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FORMATION OF THE PROTECTIVE POTENTIAL OF UNDERGROUND STEEL PIPELINES IN THE CONTEXT OF THE DEVELOPMENT OF MODERN CONVERTER TECHNOLOGIES

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ФОРМУВАННЯ ЗАХИСНОГО ПОТЕНЦІАЛУ ПІДЗЕМНИХ СТАЛЕВИХ ТРУБОПРОВОДІВ В УМОВАХ РОЗВИТКУ СУЧАСНИХ ПЕРЕТВОРЮВАЛЬНИХ ТЕХНОЛОГІЙ

Goal. To study the processes of forming the protective potential of underground steel pipelines in the face of the development of modern converter technologies. To evaluate the influence of the output signal parameters of cathodic protection rectifiers on the electrochemical protection of steel underground pipelines.

Methodology. The computer modeling of electrochemical processes in underground steel pipelines under cathodic protection is performed. The spectral composition of the output signals of different types of rectifiers is analyzed. The influence of the waveform on the electrical system pipeline – soil – electrochemical protection is considered.

Research results. The paper demonstrates that pulsations in the output signal of rectifiers affect the value of the impedance of the pipeline, which can cause a local decrease in the efficiency of cathodic protection. The opportunity to purposefully control the power spectrum of the rectifier output signal in order to increase the efficiency of electrochemical protection is proposed. Which is especially useful in cases of heterogeneous pipeline structure or variable environmental conditions.

Scientific novelty. The correlation between the frequency characteristics of the output signal of the cathodic protection station rectifier and the processes of forming the protective potential of the pipeline is proved. The possibility of improving the performance of electrochemical protection and minimizing the negative effects of alternating current by optimizing the spectrum of the output signal is proposed.

Practical significance. The obtained results can be used to develop new algorithms for controlling cathodic protection stations for underground steel pipelines, which reduces energy costs and increase reliability. The proposed methods can be integrated into modern cathodic stations and taken into account when designing new pipeline protection systems.

Keywords: *cathodic protection, underground steel pipelines, impedance, rectifiers, electrochemical protection, spectrum.*

Introduction. Ukraine's gas transportation system (GTS) is one of the pillars of the country's economy. Its reliable and uninterrupted operation ensures the supply of natural gas to domestic consumers and the transit of gas to European countries. It consists of about 33.2 thousand km of main pipelines [1], a developed network of gas distribution pipelines (according to the NCREPU, about 290 thousand km [2]), as well as all the equipment such as compressor and gas distribution stations, underground gas storage facilities, etc. that ensures the system's performance of its functions. According to the current construction standards [3], external gas pipelines are supposed to be underground, and their material is selected in accordance with the conditions of laying [4], such as soil corrosion activity, the presence of stray current sources, etc.

Steel pipelines are a widespread choice, as they provide excellent mechanical properties at relatively low capital costs, but require reliable corrosion protection against electrochemical corrosion throughout the entire service life. This protection is achieved through the combined operation of passive and active means [5]. Passive protection is represented by various coatings that prevent contact of the pipeline material with the surrounding corrosive environment by isolating it. At the same time, active protection suppresses corrosion currents generated in the process of electrochemical corrosion in places where passive protection can no longer effectively isolate the pipeline from the ground and contact points are formed. It is important to understand that corrosion currents have very small absolute values and can reach several micro amperes, and even 4.5 μA during the year can be sufficient for a through hole in a 5 mm thick wall.

Both types of electrochemical protection are constantly evolving to provide more reliable, durable, and cost-effective protection. Thus, in the field of passive protection, a variety of coatings are presented that have different types of properties, such as protective organic coatings, self-cleaning, self-healing, etc. [6]. On the other hand, any cathodic protection station is based on a rectifier, which acts as a source of direct voltage. Their design is constantly evolving and becoming more complex, while converter technology and semiconductor manufacturing are constantly improving and developing, operating frequencies are increasing, and sizes are decreasing [7].

It is important to understand that, although the output signal of the CPS rectifiers is considered to be constant, it still has a variable component due to the peculiarity of their design. The power spectral analysis of the CPS rectifiers output signal connected to the model of an underground steel pipeline clearly demonstrates the presence of power up to 0.1 mW in the high frequency range.

The current state of electrochemical protection. There are two main methods of ECP of underground steel pipelines [8] (fig. 1).

