ENERGY SYSTEMS AND ELECTRICAL NETWORKS

THE PROBLEM OF COORDINATION OF LEVELS OF SHORT-CIRCUIT CURRENTS IN POWER SYSTEMS

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The problem of coordination of short-circuit (fault) currents is considered. Data on the dynamics of variation of the levels of single-phase and three-phase short-circuit currents (their highest values) in networks rated for different voltage are presented for a long-term period. The main factors (integral parameters of the networks) affecting the values of short-circuit currents are listed. Statistics of variation of rated parameters of electrical equipment in past years and in the recent period is presented and predictions for the future are made. Basic methods and means for limiting short-circuit currents are discussed. A method of automatic and stationary network separation and a method of circuit design are described in detail. The efficiencies of different methods are compared. The effect of integral parameters of the network on the maximum level of short-circuit currents is shown. The aspects of the switching life of breakers and of allowance for probabilistic characteristics of faults and for the risk factor of decision-making are considered. It is shown that coordination of the levels of short-circuit currents is a possible means for raising the reliability of power installations and systems.

Keywords: short-circuit current, coordination of levels of short-circuit currents, level of short-circuit current, limitation of short-circuit currents, parameters of electrical equipment, structure and parameters of power systems, influencing factors, standardization of parameters of electrical equipment, methods and means for limiting short-circuit currents.

Statement of the problem. In different-voltage networks of power systems the level of short-circuit (fault) currents increases continuously to this or that degree. The requirements on electrical equipment, conductors, line (auto)transformers, and design of switchgears become more and more rigid. The problem of optimum agreement between the dynamics of the parameters of electrical equipment and the requirements of power systems or of coordination of the parameters of electrical equipment with the existing or expected levels of short-circuit (SC) currents becomes urgent [1].

The problem is comparatively new; it appeared in the 1960 – 1970s due to the rapid development of the power industry manifested by growth in the unit power of generating units, power plants, substations, and power systems rated for medium, high, extrahigh, and ultrahigh voltages. The problem should be solved by a system approach with allowance for the dynamics of variation of SC currents and parameters of electrical equipment, results of new developments in electrical power engineering, and requirements on the reliability and efficiency of operation of power systems. This is part of the more general problem of designing the structure, parameters, and operating conditions of power systems and their components, which is solved in all stages of power system control from prediction and planning to design and operation. The problem is quite complex and requires consideration of interrelated aspects. The results presented in the given paper have been obtained by workers of the department of power plants of the Moscow Power Institute in cooperation with workers of the research department. The list of publications presented in the references, which is by far not full, confirms this circumstance.

Levels of short-circuit currents and dynamics of their variation. We are interested in the maximum (highest) values $I_{\mathrm{s.max}}$ of three-phase $I_{\mathrm{s}}^{(3)}$ and single-phase $I_{\mathrm{s}}^{(1)}$ short-circuit currents ($I_{\mathrm{s.max}}^{(3)}$ and $I_{\mathrm{s.max}}^{(1)}$) at design operating conditions of an electrical installation or a power system. Their dynam-

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ics is analyzed with prehistory (10 – 25 years) and for the coming 10 – 15 years. Data are commonly taken from computations of short-circuit currents in electrical networks under conditions of maximum load.

The dynamics of the levels of SC currents in power systems of the USSR is presented in [2]. As an example, we give the variation of $I_{s.max}$ in 110 – 500-kV networks of one of the largest regional power systems of the country for over 50 years (in what follows we will use the term "regional power system") in Table 1. Stabilization of SC currents at a level of 40 kA in 110 – 220-kV networks is a consequence of their purposeful limitation. Without this measure fault currents in a considerable number of nodes of 110 – 220-kV networks would have exceeded 100 – 130 kA and would have required replacement of 1/3 of the installed switching units.

Information of the levels of SC currents is also frequently presented in the form of current-time characteristics and curves of distribution over different-voltage networks and nodes of different networks of specific power systems.

Basic influencing factors. The maximum permissible level of SC currents in networks rated for different voltage is an important performance characteristic of a power system. The requirements on switching equipment should allow for the strategy of development of the systems, power plants, and networks, for the potential availability of equipment with specified parameters, for the reliability of operation of power plants, substations, load centers, and systems as a whole, and for the cost of creation of a network with this or that maximum level of SC currents.

The value of SC current depends on the structure and parameters of the electrical network, on the installed power of the generators feeding the networks of generator and enhanced voltage, and on the installed power of (auto)transformers that realize coupling with networks rated for another voltage and are fed from other sources. In this connection, the maximum level of SC currents depends on the integral parameters of networks. These parameters include the density of the electric network σ_c (in km/km^2), the area of power supply s_{ps} per one substation, and the average length l_{av} of lines of the considered voltage class. These parameters characterize the rigidity of electric coupling in the power system and are computed as follows: $\sigma_c = l_\Sigma/s$, $s_{ps} = s/n_{ss}$, $l_{av} = l_\Sigma/n_l$, where l_Σ is the total length of lines of the considered voltage class in a region with area s, km; n_{ss} is the number of substations therein, and n_l is the number of lines therein.

Standardiation of parameters of electrical equipment. The power industry continuously improves the design of electrical equipment and advances its parameters and characteristics in order to meet the tightening requirements of the developing power systems. Table 2 presents the dynamics of variation of rated breaking currents $I_{br.rat}$ of circuit breakers covering the statistics of past years, the recent period, and predictions made with allowance for the attained world level.

The rated parameters of electrical equipment are standardized. The currents of the equipment and the power of line (auto)transformers are standardized on the basis of a series of preferred numbers. However, the scale of complex power of generators (especially of hydrogenerators) is not based on this rule, which complicates the choice of elements for units. We suggest a gradation of rated breaking currents on the basis of the data of Table 2 and of a series of preferred numbers (Table 3).

Methods and means for limiting short-circuit currents. The following methods for limiting SC currents are known: circuit design, stationary and automatic separation of the existing networks in operation, use of current-limiting devices of various kinds, use of current-limiting reactors and resistors for limiting short-circuit currents to ground, which are connected to neutrals of power unit transformers and coupling autotransformers, and partial ungrounding of transformer neutrals.

