# МОНІТОРИНГ, ДІАГНОСТИКА ТА КЕРУВАННЯ ЕНЕРГЕТИЧНИМИ ПРОЦЕСАМИ ТА ОБЛАДНАННЯМ

# MONITORING, DIAGNOSTICS AND CONTROL OF ENERGY PROCESSES AND EQUIPMENT

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## SIMULATION AND ANALYSIS OF THE INFLUENCE OF THYRISTOR CONDUCTION TIME IN THREE-PHASE CONTROLLED RECTIFIERS ON HARMONIC DISTORTIONS IN THE POWER SUPPLY NETWORK

***Background.*** *Modern technologies related to power electronics and microprocessors create new challenges for ensuring high-quality electrical energy. The use of single-phase and three-phase rectifiers for supplying loads often leads to current waveform distortion, which negatively affects equipment performance and reduces the operational characteristics of energy systems. The main issue is harmonic distortion caused by load nonlinearity, which can degrade the quality of electrical energy and affect the performance of transformers and cable lines.* ***Objective.*** *The aim of the study is to analyze the changes in power quality indicators when the control angle of thyristors in a three-phase asymmetrical controlled bridge rectifier is modified. The study is conducted through analytical calculations and computer simulation.* ***Methods.*** *The research was carried out based on a simulation model of a three-phase asymmetric bridge rectifier. MATLAB® and Simulink® environments were used for simulating three cases: without a filter, with a filter but without considering the internal resistance of the transformer, and with a filter, taking into account the transformer's internal resistance. The simulation included an analysis of parameter changes at different thyristor control angles.* ***Results.*** *It was found that increasing the control angle leads to an increase in the harmonic distortion coefficient in the network, which may exceed the permissible limits defined by IEEE 519-2022 and DSTU EN 50160:2023 standards. The study also explored the impact of LC filters on power quality, particularly their negative effect in the form of a reduced power factor.* ***Conclusions.*** *The change in the thyristor control angle affects the quality of electrical energy by increasing harmonic distortion and reducing the power factor. The obtained results emphasize the need for careful selection of rectifier control parameters and harmonic filtering to ensure compliance with regulatory requirements. An important recommendation is to consider the internal resistances of transformers when designing such circuits, as they influence the level of current and voltage distortion in the electrical network.*

**Keywords***: harmonic distortions, thyristor rectifier, total harmonic distortion, power quality, computer modeling*

**Introduction.**

The development of modern household and industrial electrical equipment, closely related to the use of technologies involving power electronics and microprocessors, presents new challenges for ensuring proper power quality. Power electronics is a key component of power supplies for various types of equipment. Single-phase rectifiers are used for loads up to 1 kVA, while three-phase rectifiers are used for loads over 1 kVA [1]. Due to their functionality, these technologies improve energy efficiency and automation, finding applications in both domestic and industrial settings. Power converters are conventionally classified by their power rating and application area, as shown in Table 1.

During the rectification process, the current flows through semiconductor devices only for part of the cycle of the fundamental frequency. As a result, power converters are often viewed as devices for regulating DC voltage. If electrical energy is used in the form of alternating current but with a different frequency, the DC current obtained from the rectifier passes through an inverter, which converts it back into alternating current with the required frequency.

The nonlinear characteristics of the components in rectifier circuits can lead to a deterioration in the quality of electrical power in medium and high-voltage networks [2-4]. At the same time, the semiconductor devices themselves are sensitive to the quality of electrical power. Harmonic distortions of voltage and current, which arise due to the nonlinearity of end consumers, can affect the efficiency of parallel-connected power consumers. These distortions can reach distribution transformers, which are generally not designed to handle high levels of harmonic components.

Table 1. Classification of Power Rectifier Applications

| **High power** | **Medium power** | **Low power** |
|---|---|---|
| In the metallurgy industry and high-voltage direct current power transmission systems. | In industry for controlling the speed of electric motors, as well as in the railway sector, electric welding equipment, and electrochemical technologies. | In household and entertainment devices: televisions, personal computers, chargers, uninterruptible power supplies, lighting systems, etc. |

The nature of current distortion at the input of the rectifier largely depends on the chosen rectification scheme, even if a pure sinusoidal voltage is supplied to the converter input. However, this assumption is only valid under theoretical conditions, without considering the resistance of lines and transformer magnetization. Current distortions can negatively affect parallel-connected loads and equipment in the electrical network upstream of the energy flow through the point of common coupling [5-11]. The analysis of scientific research shows that higher harmonic components of voltage and current, caused by the nonlinearity of loads from end users, can significantly affect power transmission cable lines [5-6] and electrical equipment in the network [7-10], leading to a reduction in their lifespan and deterioration of operational characteristics. Furthermore, high-frequency harmonics increase losses due to eddy currents and hysteresis, resulting in the heating of transformers. These effects combine, creating issues in the operation of each component of the energy system [11, 12]. Research indicates that the problem of harmonic distortions is systemic, not local. The mutual influence of electrical equipment through the point of common coupling is presented in the form of a schematic diagram of the power grid in Figure 1.

