltage cascade amplifiers required careful tuning and had difficulty maintaining stability and accuracy at high frequencies.

Y.M. Tuz (2012), in the monograph "Broadband high-voltage measuring amplifiers", described methods and configurations of operational amplifier stages for generating high voltage over a wide frequency range while maintaining accuracy. In their work, they considered the PA94 amplifier as an amplifier element. Using four stages (Fig. 1), these elements provided 1,000 V signal generation in the band up to 100 kHz. However, due to the limited rise rate, the accuracy characteristics of 1,000 V signal reproduction at high frequencies were significantly degraded to 3,000 ppm. In addition, a proportional increase in the number of stages to achieve higher voltages was limited by the quality of the element base. Phase shifts that occurred in cascades degraded accuracy and caused harmonic distortion. Phase correction required an additional complication – the use of independent feedback links, which added complexity and reduced the reliability of the system.

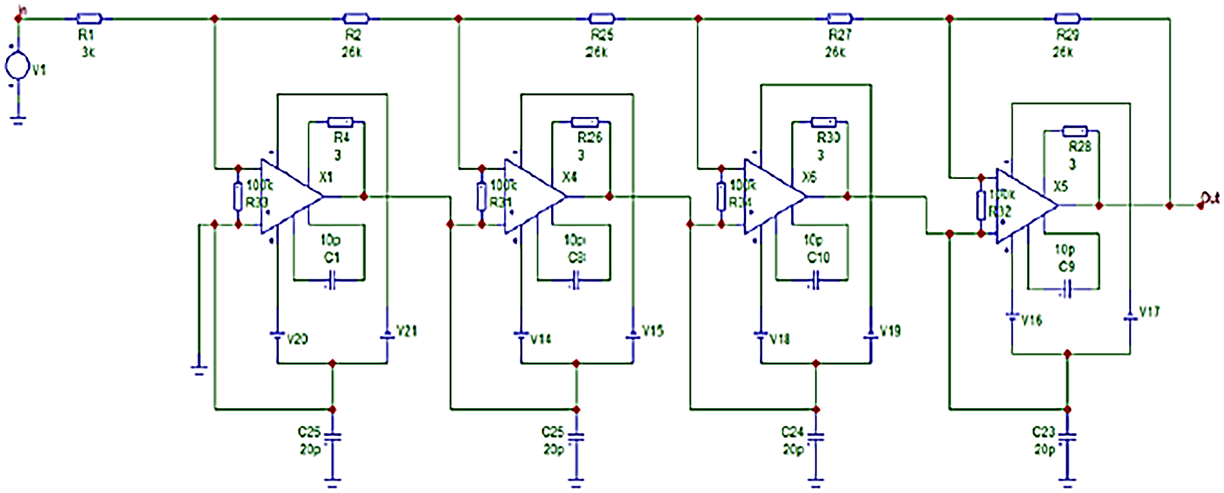

Figure 1. HVMA scheme for four operational amplifiers

Source: created by the authors based on Y.M. Tuz (2012)

The industry offers a variety of generators, however, a review of existing solutions has shown that none of the available approaches meet all the requirements. The transformer converters were reliable, but did not support a wide frequency band and constant voltage. Cascade amplifiers based on operational amplifiers and optocouplers provided constant voltage generation, but had low accuracy and a narrow frequency band. PA94-based broadband amplifiers allowed high-voltage and wide-band operation, but had limitations in the rise rate and accuracy of signal reproduction at high frequencies. Therefore, it is necessary to continue research to develop optimal solutions that can meet all the requirements of metrological certification and calibration of thermoelectric transducers.

In the course of studying various amplifier circuits with inverting and non-inverting stages, and using dependent and independent connections, it was found that distortions of the output signal occurred at a frequency of 100 kHz. Instead of a sinusoidal shape, the signal took on a triangular shape. This phenomenon was particularly evident when two or more amplifiers were cascaded together according to the inverting amplifier circuit. To avoid such distortions, it was proposed to use a series cascade connection of individual operational amplifiers, which helped to connect power supplies in series, thus creating a voltage adder (Song *et al.*, 2023). To analyse the functioning of this scheme, simulations were performed in the MicroCap software environment. A block diagram of the HVMA model is shown in Figure 2.

