The object of the research is methods of current amplitude identification without using current transformers. Most solutions are built on reed switches, which have a limitation of the operation speed due to the mechanical nature of the reed contacts. Therefore, the time duration is a random variable with a significant variation. Thus, the problem that needs to be solved is the reduction of the error of current amplitude identification associated with the mechanical properties of contacts. According to the conducted literature analysis, the presence of contact bounce of reed switches increases the errors of sinusoidal current amplitude identification approximately up to 8–10 %. The mathematical modeling allowed us to investigate this phenomenon and research its influence on the method. The suggested model was then approved via in-situ modeling. Consequently, to reduce the errors of measuring the current amplitude via a reed switch, the replacement with an analog or discrete Hall sensor was proposed. A mathematical model of the discrete Hall sensor operation and a method for identifying the amplitude of the alternating current were developed. During the experiment, it was found that the analog Hall sensor has a limitation in measuring currents of large rates, at which the discrete sensor worked stably. Hence, the last was chosen. It is worth noting that the study of the behavior of the Hall sensor was limited to the value of the alternating current amplitude, four times the opening current with an average error of less than 3 %. The method suitable for discrete Hall sensors simplifies and reduces the cost of the measuring instrument design. However, the practical implementation of the suggested method requires also the application of devices concentrating the magnetic field on the Hall sensor surface

Keywords: Hall sensor, magnetic field, reed switch, contact bounce, sinusoidal signal

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DEVELOPMENT OF THE ERROR REDUCING METHOD FOR THE DETERMINATION OF THE ALTERNATING CURRENT AMPLITUDE WITHOUT THE USE OF CURRENT TRANSFORMERS

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1. Introduction

Nowadays, monitoring the parameters of electrical network installations is essential to ensure the reliability of automation devices, such as relay protection (RP). Moreover, it has been historically demonstrated that faults in relay protection can lead to serious technogenic accidents. For example, the shutdown of entire cities and states in the United States in 1977 led to riots and looting. Another case in Sweden and Denmark in 2003 caused the shutdown of Copenhagen airports and the Stockholm metro. An accident in the UK in 2018 caused more than 200,000 people to be stuck in the subway of London. In Venezuela in 2019, an RP malfunction led to the total blackout of 23 states. Consequently, various methods are needed to ensure the operability of these devices. One of the main ways to improve reliability is redundancy and majorization, which entails increasing the number of expensive, metal-intensive, high-quality current transformers. Also, during many years of research and industrial operation, the phenomenon of rising errors at high alternating current (AC) rates due to saturation has been revealed. Therefore, new solutions for measuring devices to control electric power systems' technological parameters are urgent.

For example, one of the known proposed methods for determining the current amplitude without transformers is based on reed switches, to be more precise by the duration of the closed state of contacts. The research results have shown sufficient accuracy in measuring the amplitude of current for some devices, which reduces costs in constructing automation devices of electric power systems and, secondly, allows for measuring the current force at large multiples. On the other hand, the reed switch has physical limitations in the speed of operation and bounce, the source of which can be external influences of different nature. The possibility of false operation of power automatics due to such mechanical disadvantages will lead to great disasters of the global level. The solution to the bounce problem can be achieved by specific schematics introduction. However, it is still too sensitive to other metallic and electric installations.

Therefore, studies devoted to increasing the veracity of the current amplitude identification without current transformers and to make sure that the operation will happen only due to the increase of the current in the defined conductor are relevant, the method of reducing the error must be developed.

2. Literature review and problem statement

In standard relay protection devices, current transformers are widely used to measure the electric current. The main disadvantage of using transformers is metal consumption, the possibility of objectionable errors in transient modes at high short-circuit currents, and harmonic measurement errors. A way to overcome these difficulties may be to use an alternative device to measure current in the relay protection system.

The paper [1] presents the results of a study on using a reed switch as a measuring element. However, as noted in the study, the significant disadvantage of using reed switches is crosstalk. A way to overcome crosstalk is demonstrated in [2]. The authors presented formulas for calculating the tripping and load currents based on the Bio-Savard-Laplace law and proposed methods for determining and eliminating the influence of interference on the calculation results. These calculations are theoretical. Experimental results are not presented in the paper. An experimental approach was used in [3], where relay protection based on a current relay with two capacitors and a reed switch for electrical installations with isolated phase busbars with a 6–35 kV voltage is realized. The response time of the proposed system was 0.025 s, which meets the requirements for relay protection devices. But there were unresolved issues related to susceptibility to external influences. The paper [4] demonstrates a system based on four reed switches and a microprocessor that uses reverse current measurements instead of tripping currents to eliminate errors. This system allows the determination of the short-circuit current with an error of ≤15 % and a response time of 0.02 s. A similar short-circuit monitoring system for distribution systems with distributed generators based on reed switches is shown in [5]. The authors developed a multilevel short-circuit detection circuit consisting of six reed switches (five for detecting current levels and one for resetting). The response time of the proposed system is not specified. The main disadvantage of the described relay protection devices built using reed switches is susceptibility to external influences and bounce. An anti-bounce system can overcome the bounce, but such a system will greatly complicate the entire design of the device, making relevant research impractical.