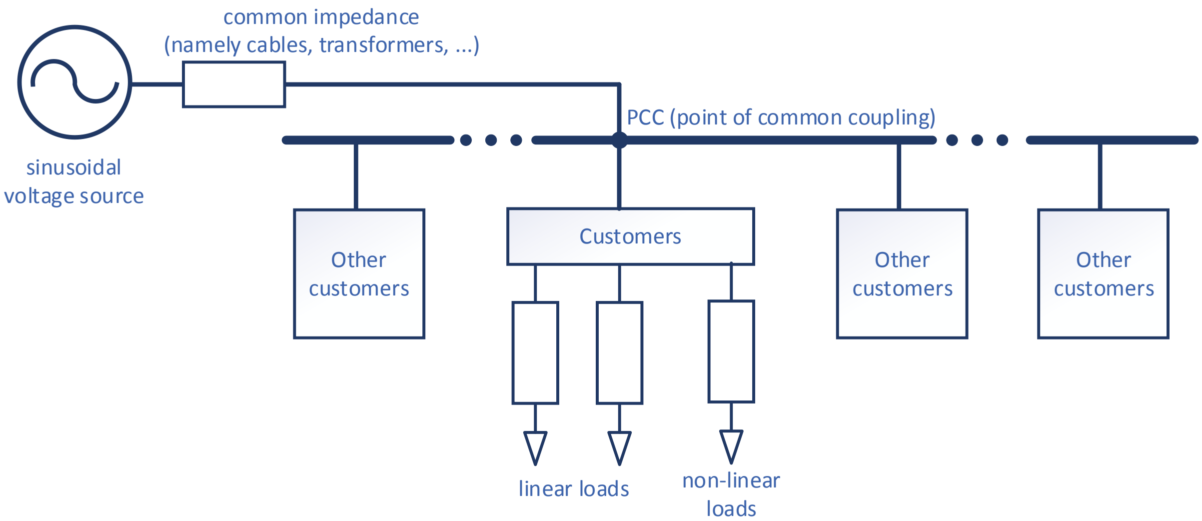



Figure 1 – *Schematic diagram of the power supply for energy consumers*

The analysis of the harmonic spectrum of the input current in single-phase and three-phase uncontrolled rectifiers has been widely conducted and published, as noted in [13-15]. In [16], based on simulation modeling, as well as theoretical and experimental methods, the results of studying the impact of changes in the control angle, the harmonic spectrum of the input current in single-phase controlled rectifiers without using a filter, and the impact of the transformer are presented. In addition, experimental evaluation and analysis of power quality in [17, 18] demonstrate significant distortion of the current waveform by certain household appliances containing single-phase rectification circuits of different configurations.

Although the use of uncontrolled rectification circuits remains widespread, the control of the rectified voltage is achieved through the use of thyristor circuits. Most textbooks on power electronics provide a detailed study of harmonics at the output of controlled rectifiers, but such an analysis of the input current is lacking both from an empirical and theoretical perspective.

**Purpose of work.**

The study is focused on analyzing the changes in power quality indicators from the power source due to the variation in the control angle of the thyristors in a three-phase asymmetric controlled bridge rectifier, using analytical calculation methods and computer modeling.

**Research material.**

Voltage and current deviations from the ideal sinusoidal waveform, particularly harmonic distortions, are important factors affecting power quality indicators. Furthermore, these phenomena are closely related to electromagnetic compatibility, which ensures the proper functioning of electrical devices in a shared electromagnetic environment.

Regulation of power quality requirements is carried out at the international level according to standards developed by the Institute of Electrical and Electronics Engineers (IEEE) in the United States [19] and the International Electrotechnical Commission (IEC) for European Union countries [20]. The main focus of these standards is on defining the maximum allowable values of power quality indicators that must be maintained at the points of common coupling of consumers to AC networks of different voltage classes under normal operating conditions.

In Ukraine, power quality requirements are regulated by the DSTU EN 50160:2023 standard [20], which sets the permissible voltage parameters at points of consumer connection. At the same time, the IEEE 519-2022 standard regulates not only voltage characteristics but also the permissible levels of current harmonic distortions at points of consumer connection (as shown in Figure 1).

The degree of harmonic distortion in the current is characterized by the Total Harmonic Distortion (THD) factor, which is determined by the following formula:

$$THD_i = \frac{\sqrt{\sum_{h=2}^{\infty} I_{(h)}^2}}{I_{(1)}} \cdot 100\%,$$

where: $h$ – harmonic order; $I_{(h)}$ – root mean square (RMS) value of the individual harmonic component of order $h$ for the current; $I_{(1)}$ – the root mean square (RMS) value of the fundamental harmonic (first-order component) for the current.