The means for limiting SC currents include single and mutually coupled reactors, (auto)transformers with split low-voltage windings, resonance current-limiting devices of various kinds, surge current limiters, back-to-back direct-current

TABLE 1. Highest Values of Short-Circuit Currents in Networks of the Regional Power System

Year	SC current, kA, at line voltage, kV					
	110		220		500	
	$I^{(3)}_{s.max}$	$I^{(1)}_{s.max}$	$I^{(3)}_{s.max}$	$I^{(1)}_{s.max}$	$I^{(3)}_{s.max}$	$I^{(1)}_{s.max}$
1950	11.6	11.0	7.8	7.1	–	–
1955	14.3	10.8	8.2	7.6	–	–
1963	25.8	31.2	13.5	13.0	10.7	11.6
1965	30.6	36.9	16.4	15.3	13.1	13.9
1970	39.5	44.7	32.0	36.9	16.6	17.6
1975	32.6	33.9	27.5	25.6	19.5	18.1
1980	34.5	37.2	30.7	29.5	21.8	19.8
1985	35.0	41.1	34.6	36.2	27.8	22.8
1990	34.5	38.7	36.3	36.5	31.7	28.2
1995	34.6	38.9	34.1	33.0	31.3	30.5
2000	30.4	37.6	35.3	34.9	32.5	29.6
2004	30.9	37.5	35.6	37.9	32.8	33.9

TABLE 2. Dynamics of Variation of Highest Levels of Rated Breaking Currents of Circuit Breakers for Different-Voltage Networks

Voltage, kV	$I_{br.rat}$ of circuit breakers, kA						
	dead tank	live tank	air	SF_6	electromagnetic	vacuum	thyristor
6	4.8/–/–	17.5/–/–	–/–/–	–/40/40	20/40/50	10/40/63	–/–/20
10	5.8/–/–	45/105/125	15/–/–	–/40/50	20/40/40	10/40/63	–/–/20
20	–/–/–	87/100/125	115/160/250	–/–/40	–/–/–	–/20/100	–/–/–
35	16.5/50/–	8.25/16/31.5	16.5/40/50	–/–/40	–/–/–	–/20/31.5	–/–/–
110	13/50/–	13/40/40	13/50/63	31.5/40/63	–/–/–	–/20/40	–/–/–
150	–/–/–	–/–/40	23/45/50	–/–/50	–/–/–	–/–/40	–/–/–
220	6.5/40/–	21/40/40	18.4/63/63	31.5/50/63	–/–/–	–/–/40	–/–/–
330	–/–/–	–/–/–	26.2/63/80	–/63/80	–/–/–	–/–/–	–/–/–
500	13.9/–/–	–/–/–	23/63/80	–/50/80	–/–/–	–/–/–	–/–/–
750	–/–/–	–/–/–	27/63/100	–/50/100	–/–/–	–/–/–	–/–/–

Note. The first figure in the stroked row represents the period of the 1950 – 1980s; the second figure represents the period from the1990s till today; the third figure represents prediction until 2020.

TABLE 3. Series of Rated Breaking Currents of Circuit Breakers at Limited Levels of Short-Circuit Currents in Networks of Power Systems

Voltage, kV	Recommended series of $I_{br.rat}$, kA																
6	6.3	8	10	12.5	16	20	25	31.5	40	50	–	–	–	–	–	–	–
10	6.3	8	10	12.5	16	20	25	31.5	40	50	63	80	100	125	–	–	–
20(27)	–	–	–	–	–	20	25	31.5	40	50	63	80	100	125	160	200	250
35	6.3	8	10	12.5	16	20	25	31.5	40	50	–	–	–	–	–	–	–
110	–	–	–	–	–	20	25	31.5	40	50	63	–	–	–	–	–	–
150	–	–	–	–	–	20	25	31.5	40	50	–	–	–	–	–	–	–
220	–	–	–	–	–	20	25	31.5	40	50	63	–	–	–	–	–	–
330	–	–	–	–	–	20	25	31.5	40	50	63	80	–	–	–	–	–
500	–	–	–	–	–	20	25	31.5	40	50	63	80	–	–	–	–	–
750	–	–	–	–	–	20	25	31.5	40	50	63	80	100	–	–	–	–
1150	–	–	–	–	–	20	25	31.5	40	50	63	80	100	–	–	–	–

TABLE 4. Dynamics of Points of Network Separation of the Regional Power System

Kind of network separation	Year	Number of separation points in networks			
		110 kV	220 kV	500 kV	Total
Stationary	1978	45	11	–	56
	1983	68	11	–	79
	1993	88	17	–	105
	2000	94	18	–	112
Automatic	1978	7	2	–	9
	1983	21	3	–	24
	1993	20	3	–	23
	2000	22	4	–	26

converters, and devices employing high-temperature superconductivity.

Efficiency of separation of electrical network and circuit design. The urgency of the problem of limitation of SC currents has not been removed [3]. To some degree this can be inferred from the dynamics of separation of networks of the regional power system (Table 4).

About 20% of the largest switching nodes in 110 – 220-kV networks have been subjected (Table 4) to stationary separation on bus-tie and section switches. Automatic separation of networks is used more rarely. It does not decrease the electrodynamic effects on the electrical equipment of connections and requires higher ratios of the limiting through currents of circuit breakers to their breaking currents. Otherwise, it becomes necessary to allow for the risk of operation of the equipment in the zone of nonstandardized parameters.

The highest rate of growth in the number of separation points of networks (10% a year) was observed (Table 4) up to the middle 1980s, when the power systems of the country developed very intensely. Decline of power consumption and low volumes of construction of generating units and electrical networks characterized the period of 1990 – 1996. Starting with 1997 the consumption grew again. Thus, in the 1990s it became possible to match to a certain degree the clearing capacity of the switching devices to the attained short-circuit currents (Table 5).

Despite the considerable volumes of network separation, the rated breaking currents of installed circuit breakers are often lower than the highest theoretical SC currents, i.e., the breakers have inappropriate clearing capacity. This is typical not only for the considered system but for other regional power systems of the country too [2]. This is connected with the high cost of updating and replacement of electrical equipment.

TABLE 5. Dynamics of the Number of Installed Circuit Breakers with Inappropriate Breaking Capacity in the Regional Power System

Rated voltage of the network, kV	Number of breakers with inappropriate breaking capacity in year		
	1978	1983	2000
110	113(7.3)	140(8.9)	26(1.0)
220	34(8.2)	90(21.1)	18(3.1)
500	0	13(28.3)	13(20.6)
Total	147	243	57

Note. The percentage of the total number of circuit breakers of the given voltage class is given in parentheses.

The efficiency of stationary separation of networks is determined by computing SC currents for the existing normal layout of the networks at maximum load and for a layout where separation of the network is eliminated (forced liquidation of all points of stationary separation of the network) [4]. For example, the loading diagram of the regional power system consists of 958 110-kV nodes, 180 220-kV nodes, and 22 500-kV nodes. The number of nodes n_n in the loading diagram exceeds the number of switchgears n_s of the considered voltage class. This is explainable by the fact that the coding of nodes in the loading diagram of a network fixes every system (circuit with two systems of buses with or without transfer bus) or a section of a system of mains (circuit with one sectionalized system of buses with or without transfer bus).

Figure 1 presents the integral distribution of SC currents over nodes of the 110 – 500-kV network of the regional power system. Analysis of the available data shows some regular features. First, liquidation of points of stationary separation increases substantially (by a factor of 1.9 – 4.4) the maximum SC currents (Table 6) in the 110 – 220-kV network. They can exceed 130 kA. The value of $I_{s.max}$ increases by a factor of 3 – 4 in a electrical installation with two sectionalized systems of mains. Under normal operating conditions the switchgear is divided into four directly uncoupled parts, and stationary separation is provided by two tripped bus-tie switches and two tripped section switches. The short-circuit current increases by a factor of 4.4 when they operate and the point of fault is simultaneously fed from the adjacent power node, where the points of stationary separation of the network are also liquidated.