Another solution is to use an analog current sensor based on the Hall effect as a measuring device [6]. The principle of operation of such a sensor is based on the strength of the magnetic field, which is created by the current flowing in the current conduit in the place where the Hall sensors are installed. The main disadvantage of using an analog current sensor based on the Hall effect is the nonlinear characteristic and disproportionality of the signal when the upper value of the excitation current is reached. The study [7] presents a non-contact matrix Hall sensor without a magnetic core for measuring high currents. This sensor consists of eight Hall elements arranged in a circle, and to eliminate the error, a digital signal processing algorithm is proposed, which is developed based on the conductor positioning algorithm and numerical integration algorithm. But when using such a complicated design, reliability issues arise. Another way could be to apply the multiple-step signal averaging approach. This approach is used in [8], which proposes to increase the noise immunity of Hall sensors by taking three consecutive measurements in the time interval $t+dt, t, t-dt$. However, this method of increasing the measurement time is impractical for relay protection systems, where one of the critical parameters is speed. The paper [9] presents a current sensor consisting of two Hall sensors placed on different bus sides. This sensor's operation principle is based on the anti-differential Hall effect. Objective difficulties are associated with the dependence of the sensor's sensitivity on the distance between the sensor and the bus, and this distance can be different depending on the thickness of the tire. The approach of using the Hall sensor as a supplementary tool for determining the root cause of failures and breakdowns of the host equipment is demonstrated in [10]. The authors proposed to embed Hall sensors in designing various substation equipment for measuring harmonics, recording tripping signals, and measuring secondary current at the distribution substation. Within the framework of the study, Hall sensors were used for additional monitoring of the operation of vacuum tube circuit breakers of the capacitor bank. However, critical parameters such as measurement error and tripping time were not specified, making it difficult to objectively assess the applicability of relay protection systems. Also, this approach does not solve the problem of using current transformers, as it does not allow replacing them completely.

The paper [11] demonstrates the development of a Hall effect current transformer (HCT). To solve the problem with the reliability of the design, the authors of the paper considered different combinations of the number of Hall sensors (up to twenty-four sensors). Single-layer and double-layer sensing structures were considered. The two-layer structure consists of an outer and inner layer, and each layer has three sensor modules; each sensor module consists of four Hall sensors. The disadvantage is the inaccurate measurement of the outer layer sensor modules, which makes devices of two layers of Hall sensors inapplicable. A more straightforward coreless HCT design consists of four Hall sensors presented in [12]. According to the experimental results indicated by the paper's authors, the developed device's accuracy class can correspond to the accuracy class 5P30 for protective current transformers. The paper does not specify the response time of the HCT, which does not allow evaluating the applicability in a relay protection device. The prerequisite for this study is the paper [13], where a microprocessor-based open architecture relay protection device based on using a reed switch for current measurement is proposed. It should be noted that unlike reed switches, devices based on Hall sensors have no bounce and no limitation of operation speed. On the other hand, they are also subject to excessive susceptibility to magnetic fields, which requires the development of additional measures to protect devices from external influences.

All this allows us to assert that it is expedient to conduct a study on the construction of measurement instruments for relay protection devices using Hall sensors and reed switches sensors and investigate their properties under the influence of a sinusoidal signal.

3. The aim and objectives of the study

The aim of the study is to reduce the error in determining the amplitude of a sinusoidal signal for the construction of relay protection devices without current transformers. This will expand the application area of relay protection devices without current transformers. The accurate identification method of alternating current without current transformers will allow us to feel the full effect of duplication and majorization of relay protection devices to increase the reliability of the power supply.

To achieve this aim, the following objectives were accomplished:

– to determine the influence of reed contact bounce on the error of identification of the amplitude of alternating current in the conductor, which will allow determining the prospects of reed sensors application or search for new solutions;

– to determine the peculiarities of using Hall sensors to identify the sinusoidal signal amplitude, which will allow approval of the developed mathematical description of identification of the magnitude of sinusoidal current and the possibility of its application;

– to calculate the error of sinusoidal signal amplitude identification using Hall sensors, which will allow evaluating the achievement of the research goal.

4. Materials and methods

The object of the study is primary transducers that are used for determining the alternating current amplitude without the application of current transformers.

The main hypothesis of the study is to improve the accuracy of the alternating current amplitude determination by replacing the physical reed switch system with a semiconductor that is capable of responding to changes in magnetic intensity.

The first task requires knowledge of the mechanics in order to describe the behavior of the mechanical contacts, theoretical foundations of electrical engineering to transfer the mechanical impact into electrical and investigate its behavior. The application of the magnetic field theory could lead to the complication of the mathematical modeling, so the simplified laws were used. Therefore, the basic laws of mechanics, theoretical foundations of electrical engineering, and the Bio-Savara-Laplace law were applied to determine the influence of reed contact bounce. The main tools necessary to solve this problem are the Matlab modeling environment and the experimental setup developed in [13], with a Gwinstek GDS-71054B oscilloscope.

Determination of the peculiarities of using Hall sensors to identify the amplitude of a sinusoidal signal was made based on applying the laws of theoretical foundations, which describe the electrical process happening in a measurement circuit based on a Hall element, and electronics, which describes the main laws required for the Hall sensor.

When solving the third problem, we applied the fundamental laws of statistics, for error processing. For the research of Hall sensor behavior in a magnetic field, the field theory was not used because it would complicate the model, so the Bio-Savara-Laplace law was used to consider the opening and closing moments. The theoretical foundations of electrical engineering and the formulas for identifying the current amplitude from [13] were used to study electrical processes in the measuring circuits. Moreover, Excel was used to automatically calculate measurement errors and identify the current amplitude.

5. Results of research on reducing the error of current amplitude determination

5. 1. Determination of the influence of reed contact bounce on the error of determining the amplitude of alternating current in the conductor

It is worth noting that the reed switch has a bounce, which was identified in earlier studies. The bounce introduces an error when measuring the duration of the closed state of the contact. To determine the influence and nature of this phenomenon, it is necessary to describe it mathematically. This phenomenon can be explained by the equations obtained in [13]:

$$\begin{cases} \left(Q^1 \subset T\right) = \bigcup_{l=1}^{k} Q_l^1 = \left\{t_i \in T \middle| x\left(t_i\right) = 1\right\}; \\ i = \left\{j, j+1, j+2, \ldots, m\right\}, \end{cases} \quad (1)$$

where $x(t_i)$ – Boolean variable of the reed switch closed state (1 when closed, 0 when open); i – serial number of time moments t_i; T – set i of time moments, l – number of sets of time moments obtained due to contact bounce, Q^1 – set of moments of time of reed switch being in the closed state.

In general, the debouncing process can be considered as follows. Taking into account the fact that the measuring circuit with a reed switch is low-power and does not form an arc, the reed switch contact resistance can be written in the form of the expression [18]:

$$R_c = R_k + R_a, \quad (2)$$

where R_k – contact resistance, R_a – resistance of the gap between the contacts.

