Arc-quenching magnetically controlled reactors (AQMCRs) with automatic ground fault capacitive current compensation for 6 to 35 kV networks

A.M. Bryantsev, A.L. Lurier, A.G. Dolgopolov, G.A. Evdokunin, B.I. Basylev

A new generation of single-phase, magnetic-bias-controlled arc-quenching reactors (AQMCRs), with an automatic control system (ACS) ensures continuous fine resonance tuning to network capacitance and permits almost non-inertial limitation of ground fault current with small values of residual current. In simplicity of construction, mass, and dimension, they are like standard analogous electromechanical devices. They are recommended for advanced use in electric networks of 6 to 35 kV of any type, but especially in the branched municipal networks of modern cities, new construction, and for the replacement of obsolete equipment.

Key words: electrical networks, arc-quenching reactors, magnetic bias, ground fault current, residual current.

The need for automatic ground-fault current compensation

According to rules adopted in Russia [1], 6 to 35 kV networks must have small ground fault currents and for that reason must work with neutrals that are either insulated or grounded by arc-quenching reactors. Failure in these networks is usually associated with damaged phase insulation and corresponding phase-to-ground faults.

Theoretically, reliable functioning of all electric-power supply systems can be ensured without disconnecting consumers during relatively long-lasting phase-to-ground fault conditions while damage is located and eliminated, or at least while back-up supply can be engaged. However, current must be small enough at the place of damage to ensure self-extinction or transition of arcing to stable state with only a small possibility of line-to-line breakdowns.

In Russia, currents of less than 5 A in networks containing high-voltage electric machines are considered safe, and currents of less than 10, 20, or 30 A are admissible in other 6, 10, 35 kV networks [2]. In many other countries, safety values are much lower. For example, in the US, long experience with 4 to 15 kV networks has resulted in a requirement of less than 7 to 10 A in all cases.

In accordance with Russian electrical station and network operating instructions [2], arc-quenching reactors must be installed in networks with high capacitive ground fault current.

The desired network behavior during single-phase-to-ground fault could be achieved by resonance tuning of the arc-quenching reactors. The features of this behavior would be minimum industrial frequency current component at the place of damage, minimum voltage-restoration speed after arc extinction, and minimum arc overvoltages during phase-to-ground fault.

In real conditions of changing network capacitance and insufficient power of arc-quenching reactors, and also absent automatic compensation systems, however, it is practically impossible to ensure such favorable resonance tuning of the reactors, especially because both overcompensation and provisional undercompensation are allowed by Russian electrical station and network operating instructions. Nevertheless, off-resonance detuning of the reactors is undesirable, not only because of the increase of the industrial frequency current component at the place of the fault, but also because detuning makes overvoltages worse [3].

Experience in 6 to 35 kV Russian networks with neutrals either insulated or grounded by non-controlled arc-quenching reactors has shown that lack of careful control of ground fault current (desirably not more than 5 to 10 A, taking into account the decompensation of arc-quenching reactors and active network losses, as well as higher current harmonics), lack of measures for overvoltage limitation, and lack of selective ground-fault protections, all lead to high network breakdown rate and often make it impractical to continue power supply during phase-to-ground fault conditions. With these deficiencies, instead of raising network reliability, continuing power supply during phase-to-ground fault conditions only raises the network breakdown rate.

Thus networks without smooth automatic ground-fault current compensation tend to experience a number of problems that result in the absence of arc self-extinction at the place of damage, significant network overvoltages, and serious power system breakdowns, among other things.

Arc-quenching, magnetic-bias-controlled reactors (AQMCRs)

The device which shows the most promise for resolving these problems is the arc-quenching, magnetic-bias-controlled reactor (AQMCR).

The first attempts to apply such devices were made as long ago as the first quarter of the 20th century [4], but they turned out to have a narrow usefulness, because they were expensive and bulky, produced significant distortion of current form by higher harmonics, and had a long transitional exit process to required functioning mode, among other things. However, these drawbacks were eliminated during the 1980’s with the development of magnetic-bias-controlled reactors with deep saturation of the magnetic circuit [5]. The theory and functionality of these devices are stated partially in [6-8].

Several dozen such reactors have been in successful use for the last ten years in Russia and other countries. Since 1996 the Energy Electrical Engineering Plant in Ramenskoe, near Moscow, has been producing them commercially [9-10]. In cooperation with other plants, Ramenskoe Energy also produces 20 and 35 kV magnetic-bias-controlled arc-quenching reactors with a rated power of up to 1,520 kVA.