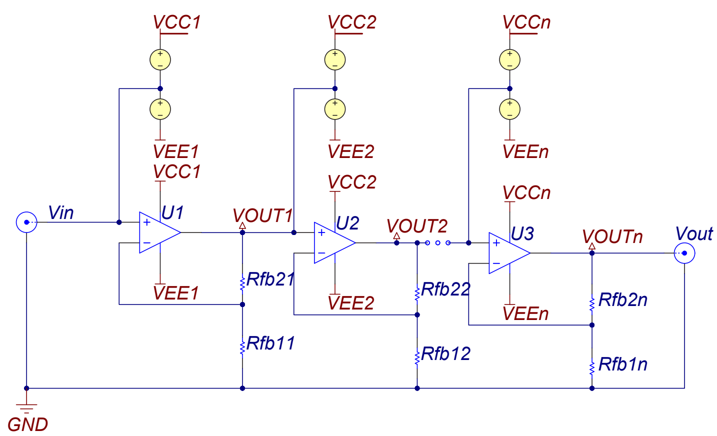

Figure 2. Block diagram of HVMA

Source: created by the authors

The described model was a circuit that consisted of series-connected stages of operational amplifiers. The stages were implemented as a separate operational amplifier, which had its own independent power supply, galvanically isolated from the power supply of other stages (Tuz, 2012; Song *et al.*, 2023). The input voltage that was applied to each stage was amplified K times by using a voltage divider across resistors $R_{(fb2)}$ and $R_{(fb1)}$ in the feedback loop. Figure 3 shows calculated diagrams of the output voltage of individual stages.

The diagram of the electrical model of HVMA is shown in Figure 4.

