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On low-resistance neutral earthing mode in 20 kV overhead and cable networks

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Abstract. The problems of justification and selection of the required single-phase short-circuit current values in cable and overhead networks of 20 kV with low-resistance neutral earthing are considered. It is shown that the desired values of the short-circuit current can be determined on the basis of harmonization of conflicting influencing factors: reliability of the relay protection and automation devices and required resistances of the earthing devices of electrical installations, including personnel safety. In this case, the main influencing factor is the electrical network structure and parameters

1 Introduction

The advantages of low-resistance neutral earthing mode in medium-voltage networks are well-known. They are conditioning for almost complete elimination of high frequency arc overvoltage and transition of single-phase short circuits to interphase (multiplace) short circuits (SC), avoidance of the personnel injury at the single-phase ground fault (SFGF), selective operation of relay protection and automation devices (RPA) at the SFGF and some other advantages.

2 SFGF current selection

The cable 20 kV electrical network with low-resistance neutral earthing has massively been introduced in Moscow since the beginning of the 2000th. At the first stages of decision-making Russian specialists took into account the experience of the west-european countries (primarily – France), where 20 kV networks were widespread from the second half of the last century [1].

By copying the 20 kV network construction scheme of Paris, at all main substations (MS) in the 20 kV neutrals of 110–220/20 kV supply transformers there were installed resistors with the resistance of Rr=12 Ohms. At the same time the SFGF current (in fact – the current running through the resistor) $I_r \approx U_{nom}/(1.73 \cdot R_r) = 20/(1.73 \cdot 12) = 0.96$ kA, where U_{nom} – nominal network voltage. The reason for choice of the current at the level of 1000 A was earlier mentioned in [2]: "Historically the value of 1000 A was adopted due to low sensitivity of the previous protection systems against ground faults…with the minimum possible setting of 0.5A (on the secondary side) which switched on phase current transformers of 1000/5 A… Respectively with the setting of 0.5 A on the secondary side the minimum possible setting on the primary side was 100 A. According to the long familiar foreign rule of relay protection for reliable operation of protection the SFGF current shall exceed the setting by 10 times. Therefore the value of the resistor current shall be nothing less than 1000 A".

At the same time nobody paid attention to foreign 20 kV network structure [1, 3]. 20/0.4 kV transformer substations (TS) commute with the 20 kV main line basically on branch lines or by load interrupter switches. The switches are installed only on connections of the 20/0.4 kV transformers. With the architecture of that kind all the electrical network is deemed to be the distribution one.

Ever since the times of the USSR, for decades the electricity supply systems of the cities in our country have been formed differently, according to the so-called two-tiered architecture. The first tier is network feeders, i.e. cable lines (CL) from the MS to distribution centers (DC), and the second – distribution networks, i.e. CL from DC to TS. From them, at 0.4 kV voltage, end consumers are powered (Fig. 1).

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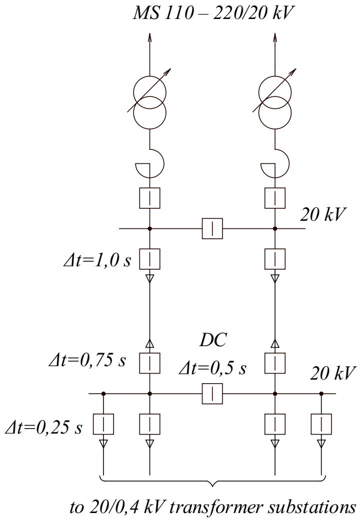

Fig. 1. Two-tiered scheme of 20 kV electric network.

With the two-tiered architecture, there appear three additional intervals of the RPA devices selectivity: on the main switch and bus section breaker of the DC, as well as on the switches that go to the TS lines; total Δt=3·0.25=0.75 s. As a result, abroad for current protections, departing from the MS lines it is sufficient to have time delay of 0.3–0.4 s, and for the two-tiered architecture – not less than 1.0 s. The latter extremely stiffens nominal conditions for feasibility and selection of conductors, machineries and earthing devices of electrical installations.