Basic technical data for a 50 (60) Hz AQMCR are given in Table 1, and the principal circuit diagram of a controlled AQMCR and possible network circuit is shown in Figure 1.

Table 1
Basic technical data of a 50 (60) Hz AQMCR

Nominal Power, KVA	190		300		480		840
Nominal voltage, kV	11.0/√3	6.6/√3	11.0/√3	6.6/√3	11.0/√3	6.6/√3	11.0/√3
Current compensation control band (in long mode)	2.5 + 25.0	4.25 + 42.5	4 + 40	6.6 + 66.0	6.3 + 63.0	10.5 + 105	11 + 110
Current, A (in mode of 2-hour compensation)	30	50	48	80	76	126	132
Residual current, A, at the point of fault	<2.0	<2.75	<2.75	<3.5	<3.5	<5.0	<5.0
Overall dimensions, W/L/H and installation dimensions, A1/A2	1030 x 1165 x 1690 550 x 660		1180 x 1240 x 1890 550 x 820		1280 x 1320 x 1990 660 x 820		1980 x 1160 x 1950 1070 x 820
Full mass, kg	1200		1650		2450		3500
Mass of oil, kg							1000

As shown in Figure 1, the AQMCR consists of an electromagnetic component and a thyristor converter. Both are situated in a common oil-filled tank and are intended for outdoor use. An outline drawing of an AQMCR reactor is given in Figure 2.

The AQMCR must be completed with an automatic control system (ACS), without which the normal functioning of arc-quenching reactors is impossible. The control system is arranged in one body and intended for use in a closed, heated room. Table 2 shows the data for the ACS:

Table 2
AQMCR ACS Data

Source voltage	220V
Frequency	50 (60) Hz
Consumed power	Not more than 300 W
Accuracy class	2.0
Mass	3.2 kg
Dimensions	26 x 27 x 16 cm

An AQMCR may be connected to a three-phase network neutral either through a substation house transformer with the neutral available for connection or, as shown in Figure 1, through a zero-phase-sequence (ZPS) grounding filter— a “neutralizer”— a special three-phase grounding reactor similar to a transformer in design, with secondary windings that are zigzag connected to the primary windings, and with the neutral available for connection. This ZPS grounding filter has negligible impedance for zero-phase-sequence voltage, but very high impedance for positive and negative phase-sequence voltage, several times higher than the no-load (open-circuit) impedance of a two-winding transformer of the same power.

The Ramenskoe Energy company has mastered the production of such filters for AQMCRs with powers of 200, 310, 500, 875 kV-A for voltage 6 and 10 kV. They are about 40% lighter than the usual two-winding transformers of analogous description.

The AQMCR and its automatic control system (ACS) [11] were designed to accomplish the following functions without manual intervention:

- Distinguish normal network functioning mode and ground fault mode;
- Measure network capacitance in normal mode;
- Achieve non-inertial exit to capacitive current compensation mode during rise of ground fault;
- Maintain self-susceptance equal to network susceptance during restoration of normal mode after self-liquidation of fault (with reactance voltage not less than 15% nominal phase-to-ground network voltage);
- Self-diagnose reactor function both in network-capacitance measurement mode and in ground-fault current-compensation mode.

To determine damaged lines by means of a network relay protection system, the AQMCR was also designed to actively consume up to 25% of nominal reactive power of reactor for a short period.

The AQMCR can operate solo, in parallel with one or more other AQMCRs, or in parallel with ordinary electromechanical reactors.

Because of improved technology and design in both the electromagnetic component and the converter, AQMCRs not only work better than their analogues do, but also require only about half as much material to construct. In mass and dimensions they are equivalent to electromechanical (plunger) arc-quenching reactors [12].

Operation of the AQMCR

AQMCRs work in the following manner:

The ACS recognizes less-than-critical instantaneous ZPS voltage on the secondary winding of a voltage transformer, which is shown in Figure 1, as normal network functioning. Critical voltage is chosen as 15% of the rated maximal instantaneous (phase-to-ground) voltage at this winding.

In this mode, current pulses of 1 msec duration are generated by the ACS and propagated into the network through the AQMCR signal winding. The recurrence rate of current pulses depends on reactor power and network conditions, and is between 3 to 10 Hz. Current pulse charges network capacitance, and this is followed by damped voltage oscillation in network-reactor resonant circuit.

