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IDENTIFICATION OF CHARACTERISTICS OF CONCEPTUAL PROTOTYPE OF MICROPROCESSOR RESOURCE-SAVING RELAY PROTECTION SYSTEM

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The object of the study is the conceptual prototype of a microprocessor resource-saving relay protection system. Currently, relay protection ensures electrical networks reliable and efficient work, however, the traditional architecture is proprietary, not allowing to fix and replace damaged parts without a company specialist. Therefore, the open-architecture relay protection is a very pressing issue, but the problem lies in meeting the relay protection requirements. The data transmission protocols nRF and ESP-NOW, Hall sensors evaluation for AC current measurement determination and sensor accuracy improvement was implemented. Experimental validation demonstrated that nRF and ESP-NOW protocols meet the delay and reliability requirements, however, the nRF protocol is more suitable due to its flexibility and obstacle penetration. The data demonstrated that the most effective conditions are without obstacles at 15 meters from the modem and with obstacles 5 meters from the modem. The experiment of Hall sensors characteristics determination demonstrated the accuracy of current measurement with the set values of the opening and closing currents. Nevertheless, it is not accurate (12.45 %) for the relay protection application. Therefore, the application of the changing values of the opening and closing currents is more effective and accuracy reaches 6.92 %. As a result, the service life of the Hall sensor was determined, and even after 10 million openings, the open state time remained unchanged. Therefore, the approximation function for current amplitude determination depending on open state time was found. On the other hand, Hall sensors may suffer from temperature drift and require further optimization to be fully reliable. The study limitation is the current range from 0 to 800 A

Keywords: relay protection, reed switch, Hall sensor, magnetic field, open architecture

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1. Introduction

Relay protection is a key element of modern electrical networks, ensuring their safety and reliability. It functions by quickly and accurately detecting faults, such as short circuits and overloads, and initiates appropriate protective measures to prevent equipment damage and minimize system downtime. Without relay protection, stable and efficient operation of power systems is impossible, as failures will result in serious economic losses and safety risks.

With the development of small-scale generation technologies and the increasing complexity of power grids, relay protection faces a number of modern challenges. One of the main challenges is to ensure the reliability and resilience of relay protection in the face of the increasing complexity of distribution network schemes and the emergence of small generation sources.

For example, in 2019, a fault on the side of high-voltage lines triggered a chain of events that disconnected about 1.1 million consumers in the London area [1]. The introduction of digital technologies and data networks makes systems more flexible, which will enable the creation of new algorithms for relay protection operation, and can reduce the risks of such blackouts and provide new opportunities for distribution network operators. However, this requires the development of solutions utilizing modern technologies. Transmission technologies are divided into wired and wireless. Wireless communications are currently favored due to their easier installation and maintenance compared to wired communications, which, although compliant, can be expensive and more labor-intensive to implement in existing electrical networks.

In [2] Sweden, the potential benefits of wireless technology in relay protection have been investigated. The annual cost of power interruptions is estimated at about 150 million euros. Information and communication technologies such as 5G or IIoT are expected to reduce the duration of power interruptions by 50 % to 75 %, which could increase the revenues of distribution network operators by up to 40 million euros per year. However, the wireless technology used must provide acceptable latency, bandwidth, density and energy efficiency. This will allow for greater flexibility, scalability and interoperability.

Another important issue is related to the interoperability of different relay protection systems. Modern power systems often include equipment from different manufacturers, which requires compatibility and seamless integration. In addition, the dynamic nature of modern power grids associated with renewable energy and distributed generation creates the need for relay protection to be adaptable to changing load conditions and network topology.

Setting up and controlling complex relay protection algorithms requires high skills and careful calibration, increasing the potential for human error and the need for highly trained personnel. Finally, many existing relay protection systems are aging and need to be upgraded to meet modern standards and requirements.

There are also issues with the measurement of primary quantities. Current transformers are the primary measurement element of relay protection. However, current transformers are prone to saturation, which can lead to signal distortion and reduced measurement accuracy, as well as a big disadvantage is the metal consumption of the current transformer design.

It is therefore pertinent to conduct research aimed at enhancing the reliability and stability of relay protection in the context of increasingly complex electrical networks and the integration of small-scale generation. Thus, the development of new algorithms and technologies that meet contemporary standards is required due to the necessity of guaranteeing the safety and stability of energy systems.

2. Literature review and problem statement

One of the alternative resource-saving solutions is the use of Rogowski current sensor instead of metal-intensive current transformer [3]. Experimental results using Rogowski's sensor on a prototype DC/AC converter showed a significant difference in the sensor's performance depending on its placement relative to the converter keys. But there were unresolved issues related to excessive sensitivity and susceptibility to temperature drift. The paper [4] demonstrates the study of harmonic characteristics of an electronic current transformer based on a Rogowski coil. Harmonic tests showed that the Rogowski coil can operate over a wide frequency range and provide stable measurements. Another study [5] compares Rogowski current sensor and traditional current transformers under different events in the electrical network. Experimental results confirm the effectiveness of Rogowski sensors for AC current measurement under different operating conditions. However, despite the results achieved, certain drawbacks remain, such as sensitivity to electromagnetic interference and the need for additional electronics for signal integration.

The study [6] proposes a relay protection method based on a fiber optic current transformer (FOCT). The principle of operation is based on the use of Faraday effect for current measurement. The developed FOCT-based relay protection system was implemented on a 300 MW generator in a hydroelectric storage power plant in China for testing under operating conditions. The testing involved measuring the maximum transient error under specified current and time conditions. However, optical fiber is highly sensitive to mechanical effects such as vibration and shock, which in turn can affect the stability and measurement reliability of the entire relay protection system. The paper [7] demonstrates an arc fault location device that utilizes ultraviolet radiation and ultrasound to increase the sensitivity of the optical sensor. The disadvantage of the proposed method is the dependence on the quality of fluorescent coating, as well as sensitivity to the influence of solar radiation and electromagnetic interference.