To study the complex impact of the nonlinearity of the rectifier circuit elements, the control angle of the thyristors, the filter parameters, and the internal resistance of the transformer’s secondary winding on the propagation of harmonics in the power supply network, a series of studies have been conducted. The studies also aim to analyze the harmonic levels and determine the moment when the regulatory limits are exceeded for three cases:

1. Without considering the filter and the internal resistance of the transformer's secondary winding.
2. Considering the filter, but without taking into account the internal resistance of the transformer's secondary winding.
3. With the filter and taking into account the internal resistance of the transformer's secondary winding.

The studies were conducted based on a classical three-phase asymmetric controlled bridge rectifier without a zero diode [1], whose block diagram is shown in Figure 2.

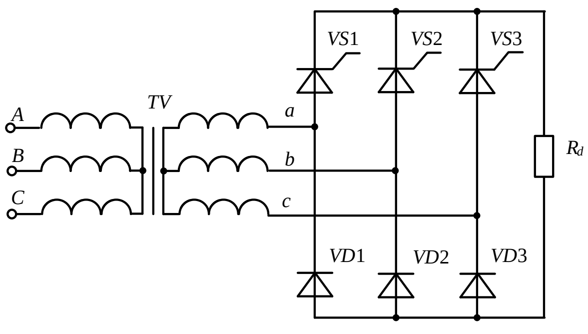
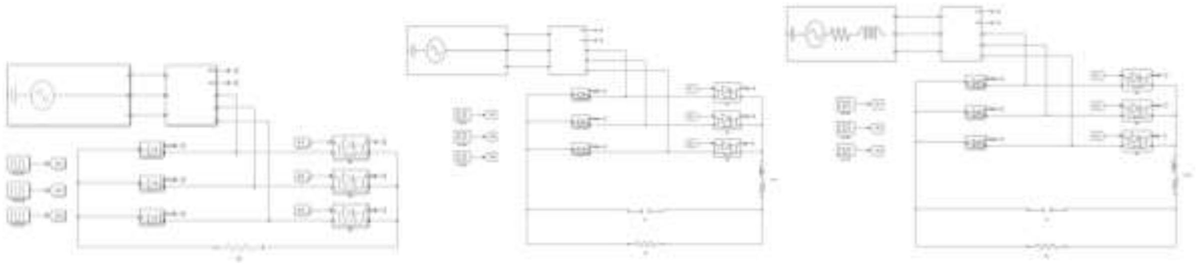



Figure 2 – *Three-phase asymmetric controlled bridge rectifier*

It is assumed that the rectifier is powered by a symmetrical three-phase source, with its windings connected in a star configuration, with a direct phase sequence, through a connected three-phase step-down transformer *TV*, where the windings maintain a star connection at the output. In the study, it is assumed that the initial phase of the phase voltage for phase *A* is 0˚. A three-phase bridge rectifier with a resistor load $R_d$ is connected to the network from the secondary winding of the transformer. The asymmetric three-phase bridge without a zero diode and filter consists of three controlled valves (thyristors $VS1$, $VS2$, $VS3$), which form the cathode valve group, and three diodes ($VD1$, $VD2$, $VD3$), which form the anode valve group. Assuming an ideal transformer with leakage inductance, at any given time, two valves are in the open state: one in the cathode group (provided that control pulses are applied to them) and one in the anode group. In the cathode group, the valve in the open state is the one whose anode has the highest positive potential relative to the zero point of the transformer's secondary winding. In the anode group, the valve in the open state is the one whose cathode has the most negative potential relative to the zero point of the transformer's secondary winding. Thus, the current in the transformer's secondary windings flows twice per network voltage period in different directions.

It is assumed that $u_a$, $u_b$, $u_c$ represents the instantaneous values of phase voltages, and $i_a$, $i_b$, $i_c$ represents the instantaneous values of phase currents, and accordingly, the line currents.

Circuit modeling and process studies were performed in the MATLAB® and Simulink® environment [21]. For computer modeling, a typical circuit of a semi-controlled three-phase rectifier and filter was used for the three research cases mentioned above.



a b c

Figure 3 – *Simulation model of the rectifier in the MATLAB® and Simulink® environment: a – without considering the filter and the internal resistance of the transformer's secondary winding; b – considering the filter, but without taking into account the internal resistance of the transformer's secondary winding; c – with the filter and taking into account the internal resistance of the transformer's secondary winding.*

The following values of the model parameters were used in the calculations: the amplitude of the electromotive force (EMF) of the ideal three-phase voltage source $E_m = 26{,}114 \cdot \sqrt{2}$ B, the network frequency $f_{net} = 50$ H, and the resistance of the resistive load $R_d = 4\ \Omega$. These parameters allow for obtaining the rectified voltage $U_d = 36$ V, which is necessary for the operation of a typical commutator electric motor used in kids quad bikes.

For the second model, the parameters of the corresponding elements remained the same. A G-shaped LC filter was added, where the inductor was connected in series with the parallel combination of the capacitor and resistive load. The filter parameters were set to the following values: $L_F = 5$ mH, $R_F = 25$ mΩ, $C_F = 1 \cdot 10^4$ μF.