It is possible to calculate network capacitance, reactor inductance, and the Q-factor of the ZPS current circuit by the character of the fluctuating process. Indeed, network capacitive susceptance is inversely proportional to voltage increase speed at the neutral. Ratio of natural resonant frequency of the circuit to network operating frequency shows the off-resonance detuning of the reactor. Oscillation damping speed characterizes network Q-factor, and the minimum permissible interval between neighboring current pulses is determined by this parameter.

Measurement and memorizing of new network capacitive susceptance values is accomplished in the ACS only by the voltage increase speed in the neutral at the moment of current pulse generation. Capacitance measurement time is 10 to 20 times less than the network voltage oscillation period. This ensures high noise immunity in case of possible neutral voltage biases, due for example to network asymmetry or during random disturbances. Because current pulse is propagated into the network at the moment the first derivative of noise induced on the voltage transformer secondary winding crosses zero, noise immunity increases many times. Even with a 15% bias of the neutral, inaccuracy of network capacitance measurement is less than 2% (Table 1).

Information obtained by measuring network capacitance is used by the ACS to produce two types of instruction signals: One establishes and indefinitely maintains the necessary reactor inductive susceptance for fine resonance tuning to network capacitance. This signal acts on the reactor converter thyristors. The other signal acts on the magnetic system of the reactor to ensure that reactor-rod magnetic flux is biased to the point at which free components of reactor’s transient processes will be zeroed when ground faults occur, and a steady-state mode corresponding to fine tuning of the reactor to arc current compensation starts immediately. Power consumed by the control system from the network is less than 300 W (Table 1).

When ground faults occur and neutral voltage exceeds 15% of rated phase-to-ground voltage, the control system ceases to generate control pulses, and inductive susceptance equal to the last network capacitive susceptance obtained before the fault, is established in the reactor.

An example of further development of a 63 A capacitive current compensation process in an AQMCR 480-11/√3 (480kVA, 11/√3 kV) followed by fault extinction and restoration of normal mode is shown in Figure 3a. For comparison, Figure 3b shows the results of calculating the capacitive current compensation with equivalent inductance with linear characteristics. Clearly, the AQMCR’s performance is equivalent to the ideal.

Compensation of the first harmonic by the reactive capacitive current is instantaneous. Residual arc current is slightly distorted by higher harmonics, but the values do not exceed the active component of reactor current, and the active total current does not exceed 3 A. During fault extinction, the reactor maintains constant inductance, and natural resonance frequency in the reactor remains equal to network frequency. This ensures smooth phase-voltage restoration without overvoltages (Figure 3a). Here again, the AQMCR's performance corresponds to the ideal (Figure 3b).

Under other capacitive current values, the AQMCR limits the arc current with the same effectiveness. Table 3 and Figure 7 show ground-fault residual current values, obtained experimentally, in an AQMCR 480-11/√3. Residual current was defined by direct measurement of resultant current in the reactor and its capacitor bank, tuned in resonance with it. Oscilligraphy of the transition to steady-state mode during single and repeated ground faults at about 5-sec intervals was carried out in order to define the transient time constant.

Table 3
Experimentally obtained ground-fault residual current values in an AQMCR 480-11/Ö3

Reactor voltage, kV	6.36	6.36	6.24
Reactor current, A	31	62	74
Reactor power, kV-A	197	394	462
Residual current, A; manual/automatic control	1.8 / 2.4	2.4 / 2.4	3.2 / 3.4
Time of exit to capacitive current compensation mode, sec.	<0.02	<0.02	<0.02

Clearly, AQMCRs are distinctly nonlinear electronic devices, able to adjust automatically with precise and almost non-inertial resonance within a broad range of network capacitance alterations. At the same time, they behave linearly during capacitive current compensation, as ordinary inductors that ensure instantaneous arc-current limitation at the fault-point to values corresponding to the strictest international requirements.

Undistorted current form achieved through intensive magnetic saturation

The above conclusion contradicts rather old, but unfortunately oft-repeated misconceptions, that magnetic-bias-controlled ferromagnetic devices, and controlled reactors in particular, are inertial devices with distinct distortion of current form [13|.

Broad-band inductance alteration during the magnetic biasing process is achieved by the fact that the magnetic core of the reactor is flat-interleaved (imbricated) and without air clearances. When unidirectional magnetic biasing flux is lacking (stand-by or no-load mode), and when the inducing winding voltage is nominal, induction in all magnetic core cross-section does not exceed the value of steel saturation induction. Thus no-load current never exceeds 1 to 2% of nominal current.