The main trend in the field of passive ECP are the development of protective organic coatings of and the smart coatings. Protective organic coatings [9, 10] are complex products consisting of various discontinuous solid functional additives, commonly known as “pigments”, which are contained in a continuous polymer phase known as a “binder”. Such coatings are generally considered to function by providing a barrier between the metal and the environment, ideally providing high resistance to ionic movement.

Smart coatings are typically categorized based on their preparation methods, functional and reactive components, and their use and application. Typical coatings include [11, 6]: self-healing [12], self-cleaning [13], and microcapsule [14] coatings.

In reality, all coatings, regardless of their nature and quality, are not absolutely solid, but have defects that form during operation, transportation, or installation. The metal in such places begins to interact with the corrosive environment, which significantly accelerates corrosion and increases the risk of cavities, damage and leaks. In practice, passive protection of underground pipelines is always combined with active protection. The main task of passive protection is to reduce the area of exposed metal, thereby reducing the current required for its active protection. Active ECP methods are divided into anodic and cathodic protection.

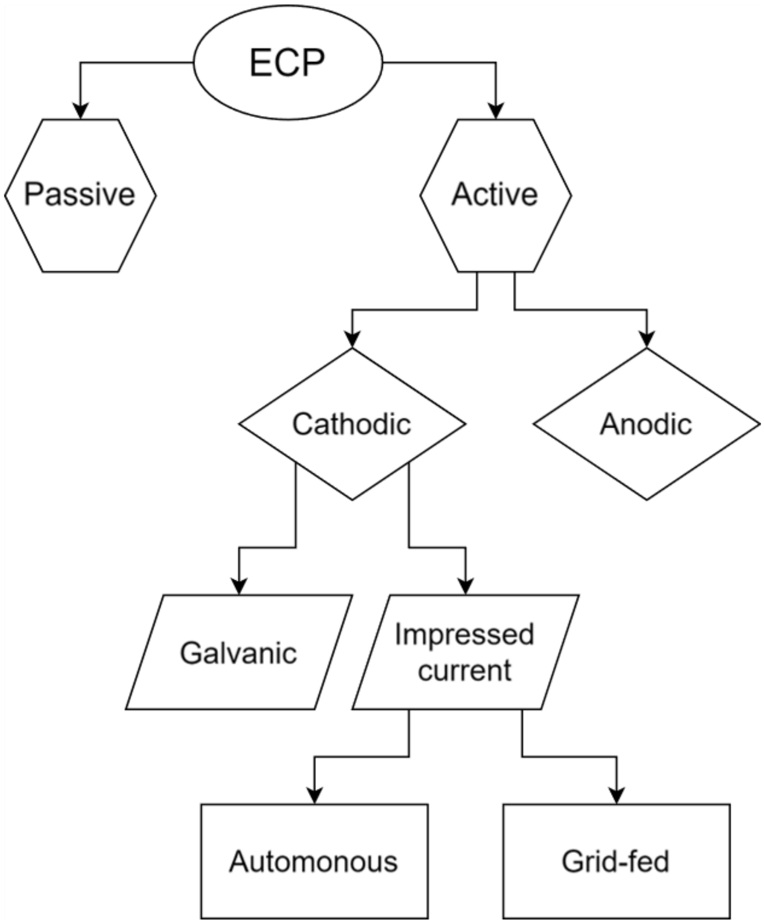

Fig. 1. Classification of electrochemical protection methods

Anodic protection is used to protect metals that are easily passivated [15], such as stainless steels or titanium alloys. This method consists in connecting a metal structure to the anode of an electrolytic system and increasing its potential to a level at which a protective oxide layer is formed on the metal surface.

The main method of active electrochemical protection of underground steel pipelines is cathodic protection, in which the object of protection is the cathode of the electrochemical system. The essence of the method is to reduce the potential of the metal to a level at which electrochemical corrosion either significantly slows down or stops completely. Cathodic protection is divided into two types: galvanic protection and impressed current protection.

With the galvanic method, the object of protection is attached to anodes made of metals that have a lower electrochemical potential than the base metal (protectors). Material of protective anodes (magnesium, zinc, aluminum) corrode instead of the object's metal, protecting it. This method does not require an external power source, but requires regular replacement of the protectors due to degradation and is usually used to protect small systems or when an external power source is not available [16].

Impressed current protection involves using an external source and connecting the metal to be protected to its negative pole. Anodes made of inert materials (graphite, platinum, or cast iron) are used as the positive pole [16]. The electric current changes the potential of the metal in such a way that corrosion slows down or stops.

