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An analysis of ground fault current compensation in a substation powering medium-voltage distribution grids

Analiza kompensacji prądów ziemnozwarciowych w stacji elektroenergetycznej zasilającej sieci dystrybucyjne średniego napięcia

***Abstract**. Quick extension of medium-voltage grids based on common use of power cables and the use of automation of the grids with an option of remote control of a switchgear result in sudden changes of its parameters. It significantly affects capacity of a line, forcing also the change of the value of ground-fault capacity current in the stations covered by scheduled configuration. The main goal of this article was to present an example of ground fault current compensation with the use of an arc-suppression coil equipped with a regulated tap switch. Based on 15 kV medium-voltage switching station, calculations of capacity current were made and arc-suppression coils for both sections of the rails of considered main power supply station were selected. The methods of setting current in a traditional choke and automatically-regulated choke were presented.*

***Streszczenie.** Szybka rozbudowa sieci średnich napięć w oparciu o powszechne stosowanie kabli elektroenergetycznych oraz wykorzystanie automatyzacji sieci z możliwością zdalnego sterowania aparaturą łączeniową, powoduje gwałtowne zmiany jej parametrów. Ma to istotny wpływ na pojemność linii, a jednocześnie wymusza zmianę wartości prądów pojemnościowych ziemnozwarciowych w stacjach objętych zmianą planowego układu.Głównym celem niniejszej publikacji jest przedstawienie przykładu kompensacji prądów ziemnozwarciowych z wykorzystaniem dławika gaszącego wyposażonego w regulowany przełącznik zaczepów. Na podstawie rozdzielni SN 15 kV wykonano obliczenia prądów pojemnościowych i dobrano dławiki gaszące dla obu sekcji szyn rozpatrywanego GPZ-tu. Przedstawiono metody ustawiania prądu na dławiku tradycyjnym oraz dławiku z regulacją automatyczną.*

Keywords: Medium voltage network, MV, Main Power Supply, MPS, Arc – Suppression Coil, Petersen's coil, National Power System, NPS.
Słowa kluczowe: Sieć średniego napięcia, SN, Główny Punk Zasilania, GPZ, Dławik Gaszący, Cewka Petersena, Krajowym Systemie Elektroenergetycznym, KSE.

Introduction

Constant extension of the medium-voltage grids and common use of the cables in their structure and application of automation of line connections result in changes of the grid parameters, which significantly affects their capacity, and also result in growing qualitative and reliability requirements of supplied electric energy [1]. The process of wiring of a medium-voltage grid affects the reduction of the risk of power cuts and affects the reduction of the number of single phase to ground fault shutdowns caused by weather conditions and animals. However, wiring of the medium-voltage grids significantly affects increasing single phase to ground fault currents and forces to apply new solutions for ground fault current compensation. Automation inside the grid can't be omitted, which by application of the switches in the medium-voltage cable connectors and in the overhead lines, allows to isolate a place of single phase to ground fault and apply an alternative grid configuration, for example, switching the part of the grid to supply from different main power supply station. It affects the change of the value of ground-fault capacity current in the stations covered by scheduled configuration. It means that for one of the stations, length of a medium-voltage grid decreases, and for the other, it increases by connected section, which changes in both cases the value of capacity current in both stations.

To meet above requirements and solve the problems, an ideal solution is the application of the arc-suppression coils with a regulated tap switch. To properly select inductance of an arc-suppression coil, ground-fault capacity current in the grid must be determined. For overhead lines, such current can be determined based on Langrehr charts, whereas, for cable lines, data provided by the producers for the value of capacity of the cables are used. The method of calculating the capacity of the cables with the use of the curves developed by Klein is also applied. These curves provide capacity of the cables depending on the thickness of insulation and dielectric constant. Measurement control of ground-fault real parameters can also be applied, that is, to measure real ground-fault, which allows to correctly set a choke [2].

This article presents the work of a neutral point in the National Power System, process of ground fault current compensation in the medium-voltage grid using traditional method and method of applying modern regulators and arc-suppression coils with steady control of compensating current in a place of single phase fault. The connections between electrical protective and controlling automation and electric shock protection near the place of single phase to ground fault were shown.

Diagrams of the medium-voltage lines were presented and calculations of the value of ground-fault capacity current were made for them and arc-suppression coils were selected for both sections of the rails of considered main power supply station. The methods of setting current in a traditional choke and automatically-regulated choke were presented, showing similarities and differences.

The method of grounding neutral point of the medium-voltage grids

Nowadays, medium-voltage lines, depending on applied solution, can work with differently grounded neutral point of the grid. The method of grounding neutral point of three-phase power line depends on fulfilment of two basic factors. The first one is connected with the reduction of overvoltage and protection of insulation of the grid and devices so as not to damage them. The second one is ensuring required fire protection to maintain safety. Due to the work of a neutral point, the grids can be divided into:

- the ones with insulated neutral point – grids, in which no star point of the windings of the transformers has galvanic connection with earth,
- the ones with grounded neutral point – grids, in which at least one star point of the windings of the transformers is connected with earth.

Solution strictly depends on voltage level, and to a lesser extent, on its structure, that is, whether it is an overhead or cable line.

Depending on the method of connecting neutral point of the grid with earth, power grids are the ones with:

- effectively grounded neutral point,
- neutral point grounded by reactance,
- neutral point grounded by resistance.

Low-voltage, medium-voltage and high-voltage grids work with effectively grounded neutral point in the National Power System. Medium-voltage grids work with neutral point insulated, grounded by reactance and impedance. Figure 1. presents the methods of work of a neutral point of the grid.

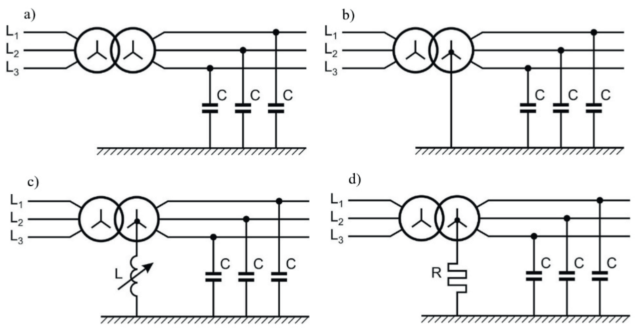

Fig. 1. The method of work of a neutral point of the grid in the National Power System: a) insulated, b) effectively grounded, c) grounded by reactance, d) grounded by resistor

Medium-voltage grids are powered by transformers with YNd or Yd configuration. Neutral point is not available for these configurations of connections. Neutral point of a medium-voltage grid can be:

- Insulated,
- Compensated, that is, grounded by an arc-suppression coil called Petersen coil,
- Permanently grounded by resistor limiting current ground fault to demanded value,
- Compensated and with occasionally grounded neutral point by a resistor called forcing resistor, whereas, three solutions are applied here:
  - primary forcing resistor switched on between neutral point of a grounding transformer and grounding,
  - secondary forcing resistor switched on to the secondary side of an arc-suppression coil,
  - secondary forcing resistor switched on to the secondary side of a single-phase forcing transformer, whereas, forcing transformer is switched on between neutral point of a grounding transformer and grounding.