Insignificant distortion of reactor current form is achieved by intensive (close to total) magnetic saturation in the basic operating section of the AQMCR's magnetic core and by less intensive saturation of other sections of the core [6].

As a result, for example in the harmonic composition of current in an AQMCR 480/√3 (Figure 4), there is practically only a third harmonic, which is less than 5% of reactor nominal current, and this 5% maximum is appreciable only in the initial stage of the saturation process. With increase of the first current harmonic, the absolute value of higher harmonics in the current decreases, but the active component conditioned by winding and magnetic-system losses begins to rise. Current-form alteration in AQMCRs 190, 300, and 840 is the same as in the AQMCR 480 shown in the figure.

AQMCRs are designed so that total residual current of higher harmonics and of active loss component in the whole band do not exceed the values indicated in Table 1.

As in all ferromagnetic devices such as transformers, transience to steady-state mode after connection to alternating voltage depends on the initial induction value of the AQMCR's magnetic system at the moment of its connection to the network. This process is shown in Figure 5 for an AQMCR 480-11/√3 under different magnetic-system residual induction values. With zero initial residual inductance, current increases smoothly from no-load current value to nominal with a time constant of about 1sec (Figure 5a). If initial residual inductance equals magnetic biasing induction in steady-state mode, then the transient process is absent (Figure 5b). And finally, if initial induction exceeds steady-state magnetic-biasing inductance, then transient process in the inducing winding of the reactor begins with values that exceed nominal current (Figure 5c).

Preparation for non-inertial mode change

In order to prepare the AQMCR for almost non-inertial transit to required compensation mode, it is necessary to arrange the thyristor control angles corresponding to required compensation current, and to make the value of initial induction equal to the magnetic biasing induction value in steady-state mode.

AQMCR inductance is prepared by the ACS before the phase-to-ground fault occurs— i.e. it's inductive susceptance is not zero. When ground fault arises, reactor voltage rises in less than 0.01 sec, and the reactor begins to compensate the capacitive current, until its inductance corresponds to network capacitive impedance.

Among arc-quenching reactors with magnetic biasing, preparation for non-inertial transience to steady-state is carried out only in AQMCRs. Analogous reactors either are not saturated at all in stand-by (ground fault waiting) mode, as we see in a controllable arc-quenching reactor 400 kVA, 11/√3 kV [14]; or are magnetized in advance by a compensation-mode magnetic biasing current in a separate winding, as in reactors with crosscut magnetic biasing [15]. In the first case, non-saturation of the reactor core results in capacitive current undercompensation during the transient period (Figure 5a). In the second case, crosscut magnetic biasing results in very deep overcompensation, due to magnetic amplification (Figure 5c).

No overvoltages

Some believe that overvoltages can arise in networks with magnetic-bias-controlled reactors because of alternating arc "peaks" together with strong oscillations of magnetic-bias-controlled reactor inductance. They suspect that, without reactance voltage, and consequently without magnetic biasing of the reactor, reactance inductance may become very high, resulting in high overvoltages because of strong changes of arc current.

These suspicions are unfounded. Calculations and experiments show that when ground faults occur at the moment of short-term current interruptions ("peaks"), reactance inductance remains on the same level, and does not reestablish instantaneously to high inductance. The reactor's lag effect and the ACS act to maintain reactance inductance at the level of compensation inductance (according to the network status as measured before the fault arises), until the fault is eliminated. The duration of peaks is very small in comparison with time interval between consequent network status measurements.

Increased current-protection relay reliability in urban networks

Contemporary electrical networks, especially in big cities, have branched configurations with multiple digressed feeders. The persistence of phase-to-ground faults in such networks may become inadmissible because overvoltages increase the possibility of double ground faults. Also, searching search for network damage by detaching individual cable lines significantly increases the possibility of equipment damage during the switching operations.

The drawback of traditional schemes with arc-quenching reactors is that damage to a feeder line in a branched cable network cannot be determined by standard current protection systems, which derives a signal to either alarm or disconnect in case of a fault.