In the third model, to enable the practical use of the rectifier with the G-shaped *LC* filter for a resistive load, it was decided to add the internal resistance of the transformer with the following parameters: $L_a = 18{,}12$ mH, $R_a = 114$ mΩ.

The studies were conducted with the control angles of the thyristor switches varying from 0˚ to 90˚ in intervals of 10˚. It is worth noting that when the control angle of the thyristors is $\alpha = 0^\circ$, the rectifier is symmetrical, considering the thyristors behaving as diodes, the ripple frequency of the rectified voltage $\left(f_{ripple}\right)$ is considered to be equal to $f_{ripple} = 6 \cdot f_{net}$, for other angles, the ripple frequency is different – $f_{ripple} = 3 \cdot f_{net}$. This clarification becomes important when recording the harmonic composition data.

The oscillograms (Fig. 4) in the coordinates of the input voltage (secondary winding of the transformer) $\left(U_g\right)$ show the family of currents of the secondary winding of the transformer for phase *A* $\left(I_g\right)$, the family of time diagrams of the load voltage $\left(U_d\right)$, and the family of time diagrams of the load currents $\left(I_d\right)$ with the control angle $(\alpha)$ varying from 0˚ to 90˚ in steps of 10˚. As expected, the current signal shapes are distorted in all considered cases. In the case of considering the internal resistances of the transformer, the phase voltage signal undergoes distortion.

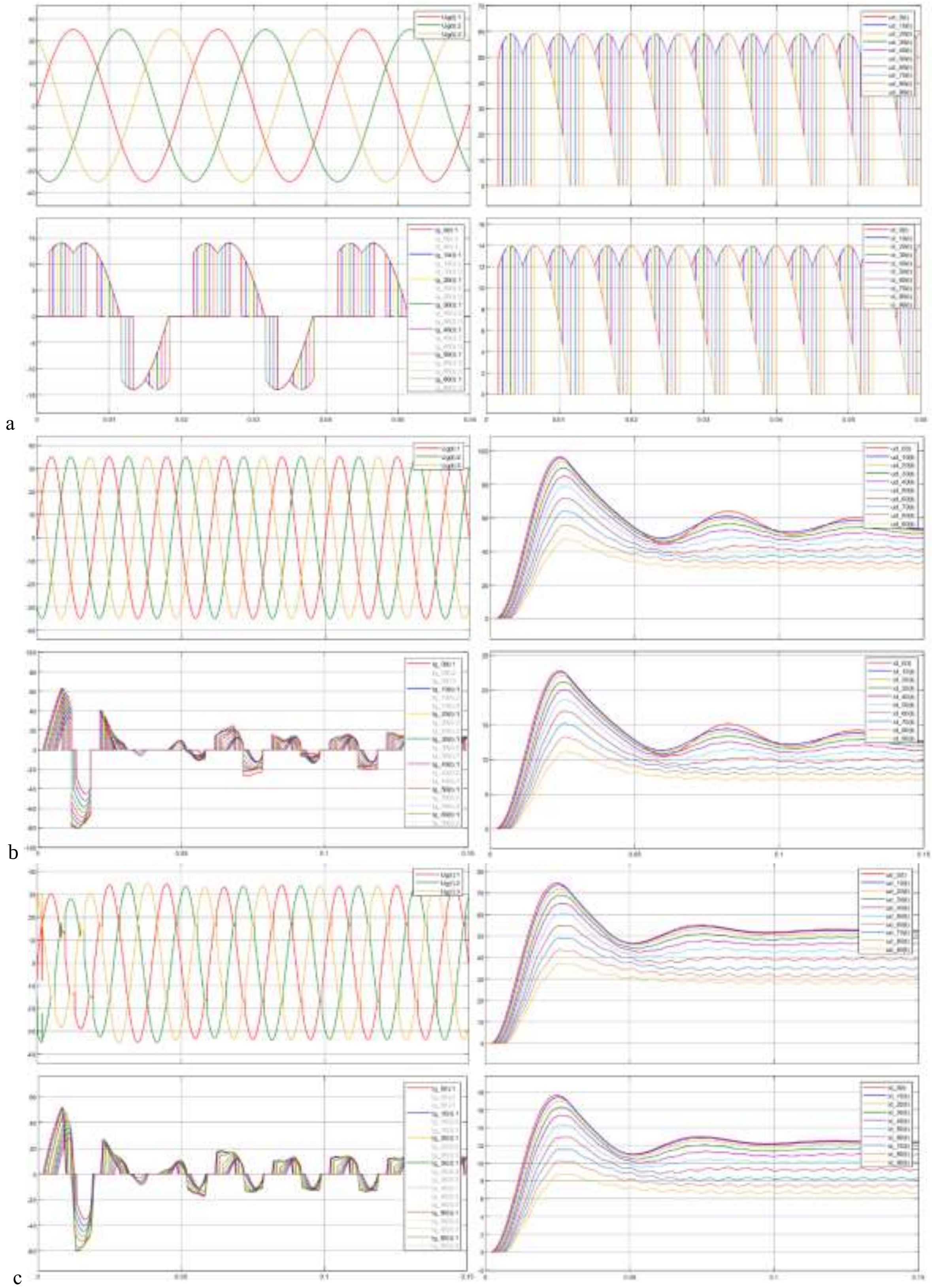



Figure 4 – *Time diagrams of the network voltage* $(U_g)$*, network current* $(I_g)$*, load voltage* $(U_d)$*, and load current* $(I_d)$ *as the control angle of the thyristors* $(\alpha)$ *changes:*