Cathodic protection stations can be divided into two large subgroups: autonomous and grid-fed. Autonomous stations are represented by installations powered by independent or renewable energy sources [17, 18] that do not require a permanent connection to the power grid. They are indispensable in cases of remote regions where it is impossible or irrational to conduct power grids. The segment of autonomous cathodic protection stations is actively developing in areas with complex and extensive geography, such as Africa and America, where continuous electrification is difficult, and weather conditions and solar insolation, on the other hand, are favorable for the introduction of renewable energy sources.

On the other hand, grid-fed cathodic protection stations are more widespread and depend on access to the power grid, the infrastructure of which has been constantly expanding over the past decades [19]. As a result, the latest developments are focused on the development and modernization of CPS operation algorithms to improve the efficiency and life cycle of the station and the protected object. Such developments include:

1. Countering various sources of stray currents [20, 21];
2. Identification of optimal anode parameters [22, 23];
3. Modeling the operation of the cathodic protection station for the development and further implementation of the latest control algorithms [24–26].

A typical cathodic protection station consists of the following elements: a transformer, converter, and control system located in a sealed enclosure; anode grounding conductors located in soil; cable lines and contact devices for connecting anodes and the object [15].

Among these elements, it is the converter that generates the output signal of the cathodic protection station, which is fed to the protected underground steel pipeline. Its task is to rectify and convert the input alternating current from the transformer into direct current [8], the value of which is set by the control system settings. The converter may consist of several functional units that vary depending on the needs and capabilities, but always includes a rectifier, which acts as a source of direct current for the electrochemical protection system. The constant development of electronics and microcircuitry has led to the creation of various rectifier circuits, the structure of which affects the shape and frequency spectrum of the output signal that is supplied to the object of protection.

Model of an underground steel pipeline. In this work, a model of an underground steel pipeline is used to verify the parameters of the converters, which is based on the model proposed in [27]. The equivalent scheme of the above model is shown in Figure 2.

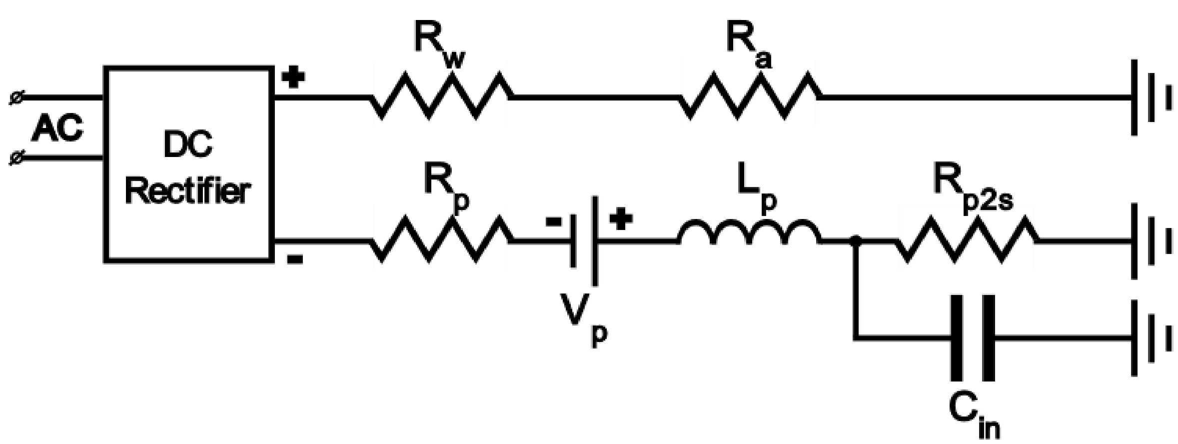

Fig. 2. Equivalent circuit of an underground steel pipeline with concentrated parameters

Where, R_w are the contact conductor resistance; R_a is resistance of anode; R_p, L_p are the resistance and inductance of the pipeline; V_p is the initial polarization voltage; C_{in} is the capacitance of the insulation; R_{p2s} is the resistance structure to soil. Resistance, inductance of the pipeline and insulation capacitance directly depend on the geometry and material of the modeled pipe (fig. 3).