In AQMCRs, reactor function can be combined with resistor function, if necessary. The signal winding of the AQMCR is made with higher rated active power and dynamic durability. Therefore a low-power (and inexpensive) resistor can be connected to its terminals. This connection can be limitlessly long with neutral voltage bias of not more than 15% of rated phase-to-ground voltage, and during a phase-to-ground fault, the resistor may shunt the signal winding for up to 1-3 seconds and be disconnected thereafter. To increase current-protection relay-operation reliability, short-term (up to 1 sec) closed-circuit faults of the signal winding are possible. Here, the active component of the reactive current reaches 25 to 30% of nominal reactive current. As result, electric current sufficient for current protection relay operations can be created in the damaged line only, by manual or automatic short-term connection of the resistor to the signal winding of the reactor.

The elaborated range of AQMCRs of different rated power permits to satisfy of demands for arc-quenching reactors for 6 to 35 kV networks. The Ramenskoe Energy plant has almost begun mass production of these reactors, and also of neutralizing ZPS grounding filters. A test station with a battery of capacitors and measuring and registering equipment has been brought into service. Apart from the usual factory commissioning tests, this makes possible the complex tuning of reactors and control systems to automatic non-inertial capacitive-current compensation mode. This significantly simplifies the in field commissioning of AQMCRs and in particular it makes artificial phase-to-ground fault commissioning tests at the substation unnecessary.

Other significant experimental results

Many interesting experimental results proving the theoretical data and parameter design of AQMCR reactors have been obtained. For example, oscillograms of transient process parameters show the almost non-inertial exit of an AQMCR 480-11/√3 reactor from stand-by mode to capacitive current compensation mode (Figure 6).

Figure 7 shows oscillograms of reactor current and voltage type in an AQMCR 300-11/√3 during repeated ground faults. At the very beginning of the first fault, and at subsequent faults, the reactor almost non-inertially passes into steady-state mode. Also, during elimination of faults, reactance current and related reactance voltage damping occur. Thus during fault interruption, the reactor maintains inductance— and as underlined earlier, this is important for arc “peaks” during short-term arc current interruptions.

Field experience

AQMCRs and their prototypes have been used in electrical networks of various purposes for more than 10 years now— in municipal cable and air distribution networks, industrial enterprises, house networks of electric stations, and elsewhere. Since 1996, the Ramenskoe Energy plant has been supplying AQMCRs and ZPS grounding filters to Russian and other networks. On average, these devices have brought about a 150 to 200% decrease in the number of phase-to-ground faults and have almost completely prevented their development into closed-circuit network faults between phases.

AQMCRs may be recommended mainly for separate installation in substations which are currently under planning or construction and for substations which do not yet have capacitive current compensation. They may be also be used successfully with already installed unregulated or step-regulated reactors. Adding AQMCRs to unregulated reactors can resolve the problem of automatic compensation of capacitive currents with values to several hundreds of amperes. The technical characteristics, mass, and dimensions of AQMCRs allow utilities to replace their electromechanical reactors without having to rebuild the substation.

Conclusions

1. Magnetic-bias-controlled arc-quenching reactors (AQMCRs) are a new generation of electromagnetic device with high dynamic characteristics and unlimited capacity for inductance alteration with mechanical shifts and changes in electric circuit.
2. They are as simple in construction, mass, and dimensions as ordinary transformers.
3. The Ramenskoe Energy plant has mastered the production of AQMCRs for electric networks of 6,10, and 35 kV, as well as the production of neutralizing zero-phase sequence (ZPS) grounding filters.
4. The functional capabilities of the AQMCR correspond remarkably to modern requirements, namely:
   - continuous fine tuning in resonance with network capacitance with exclusion of possible resonance and arc overvoltages in network and in reactor;
   - practically non-inertial ground fault current limitation in combination with smooth inductance alterations over a wide range;
   - guaranteed small values of residual current; and
   - the possibility of short-term creation of high active current in network functioning emergency mode for prevention of overvoltages and for selective search of damaged feeder by relay protection.
5. In the field, AQMCRs have brought about an average one-and-a-half to two times decrease in the number of phase-to-ground faults, and have almost completely eliminated the development of phase-to-ground faults into closed-circuit network faults between phases.
6. AQMCRs may be recommended for advanced use in electric networks of 6 to 35 kV of any type, but especially in the branched municipal network of modern cities, new construction, and for the replacement of obsolete equipment.

