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REVIEW

Wide-Range Inductive Sensors of Currents with Nanosecond Rise Times for Measuring Parameters of High-Current Pulses (Review)

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Abstract—The design and characteristics of inductive current sensors (modernized Rogovski coils) and inductive sensors on their basis (in the form of a part of a tore) with shielded coils for measuring the parameters of pulse currents in conductors with diameters of up to 1.7 m and electron beam currents of 10–2000 kA with durations of 10–100 ns in a self-integration mode. The Rogovski coils and sensors have current rise times of nanosecond duration and improved noise immunity and mechanical strength. Methods for the calibration of Rogovski coils for determining their transient response and amplitude sensitivity are presented. Specific features of the certification of large-diameter devices are pointed out, and a new method for certifying such sensors is expounded. The sensors are used in experimental investigations and the refinement of units of high-current linear induction accelerators as well is in the starting and adjustment work with a high-power LIA-30 electron accelerator with water-insulated radial lines in the inductors of accelerating modules and for monitoring its parameters (40 MeV, 100 kA, 20 ns). Such sensors are applicable for recording pulse current characteristics in other electrophysical facilities.

INTRODUCTION

The development, experimental investigation, and subsequent application of high-power electrophysical installations with a stored energy of hundreds of kilojoules and higher require measurements of pulse current parameters (amplitude, shape, durations of pulses, rise times, and edges) in numerous units. The pulse amplitudes and durations range from several kiloamperes to tens of megaamperes and from a few nanoseconds to tens of microseconds (and longer), respectively. The current monitoring is complicated in multimodule large-size facilities with electric systems separated by long distances and operating in a strictly specified time sequence (e.g., [1–4]). The currents in such systems should be monitored in tens and hundreds of extended channels whose cable lines often intercross, forming complex loops.

Some signals from measuring circuits arrive at oscilloscopic recorders or, via appropriate analog-to-digital converters (ADCs), to a PC that stores, analyzes, and yields information. Some signals are used to trigger the control instrumentation or other instruments functionally associated with these circuits; the signals are taken off the current sensors in units of the systems enabled earlier.

In order to prevent the untimely triggering of instruments, it is necessary to have signals at the outputs of the measuring channels with profiles and durations most identical to the parameters of actual current pulses. In addition, nondistorted signals simplify the interpretation of the experimental results.

In high-power electrophysical installations, spark gaps are most frequently used as high-current switches of electric energy storages and, when operating, produce significant scattered high-frequency electromagnetic fields. The latter, together with pulse fields produced by high currents flowing through spatially separated conductors, may induce noises in elements of measuring circuits and substantially distort the profiles and amplitudes of valid signals.

As a rule, primary current sensors are most sensitive to scattered fields; therefore, these sensors are developed taking into account the requirements of increased noise immunity.

An example of such a powerful multimodule large-size facility is an iron-free (without ferromagnetic cores) LIA-30 linear induction electron accelerator with water-insulated radial lines in inductors. It has the maximum acceleration energy for this type of facilities (40 MeV, 100 kA, 25 ns) and the highest bremsstrahlung dose (100 Gy/pulse) at a distance of 1 m from the target [5–8].

The first element operating in LIA-30 is a capacitor bank with an energy capacity of 6.25 MJ. Its total current with an amplitude of 1.5 MA and a rise time of 0.75 ms flowing through solenoids excites a longitudinal magnetic field with an induction of 0.5 T in the beam acceleration and transmission channel ~30 m

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long. The sequence of successively enabled systems is as follows: a part of the high-voltage synchronization system with a current of ~100 kA and ~30-ns duration triggering 72 Marx generators, which charge 288 radial lines by a total current of ~5 MA up to a voltage of 500 kV for 0.85 μs; the other part yielding a current of ~0.6 MA and triggering 144 inductors with a total switching current of ~250 MA and ~25-ns duration; and the inductors generating an electric field for acceleration of an electron beam (~100 kA and ~25 ns).

LIA-30 also includes the following components: an automated control and monitoring system; several high-power rectifiers (5–100 kV) with switching and distributing equipment; systems for measuring the characteristics of bremsstrahlung fields and photoneutron fluxes; a large number of oscilloscopic recorders of various types; vacuum, water-preparation, oil-purification systems, and a system for filling the accelerator units with a gas; and a PC-based data acquisition, processing, and storage system for the analysis of the results of LIA-30 operation and experiments performed on it.

It is obvious that, when designing the units of the LIA-30 accelerator and experimentally studying its characteristics (its systems consume high currents and energies, are connected by numerous electric circuits, and spatially separated by long distances) and for controlling the joint operation of different systems of this facility, the devices and channels for measuring a large number of high pulse voltages and currents were developed with provision of measures for reducing the voltages and currents induced in cable lines [9].

This concerned the primary sensors to the highest degree, since they are most sensitive to scattered electromagnetic fields. Measurements of current parameters require sensors for duration ranges of ~1–1000 μs and 10–100 ns. Sensors designed for shorter pulse durations can reproduce pulse shapes with high accuracy and stability, but they are simultaneously very sensitive to noise. Moreover, a number of requirements are imposed on these sensors: the recording of pulses with amplitudes of 10–2000 kA, a nanosecond transfer characteristic, a high sensitivity ensuring an output signal amplitude of tens of volts without using any amplifiers; placement in vacuum volumes and at a gas pressure of $\geq 10^5$ Pa in narrow circular grooves of reverse current conductors ≤1.7 m in diameter; a high mechanical strength; current measurements of electron beams and conductors; long-term preservation of the electric characteristics; the possibility of calibration beyond the operating conditions; and prompt sensitivity variations without dismounting a sensor and without losing the vacuum tightness of the sensor-containing equipment.

Analyzed were the known types and designs of current sensors that could satisfy the above conditions and could be used in experimental investigations and the optimization of the developed accelerator units as well as for monitoring their operating conditions in the facility. Inductive sensors (ISs) occurred to be the most suitable devices; however, ISs ready to use in an accelerator did not exist, and they should have been developed. A Rogovski coil [10] was taken as a basic element, making it possible to galvanically isolate an IS from the circuit of the measured current and, therefore, not to form any closed circuits together with other lines and accelerator units.

An analysis has shown that, in ISs, it is expedient to use coils with independent insulated shields with narrow azimuthal slots serving as reverse conductors of the coils: this ensures subnanosecond and nanosecond signal rise times. In addition, an independent shield fully insulates an IS from a conductor with a high current directed oppositely to the measured current, making it possible to avoid the flow of this current in this shield and possibly sparking in it at contact locations. The shield reduces capacitive couplings between the coil and other conductors. As a whole, this reduces the level of spurious pickups at the IS output.

The presence of a shield ensures the IS sensitivity and transfer characteristic calibration beyond the permanent IS location and long-term maintenance of this characteristic upon the sensor displacement.

A self-integration mode of the IS operation was selected as a regime with the highest noise immunity ensuring minimal distortions of the signal profile and amplitude and, in an ideal case, reproducing the actual shape of the pulse current recorded. This mode is implemented if the relation

$$L/R >> t \tag{1}$$

is satisfied. Here, L is the inductance of the IS coil, R is the resistance of the load resistor (one of its leads is connected to one of the coil's lead, and its second lead, to the shield), and t is the current pulse duration.

In order to reduce the signal shape distortions, the electrical length t_0 of the coil (the one-way propagation time of an electromagnetic wave along all the coil's turns) must satisfy the inequality

$$2t_0 > t. \tag{2}$$

The condition $t_0 > t$ is preferable.

Below, we describe several wide-range ISs used at various stages of designing a LIA-30 accelerator, most of which are actually inventions. Methods of the experimental certification of the IS characteristics and their features for ISs with diameters of >1 m are also considered. Of course, such sensors can be used in other electrophysical facilities.