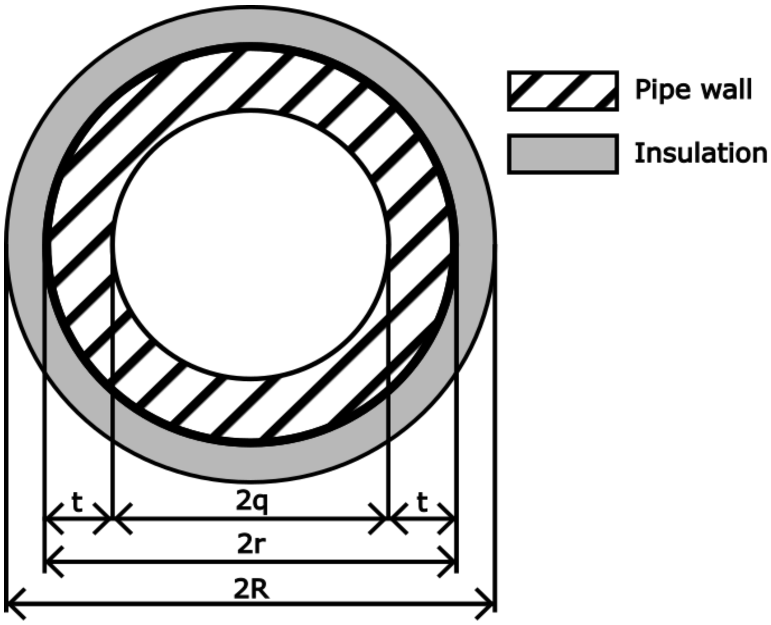

Fig. 3. Pipeline cross-section

R_w is determined by wires length and cross-section; R_a depends on anode composition and resistance of anode bed.

The active resistance of the pipeline R_p:

$$R_p = \frac{\rho}{\pi(D-t)t} l,$$

where, ρ is the electrical resistivity of the pipeline material in $\Omega \cdot mm^2/m$; D is outer diameter of pipe; t pipe wall thickness; l is the length of the section.

V_p is determined by pipe material.

The inductance of a pipeline is defined as the inductance of a hollow straight wire of circular cross-section:

$$L_p = \frac{\mu_0 l}{2\pi}\left(\ln\frac{2l}{r} - 1\right) + L_i,$$

where μ_0 is the magnetic constant; r is outer radius of pipe; L_i is the internal inductance, which is equal to:

$$L_i = \frac{\mu l}{2\pi m r}\frac{\sinh m t - \sin m t}{\cosh m t - \cos m t},$$

where μ is the magnetic permeability of the pipeline material; t is the pipe wall thickness;

$$m = \sqrt{2\omega\mu\gamma},$$

where $\omega = 2\pi f$ is the angular frequency; γ is the electrical conductivity of the material.

The capacitance of a pipeline can be roughly calculated by treating the pipeline segment as a cylindrical capacitor. In this case, the metal-insulation junction is the inner plate of the capacitor, and the insulation-ground junction is the second plate of the capacitor. As a result, the capacitance is equal to:

$$C_{in} = \frac{2\pi\varepsilon_0\varepsilon l}{\ln\frac{R}{r}},$$

where ε_0 is the electric constant; ε is the dielectric constant of the insulation; R is the radius of the pipeline in the insulation.

The pipe-to-soil resistance is determined by the formula:

$$R_{p2s} = \frac{R_c}{A(2 - CE)},$$

where R_c is the coating resistance of the pipeline insulation depending on the coating material, Ohm m^2; A is the pipe surface area; CE is the coating efficiency depending on the coating state and age.

The pipe surface area is equal to:

$$A = \pi D l.$$

The proposed circuit is connected to rectifiers as a load and directly affects its operation, the output signal shape and, as a result, the power distribution by frequency.

Rectifier circuits. The main purpose of a rectifier is to convert AC voltage to DC voltage. For rectifier circuits, the main focus is achieving energy efficiency, increasing performance, and reducing the size and weight of the device. This has led to the appearance of a large number of technical solutions, each of which has both its strengths and limitations. In this diversity, we will focus on the basic and most popular schemes of single-phase rectifiers, since single-phase power supply is the most widespread in public and industrial facilities.

The full-wave center-tapped rectifier (fig. 4) is powered by two series-connected transformer secondary windings with a common (zero) point. This circuit is usually used for output power up to 500 W. The output voltage ripple frequency is equal to twice the supply frequency. The disadvantage is the complex structure of the transformer, as well as, the high reverse voltage on the semiconductors.