Figure 2. presents the methods of grounding neutral point of a medium-voltage grid.

However, the majority of the medium-voltage lines work with grounded neutral point through reactance. The solu-

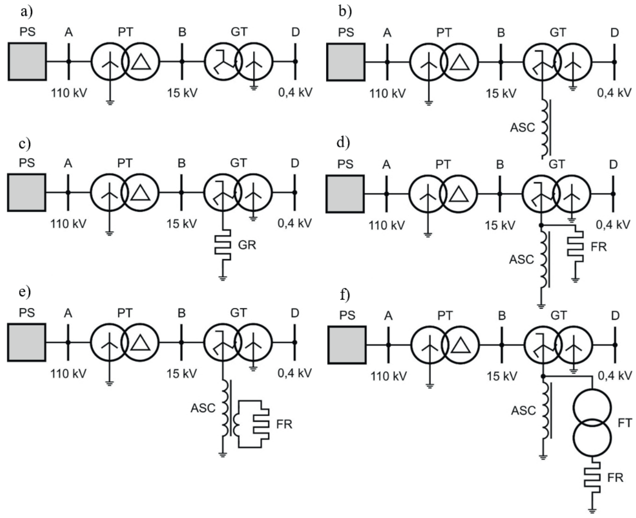

Fig. 2. The methods of grounding neutral point of the grid with ineffectively grounded neutral point: a) grid with an insulated neutral point, b) compensated grid, grounded by arc-suppression coil called Petersen coil, c) grid with a neutral point grounded by a grounding resistor, d) compensated grid with directly activated high -voltage forcing resistor, parallel to Petersen coil, e) compensated grid with a low-voltage forcing resistor activated to an additional winding of Petersen coil, f) compensated grid with a low-voltage forcing resistor activated to the secondary side of an additional forcing transformer activated parallel to Petersen coil working in single phase: PS – Power System, PT – Power Transformer, GT – Grounding Transformer, ASC – Arc-Suppression Coil, GR – Grounding Resistor, FT – Forcing Transformer, FR- Forcing Resistor

tion strictly depends on voltage level, and to a lesser extent, on its structure, that is, whether it is overhead or cable line.

The selection of the type of work of a neutral point is affected by two main issues:

- reduction of overvoltage,
- keeping appropriate conditions of electric shock safety.

During ground-fault, in the elements of electric devices, which had no voltage before and earth near the place of single phase to ground fault, voltage appear that may shock a person standing near the place of fault.

In the grid with an insulated neutral point, during single phase to ground fault, current flows despite the lack of galvanically closed electric circuit.

It results from substantial capacity and low line leakage towards earth and maintaining voltage between undamaged wires and earth. Such voltage causes that capacity current flows through healthy wires of power lines. The value of such current may not exceed limit values, in which, as a result of line shutdown, electric arc in a place of ground-fault intrinsically deactivates, eliminating electric shock hazard. The value of such current may not exceed:

- 50A in the cable grids and overhead and cable grids, regardless of rated voltage of the grid,
- in the overhead grids and overhead and cable grids, the value of current depends on rated voltage of this grid.

The value of single phase current in a place of ground fault depends on rated voltage of the grid, length of a line, transition resistance in a place of ground fault and value and natural phase of movement of neutral point of the grid. Table 1 shows the values of single phase to ground fault current with earth depending on voltage of the medium-voltage grid.

Table 1. The value of single phase to ground fault current depending on voltage of a medium-voltage grid

Rated voltage U_n [kV]	**3÷6**	**10**	**15÷20**	**30÷40**	**60**
Single phase to ground fault current I_z^{1f} [A]	30	20	15	10	5

Approximate maximum value of earth current can be determined using the formula (1):

$$I_z^{1f} = I_c = I_c^k + I_c^n = U_N(0,22\, l_k + 0,003\, l_n) \quad (1)$$

where:
I_z^{1f} – ground-fault current [A],
I_c – total capacity current of ground-fault of the lines [A],
I_c^k – capacity current of ground-fault of the cable lines [A],
I_c^n – capacity current of ground-fault of the overhead lines [A],
U_N – rated voltage of a power grid [kV],
l_k – length of electrically connected cable lines [km],
l_n – length of electrically connected overhead lines [km].

Above formula shows that the value of earth current in the grid does not depend on the place of single phase to ground fault, but on extensiveness of the grid. The longer and more extensive grid, the higher capacity current. During ground-fault in the grid with an insulated neutral point, voltage asymmetry of phase voltages always occurs, whereas, line-to-line voltage does not change [6]. Ground fault of one phase makes voltage of this phase towards earth to drop to zero, whereas, phase voltages of the phases ungrounded towards earth increase to the value of line-to-line voltage [6–8]. Figure 3 presents asymmetry of voltages during single phase to ground fault with earth.

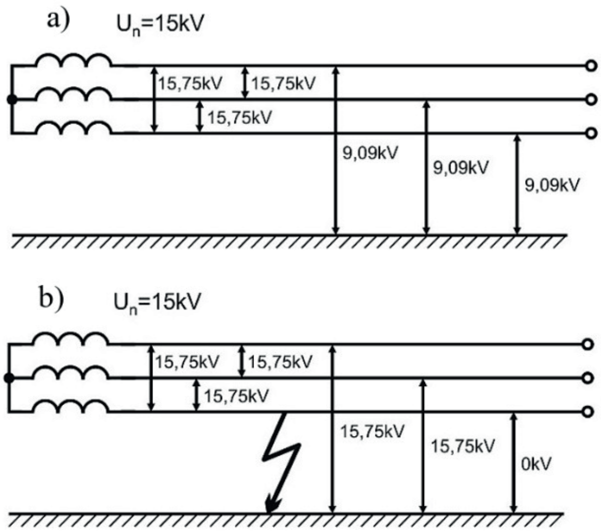

Fig. 3. The value of phase and line-to-line voltages in the medium-voltage grid; a) normal work, b) work with grounded phase L_1 [2]

During of single phase to ground fault, capacity current flows only through undamaged phases, and its value is higher by, because phase voltage U_{L2} and U_{L3} is also increased by. The flow of capacity current of single phase to ground fault in the medium-voltage lines was presented on Figure 4.