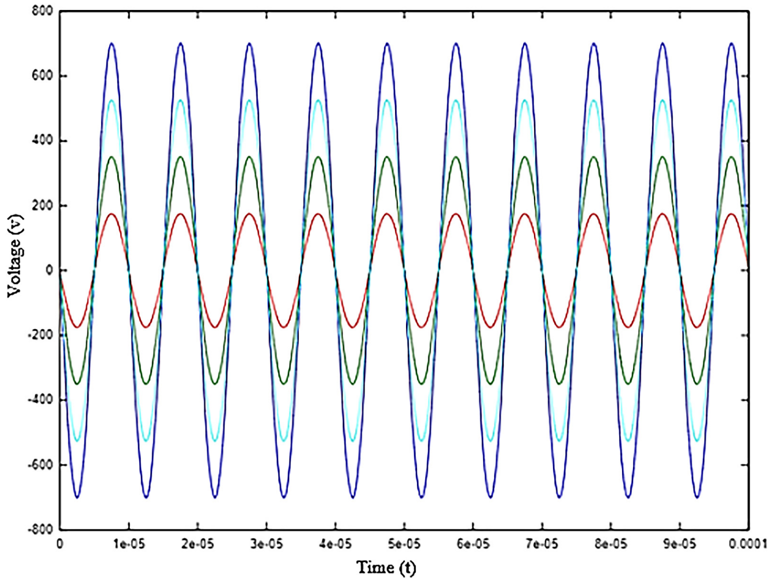

Figure 3. Output voltage diagrams at stage outputs

Source: created by the authors

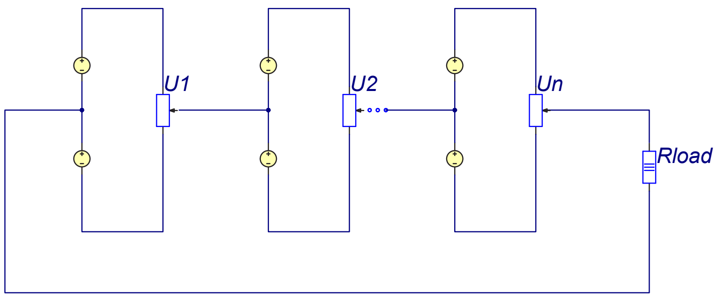

Figure 4. Electric model of HVMA

Source: created by the authors

The utility model belongs to the field of radio engineering and can be used to build radio and telecommunications systems for various purposes, for example, in automation and measurement equipment devices (Junglas & Maas, 2021; Hu & Ma, 2021). The closest to the utility model is the IALC 5.035.004 amplifier developed by the AED Research Institute of National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", which is a high-voltage inverting cascade amplifier with virtual power supply and general dependent feedback. The disadvantage of this amplifier is the low input impedance, which affects the input signal, which leads to an additional error in the output signal. In addition, the feedback link of such an amplifier is very sensitive to parasitic characteristics of elements and structures, and accordingly the cascade with the worst characteristics leads to degradation of the characteristics of all other stages (Montaseri *et al.*, 2022; Mehrotra & Hopkins, 2023). The utility model is based on the task of expanding the operating range of the input voltage, while reducing the error of the output signal and reducing the sensitivity of the feedback link to parasitic characteristics of elements and structures.

This problem is solved by the fact that a high-voltage non-inverting broadband cascade amplifier (Fig. 5), divided into separate stages with independent power supply, connected in series and containing an operational amplifier, a gain divider, according to the utility model, the stages are configured according to a non-inverting feedback circuit and a transistor repeater and a voltage divider of the operating point are added to each stage.

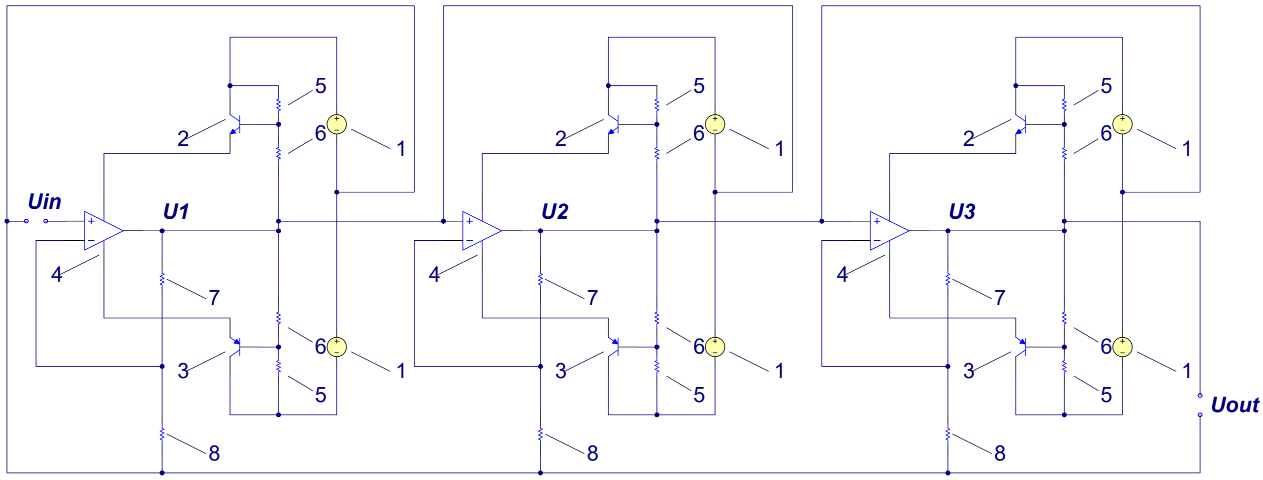

Figure 5. High-voltage non-inverting broadband cascade amplifier
Source: created by the authors