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FIGURES:

Fig. 1. Circuit of connection of magnetic-bias-controlled arc-quenching reactor (AQMCR) to three-phased network:

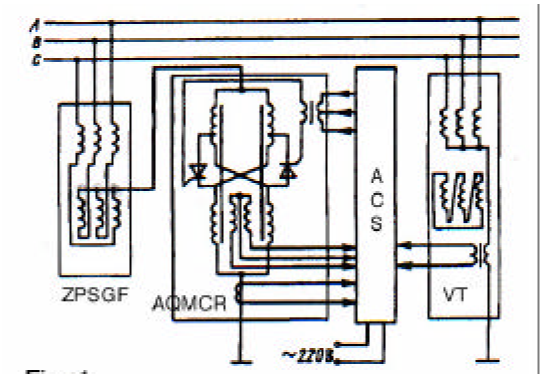

Fig. 1

- AQMCR Arc-Quenching Magnetically (magnetic biasing) Controlled Reactor
- ACS - Automatic Control System
- ZPS GF: Zero-Phase-Sequence Grounding Filter (oil-cooled 3-phase grounding reactor - "neutralizer" for creation of "artificial" neutral)
- VT: Voltage Transformer

Fig. 2. Design and basic dimensions of AQMCRs.

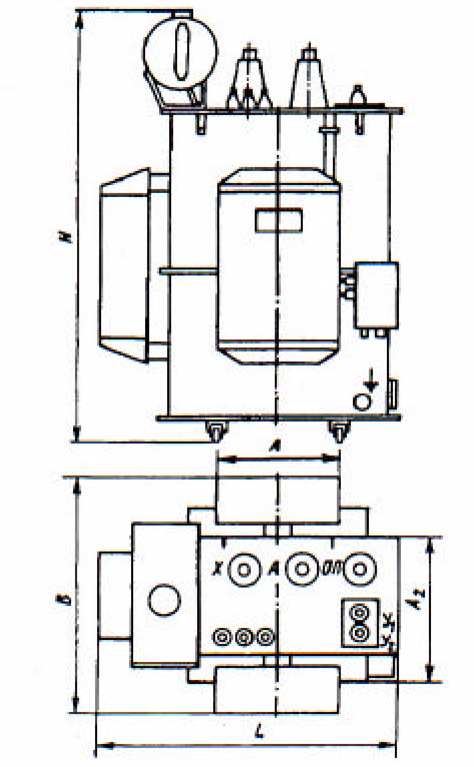

Fig. 2

Fig. 3. Curves of the transient process during single phase-to-ground fault (calculation):

(a) neutral is grounded by AQMCR 480-11/√3;