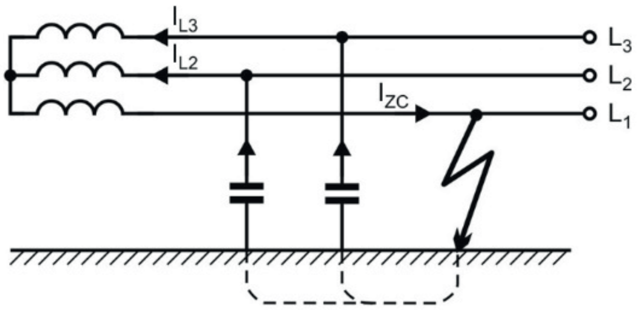

Fig. 4. Direction of flow of capacity current I_{ZC} in a medium-voltage line in ground fault of phase L_1 [3]

In the medium-voltage overhead grids and overhead and cable grids, in which ground-fault current exceeds the values given in table 1 in order to limit the effects of During of single phase to ground fault, capacity current flows only through undamaged phases, and its value is higher by, because phase voltage U_{L2} and U_{L3} is also increased by. The flow of capacity current of single phase to ground fault in the medium-voltage lines was presented on Figure 4.

Current and limit electric shock hazard in a place of single phase to ground fault capacity current is compensated by induction current of the character opposite to single phase to ground fault current. Reactance of controlled inductance is activated between star point of configuration and earth. Petersen coil, also known as arc-suppression coil acts as regulated reactance [9, 16]. Grounded N point of a transformer towards earth has the potential corresponding to phase voltage and current of inductive character flows through the choke winding. Such current, with properly selected inductance of a choke, compensates capacity current in a place of single phase to ground fault [10, 11]. An example of activation of an arc-suppression coil compensating of single phase to ground fault capacity current was presented on Figure 5.

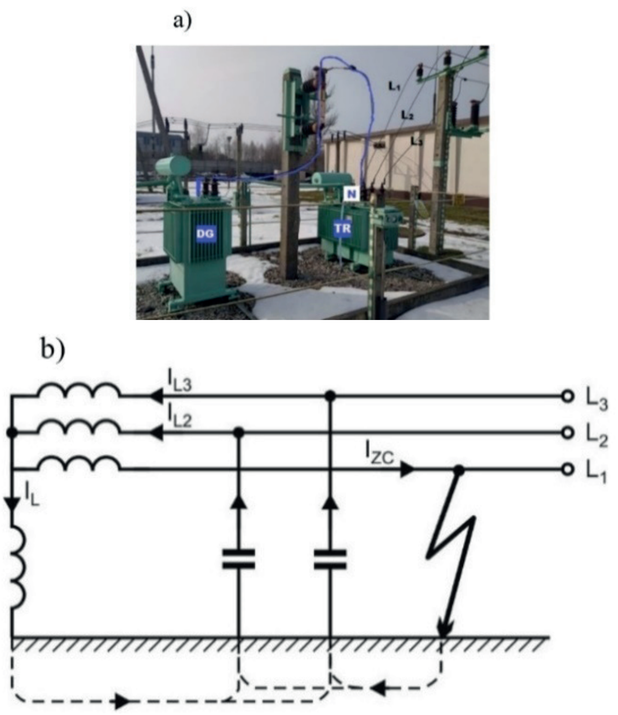

Fig. 5. Ground fault current compensation: a) a view of DG arc-suppression coil connected to N point of transformer TR, b) current distribution during ground fault with compensation

Accurate compensation is not applied in practical solutions due to the possibility of occurrence of current resonance [12]. That's why detuning of compensated grid is maintained between –5% and +15%. Grid detuning coefficient is calculated using the formula (2):

$$s = \frac{I_L - I_c}{I_c} * 100\% \tag{2}$$

where:
s – grid detuning coefficient,
I_L – total induction current of compensation devices connected to the grid,
I_c – total capacity current of ground-fault of the grid.

Due to detuning of current choke from capacity current in the grid, residual current flows through compensation. The value of residual current can be calculated from the following formula (3):

$$I_{res} = I_L - I_{CS} \tag{3}$$

where:
I_{res} – residual current,
I_L – current (induction) of a choke connected to the grid,
I_{CS} – total capacity current of the grid.

In order to improve working conditions of ground-fault protection devices, the value of earth ground fault current is increased through automatic disconnection in the event of single phase to ground fault circuit occurs of a forcing resistor in a winding circuit of an arc-suppression coil for a few seconds [14].

The value of grounding resistor connected to N point of the windings of a transformer in the cable grids should be selected so as not to exceed 500 A, whereas, in the overhead grids, 120 A [2, 4]. The value of grounding resistor limiting ground-fault current is defined using the following formula (4):

$$R = \frac{U_N}{\sqrt{3} * I_z} \tag{4}$$

where:
U_N – rated voltage of the grid,
I_z – depending on type of the grid; 500 A for a cable one and 120 A for an overhead.

With such selected resistor and current level resulting from it, medium-voltage grids are classified as grids of low level of ground-fault current. Where with small resistances of protective grounding of the stations and poles, fire protection requirements are met.

Zero-sequence resistive current forcing arrangement of ground fault current is a part of a medium-voltage security system. Stimulating zero-sequence resistive current forcing arrangement starts from overvoltage protection of a transmitter connected to a circuit of open triangle of voltage transformers of measuring bay or from overvoltage protection of a transmitter connected to a circuit of a current transformer of an arc-suppression coil [13].

