A study of the functioning of reed switches under the influence of a magnetic field created by a current in a conductor in a transient mode with the presence of an aperiodic component has been carried out. A well-known method for determining current using reed switches was implemented. At the same time, it was determined that the originally formulated method did not give the required result within the limits of errors. This is most likely due to the peculiarities of the mechanism of movement of the reed switch contacts. Alternatively, the measurements were taken to take the return currents instead of the pick-up currents and the time between the return times. They are more stable. Simulation is performed, experimental determination of the value of surge current by measuring time is carried out. The main element of the created installation was the power transformer coil with low active and high inductive resistance. As part of the study, the reed switches were placed in a magnetic field with an aperiodic component, as in the transient mode. This study will show the applicability of reed switches for the construction of relay protection devices that will not need current transformers to obtain information about the primary current in the conductor. In the course of the research, it was found that the error in determining the magnitude of current was no more than 10 %. Using microprocessors, it is possible to build relay protection devices with a speed of up to 20 ms. This result makes it possible to build new devices. Since in the well-known developments, it was only said about determining the magnitude of current in a steady state. When building relay protection devices on reed switches, without using current transformers, it will be possible to build backup protections that duplicate not only the devices themselves, but also the primary measuring transformers with other sensitive elements. This will improve the reliability of the power supply

Keywords: relay protection, reed switch, microprocessor, surge current, time measurement, magnetic field, transient

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DETERMINATION OF THE MAGNITUDE OF SHORT-CIRCUIT SURGE CURRENT FOR THE CONSTRUCTION OF RELAY PROTECTION ON REED SWITCHES AND MICROPROCESSORS

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1. Introduction

At international conferences of the CIGRE European Committee over the past 15 years, the relevance of the development of relay protection that does not use information from current transformers has been repeatedly noted. One of the reasons is increased reliability. At this stage, only current transformers are used to measure the primary current to improve reliability in duplication and majorization. These developments will make it possible to duplicate not only relay protection devices, but also primary sensitive elements – current transformers. Some studies have shown that one of the possible ways to solve the problem is to build relay protection on reed switches, which in some properties are superior to other magnetically sensitive elements. Recently proposed methods of obtaining information with the help of reed switches and a microprocessor make it possible to determine the magnitude of current in the steady-state short-circuit mode, but its magnitude in transient modes remains unknown. Therefore, studies that are devoted to testing the performance of the method for determining the magnitude of shock current using reed switches and a microprocessor, modernizing it to reduce errors, deriving the dependence of the behavior of reed switches on the acting magnetic field in the presence of an aperiodic component and experimental confirmation will determine the possibility of identifying the value of shock current using reed switches and microprocessor.

2. Literature review and problem statement

Relay protection is necessary to identify and disconnect elements of the electric power system in emergency situations. Relay protection devices receive primary information from measuring transformers [1]. Instrument transformers, in particular current transformers, are necessary to obtain information about the primary current (magnitude, phase, etc.) [2]. However, current transformers are prone to saturation [3], which can cause difficulties in the implementation of protection functions [4]. Current transformers, due to the presence of iron cores, are very metal intensive [5]. Errors in transient modes can also occur [6]. Due to the above-mentioned shortcomings, the question was raised [7] about the development of relay protection without the use of measuring transformers. Including at international conferences of the CIGRE European Committee [8]. This issue was called one of the unresolved issues in the global energy sector. An alternative can be magnetic current transformers, Rogowski coils [9], Hall sensors, etc. Magnetic current transformers do not need a ferro- or ferrimagnetic core and thus do not suffer from magnetic saturation, hysteresis, and other magnetic nonlinearities. The new current sensor concept using a circular array (Kelvin-Stokes arrays) has two major drawbacks. The first drawback is the limited frequency response due to the limited bandwidth of the sensors used for the array. The second drawback is the temperature drift of the sensitivity of the circular sensor array, caused by the temperature drift of the individual sensors used for the array [10]. The design and testing process of PCB Rogowski-coil transducer and electronic circuit shows the linearity and error rates of PCB Rogowski-coil current sensors [9]. There is a DC offset voltage of about 2.5 V existing in Hall integrated circuits and the thermal drift phenomenon of this DC offset may arise due to ambient temperature. Both are factors affecting the accuracy of the Hall-effect current transformer [5].

All of them have advantages and disadvantages. Having analyzed the characteristics of alternatives to current transformers, we chose a reed switch for the research and construction of relay protection devices [11]. Since, unlike other sensitive elements, when using reed switches, control circuits are used, and not measurement circuits, which has a positive effect in the form of the absence of interference.