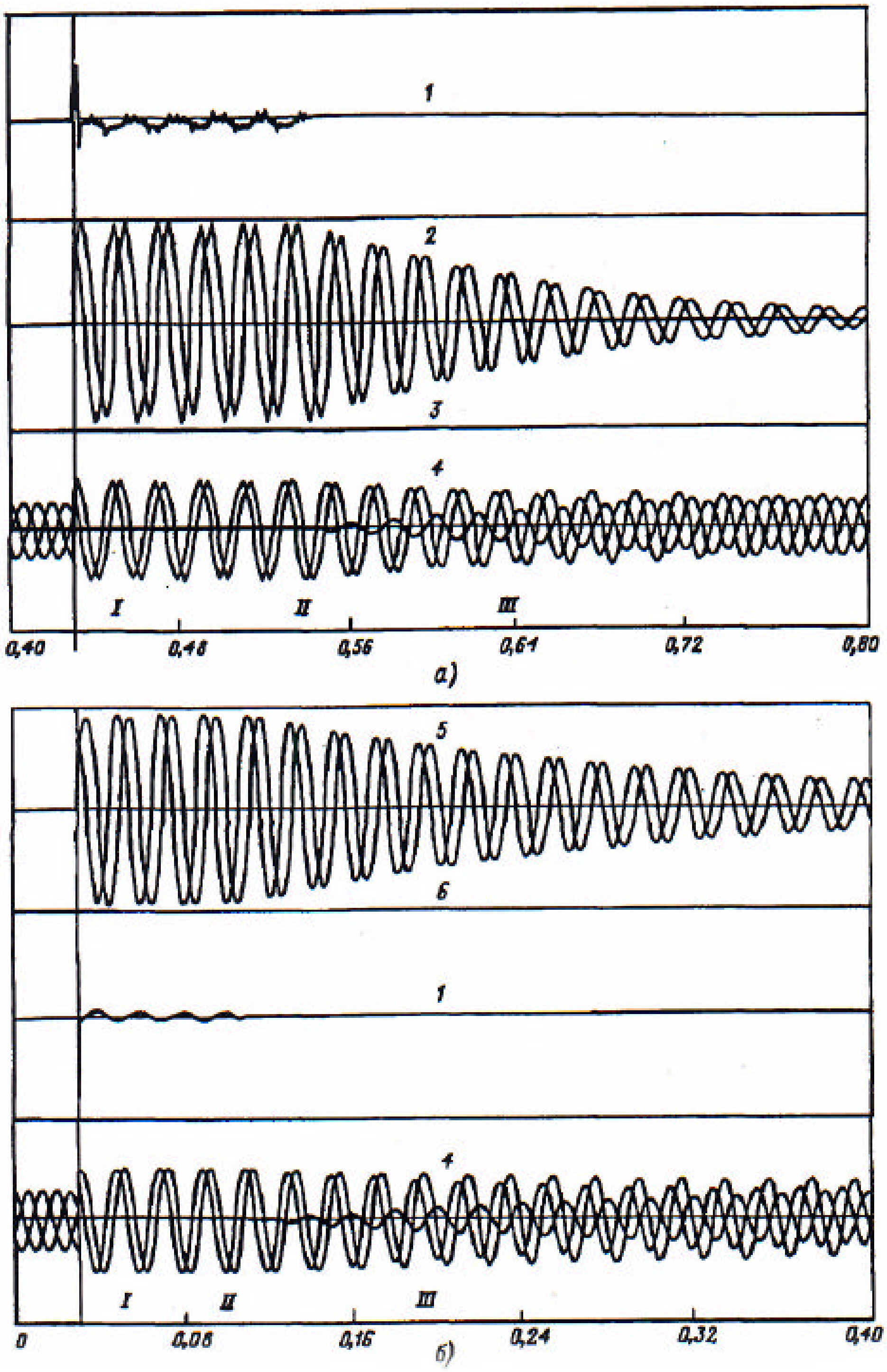

Fig. 3

(b) Equivalent constant inductance in the neutral;
(I) Normal network functioning mode;
(II) Phase-to-ground fault;
(III) Reestablishment of normal functioning after fault extinction;
(1) Ground fault current;
(2) Reactance voltage;
(3) Reactor current;
(4) Network phase voltage;
(5), (6) Voltage and current of equivalent inductance correspondingly.

Fig. 4. Nonlinear distortions of AQMCR 480-11/√3 current:
(1) Root-mean-square for higher current harmonics (current of distortion);
(2) Third current harmonic.

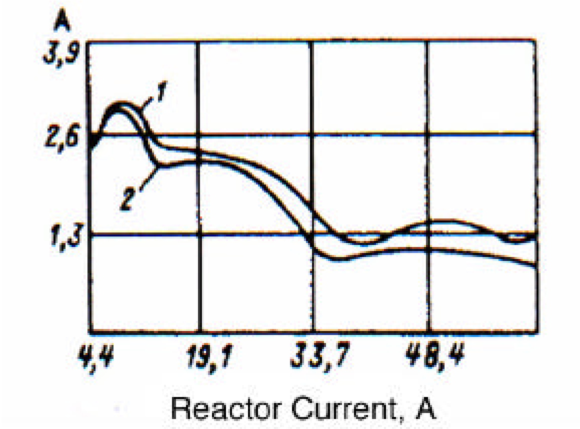

Fig. 4

Fig. 5. Curves of transit process in AQMCR 480-11/√3 to steady-state mode under different initial values of magnetic-core rod induction (calculation):