In-phase component in an earth of single phase to ground fault current is forced through connecting forcing resistor with [15]:

- low-voltage windings of a separate forcing transformer,
- additional low-voltage windings of a special ground-fault neutralizer,
- star point of a grounding transformer, parallel to ground-fault neutralizer.

must be corrected [19, 20]. This correction, to some degree, eliminates underestimation of single phase to ground fault capacity current resulting from the lack of section and length of the lines in documentation. Taking this correction into account, we receive (6):

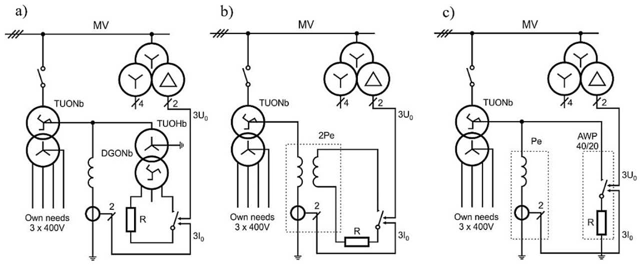

Fig. 6. The methods of forcing in-phase component: a) Grounding transformer with an arc-suppression coil and additional winding to measure current and low-voltage forcing resistor b) Grounding transformer with an arc-suppression coil and additional windings to measure current and voltage, c) Grounding transformers with an arc-suppression coil and additional winding to measure current and forcing resistor added to a neutral point of a grounding transformer: TUONb, TBN – grounding transformers, – forcing transformer, DGONb – arc-suppression coil, $3U_0$ – open triangle configuration of voltage transformers, $3I_0$ – measurement of zero component of current, AWP 40/20 – high-voltage forcing resistor, Pe – arc--suppression coil with an additional winding to measure current, 2Pe – arc-suppression coil with additional windings to measure current and voltage and special winding to force the flow of in-phase component of single phase to ground fault current with the parameters: 500 A, 10 s

The examples of forcing in-phase component during compensation of single phase to ground fault current were presented on Figure 6.

The calculations of single phase to ground fault capacity current for the medium-voltage lines powered by the main power supply station 1

The value of capacity current of single phase to ground fault for specific medium-voltage lines is necessary to select setpoints of ground-fault protection devices for feeder bays, whereas, total value from specific feeder bays is necessary to set current in an arc-suppression coil [17, 18]. It is one of the methods of determining current of an arc-suppression coil in the medium-voltage switching stations. Such current can be determined using calculation or measurement method. The calculations are made using the formula below (5):

$$I_C = I'_C l \tag{5}$$

where:
I_C – capacity current of single phase to ground fault of a line section, or the whole line,
I'_C – capacity current of single phase to ground fault for specific line section in A/km is taken from the boards provided by the producers of the cables or wires that specific section is made of [3]

During calculations, attention must be paid to the fact that capacity current of the cables is given for rated voltage equal to nominal voltage of the grid. Nominal voltage of the grid is usually higher by about 5% than nominal and the formula (5)

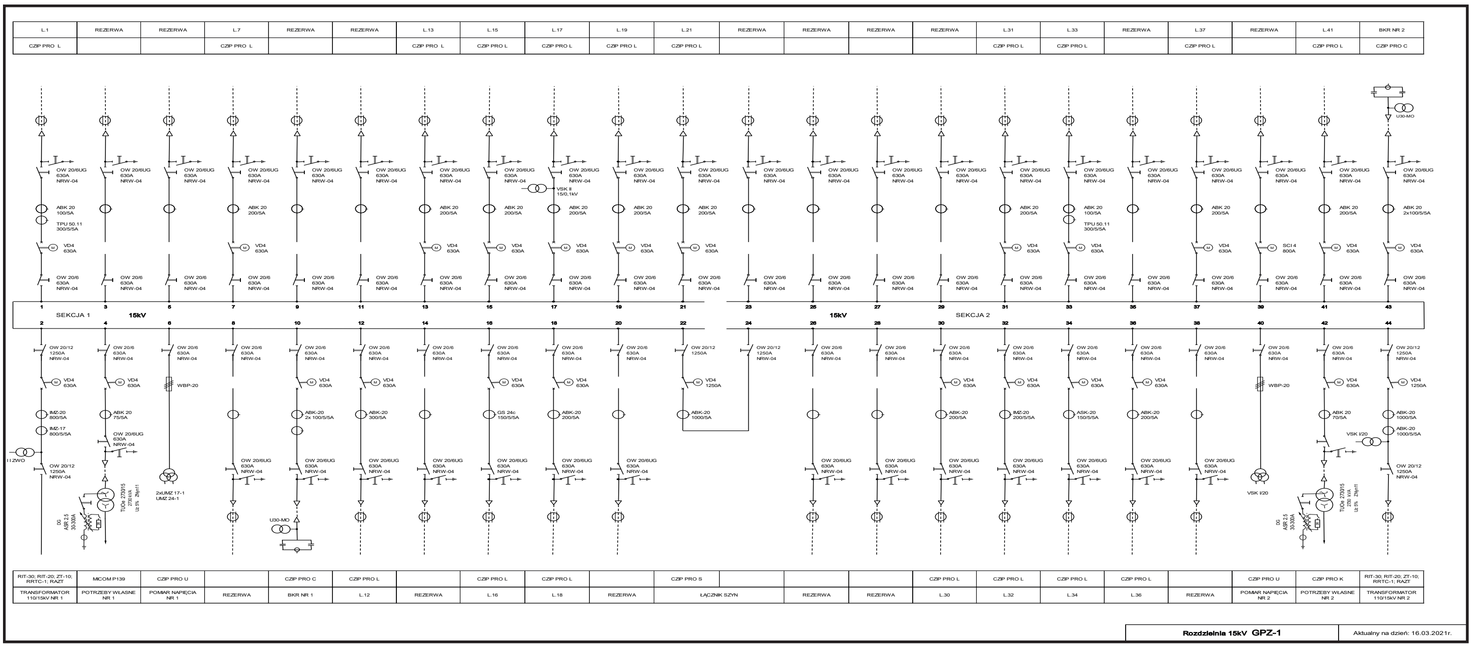

Fig. 7. Single line diagram of an example of main power supply station-1 with medium-voltage lines

$$I_C = 1{,}05\, I_{Cobl} \tag{6}$$

where:
I_{Cobl} – capacity current of ground-fault calculated based on unit values of specific sections of a given line [3].

Data concerning the values of capacity current of ground--fault for the cables given in Table 2 were used during calculations. They were taken from the boards of electric parameters of the cables and wires according to producers' catalogues.

Table 2. Unit capacity current of ground-fault for screened cables in paper and oil insulation and AFL wires [3]

Cross-section [mm^2]	Electrical Voltage [kV]	Capacity current of ground- fault [A/km]
Oil-paper insulated cables with shielding		
35	8,7/15	2,02
50	8,7/15	2,32
70	8,7/15	2,63
95	8,7/15	2,94
120	8,7/15	3,23
150	8,7/15	3,54
185	8,7/15	3,85
240	8,7/15	4,27
300	8,7/15	4,60
AFL overhead conductors		
Insulated or uninsulated conductors	15	0,03–0,04
From the producer's catalog		
35	15	0,0351
70	15	0,0365
95	15	0,0372
120	15	0,0376

For presented example, medium-voltage lines connected radially to the main power supply station 1 were analysed and its diagram was presented on Figure 7.