*a – without considering the filter and the internal resistance of the transformer's secondary winding;*
*b – with the filter, but without considering the internal resistance of the transformer's secondary winding;*
*c – with the filter and considering the internal resistance of the transformer's secondary winding.*

The obtained simulation results, recorded in the MATLAB® and Simulink® environment, are presented in the form of graphs showing the dependence on the change in the control angle, for the root mean square value of the network phase current (Fig. 5), its total harmonic distortion (THD) normalized to a reference value (Fig. 6), active power (Fig. 7) and reactive power of the network (Fig. 8), the change in the phase shift angle between voltage and the first harmonic of the phase current (Fig. 9), and the power factor (PF) (Fig. 10), the value of the zero harmonic component of the rectified current (Fig. 11), and the rectified current ripple factor (Fig. 13).

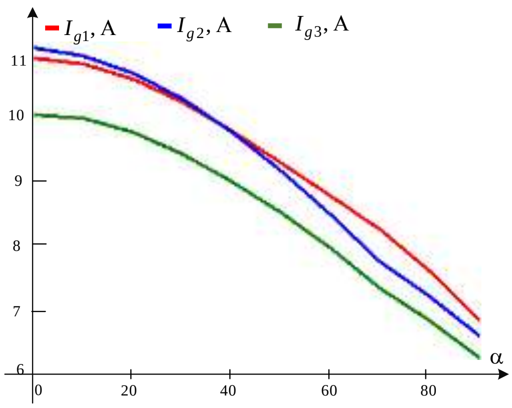



Figure 5 – *Dependence of the phase current magnitude on the thyristor control angle*

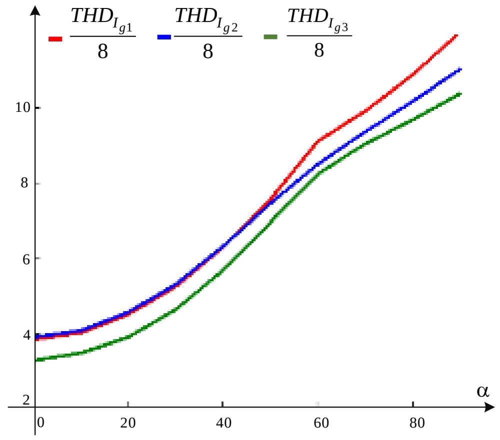



Figure 6 – *Dependence of the phase current THD magnitude on the thyristor control angle*

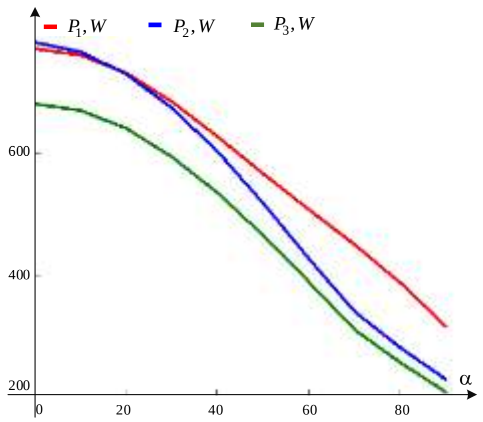



Figure 7 – *Dependence of the active power magnitude of the network on the thyristor control angle*

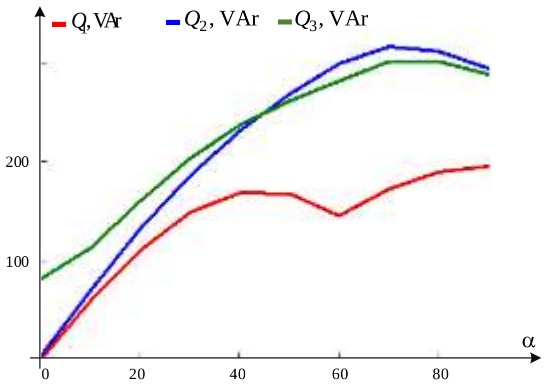



Figure 8 – *Dependence of the reactive power magnitude of the network on the thyristor control angle*