ROGOVSKI COIL WITH A PROMPTLY REPLACEABLE LOAD RESISTOR

At the initial stages of the development and experimental study of the optimal and limiting characteristics of prototypes and full-scale units of the LIA-30 accelerator, their electric parameters were controlled within wide ranges. Sensors of current pulses with durations

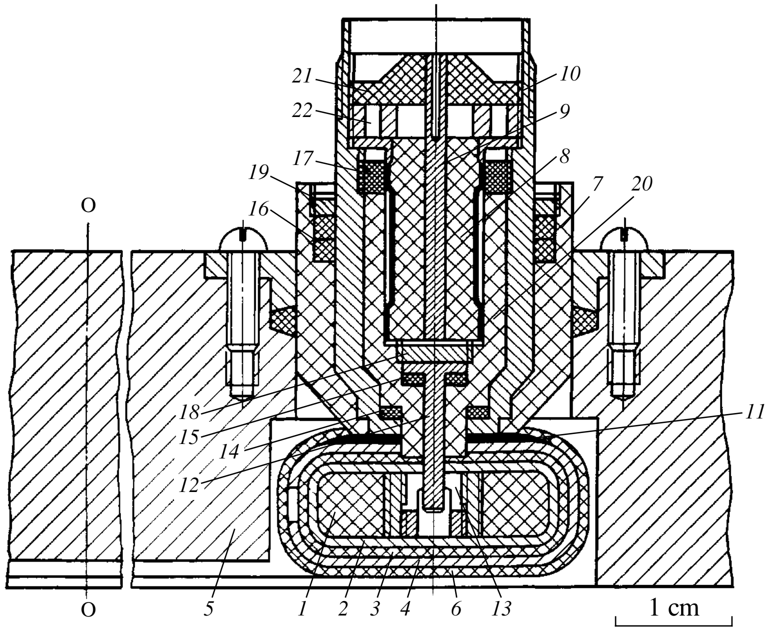

Fig. 1. Design of an RC with a load resistor unit: (*1*) core; (*2*) coil; (*3*) fluoroplastic film; (*4*) shield; (*5*) flange of the reverse conductor; (*6*) insulating film; (*7*) caprolon sleeve; (*8*) resistor; (*9*) rod; (*10*) outer tubular conductor; (*11*) figured washer; (*12*) pressing electrode; (*13*) spring jack; (*14–16*) rubber gaskets; (*17–19*) threaded parts; (*20, 21*) caprolon insulators; and (*22*) compressing nut.

of 10–100 ns and amplitudes varied by one–two orders of magnitude were necessary for the measurements. In order to have the most precise signal image on the oscilloscope screen, the IS amplitude sensitivity should be varied without dismounting the IS from the system and without losing the vacuum tightness of the unit with the measured current. These conditions significantly promote the investigations and make them less laborious.

For this purpose, an updated Rogovski coil (RC) with a low-inductance resistive load unit and a subnanosecond rise time was designed (Fig. 1). Since the RC sensitivity is proportional to the load resistance and its integration constant is inversely proportional to it, the RC design provides for the replacement of the load resistor without disassembling the RC and, consequently, the high-current device.

As is known, the design of the RC load unit, the inductances of the connections of its coil terminals with the resistor and cable lead, and the stray capacitances of the unit's elements and wires have a significant effect on the transfer characteristic, especially in the subnanosecond and nanosecond ranges. Therefore, the loading unit has such a structure that, when the resistor is replaced, the spurious inductances and capacitances retain their stable minimum values. The RCs of such a design with diameters of 100–1100 mm were used to measure currents with amplitudes of 10–700 kA, rise times of ≥3 ns, and durations of 20–100 ns [11].

A toroidal dielectric core *1* (polystyrene, organic glass, etc.) with a coil *2* and several layers of a fluoroplastic film *3* between the coil and shield *4* is located in a circular groove in the flange *5*. The shield and RC are insulated from the flange by a film *6* and dielectric caprolon sleeve *7*, which reduce signal distortions due to sparking appearing upon flow of a reverse pulse current through the shield. The latter is made of an X18H10T foil 0.3 mm thick and consists of several segments jointed by electric contact welding along the RC azimuth.

The current duration in our measurements was comparable to or shorter than the travel time of an electromagnetic wave in the RC; therefore, during winding, much attention was drawn to the pitch regularity and the uniformity of the coil characteristic impedance with respect to the shield. Together with a high resistivity of the shield material, which is the outer conductor of the coil, these measures reduce the probability of exciting parasitic microwave oscillations superimposed on the valid signal and their amplitude [12].

Resistor *8* (C2-10-2) with removed wire leads and with holes drilled in its end contacts is soldered by one contact (the lower one in Fig. 1) to rod *9*. Its upper end together with the outer tubular conductor *10*, which is coaxial to the rod, has a form of a standard CP-75-166Φ connector. Signals from this connector are transmitted via an PK-75-9-12 cable to an oscilloscope.

Conductor *10* is connected to the shield *4* via spacer *11*, which is welded to both of them. Via pressed electrode *12* and spring jack *13*, the lower contact of the resistor is connected to the end of coil *2* connected to the jack *13*. Rubber gaskets *14–16* seal the load unit when screwing down parts *17–19*. Elements *7, 17, 20*, and *21* are made of caprolon. Resistors *8* can be replaced by screwing out the central insulator *21* and

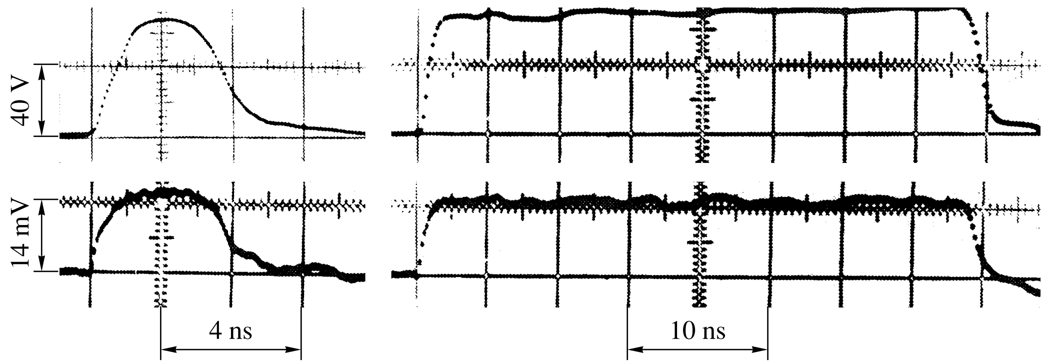

Fig. 2. Calibration current pulses (upper oscillograms) and RC signals corresponding to them (lower curves).

spring nut *22* from conductor *10*. In this case, the vacuum tightness of the volume on the side of the jack in flange *5* remains undisturbed.

A number of Rogovski coils with diameters of frames of 100–1070 mm were equipped with such loading units. Since the effect of stray inductances and capacitances of the RC elements in a transient regime, the skin effect for the current in the winding and shield, resonance effects, etc. are difficult to calculate; the RC rise time τ and sensitivity K were tested experimentally.

For this purpose, the RC was placed in a coaxial chamber with conical junctions (their wave impedances were matched) [13]. A calibration current pulse from a Г5-47 generator was applied to the input of one of these junctions. This calibration pulse was monitored by an C7-5 stroboscopic oscilloscope at the output of the second junction loaded into a matched resistance (a resistor and cable connected in parallel). The same oscilloscope recorded the RC signal.

At an outer diameter $D < 200$ mm of the RC, a flat cylindrical chamber [14] was used, and for $D > 500$ mm, the RC coil was employed as a distributed energy storage switched to the RC load by a low-impedance small-size spark gap with a solid insulation [15, 16] (see below).

As an example, Fig. 2 shows the profiles of calibration current pulses and the corresponding signals from the RC with the following parameters: the average diameter of the toroidal dielectric frame is 250 mm; the diameter of the opening is 240 mm; the area of turn cross section is 9×6 mm^2; the number of turns is 237 with a pitch of 3 mm (ЭЛ wire 0.5 mm in diameter); the coil inductance, electrical length, and wave impedance are 12.6 μH, 45 ns, and 280 Ω, respectively; and the length of the signal-transmitting PK-75-9-12 cable is ~5 m.

By measuring the rise times t_1 (calibration current pulse) and t_2 (signal) at the oscilloscope input, we determine τ from the formula

$$\tau = (t_2^2 - t_1^2 - \tau_\kappa^2 - \tau_o^2)^{0.5}, \tag{3}$$

where τ_c and τ_o are the rise times of the transmitting cable and oscilloscope, respectively. In our case, $t_2 =$ 1.4 ns, $t_1 = 1.25$ ns, $\tau_c = 0.12$ ns [17], and $\tau_o = 0.35$ ns; consequently, $\tau = 0.5$ ns. The RC sensitivity (here, $K = 1.4 \times 10^{-2}$ V/A) is determined from the amplitude of the calibration current pulse and its decay in given pulse-duration and profile ranges.

The droop of the signal top obtained in a RC calibration by a long pulse makes it possible to take into account the pulse shape change when recording an actual current pulse, because, in the current transformer mode, the equivalent active resistance between the shield and coil's end generally changes with time [18]. The average decay time constant T can be estimated by the expression

$$T = t[\ln A - \ln(A - \Delta A)]^{-1}, \tag{4}$$

where A is the RC signal amplitude and ΔA is the amplitude decrease in the time t.

As a rule, the sensitivity was refined for the RC located in the flat chamber of the coaxial storage consisting of K15-10 capacitors (50 kV, 4.7 nF), which were arranged uniformly along a circle by passing decaying sinusoidal current pulses along the RC axis. The storage was switched by a small-size spark gap with a solid insulation. The current half-wave duration (~100 ns) and maximum amplitude (60 kA) were measured and calculated from the RC circuit characteristics to an accuracy of ~2%. In some cases, the RC operation test and its τ and K certification were performed using a generator with a current rise time adjusted between 1.5 and 15 ns and an amplitude of up to 40 kA [19].

When working with such RCs, there were cases of the appearance of local nonuniformities in the coil wave impedance ρ with respect to the shield localized at various points along the frame (core) circumference. This is associated primarily with an insufficient mechanical strength of the core at its small cross section and large diameter as well as with an effect of shock and static mechanical loads on the RC during measurements.