The calculations of capacity current of single phase to ground fault were made for medium-voltage lines marked on the diagram (Figure 7) with the numbers 7, 13 and 32. Lines 7 and 13 are connected radially to the main rails of 15 kV switching station, whereas, line 32 can be powered inside the grid by other main power supply station using radio-controlled disconnector PO.R. The diagrams of analysed lines 7 and 13 were presented on Figure 8 and Figure 9.

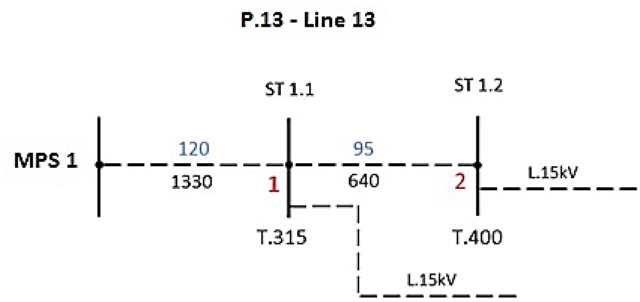

Fig. 8. Single line diagram of the medium-voltage line 13 powered by the main power supply station 1: ST – transformer station along with its number, T.315 – 315 kVA transformer, 120, 95 – wire diameter, 1330, 640 length of the sections, 1,2 grid nod

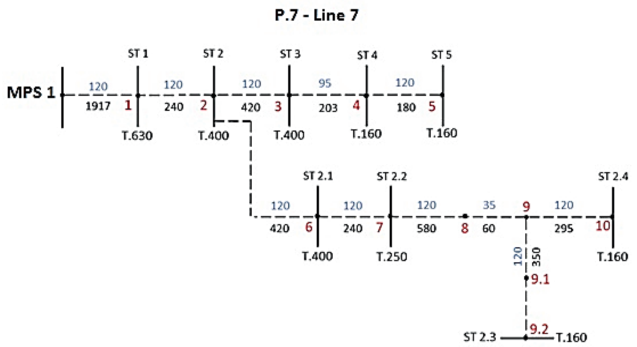

Fig. 9. Single line diagram of the medium-voltage line 7 powered by the main power supply station 1

Whereas, the lines allowing to power inside the grid using other main power supply station were presented on Figure 10.

The calculations of single phase to ground fault capacity current for the line 13:

Table 3 presents a full set of parametric data of 15 kV medium-voltage lines for analysed section of the line 13.

Table 3. Set of data and parameters for the sections of the line 13

Number of nodes	3		
Number of line sections	2	2	cable
		0	overhead
Number of transformers 15/04 kV	2	1	315kVA
		1	400kVA

The calculations were made for two line sections (Figure 8) between nodes: main power supply station 1 – 1 and 1–2. For these line sections, the values of capacity current of single phase to ground fault were obtained:

Line section of main power supply station 1–1:

$$I_C = I_C' l = 3,23 * 1,330 = 4,296 \ [A]$$

Line sections 1–2:

$$I_C = I_C' l = 2,94 * 640 = 1,882 [A]$$

Table 4 presents a full set of calculations for the medium-voltage line 13.

Accepting the fact of incomplete data about the length of the line sections, diameters and rated voltage maintained in the lines to above 15kV, the result of the calculations were corrected based on the formula (6):

$$I_C = 1,05 \cdot I_{Cobl} = 1,05 \cdot 6,178 = 6,49 [A]$$

The calculations of single phase to ground fault capacity current for the line 7:

Table 5 presents a full set of parametric data of 15 kV medium-voltage lines for analysed section of the line 7.

Table 5. A list of data and parameters for the sections of the line 7

Number of nodes	13		
Number of line sections	12	12	cable
		0	overhead
Number of transformers 15/04 kV	9	4	160kVA
		1	250kVA
		3	400kVA
		1	630kVA

Table 4. A list of results of calculations for the line 13

Start node	End node	Line type Overhead/Cable	Type cable	Material and cross--section	Length [km]	Ipoj. [A/km]	Ipoj. [A]
GPZ 1	1	Cable	Oil insulation	AL 120	1,330	3,23	4,296
1	2	Cable	Oil insulation	AL 95	0,640	2,94	1,882
						SUMA	**6,178**