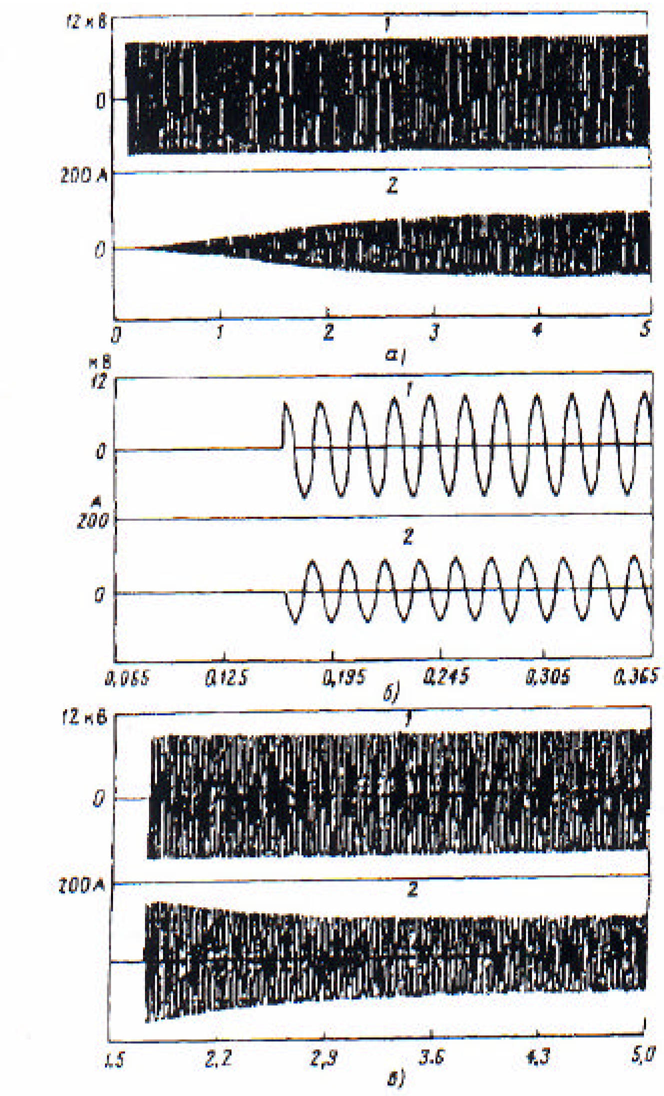

Fig. 5

(a) No initial induction;

(b) Initial induction equal to steady-state value value of magnetic bias induction;

(c) Initial induction exceeds steady-state value value of magnetic biasing induction;

(1) Reactor voltage;

(2) Reactor current.

Fig. 6. Oscillograms of transient process, experimentally proving almost non-inertial exit of AQMCR 480-11/√3 from stand-by (ground fault waititg) mode to capacitive current compensation mode, obtained during test of reactor at Ramenskoe Energy plant:

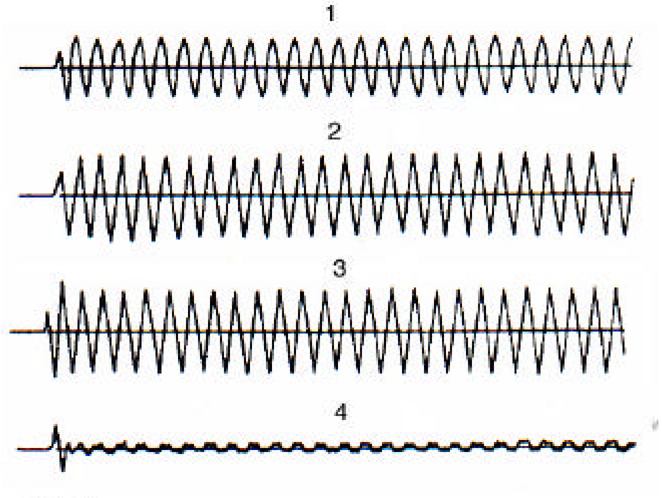

Fig. 6

(1) Reactor and capacitor bank voltage;

(2) Reactor current;

(3) Capacitor bank current;

(4) Total current.

Fig. 7. Oscillograms of current (a) and voltage (b) of AQMCR 480-11/√3 during repeated phase-to-ground faults (obtained at Ramenskoe Energy plant).

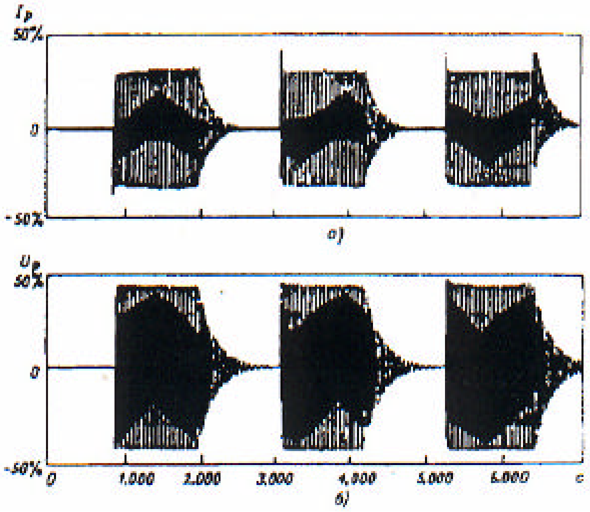

Fig. 7