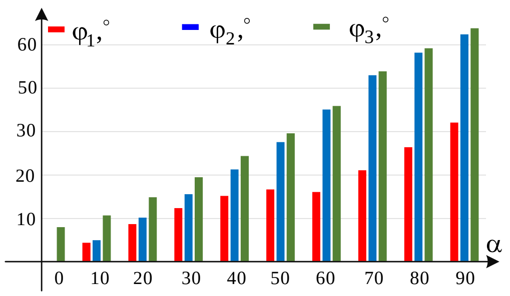



Figure 9 – *Effect of the thyristor control angle on the phase shift between voltage and the first harmonic of the network current.*

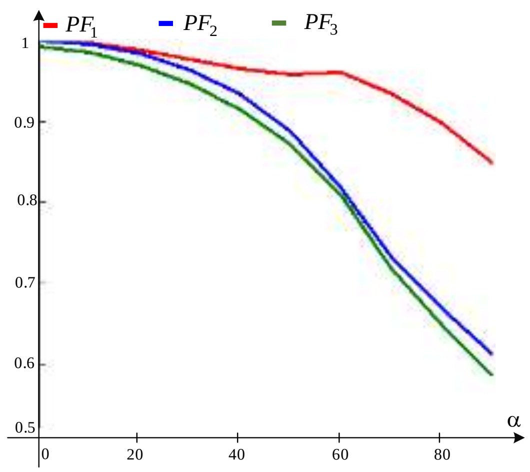



Figure 10 – *Dependence of the PF value on the thyristor control angle.*

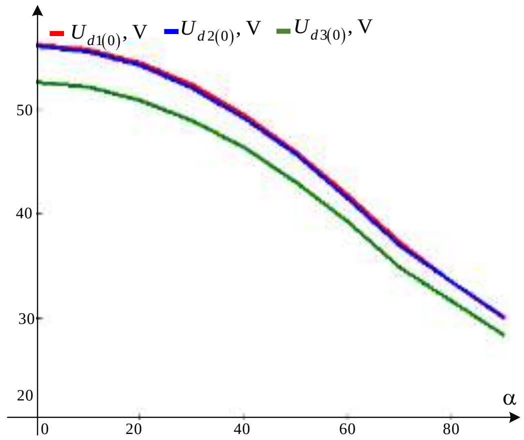



Figure 11 – *Dependence of the zero harmonic value on the thyristor control angle.*

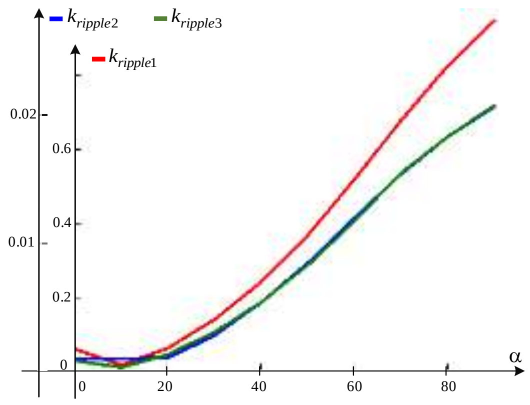


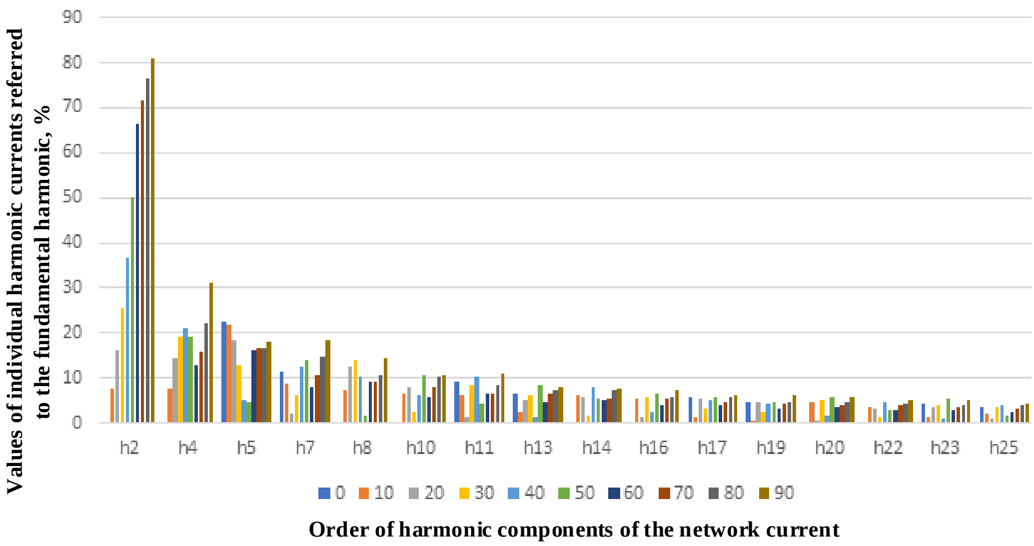

Figure 12 – *Dependence of the ripple coefficient value on the thyristor control angle.*

The analysis of the obtained results shows that increasing the control angle leads to a decrease in the root mean square value of the phase current and the value of the rectified voltage at the zero harmonic. At the boundary points, the reduction in the phase current is approximately 1.6 times, and the rectified voltage decreases by a factor of 1.86, with this trend being consistent for all three cases.