Another still studied not enough solution is the use of a reed switch as a measuring element. In [8], the use of reed switches instead of current transformers and current relays for protection of 6–35 kV electrical installations is demonstrated. A design was developed where two reed switches were installed near each busbar. However, as noted by the authors of the paper, when using the developed design there are problems with the sensitivity of reed switches, which are sensitive to magnetic fields from neighboring phases and electrical installations, which can lead to false triggering. The study [9] demonstrates a method for protecting double power lines, which is also based on controlling the sequence of triggering of reed switches installed near the phases of the lines and measuring the time t between their triggering. The use of a large number of reed switches and complex algorithms for signal processing and time delays increases the complexity of the system. Another study [10] presents the use of a current relay with two capacitors and a reed switch, this design is installed inside the bus body. It should be noted that reed switch based systems have limitations and can only be used to protect electrical installations up to 100 kV. In addition, sensitivity and debounce problems also remain. In [11], it is proposed to install inductive coils inside the working cell to measure EMF at different points, and reed switches are installed at the points with maximum magnetic induction. However, the study also does not eliminate the problem of reed switch bounce, which can lead to false relay protection tripping.

Another alternative solution is to use a Hall sensor instead of a current transformer [12]. The developed design uses a specially folded busbar that mitigates the skin effect and allows measuring currents up to 250 A at frequencies up to 10 kHz. The Hall sensor is asymmetrically mounted in the gap between two parallel parts of the busbar, where the magnetic field becomes more homogeneous as the current frequency increases. Ferromagnetic plates are used to reduce the influence of external magnetic fields. However, the folded busbar creates a higher magnetic flux density, which leads to saturation of the sensor at low currents. The paper [13] presents a current sensor whose design is based on the use of a circular arrangement of eight magnetic sensors and the closed-loop principle. Hall sensor and Fluxgate sensor are used and compared as sensors. The output signals of the sensors are summed, amplified and filtered to obtain a symmetrical signal, and to compensate for the measured current, a coil with 2,000 turns is placed around the sensors placed in a circular arrangement, creating an opposite magnetic field. Experimental data from the study showed that the design with Fluxgate performed better than the developed prototype with Hall sensors in terms of the presence of temperature drift. A solution to improve this characteristic is presented in [14]. The study proposes a method to optimize the Hall sensor design using a physically informed Gaussian Process based model. As part of geometry optimization, three types of Hall plate geometries were analyzed and their design optimized to minimize bias and maximize sensitivity. Experimental results showed that the optimized Hall sensors exhibited higher Hall voltage measurement accuracy at different temperatures, and temperature drift was significantly reduced. However, further research is needed to enable the results to be applied within relay protection systems.

The current challenge is to evaluate state-of-the-art solutions, in particular a conceptual prototype of a microprocessor-based resource-efficient relay protection system based on open architecture and applying Industrial Internet of Things (IIoT) technologies to provide reliable and efficient protection of electrical networks in the context of modern challenges. This paper is a continuation of [15, 16] and is devoted to the study of the characteristics of a conceptual prototype of a microprocessor-based resource-saving relay protection system based on open architecture. Also, in the market of relay protection devices, devices using the technology of the Internet of Things are increasingly appearing. However, the IoT is often only used for storage and visualization of measurement data and boundary calculations, but the capabilities and advantages of the IoT are not directly applied to relay protection control functions. Therefore, the implementation of IoT is also of interest for this study.

3. The aim and objectives of the study

The aim of the study is to identify the characteristics of the conceptual prototype of microprocessor resource-saving relay protection system based on open architecture with the application of industrial Internet of Things technology.

To achieve this aim, the following objectives are accomplished:

– to select the data transmission protocol for the prototype of microprocessor resource-saving relay protection system based on open architecture with the application of industrial Internet of Things technology;

– to determine the error of AC current amplitude detection in a conductor using the prototype of microprocessor-based resource-saving relay protection system with a Hall element;

– to investigate the properties of the Hall element as a sensing element of the prototype microprocessor resource-saving relay protection system.

4. Materials and methods

The object of the study is the conceptual prototype of the resource-saving relay protection. The main hypothesis of this study lies in the possibility of applying Hall Sensors and wireless network based on open architecture for relay protection. The applied assumptions are the absence of temperature shift consideration and linearity of the current in the conductor. To select the data transmission protocol for the prototype of microprocessor resource-saving relay protection system based on open architecture with the use of industrial Internet of Things technology, the basic principles of radio engineering, information theory, and encryption theory were applied. In order to investigate the characterization of Hall sensors, it is necessary to apply the experimental setup reported in [15]. However, in this case, the circuit diagram (Fig. 1) includes the application of three unipolar Hall sensors (SS443A), which are installed on the same side and operate in one identical half-wave. Consequently, the oscillogram will be presented as a step function at the time of opening and closing of the Hall sensors in the half-wave. Moreover, a current transformer (CT) was used to obtain the primary information about the current flowing through the conductor. The signal was taken by an oscilloscope in the form of voltage using resistors R1–R4.

Moreover, the process of opening and closing of the Hall sensor is to reach a certain value of the magnetic field induction, which can be calculated by the Biot-Savart-Laplace law [16]:

$$B = \frac{\mu_0 I}{2\pi s}. \tag{1}$$

It should be noted that in the case of the selected SS443A Hall sensors, the opening induction was 180 militesla (mTl) and the closing induction was 75 mTl [16]. This value is large, so the magnetic field generated by the cable may not be sufficient.