In general, the resistance R_a tends to infinity when the reed switch is open and depends on the distance between the contacts [14]:

$$R_a = \rho \frac{l}{S}, \quad (3)$$

where ρ – the specific resistance of the gap, l – the distance between contacts, S – cross-section of contacts.

When the reed switch is placed at the required distance from the current conductor and when the passing current reaches the set value, the reed switch is triggered by closing its contacts and, taking into account that the medium inside the reed switch bulb is a vacuum, the force with which the contacts close can be described by the expression:

$$\vec{F} = \vec{F}_{mf} - \vec{F}_b = m\vec{a}, \tag{4}$$

where $\vec{F}_{mf}$ – magnetic field force; $\vec{F}_b$ – reed mechanical contact force; m – contact mass, $\vec{a}$ – contact acceleration.

Due to the mechanical inertia of the contact movement, an elastic force appears at the moment of contact, which leads to rattling. The cause can be either insufficient force or too high magnetic field strength.

In general, the resulting force is zero at the moment of contact between the contacts. Consequently, the maximum elastic power will be equal to the force of the magnetic field on the contacts:

$$F_{b\max} = kx_0 = F_{mf}, \tag{5}$$

where k – elasticity coefficient; x_0 – amplitude of oscillations of the contact gap value.

The oscillations are damped by the magnetic field applied to the contacts, which can be considered as having only one direction, and the reed switch remains closed. Considering the above, the resulting force of contact movement can be written as follows [15]:

$$F = \vec{F}_{mf} - \vec{F}_b = F_{mf} - kx_0 e^{-t/T}\sin(\theta t) = \\ = F_{mf} - F_{mf}e^{-t/T_c}\sin(\theta t) = F_{mf}\left(1 - e^{-t/T_c}\sin(\theta t)\right), \tag{6}$$

where T_c – damping time constant, θ – cyclic frequency of contact oscillations.

On the other hand, the contact acceleration can be written as follows:

$$\vec{a} = \frac{\vec{F}}{m} = \frac{F_{mf}\left(1 - e^{-t/T_c}\sin(\theta t)\right)}{m}. \tag{7}$$

In this case, according to (2), (3), (8) and the basic laws of mechanics, the resistance can be written as follows:

$$R_c = R_k + \rho\frac{\left(l - \dfrac{F_{mf}\left(1 - e^{-t/T_c}\sin(\theta t)\right)t^2}{2m}\right)}{S}. \tag{8}$$

Taking into account the technical characteristics of the reed switch [16], expression (10) can be written as:

$$R_c = R_k + R_a\left(1 - e^{-t/T_c}\sin(\theta t)\right). \tag{9}$$

Considering that counting starts at the moment of closure, and that the resistance can only take positive values, equation (10) can be transformed into:

$$R_c = R_k + \left|R_a e^{-(t+t_i)/T_c}\sin\left(\theta(t + t_i)\right)\right|. \tag{10}$$

Moreover, the reed switch actuation is observed by the presence of voltage drop on the resistance connected in series with the contact (Fig. 1).

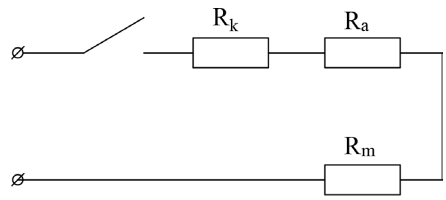


Fig. 1. Measurement circuit wiring diagram

The voltage drop across the resistance, as it is known from [17], is determined from Ohm's law:

$$U = I \cdot R_m, \tag{11}$$

where I – current strength, R_m – resistance on which the voltage drop is measured.

The formula determines the total resistance of the circuit in this case:

$$R_t = R_m + R_c. \tag{12}$$

According to Ohm's law for a complete circuit, the current can be calculated as follows:

$$I = \frac{U_s}{R_t} = \frac{U_s}{(R_m + R_c)}, \tag{13}$$

where U_s – source voltage.

Substituting (10) into (12), expression (13) can be written in the following form

$$U = U_s\frac{R_m}{\left(R_m + R_k + \left|R_a e^{-(t+t_i)/T_c}\sin\left(\theta(t + t_i)\right)\right|\right)}. \tag{14}$$

The time to the first contact closure is very short. Hence, the following assumptions can be made from [18]: t_i=0 s, T_c=0.5 ms, θ=2,000 Hz. Based on these results, simulations showing the behavior of the reed switch after contact closure were performed (Fig. 2).

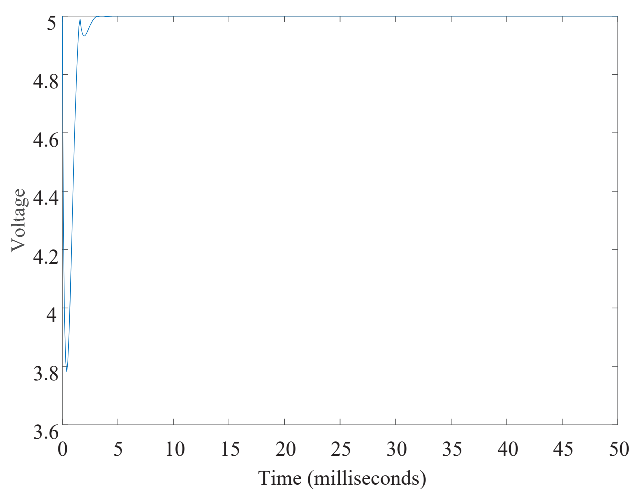


Fig. 2. Reed switch actuation behavior

The obtained dependence demonstrates the presence of bounce. It also decreases the contact closed time. Closed state time is one of the main parameters for determining the value of AC magnitude. Consequently, bounce introduces errors in the measurement of current amplitude. For this reason, it is necessary to use other methods of determination, methods of current measurement, one of them is the replacement of the sensing element, for example, the use of Hall sensors, the operation of which is more stable (Fig. 3).