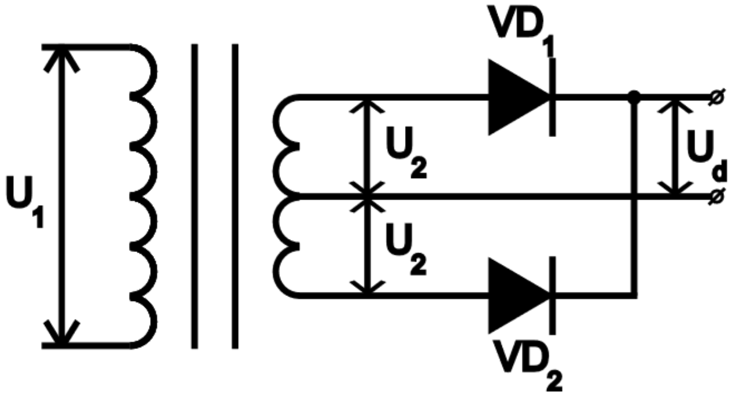

Fig. 4. Full-wave rectifier with center-tapped transformer circuit

The power distribution shows (fig. 5) the presence of values up to 1 mW up to a frequency of 2.4 kHz.

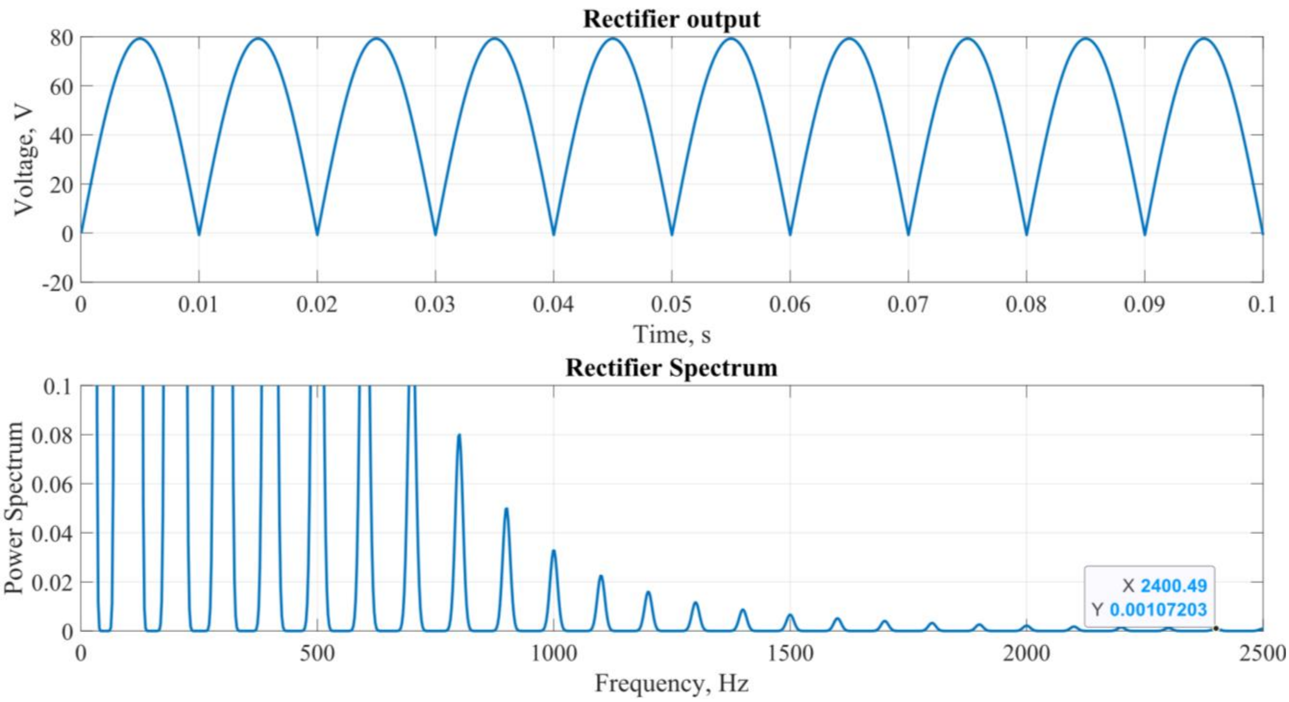

Fig. 5. Output signal and power spectrum of full-wave rectifier with center-tapped transformer

The single-phase bridge circuit (fig. 6), compared to the full-wave center-tapped rectifier circuit, has a simpler transformer design with a similar output voltage waveform and ripple frequency, as well as a twice lower reverse voltage. This scheme is widely used in a wide range of power levels, as it has better efficiency, more rational use of the transformer, which allows to reduce its design power and size. The disadvantage is a larger number of semiconductors. Regulation of the rectified voltage is achieved by implementing a control scheme that creates an adjustable delay in the opening of thyristors.