To increase the sensitivity of Hall sensors, a magnetic field concentrator was used, in particular, a magnetoconductor with a small cut to place the sensing bodies in it (Fig. 2).

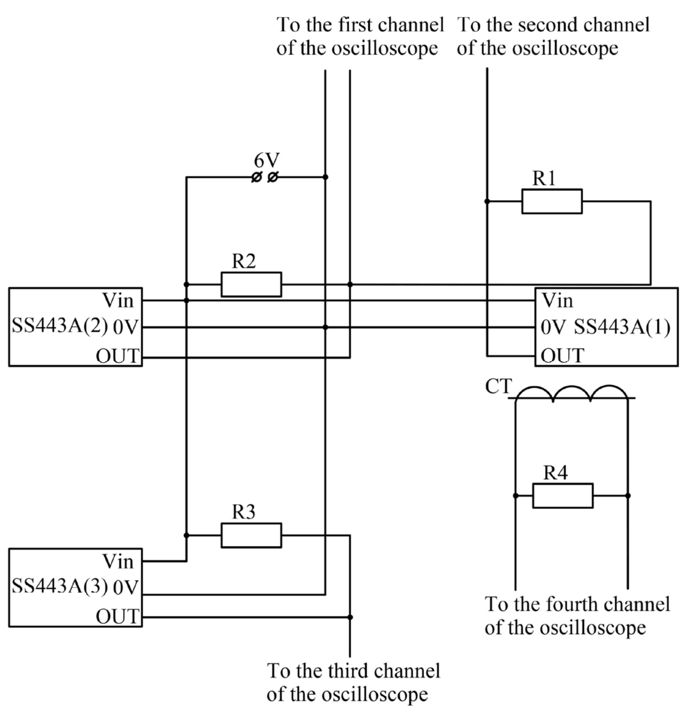

Fig. 1. Hall sensor wiring diagram

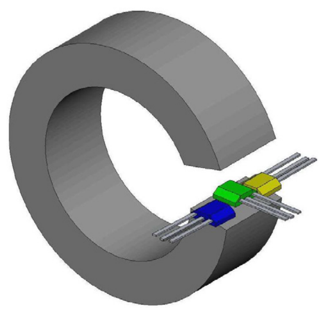

Fig. 2. 3D model of the magnetic core

Moreover, the values of Hall opening and closing currents are calculated by the known formula:

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

where B_o, B_{cl} – values of opening and closing inductions [14].

In this case, the Hall sensor output value takes logical values according to Boolean algebra. When the Hall sensor is open, the output value becomes a logical one, when it is closed, it becomes a zero.

Mathematically, this phenomenon is represented in the form of an expression:

$$f(t) = \begin{cases} 1 \text{ if } i(t) > I_o. \\ 0 \text{ if } i(t) < I_{cl}, \end{cases} \quad (3)$$

where i_o, i_{cl} – Hall sensor opening and closing current, $i(t)$ – alternating current.

Graphically, this formula can be represented in Fig. 5. Here we consider the operation of three Hall sensors.

Moreover, the task of determining the error of amplitude detection is carried out by the threshold value from the common set of values:

$$\begin{cases} I_{o(t)} = \sup(I_o); \\ I_{cl(t)} = \sup(I_{cl}). \end{cases} \quad (5)$$

Then, according to [16], the amplitude can be calculated by the formula:

$$I_m = \frac{\sqrt{I_{o(t)}^2 + I_{cl(t)}^2 - 2I_{o(t)}I_{cl(t)} \cdot \cos(\omega\Delta t)}}{\sin(\omega\Delta t)}, \quad (6)$$

where Δt – the time at which the Hall sensor is in the open state.

In this case, the values of absolute and relative errors are determined by the known formulas:

$$\begin{cases} \delta I = I_{m(calc)} - I_{m(meas)}; \\ \varepsilon I = \dfrac{\delta I}{I_{m(meas)}}, \end{cases} \quad (7)$$

where δI – absolute error;

$I_{m(meas)}$ – measured value;

$I_{m(calc)}$ – estimated value.