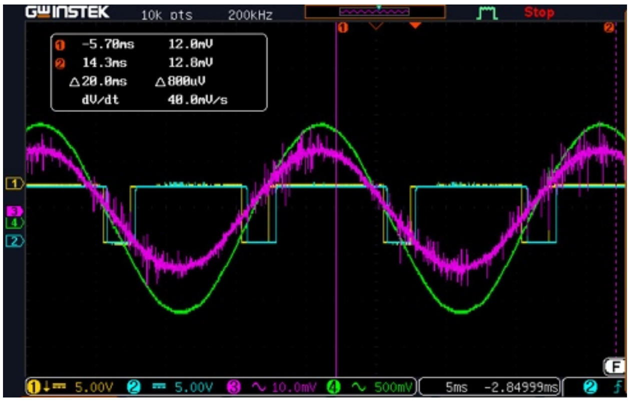


Fig. 3. Oscillogram of the reed switch, analog and discrete Hall sensors operation

To experimentally confirm the obtained result by mathematical modeling, oscillograms were taken. Fig. 3 shows the oscillogram, which shows four beams: pink – sinusoidal signal in the current path, green – output of the analog Hall sensor, yellow – the work of reed contacts, blue – discrete Hall sensor. From the oscillogram, we can see that when the influencing sinusoidal signal increases, the analog Hall sensor opens proportionally, and when it decreases, the Hall sensor closes. Thus, the output signal from the analog Hall sensor repeats the shape of the applied sinusoidal signal. The discrete Hall sensor, as well as the reed switch, works differently. When the influencing sinusoidal signal increases and the reed switch reaches a certain value, the contacts of the reed switch close, and the discrete Hall sensor opens. When the sinusoidal signal decreases and the reed switch reaches a certain value, the contacts open, and the binary Hall sensor closes.

In Fig. 4, the oscillogram shows that when the amplitude of the influencing sinusoidal signal increases, the output of the analog Hall sensor ceases to be linear. This is due to reaching the upper value of the excitation voltage of the Hall sensor. At the same time, the operation of the reed switch and discrete Hall sensor did not change.

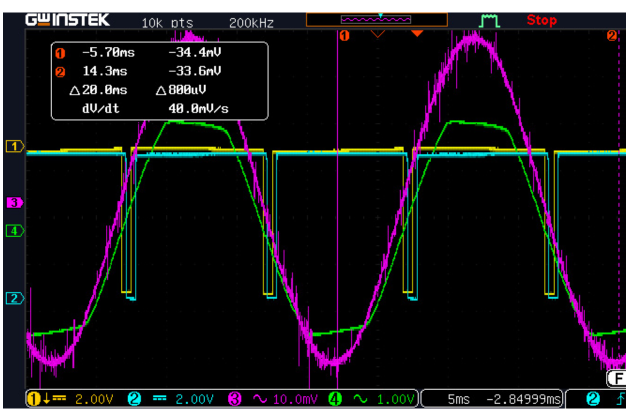
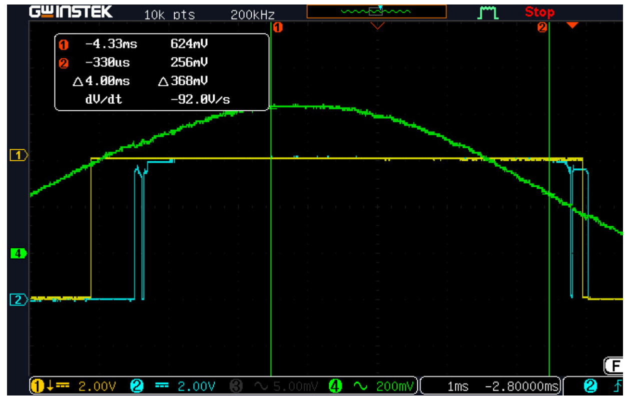
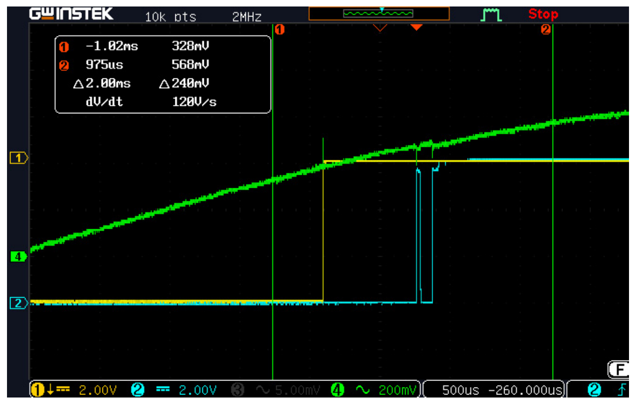


Fig. 4. Oscillogram of the reed switch, analog and discrete Hall sensor operation

Fig. 5 shows the operation of reed contacts and discrete Hall sensors. A closer look at Fig. 5, *b*, *c* shows the rattle of the reed contacts, while the opening and closing of the discrete Hall sensor occur without any transients.



a



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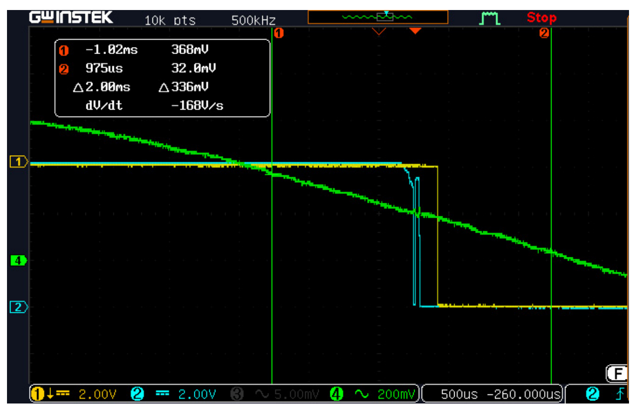


c

Fig. 5. Oscillogram of reed switch and discrete Hall sensor operation: *a* – full half-wave; *b* – moment of operation; *c* – moment of return

Hence, it follows that for further study of the peculiarities of using Hall sensors to identify the amplitude of a sinusoidal signal, only the discrete one is suitable.