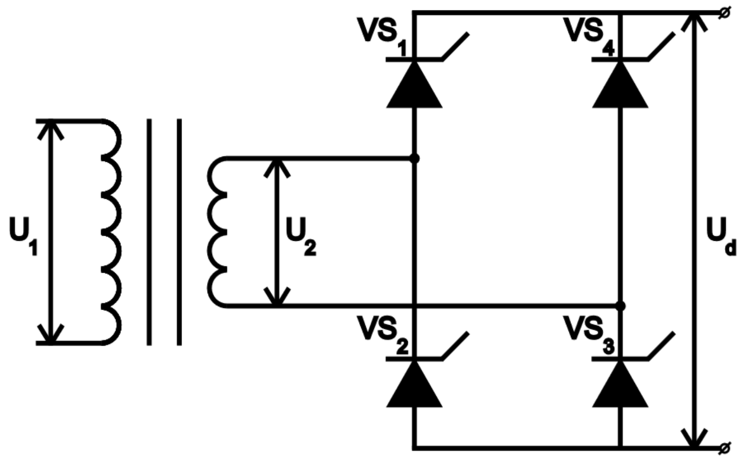

Fig. 6. Controlled bridge rectifier circuit

Fig. 7 shows that changing the control angle leads to a greater power distribution over different frequency.