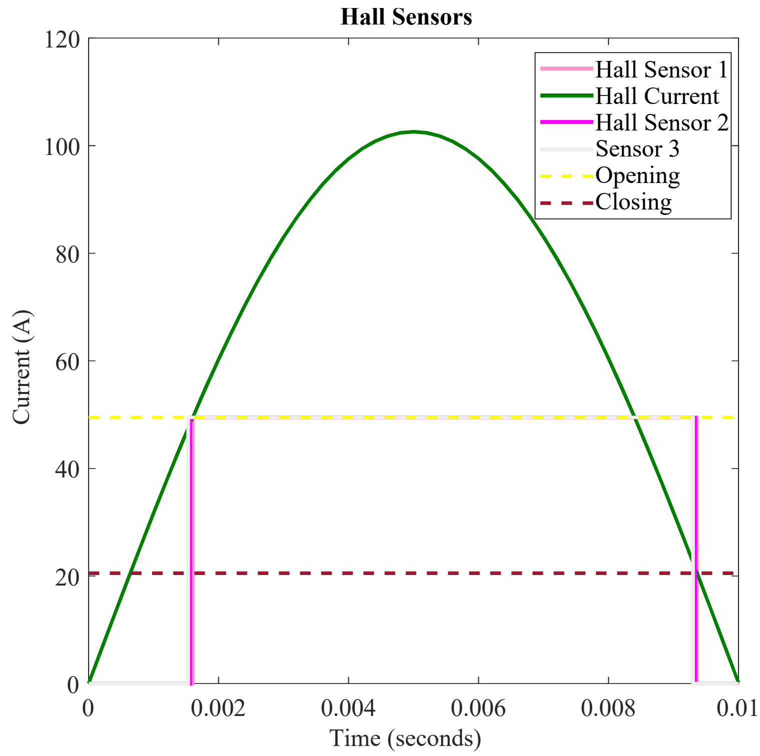

Fig. 3. Hall sensor opening and closing schedule

To determine the error of identification of the alternating current amplitude in the conductor using the prototype of microprocessor-based resource-saving relay protection system with Hall element, the laboratory bench [15], oscilloscope GW GDS-71054B, Hall sensors SS443A, current transformer 2000/5 A, as well as the basic principles of electrical engineering, statistics, magnetic field theory were used.

In order to investigate the property of the Hall element as a sensing element of the prototype of the microprocessor resource-saving relay protection system, the laboratory bench [15], the oscilloscope GW GDS-71054B, Hall sensors SS443A, current transformer 2000/5 A, as well as the basic provisions of electrical engineering, statistics, magnetic field theory were used.

5. Results of the microprocessor resource-saving relay protection system conceptual prototype based on open architecture research

5. 1. IoT wireless communication protocol selection with appropriate requirements consideration

There are many available wireless communication technologies in IoT that could be used to transfer data for indoor and outdoor scenarios. Long range of omnidirectional communication vs high throughput and low delay is the main deciding point depending on the application scenario. Relay protection system requires a small delay around 1 ms, high reliability and semi-long communication distance. Another factor could be the maximum size of the payload, to estimate whether all of the required data could be sent over a single packet of information. However, since the payload size for the relay protection system is relatively small, this is not a concern for most of the modern IoT communication protocols. Wireless communication technologies that were tested for the purposes of the proposed relay protection system include: LoRa, nRF and ESP-NOW communication protocols. These were chosen because modules are readily available on the market, there is an abundance of documentation about the protocols and they are widely used in existing IoT networks.

Estimation of an appropriate protocol started with the Long-Range (LoRa) communication protocol. By calculating the airtime of a packet, it was concluded that it violates the low delay requirement of the proposed relay protection system. In the best case scenario that uses the fastest data transfer settings available, a payload of 32 bytes would be transmitted for over 35 ms, which is not acceptable for near real-time systems, such as the proposed relay protection system. Therefore, a decision was made to abandon LoRa as a communication protocol for the platform.

Two other competitors, nRF and ESP-NOW, both work on a similar frequency spectrum of 2.4 GHz, which allows for a much higher bandwidth, and achieves a round-trip time of 1–2 ms, which is acceptable. Several experiments were conducted for both ESP-NOW and nRF (Table 1).

Table 1

Reference and through wall average experimental results of ESP-NOW

Experiment	# of pckts	Time (ms)	Variance	stDev
Reference (avg)	1,000	2.261	3.204	1.747
Through wall (avg)	543.9	2.173	2.446	1.463

According to ESP-NOW specification, the longest time required for a packet to reach the destination is up to 20 ms, however, it assumes that 10 consecutive packets will be missed (Table 2). The average results shown in Table 1 suggest that an average time requirement is approximately 2 ms. It is apparent that ESP-NOW, similarly to other 2.4 GHz technologies, such as Wi-Fi and Bluetooth, drops the packet receive ratio once wall-like obstacles are introduced (Table 3). Experiments in Fig. 1, 2 show that the overall loopback time for ESP-NOW is not affected by the strength of the signal.

Similar experiments were conducted for nRF communication technology. However, since there is a far wider settings range for nRF compared to ESP-NOW, more experiments were conducted to account for it.

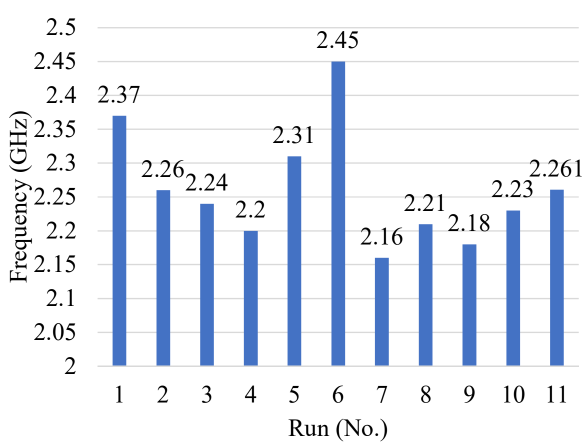

Fig. 4. Reference experimental results of ESP-NOW (the average is Run 11)

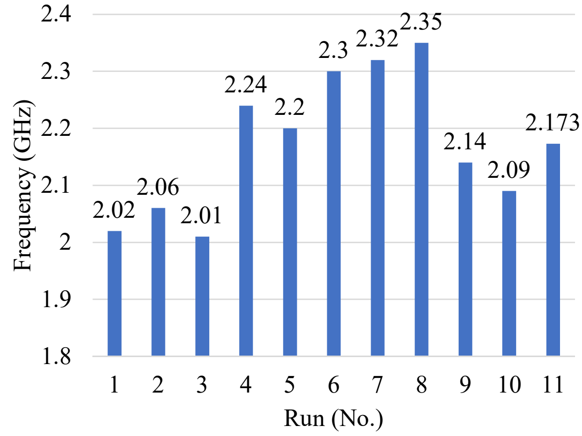

Fig. 5. Through wall experimental results of ESP-NOW (the average is Run 11)

Tables 2, 3 show a similar trend of nRF compared to ESP-NOW. Both nRF and ESP-NOW can be used for time-sensitive IoT applications assuming a fitting context of use. Here, a fitting context is a hangar-like structure with open indoor areas or walls that can be penetrated by 2.4 GHz with relative ease.