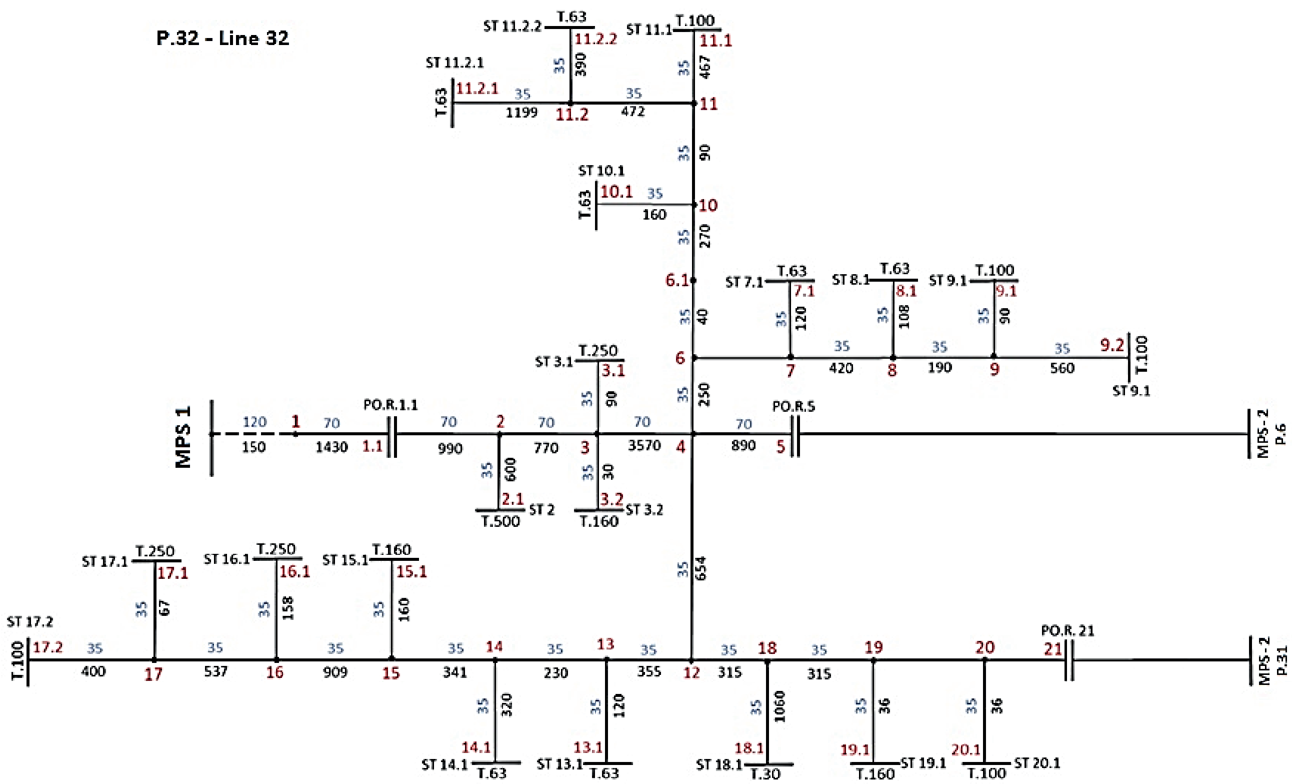

Fig. 10. Single line diagram of the radial line 32 with radio-controlled disconnectors inside the grid: PO.R.1.1 – radio-controlled disconnecting point

Table 6. A list of results of calculations for the line 7

Start node	End node	Line type Overhead/ Cable	Type cable	Material and cross--Msection	Length [km]	Ipoj. [A/km]	Ipoj. [A]
GPZ 1	1	Cable	Oil insulation	AL 120	1.917	3,23	6,192
1	2	Cable	Oil insulation	AL 120	0.240	3,23	0,775
2	3	Cable	Oil insulation	AL 120	0.420	3,23	1,357
3	4	Cable	Oil insulation	AL 95	0.203	2,94	0,597
4	5	Cable	Oil insulation	AL 120	0.180	3,23	0,581
5	6	Cable	Oil insulation	AL 120	1.230	3,23	3,973
6	7	Cable	Oil insulation	AL 120	0.240	3,23	0,775
7	8	Cable	Oil insulation	AL 120	0.580	3,23	1,873
8	9	Cable	Oil insulation	AL 35	0.060	2,02	0,121
9	9.1	Cable	Oil insulation	AL 120	0.350	3,23	1,131
9.1	9.2	Cable	Oil insulation	AL 35	0.120	2,02	0,242
9	10	Cable	Oil insulation	AL 120	0.295	3,23	0,953
						SUMA	**18,570**

The calculations were made for 12 line sections between the nodes marked on Figure 9. For these line sections, obtained values of single phase to ground fault capacity current were presented in Table 6.

Corrected result of calculations of total capacity current of the line sections based on the formula (6):

$$I_C = 1{,}05 \cdot I_{Cobl} = 1{,}05 \cdot 18{,}570 = 19{,}5[A]$$

The calculations of single phase to ground fault capacity current for the line 32:

Table 7 presents a full set of parametric data of 15 kV medium-voltage lines for analysed section of the line 32.

Table 7. A list of data and parameters for the sections of the line 32

Number of nodes	45		
Number of line sections	44	1	cable
		43	overhead
Number of transformers 15/04 kV	20	1	30 kVA
		8	63kVA
		5	100kVA
		2	160kVA
		3	250kVA
		1	1000kVA
Number of connectors	3	3	Radio controlled disconnecting points (PO.R)

The calculations were made for 44 line sections on the BSW and ŻN pole structures between the nodes shown on Figure 10. For these line sections, obtained values of single phase to ground fault capacity current were presented in Table 8.

Corrected result of calculations of total capacity current of the line sections based on the formula (6):

$$I_C = 1{,}05 \cdot I_{Cobl} = 1{,}05 \cdot 1{,}256 = 1{,}32[A]$$

After making calculations for all lines belonging to the section 1 or 2 of 15 kV main power supply switching station 1, current is set in a choke according to calculated current. Modernization of a line or change of a planned work configuration requires to change the value of current set in the chokes. Using computational method, calculations must be made every time due to extension of the medium-voltage grids. It is a laborious, time-consuming activity, which may result in computational errors.

In order to avoid above problems, a method is applied to tune the chokes to capacity current of ground-fault in the grid. This method includes taking the measurements of voltage of asymmetry for all choke taps and for the grid without a choke. It does not always allow to determine of single phase to ground fault capacity current, but compensation can be assessed. When capacity current in the grid has the value of about 48A, then choke should be set to the tap of 52,5A (overcompensation). Residual current, that is, 4,5A is lower than limiting current 30A. There can be a situation when voltage curve of minimum current range (30A) set on a choke drops down, it means that choke should be replaced with the one of lower current range. Because of single phase to ground fault capacity current is lower than the lowest current that can be set in a choke (>30A), which may be caused by, for example, new point of division of the medium-voltage grids. The situation can also be reverse when capacity current is higher than maximum current range of a choke. Then, choke must be replaced with a choke of higher current range. Before making the measurements (tunning of the chokes), the results of the measurements must be compared with the results of calculations of line currents in a given section. In order to verify, we can disconnect the lines, in which we know capacity current of ground-fault and by such value, current for the section should be lower [3].

Follow-up compensation of single phase to ground fault capacity current for the medium-voltage lines powered by the main power supply station 1

Follow-up compensation does not differ from traditional compensation of earth capacity current. However, the very