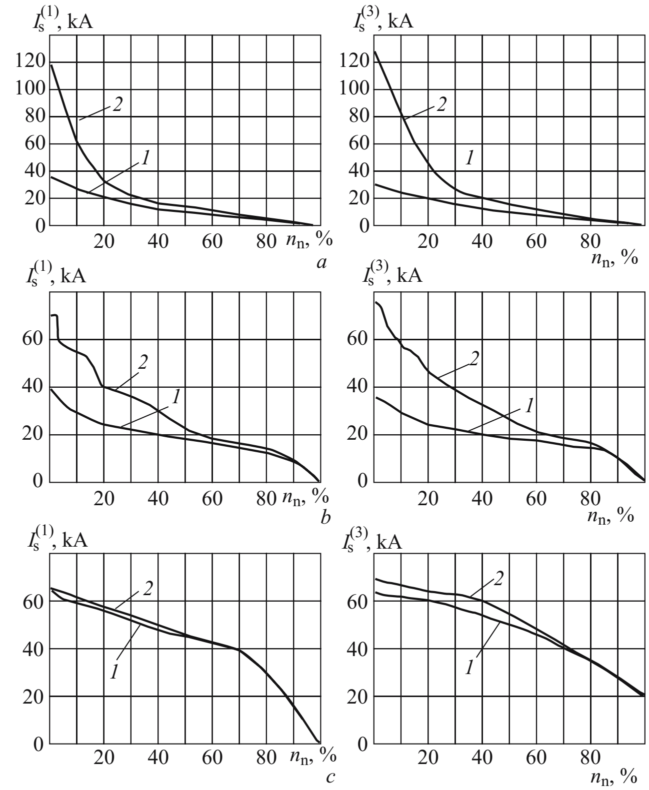

Fig. 1. Integral distribution of single-phase and three-phase short-circuit currents in networks: *a*, 110 kV; *b*, 220 kV; *c*, 500 kV; *1*, actual circuit with open points of stationary separation of network; *2*, circuit with forcibly closed points of stationary separation of network.

Second, the curves of integral distribution of SC currents (Fig. 1) reflect a generalized effect of current limitation in the form of the proportion $k_{lim} = A_2/A_1$ (Table 7), where A_1 is the area of the figure formed by the coordinate axes and curve *1* of integral distribution (distribution in the actual circuit with open points of stationary separation) and A_2 is the same for curve *2* (in the circuit with closed points of network separation). The value of the coefficient k_{lim} can be treated as the mean limitation of SC currents per each node of the network.

Third, due to the stationary separation of 20% of the largest 110 – 220-kV switching nodes, SC currents have been stabilized at a level of up to 40 kA in all nodes of the 110 – 220-kV networks of the considered power system,

TABLE 6. Maximum Design SC Currents in the Regional Power System

Parameter	Maximum SC current, kA, in networks		
	110 kV	220 kV	500 kV
Loading diagram of the network:			
actual with open points of stationary separation of network	37.5/30.9	37.9/35.6	33.9/32.8
with forcedly closed points of stationary separation of network	121.4/134.4	71.9/74.8	33.9/35.0
Growth in SC current, rel. units	3.2/4.4	1.9/2.1	1.0/1.07

Note. The numerators present single-phase SC currents; the denominators present three-phase SC currents.

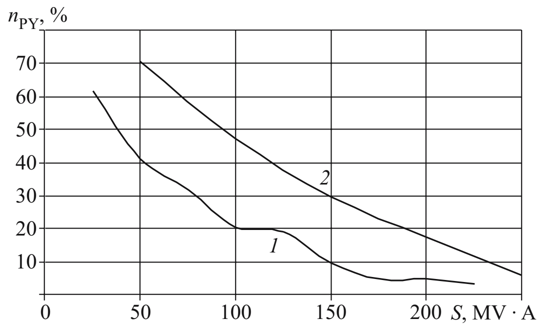

Fig. 2. Integral distribution of power flows on buses of electrical installations: *1*, 110 kV; *2*, 220 kV.

which made it possible to use electrical equipment with relatively low switching capacity and thus relatively low cost.

Theoretically, liquidation of points of stationary separation of 110 – 220-kV networks and the resulting growth in the levels of SC currents can lead to a situation where 832 (33%) of the 2520 110-kV circuit breakers operating in the regional system (Table 8) will require replacement as well as 216 (36%) of the 595 220-kV breakers.

Circuit breakers with $I_{br.rat}$ = 80 kA are one-off devices and breakers rated for 100 kA are used in single cases in the world. Therefore, we can speak of only conservative estimates of the cost of breakers with $I_{br.rat}$ = 80 – 160 kA. In the first approximation it should be proportional to $I^2_{br.rat}$. The cost of a breaker rated, for example, for 110 kV with $I_{br.rat}$ = 80 – 160 kA can be $100,000 – 400,000. Additional expenses for design, construction, and make-ready work will increase the cost by at least 30%. For comparison, the trade price of a 100-MW turbogenerator without auxiliary systems is about $1,000,000.

TABLE 7. Generalized Effect of Current Limitation Due to Stationary Separation of the Network

Network, kV	Coefficient k_{lim}, rel. units, due to SC	
	single-phase	three-phase
110	1.91	2.08
220	1.47	1.56
500	1.02	1.05

According to a conservative estimate, the cost of replacement of circuit breakers due to the marked increase in the levels of SC currents in the course of liquidation of points of stationary separation of 110 – 220-kV networks in only one regional power system (Table 4) should be no less than $120,000,000.

Circuit design commonly consists in transition from circuits with busbars in electric installations to block or half-block (mixed) circuits and matching of the power production by power plants with that of the adjacent networks of the power system. Thus, we can state that stationary separation of an electrical network divides the switching nodes into electrically untied parts. The same principle is used in the “branching from passing lines,” “in-out,” and other circuit design solutions.

Circuit design is used more frequently in two-transformer step-down substations for inserting them into two-circuit transit. It is obvious that the current-limiting effect here has a local nature, i.e., acts only for the considered subdivided node of the network.

The negative effect of stationary separation of a network consists in disturbance of the natural distribution of the flows of active power. This is accompanied by growth in the power losses in the network. Figure 2 presents the integral distribution of possible power flows through bus-tie or section switches upon liquidation of points of stationary separation of 110 – 220-kV networks (Table 4) in switchgears of the respective voltage classes.