Table 2

Reference experiments for nRF with various settings

Bandwidth	Bytes	Packets	Time (us)	StDev
250Kbps PA MIN	1	1,000	1,673.33	1,410.1
	4	1,000	2,376.57	2,102.88
	16	1,000	4,288.25	4,012.95
1Mbps PA MIN	1	1,000	938.91	1,016.39
	4	999	1,738.91	2,135.84
	16	1,000	2,402.15	2,534.96
250Kbps PA MAX	1	999	2,280.41	1,985.61
	4	1,000	2,390.84	2,111.19
	16	1,000	3,755.6	3,779.43
1Mbps PA MAX	1	1,000	1,992.04	1,718.12
	4	1,000	2,299.07	1,917.22
	16	1,000	3,620.68	3,229.16

Table 3

Through wall experiments for nRF: PA MAX & 1Mbps & 4 bytes

nRF24L01	Pckts	Time (us)	StDev
5 meters	997	1,374.01	941.87
15 meters	997	2,180.86	2,515.73
5 meters w/wall	997	1,228.22	507.08
25 meters w/mul. walls	502	9,989.71	8,434.01
35 meters w/mul. walls	0	0	0

5. 2. Determination of the error of identification of the alternating current amplitude in a conductor based on the application of a Hall sensor

In turn, measurements were made on five main parameters, the duration of the open state of the Hall sensor, the amplitude calculated as the average of the maximum and minimum peak, the opening and closing value (Fig. 6).

The averaged results are recorded in Table 4 with the values of amplitude and errors.

Moreover, the obtained values are further converted into current values from the well-known Ohm's law [16]:

$$\frac{U_m}{R} = I_m. \quad (8)$$

Taking into account (8), the obtained results are graphically depicted in Fig. 7.

However, for a complete analysis, the graph can be plotted against a larger amount of data (Fig. 8).

In this case, we considered the calculated values for the opening and closing currents of 100 and 4 A, respectively.

Table 4

Averaged values of measurements and calculations

No.	U_{meas}, V	U_{calc}, V	U_o, V	U_{cl}, V	Δt, sec	ΔU	δU
1	196	203.4348408	100	4	0.0083	–0.03793	3.793
2	324	331.4426232	100	4	0.008983	–0.02297	2.2971
3	520	531.9651966	100	4	0.00937	–0.023	2.301
4	740	703.7203861	100	4	0.00953	0.049	4.90265

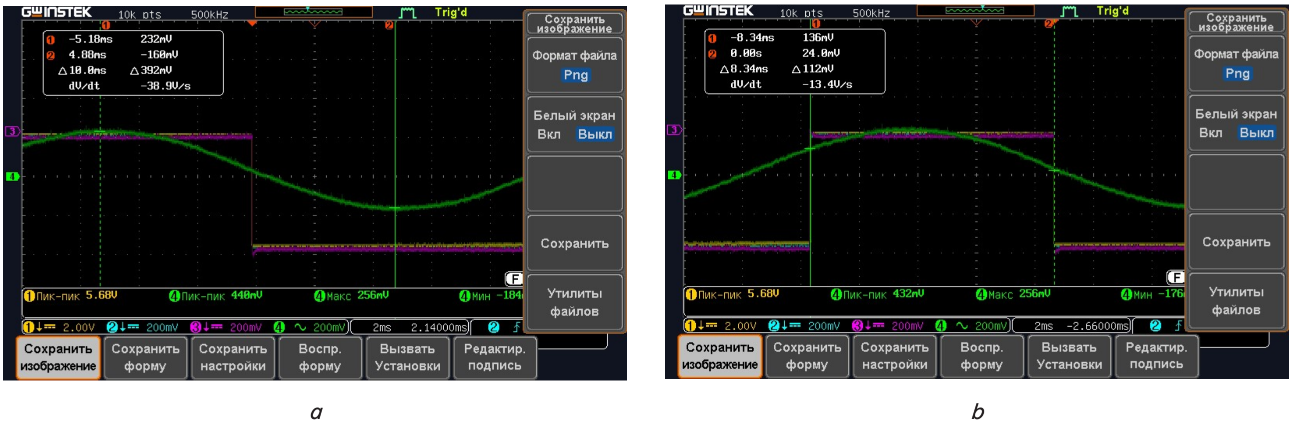

Fig. 6. Measurement process: *a* — amplitudes; *b* — values of open state time, open and close voltages