5. 2. Determination of the features of using Hall sensors to identify the amplitude of a sinusoidal signal

The hypothesis is confirmed by applying the experimental setup developed in [16]. However, in this case, to use Hall sensors 3, 4 and to compare its accuracy for the reed switch, the installation was additionally equipped with a magnetic conductor 2, which is installed around the cable 1, as well as a low-power current transformer that allows us to determine the magnitude of the current flowing through the cable (Fig. 6). The reed switch is mounted longitudinally on a particular torus-shaped structure made of plastic, which does not cause a change in the distribution of magnetic flux in space.

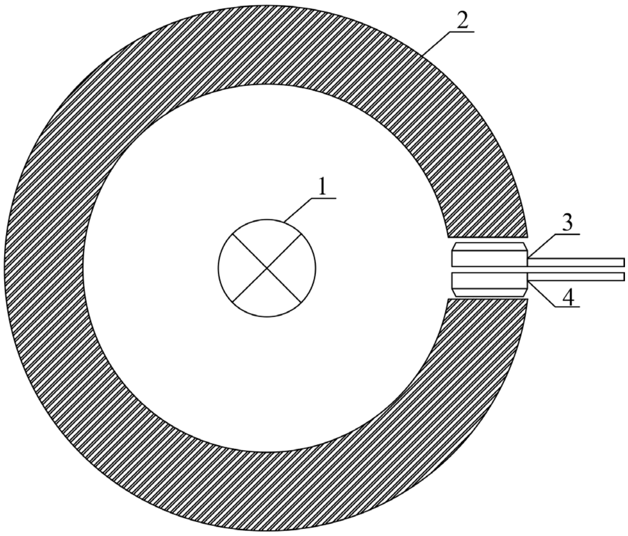


Fig. 6. Hall sensor installation diagram

The reed switch is mounted longitudinally on a particular torus-shaped structure. Hall sensors were installed in the section of the magnetic core to concentrate the magnetic field because, without it, the operation of the Hall sensor is impossible. Moreover, the Hall sensors' front parts were placed opposite each other to open both positive and negative half-waves. Fig. 7 shows the measurement scheme based on Hall sensors and reed switch.

In this case, the principle of operation of the Hall element is presented by changing the voltage at the output, which is proportional to the change in the magnetic field strength [16]:

$$V = \frac{1}{qnt} IB, \qquad (15)$$

where I – current at the Hall element contacts, q – number of charges, B – induction of the external magnetic field; n – concentration of carriers, t – thickness of the Hall element.

Then, the amplified current at the output of the comparator goes to the base of the transistor, which opens, generating a discrete output signal in the form of voltage (Fig. 1).

Four batteries powered the circuit with a voltage of 1.5 V, connected in series to obtain 6 V. To observe the output signals, resistors R1 and R2 with a resistance of 10 kOhm were used, connected in parallel to the power supply input and the output of the corresponding Hall sensor. The reed switch S1 is bound by one contact to the positive pole of the power supply and through the resistor R3 with a resistance of 1 kOhm to the negative pole. The obtained values of reed switch actuation and Hall sensor opening were compared using an analog Hall sensor (SS49E) and a current transformer. Moreover, the measurement with adjustment of the linear autotransformer up to 50 V is more accurate with applying the Hall sensor. Measurement with autotransformer adjustment from 50 V and above is more accurate with a current transformer. To increase the accuracy of the current transformer, four additional 100 ohm resistors were installed in parallel in the circuit, resulting in a total secondary resistance of 18 ohms.

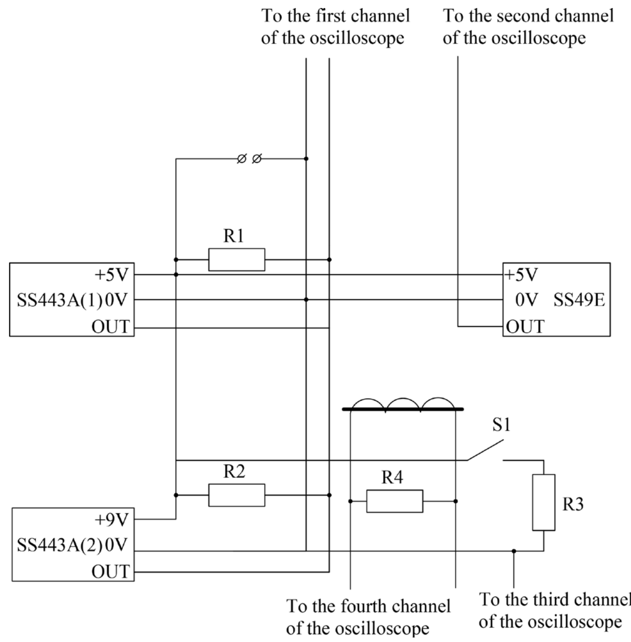


Fig. 7. Measurement scheme

On the other hand, the current can be measured using a Hall sensor. It is known from (1) that the change in output voltage is proportional to the change in magnetic field strength.

Fig. 8 shows that the discrete Hall sensor's operation principle is very similar to the process of reed contacts under the influence of a sinusoidal signal. Let us derive a mathematical description of amplitude identification using the Bio-Savara-Laplace law.

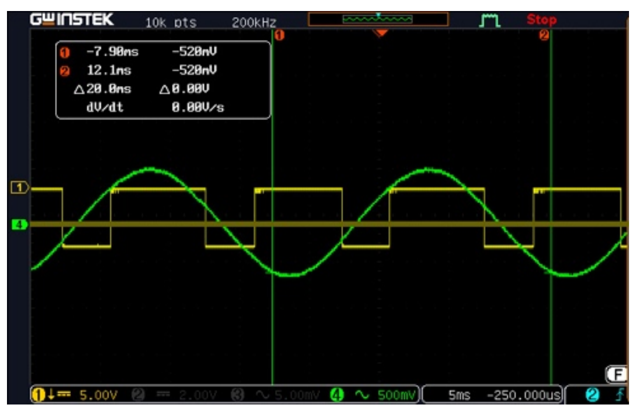


Fig. 8. Oscillogram of operation of the discrete Hall sensor under the influence of a sinusoidal signal

In this case, the induction of the magnetic field generated by the conductor is determined by the Bio-Savara-Laplace law. Moreover, the general form of the calculation formula is:

$$B = \frac{\mu_0 I}{4\pi s}\left(\sin\theta_2 - \sin\theta_1\right), \qquad (16)$$

where I – current value of the current conduit at a certain moment of time, θ_1, θ_2 – initial and final angles of the Hall sensor and conductor arrangement, s – distance from the Hall sensor to the current conduit.