In Russia, there is no regulatory framework for development of the 20 kV electric network. According to [4], operation of networks up to 35 kV could provide for different neutral earthing mode, including through a resistor. At the same time, the requirements for earthing devices of electrical installations above 1 kV, which is one of the basic criteria of the electrical safety, are standardized only for networks with effectively earthed and isolated neutral. Therefore, when providing electrical safety in a 20 kV network with low-resistance neutral earthing, there remains to take into account the standards for contact voltage and step potential [5, 6].

Thus, according to the well-known permissible fault voltage curve (on contact) $U_f(t)$ for the time of fault (trip) t given in [6], it is not difficult to estimate the required resistance of the earthing device $Re(t) = U_f(t)/I_r$ depending on the SFGF current $I_{sfgf} = I_r$, created by the resistor (Table 1).

Table 1. Values of the permissible resistances of the earthing devices.

SFGF trip interval, sec	up to 0,1	0,2	0,5	0,7	1,0	1,0–5,0
Fault voltage, V	500	400	200	130	100	70
Permissible resistance of the earthing device, Ohm						
I_r = 1000 A	0,49	0,39	0,20	0,13	0,10	0,07
I_r = 800 A	0,6	0,49	0,24	0,16	0,12	0,09
I_r = 600 A	0,80	0,63	0,32	0,21	0,16	0,11
I_r = 400 A	1,12	0,89	0,45	0,29	0,22	0,16

Note: The resistances of the earthing devices were evaluated under the condition of imposing capacitive current with the value of 200 A on the resistor current.

From Table 1 it follows that with the adopted on all MS of $I_r \approx 1000$ A, two-tiered net-work architecture and the SFGF trip time delay of 0.75 s (see above), the resistance of the earthing devices for the 20 kV DC in the cable networks should be slightly more than 0.1 Ohm, which is unattainable. In default of regulatory requirements for earthing devices of 20 kV electrical installations in the country, engineering companies took the easy route by adopting as the target value the minimum possible from [4] – 0.5 Ohm for electrical installations with effectively earthed neutral. However, in the urban setting it is extremely difficult to achieve even such resistances for widely used compact DC and TS, provided that high priced special depth electrodes are used.

The requirements for the earthing devices resistance are mitigated (see Table 1) as the SFGF current decreases. The latter is limited to reliable operation of RPA devices, namely the minimum permissible sensitivity coefficient Cs, which for cable networks is adopted as [4] $C_s > 1.25$, and for overhead – $C_s > 1.5$.

Overcurrent SFGF protection in cable networks of the above-mentioned region is made by undirected residual current protection (RCP). The method of choosing the parameters of their operation is known (see, for example, [7, 8]) and therefore is not described in detail.

In the switchgear cubicles there are installed single-phase current transformers. Based on them, zero sequence current filters (ZSCF) are configured. In this case, the operative current I_{op} of the RPA devices is graded from the unbalance current of the I_{ub} of the current transformers at the short-circuit (short-circuit currents, as a rule, are limited to 12 kA). As seen from Table 2 it turns to be impossible to provide the required sensitivity of the RCP here.

Table 2. Calculated values of the RPA sensitivity coefficients.

SFGF protection	Operative current alternative	Sensitivity coefficient $C_s=I_{sfgf}/I_{op}\geq 1.25$	Current/ resistor resistance, A/Ohm
Undirected residual current protection with ZSCF	$I_{ub}= C_{unif}\cdot\varepsilon\cdot I_{sc}$; $I_{op} = C_r\cdot I_{ub}$	I_{sc}=12 kA C_s=0.29–0.73	1000/12
As above, but with time grading from short circuits between phases	$I_{ub}= C_{unif}\cdot\varepsilon\cdot I_{load}$; $I_{op} = C_r\cdot I_{ub}$	I_r=400–1000 A C_s=6.7–16.7	90/130
Undirected residual current protection with CBCT	$I_{op} = C_r\cdot C_{ck}\cdot I_c$	I_c=68–85 A C_s=1.25–1.50	230/50

Legend: C_{unif} – coefficient of current transformers uniformity; ε – error of the current transformer winding; C_r – coefficient of reliability; C_{ck} – coefficient of capacitive kick; I_{sc} – short-circuit current.