As a result of small deformations (including those during the RC calibration) of the core (probably, together with the shield), the coil turns may be displaced, changing the winding pitch and, thus, the interturn capacitance and their capacitance relative to the shield. Moreover, liquids (water, oil) used as insulators in the accelerator units may penetrate into the shield cavity.

The ρ nonuniformities led to the excitation of oscillations in the coil and RC shield space as in a cavity [12]. This could distort the signal profile, and distortions depended on the azimuthal position of nonuniformities with respect to the coil end to which the resistor is connected. In order to fix the turns more rigidly, the space between the coil and shield was filled with an epoxy compound [20]. This is a fairly laborious technological procedure, and, during the compound solidification, mechanical stresses that may also shift turns arise.

In order to reduce signal distortions determined by excited microwave oscillations, we developed a RC with a sealed shield [21]. By filling the shield cavity with replaceable liquids with different permittivities ε (e.g., capacitor oil with ε = 2.3; glycerin, ε = 42), we can vary the interturn and turn–shield capacitances. This helped change the resonant frequencies upon appearance of ρ nonuniformities and, in most cases, rapidly quench oscillations or even avoid their excitation.

However, a more convenient method was when, inside the shield cavity, 8–12 washers of a spatially conducting polymer (polyethylene mixed with finely grained graphite and acetylene carbon black) [22] were set between the shield and coil azimuthally at equal distances. Each washer had a contact of the cylindrical surface of its inner hole with the turn located opposite to it and skinned off the insulation at this place. The washer resistance was 20–30 times higher than that of the RC load resistor.

In addition, a ring spacer made of such a spatially conducting material was placed in a circular slot. The height and thickness of the ring were much smaller than the skin-layer depth at a frequency equivalent to the duration of the measured current. At such a RC design, oscillations propagating in the coil were suppressed by active resistances of the washers and high-frequency oscillations in the shield cavity were quenched at the expense of loading the slot by the active resistance of the spacer. As a result, the noise level due to the coil's ρ nonuniformities along the coil length decreased by one–two orders of magnitude and was almost undetectable against the background of valid signals.

COAXIAL-CABLE ROGOVSKI COILS

In the aforementioned RC with additional washers and a spacer, the contacts between washers and turns were sometimes disturbed because of possible deformations of RC parts. In addition, it is difficult to ensure a uniform coil pitch on a flexible and fragile core with a diameter of >1 m for such RC*s*. Although the current in the coil is a weak function of the pitch size and its variation [20], nevertheless, this affected the azimuthal nonuniformities in the ρ value. Therefore, an original RC in which changes in the coil pitch had no effect on ρ was developed [23].

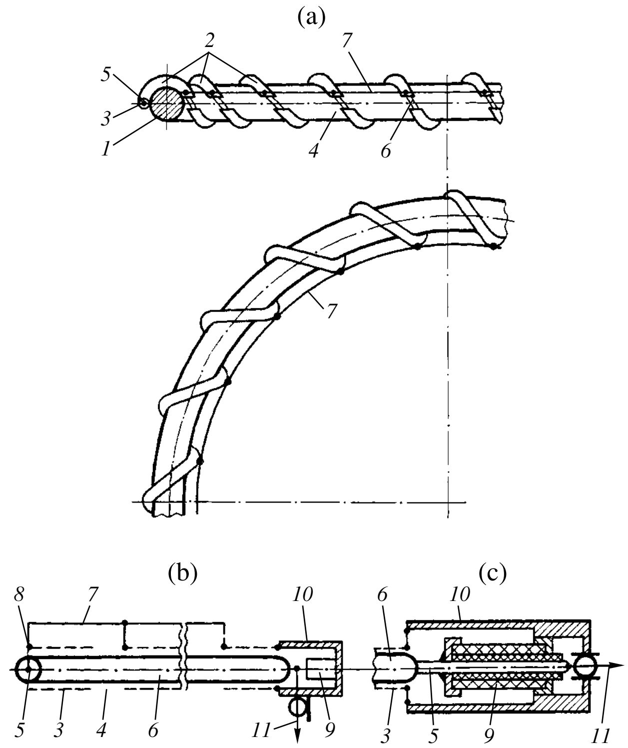

Fig. 3. (a) Schematic drawing of an RC with a coaxial-cable coil, (b) developed views of the coil's turns and their shields, and (c) a version of load resistor connection: (*1*) core; (*2*) cable; (*3*) cable braid; (*4*) gap in the braid; (*5*) inner conductor; (*6*) cable dielectric; (*7*) circular conductor; (*8*) conductor; (*9*) resistor; (*10*) coaxial electrode; and (*11*) cable. Dashed lines are the shields (braids) of the turns.

A coaxial cable *2* is wound as a coil with a pitch on a toroidal dielectric core *1* (Fig. 3a); each turn of the outer conductor *3* (braid) has a break *4* on the surface of the cable's solid dielectric *6*. The outer conductor *3* serves as a screen for the inner conductor *5*.

All adjacent screens are electrically interconnected without short-circuiting any break *4* and without forming a circuit closed around the generatrix of the coil *2* tore. This interconnector is a circular conductor *7* soldered, for example, only to the beginnings (Fig. 3b) or only to the ends of all turns of the braid (more than two conductors *7* can be used).

The beginning of the first turn of conductor *5* is connected by a low-inductance conductor *8* (directly over the end of dielectric *6*) to the beginning of shield *3*. The end of conductor *5* of the last turn is connected to the load resistor *9* (a low-inductance connection is also provided). This resistor is inserted into electrode *10* coaxial to it and connected to the end of the screen of the last turn. The signal from resistor *9* is transmitted by cable *11* to a recorder. Figure 3c shows a version of the

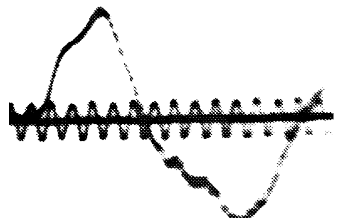

Fig. 4. Signals from an RC in measurements of a current with an amplitude of the first half-wave of 310 kA (100-MHz markers).

resistor connection. Here, conductor *5* is located at the central opening of the insulating case of the resistor [11].

Thus, conductor *5* of the toroidal coil of the RC and outer braid *3* coaxial to it forming a shield from a series of segments connected in parallel (their number is equal to the number of coil's turns) are secured by a solid insulation along the entire coil length (except for breaks *4*), and adjacent turns of conductor *5* are almost entirely screened from each other. Therefore, local changes in the winding pitch during the RC manufacture or service and deformations in the core *1* do not affect the wave impedance ρ of the coil remaining constant along its entire length. In a combination with the absence of a common hollow shield, this factor produces no conditions for exciting spurious electric oscillation and increases the measurement accuracy of the pulse current amplitude and time parameters.

The penetration of liquids with various dielectric and magnetic constants into a RC and full or partial immersion of a RC into such liquids do not modify its electric characteristics. Minimal stray capacitances and inductances of the connections between the beginning of *5* and the beginning of the first shield's turn and between the beginning of the last turn of *5* and the shield and resistor *9*, together with the possibility of matching the wave impedances of resistor *9* and electrode *10*, ensure minimum signal distortions and rise times of subnanosecond duration.

The coaxial arrangement of conductors *3* and *5* substantially reduces the noise due to the component of the measured-current-produced magnetic flux parallel to the central axis of the RC. Each segment of braid *3* can have its own outer insulation (not shown in Fig. 3), and the entire coil can be fully encased in a film or another type of insulation to prevent the RC elements from heavy currents (reverse to the measured ones) flowing through them and from sparking responsible for distortions in the measured signal.

The absence of a bulky common RC shield, especially at large diameters (>300 mm), reduces the RC overall dimensions and the voltage drop across the inductance of the circular slot in the reverse conductor with the measured current and, thus, reduces the probability of a breakdown to the RC coil at this point and of an interference generation. Thanks to the absence of capacitive coupling between adjacent layers, the coil can be wound as a multilayer one (see below), thus making it possible to extend the electric length (delay time) of the coil and its inductance (time constant) as well as to sectionize the coil for determining the current position.

The RCs of the type described above with openings of 100–1700 mm in diameter were produced and applied to recording currents of up to 700 kA with pulse rise times and lengths (at the base) of ≥3 and 20–80 ns, respectively. Shielded wires with fluoroplastic insulation, such as МГТФЭ-0.12 (ТУ16-505.185-71) with an outer braid diameter of 1.5 mm and an inner conductor diameter of ~0.5 mm, were convenient to wind coils (the insulation is not damaged during braid soldering).

The break width in each turn of the braid was ~1 mm, which ensures a sufficient breakdown strength between the end and beginning of turns of adjacent shields: a voltage produced at a single turn in a measurement is no higher than a few volts. For a typical turn length of ~50 mm, the interturn capacitance of the inner wires decreased by a factor of ~50 as compared to the capacitance of ordinary RC*s*.

During the RC manufacture, the braid was taken off, cut into segments with a length ~1 mm shorter than the turn length; these segments were then successively threaded on the insulation of the inner conductor, and, during the procedure of its winding on the core, they were adjusted in the selected positions. The braid turns were soldered to the circular conductor. The coil was wrapped externally in several polyethylene film layers.