This amplifier consisted of three stages, with each stage containing two power sources (1), an operational amplifier (4), and a transistor repeater based on a bipolar NPN transistor (2) and a PNP transistor (3). In addition, two dividers were present in each stage: one for setting the operating voltage, which consisted of resistors (5) and (6), and the other for adjusting the signal gain, which included resistors (7) and (8) (Jung *et al*., 2020; Roongmuanpha *et al*., 2021). The technical result of the claimed solution is an extension of the operating range of the input voltage and a reduction in the error of the output signal. And due to independent feedback, the sensitivity of the feedback link to parasitic characteristics of elements and structures decreases and the influence of other working stages (Bai *et al*., 2021; Lee *et al*., 2021). The proposed combination of features that determines the essence of the utility model was not known from previous technical solutions, so this utility model met the criterion of innovation. The proposed high-voltage non-inverting broadband cascade amplifier can be implemented according to the scheme shown in Figure 5.

The utility model was illustrated by an example of its application. This model was a non-inverting broadband cascade amplifier consisting of separate independent stages connected in series to extend the operating range of the input voltage. Each stage was made in the form of a separate operational amplifier, tuned according to a non-inverting feedback circuit, with independent power supply, a transistor repeater and a voltage divider of the operating power point.

The input voltage applied to each stage was amplified by Kn times, which was provided by a voltage divider of the operating power point on resistors 5 and 6. Additional transistor stages helped to double the operating range of the output voltage by shifting the operating power point. A floating supply voltage shaper for each stage was implemented using the following components: 1, 2, 3, 5, 6. The supply voltage sources 1 were connected in series, creating a bipolar supply voltage with a nominal value equal to twice the maximum value of the operating voltage of the operational amplifier 4. Input signal (U_{in}) received on a non-inverting input of operational amplifier 4, output signal on the first stage (U_{out1}) was formed according to equation (8).

High-voltage non-inverting broadband cascade amplifier: utility model patent (2023) was capable of implementation in industrial production. Thus, this technical solution met the criterion of industrial suitability and could be protected by a patent of Ukraine for a utility model. In the field of high-voltage generation by broadband amplifiers, the use of low-voltage amplifier stages together with the voltage doubling method is considered. The main problem is that operational amplifiers (OAs) with better frequency characteristics and higher gain rates usually have a low supply voltage. One possible solution is to use high-speed amplifiers such as the Apex PA98 instead of the Apex PA94. Apex PA98 amplifiers have a wider bandwidth and higher build-up rate compared to the PA94, but their operating voltage is half that. Using the voltage doubling method described in the patent, it was possible to expand the frequency band to 150 kHz when generating a 1,000 V signal with a moderate deviation of 680 ppm. This method ensured high accuracy and stability when working with high voltages over a wide frequency range.

The voltage doubling method consists of cascading multiple amplifiers with independent power supplies, which allows doubling the output voltage. Each stage contains an operational amplifier and feedback links that ensure accurate signal processing. For stable and efficient operation, operational amplifiers are powered by transistor repeaters that provide the required power levels. By carefully selecting the gain and supply voltage, the amplifier system achieves an extended output voltage range. Existing methods of high voltage generation often have certain limitations. For example, transformer converters provide stable operation, but do not support a wide frequency band and constant voltage signals. Cascade amplifiers based on operational amplifiers and optocouplers can generate constant voltage signals, but have low accuracy and a narrow frequency band. Y.M. Tuz (2012) described methods for configuring operational amplifier stages for generating high voltage over a wide frequency range, but while maintaining the accuracy and speed of signal rise.

The new approach under consideration allows using high-speed amplifiers with low supply voltage to generate high voltage in a wide frequency band. This ensures high accuracy and stability of the output signal. For example, the use of Apex PA98 amplifiers and the voltage doubling method allows reaching 1,000 V in the band up to 150 kHz with a deviation of 680 ppm. This significantly improves the frequency response and signal growth rate compared to conventional approaches (Dovhal & Tuz, 2024). A review of existing solutions has shown that the new approach using low-voltage amplifier stages and the voltage doubling method has significant advantages. It allows achieving high accuracy and stability when generating high voltage over a wide frequency range. This makes it promising for further research and implementation in the metrological certification and calibration of thermoelectric transducers.