In the well-known works [11, 12], the construction of relay protection devices on reed switches, solutions concern only the steady state. This severely limits the application of the proposed solutions. Since when a short circuit (SC) occurs, there is a transient process, the current may not be sinusoidal, since there will be an aperiodic component in it. Hence the task in solving the problem is how to determine short-circuit surge current using reed switches. A known method for determining the aperiodic component of short-circuit current using reed switches is given in [13]. However, no research has been conducted on it. There is no information on the operability of the method described in [13]. Determination of the magnitude of surge current using reed switches and a microprocessor without using information from measuring current transformers will make it possible to build new full-fledged resource-saving relay protection devices, which in the future will make it possible to provide redundancy not only for the relay protection devices themselves, but also for primary measuring devices operating on another principle.

3. The aim and objectives of the study

The aim of the study is to determine the magnitude of surge current using reed switches and a microprocessor without using information from measuring current transformers.

To achieve the aim, the following objectives were set:

– to consider the well-known method of measuring short-circuit current using reed switches;

– to derive, based on the well-known method of measuring short-circuit current, formulas for determining surge current using reed switches;

– to determine the error and speed of the proposed solution for determining shock current using reed switches and a microprocessor.

4. Materials and research methods

To solve the first problem, the basic provisions of the theoretical foundations of electrical engineering, electromagnetic transient processes, electronics and relay protection are used. The basics of the Biot-Savart-Laplace law are also used.

To solve the second problem, a method was used to transform formulas using rules and laws.

To solve the third problem, the basic provisions of mathematical and physical modeling, as well as a full-scale experiment were used. The simulation was carried out by constructing a time-varying sinusoid of current and the reaction of the reed switch contacts to the magnetic field created by the alternating current. During the experiment, the following equipment was used: UNI-T UPO3254E oscilloscope; AC voltage source Matrix APS 6100.

5. Results of research to determine the magnitude of surge current using reed switches and a microprocessor

5. 1. Method for determining the total short-circuit current

A known method for measuring short-circuit current is given in [14], in which the time t_1 between the moments of closing and opening the contacts of the first reed switch, the time $t_{1,2}$ between the closure of the contacts of the first and second reed switches and the time t_3 between the moments of closing and opening the contacts of the second reed switch are recorded. The first and second reed switches are located in the magnetic field of the conductor so that they close the contacts at the corresponding operating currents I_{cl1} and I_{cl2} in the conductor and open the contacts at the return currents I_{br1} and I_{br2}. The second reed switch is configured so that it closes the contacts at the pickup currents $I_{cl2}>I_{cl1}$ and returns at the return currents $I_{br2}>I_{br1}$. Equations are derived for I_{cl1}, I_{cl2}, I_{br1} and I_{br2} according to the formula:

$$I_{full} = I_m \cdot \sin\left(\omega \cdot t - \varphi_n\right) + i_{ma} \cdot e^{-\frac{t}{T_a}}, \tag{1}$$

where I_m is the amplitude of the periodic component of the measured current;

t is any moment in time;

φ_n is the electrical angle, counted from the moment of the onset of short circuit until the moment the periodic component of the measured short-circuit current passes through zero;

i_{ma} is the initial value of the aperiodic component of the measured current;

ω is the angular frequency of the current;

T_a is a time constant, using t_1, $t_{1,2}$, t_3. The amplitude of the periodic component I_m and the initial value of the aperiodic component i_{ma} of the measured current are found from a system consisting of four equations. The formula (1) determines the total short-circuit current I_{full} at any time [13].

The time required to determine the current components in this method is up to 0.02 seconds from the onset of short circuit (SC), because the calculation begins to work after the first reed switch opens, and if present $i_{ma}=I_m$, the first half-wave can reach the duration of the period.

With the aim of increasing the speed, by using information only about the operating currents, a method for measuring short-circuit current was developed [14]. It records the time $t_{1,2}$ between the closure of the contacts of the first and second reed switches, which are located in the magnetic field of the conductor so that they close the contacts at the corresponding operating currents I_{cl1}, I_{cl2} in the conductor. The second reed switch is set so that it closes the contacts at the operating current $I_{cl2}>I_{cl1}$, equations are drawn up for I_{cl1}, I_{cl2}, using $t_{1,2}$, and the amplitude of the total short-circuit current is determined using formula (1). The method differs in that four reed switches are used, which are installed at safe distances h_1, h_2, h_3, h_4 from the conductor. The angle between the perpendicular line of the longitudinal axis of the conductor and the longitudinal axis of the first reed switch, the second, third and fourth reed switches is 90°. The reed switches are configured so that they are triggered at the pickup currents $I_{CL4}>I_{CL3}>I_{cl2}$. Additionally, the times between the closure of the second and third reed switches, the third and fourth reed switches are measured and the amplitude of the periodic component I_m and the initial value of the aperiodic component i_{ma} of the measured current from the system are determined [14]:

$$\begin{cases} I_{cl1} = I_m \cdot \sin(\omega \cdot t_n - \varphi_n) + i_{ma} \cdot e^{-\frac{t_n}{T_a}}, \\ I_{cl2} = I_m \cdot \sin(\omega \cdot (t_n + t_{1,2}) - \varphi_n) + i_{ma} \cdot e^{-\frac{(t_n+t_{1,2})}{T_a}}, \\ I_{cl3} = I_m \cdot \sin(\omega \cdot (t_n + t_{1,2} + t_{2,3}) - \varphi_n) + \\ +i_{ma} \cdot e^{-\frac{(t_n+t_{1,2}+t_{2,3})}{T_a}}, \\ I_{cl4} = I_m \cdot \sin(\omega \cdot (t_n + t_{1,2} + t_{2,3} + t_{3,4}) - \varphi_n) + \\ +i_{ma} \cdot e^{-\frac{(t_n+t_{1,2}+t_{2,3}+t_{3,4})}{T_a}}, \end{cases} \tag{2}$$

where $t_{1,2}$ is the time between the closure of the contacts of the first and second reed switches;

$t_{2,3}$ is the time between the closure of the contacts of the second and third reed switches;

$t_{3,4}$ is the time between the closure of the contacts of the third and fourth reed switches;

t_n is the time until the contacts of the first reed switch are closed;

I_{cl1} – actuation current of the first reed switch;

I_{cl2} – actuation current of the second reed switch;

I_{cl3} – actuation current of the third reed switch;

I_{cl4} – actuation current of the fourth reed switch.

Then the amplitude of the total short-circuit current I_{full} is determined using its periodic and aperiodic components [14].

However, in laboratory conditions, it was confirmed that the operating current I_{cl} of the reed switch changes depending on the magnitude of the acting magnetic field induction created by the current in the IC or in the conductor. In Fig. 1, the dependences of the change in the MC operating current on the multiplicity $K=I_{SC}/(K_{tr}*I_{clK})$ of short-circuit current (SC) are presented. Therefore, the trip currents cannot be used when determining the periodic and aperiodic components of short-circuit current.

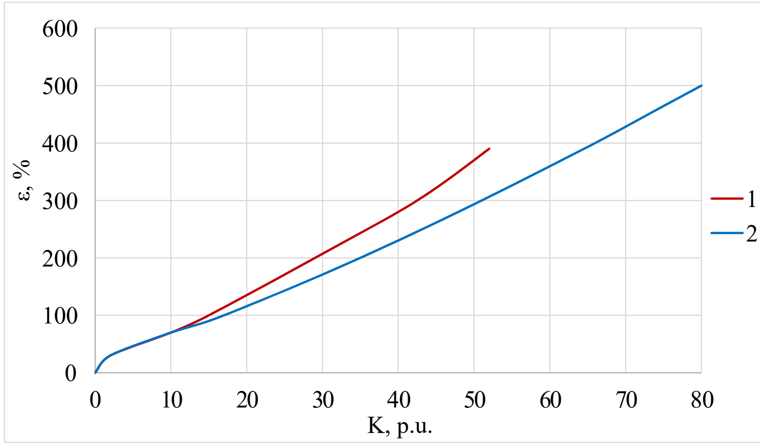

Fig. 1. $\varepsilon_{1cl}=f(K)$: 1 – KEM3; 2 – KEM2

$$\varepsilon = \frac{\left|I^n_{clK} - I_{clK}\right|}{I^n_{clK}} \cdot 100\,\%, \tag{3}$$

where ε – percentage of change in the operating current, %;

I_{clK} – minimum reed switch actuation current, i. e. when $I_{mK}/I_{clK}=1$ (I_{mK} – amplitude of the alternating current in the coil);

I^n_{clK} – operating current in n-measurement with increasing current to I^n_{mK}.

In the developed method [14], the actuation currents of the reed switches are replaced by the return currents. In this case, it is necessary to comply with the condition $I_{BR4}<I_{BR3}<I_{BR2}<I_{BR1}$ and measure the time between their returns. System (2) takes the following form

$$\begin{cases} I_{br1} = I_m \cdot \sin(\omega \cdot t_n - \varphi_n) + i_{ma} \cdot e^{-\frac{t_n}{T_a}}, \\ I_{br2} = I_m \cdot \sin(\omega \cdot (t_n + t_{1,2}) - \varphi_n) + i_{ma} \cdot e^{-\frac{(t_n+t_{1,2})}{T_a}}, \\ I_{br3} = I_m \cdot \sin(\omega \cdot (t_n + t_{1,2} + t_{2,3}) - \varphi_n) + \\ +i_{ma} \cdot e^{-\frac{(t_n+t_{1,2}+t_{2,3})}{T_a}}, \\ I_{br4} = I_m \cdot \sin(\omega \cdot (t_n + t_{1,2} + t_{2,3} + t_{3,4}) - \varphi_n) + \\ +i_{ma} \cdot e^{-\frac{(t_n+t_{1,2}+t_{2,3}+t_{3,4})}{T_a}}, \end{cases} \tag{4}$$

where $t_{1,2}$ – time between the opening of the contacts of the first and second reed switches;

$t_{2,3}$ – time between the opening of the contacts of the second and third reed switches;

$t_{3,4}$ – time between the opening of the contacts of the third and fourth reed switches;

t_n – time until the opening of the contacts of the first reed switch;

I_{BR1} – return current of the first reed switch;

I_{BR2} – return current of the second reed switch;

I_{BR3} – return current of the third reed switch;

I_{BR4} – return current of the fourth reed switch.