In order to obtain a subnanosecond rise time, it is expedient to wind the coil with a pitch, to displace the breaks in adjacent screens in the circular direction (e.g., in a staggered manner) by a distance exceeding the break width, and to connect the beginnings and ends of all turns' screens with circular conductors. ОМЛТ, С2-10-2 or УНУ-Ш resistors were used. According to the drawing in Fig. 3c, the wire leads were removed, and holes were drilled in the end caps of the resistors [11].

Several RCs were manufactured with two- and three-layer coils and also with a four-sectional coils; breaks in layer braids were positioned one opposite to another.

RCs with diameters of >300 mm were certified by the rise time τ with the use of coils as distributed energy storages, which were preliminarily charged up to 1 kV and switched to the RC load by a small spark gap with a solid insulation [16]; τ < 1 ns was usually obtained. The RC sensitivity was determined experimentally, as it was for the RC in Fig. 1, and typically amounted to 10^{-2}–10^{-3} V/A. Figure 4 shows a waveform taken off a RC with an outer diameter of the core of 1.18 m.

The use of several RCs with various geometrical and electric parameters has confirmed their high noise immunity, operation stability, long-term preservation of electric characteristics, and uselessness of periodic tests of the sensitivity and rise time.

ROGOVSKI COILS WITH A METALLIC CORE

Sensors are set into circular grooves of reverse tubular conductors, so that they do not protrude outside the inner surfaces of conductors and do not reduce the breakdown strength between the coaxial conductors. In addition, this prevents sensors from a breakdown between them and the high-voltage inner conductor and, consequently, protects the valid signal from noise.

However, in measurements of currents of hundreds of kiloamperes, the voltage drop $L_{gr}(dI/dt)$ across the groove inductance L_{gr} reaches $\geqslant$100 kV [24] and may initiate a breakdown to the sensor shield or coil, form a path for a flow of a fraction of a heavy reverse current through these elements, and, thus, distort the signal. Therefore, when dealing with high currents, it is desirable to minimize L_{gr} of grooves and use sensors with a minimum cross section involving a decrease in their mechanical strength. Note that, along with ordinary mechanical loads affecting sensors during their service, they are exposed to a pressure $p = H^2/8\pi$ produced by the magnetic field (e.g., ~1 MPa at I = 1 MA).

The RC stiffness is usually determined by its core. Polystyrene and plexiglas most frequently used as core materials are fragile substances, and, when the cores of small cross sections are manufactured from them, problems arise, especially for large-diameter RCs (>500 mm). The core of thin sheet polyethylene is insufficiently strong and has a low yield stress under mechanical loading.

At high currents and small grooves, the aforementioned factors may lower the stability of the RC electric characteristics. Therefore, the RC operation must be periodically checked by passing a calibrating current pulse along its axis and measuring the signal rise time and amplitude sensitivity.

Analyzing has shown that, when measuring current pulses with durations <100 ns, the cross section of the core (and, thus, of the RC as a whole) can be reduced with a simultaneous increase in the mechanical strength by using a metallic core [25].

The effect of a short-circuited loop in the cross section of such a core is insignificant in measurements of currents with durations of tens of nanoseconds and shorter. The magnetic field created by the measured current is concentrated near the core surface due to the effect of expelling the magnetic flux from the area of the closed turn contour. Therefore, the total magnetic flux intersecting each turn of the coil and inducing an emf in it decreases insignificantly as compared to the flux in the absence of a metallic core. The current induced in the core penetrates to a small depth δ due to a skin effect; for Al, $\delta \approx 20$ μm at a frequency of 20 MHz equivalent to the recording of a current pulse with a duration of ~25 ns.

Figure 5 shows the design of a RC with a metallic core [26]. Coil *2* is wound with a МГТФ-0.12 wire on a toroidal core *1* made from the Д16 alloy. Resistor *3* (УНУ-Ш) with resistive layers on end surfaces and with metallized outer *4* and inner *5* cylindrical surfaces is tightly inserted into a hole in the core. The end *6* of the coil's conductor is soldered to lead *5*, and its second end *7* is connected to the core near the hole. Grooves *8* on the core fix the turns of the coil.

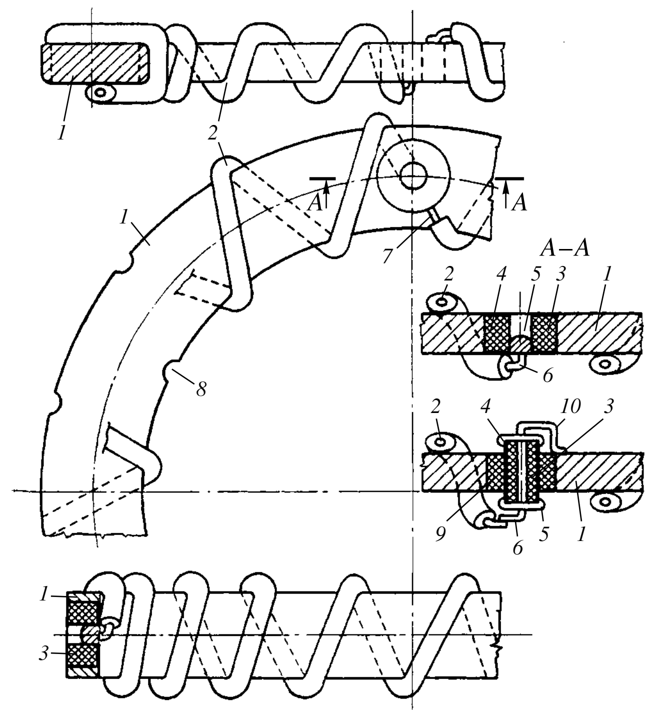

Fig. 5. Schematic diagram of an RC with a metallic core: (*1*) core; (*2*) coil; (*3*) resistor; (*4, 5*) metallized resistor surfaces; (*6, 7*) coil's leads; (*8*) groove; (*9*) insulating sleeve; and (*10*) resistor lead.

A signal from resistor *3* is transmitted by a cable (not shown in Fig. 5), whose central conductor enters lead *5* as into a jack, and its braid is connected to the core near the resistor. An RC with a C2-10-2 resistor insulated by sleeve *9* is shown in the section *A–A*; wire lead *10* is connected to the core *2*. In the bottom of Fig. 5, we see an RC version with the largest side of the rectangular cross section of core *1* parallel to the common axis of the device with the measured current.

RCs with steel, copper, and Al-alloy cores with cross sections of 18×16 to 16×2 mm^2 and outer diameters of up to 1.7 m were manufactured according to Fig. 5 and used in the self-integration mode to measure currents of 100–600 kA with durations of 20–60 ns. For an insulation thickness of 0.5 mm between the wire and core, an increase in the signal amplitude at the RC output is ~10% and can be canceled by a decrease in the rating of the load resistor.

The core was convenient to be used as a reverse conductor of the RC coil. The core and coil form a line with

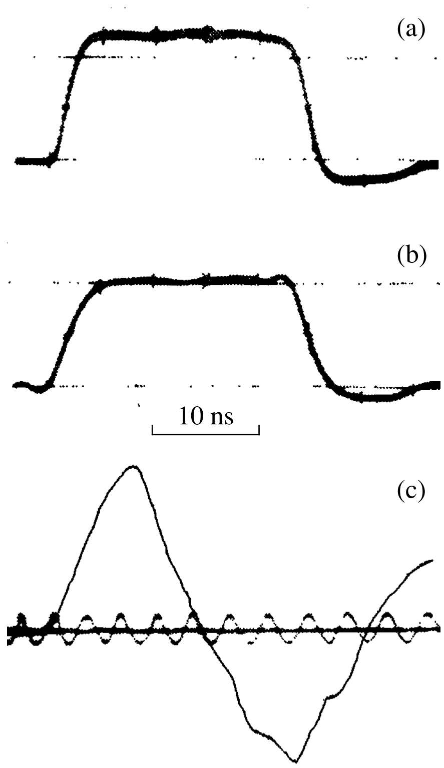

Fig. 6. (a) Calibrating current pulse and (b) the RC signal corresponding to it (RC has an Al-alloy core with an outer diameter of 1.2 m and a cross section of 3×16 mm^2); and (c) signal from the RC when measuring a current with an amplitude of the first half-wave of 590 kA (100-MHz markers).

distributed parameters, so that the core operates as an external shield. Therefore, such a shield can be rejected if it is necessary to reduce the total RC cross section and decrease the size of the circular groove in the conductor (i.e., to reduce the wall thickness of this conductor and its outer diameter). In addition, a shield is not obligatory if the absence of a breakdown between the coil and central conductor with the measured current is guaranteed, a breakdown between the coil and the groove walls is also excluded, and charged particles of the beam whose current is measured by the RC do not fall on the coil.

Generally speaking, it is advisable to have a shield for the RC since noises are suppressed by it. A shield makes it possible to calibrate the RC outside of the working facility and then to install the RC in the groove without changing its characteristics. The shield can be connected at one point to the conductor with the groove and (this is more expedient) to the point of connection of the load resistor to the core.