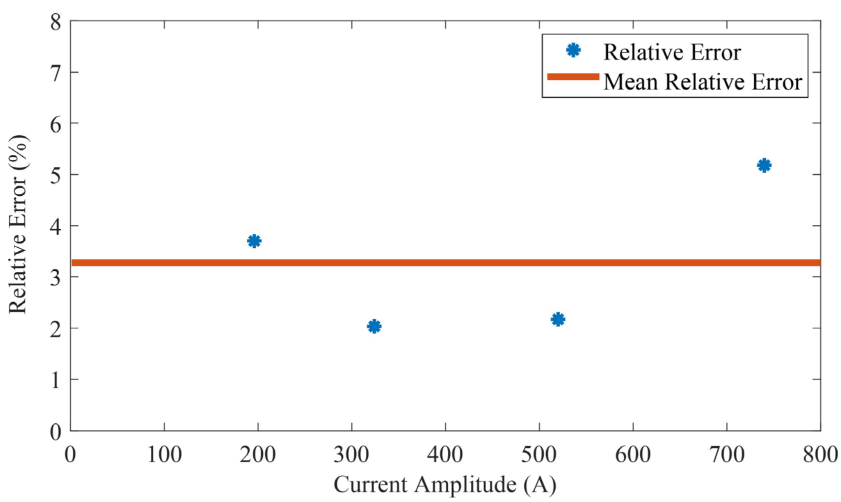

Fig. 7. Relative error distribution graph for averaged values

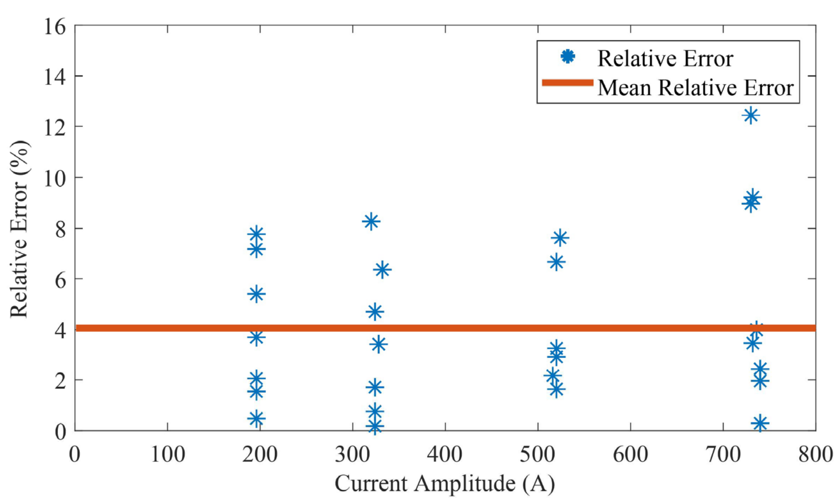

Fig. 8. Relative error distribution graph

5. 3. Investigation of Hall sensor properties

It is worth noting that most measuring bodies, whose operation is based on actuation and return, tend to degrade in the process of closing and opening the electric circuit.

In order to achieve greater accuracy, as well as to determine the stability of the device that receives information from Hall sensors, it is necessary to consider their properties. First of all, it is necessary to determine the dependence of the values of the opening currents on the amplitude. In order to find this formula, an approximation can be applied, as a result of which the dependence of the opening current on the amplitude is obtained:

$$I_{op} = 0.1894 I_m + 61.7918. \quad (9)$$

As a result, this dependence is graphically depicted in Fig. 9.

On the other hand, it is also necessary to determine the variation of the current amplitude from the duration of the Hall sensor being in the open state:

$$I_m = 4.1288 \cdot 10^8 \cdot \Delta t^2 - 6.966 \cdot 10^6 \cdot \Delta t + 2.958 \cdot 10^4. \quad (10)$$

As a result, this dependence will be depicted on the graph as a curve of the second-degree polynomial (Fig. 10).

In order to determine the trend of degradation of the sensing body, the standard uses methods of statistical analysis. The simplest of all is the method of approximation, which is built on the basis of existing known mathematical functions. In the case of this study, it is necessary to determine the trend of the sensing current in relation to the number of actuations:

$$\begin{cases} I_{o(196)} = 100; \\ I_{o(324)} = 0.0028 \cdot n^2 - 0.003 \cdot n + 122.1099; \\ I_{o(520)} = -0.0095 \cdot n^2 + 0.7505 \cdot n + 155.7722; \\ I_{o(740)} = 0.0008 \cdot n^2 + 0.0312 \cdot n + 210.3732. \end{cases} \quad (11)$$

The obtained dependencies are graphically shown in Fig. 11. Expressions (11) were obtained using data collected over a period of 9 days by setting the magnetic core around the power cable through which the opening current flowed at a minimum value. Under such conditions, the tests were conducted for 4–8 hours. Consequently, the number of openings and closings, taking into account an actuation frequency of 50 times per second, was calculated with respect to seconds and was 9,720,000.