It can be seen from Fig. 2 that the values of power flows are quite high. In separation of the network they are distributed over the network of the power system instead of the mains of electrical installations that have negligibly low resistivity. However, the power losses do not grow noticeably due to the relatively small distances between nodes in the network. For example, stationary separation of the network in the regional system considered increases the loss in the active power from 345 to 381 MW in networks rated for 110 kV and higher. The cost of the lost power here is several times lower than the cost of replacement of circuit breakers for ensuring the requisite $I_{br.rat}$. In addition, we should take into account the maintenance of electrodynamic stability of the (auto)transformers and switchgear busbars. Thus, it can

TABLE 8. Number of 110-kV Circuit Breakers to Be Replaced in Liquidation of Stationary Separation of Network in the Regional Power System

$I_{br.rat}$ of installed breakers, kA	Number of circuit breakers									
	total number of breakers requiring replacement	their part to be replaced by breakers with $I_{br.rat}$, kA								
		20	31.5	40	50	63	80	100	125	160
<20	12	4	8	–	–	–	–	–	–	–
20	171	–	74	24	6	15	8	25	19	–
31.5	333	–	–	53	41	21	25	117	56	20
40	310	–	–	–	42	91	51	93	33	–
50	6	–	–	–	–	–	4	2	–	–
Total range	832	4	82	77	89	127	88	237	108	20

be inferred that stationary separation of an electrical network is objectively the most effective method for limiting the levels of SC currents.

Efficiency of limitation of short-circuit currents to ground. The methods for limiting SC currents to ground have always attracted attention. The tendency to supply the power produced by power plants to networks rated for 220 kV and higher, when it is necessary to ground the neutrals of power unit transformers, and the use autotransformers operating with grounded neutrals, often creates such conditions in networks of power systems when $I_s^{(1)} > I_s^{(3)}$. This circumstance makes it necessary to check the switching capacity of circuit breakers with respect to $I_s^{(1)}$ and complicates the conditions of their operation, because single-phase faults appear much more frequently (by more than a factor of 40) than three-phase faults.

The following relation holds for networks with this or that kind of grounding of (auto)transformer neutrals if we neglect the active components of the resistances and assume that $x_2 = x_1$:

$$I_s^{(1)}/I_s^{(3)} = 3/(2+\alpha);\ \ \alpha = x_0/x_1,$$

where x_1, x_2, and x_0 are equivalent resistances of the circuits of positive-, negative-, and zero-phase sequences, respectively, with respect to the fault point. If $\alpha < 1$ we have $I_s^{(1)} > I_s^{(3)}$; at $\alpha \to 0$ we have $I_s^{(1)} \to 1.5 I_s^{(3)}$.

The condition $I_s^{(1)}/I_s^{(3)} \le 1$ $(\alpha \ge 1)$ is favorable for the formation of an electrical network. Parameter α depends on the kind of grounding of the neutrals and is related to the grounding factor as

$$K_{\text{ground}} = \frac{U_{\text{i.ph}}}{U_{\text{n.rat}}} = \frac{\sqrt{\alpha^2 + \alpha + 1}}{\alpha + 2},$$

where $U_{\text{n.rat}}$ is the rated voltage of the network and $U_{\text{i.ph}}$ is the voltage of the intact phase at single-phase fault in the network.

To suit the operating conditions, the insulations of electrical installations of a 110-kV (and high-voltage) network should be grounded effectively, i.e., the voltage of the intact phases at an ground fault at any point should not exceed 80% of the line (1.4-phase) rated voltage. The latter is determined by the operating conditions of what are known as 80% dischargers mounted in the network and is obeyed at $\alpha < 5$ (if we neglect the active resistances of the network components).

On the whole, when choosing the mode of grounding of 110-kV (and higher-voltage) networks determined by the mode of grounding of neutrals we should ensure the following conditions:

$$I_s^{(1)}/I_s^{(3)} \le 1\ \ (\alpha \ge 1);$$

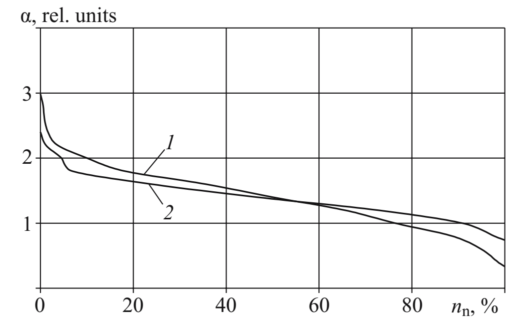

Fig. 3. Integral distribution of parameter α: *1*, 110 kV; *2*, 220 kV.

$$K_{\text{ground}} = U_{\text{i.ph}}/U_{\text{n.rat}} \le 0.8\ \ (\alpha < 5);$$

$$U_{\text{nt}} \le U_{\text{nt.per}};\ \ U_{\text{nt.per}} \le U_{\text{nt.per.imp}};$$

where $U_{\text{nt.per}}$ and $U_{\text{nt.per.imp}}$ are the permissible test (one-minute) commercial-frequency voltage and the permissible impulse voltage on the neutral due to a fault or another transient process in the network.

The neutrals of existing transformers rated for 110 kV and higher voltage and of autotransformers rated for 220 kV and higher voltage commonly have insulation of the 35-kV class at one-minute test voltage of 85 kV. As a rule, the mode of partial ungrounding of the neutrals is permissible only for 110-kV transformers. In 220-kV and higher-voltage networks the currents of single-phase faults are limited by inserting reactors or resistors into the neutrals of (auto)transformers.

The regional system considered has 168 transformers with ungrounded neutrals or 18% of the total number of 110-kV transformers. The 220-kV and higher-voltage transformers have dead grounding of the neutrals, because the latter have a weakened insulation (of the 35-kV class) with $U_{\text{nt.per}} = 85$ kV. The twelve 500/110 and 500/220 kV autotransformers are equipped with current-limiting reactors. The limiting ratio $I_s^{(1)}/I_s^{(3)}$ is insufficient (Tables 6 and 7) for the requisite limitation of the levels of short-circuit currents. With allowance for the structure and parameters of actual adjacent networks the effect due to the limitation of short-circuit currents to ground is even lower. Figure 3 presents the integral distribution of parameter α in 110 – 220-kV networks of the regional power system. Its range is $0.33 \le \alpha \le 2.99$ (110 kV) and $0.74 \le \alpha \le 2.21$ (220 kV). Consequently, the condition that $\alpha < 5$ is obeyed at every node of the network. In 24 and 12% nodes at 110- and 220-kV networks, respectively (Fig. 3), the condition that $\alpha \ge 1$ is not obeyed, i.e., $I_s^{(1)} > I_s^{(3)}$ $(\alpha < 1)$.

The effect of α on the proportion of $I_s^{(1)}$ to $I_s^{(3)}$ can be inferred from Figs. 4 and 5. The coefficient $K_\alpha = [(I_s^{(1)} - I_s^{(3)})/I_s^{(3)}] \times 100$ reflects the proportion of $I_s^{(3)}$ to $I_s^{(1)}$ in percent, i.e., $-28.1 \le K_\alpha \le +38.0\%$ (110 kV) and $-9.5 \le K_\alpha \le +28.6\%$ (220 kV). The absolute difference $I_s^{(1)} - I_s^{(3)}$ shows that in the

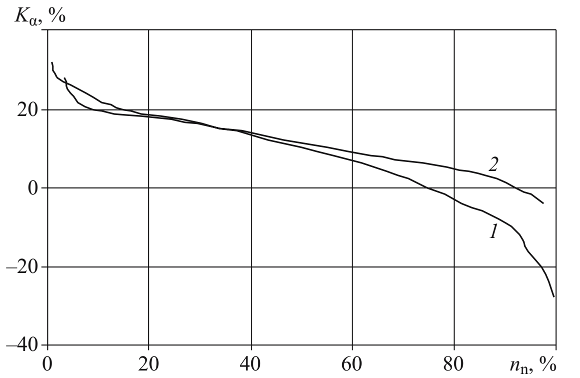

Fig. 4. Integral distribution of coefficient K_α: *1*, 110 kV; *2*, 220 kV.