The rise time of the transfer characteristic of an RC >300 mm in diameter was determined experimentally, as was described above. The τ value significantly depends on the resistor inductance and on the manner in which this resistor is connected to the signal-transmitting cable. These RCs have a minimal inductance, which usually results in $\tau \sim 1$ ns; the integration time constant is >1 μs; and the sensitivity is 10^{-2}–10^{-3} V/A.

Most of the RCs used in the experiments had outer shields with an azimuthal slot electrically connected to the core near the load resistor. The shield additionally reduces the wave impedance ρ of the coil, since now it forms a line with the inner core and outer shield. However, the effect of ρ on the voltage amplitude U of the signal across the resistor $R \ll \rho$ in the self-integration mode is small [27]:

$$U \approx IR\rho[w(R+\rho)]^{-1}, \quad (5)$$

where I is the measured current and w is the number of coil's turns. This formula is applicable to all RCs described in this review. Several sensors had coils wound with cables and sectionized coils for monitoring the position of the electron beam current.

Figure 6 shows oscillograms of signals taken off a RC.

The use of RCs with metallic cores simplifies their manufacture, especially at diameters of >500 mm; increases the mechanical strength of the RCs; reduces their cross section and overall dimensions; and improves the measurement accuracy and stability of RC electric characteristics.

INDUCTIVE SENSOR WITH A MULTILAYER COIL

When parameters of currents with durations of 50–100 ns were measured in facilities with reverse tubular conductors ≤150 mm in diameter, the inductance L of a single-layer coil of an RC was insufficient for the self-integration mode even if the coil was wound with a minimal-diameter wire that still ensured an allowable loss level in the active resistance of the skin layer. This obliged us to record pulse currents in a less-noise-immunity differentiation mode with subsequent signal processing for obtaining the actual current pulse shape. In order to ensure the self-integration mode under such conditions at a signal amplitude optimal for oscilloscopic recording, an appropriate sensor was developed [28].

The inductance L and electric length t_0 of an RC with a small outer diameter can be increased if a multilayer coil with wave-impedance-matched layers is used and the interlayer capacitive coupling is minimized. For this purpose, the first layer is wound on the core and a shield is put on it. The same procedure recurs for the subsequent layers and shields. The transfer of the coil's wire from a lower layer to the next one provides a minimum inductance, and the wave impedances of all layers are identical.

It is sufficient to implement a low-inductance connection of the inner and outer shields of each layer at a single point near the location of the transfer of the coil's wire from one layer to another and also at the points of connections between the beginning of the coil's first layer and the shield and between the end of the last layer and the load resistor. The second lead of the latter is connected to the outer shield of the upper layer. The azimuthal slot in each shield should be comparatively narrow, and the slots in adjacent shields should be shifted with respect to each other.

Figure 7 shows an RC with a two-layer coil (for simplicity). Shield *2* with an azimuthal slot *3* is put on a toroidal polystyrene core *1* (shield *2* can be removed, but it simplifies the matching of the wave impedances of coil's layers). The first layer *4* is wound by a wire with a thin insulation (e.g., polyethylene) over the shield. The beginning *5* of the wire is connected to shield *2*.

Shield *6* with a slot *7* encloses the layer *4*. Segment *8* of the last turn of layer *4* passes through a hole in shield *6* to the second layer *9*, which is wound on shield *6* with a pitch identical to that of layer *4*. Shields *2* and *6* are connected by a short conductor *10*. In shield *11* embracing layer *9*, slot *12* is displaced with respect to slot *7*. The end of the last turn of layer *9* is connected (by conductor *13* through a hole in shield *11*) to contact *14* of load resistor *15* and, via its resistive layer (thick line) and a tubular conductor *16*, to shield *11*. Shields *6* and *11* are connected by conductor *17*. A signal from resistor *15* is transmitted by the cable to a recorder (not shown in Fig. 7). The wave impedance ρ of the layer with outer and inner shields can be calculated from the formula

$$\rho \approx 0.6 \cdot 10^2 wrd\varepsilon^{-0.5} ABC, \qquad (6)$$

where w is the total number of turns in the layer wound with a pitch equal to the double thickness of the coil's wire insulation; r and d, m, are the layer dimensions (Fig. 7); ε is the effective value of the relative permittivity of the insulation between the wire and shields; and A, B, and C are the factors calculated by the formulas

$$A = [\ln(r_2/r)\ln(r/r_1)]^{0.5},$$

$$B = [d^2 + (d^4 - d^2 r^2)^{0.5}]^{-0.5},$$

$$C = \{d^2 \ln(r^2/r_1)$$

$$- \ln(r/r_1)[r_1^2 - r^2 + 2r_2 r \ln(r/r_2)]$$

$$- \ln(r_2/r)[r^2 - r_1^2 + 2rr_1 \ln(r_1/r)]\}^{-0.5},$$

where r_1 and r_2 are the dimensions in Fig. 7.

Among the parameters included in formula (6), a change in the number of turns w in a layer (i.e., coil pitch variation) is most suitable for the equalizing ρ of layers in practice. It is also possible to match ρ at the locations of transfers from one layer to another by connecting a resistor in series with the coil wire or between the wire and shield. It is desirable to select a shield with a thickness exceeding that of the skin layer in the frequency band of the measured current.

Note that a mutual inductance of the inner and outer windings (provided the circular slot in the shield is small) is absent, because, when a short current pulse travels along such a cable, the magnetic field remains within the shield. Due to the existence of circular slots in the shields, a part of the magnetic flux may penetrate from one coil to another. For slot widths within 1.5 mm, this effect was actually imperceptible.

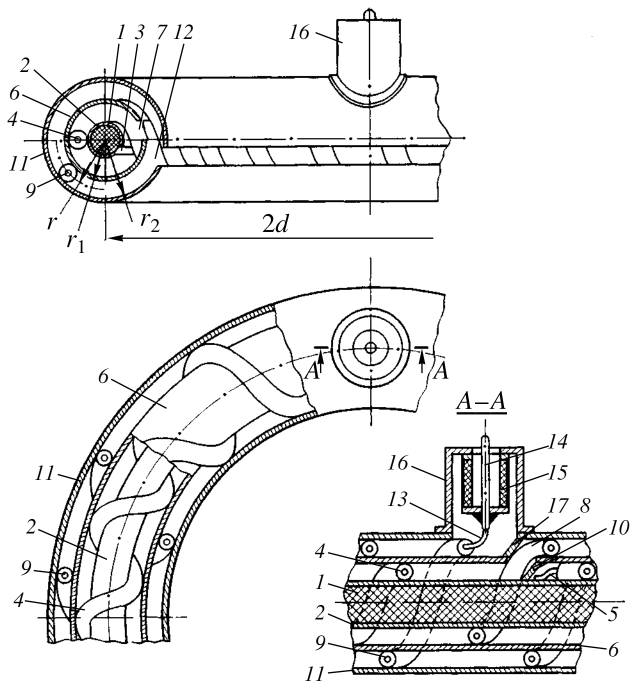

Fig. 7. Schematic drawing of an inductive sensor with a multilayer coil: (*1*) core; (*2, 6, 11*) shields; (*3, 7, 12*) azimuthal slots; (*4, 9*) coils; (*5*) coil's lead; (*8*) junction between the coils; (*10, 17*) conductors connecting the shields; (*13*) conductor; (*14*) contact rod; (*15*) resistor; and (*16*) tubular conductor.

Several RCs with outer diameters of 80–150 mm were manufactured with two- and three-layer coils (МГТФ-0.12 wire) and with 12Х18Н10Т foil shields of rectangular cross sections jointed by spot electric welding; the outer shield was insulated from the reverse conductor by a film in order to reduce noise from sparking at the shields' contacts upon high current flow through them. A resistor (С2-10-2, 2 Ω) with removed wire leads and holes drilled at its ends served as the RC load. The RC time constant reached 5 μs.

Figure 8 shows the shape of a calibration current pulse and the corresponding RC signal reproducing the rise time with a duration of ~1.3 ns without distortions for an RC with a three-layer coil. Pulse currents with amplitudes of up to 60 kA and durations of ~100 ns were recorded by RCs in the self-integration mode. Sectionized sensors of similar design having multilayer coils in the form of a part of a tore (as a rule <45°) with nanosecond rise times were also used in experiments. Such RC are described in detail in [29].

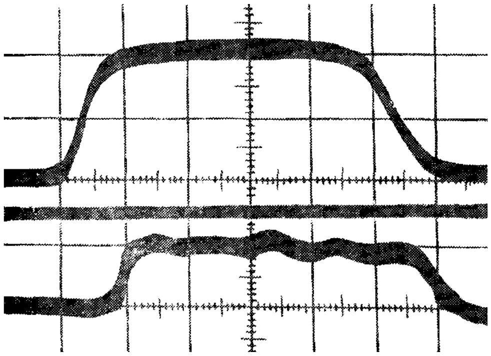

Fig. 8. Calibrating current pulse (upper curve) and recorded IS signal (lower curve). The horizontal scale is 2 ns/division.