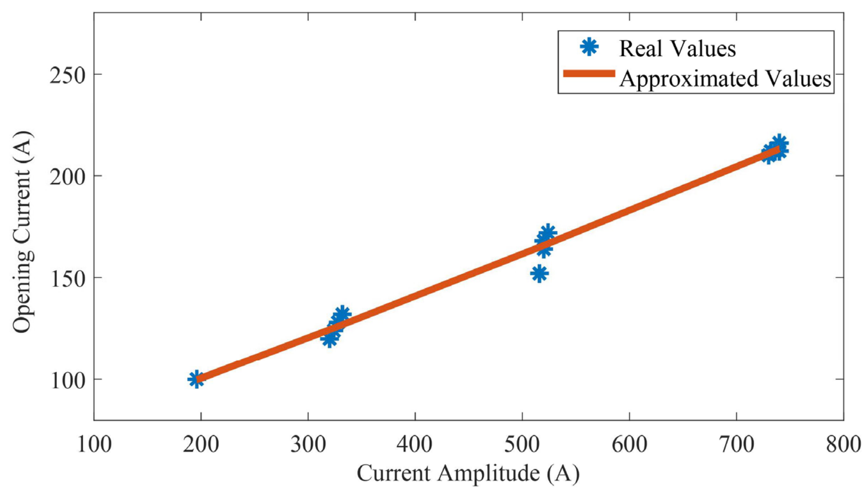

Fig. 9. Dependence of opening current value on amplitude

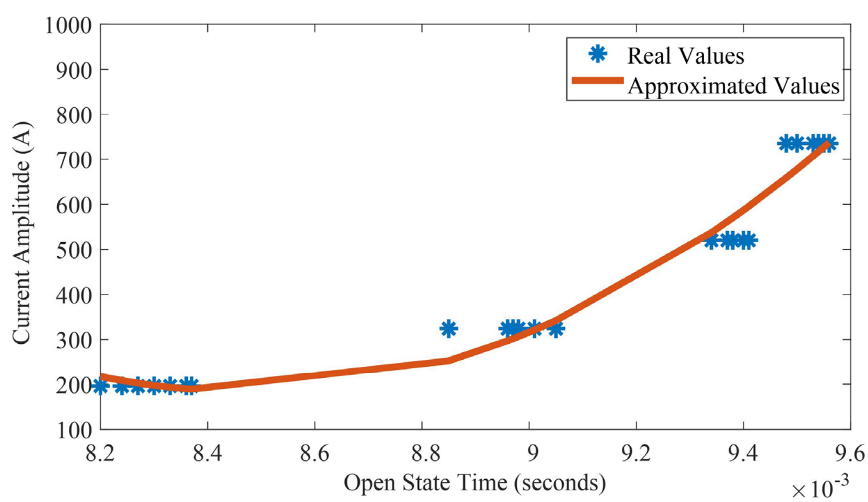

Fig. 10. Dependence of the current amplitude change on the duration of the Hall sensor open state

Consequently, it is better to calculate the amplitude values from the tripping currents at different moments of time. Table 5 presents data for averaged values of calculated amplitude with opening and closing currents and open state time.

Fig. 12 shows the distribution of relative error values from Table 5.

Consequently, the relative error plot from Fig. 7, 13 is also presented for comparison (Fig. 13).

It should be noted that the relative error without considering changes in opening currents reached a maximum of 12.45 %, and with taking into account – 6.92 %. Moreover, in the first case the average relative error.

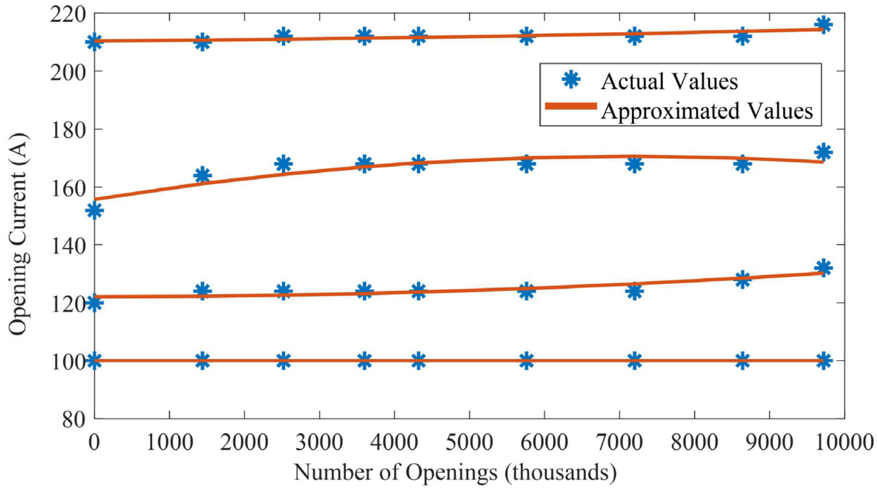

Fig. 11. Trends of tripping current vs. tripping quantity

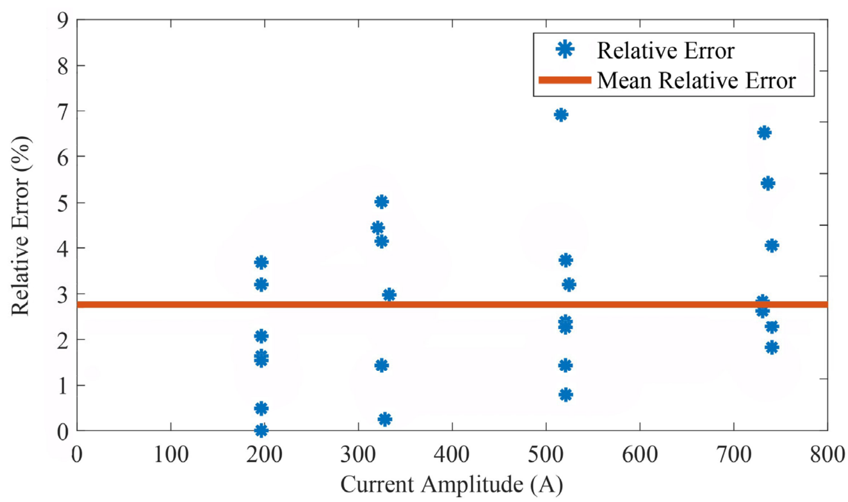

Fig. 12. Relative error distribution graph for averaged values considering changes in opening and closing currents

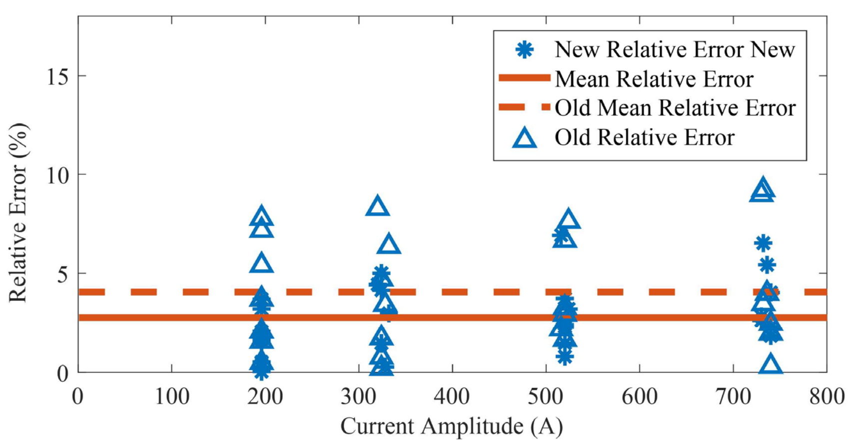

Fig. 13. Distribution of relative errors without considering changes in the opening and closing currents and with considering