Cascade connection of amplifiers is an effective method of extending the range of operating voltages and frequencies of amplifiers. In cascade circuits, each amplifier amplifies the signal coming from the previous stage, thereby increasing the total output voltage of the system. However, cascading also brings a number of problems, among which the main ones are signal stability and error control. In cascade circuits, the main task is to ensure stable gain at each stage to avoid cumulative signal distortion. The amplifiers in the stage must be optimally tuned so that each subsequent amplifier receives a signal with the required voltage level and minimal distortion. This requires careful selection of the feedback and resistance parameters of the resistors used to adjust the signal gain.

DISCUSSION

A high-voltage operational amplifier PA94 was used in the study, which allowed achieving stability and high accuracy of the output signal, which is critical for ensuring reliable operation of electronic systems under variable load conditions. This solution has significantly improved the reliability of electronic devices in industrial and scientific systems where load fluctuations often occur. Stability of characteristics in such conditions is a crucial factor for ensuring smooth operation of systems.

Cascade coupling of amplifiers proved to be an effective method for extending the frequency range and increasing the operating voltage, which contributed to improving the efficiency and functionality of amplifiers in systems that require a wide frequency range and high voltage. This ensured reliable operation in difficult operating conditions. Comparison with the study by J. Chen *et al*. (2022), where thin-film transistor-based amplifiers focus on compactness and energy efficiency, have demonstrated good results for high voltage industrial applications where stability under variable loads is important. An innovative approach to minimising errors through the additive error correction scheme has significantly improved the quality of the output signal and reduced its distortion (Hula & Hryha, 2024). This ensured the stability of the system even under variable operating conditions, which is especially useful for high-precision systems such as medical devices or process control systems. Reducing errors helped to avoid possible failures in operation, which is important for modern technologies (Smailov *et al*., 2023).

Compared to the study by M.M. Tarar *et al*. (2024), who developed a multi-stage distributed amplifier (LC-CMS-DA) based on 65 nm CMOS technology, demonstrated higher stability indicators at high voltages. Amplifier by M.M. Tarar *et al*. (2024) provided a peak gain of 21.5 DB over 50 GHz bandwidth, which is an important indicator for high-frequency systems. However, this approach was not as effective for tasks that required high operating voltage and signal stability under variable loads. Specialised software was used to achieve accurate device operation parameters, which significantly improved the efficiency and reliability of the amplifiers. Optimisation of operating parameters under high voltage and variable loads provided better results compared to other approaches.

The study by Z. Wang *et al*. (2023), which focused on broadband millimetre wave amplifiers for 5G and satellite communications, demonstrated high-frequency performance with a frequency range of 25.8-36.9 GHz. This made the amplifier suitable for high-frequency communication systems. However, unlike the solution, which focused on stability at high voltages, approach by Z. Wang *et al*. (2023) was aimed at the narrow industry of high-frequency applications and failed to provide the same efficiency in high-voltage operations. One of the technical innovations in the study by Z. Wang *et al*. (2023) was the possibility to use a magnetically coupled resonator network for output matching, which provided high performance when working with large and small signals. This made the amplifier effective for modern communication systems such as 5G. However, its performance in industrial applications with high operating voltage was not as high, as the focus on signal stability under variable load and high voltage is an important aspect for industrial systems.

The research involved the development of cascade power amplifiers with an emphasis on the stability and accuracy of the output signal under variable load conditions. The use of a high-voltage operational amplifier ensured not only stable operation of electronic systems, but also increased efficiency in industrial conditions (Bondarenko *et al*., 2019). Compared to the study by C. Zhao *et al*. (2022), which focuses on a broadband CMOS low-noise amplifier (LNA) with multiple resonant frequencies, the current study focused on achieving high stability under different loading conditions. C. Zhao *et al*. (2022) discussed the development of an LNA that uses a common source (CS) topology and inductive degeneration to expand the bandwidth. While both studies highlight the importance of working with broadband amplifiers, the current study focused on stability and high output power under variable loads. The cascade amplifier connection technology used in the current study provided an extension of the frequency range and an increase in the operating voltage. C. Zhao *et al*. (2022) focused on achieving multiple resonant frequencies to reduce noise, which has improved the overall performance of the amplifier, but narrow bandwidth is still a limitation. In the above study, cascade connection technology not only improved performance over a wide frequency range, but also ensured stable operation of the system under high loads, making this solution more suitable for high-voltage industrial applications.