INDUCTIVE SENSOR WITH REMOTELY MODIFIED CHARACTERISTICS

In some operating modes of the LIA-30 accelerator, especially when it was operated synchronously with a БР-1 fast pulse nuclear reactor [30, 31], the necessity of remotely changing the IS electric characteristics was provided. This concerned primarily the sensors measuring the currents in circuits located close to the target unit of the facility and, consequently, close to the reactor.

It was necessary to vary the following parameters: the sensitivity K for obtaining an optimal signal level, since its additional division in the recording channel favors a distortion of its profile; the integration time constant $t_c = L/R$ for, for example, changing from the RC self-integration mode to the differentiation regime and back; the electric length $t_0 = (LC)^{0.5}$, where C is the capacitance of the coil's turns with respect to the shield; and the wave impedance $\rho = (L/C)^{0.5}$, which determines R (at fixed K values):

$$K \approx R\rho[w(R+\rho)]^{-1}. \tag{7}$$

Table

Characteristic	Rogovski coil	
	[27]	[18]
ρ, Ω	5000	2200
R, Ω	50	7.2
t_c, μs	~1000	140
t_0, ns	Large	450
τ, ns	2	<10
I, kA		50
t, ns	$10–10^6$	>40
d_{av}, cm	16	20

Note: d_{av} is the average diameter.

From (5) and (7), it follows that, by varying ρ, we can change K and the signal amplitude U. However, RCs without ferromagnetic cores in the self-integration mode, which are intended for measuring high currents with $t \geq 20$ ns, usually have $R = 0.1–5$ Ω (e.g., [11, 20]), and $\rho > 100$ Ω; therefore, K can be varied due to changes in ρ only by ~10%. By increasing R, K can be raised only up to $R = \rho$, above which the signal shape is distorted at $t > 2t_0$ [32]. Therefore, in order to extend the dynamic range of I and t measurements (by increasing t_0 with the possibility of varying K through changes in R), RCs with ferrite cores are used. The characteristics of two of such cores [18, 27] are listed in the table.

However, in our situation, it was impossible to vary the characteristics of a particular RC by promptly changing R, as it was described at the beginning of this review, or by demounting the RC for replacing its core or substituting a coil with another geometry and number of turns. Immediately after a pulse operation, the nuclear reactor has a high radioactivity decaying with time, and it is prohibited to approach it.

An RC with promptly varied characteristics was developed and successfully tested. This was achieved by a remote change in the coil C and (or) L values and, correspondingly, in the parameters K, ρ, t_0, and t_c depending on them [33]. The RC is equipped with a hermetically sealed shield similar to that described in [21] but having an improved design: its dielectric core is hollow and sealed. By changing the permittivity of the medium inside the core cavity, one can vary the coil capacitance relative to the shield. Filling the core cavity with magnetic fluids with various permeabilities changes the coil inductance.

The demountable shield *1* of the RC (Fig. 9) consists of two parts. The toroidal cavity in the shield is sealed by three rubber gaskets *2* in grooves. Polyethylene ring *3* is set between the parts of the shield. Screws *4* (metal) and *5* (caprolon) compress the gaskets. A single-layer toroidal coil *6* is wound on a hollow glass-tube core with a pitch by a wire with an insulation or without it. The coil is fixed in the shield cavity by dielectric spacers *7* with holes in their walls. The spacers were cut along their diameter and, after they were set uniformly over the core circumference, their halves were glued together.

Two thin tubes *9* extend from opposite sides of the shield cavity through a seal. Two dielectric tubes *10* extend from this cavity in a similar manner, and their outlets are sealed with a glue. The coil's leads are connected to the shield and low-inductance resistor R, whose signal is transmitted by a cable to a recorder (for simplicity, Fig. 9 shows single tubes *9* and *10*, and the resistor and cable are omitted). When the coil is wound without a pitch, two gaps with mismatched ρ form at sites where tubes *10* branch off the core. In order to reduce the reflection from these regions, they should have a minimum length, or, when winding the coil with a pitch, the latter should be close to the length of one of these gaps. The RC fully mounted in the shield is set in a circular groove of the reverse coaxial conductor of a high-current section of a high-voltage facility. Tubes *9* and *10* and the cable are led out through the walls of the conductor and are sealed if necessary. Tubes *9* and *10* are connected to independent hydrosystems *11* and *12*, respectively.

The remotely controlled system *11* displaces the air from the cavity between the shield and coil and fills it with a high-frequency liquid dielectric with a relative permittivity *E* selected in accordance with the required changes in C, ρ, K, and t_0. At an ideally dense coil wound with a thin wire, the C value is calculated from the formula

$$C, \Phi = 2\pi^2 \varepsilon\varepsilon_0 D[\ln(r_1/r)]^{-1} \times \{1-(2r_1/D)^2[1-r^2/r_1^2+(2r/r_1)\ln r/r_1]\}, \quad (8)$$

where $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m is the dielectric constant; D, m, is the average diameter of the coil's core; r_1 is the radius of the cavity in the shield; and r is the outer radius of a turn on the core [34]. Formula (8) does not take into account the presence of a circular slot in the shield, solid insulation of the wire, and the actual profile of the exterior insulation surface. In particular, when a coil is wound with a pitch, a decrease in C can be estimated on the basis of [35].

The system *12* displaces the air from the core cavity and fills it with a magnetic liquid with a relative permeability μ [36]. The inductance of the solid coil

$$L, \text{H} = 2\mu\mu_0 w^2 r^2 [D + (D^2 - 4r^2)^{0.5}]^{-1}, \quad (9)$$

where $\mu_0 = 4\pi \times 10^{-7}$ H/m is the magnetic constant, increases by a factor μ, thus increasing the values of ρ, K, t_c, and t_0. The effect of the primary current magnetizing the ferromagnetic is almost fully canceled by the secondary current through the coil, and the intensity of the magnetic field in the ferromagnetic bulk will be below its saturation threshold. Filling this cavity with deionized water ($\varepsilon = 81$) at a winding pitch of ~$2r$ can raise C up to ~20% as compared to the value in the case of the presence of air in the cavity. A substance in the shield cavity changes C proportionally to its ε; i.e., if it is water, C becomes 81 time higher.

An RC shown in Fig. 9 was tested with the following parameters: $D = 120$ mm, $r_1 = 9$ mm, the radius of the core cross section is 6 mm, and $w = 600$ densely wound turns of a ПЭВ-2 wire 0.5 mm in diameter (except for 6-mm gaps for tubes *10*). The calculated parameters with air in the shield and core cavities are as follows: $C = 630$ pF, $L = 160$ μH, $\rho = 500\ \Omega$, $t_0 = 320$ ns, $K = 1.6 \times 10^{-2}$ V/A, and $t_c = 16$ μs (for $R = 10\ \Omega$). For water in the shield cavity, $C = 51$ nF, $\rho = 56\ \Omega$, $t_0 = 2.9$ μs, and $K = 1.4 \times 10^{-2}$ V/A.

The RC was set in a metallic chamber with coaxial conic electrodes at its ends. A calibration current pulse with a rise time of ~3.5 ns and $t = 20$ ns was passed

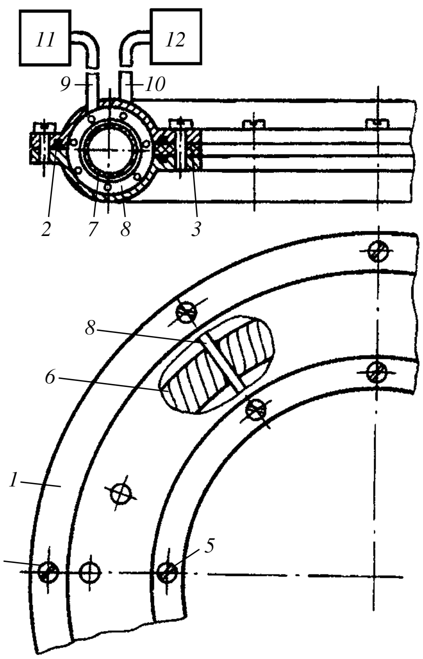

Fig. 9. Schematic drawing of an RC with remotely varied characteristics: (*1*) shield; (*2*) rubber gasket; (*3*) polyethylene ring; (*4, 5*) screws; (*6*) coil; (*7*) hollow core; (*8*) insulating spacers; (*9, 10*) tubes; and (*11, 12*) hydrosystems.

along the RC axis. The shield cavity was filled with glycerin ($\varepsilon = 42$) or deionized water. Measurements have shown that the signal taken off R reproduced the current profile with slight distortions for both the air and the aforementioned fluids filling the cavity. Note that the quantities C, ρ, K, and t_0 changed in accordance with ε of the dielectric in use and took values close to the calculated ones within the calculation and measurement accuracies (≤20%).

A magnetic fluid was utilized for qualitative tests of the RC operation and represented a suspension of a finely dispersed amorphous magnetic powder in a mixture of oleic acid with silicone oil. The methods for obtaining efficient magnetic fluids are expounded in [36]. When such a fluid filled the core cavity, the inductance increased by a factor of ~15 (for both air and the aforementioned liquids in the shield cavity); the values of ρ, K, t_c, and t_0 also increased. However, upon the passage of a calibration current pulse, the signal rise time was extended to ~5.5 ns, which is apparently associated with insufficiently high frequency characteristics of the magnetic fluid components. In addition, significant noise arose at the signal front and behind it evidently due to a disturbance of the ρ uniformity along the coil length caused by a ferrite powder segregation.