In order to provide the required sensitivity for protection against the SFGF with the current I_r=400–1000 A, there could be introduced an additional time delay, exceeding that for protection from short circuits between phases by a selective interval (0.2–0.3 s), or blocking of the protection against the SFGF at the start-up of the overcurrent protection (OP). In this case, the RCP is graded from the load currents I_{load}. Here, at I_r=400–1000 A and theoretically possible I_{load} = 1000 A, the calculated sensitivity coefficient of the protections shall be (see Table 2) C_s= 6.7–16.7, which significantly exceeds the required value. Therefore, in order to ensure the normalized $Cs\geq 1.25$ for cable networks, it is sufficient to adopt the minimum current of the resistor I_{rmin}=90 A (130 Ohm). With that current, the sensitivity of the RCP shall be guaranteed oversized. However, introduction of an additional time delay is not advisable due to toughening of the requirements for the earthing devices resistance.

To ensure sensitivity of undirected RCP, responsive to the fundamental current harmonic $3I_0$ with an isolated cable core balance current transformer (CBCT), as the condition for choosing the current of the resistor there is adopted the offset from the peak capacitive current I_c of the connection. For the cable with a core section of 500–630 mm^2, with the capacitance C = 0.42–0.46 mfd/km and the maximum possible CL length of 15–17 km in the megapolis conditions, I_c=68-85A. Whence the required value of I_{rmin}=230A. It is provided by the resistor resistance of only 50 Ohm (see Table 2). Thus, for the real power system diagram of 20 kV, the value of the resistor current could be four times smaller than that accepted at the moment (about 1 kA). The latter is fundamentally important from the standpoints of acceptable resistance of earthing devices and ensuring the personnel safety.

Thus, when selecting the SFGF current in the networks with low-resistance neutral earthing, it is necessary to harmonize the conflicting influencing factors: reliability of RPA devices operation, required resistances of earthing devices of electrical installations, including the personnel safety. In this case, the main influencing factor is the structure and parameters of the electrical network, namely, its configuration, the schemes of distribution centers of the electrical installations, equipment parameters. Unlike the 20 kV cable networks (there have already been built more than 1000 km only in Moscow), the decisions on construction of the overhead networks of the voltage class and the neutral mode under consideration are only being made. In view of the above, it is critical to avoid previously made mistakes.

When choosing the SFGF current in the overhead networks, it is necessary to take into account their specific preferred configuration (Fig. 2) [9]. It is represented by a well-known loop circuit with connection from two geographically separated MS of 110/20 kV, sectionalized by reclosers – automatic distribution stations of the overhead line (OL). Transformer substations 20/0.4 are connected to the main line on branches with installation of a disconnecting device or recloser (depending on the branch length). Transformers 20/0.4 are protected by 20 kV fuses. In the normal operation mode the circuit layout is opened at one of the reclosers using automatic load transfer (ALT). The number of branches to the TS between switching devices of the main line is shown in Fig. 1 conventionally (usually there are 5–7 of them). Mainly there are installed single-transformer package substations (PTS) of the column (nominal transformer capacity S_{nom}=16–100 kV·A), mast (S_{nom}=160–250 kV·A) and kiosk (S_{nom}=400–1000 kV·A) types.