The development of cascade amplifiers also considered the technology of additive error correction, which minimised distortion and maintained signal stability (Bondarenko *et al*., 2018). While the study by C. Zhao *et al*. (2022) demonstrates the application of inductive degeneration to generate multiple resonant frequencies and improve the noise characteristics of an amplifier, this study focused on signal stability under high voltage and wide bandwidth conditions. This solution was important for applications where high reliability is required when working with unstable loads. Also worth noting is the comparison with study by S.R. Boroujeni *et al*. (2020), which refers to a broadband CMOS low-noise amplifier (LNA) using a common source topology with inductive degeneration. In this study, it was proposed to use a shunt resonator to improve the bandwidth of the amplifier by generating multiple resonant frequencies. Both approaches demonstrate advances in the development of wide-band amplifiers, but the main emphasis remains different. In the study by S.R. Boroujeni *et al*. (2020), the emphasis is placed on noise characteristics and bandwidth, while the current study emphasises the need for stable operation of power amplifiers under high voltage and alternating load conditions. The use of software to optimise the operation parameters of devices helped to determine the optimal conditions for ensuring the efficiency of amplifiers. This made it possible to achieve stable performance under variable load conditions. Compared to the study by S.R. Boroujeni *et al*. (2020), where the main goal was to improve bandwidth and reduce noise through the use of an innovative topology, the current study focused on stability when operating at high voltages, which is important for tasks where accuracy and reliability are critical.

Overall, the successful integration of state-of-the-art materials and technologies to create high-voltage amplifiers with improved stability and accuracy characteristics was demonstrated. Compared to other studies, such by S.R. Boroujeni *et al*. (2020) and C. Zhao *et al*. (2022), which focused on improving noise performance and bandwidth in low- voltage systems, this study focused on ensuring stable operation under high voltages and variable loads, making it more suitable for industrial and scientific applications where high voltage and stability are key requirements. L. Xu *et al*. (2020) developed a high-voltage operational amplifier based on the general principles of operational amplifiers, particularly for applications with piezoelectric actuators. The main innovation is the use of the amplifier as a non-inverting one, considering the effect of piezoelectric elements on the circuit. In addition, the simplicity of the design and feedback principles ensured low noise, compactness, and the possibility of implementation using discrete components (Bagatskyi *et al*., 2023). In an experiment focused on precise positioning, it was shown that the amplifier works in accordance with theoretical expectations.

The study of cascade power amplifiers is also focused on high-voltage operation, but the emphasis is on the stability of the output signal under variable loads. While research on a high-voltage operational amplifier has focused on providing low noise and compactness, achieving stability at high voltages and a wide frequency range has been a key aspect here. Since research on operational amplifiers uses piezoelectric actuators for precise positioning, this increases its potential in areas such as precision mechanics and control. Overall, the study showed successful integration of modern materials and methods to achieve high stability and accuracy of the output signal. Compared to other studies, this solution has shown advantages for applications that require stability and accuracy under variable loads and high voltages. The results of the study have significant potential for further use in industry and science, where the accuracy, stability and reliability of electronic systems are important. This approach opens up new opportunities for improving technologies in the field of high-voltage electronics and contributes to the further development of the modern industry.

CONCLUSIONS

The use of high-voltage operational amplifiers PA94 helped to ensure high stability of the output signal even under variable loads. The amplifiers have demonstrated reliability and versatility, which makes them promising for use in various industries. The high technical characteristics of the PA94, such as the ability to work with capacitive loads and transmit direct and pulsed currents, allow expanding the scope of their application. Cascade coupling of multiple amplifiers has become a key methodological approach in the study. It helped to significantly expand the frequency range and operating voltage range of amplifiers. This method has proven to be particularly effective in achieving high output voltage values while maintaining high signal accuracy, which is important for many industrial applications.