The use of reed switch return currents, which are constant values for one design point of the reed switch installation at different multiplicities K, makes it possible to calculate an increase in the accuracy of determining the value of the total short-circuit current.

5. 2. Derivation of formulas for determining impulse current using reed switches

Derivation of formulas for the methodology for calculating short-circuit surge current SC. The calculation is carried out as follows. From the system of formulas (4), the second equation is divided by the first; $\sin(\omega\cdot t_n-\varphi_n+\omega\cdot t_{1,2})$ is decomposed into $\sin(\omega\cdot t_n-\varphi_n)\cdot\cos\omega\cdot t_{1,2}+\cos(\omega\cdot t_n-\varphi_n)\cdot\sin\omega\cdot t_{1,2}$. $e^{-\frac{t_n+t_{1,2}}{T_a}}$ is presented as $-\frac{t_n}{e^{T_a}}\cdot\frac{t_{1,2}}{e^{T_a}}$, while it is reduced to $i_{ma}\cdot e^{\frac{t_n}{T_a}}$ and the equation takes the form:

$$I_{br2}-I_m\cdot\begin{pmatrix}\sin(\omega\cdot t_n-\phi_n)\cdot\cos(\omega\cdot t_{1,2})+\\+\cos(\omega\cdot t_n-\phi_n)\cdot\sin(\omega\cdot t_{1,2})\end{pmatrix}=$$

$$=e^{-\frac{t_{1,2}}{T_a}}\cdot\left(I_{br1}-I_m\cdot\sin(\omega\cdot t_n-\phi_n)\right). \quad (5)$$

The brackets are opened, the arguments containing the amplitude of the periodic component of the measured current I_m are transferred to the right side of the equation, and $I_{br1}\cdot e^{-\frac{t_{1,2}}{T_a}}$ – to the left. On the right-hand side of equation (5), the argument $I_m\cdot\sin(\omega\cdot t_n-\varphi_n)$ is placed outside the bracket:

$$I_{br1}\cdot e^{-\frac{t_{1,2}}{T_a}}-I_{br1}=I_m\cdot\sin(\omega\cdot t_n-\varphi_n)\times$$

$$\times\left(e^{-\frac{t_{1,2}}{T_a}}-\mathrm{ctg}(\omega\cdot t_n-\varphi_n)\cdot\sin(\omega\cdot t_{1,2})-\cos(\omega\cdot t_{1,2})\right). \quad (6)$$

For the third and fourth equations of the system (4), operations similar to (5)–(7) are performed. The result is:

$$I_{br3}\cdot e^{-\frac{t_{1,4}}{T_a}}-I_{br4}=I_m\cdot\sin(\omega\cdot t_n-\varphi_n)\times$$

$$\times\left[\begin{matrix}\cos\begin{pmatrix}\omega(t_{1,2}+t_{2,3})\cdot e^{-\frac{t_{1,2}}{T_a}}+\\+\mathrm{ctg}(\omega\cdot t_n-\varphi_n)\cdot\sin(\omega\cdot t_n-\varphi_n)\end{pmatrix}\times e^{-\frac{t_{1,2}}{T_a}}-\cos\left(\omega\left(t_{1,2}+t_{3,4}+t_{2,3}\right)\right)-\\-\mathrm{ctg}(\omega\cdot t_n-\varphi_n)\cdot\sin\left(\omega\left(t_{1,2}+t_{2,3}+t_{3,4}\right)\right)\end{matrix}\right]. \quad (7)$$

Further, equation (7) is divided by (6), $\sin(\omega\cdot t_n-\varphi_n)$ canceled, is determined by $\mathrm{ctg}(\omega\cdot t_n-\varphi_n)$:

$$\mathrm{ctg}(\omega\cdot t_n-\varphi_n)=$$

$$=\frac{\left(I_{br1}\cdot e^{-\frac{t_{1,2}}{T_a}}-I_{br2}\right)\cdot\cos\left(\omega(t_{1,2}+t_{2,3})\right)\cdot e^{-\frac{t_{3,4}}{T_a}}-\left(I_{br1}\cdot e^{-\frac{t_{1,2}}{T_a}}-I_{br2}\right)\cdot\cos\left(\omega(t_{1,2}+t_{2,3}+t_{3,4})\right)-\left(I_{br3}\cdot e^{-\frac{t_{3,4}}{T_a}}-I_{B4}\right)\cdot e^{-\frac{t_{1,2}}{T_a}}}{\left(I_{br1}\cdot e^{-\frac{t_{1,2}}{T_a}}-I_{br2}\right)\cdot\sin\left(\omega(t_{1,2}+t_{2,3}+t_{3,4})\right)-\left(I_{br3}\cdot e^{-\frac{t_{3,4}}{T_a}}-I_{B4}\right)\cdot\sin(\omega\cdot t_{1,2})-\left(I_{br1}\cdot e^{-\frac{t_{1,2}}{T_a}}-I_{br2}\right)\cdot\sin\left(\omega(t_{1,2}+t_{2,3})\right)\cdot e^{-\frac{t_{3,4}}{T_a}}}+$$

$$+\frac{\left(I_{br3}\cdot e^{-\frac{t_{3,4}}{T_a}}-I_{br4}\right)\cdot\cos(\omega\cdot t_{1,2})}{\left(I_{br1}\cdot e^{-\frac{t_{1,2}}{T_a}}-I_{br2}\right)\cdot\sin\left(\omega(t_{1,2}+t_{2,3}+t_{3,4})\right)-\left(I_{br3}\cdot e^{-\frac{t_{3,4}}{T_a}}-I_{B4}\right)\cdot\sin(\omega\cdot t_{1,2})-\left(I_{br1}\cdot e^{-\frac{t_{1,2}}{T_a}}-I_{br2}\right)\cdot\sin\left(\omega(t_{1,2}+t_{2,3})\right)\cdot e^{-\frac{t_{3,4}}{T_a}}}, \quad (8)$$

and is:

$$\sin(\omega\cdot t_n-\varphi_n)=\sqrt{\frac{1}{1+\mathrm{ctg}^2(\omega\cdot t_n-\varphi_n)}}=0.48708\ \text{rad}. \quad (9)$$

Then the amplitude of the periodic component of the measured current is determined I_m:

$$I_m=$$

$$=\frac{I_{br1}\cdot e^{-\frac{t_{1,2}}{T_a}}-I_{br2}}{\sqrt{\frac{1}{1+\mathrm{ctg}^2(\omega\cdot t_n-\varphi_n)}}\cdot\left(e^{-\frac{t_{1,2}}{T_a}}-\cos(\omega\cdot t_{1,2})-\mathrm{ctg}(\omega\cdot t_n-\varphi_n)\cdot\sin\omega t_{1,2}\right)}=$$

$$=75.006\ \text{A}. \quad (10)$$

Find the instantaneous value of the periodic component of the current I_M at point M (Fig. 3):

$$I_M=I_M\cdot\sin(\omega\cdot t_n-\varphi_n)=36.53\ \text{A}, \quad (11)$$

and the instantaneous value of the aperiodic current component i_N at point N:

$$i_N=i_{ma}\cdot e^{-\frac{t_n}{T_a}}=I_{br1}-I_m\cdot\sin(\omega\cdot t_n-\varphi_n). \quad (12)$$

To find the initial value i_{ma} of the aperiodic component of the measured current in equation (12) at the moment when the periodic component of the measured current I_m passes zero $\varphi_n=0$ is taken, then $\omega t_n=\varphi_1$ and $\varphi_1=\arcsin(I_M/I_m)$, which are substituted into the formula (12) and are determined:

$$i_{ma}=\frac{i_N}{\exp\left(-\frac{\arcsin(I_M/I_m)}{T_a}\right)}=$$

$$=\frac{I_{br1}-I_m\cdot\sin(\omega\cdot t_n-\varphi_n)}{\exp\left(-\frac{\arcsin(I_M/I_m)}{\omega T_a}\right)}=64.76\ \text{A}. \quad (13)$$

Taking this value as the amplitude of the aperiodic component at the transition of the total short-circuit current through zero at $\varphi_n=0$, a curve of the aperiodic component of the measured current is constructed (Fig. 3, curve 3). Based on the data obtained, the curve of the total short-circuit current I_{full} (Fig. 3, curve 1) is plotted at any time according to the formula:

$$I_{full}=I_m\cdot\sin(\omega\cdot t-\varphi_n)+i_{ma}\cdot e^{-\frac{t}{T_a}}. \quad (14)$$

The magnitude of shock current occurs in 0.01 seconds after the occurrence of short circuit. Therefore, substituting the primary data into the formulas for determining the periodic and aperiodic components, the value of shock current is obtained. $I'_{Mfull}=146$ A. In this case, the actual I_{fullF} value was 141 A. Thus, the determination error was

$$e=\frac{I_{fullf}-I_{fullf}}{I_{fullf}}*100\,\%=$$

$$=\frac{|141-146|}{141}*100\,\%=3.5\,\%. \qquad (15)$$

The resulting value shows the level of error in determining the magnitude of shock current using 4 reed switches according to the proposed method.