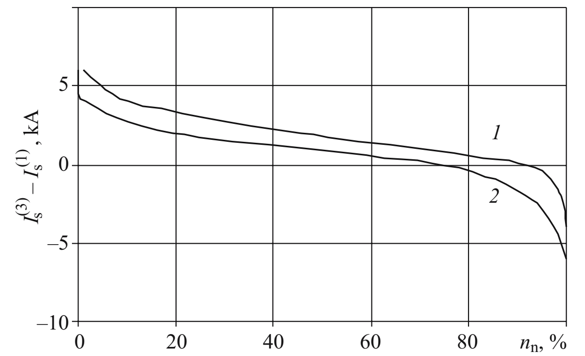

Fig. 5. Integral distribution of the absolute difference $I_s^{(1)} - I_s^{(3)}$: *1*, 110 kV; *2*, 220 kV.

majority of nodes of the network (94% for 110 kV and almost 100% for 220 kV) $I_s^{(1)} - I_s^{(3)} > -2$ kA ($-6.2 \le I_s^{(1)} - I_s^{(3)} \le +6.5$ kA at 110 kV and $-2.6 \le I_s^{(1)} - I_s^{(3)} \le +7.4$ kA at 220 kV).

The value of 2 kA corresponds to 10% of the minimum breaking capacity of the breakers (99.9% circuit breakers of the power system with $I_{br.rat} \ge 20$ kA) and is equal to the 10% error taken in computation of SC currents during checks of switchgears for the breaking capacity and thermal and electrodynamic stability, and in the choice of settings for devices of relay protection and automatics. Consequently, from the standpoint of the choice of rated parameters of circuit breakers the potential effect due to limitation of single-phase short-circuit currents to the level of three-phase currents ($\alpha = 1$) is comparable with the error of computation of the currents themselves.

This occurs because the value of $I_s^{(1)}$ is proportional to $3(x_1 + x_2 + x_0)$. As a rule, $x_1 \approx x_2$. Therefore, the noticeable decrease in x_0 is balanced in the sum of $x_1 + x_2 + x_3$. For example, in the overwhelming majority of nodes of the 110 – 220-kV network (Fig. 4) $x_0 > 0.8x_1$. At the given 20% decrease in x_0 relative to the case of $x_1 = x_0$ the current $I_s^{(1)}$ increases by only $(3.0/2.8) \times 100 - 100 = 7\%$. However, for the power system to function normally the current limitation factor at any kind of fault should be several times higher (Table 4). Similar effects lead to comparatively low current-limiting properties of reactors and resistors inserted into neutrals of (auto)transformers [5] and to partial ungrounding of transformer neutrals [6].

In order to limit single-phase short-circuit currents at problem nodes (five large substations and one power plant) 12 current-limiting reactors with inductive reactance x_r (Table 9) were mounted into the neutrals of 500/110 and 500/220 kV autotransformers (AT) of the regional power system over ten years ago. Computations show that for each individually taken autotransformer branch the effect of current limitation attains 40, 30, and 15% at a voltage of 110, 220, and 500 kV respectively. It seems that this fact makes specialists think that mounting of resistances in neutrals is an

TABLE 9. Total and Standardized Necessary Current Limitation by Means of Reactors and Resistors Mounted in Neutrals of Autotransformers with Allowance for the Inhomogeneity of the Electrical Network

Number of object	Number of AT	x_r, Ω	Current limitation on buses, %					
			total			standardized necessary		
			500 kV	220 kV	110 kV	500 kV	220 kV	110 kV
1	1	9.89	1/1	10/10	–	0/0	6/6	–
2	2	5.089	1/2	–	9/11	0/0	–	9/11
2	3	9.501	1/1	10/10	–	0/0	6/6	–
3	4	5.0	1/1	–	12/14	0/0	–	12/14
3	5	9.5	1/1	7/7	–	0/0	7/7	–
4	6	5.0	~0/0	–	32/29	0/0	–	15/15
4	7	5.0	~0/0	–	24/21	0/0	–	6/6
5	8	5.06	1/0	–	31/27	0/0	–	5/5
5	9	9.92	1/1	10/11	–	0/0	5/5	–
5	10	9.85	1/1	8/9	–	0/0	7/7	–
6	11	9.5	~0/0	17/16	–	0/0	0/0	–
6	12	9.5	~0/0	22/20	–	0/0	6/6	–

Note. Numerators, grounding through reactor; denominators, grounding through resistor.

effective measure. In the actual fact, the proportion of limitation of the total SC current (i.e., with allowance for the actual parameters of the external network) used for making the choice and testing of electrical equipment is not this noticeable. It is necessary to take into account not only the overall current limitation but also the standardized necessary one.

Under the condition that $I_s^{(1)} > I_s^{(3)}$ the standardized necessary current limitation equal to $(1 - I_s^{(1)}/I_s^{(3)}) \times 100\%$ is understood as the decrease in the single-phase SC current until the attainment of the boundary of the zone in which the computed parameter is $I_s^{(3)}$ instead of $I_s^{(1)}$ (Table 5), i.e., $I_s^{(3)} = I_s^{(1)}$. It is obvious that the standardized necessary current limitation is equal to zero if $I_s^{(3)} \geq I_s^{(1)}$ in dead-grounded neutrals (connection of resistances into neutrals will cause excess current limitation from the standpoint of the choice of rated parameters for the equipment). Finally, the overall current limitation is equal to the standardized necessary one if $I_s^{(1)} > I_s^{(3)}$ even when resistances are mounted in neutrals.

It can be seen from the data of Table 9 that the standardized necessary limitation of currents $I_s^{(1)}$ is 5 – 15, 0 – 7, and 0% in network nodes rated for 110, 220, and 500 kV respectively. The relatively high efficiency of this current-limitation measure in the developed network made specialists doubt practical expediency of the introduction of resistances into neutrals of the autotransformers of the nearest nodes of the network and turn to network separation on 110 – 220-kV buses of the majority of the analyzed power units.

A similar inference was made for hypothetical cases where reactors were replaced by current-limiting resistors whose active resistances had absolute values equal to the resistances of the reactors. It turned out that the current limitation properties of the reactors and the resistors were virtually the same. The maximum difference in the effect of current limitation did not exceed 2 – 4% (Table 9), which is inessential from the standpoint of the choice of rated parameters for electrical equipment. This means that the parameters of an electrical network change regularly with change in the mode of grounding of neutrals [5]. The presence of an inductive reactance or an active resistance in the neutral of an autotransformer primarily redistributes the fractions of active and reactive components in the total equivalent and influences inconsiderably the modulus of the total equivalent resistance relative to the fault point. Therefore, from the standpoint of the choice of rated parameters of circuit breakers we can speak of approximately equal current limitation properties of reactors and resistors, though the latter are structurally more intricate and less suitable for mounting in outdoor switchgears.