Table 5

Averaged values of measurements and calculations with changes in opening and closing currents

No.	U_{meas}, V	U_{calc}, V	U_o, V	U_{cl}, V	Δt, sec	ΔU	δU
1	196	195.7103614	100	0	0.0083	0.00148	0.147994
2	324	319.1257732	125	–26	0.008983	0.018059	1.805907
3	520	507.3808633	166	–69	0.009373	0.024871	2.487113
4	740	755.2240614	212	–102	0.009527	–0.02604	2.604327

6. Discussion of the open architecture relay protection conceptual prototype research results

In comparison with the traditional systems [4–12] using data transmission protocols that are mostly from IEC 61850, the prototype demonstrated similar accuracy. Three IoT wireless communication technologies were tested for the application in a resource-saving relay protection system: LoRa, ESP-NOW and nRF. For LoRa experiments, an ESP32-based development with an included SX1278 LoRa module was used. For ESP-NOW experiments, common ESP8266 nodes were used, which have an innate ability to transmit or receive ESP-NOW data. For nRF experiments, an nRF24L01 type transceiver was used in conjunction with an STM32F103 board, since most STM32 boards don't have a wireless communication module from the box. LoRa airtime calculations for a desired payload of 32 bytes with subsequent experiments concluded that LoRa is not suitable for time-sensitive applications. The payload is transmitted using the fastest available settings, which do not guarantee a long range, for over 35 ms. ESP-NOW and nRF experiments, on the contrary, demonstrated acceptable results in terms of packet size and transmission delay. An average time on air for a packet is around 2 ms (Fig. 1, 2 and Tables 2, 3), because both ESP-NOW and nRF have a higher frequency of 2.4 GHz, and therefore a higher bandwidth. They are, however, suited only for open indoor environments or for environments with walls that do not block radio communication. Both of the wireless communication protocols fit the requirements, the choice of one over another solely depends on the hardware selected for the system.

Based on the analysis performed, it can be noted that the method can be applied to determine the amplitude based on the set value of the opening and closing currents (Fig. 5). However, in the case of relay protection applications, this method is undesirable due to large errors (Fig. 6). It is also worth noting that this study is limited by the conditions of the laboratory bench, so that the data are adequate for current amplitude values from 200 to 800 A.

Moreover, the use of Hall sensors can be considered as an alternative to reed switches, due to the presence of some advantages in comparison with the latter [8–11]. On the other hand, based on formula (2), the values of opening and closing currents were calculated similarly with reed switches. However, in this study, due to the linear dependence of the induction value on the current value, the opening and closing currents were determined empirically. In this case, in turn, similarly as with the reed switch using expression (6), the determination of the AC current value is possible. However, as was determined in the study [12–14], Hall sensors have the advantage of no mechanical contact and therefore no bounce.

In this case, the study of Hall properties allowed us to identify the causes of measurement errors on the one hand and on the other hand to determine the service life. According to the formula (8) and the graph in Fig. 7, it can be noted that the opening current value changes proportionally to the current amplitude. As a consequence, the application of the set value leads to an increase in the measurement error, however, according to Fig. 6, we can notice only one value of relative error exceeding the value of 10 %. This phenomenon can be explained by the fact that the calculation of the current amplitude value is more influenced by the time of the open state of the Hall sensor, which is explained by expression (10) and the graph in Fig. 8. Thus, according to (11), taking into account small errors of human factor and accuracy of oscilloscope GW GDS-71054B, the values of relative error for Hall sensors SS443A did not change even after 10 million actuations. However, the study is limited due to the absence of temperature drift consideration, which can introduce changes in measurement values. It should be noted that the disadvantage in this study is the result of a relatively small number of actuations, as well as the limited operating conditions. As a consequence, the obtained dependencies are reliable only for the range of current amplitude changes from 0 to 800 A. In the future research, the study will be done in the field of Hall sensors characteristics including the temperature drift. Nevertheless, the study demonstrated a high possibility of the Hall sensors-based relay protection application on real industrial installations. However, the applied assumptions allow to do that only on the devices with voltages not higher than 35 kV.

7. Conclusions

1. The nRF protocol with the lowest data transmission delay and high possible signal penetration through the wall was selected. Moreover, the effective range of the communication system is 15 meters without obstacles and 5 meters with obstacles.

2. The application of Hall sensors in relay protection allows the detection of AC current magnitudes in a conductor, similar to the reed switch. By applying the Biot-Savart-Laplace law, it was possible to obtain values with a relative error of 12.45 %. To increase the accuracy, it is necessary to take into account the changes in opening and closing currents depending on the amplitude of the influencing alternating current, which allowed us to obtain values with a relative error of 6.92 %.

3. By investigating the properties of the Hall element by placing it in an alternating magnetic field, an operating time of about 10 million actuations was achieved. As a result, the parameters of the investigated Hall elements, the opening and closing currents, as well as the closed state time depending on the applied alternating current, did not change. The changes were less than 1 %. Consequently, the removed dependence of the AC current in the conductor on the time of the closed state of the Hall element is stable and can be used to determine the amplitude of the AC current.

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.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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