5. 3. Determination of the error and speed of the proposed solution for determining shock current using reed switches and a microprocessor

Fig. 2 shows a device for implementing the proposed method.

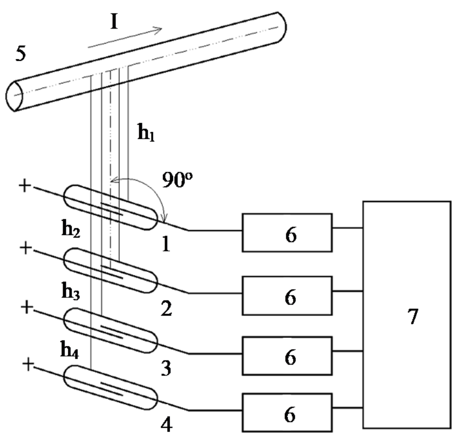

Fig. 2. A device that implements the method

Fig. 3 shows the dependences $I=f(\mathrm{t})$, where curve 1 is the total short-circuit current I_{full}, curve 2 is the rated current I_{nom}, curve 3 is the current of the aperiodic component I_{ma}, and curve 4 is the current of the periodic component I_m.

The method for determining the magnitude of short-circuit surge current can be implemented using a device in which the first 1, second 2, third 3 and fourth 4 reed switches (Fig. 2) with normally open contacts are placed in the magnetic field of the conductor 5 with current and are connected through anti-bounce circuits 6 to the microcontroller 7 (MC).

Reed switches type MKA14103 group A manufactured by Ryazan Metal Ceramics Instrumentation Plant JSC, 6 – well-known anti-bounce circuits, microcontroller 7 (MC), for example, ATMega 328p can be used.

Implementation of the method. The first 1, second 2, third 3 and fourth 4 reed switches with normally open contacts are installed near conductor 5 at a safe distance. The distance from conductor 5 to the first 1 reed switch h_1=0.1 m, the distance from conductor 5 to the second 2 reed switch h_2=0.13 m, the distance from conductor 5 to the third 3 reed switch h_3=0.16 m, the distance from conductor 5 to the fourth 4 reed switch h_4=0.19 m. The angle between the perpendicular line of the longitudinal axis of the conductor 5 and the longitudinal axes of the first reed switch 1, the second 2, the third 3 and the fourth 4 reed switches is 90°. The reed switches are selected so that the return currents I_{BR1}, I_{BR2}, I_{BR3}, I_{BR4} of the first 1, second 2, third 3 and fourth 4 reed switches correspond to inequalities

$$I_{BR1}>I_{BR2}>I_{BR3}>I_{BR4}. \qquad (16)$$

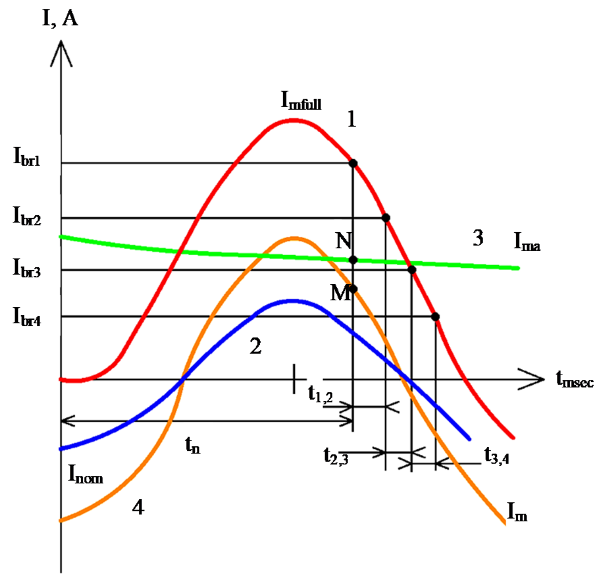

Fig. 3. Change of the shape of the determined short-circuit current (SC) in time

Short-circuit current flows in conductor 5. With an increase in the current, the reed switches are triggered, after reaching the maximum value, it decreases. When the value drops to the return current I_{BR1}=100 A of the first reed switch 1 (Fig. 3, curve 1), the previously closed contacts open. This occurs under the action of the return of the magnetic field created by the current I_{BR1} with the return intensity H_{br1} in the gap between the contacts of the first reed switch 1, directed along its longitudinal axis. The second reed switch 2 opens the contacts at the return current I_{BR2}=75 A. Reed switch 3 opens the contacts at the return current I_{BR3}=50 A. Reed switch 4 opens the contacts at the return current I_{BR4}=25 A.

With an increase in the current in conductor 5, the reed switches are triggered. If one of the reed switches did not work due to insufficient current in the conductor, then the microcontroller does not perform any calculations.