As for partial ungrounding of neutrals, all cases of application of this measure in the considered regional system were explained by the desire to ensure selectivity of backup current protection of the zero-phase sequence rather than to allow for the conditions of limitation of SC currents. It is known that the mode of grounding of transformer neutrals connected to branches outgoing from 110 – 150-kV lines is chosen with the aim to ensure maximum possible sensitivity of the zero-phase sequence protection by grounding the neutrals of the minimum possible number of transformers. The earlier experience of grounding the neutral of only one transformer at every 110-kV substation independently of the number of transformers has proved to be expedient.

For example, in one of the regions of the 110-kV network fault currents have been computed for the case of forced grounding of the normally ungrounded neutrals (Table 10) [6]. It can be seen from the data of Table 10 that the general limitation of currents at partial ungrounding of neutrals amounts to 3.9 – 18.8%, whereas the standardized necessary current limitation is only 0 – 5.6%.

TABLE 10. Total and Standardized Necessary Current Limitation by Means of Partial Ungrounding of Neutrals of 110-kV Transformers

Substations	n_t	$n_{nt.un}$	$I_{s.un}^{(1)}$, kA	$I_s^{(1)}$, kA	$I_s^{(3)}$, kA	$I_{br.rat}$, kA	Overall current limitation, %	Standardized necessary current limitation, %
1	2	1	15.2	16.5	16.0	26.3	7.9	3.0
2	2	1	9.4	10.1	11.8	31.5	6.9	0
3	2	1	15.8	17.0	17.3	20	7.1	0
4	2	1	16.6	17.9	16.9	40	7.3	5.6
5	4	3	13.8	17.0	17.2	25	18.8	0
6	2	1	9.9	10.8	11.8	26.3	8.3	0
7	2	1	11.6	13.6	14.7	25	14.7	0
8	3	2	27.4	28.8	27.7	31.5	4.9	3.8
9	2	1	6.4	7.1	7.1	20	9.9	0
10	3	2	12.5	14.5	14.6	18.4	13.8	0
11	2	1	13.1	13.8	14.6	31.5	5.1	0
12	2	1	7.8	8.1	9.5	20	3.7	0
13	2	1	6.5	6.8	6.4	20	4.4	4.4
14	2	1	19.4	20.5	20.6	40	5.4	0
15	2	1	17.5	18.2	19.6	20	3.9	0

Note. n_t is the total number of transformers in the considered node; $n_{nt.un}$ is the same but at normally ungrounded neutrals; $I_{s.un}^{(1)}$ is the single-phase short-circuit current at normally ungrounded neutrals; $I_s^{(1)}$ is the same but at forcibly grounded neutrals.

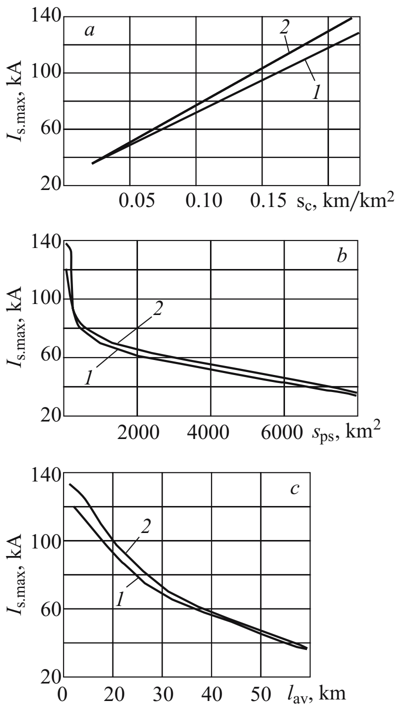

Fig. 6. Dependence of maximum short-circuit current in electrical network on: *a*, the density of the network; *b*, the area of supply per one substation; *c*, the average length of the line: *1*, $I_s^{(1)}$; *2*, $I_s^{(3)}$.

Thus, the methods for limitation of single-phase short-circuit currents are local measures and thus do not affect the structure and parameters of the entire network as occurs in the case of its stationary separation. Note that condition $I_s^{(1)} > I_s^{(3)}$ commonly arises on the buses of power plants and substations, which are especially carefully considered when the choice of points for stationary separation of the network is made.

Use of integral parameters of electrical networks. The maximum short-circuit current turns out to be obviously connected with the integral parameters of electrical networks (Table 11).

Figure 6 presents dependences of $I_{s.max}$ in a layout with forcedly closed points of stationary separation of networks (Table 4) on the integral parameters of the networks (Table 11). It can be seen that $I_{s.max}$ is directly proportional to the density of the network. The dependence of $I_{s.max}$ on the area covered by power supply s_{ps} also presents interest. At $s_{ps} > 400$ km² (the radius of power supply of one substation is 11.3 km) $I_{s.max}$ starts to grow uncontrollably and the dependence $I_{s.max} = f(s_{ps})$ goes almost in parallel to the ordinate axis; at $s_{ps} \approx 2400$ km² (the radius is 27.6 km) $I_{s.max}$ exceeds 60 kA, i.e., the highest rated breaking current of standard circuit breakers. These obvious functional relations make it possible to plan the structure and parameters of electrical networks for a long-term period.

TABLE 11. Integral Parameters of Electrical Networks of the Regional Power System

Network voltage, kV	σ_c, km/km²	s_{ps}, km²	l_{av}, km
110	0.2177	111.1	12.2
220	0.1029	839.3	28.3
500	0.017	7833.3	61.5

Analysis of means for limiting SC currents. We studied various means for limiting SC currents, i.e., single and coupled reactors, transformers with split winding, resonance current-limiting devices of various kinds, limiters of surge current, back-to-back direct-current converters, and devices with high-temperature superconductivity. Any novel current-limiting device proves to be technically suitable but its use requires considerable investment [7].

We used a system approach for prediction and optimization of the levels of SC currents, studied the difficulties of realization of these multifunctional problems, and determined the engineering and economical constraints. New estimation models for prediction and optimization of SC currents were suggested. Functional relations between engineering and economical characteristics of power equipment of various kinds were determined. The corresponding regression equations are used by foreign trade organizations [8].

As a result of a study of the effect of SC currents on the electrodynamic and thermal stability of electrical equipment

— amended methods for computing the electrodynamic and thermal stability of conductors and apparatuses have been developed [9];

— conditions of safe approach of flexible conductors of transmission lines at faults have been determined [10];

— facts and conditions of ignition of conductors due to faults were studied experimentally and the maximum permissible heating temperatures at a fault determined;

— methodological recommendations for computing vibrations of flexible conductors at a fault have been suggested.