The initial and final angles of location of the Hall sensor from the conductor are taken as $\theta_1 = -\pi/2$ and $\theta_2 = \pi/2$, therefore the equation of dependence of the magnetic field value and current flowing in the conductor has the following form:

$$B = \frac{\mu_0 I}{2\pi s}. \quad (17)$$

The output signal of the Hall element is analog, which, in turn, has limitations. The use of a discrete Hall sensor eliminates this drawback in current measurement. In this study, we used SS443A, which in the circuit contains a Hall element connected to the chopper, generating the transistor opening current based on the currents at the contacts of the Hall element and the comparator (Fig. 9) [18].

Considering the abovementioned, the Hall sensor, unlike the reed sensor, performs the function of opening and closing, not actuation.

For this reason, the calculation of the opening and closing currents of the sensor can be determined by the following expressions:

$$\begin{cases} I_o = \dfrac{2\pi s B_o}{\mu_0}; \\ I_{cl} = \dfrac{2\pi s B_{cl}}{\mu_0}, \end{cases} \quad (18)$$

where B_o, B_{cl} – magnetic field induction of opening and closing of the Hall sensor.

According to the obtained values, as well as the duration of the open state of the Hall sensor Δt, we can determine the amplitude values of the current intensity by the following formula [19]:

$$I_m = \frac{\sqrt{I_o^2 + I_{cl}^2 - 2 I_o I_{cl} \cdot \cos(\omega \Delta t)}}{\sin(\omega \Delta t)}. \quad (19)$$

It should be noted that the Hall sensor does not have rattle due to the inertia of the contact. It should be noted, however, that due to the presence of a transistor in the circuit, the polarity of the magnetic field plays an important role. For this reason, two Hall sensors were used.

5. 3. Calculation of the error in determining the amplitude of a sinusoidal signal using Hall sensors

The error calculation is derived (2) based on experimental measurements of the instantaneous values of the opening/closing values of the Hall sensors and the open state time in one half-wave, as shown in Fig. 10.

Fig. 10 shows the oscillograms of the discrete Hall sensor under the influence of a sinusoidal signal of different multiplicity. As the amplitude increases, the open time of the Hall sensor increases. Below are the results of measurements and calculations of the sine signal amplitude values.

It should be noted that the open-state time of the discrete Hall sensor and the steady-state alternating current should be measured in microseconds. Consequently, to track changes in the parameters, an oscilloscope was used, which measures only the voltage drop. Considering this fact, as well as the limitations of the current transformer and analog Hall sensor, the measurements were carried out according to the following dependence:

$$\begin{cases} U_1 = k_1 I, \text{ if } I < I_{\max 1}; \\ U_2 = k_2 I, \text{ if } I < I_{\max 2}, \end{cases} \quad (20)$$

where I – actual alternating current, U_1 – voltage at the current transformer, U_2 – voltage at the output of the analog Hall sensor, k_1 – conversion factor of the current transformer, k_2 – conversion factor at the output of the analog Hall sensor.

Moreover, the magnetic flux and the current flowing through the conductor are in the same phase according to the inductance dependence. Consequently, the output signal from the analog sensor is also in the same phase. The phase shift of the current transformer is eliminated by the fact that most of its load is reactive.

Absolute ΔU and relative ΔU errors were calculated relative to the measurements obtained from the analog Hall sensor SS49E and current transformer, according to the formulas:

$$\begin{cases} \Delta U = U_{meas} - U_{calc}; \\ \delta U = \dfrac{U_{meas} - U_{calc}}{U_{meas}} \cdot 100\,\%, \end{cases} \quad (21)$$

where U_{meas} – measured current amplitude, U_{calc} – calculated current amplitude.

Multiple measurements achieve the reliability of the results at the same current value. Measurements were made at seven different current amplitudes. The obtained results are then presented in the form of a table, and the errors are indicated in the form of graphs.

Table 1 summarizes the results of the experimental measurement of the open state time of the Hall sensor under the influence of an alternating sinusoidal signal. Graphically, these two signals are presented in Fig. 10. During the experiment, the voltage level at the opening of the Hall sensor, the voltage level at closing, the open state time, and the amplitude of the applied signal were recorded.

Fig. 11 graphically shows the error level in determining the amplitude of a sinusoidal signal by measuring the time of the open state of the Hall sensor.

At a multiplicity of the amplitude of the influencing signal relative to the value of the Hall sensor opening from 2 to 4, the error did not exceed 3 %.