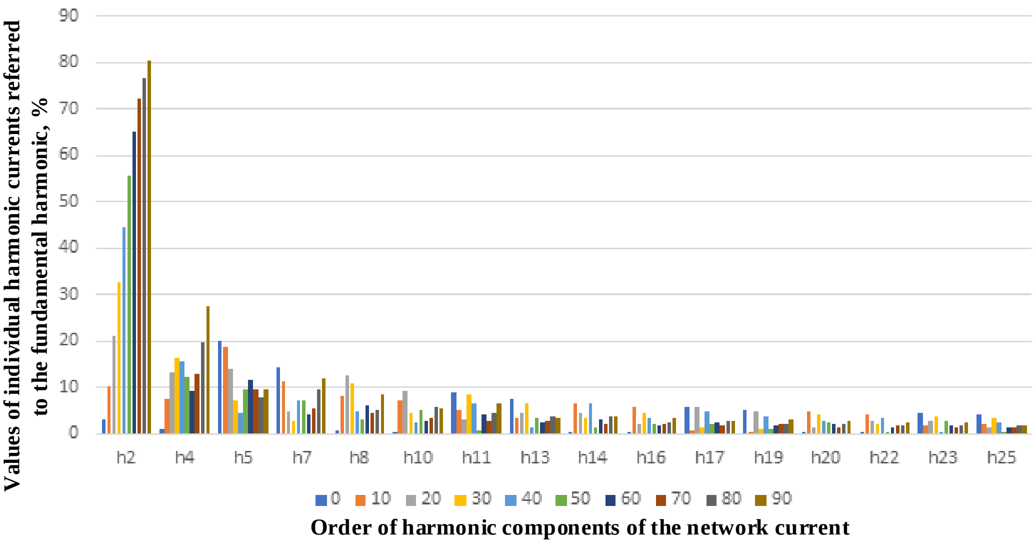
The ability to control the rectified voltage by changing the angle (α) introduces additional nonlinearity to the rectifier circuit. Thus, the shorter the conduction time of the thyristors, the more harmonics are generated, increasing the total harmonic distortion (THD) of the current. As a result, the THD of the network current (THDi) increases, exceeding the allowable value by 3.27 times at α = 30° and by 10.365 times at α = 90°. From the graphs presented in Fig. 6, it is evident that the use of a filter helps reduce the harmonic components in the network current curve by 8-15%, depending on the thyristor control angle.

Along with the increase in nonlinearity of the rectifier circuit, an increase in the control angle leads to an increase in the phase shift angle between the phase voltage and current of the network in the fundamental harmonic component at the input of the rectifier circuit, ranging from $\varphi = 0^{\circ}$ to $\varphi = 32^{\circ}$ for the case of the circuit without a filter. The presence of the filter worsens the situation due to the increase in the phase shift angle, ranging from $\varphi = 8^{\circ}$ to $\varphi = 53{,}8^{\circ}$. This explains the decrease in the power factor and the increase in the generation of reactive power. At the same time, from the graphs (Fig. 10), it is evident that the use of the filter leads to a reduction in the power factor: $\alpha = 30^{\circ}$ the decrease is 3.15%, for $\alpha = 60^{\circ}$ – 15.7%, and for $\alpha = 90^{\circ}$ – 31%.

The harmonic composition of each phase current waveform was analyzed using the Fast Fourier Transform (FFT) function in MATLAB® and Simulink®. Figure 13 shows the spectral composition of the input current for three cases when applying the control angle change.




a

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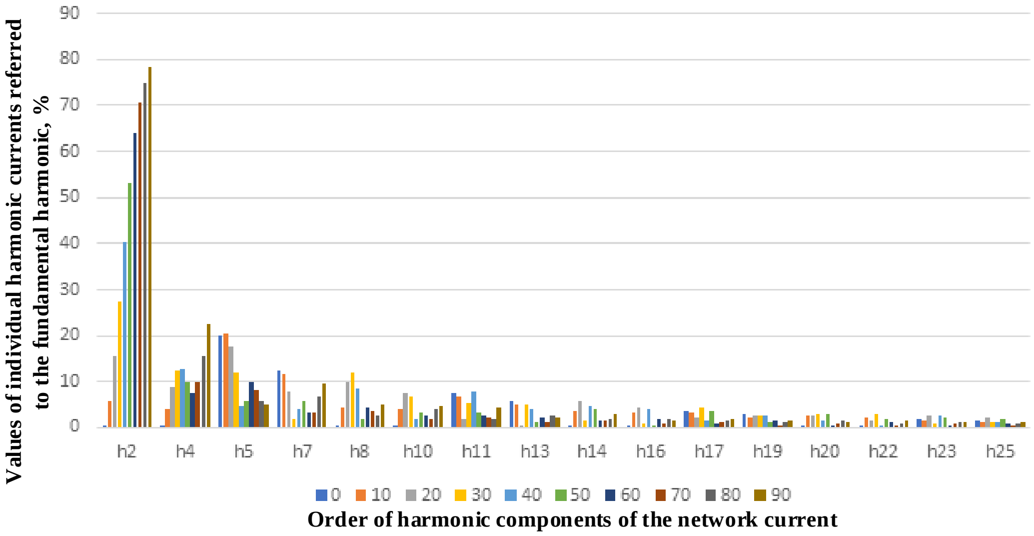