The study performed made it possible to develop improved methods for computing the electrodynamic and thermal stability of conductors and electrical apparatuses at faults. Specifically, the suggested method for computing the thermal stability of conductors and electrical apparatuses at faults is substantially superior to the one given in the standards of the International Electrotechnical Commission (IEC, issue No. 865, 1986), i.e.,

— the method of the IEC is applicable only to the simplest cases, when the loading diagram contains only one generator, whereas the developed method allows for a variety of loading diagrams;

— the use of the IEC method requires preliminary determination of the value of steady-state fault current, though in the recent systems protecting synchronous generators steady-state current is a fictitious quantity and its use is connected with increase in the number of necessary data on the parameters of synchronous generator and in the volume of computation. For this reason the suggested method does not employ the steady-state fault current for evaluating the degree of thermal effect of the fault current on conductors and electrical apparatuses;

— in contrast to the IEC method the suggested method makes it possible to allow for the thermal effect of various sources of energy, i.e., the power system as a whole, synchronous generator and synchronous compensators, and synchronous and asynchronous electric motors.

Workers of the department of power plants of the Moscow Power Institute have determined the conditions of dangerous approach of conductors of transmission lines and switchgears at faults. They developed a criterion for determining in what cases a check of flexible conductors for dangerous approach at fault cannot be performed. The results of the study were used for developing the appropriate guidelines.

Another result of the research in the field of coordination of levels of short-circuit currents is the creation of a series of important guidelines and standards:

GOST 26522–85. Faults in Electrical Installations. Terms and Definitions;

GOST 27514–87. Faults in Electrical Installations. Methods for Computation in AC Electrical Installations Rated for Voltage Exceeding 1 kV;

GOST R 50270–92. Faults in Electrical Installations. Methods for Computation in AC Electrical Installations Rated for Voltage Below 1 kV;

GOST 29176–91. Faults in Electrical Installations. Methods for Computation in DC Electrical Installations.

GOST R 50254–92. Faults in Electrical Installations. Methods for Computation of Electrodynamic and Thermal Effects of Short-Circuit Currents;

RD 153-34.0-20.527–98. Guidelines on Computation of Short-Circuit Currents and Choice of Electrical Equipment;

RD 153-34.3-20.672–2002. Guidelines for Checking Flexible Conductors of Transmission Lines and Switchgears for the Possibility of Their Dangerous Approach and Whipping at Faults.

In addition, draft chapters 1.3 and 1.4 have been prepared for the new Rules for Design of Electrical Installations and approved by the scientific and engineering society of the UPS of Russia Company.

Methods and procedures for computing SC currents. Modified methods and models for computing SC currents in AC networks rated for voltage exceeding 1 kV have been developed. Methods for computing the SC current at the initial moment of a fault and at an arbitrary moment of time have been suggested and curves describing the damping of SC currents due to different kinds of generator with different excitation systems plotted. A stricter computation of the surge current of a fault has been performed. Methods and models for computing SC currents in electrical installations rated for voltages below 1 kV have been developed with allowance for the parameters of the electric arc, variation of the resistivity of the conductors due to a fault, and characteristics of complex-load nodes [11 – 18]. A method has been suggested for determining SC currents in power systems having back-to-back direct-current converters, in particular, for determining the currents on the side of inverters and rectifiers.

The change in the social and economic conditions in the country makes it necessary to analyze new loading structures, determine the relative constitution of consumers, and develop methods for their allowance in computation of short-circuit currents under the existing conditions. Methods are especially in demand for special fault conditions that lead to considerable errors in the determination of SC currents when neglected. In the present work we considered the following special conditions: short-circuit currents in nodes with complex loading and autonomous systems of power supply, growth in the active resistance of conductors due to heating by SC currents, appearance of free-burning arcs on overhead transmission lines (OTL) rated for 6 – 750 kV, steady or spontaneously extinguishing arcs in electrical installations with 6 – 19-kV cable lines and in AC and DC electrical installations rated for up to 1 kV, displacement of conductors due to faults on OTL, and faults in DC electrical installations fed from different sources (accumulators, converters, generators).

The performed analysis of accidents in electrical installations rated below and above 1 kV has shown that one of the chief causes of nonoperation of relay protections and failures of electrical equipment is neglect of the effect of factors arising under special fault conditions. The results of the analysis were used for determining the main factors necessary for simultaneous allowance for nonlinearity of short circuits in computations of SC currents under special conditions. The study was aimed at determining the effect of complex loads on currents under various fault conditions, computing the values and determining the time variation of shirt-circuit currents load nodes depending on the type and constitution of consumers, and developing methods for computing SC currents in nodes of complex load and autonomous systems of power supply rated below and above 1 kV.

Depending on the problem posed, fault conditions in the power system were studied experimentally, using a three-phase physicomathematical model of a node of a power system, and using computer simulation. The results of theoretical generalization of the methods of rendering equivalent the loads used for computation of SC currents in electrical systems were used for developing new methods of rendering lods equivalent (in the form of full and simplified models).

Full-scale tests of the effect of complex load on SC currents in power systems have not been performed earlier either in foreign countries or in Russia. Pioneer studies of the kind were performed by the Tulaénergo Company at four substations with different constitution of consumers of the complex load at three voltage levels (10, 35, and 110 kV). The tests showed that complex load affects substantially the values and the manner of variation of SC currents in networks rated for different voltage (in 35 – 110-kV networks the SC current of the load amounted to 5 – 15% of the current at the place of the fault, in 6 – 10 kV networks it amounted to 20 – 25%). The degree of this effect depended primarily on the relative constitution of the consumers that differed substantially in long-lasting faults due to tripping of some consumers.

When determining the minimum values of SC currents under special conditions it is necessary to take into account the growth in the active resistance of the conductors as a result of their heating by SC current. This effect is known as thermal decline of SC current.

Reliable data on growth in the active resistance of cable cords at faults have been obtained experimentally. Most damage cases in the form of faults on OTL and switchgear are accompanied by an electric arc with parameters varying in time. The considerable SC currents cause displacement of flexible conductors in space, which leads to changes in the interphase distances and inductive reactances of positive-phase and negative-phase sequences of the OTL. At long-lasting faults the thermal decline of SC currents comes into play and increases the active resistance of the conductors heated by SC current.

The phenomena mentioned affect each other during the fault, which makes it necessary to develop a complex mathematical model for computing the nonlinearity in systems with flexible conductors.

The mathematical model consists of a system of differential and algebraic equations that describe the variation of the parameters of the fault occurrence in a nonlinear system under the effect of the following factors: the evolution of the free-burning arc at the place of the fault, the motion of the split-phase conductors, the growth in the active resistance of the conductors heated by SC current, the variation of the inductive reactance of the positive-phase, negative-phase, and zero-phase sequences of the OTL, and the growth in the length of the OTL conductors due to their heating (temperature-induced elongation).

The variation of the parameters of a free-burning electric arc, for example, of the inductive reactance of the positive(negative)-phase and zero-phase sequences per unit length and of the active resistance and characteristic impedance of OTL with different structures due to a fault, has been described. It has been shown that the nonlinearity of a system with flexible conductors primarily affects the SC currents on OTL rated for 6, 10, 35, 110, and 220 kV; the OTL rated for 330, 500, and 750 kV are affected less.