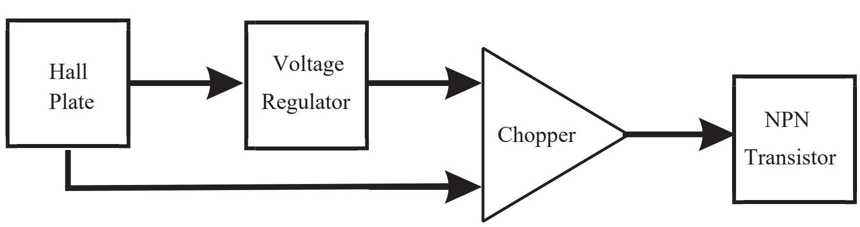
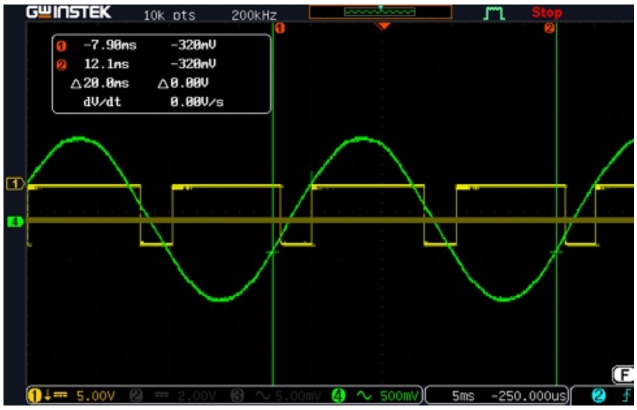
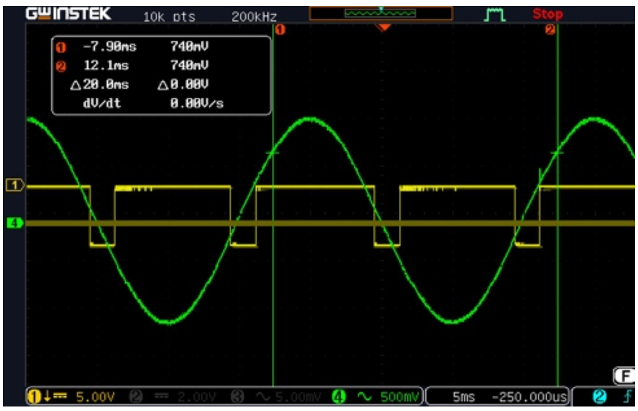


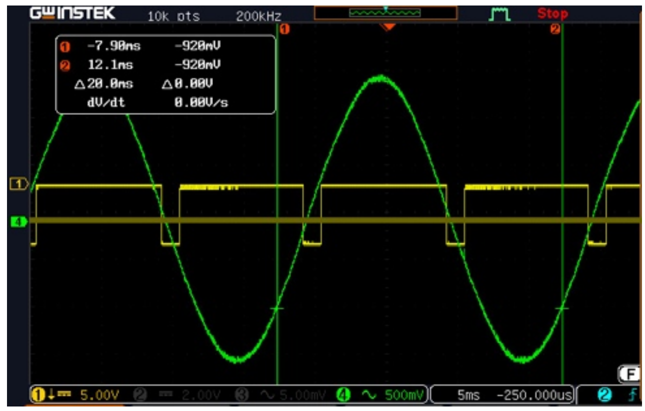
Fig. 9. Hall sensor SS443A circuit diagram



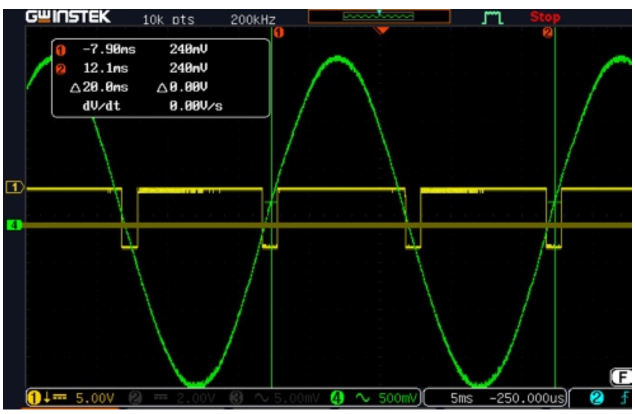
a



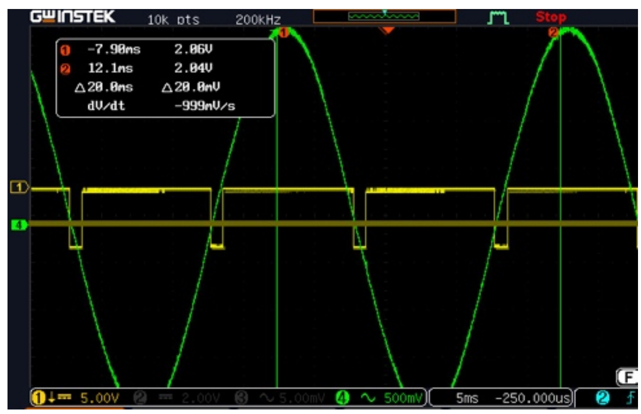
b



c



d



e

Fig. 10. Oscillogram of operation of the discrete Hall sensor under the influence of a sinusoidal signal of different multiplicity: *a* – multiplicity 2; *b* – multiplicity 3; *c* – multiplicity 3, 5; *d* – multiplicity 4; *e* – multiplicity 5

Table 1

Experimental results

No.	U_{meas}	U_{calc}	U_o	U_{cl}	Δt	ΔU	ΔU
1	880	894.9357074	430	180	0.00776	14.93570744	1.697239
2	1,170	1180.264273	460	150	0.00832	10.26427309	0.877288
3	1,440	1445.613428	480	130	0.008636	5.61342818	0.389821
4	1,680	1709.240232	520	140	0.008755	29.24023185	1.74049
5	1,840	1884.137926	508	100	0.008962	44.13792575	2.3988