Table 8. A list of results of calculations for the line 32

Start node	End node	Line type Overhead/Cable	Type cable	Material and cross-section	Length [km]	Ipoj. [A/km]	Ipoj. [A]
GPZ 1	1	Cable	Oil insulation	AL 120	0.150	3,23	0,485
1	1.1	Overhead	Al-Fe	AFL 70	1.430	0,0365	0,052
1.1	2	Overhead	Al-Fe	AFL 70	0.990	0,0365	0,036
2	2.1	Overhead	Al-Fe	AFL 70	0.600	0,0365	0,022
2	3	Overhead	Al-Fe	AFL 70	0.770	0,0365	0,028
3	3.1	Overhead	Al-Fe	AFL 35	0.090	0,0351	0,003
3	3.2	Overhead	Al-Fe	AFL 35	0.030	0,0351	0,001
3	4	Overhead	Al-Fe	AFL 70	3.570	0,0365	0,130
4	5	Overhead	Al-Fe	AFL 70	0.890	0,0365	0,032
4	6	Overhead	Al-Fe	AFL 35	0.250	0,0351	0,009
6	7	Overhead	Al-Fe	AFL 35	0.450	0,0351	0,016
7	7.1	Overhead	Al-Fe	AFL 35	0.120	0,0351	0,004
7	8	Overhead	Al-Fe	AFL 35	0.420	0,0351	0,015
8	8.1	Overhead	Al-Fe	AFL 35	0.108	0,0351	0,004
8	9	Overhead	Al-Fe	AFL 35	0,190	0,0351	0,007
9	9.1	Overhead	Al-Fe	AFL 35	0.210	0,0351	0,007
9	9.2	Overhead	Al-Fe	AFL 35	0.560	0,0351	0,020
6	6.1	Overhead	Al-Fe	AFL 35	0.040	0,0351	0,001
6.1	10	Overhead	Al-Fe	AFL 35	0.270	0,0351	0,009
10	10.1	Overhead	Al-Fe	AFL 35	0.160	0,0351	0,006
10	11	Overhead	Al-Fe	AFL 35	0.090	0,0351	0,003
11	11.1	Overhead	Al-Fe	AFL 35	0.467	0,0351	0,016
11	11.2	Overhead	Al-Fe	AFL 35	0.472	0,0351	0,017
11.2	11.2.1	Overhead	Al-Fe	AFL 35	1.199	0,0351	0,042
11.2	11.2.2	Overhead	Al-Fe	AFL 35	0.390	0,0351	0,014
4	12	Overhead	Al-Fe	AFL 35	0.654	0,0351	0,023
12	13	Overhead	Al-Fe	AFL 35	0.335	0,0351	0,012
13	13.1	Overhead	Al-Fe	AFL 35	0.120	0,0351	0,004
13	14	Overhead	Al-Fe	AFL 35	0.230	0,0351	0,008
14	14.1	Overhead	Al-Fe	AFL 35	0.320	0,0351	0,011
14	15	Overhead	Al-Fe	AFL 35	0.341	0,0351	0,012
15	15.1	Overhead	Al-Fe	AFL 35	0.160	0,0351	0,006
15	16	Overhead	Al-Fe	AFL 35	0.909	0,0351	0,032
16	16.1	Overhead	Al-Fe	AFL 35	0.158	0,0351	0,006
16	17	Overhead	Al-Fe	AFL 35	0.538	0,0351	0,019
17	17.1	Overhead	Al-Fe	AFL 35	0.067	0,0351	0,002
17	17.2	Overhead	Al-Fe	AFL 35	0.400	0,0351	0,014
12	18	Overhead	Al-Fe	AFL 35	0.315	0,0351	0,011
18	18.1	Overhead	Al-Fe	AFL 35	1.060	0,0351	0,037
18	19	Overhead	Al-Fe	AFL 35	0.315	0,0351	0,011
19	19.1	Overhead	Al-Fe	AFL 35	0.036	0,0351	0,001
19	20	Overhead	Al-Fe	AFL 35	1.020	0,0351	0,036
20	20.1	Overhead	Al-Fe	AFL 35	0.516	0,0351	0,018
20	21	Overhead	Al-Fe	AFL 35	0.391	0,0351	0,014
						S	**1,256**

process of automatic tunning of current of an arc-suppression coil to capacity current of ground-fault is based on constant measurements of current in compensated grid and automatic steady control (tap) adjusted to actual grid configuration. In addition, chokes with steady change of inductance are applied, for example: 2728 kVAr, cooperating with the grounding transformers (own needs) 2730 kVAr TUOe 2730/15 and own needs – 100 kVA.

Arc-suppression coil with a regulated tap switch was built as a set of two connected in parallel single-phase induction coils with divided winding set on a one ferromagnetic core immersed in a vat containing oil. Inside the choke, there is also a tap switch electrically integrated with the choke coils, which is powered using an engine, which after giving an impulse from a regulator changes the location of a switch, changing in this way inductance of a choke. This choke is designed for steady control of compensating current in the medium-voltage compensated grids. It works as a mobile core, on the one hand, there is an immobile part of a core with two columns with two windings connected in series, secured side by side. On the other hand, there is a mobile part of a core, which is mounted on the columns, and change of location of lower part of a core results in reduction or enlarging the crack between the cores and changing in this way inductance configuration. It is regulated using an engine and controlled by REG DP regulator. It is used not only to enter and keep scheduled values of operation of a choke, but also, based on obtained results, to calculate the parameters of the grid, such as: capacity of the grid, capacity current, voltage of asymmetry and current measurements of U_o and I_o. Parameters registered by a regulator are available in SCADA system (Supervisory Control And Data Acquisition), through engineering connection conducted based on local area network [3].

Display regulator presented on Figure 11 measures capacity current in the grid that it was connected to and after detecting deviation from normal state (programmed), it starts tuning to the current value of capacity current in the grid by measuring the value of residual voltage.

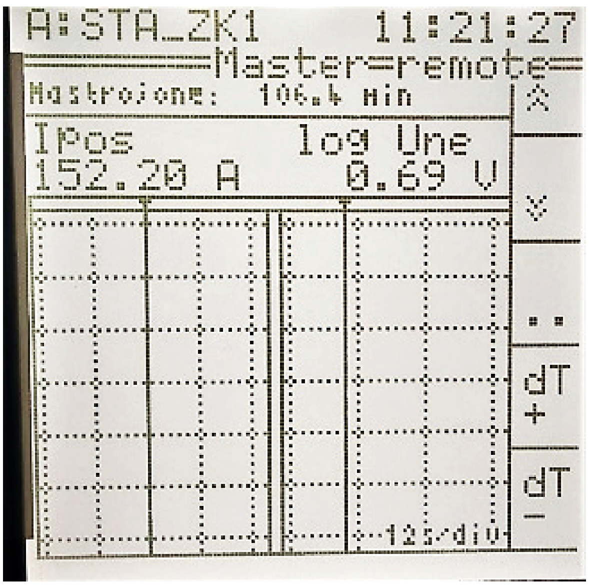

Fig. 11. A view of a regulator display with a current position of a choke and Une (Uo) voltage logarithmically within the range of three decades, which corresponds to the range 0,1 …100V, pace of change registration (refreshing) 12 s/scale

It corresponds to relocation of a resonance curve to the normal state to the left (line disconnection, reduction of capacity) or to the right (line connection, increasing capacity), which was presented on Figure 12.