Allowance for the joint action of SC-induced nonlinearity factors makes it possible to analyze more carefully the causes and consequences of faults, amend the computational SC conditions, choose circuit breakers and parameters of line protection, and evaluate the electrodynamic stability of OTL and switchgears with flexible busbars.

The reliability and fire safety of electrical installations rated below 1 kV depend considerably on the reliability of computation of SC currents in the stages of design, setting of protections, and choice of equipment. The earlier used computation methods did not allow for the joint effect of such factors as the electric arc at the place of the fault, the growth in the active resistance of conductors, electric motors, complex load, and generators of autonomous systems of power supply.

Computational and operating experience and experimental data show that SC currents depend substantially on the active resistance of the arc. The absence of a method for taking into account the resistance of the arc in SC computation both in Russia and in foreign countries has made researchers conduct full-scale tests in 0.4-kV auxiliary systems of some substations and perform computer simulations of faults in the electric arc system.

These studies were used for developing an amended procedure for computing SC current in dc electrical installations rated below 1 kV, which allows for the joint effect of the main factors of special fault conditions on the SC current and gives results with the least error relative to experimental data. The amended method is widely used for design and maintenance of electrical installations rated below 1 kV.

It is known that many DC systems consist of a set of parallel-operating sources, i.e., accumulator banks, DC generators, and static converters. This creates special fault conditions whose influence on the SC currents should be taken into account jointly, as well as the effects of the electric arc and of the thermal decline of the SC current.

Many experimental and theoretical studies of fault modes in dc electrical installations have been performed in order to solve this problem. Full-scale experimental studies of the joint action of different power sources (accumulators, reversible motor generator, and static converter) were performed at operating power plants and substations in a DC system.

The data obtained made it possible to develop recommendations for more accurate computation of probabilistic maximum and minimum SC currents at DC electrical installations than the earlier used ones and to create a method for computing SC current in installations fed from different power sources with allowance for the nonlinearity of the short circuit.

The developed theoretical and practical aspects of computational methods and experimental determination of SC currents and their electrodynamic and thermal actions under special conditions make it possible to solve important scientific and engineering problems of the power industry.

Substantiation of switching life. An important aspect of operation of electrical installations is the switching (service) life of circuit breakers. Field data on the switching life of various types of circuit breaker have been studied in order to determine the possibility of exhaustion of their life. As a result, an analytical dependence of the guaranteed number of switching operations on the switched load current and on the SC current was suggested. This analytical dependence was used to develop a mathematical model and a method for evaluating the retained life of circuit breakers in operation. It was suggested to treat the retained life of a breaker at the level of one cutoff of the net breaking current of the breaker as the criterion for repairing the breaker. The method makes it possible to compute the retained service life of a breaker for various compositions of initial statistical data.

In the absence of statistical data for a specific breaker it is suggested to use the probabilistic characteristics of faults and fault currents. In order to develop the probabilistic characteristics of faults, we performed an analysis of a data system on faults in a power system, determined representative sources of data on faults, and collected and processed ample statistical material on faults. This allowed us to develop such probabilistic characteristics as the specific number of faults for electrical installations of different types and levels of voltage, the distribution of faults over the types, and the distribution of faults over the length of a transmission line. We also evaluated the probability of exhaustion of the service life of breakers for different types of connection. The method developed permits allowance for the service life of a breaker upon fault both in the home connection and in adjacent regions of the network.

Allowance for probabilistic characteristics of faults. In the operation of power systems and individual electrical installations the equipment may serve outside the zone of rated parameters. This problem has become especially urgent in recent years under conditions of limited financing and lack of means for updating and replacing the equipment. This makes the personnel of power systems prolong operation of devices that have served for the scheduled time and cope with situations where the actual parameters of operation of the system exceed the rated parameters of the electrical equipment. For example, hundreds of circuit breakers and tens of transformers with permissible SC currents substantially lower than the actual possible ones serve in high-voltage networks of power systems. Decisions on continuation of service of the equipment under such conditions are in the risk zone [19 – 20].

In the design of a power system the probability of appearance of dangerous operating conditions, for example, faults, should be taken into account. Then the design conditions for choosing the electrical equipment become easier, which finally results in savings due to installation of equipment rated appropriately for the operating conditions. Here the risk due to decision making and the risk due to faults are also possible.

The existing standards and regulations do not stipulate allowance for probabilistic characteristics of faults in the choice of the equipment. Therefore, allowance for probabilistic characteristics in the stages of design and operation of electrical equipment has not become obligatory yet. It has been shown that the risks arising should be taken into account when making a decision on prolongation of the service of electrical equipment outside the zone of standardized parameters and in design with allowance for probabilistic characteristics. Here the risk is understood as the probability and the numerical expression of dangerous consequences due to specific decisions, natural calamities, technogenic emergencies, and ecological catastrophes.

In the general case the risk will be determined as

$$R = vc,$$

where R is the risk measured as a consequence of the event per unit time under the conditions that the equipment operates when its rated parameters are exceeded; v is the frequency of the event per unit time; c is the cost of consequences per one event. The risk at a fault is determined by the sum of three components, i.e.,

$$R = R_{\mathrm{m}} + R_{\mathrm{s}} + R_{\mathrm{e}},$$

where R_{m} is the material component of the risk due to the fault, which is determined by the performance losses due to the fault, R_{s} is the social component of the risk, which is determined by the consequences of the fault for people (traumas, casualties, diseases, invalidity, death); R_{e} is the ecological component of the risk due to the fault, which is determined by the negative action on the ambient (ground, water, air) at random emergency situations in electrical installations.

In order to determine the social component due to the risk caused by fault the possible cost of human life was economically substantiated for using in technical and economic assessment. The cases of most frequent risks due to faults have been considered and expressions have been obtained for computation of material and social components of the risk due to faults arising in the operation of equipment that has exhausted the scheduled service term, of breakers rated for breaking current lower than the actually possible design fault current in the circuit, and due to an insufficiently efficient system of diagnostics of transformers. Allowance for the risk factor in decision-making can influence substantially the operation of electrical installations.

Coordination of levels of SC currents as a possible means for raising the reliability of electrical installations and power systems [21]. Measures have been developed for coordination of levels of SC currents. A coordination strategy has been suggested for various conditions in power systems. Refusal to timely coordinate the levels of SC currents can have unfavorable consequences for producers and consumers of electric power and for delivery companies.

If the measures on coordination of levels of SC currents are effective, the reliability of the power system and of its components increases, the equipment operates under appropriate conditions, the permissible levels of SC currents are controlled systematically, the cost of maintenance of the equipment decreases, and planning of repair, purchasing, and replacement of electrical equipment is better substantiated.

CONCLUSIONS

1. Coordination of levels of SC currents in electrical networks is a very important way for raising the efficiency of operation of power systems.

2. It is expedient to take measures for coordination of levels of SC currents in every power system in networks rated for any voltage and to stipulate them in the scheduled operation of maintenance services.

3. Every power system should have a data bank on the installed electrical equipment including the equipment with exhausted scheduled life, its parameters, terms of commissioning and overhauls, and recommended levels of SC currents in the networks and their dynamics.

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