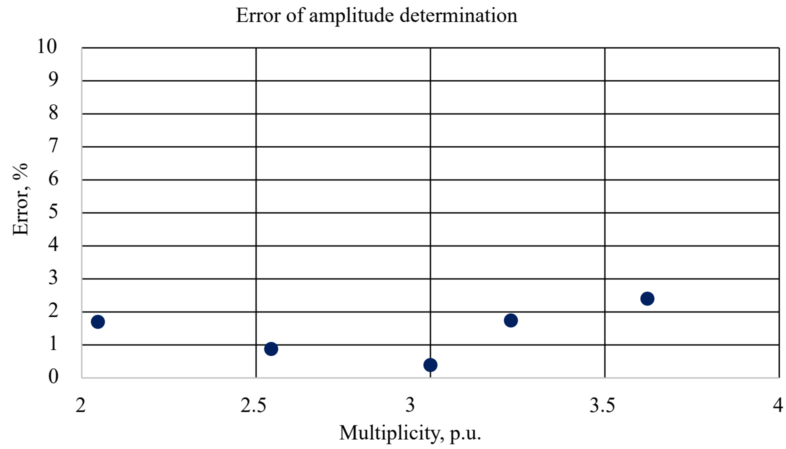


Fig. 11. Error in determining the amplitude of the sinusoidal signal

6. Discussion of experimental results of reducing the error in AC amplitude determination

The mathematical model (14) allowed simulations in MatLab to determine debounce's influence on the result of measuring the time of the closed state of reed contacts (Fig. 4). The previous works [2–4] demonstrated only the results of the work without research of the mechanical contacts behavior. The developed mathematical model (14) makes it possible to investigate the behavior of the reed contacts (Fig. 2) in different power grid operation modes. According to the known laws and formulas from [15] for oscillating and vibrating impacts presented as formulas (4)–(6). The initial condition for the mathematical model is the moment of the contact's trip. Research of electrical processes in the measurement circuit was conducted due to the basic laws of the electrical engineering theory [14]. The application of the formula (10) allows investigating other types of the mechanical contacts trip processes. Thus, the proposed mathematical model allows us to study the possibility of reed switch application for current amplitude identification. The limitation of the bounce nature research is the limitation of the oscilloscope that cannot be determined precisely. The main disadvantage of the model is the absence of consideration of the material of the contacts and physical and chemical properties of the surface. Thus, the reed switch bounce has a random nature and can be considered by introducing a correction factor, which will at least have higher accuracy in determining the bounce effect. Development of the mathematical model in future will help to predict the result of the reed switch operation. It was possible to conduct modeling and assess the level of influence of contact bounce due to applying the laws of mechanics (5)–(7) when considering the work of reed contacts. Consequently, the scientific novelty of the study lies in the mathematical description of reed contact bounce under the influence of sinusoidal current of industrial frequency.

The developed mathematical model of the discrete Hall sensor allowed us to conduct experiments to identify the current amplitude. The suggested model can assist in choosing the discrete Hall sensor and instruments for magnetic field concentration. It should be noted that analog and discrete Hall sensors have differences in the principle of operation when exposed to a sinusoidal signal, as shown in Fig. 5. Due to the limitation of the excitation voltage, the analog Hall sensor can only be used in a limited range, as shown in Fig. 6. It should be noted that the discrete Hall sensor has no bounce, unlike the reed switch (Fig. 7), which allows us to conclude that its application is promising as an alternative solution. However, research in this direction is necessary. It is also worth noting that the method must include the opening and closing moments via the Bio-Savar-Laplace law through formulas (18), (19). However, if the Hall sensor is placed under different angles, those mathematical equations will not be applicable. Therefore, the condition must be found through (16). On the other hand, the proposed method did not consider the application of the Hall sensor at different angles and does not take into account any interference as well as the temperature dependability. The limitation of the proposed method is the absence of consideration of the aperiodical part of the current as the experimental installation was not prepared for such research. In the future research, the introduction of the temperature and interference functions for a discrete Hall sensor as well as consideration of the aperiodic part in identification will be achieved.

The developed laboratory setup allowed us to study the behavior of Hall sensors under the influence of an alternating sinusoidal signal (Fig. 1). The logic circuit using an oscilloscope made it possible to obtain information about the state of Hall sensors at any moment (Fig. 2). The main feature of the Hall sensor operation when a sinusoidal signal is applied is that the Hall sensor has two characteristics – the opening and closing moments. These two changes in the Hall sensor's state occur when the sinusoidal signal's half-wave increases/decreases. The opening and closing occur in each half-wave. Precisely, when signals with a frequency of 50 Hz are applied, the Hall sensor operates with a frequency of 100 Hz (Fig. 9). This property of the Hall sensor allows applying the Bio-Savara-Laplace law to develop a mathematical description of determining the amplitude of a sinusoidal signal acting on the Hall sensor (15). Based on (17), due to the available values of the magnitudes of the influencing signal at the opening/closing of the Hall sensor and measurement of the open state time, it is possible to determine the magnitude of the amplitude of this signal. In the future, it will allow building new relay protection devices with unique properties, which may be superior to the existing ones, because using semiconductors as sensing elements for this model is a fundamentally new solution. The method of the current identification was justified through the use of the analog Hall sensor and the current transformer can be justified by formula (15) that demonstrates the linear law of the voltage change and the current change in the conductor. Therefore, the formula (20) for the current determination allows us to measure it. The error of determining the amplitude of a sinusoidal signal with the help of a Hall sensor is an important parameter that will allow evaluating the prospects of using Hall sensors via formula (21). The result is better than known studies [5, 6] of devices built using reed switches as sensing elements. Unlike the reed switch, the result is explained by the absence of metal moving contacts in the Hall sensor. The semiconductor element shows more stable operation, reflected in the reduced error in determining the amplitude of the influencing signal. In further studies, it is necessary to determine the parameters of Hall sensors at higher multiples. In the current study, the main limitation was the current rate of four due to the experimental setup and power source limitations. The practical significance lies in increasing the accuracy of current value determination without the use of current transformers by using Hall sensors, which have a number of advantages over reed switches. However, further research on this solution is needed. The main disadvantage of the research is the absence of consideration of the temperature and near magnetic field interference from other phases or installations. The suggested experimental installation further can be used to check other types of current amplitude identification methods. The suggested device can also determine the characteristics of the magnetic field. In addition, the proposed prototype of measurement device requires compulsory calculation of the magnetic field concentration instruments. In the future research, it can be studied by modifying the setup with adding more phases and imitations of the interferences.

7. Conclusions

1. According to the proposed mathematical model of the reed switch bounce, it takes up to 10 % of the closed state time, which introduces the error in the current amplitude identification. The proposed mathematical model can be further used to upgrade the existing solutions on the reed switches. The experiment justified the veracity of the mathematical model.

2. When determining the features of using Hall sensors to determine the amplitude of a sinusoidal signal, it was found that discrete Hall sensors placed in the magnetic circuit window allow them to be used to determine the amplitude using a mathematical model developed based on the Biot-Savary-Laplace law. The open state time is at most 10 ms.

3. As a result of calculating the amplitude of the variable sinusoidal signal acting on the Hall sensor, the error did not exceed 3 %. The experiments were conducted at a diversity of the influencing signal's amplitude relative to the Hall sensor's opening value from 2 to 4.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

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