Replacing the spacers *8* by those made of polyethylene doped with carbon black with a resistance of ~1.5 kΩ between the cylindrical surfaces with outer and inner diameters, which were in contact with the shield and coil's turns with stripped enamel, respectively, almost

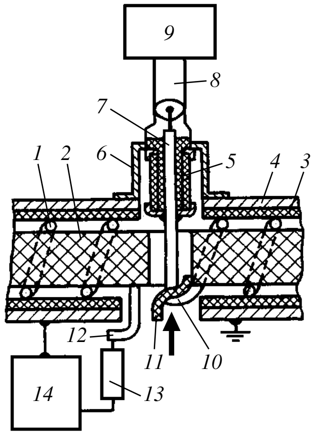

Fig. 10. Circuit for the IS rise-time calibration: (*1*) coil; (*2*) core; (*3*) insulating film; (*4*) shield; (*5*) resistor; (*6*) conductor; (*7*) contact lead; (*8*) cable; (*9*) oscilloscope; (*10*) coil's lead; (*11*) film; (*12*) coil's second lead; (*13*) resistor; and (*14*) dc power supply unit.

fully prevented the spurious oscillation mentioned above. Substituting a ring made of a bulk-conducting material for ring *3* contributed to a more intense attenuation of the noise. The appearance of spurious oscillations due to resonances in the RC winding caused by a capacitance between its turns and the shield, local irregularities, and other factors was analyzed in [12].

Thus, the possibility of remotely changing C and L of a shielded RC coil by one–two orders of magnitude, as well as the values of ρ, t_c, t_0, and K, was shown experimentally. The use of such an RC for measuring the parameters of high-current pulses in electrophysical installations simplifies the formation of signal amplitudes optimal for recording by appropriate equipment and change from the RC self-integration mode to the differentiation mode and vice versa. Additional data on such RCs are available in [37].

CALIBRATION OF LARGE-DIAMETER INDUCTIVE SENSORS

Measurements of pulse currents with durations of ≤100 ns by large-diameter inductive sensors, including RCs, in the current transformer mode require the knowledge of their parameters: electric length t_0, integration time constant t_c, wave impedance ρ, amplitude sensitivity K, and rise time τ. The first three parameters are calculated to a sufficient accuracy or determined from simple measurements.

The values of K and τ cannot be calculated to a sufficient accuracy, especially in the sub- and nanosecond ranges, because it is difficult to take into account the stray capacitances and inductances of an RC, the skin effect for the current in the winding and shield, the resonance effects in the coil and shield cavity, etc. The analysis of the operation of an RC as a helix line [14, 18, 27, 38] ignores the nonuniformity introduced by the azimuthal slot and the fact that the shield is not closed around each turn.

Therefore, RCs are certified with respect to K and τ experimentally: an RC is set in a testing chamber, and a calibration current pulse is passed along its axis through a cable (e.g., [14]). However, the passage of a calibration pulse through disk electrodes of a short cylindrical chamber is accompanied by a transformation of the pulse shape and a change in its amplitude. As the RC diameter increases and the current pulse duration diminishes, the certification error grows. Coaxial chambers with conical junctions yield more accurate results [13]. Note that such chambers are too bulky for RCs with outer diameters of >500 mm [39]. For example, for a 1-m-diameter RC, the facility has a total length of >10 m and a maximum diameter of >1 m.

We have proposed and used (for the RCs described above) a more simple and prompt calibration method for RCs with diameters of 500–1700 mm and sub- and nanosecond rise times. This method is also applicable to RCs of smaller diameters.

Analyzing the operation of shielded self-integrating RCs with sub- and nanosecond rise times has shown that τ is determined mainly by the stray inductances and capacitances of the load resistor and sections of connections of its leads with the shield and coil's end (it is assumed that the coil has a uniform wave impedance ρ in the azimuthal direction). Dielectric losses (polystyrene, fluoroplastic, and polyethylene) in the coil's toroidal core and in the insulation of its turns have a much smaller effect (at least, by an order of magnitude).

Thus, if, under the action of an induced emf, the load current is determined by the aforementioned impedances, then, in order to certify the RC in τ, it is sufficient to produce a voltage jump at the coil and to record the current in the resistor regardless of the method of voltage generation.

In order to determine τ, the RC coil that can be regarded as a line with distributed parameters is charged to a certain voltage and is then discharged through the RC load and switch. The spurious capacitance and inductance of the switch must be much lower than the inductances and capacitances of the RC load unit [15]. These measurements do not require a bulky calibration chamber, generator, and recorder of the calibration current pulse parameters, thus simplifying the K and τ measurement procedure. Consider this for the following example.

Coil *1* (Fig. 10) of an RC is wound on a toroidal dielectric core *2* and insulated by several film layers *3* from metallic shield *4*. One end of load resistor *5* (OMJIT or C2-10-2 with removed wire leads and holes drilled at the ends) is connected, by using a tubular conductor *6*, to shield *4*, and its second end is connected to rod *7*. The other end of the latter is connected to cable *8* linking the RC to oscilloscope *9*. The discharge gap is formed by the end of the rod's second lead and the coil's end *10*, between which insulating film *11* is laid. The coil's second end *12* is disconnected from shield *4* and, via resistor *13*, is connected to current source *14*.

The distributed capacitance of the coil is charged with respect to shield *4* from source *14*, a breakdown of film *11* occurs, and the rise time t_r and the shape of the current in resistor *5* are recorded by oscilloscope *9*. To initiate the switch operation, it was convenient to mechanically break the film structure by pressing to the coil's end *10* (indicated by an arrow). In this case, in order not to increase the stray capacitance of the coil's end, the pressing object should be a thin dielectric.

Since the discharge has resistive and inductive phases of its development in time, then, in order to take into account their contribution to τ, we can measure t_r at the same charging voltage and alternate breakdown of dielectric media with different breakdown strengths E (i.e., at different gaps between the switch's electrodes). Then, we plot the dependence of t_r on E and extrapolate this function to the zero gap width at which $t_r \approx t_{rec}$ —the rise time determined by the entire recording channel: transmitting cable *8* and oscilloscope *9*. The knowledge of the rise time τ_c in the cable and τ_o in the oscilloscope allows for the calculation of the signal rise time t'_r at the RC output from the formula

$$t'_r = (t_v^2 - \tau_c^2 - \tau_o^2)^{0.5}. \tag{10}$$

The t'_r value can be taken for τ, although, in practice, the latter is slightly larger because of ignoring the loss in the RC dielectric. When the measurements are completed, film *11* is removed, the end *10* is connected to rod *7*, and lead *12* is connected to shield *4*.

Figure 11 shows oscillograms of signals at a 2-Ω C2-10-2 resistor for an RC with a 734-mm-diameter opening for breakdowns in air and polyethylene in the discharge gap. Figure 12 presents a dependence $t_r(E)$, where averaged values of the breakdown strength in the self-breakdown of the insulations in use (air, capacitor paper, Dacron, and polyethylene) are plotted on the horizontal axis. For the breakdowns of air and polyethylene, the times t_r are 10 and 0.7 ns. For a PK-75-9-12 transmitting cable 5 m long, τ_c = 0.12 ns, and for a 6ЛОР-04 oscilloscope, τ_o = 0.35 ns. Using formula (10) for t_r = 0.7 ns, we determine τ = 0.6 ns.

In order to certify an RC in the sensitivity K at a known τ, a calibration current pulse with a flattened leading edge can be applied if the pulse rise time is much shorter than the RC integration time constant, which is typically >1 μs for the RC with the aforementioned diameters. After the electric characteristics of such a circuit were measured or calculated, the calibration current amplitude was determined with an error of ≤2% and, correspondingly, the K error was ≤ ±5%.

When measuring short current pulses, a correction related to a decrease in the amplitude upon signal transmission along the cable from the RC to the recorder should be introduced to the K value. This can be done for any pulse duration by restoring the actual pulse shape from that registered by the recorder, if the transfer characteristics of all circuit components of the measurement channel are known. This problem is not discussed here.

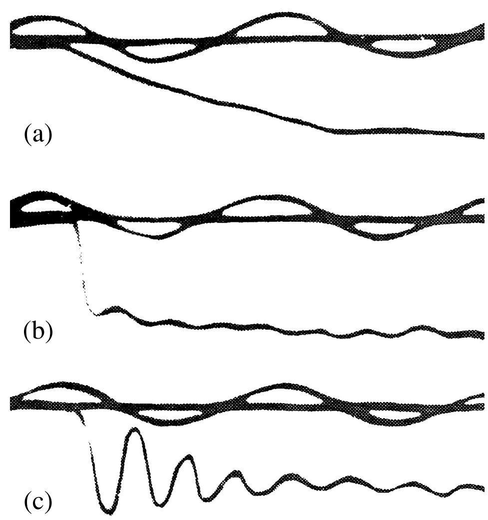

Fig. 11. RC signals for (a) air and (b) polyethylene breakdowns; and (c) effect of the additional capacitance (4 pF) of a metallic striker (100-MHz markers).