But if the current in conductor 5 is sufficient to trigger all four reed switches, then when the current in the primary circuit begins to decrease and the contacts of the first reed switch open, the microcontroller records this moment and starts a timer, after the contacts of the second reed switch open, the microcontroller records this moment, stops the timer, saves the time as $t_{1,2}$=1.091 msec (according to Fig. 3, curve 1) and starts the second timer. The microcontroller detects the moment of opening the contacts of the third reed switch, stops the second timer, saves the time as $t_{2,3}$=1.032 ms and starts the third timer. When the contacts of the fourth reed switch are opened, the microcontroller records this moment, stops the third timer and saves the time as $t_{3,4}$=1.089 ms.

In the microcontroller 10 (MC), the values of I_m and i_{ma} are calculated according to the formulas for decomposing short-circuit current into aperiodic (Fig. 3, curve 3) and periodic components (Fig. 3, curve 4) [25]. Then the total short-circuit current I_{full} is determined for any moment of time according to the well-known formula (1) [15].

Validation of formulas and errors. To check the efficiency of the method and the correctness of the formulas derived by solving the system of equations (4), mathematical modeling was carried out to determine the magnitude of the total short-circuit shock current SC [16]. For this, using MS Excel, the short-circuit current of an electrical installation with the presence of an aperiodic component was simulated.

Table 1 shows the measurement data when simulating the return currents and the time intervals between them. The last four columns show the calculated values of the periodic and aperiodic components of short-circuit current, the magnitude of shock current and the error in determining the magnitude of short-circuit shock current SC, respectively.

Table 1

Results of calculations of simulated measurements

I_{br1}, A	I_{br2}, A	I_{br3}, A	I_{br4}, A	t_{12}, sec	t_{23}, sec	t_{34}, sec	I_m, A	I_{ma}, A	I_{full}, A	ε, %
100	75	50	25	0.001091	0.001032	0.001089	75.0	64.7	139.7	4.2
110	80	60	40	0.001372	0.000828	0.000834	75.0	65.4	140.5	3.7
120	110	100	90	0.000555	0.00049	0.000452	75.0	66.3	141.4	3.1
110	90	70	50	0.000942	0.000847	0.000824	75.0	65.5	140.5	3.7
125	75	60	20	0.002455	0.000619	0.00174	75.0	66.9	142	2.7
130	120	40	35	0.000686	0.003589	0.000217	74.8	67.7	142.6	2.3

Fig. 4 presents a setup for an experimental study of the method for determining the magnitude of short-circuit surge current.

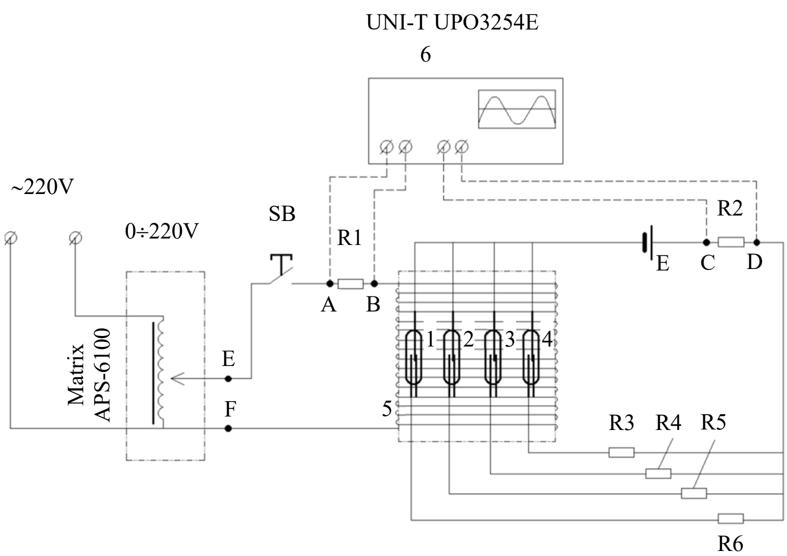

Fig. 4. Laboratory setup for creating current with an aperiodic component

Regulated AC voltage source Matrix APS6100 is connected to the mains supply, with its help the value of the flowing current in the laboratory installation is regulated. Four reed switches 1, 2, 3 and 4 are installed in the inductor 5, which is made of the winding of a power transformer with a window size of 100×150 mm, the cross-section of the winding wire is 0.5 mm^2. Matrix APS6100 is connected to the network and the required voltage is set at its output [16]. Then the circuit is closed using the SB button, and current is supplied to inductor 5. Moreover, due to the small active and large inductive resistance, the first half-waves are not sinusoidal, since there is an aperiodic component. The shape of the flowing current, as well as the values of the components, were determined using a UNI-T UPO3254E oscilloscope connected by the first channel to the resistor R1. Reed switches 1–4 with seriesconnected resistances R6, R5, R4 and R3 to their closing contacts, respectively, are connected in parallel with the circuit section, which consists of a constant voltage source and resistance R2. Dropouts of the reed switch contacts are monitored using the second channel of the oscilloscope connected to resistor R2. Also, the number of oscilloscope channels allows you to track the operation and return of the reed switches directly on the resistors R6, R5, R4 and R3.