The use of an additive error correction scheme minimised distortion of the output signal and improved its quality. This scheme helped to maintain the stability of the amplifiers even in difficult conditions, which increased the reliability of the developed system. Minimising errors is critical to ensuring the accuracy and efficiency of amplifiers in industrial and scientific research. Modelling and computational studies have played a crucial role in the process of optimising the amplifier design. The use of specialised software allowed performing accurate calculations, which helped to find the optimal parameters of the devices and their design features. This contributed to improving the efficiency and reliability of the developed systems. The results of the study showed that the use of modern materials and methods makes it possible to create high-voltage amplifiers with improved technical characteristics that meet the requirements of modern industry and science. These amplifiers have the potential for further improvement and development, which opens up new prospects for their application in various industries.

One of the main limitations of this study was its focus on operational amplifiers PA94, which may limit the application of the results obtained for other types of amplifiers or technologies. Although the use of a cascade connection of amplifiers helped to extend the frequency range and operating voltage interval, this method did not always provide efficient operation at very high frequencies due to the internal characteristics of the PA94. In addition, the complexity of the design of amplifiers due to the use of a cascade connection and an additive error correction scheme complicated their production and maintenance. High-voltage operation also caused problems with heat dissipation, which affected the stability and reliability of the amplifiers. In addition, the simulation results, although useful, did not always fully correspond to the actual operating conditions, which could lead to deviations in performance.

To further improve these amplifiers, it would be advisable to conduct additional experimental studies under conditions as close to real conditions as possible to test the accuracy of the simulation results. In addition, it would be worth considering simplifying the design of amplifiers without reducing their performance, which could reduce production costs and increase their reliability. It is important to pay attention to improving heat dissipation systems to ensure stable operation of high-voltage amplifiers. To further expand the frequency range of amplifiers, the use of new materials or technologies may be considered. It would also be useful to explore the possibility of using similar methods for other types of high-voltage amplifiers, which could allow scaling the results to other areas.

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CONFLICT OF INTEREST

None.

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Методи формування високої напруги шляхом каскадування підсилювачів

Анотація. Метою даного дослідження було створення нової моделі високовольтного вимірювального підсилювача, яка б включала кілька каскадів операційних підсилювачів для збільшення діапазону робочої напруги шляхом послідовного «віртуального» підключення вихідних напруг кожного з каскадів. Методологія дослідження включала використання каскадного з’єднання підсилювачів, схеми адитивної корекції похибки, а також моделювання та розрахункових досліджень для оптимізації конструкції високовольтних операційних підсилювачів. Результати дослідження показали, що використання високовольтних операційних підсилювачів PA94 забезпечує високу стабільність і точність вихідного сигналу навіть при змінних навантаженнях. Каскадне з’єднання підсилювачів дозволило розширити частотний діапазон та збільшити робочу напругу, що підвищило ефективність їх роботи. Застосування схеми адитивної корекції похибки значно зменшило спотворення сигналу, підвищивши його якість. Моделювання та розрахункові дослідження оптимізували конструкцію підсилювачів, що сприяло досягненню високих технічних характеристик. Завдяки поєднанню цих методів було створено надійну систему з поліпшеними параметрами. Підсилювачі показали перспективність для широкого спектру промислових і наукових застосувань. Вони здатні працювати в складних умовах із високою точністю. Дослідження підтвердило важливість інтеграції сучасних технологій у розвиток електронних систем. Розрахункові дослідження нової моделі високовольтного вимірювального підсилювача демонструють, що застосування кількох каскадів операційних підсилювачів разом зі схемою адитивної корекції похибок дозволяє значно розширити частотний діапазон підсилювача та збільшити робочий інтервал напруг, що призводить до покращення якості вимірювань

Ключові слова: високовольтний вимірювальний пристрій; опір; діапазон; калібратор; електроніка