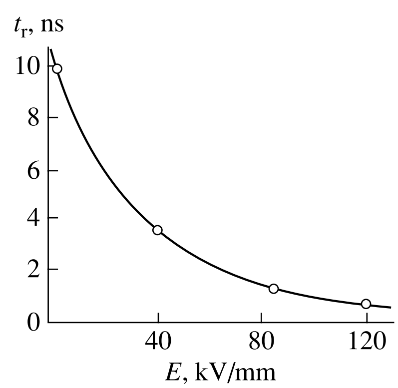

Fig. 12. Rise-time t_r duration of a current pulse through a resistor as a function of the dielectric breakdown strength E_e.

The method described was used for the calibration of almost all inductive sensors with diameters above 300 mm and for checking the stability of their characteristics during measurements.

CONCLUSIONS

When units of a LIA-30 high-power linear pulsed induction electron-beam accelerator with a record acceleration energy (40 MeV, 100 kA, 20 ns) were being designed, experimentally studied, and refined, it became necessary to purposefully develop a series of electric sensors, including devices for measuring high pulse currents. A considerable part of such sensors was represented by modified shielded Rogovski coils and inductive sensors on their basis with coils in the form of a part of a tore with sub- and nanosecond rise times. RCs for recording currents with amplitudes of 10–2000 kA and durations of 10–100 ns were 80–1700 mm in diameter and operated in the self-integration mode ensuring the highest noise immunity and precision in reproducing the signal shape.

ISs with coaxial-cable coils with circular metallic cores, which simultaneously serve as reverse conductors, and with multilayer coils have the most original designs. These sensors with small cross sections are convenient to set in narrow and shallow circular grooves of high-current conductors of facilities. A simple method for certifying the transfer characteristic and sensitivity has been developed for large-sized sensors. Such devices can also operate in the differentiation mode. They are applicable for monitoring the parameters of pulse currents in other electrophysical installations.

REFERENCES

1. Al'bikov, Z.A., Velikhov, E.P., Veretennikov, A.I., *et al.*, *At. Energ.*, 1990, vol. 68, no. 1, p. 26.
2. Sincerny, P., Childers, K., Goyer, I., *et al.*, Abstracts of Papers, *XI Int. Conf. on High Power Particle Beams, BEAMS 96*, Prague: Prague Inst. of Plasma Phys., 1996, vol. 2, p. 1003.
3. Pavlovskii, A.I., Bossamykin, V.S., Savchenko, V.A., *et al.*, *Dokl. Akad. Nauk SSSR*, 1980, vol. 250, no. 5, p. 1118.
4. Galakhov, I.V., Gasheyev, A.S., Grusin, I.A., *et al.*, Abstracts of Papers, *XI Int. Conf. on High Power Particle Beams, BEAMS 96*, Praque: Praque Inst. of Plasma Phys., 1996, vol. 2, p. 950.
5. Pavlovskii, A.I., Bossamykin, V.S., Gerasimov, A.I., *et al.*, Abstracts of Papers, *IX Int. Conf. on High Power Particle Beams, BEAMS 92*, Springfield: NTIS, 1992, vol. 2, p. 273.
6. Pavlovskii, A.I., Bossamykin, V.S., Gerasimov, A.I., *et al.*, *Vopr. At. Nauki Tekh., Ser.: Fiz. Radiats. Vozdeistviya Radioelektron. Appar.*, Moscow: TsNIIUEI, 1994, nos. 3–4, p. 3.
7. Bossamykin, V.S., Gerasimov, A.I., Pavlovskii, A.I., *et al.*, *Prib. Tekh. Eksp.*, 1997, no. 2, p. 5.
8. Pavlovskii, A.I., Bossamykin, V.S., Gerasimov, A.I., *et al.*, *Prib. Tekh. Eksp.*, 1998, no. 2, p. 13.
9. Gerasimov, A.I. and Gorkunov, V.S., *Radiatsionnaya stoikost' elektronnykh sistem, STOIKOST' 2000* (Radiation Stability of Electronic Systems: Stability 2000), Moscow: SPELS, 2000, no. 3, p. 177.
10. Schwab, A.J., *Hochspannungsmesstechnik; Messgerate und Messverfahren*, Berlin: Springer, 1981. Translated under the title *Izmereniya na vysokom napryazhenii*, Moscow: Energoatomizdat, 1983.
11. Gerasimov, A.I. and Dubinov, E.G., *Prib. Tekh. Eksp.*, 1983, no. 3, p. 110.
12. Anderson, J.M., *Rev. Sci. Instrum.*, 1971, vol. 42, no. 7, p. 915.
13. Ivanov, B.I. and Miroshnichenko, V.A., *Prib. Tekh. Eksp.*, 1973, no. 5, p. 138.
14. Stefanovskii, A.M., *Prib. Tekh. Eksp.*, 1967, no. 2, p. 149.
15. Gerasimov, A.I. and Dubinov, E.G., USSR Inventor's Certificate no. 785794, *Byull. Izobret.*, 1980, no. 45, p. 199.
16. Gerasimov, A.I. and Dubinov, E.G., *Prib. Tekh. Eksp.*, 1983, no. 2, p. 139.
17. Medved', S.V. and Simonov, Yu.M., *Preprint of Joint Inst. for Nuclear Research*, Dubna, 1967, no. 13-3645.
18. Vasserman, S.B., *Prib. Tekh. Eksp.*, 1972, no. 2, p. 99.
19. Pavlovskii, A.I., Kuleshov, G.D., Gerasimov, A.I., *et al.*, *Prib. Tekh. Eksp.*, 1976, no. 3, p. 134.
20. Pellinen, D.G., Di Capua, M.S., Sampayan, S.E., *et al.*, *Rev. Sci. Instrum.*, 1980, vol. 51, no. 11, p. 1535.
21. Gerasimov, A.I. and Dubinov, E.G., USSR Inventor's Certificate no. 651429, *Byull. Izobret.*, 1979, no. 9, p. 225.
22. Gerasimov, A.I. and Dubinov, E.G., USSR Inventor's Certificate no. 791105, *Byull. Izobret.*, 1982, no. 4, p. 237.
23. Gerasimov, A.I. and Dubinov, E.G., *Prib. Tekh. Eksp.*, 1988, no. 3, p. 93.
24. Exdahl, C.A., *Rev. Sci. Instrum.*, 1980, vol. 51, no. 12, p. 1649.
25. Gerasimov, A.I., USSR Inventor's Certificate no. 1213854, *Byull. Izobret.*, 1986, no. 46, p. 284.
26. Gerasimov, A.I., *Prib. Tekh. Eksp.*, 1991, no. 1, p. 150.
27. Nassisi, V. and Luches, A., *Rev. Sci. Instrum.*, 1979, vol. 50, no. 7, p. 900.
28. Gerasimov, A.I., USSR Inventor's Certificate no. 1233651, *Byull. Izobret.*, 1986, no. 44, p. 288.
29. Gerasimov, A.I., *Prib. Tekh. Eksp.*, 1989, no. 3, p. 110.
30. Bossamykin, V.S., Koshelev, A.S., Gerasimov, A.I., *et al.*, *Advanced Pulsed Neutron Sources: Physics of/at Advanced Pulsed Neutron Sources; PANS-II*, Dubna: Ob. Inst. Yad. Issled., 1995, p. 114.
31. Voinov, M.A., Gerasimov, A.I., Gordeev, V.S., *et al.*, *Vopr. At. Nauki Tekh., Ser.: Yad.-Fiz. Issled.*, 1999, no. 3, p. 82.

32. Krompholz, H., Doggett, J., Schoenbach, K.H., *et al.*, *Rev. Sci. Instrum.*, 1984, vol. 55, no. 1, p. 127.

33. Gerasimov, A.I. and Dubinov, E.G., USSR Inventor's Certificate no. 923280, *Byull. Izobret.*, 1983, no. 21, p. 208.

34. Iossel', Yu.Ya., Kochanov, E.S., and Strunskii, M.G., *Raschet elektricheskoi emkosti* (Calculation of Electric Capacity), Leningrad: Energiya, 1969.

35. Efimov, I.E. and Ostan'kovich, G.A., *Radiochastotnye linii peredach* (Radio-Frequency Transmission Lines), Moscow: Svyaz', 1977.

36. Blum, E.Ya., Maiorov, M.M., and Tsebers, A.O., *Magnitnye zhidkosti* (Magnetic Liquids), Riga: Znanie, 1989.

37. Gerasimov, A.I., *Prib. Tekh. Eksp.*, 1994, no. 1, p. 131.

38. Cooper, J.J., *J. Nucl. Energy, Part C*, 1963, vol. 5, no. 5, p. 285.

39. Lewis, I.A.D. and Wells, F.H., *Millimicrosecond Pulse Techniques*, London: Pergamon, 1954. Translated under the title *Millimikrosekundnaya impul'snaya tekhnika*, Moscow: Inostrannaya Literatura, 1956.