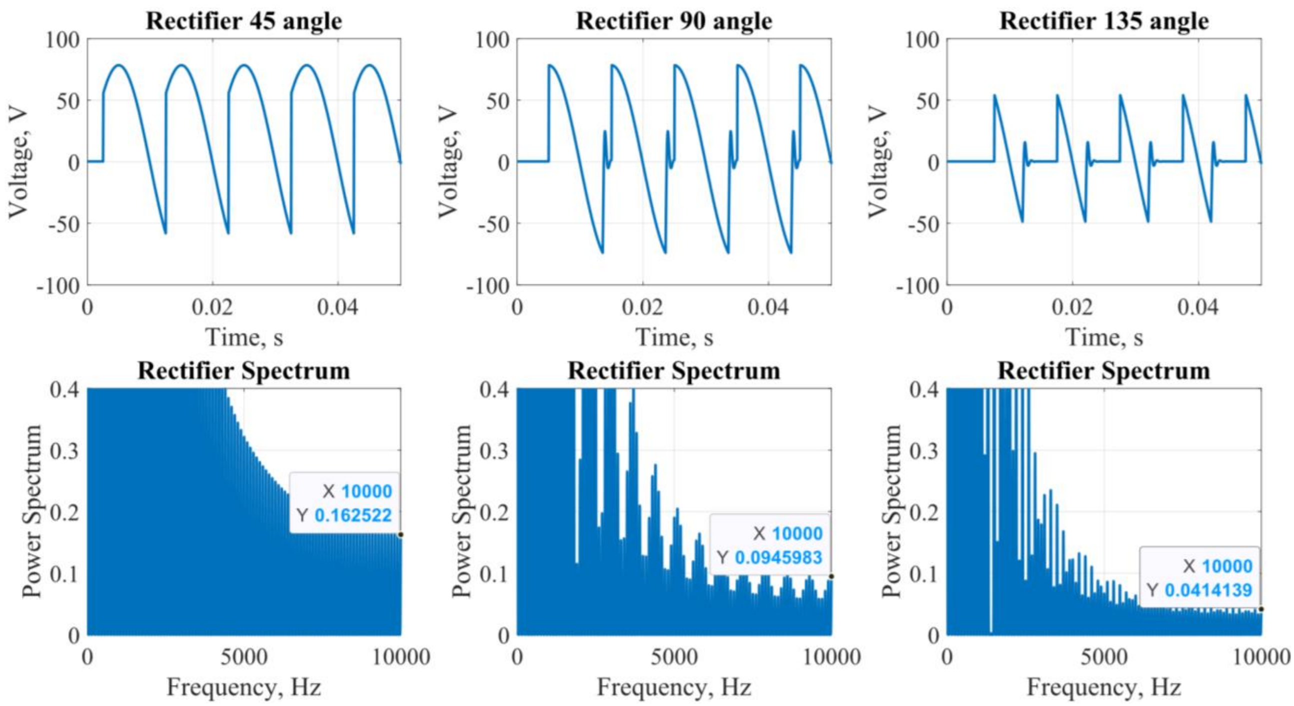

Fig. 7. Output signal and power spectrum of controlled bridge rectifier

The voltage-adding rectifier circuit (fig. 8) uses a slightly modified principle. In this case, the minimum output voltage is provided by uncontrolled rectifiers VD1 and

VD2, and its increase is achieved by turning on thyristors VS1 and VS2. This scheme requires an additional transformer winding.

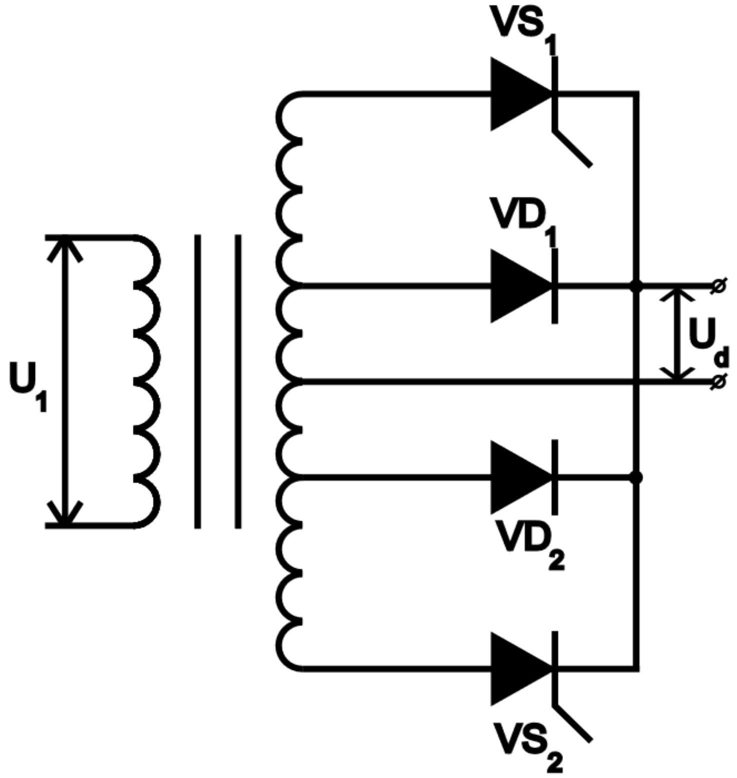

Fig. 8. Controlled voltage-adding rectifier circuit

Fig. 9 shows that a significant difference in the waveform and a change in the control angle have a significant impact on the power spectral distribution.