Fig. 5 presents a block diagram of the device to implement the method and determine the magnitude of short-circuit surge current SC.

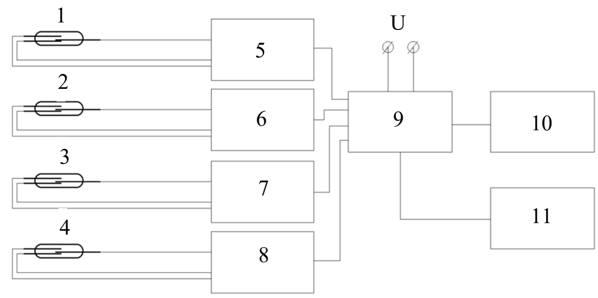

Fig. 5. Microprocessor device for determining the magnitude of short-circuit surge current SC

Reed switches 1–4 are fixed at a safe distance from the current conductor, anti-bounce circuits 5–8 are connected to the contacts of the reed switches, which are connected to the microprocessor 9. To display information, a display 10 is provided, as well as an output relay 11, the contacts of which can be connected either to the blinker, or into the circuit of the circuit breaker tripping coil.

Table 2 shows the results of calculating the values of shock current during experimental measurements carried out on a laboratory installation (Fig. 4). In this case, errors in the installation of the reed switches themselves were not taken into account.

The table shows the known values of the reed switch return currents (1–4 columns), the measured times between the reed switch return moments (5–7 columns), the calculated values of the currents (8–10 columns) and the error in determining the magnitude of surge current.

Table 2

Results of calculation of experimental measurements

I_{br1}, mA	I_{br2}, mA	I_{br3}, mA	I_{br4}, mA	t_{12}, sec	t_{23}, sec	t_{34}, sec	I_m, mA	I_{ma}, mA	I_{full}, mA	ε, %
570	440	320	190	0.000415	0.000405	0.000409	963.8	339.8	1303.7	8.8
255	190	130	72	0.000405	0.000401	0.00039	518.9	127.2	646.2	10.2

6. Discussion of experimental results on determining shock current using reed switches and a microprocessor

As a result of checking the method for determining the magnitude of surge current using reed switches and a microprocessor without using information from measuring current transformers, the actuation currents of the reed switches were replaced with return currents (4). This is due to a certain error, which was introduced due to varying operating currents (Fig. 1).

The change in the values of operating currents can be explained by the physics of the ongoing process, since it is necessary to close the contacts, from the moment of starting until the moment of closing.

The proposed version of calculations made it possible to obtain the magnitude of shock current using reed switches with a reduced error (Table 1).

The use of return currents reduces the error, but increases the time for determining surge current due to the fact that the determination occurs in the second half of the half-wave. Whereas when using operating currents, the determination occurs in the first half-wave of the alternating current.

To test the proposed method, a setup was assembled that allows simulating transient current (Fig. 4).

It is important to use reed switches with a trigger life of about 10^{12} times. An important step is testing the reed switch to change its parameters during operation. Experiments have shown that from a batch of 20 pieces, one reed switch comes across unusable.

During the research, it was possible to create a limited current multiplicity, which affects the reed switches. This limitation is related to the power supply capacity. It is necessary to continue this study at multiples up to 60–80. The limitation of the study is that only one type of reed switch was tested.

The next stage of the research is to plan the creation of an algorithm for the operation of the device on a reed switch and microprocessor and experimental testing.

7. Conclusions

1. When considering the method for determining surge current using reed switches, it was found that the use of the values of operating currents would not provide high accuracy, due to the instability of this value. They can increase up to 500 % of the original value. To improve the accuracy and reduce the error, the values of reed switch return currents were chosen.

2. The derived formulas based on the well-known method of measuring short-circuit current of the formulas for determining impulse current using reed switches made it possible to obtain a step-by-step calculation for determining surge current using reed switches.

3. As a result of the simulation, the correctness of the calculation formulas was confirmed. The error was determined (only I_{fullF} was replaced by $I_{full\mathrm{M}}$, used in modeling and I_{full} by the calculated theoretical I_{fullR}) and ranged from 2 to 4.5 %. Errors in determining the magnitude of short-circuit shock current using four reed switches during experimental measurements in the assembled installation were 8–10 %. The proposed method for determining short-circuit surge current SC in the primary circuit using four reed switches located near the current-carrying buses of the electrical installation and a microprocessor makes it possible to determine its value with an error of ≤15 %. When implemented on a microprocessor, the response time will be 20 ms.

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