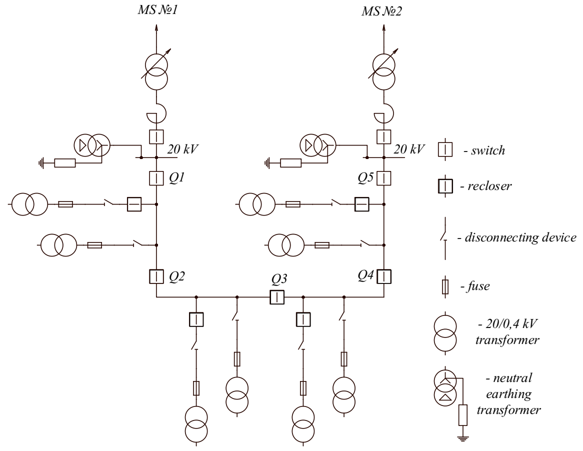

Fig. 2. Typical configuration of the overhead network.

The scheme shown in Fig. 2, in real conditions may even be more cumbersome and have a greater number of distribution stations. The minimum selective time interval of the RPA terminals of modern reclosers, guaranteed by the manufacturer, is only 0.1 s. The latter is less than that of the RPA devices installed in the switchgear cubicle (SC) of the MS and DC (0.2–0.3 s). However, even in the simplest scheme in Fig. 1 in the repair mode, let us assume, when the Q5 switch is turned off (in which case Q1 to Q4 shall be switched on), the time delay of the protection from the SFGF in the head sections will exceed 0.5 s, inclusive of the fuses blowing time (of the fuse links). Herewith, the cost of the earthing device may exceed (and noticeably) the expenses for the PTS itself, which is unreasonable. Therefore, interval grading of the RPA devices in the overhead networks is not applicable.

The operation of undirected residual current protection shall be based on the minimum possible time Δt of unselective circuit breakers operation at the SFGF and then their sequential single acting autoreclosing (AR) with acceleration of protection, starting with the MS circuit breaker. The protection acceleration time t_a in the overhead networks is usually taken to be not less than 0.1 s. The minimum possible time for the protection grading t_{gr} of the MS and the "downstream" recloser is 0.2 s, i.e. the selective time interval, guaranteed by the manufacturer for the RPA devices (see above). Therefore $\Delta t = t_a + t_{gr} = 0{,}1+0{,}2=0{,}3$ s.

For protection against the SFGF in the overhead networks, due to obvious constructional features, it is necessary to focus on the use of zero sequence current filters (rather than zero-sequence current transformers, as in cable networks). The operating current is assumed to be the highest, based on the three conditions of grading from:

- The unbalance current;
- The own capacitative current of the connection;
- The time-current characteristics of the fuse links melting.

The first two conditions of grading in the overhead networks, as a rule, are not determinative. When grading from the unbalance current, premised on the three-phase fault current $I^{(3)}$ at the entrance of the protected zone, usually K_s<1.5. Therefore, in order to increase the sensitivity of the RPA devices, it is necessary to provide for blocking of the protection against the SFGF when starting the overcurrent protection (OP). In this case, operating current of the OP instead of $I^{(3)}$ is taken into account. As for the grading from the capacitative currents, the latter in the overhead networks, all other conditions being equal, in comparison with the cable networks are about the next lower order and are not a weighty influencing factor from the positions under consideration.

The third condition (see above) is the determining factor when choosing the actuation data of the RPA devices. The time Δt = 0.3 s shall be sufficient for blowing in the first place the fuse of the protected connection if the latter is damaged. Therefore, the tripping currents of the RPA devices should be adjusted from the time-current characteristics of the fuse links melting in the following manner [8]: $I_{tr} = (1+\varepsilon)\cdot I_f(t)$, where ε=0,15 is the coefficient, making allowance for errors of the RPA terminals and the current transformers (for reclosers 0.05 is sufficient); $I_f(t)$, – the melting current of the fuse-link of the fuses, depending on the time, taking into account the standard 20% variation of their time-current characteristics.