c

Figure 13 – *Values of the harmonic series of the grid current as a function of the thyristor control angle, normalized to the fundamental harmonic for three simulation cases:*
*a – without considering the filter and the internal resistance of the transformer's secondary winding;*
*b – with the filter considered, but without the internal resistance of the transformer's secondary winding;*
*c – with the filter and the internal resistance of the transformer's secondary winding.*

A detailed analysis of the amplitude-frequency characteristics of the phase currents was conducted for the control angles $\alpha = 0^{\circ}; 20^{\circ}; 30^{\circ}; 60^{\circ}; 70^{\circ}; 90^{\circ}$. It was established that for all control angles, the harmonic components of the grid current are observed up to the 50th harmonic. The diagrams (Fig. 13) show the amplitudes of the harmonic components of the input current normalized to the fundamental harmonic.

**Conclusions**.

This study analyzes the impact of thyristor rectifiers on power quality in three-phase networks. The results of the modeling conducted using the MATLAB®/Simulink® environment showed that asymmetric controlled rectifiers can cause significant harmonic distortions, leading to the total harmonic distortion (THD) exceeding the permissible limits defined by the IEEE 519-2022 and DSTU EN 50160:2023 standards.

The proposed use of LC filters to reduce the harmonic levels revealed their negative impact on the system: a decrease in the power factor and the current magnitude in the network. This highlights the need for careful filter design to ensure the optimal functioning of the power system.

Thus, the results of the study emphasize the importance of considering harmonic distortions during the design and operation of thyristor rectifiers in three-phase systems, as well as the need to implement appropriate measures to ensure proper power quality in accordance with current standards.

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# МОДЕЛЮВАННЯ ТА АНАЛІЗ ВПЛИВУ ЧАСУ ПРОВІДНОСТІ ТИРИСТОРІВ У ТРИФАЗНИХ КЕРОВАНИХ ВИПРЯМЛЯЧАХ НА ГАРМОНІЧНІ СПОТВОРЕННЯ В МЕРЕЖІ ЕЛЕКТРОЖИВЛЕННЯ

***Проблематика.*** *Сучасні технології, пов’язані із силовою електронікою та мікропроцесорами, створюють нові виклики для забезпечення високої якості електричної енергії. Використання однофазних та трифазних випрямлячів для живлення навантажень часто призводить до спотворення форми струму, що негативно впливає на ефективність роботи обладнання та знижує експлуатаційні характеристики енергетичних систем. Головною проблемою є гармонічні спотворення, спричинені нелінійністю навантажень, які можуть погіршити якість електричної енергії та вплинути на працездатність трансформаторів і кабельних ліній.* ***Мета дослідження.*** *Метою дослідження є аналіз змін показників якості електроенергії при зміні кута керування тиристорами в трифазному несиметричному керованому мостовому випрямлячі. Дослідження проводиться за допомогою аналітичного розрахунку та комп'ютерного моделювання.* ***Методика реалізації.*** *Дослідження проводились на базі імітаційної моделі трифазного мостового несиметричного випрямляча. Для цього використовувались середовище MATLAB® та Simulink®, де проводили моделювання трьох випадків: без фільтра, з фільтром, але без врахування внутрішнього опору трансформатора, а також з фільтром і врахуванням внутрішнього опору трансформатора. Моделювання включало аналіз змін параметрів при різних кутах керування тиристорами.* ***Результати дослідження.*** *Встановлено, що збільшення кута керування призводить до зростання коефіцієнта гармонічних спотворень у мережі, що може перевищувати допустимі межі, визначені стандартами IEEE 519-2022 та ДСТУ EN 50160:2023. Також досліджено вплив LC-фільтрів на якість електроенергії, зокрема їхній негативний ефект у вигляді зменшення коефіцієнта потужності.* ***Висновки.*** *Зміна кута керування тиристорами впливає на якість електричної енергії, збільшуючи гармонічні спотворення та знижуючи коефіцієнт потужності. Отримані результати підкреслюють необхідність ретельного вибору параметрів керування випрямлячами та фільтрації гармонік для забезпечення відповідності нормативним вимогам. Важливою рекомендацією є врахування внутрішніх опорів трансформаторів при проектуванні таких схем, оскільки вони впливають на рівень спотворень струму та напруги в електричній мережі.*

**Ключові слова:** *гармонійні спотворення, тиристорний випрямляч, загальний коефіцієнт гармонічних спотворень (THD), якість електроенергії, комп'ютерне моделювання*

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