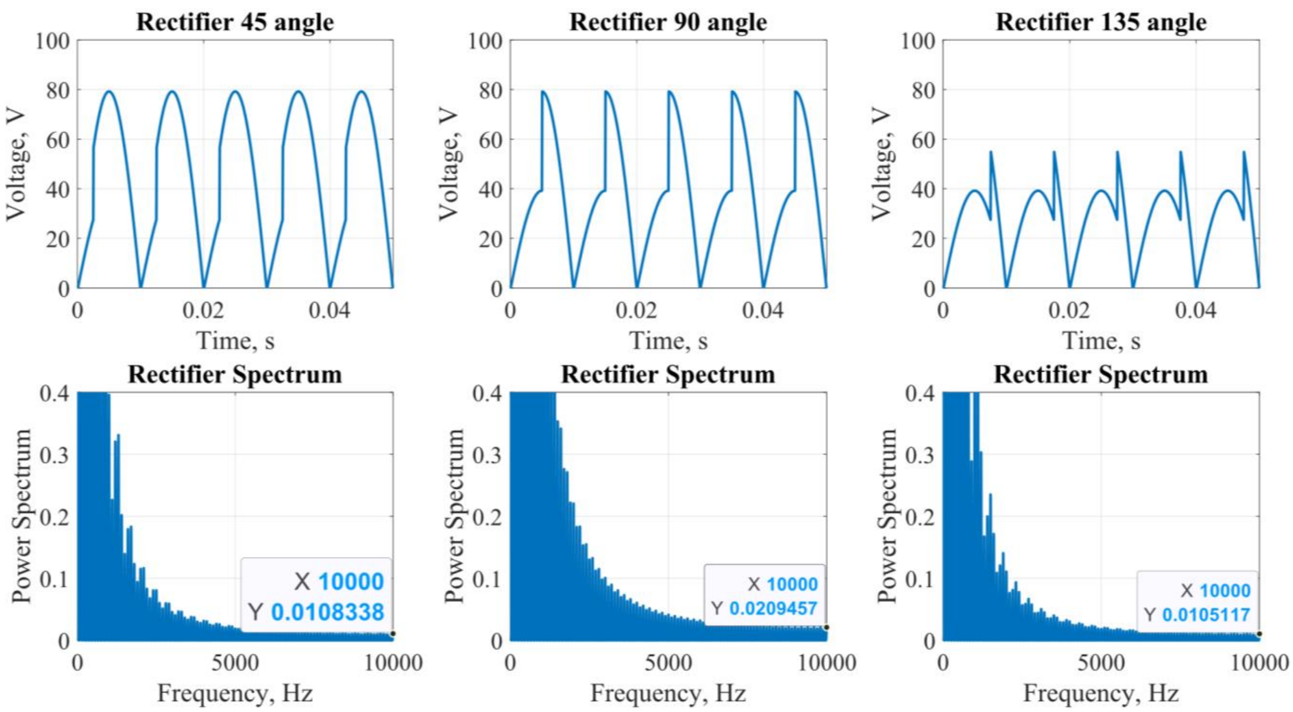

Fig. 9. Output signal and power spectrum of controlled voltage-adding rectifier

Conclusions. A rectifier as a component of an electrochemical protection system is a source whose output signal is not purely constant. Considering the cathodic protection station – pipeline – soil as a system with electrical parameters, it should be taken into account that the pulsating form of the CPS output signal will affect the value of reactive impedances in the underground steel pipeline equivalent circuit. As a result, the currents flowing in the system are also affected. An increase in frequency leads to an increase in currents flowing from the pipeline through the insulation to the environment, which can manifest itself in the form of a localized weakening of the object's protection.

On the other hand, by influencing the operating modes of the CPS rectifier, and consequently the power distribution over frequency of the output signal, it is possible to intentionally control the electrical parameters of the system and implement various algorithms that would take into account possible features of its structure, such as heterogeneity, different materials or diameters of pipeline sections, etc.

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АНОТАЦІЯ

Мета. Дослідити процеси формування захисного потенціалу підземних сталевих трубопроводів в умовах розвитку сучасних перетворювальних технологій. Оцінити вплив параметрів

вихідних сигналів випрямлячів катодного захисту на електрохімічний захист сталевих підземних трубопроводів.

Методика досліджень. Виконано комп'ютерне моделювання електрохімічних процесів у підземних сталевих трубопроводах, що знаходяться під катодним захистом. Здійснено аналіз спектрального складу вихідних сигналів випрямлячів різних типів. Розглянуто вплив форми сигналу на електротехнічну систему трубопровід – ґрунт – електрохімічний захист.

Результати досліджень. Продемонстровано, що пульсації вихідного сигналу випрямлячів впливають на значення загального опору трубопроводу, що може спричиняти локальне зниження ефективності катодного захисту. Запропонована можливість цілеспрямованого керування спектром потужності вихідного сигналу випрямляча для підвищення ефективності електрохімічного захисту, особливо у випадках неоднорідної структури трубопроводу або змінних умов навколишнього середовища.

Наукова новизна. Доведено взаємозв'язок між частотними характеристиками вихідного сигналу випрямляча станції катодного захисту та процесів формування захисного потенціалу трубопроводу. Запропонована можливість покращення характеристик електрохімічного захисту та мінімізації негативних впливів змінного струму шляхом оптимізації спектра вихідного сигналу.

Практичне значення. Отримані результати можуть бути використані для розробки нових алгоритмів керування станціями катодного захисту підземних сталевих трубопроводів, що дозволить знизити енергетичні витрати та підвищити надійність. Запропоновані методи можуть бути інтегровані у сучасні катодні станції та враховані під час проектування нових систем захисту трубопроводів.

Ключові слова: *катодний захист, підземні сталеві трубопроводи, повний опір, випрямлячі, електрохімічний захист, спектр.*