When selecting the resistance of the earthing devices of the PTS 10(6) kV, i.e. in the networks with the isolated neutral, more stringent requirements to their values are specified not by the side of 10(6) kV of the electrical installation (where $R_e \leq 250/I_{SFGF}$, and not more than 10 Ohm [4]), but the side of 0.4 kV. For it R_e=4 Ohms. The implementation of such earthing device is not burdensome, both financially and materially. It would be advisable that these values shall be preserved for the 20 kV electric network, for example, not 4, but at least 2 Ohms. As it was already noted earlier, R_e=0.5 Ohm is not acceptable, since the costs for it may exceed those for one particular PTS, i.e. the electrical installation for the wide use, which should be as economical as possible. For example, at R_e=4 Ohms, in the conditions of the Moscow region, it is sufficient to install six electrodes on the area of 5×10 m, and for R_e=2 Ohms – 15 on the area of 10×20 m. At the same time, the estimated cost of the earthing device according to the current prices shall be about 20 and 60 thousand rubles respectively.

Table 3 represents the characteristics of interrelations among the basic influencing factors (such as the transformer power, the operative current of the RPA devices, the resistance of the earthing device from the electrical safety position, the sensitivity coefficient of the RPA devices), at the SFGF current change from 100 to 400 A and its unselective circuit breaker operation at Δt=0.3 s.

In the calculations of Table 3, there were taken into account the actual parameters of the 10 kV network, which was supposed to be "switched" to the voltage of 20 kV. The length of the main line between the MS was 26 km with the total length with the branches of about 60 km. The SFGF current of 100–400 A is the current at fault close to the buses of the MS, the minimum SFGF current – the current at the end of the protected zone in the network maintenance diagram, i.e. at the temporary power supply from the single MS. The possible 40% overload of the oil transformers was taken into account. The shadows in Table 2 indicate the zones in which the required sensitivity coefficient of the RPA devices is provided. For the record, the RPA operative current at the unbalance current grading (with the allowance for blocking of the protection from the SFGF during the start-up of the OP) is 31 A, and in case of grading from its own capacitative current, it is only 21 A.

Table 3. Alternatives of the earthing device resistance at the simultaneous unselective operation of the RPA devices within 0.3 s

Transformer capacity, kV·A	Operative current of the RPA, A	SFGF current, A			
		100	200	300	400
		Minimum SFGF current, A			
		90	163	222	275
		Earthing device resistance, Ohm			
		4,25	2,13	1,42	1,06
		Sensitivity coefficient of RPA, rel. unit			
Up to 75	37	2,4	4,4	5,9	7,4
160	84	1,0	1,9	2,7	3,3
250	101	0,9	1,6	2,2	2,7
400	145	0,6	1,1	1,5	1,9
630	248	0,4	0,7	0,9	1,1
1000	386	0,2	0,4	0,6	0,7

3 Conclusion

Thus, in the opinion of the authors, for the time being, the SFGF current at the level of 200 A is the most compromise for domestic 20 kV overhead electric networks with low-resistance neutral earthing (the resistor resistance being 60 Ohm) under the following restrictions: the resistance of the earthing devices is not more than 2 Ohm, and the power of the step-down transformers – not more than 250 kV·A. With the capacity of above 250 kV·A, it is necessary to provide for unselective operation of RPA devices with regard to grading from the time-current characteristics of the fuses. Any SFGF shall be eliminated by unselective circuit breaker operation within 0.3 s, followed by the circuit restoration in the series of the sequential single-shot AR with acceleration of protections starting from the power center switch. The identified limitations of the transformers power may have a positive effect in terms of creation incentives for disaggregating of 20/0.4 kV transformer substations. This makes it possible to significantly simplify and reduce the cost of the 0.4 kV networks, which is an alternative to the tendency of the recent years – the introduction of a new intermediate voltage level equal to 0.95 kV.

Touching upon the 20 kV cable networks with the neutral earthing mode under consideration, it has to be recognized that only by means of the circuit designs and selection of the required minimum SFGF current, it is possible to achieve acceptable resistances of the earthing devices and the required electrical safety.

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