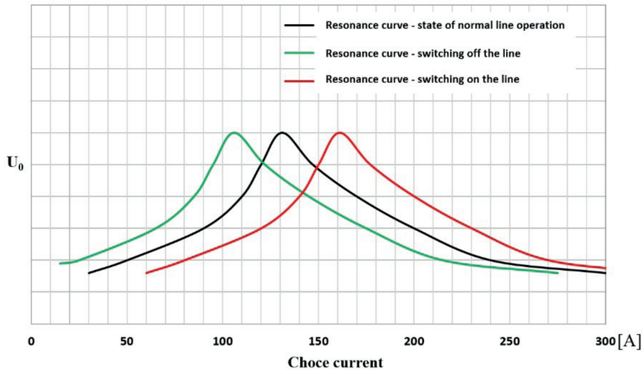

Fig. 12. Resonance curves depending on configuration of a medium--voltage grid

The change of residual voltage, which is analysed on an ongoing basis by a regulator activates searching for resonant maximum towards resting position due to the fact that regulator does not recognize whether grid was extended or reduced. Resting position is entered manually in the memory of a regulator before activation of a regulator and it is the value for normal grid configuration (capacity current is calculated from total length of the cables/lines). Resting position is also necessary to set a choke in a position, in which regulator can't be effectively tunned to new conditions in the grid. At the moment of searching for resonant maximum, choke is moved by about 1,5% of maximum scope of movement and steepness of residual voltage is checked. If the growth of residual voltage is confirmed, then choke is moved by 5% of movement range. If the growth of residual voltage is not confirmed, then direction of searching is changed. The process is continued until the moment of determination of resonance curve for new grid configuration. Well-determined resonance curve should have resonance point achieved at least once in the process of tuning of a choke to new conditions. At the moment of accepting position of a choke, residual voltage and position (of current) of a choke are measured. If residual voltage is measured in accordance with residual voltage specified from a resonance curve through regulator and is within the limit of tuning activation, then tuning operation is successful and the whole process of tuning is finished. The value of measured residual voltage is remembered as a reference value to new switching/tuning [5]. A view with determined resonance curve was presented on Figure 13.

Replacing traditional compensation with follow-up compensation requires to prepare technical documentation concerning primary and secondary circuits. Whereas, a basis for selection of a compensation set is knowledge of the values of capacity current for each section of medium-voltage station and developmental and redundant assumptions. The next stage is making calculations and developing a project of connecting, in which primary and secondary circuits are taken into account.

Total value of capacity current calculated for the length of the cables and lines using the formulas (5) and (6) for the section 1 and 2 in the main power supply station 1 according

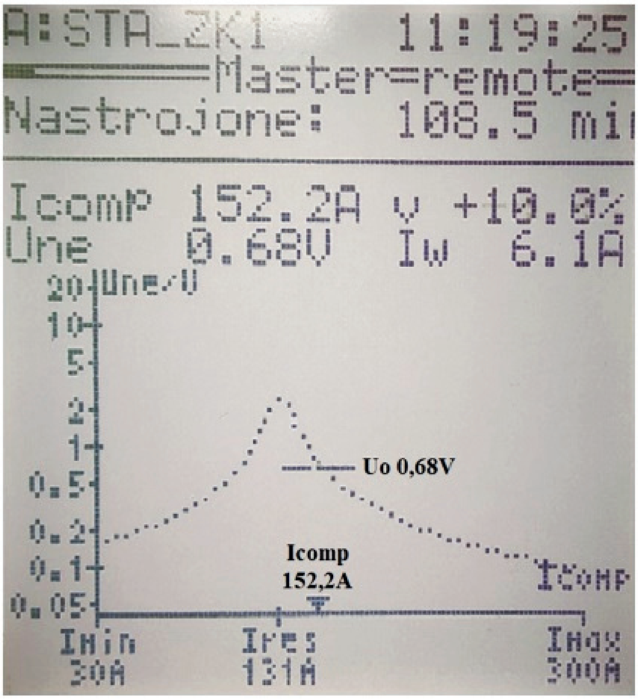

Fig. 13. A view of DP regulator with a resonance curve

to Figure 7 is: 85 A – section 1 and 65 A – section 2. Due to the application of radio disconnectors inside the grid. capacity current in an unplanned (emergency) configuration will increase by 25 A per section.

$$Ic_{S1} = 85 + 25 = 110A$$

$$Ic_{S2} = 65 + 25 = 90A$$

The selection of required higher scope of control of induction current of a choke from the formula (6) is:

Section 1

$$I_L = 1{,}1 \cdot I_{CS1} = 1{,}1 \ \cdot 110A = 121\ A$$

Section 2

$$I_L = 1{,}1 \cdot I_{CS1} = 1{,}1 \ \cdot 110A = 121\ A$$

Because it was assumed that bays of own needs in the substations must be symmetrized and redundant for proper compensation for the grid after giving one of compensation sets for inspection or due to failure. Therefore, chokes for a compensation set for both sections from Figure 7 must be selected just like in section 1, in which required induction current is higher, that is, 121A.

Assuming that there are reserve bays in the main power supply station 1, growth of capacity current in the sections by about 25A must be taken into account, which results from extension of a grid and due to connecting new customers. Induction choke should be selected to the current, bearing in mind the necessity of mutual reserving of compensation sets in the sections

Section 1

$$I_{LS1} = 121 + 25 = 146\ A$$

Section 2

$$I_{LS2} = 99 + 25 = 124\ A$$

Therefore, current that choke must be selected to in each section of 15kV switching station is

$$I_{LS1,2} = I_{LS1} + I_{LS2} = 146 + 124 = 270\ A$$

While choosing an arc-suppression coil from a catalogue, worktime of a choke in high current range must be taken into account. This parameter is very important in an emergency situation, work of one choke in two sections of the rails. Therefore, considering worktime of a choke in high current range, the choke of the parameters presented in Table 8 was selected.

Based on the selection, follow-up compensation for both sections of 15 kV medium-voltage switching station from Figure 7 in the bay 4 and 41 was applied. Its diagram was presented on Figure 14.

Conclusions

Current changes that occur in the structure of the power grids are related to their extension and the use of the cables significantly affects the reduction of grid failures. The cable lines are less susceptible to weather conditions such as, for example, gales, and lower number of failures affects SAIDI

Table 8. Nominal parameters of an arc-suppression coil selected in 15 kV switching station

<table>
<tr><td colspan="6">Grounding transformer
Type: TUOe 2730/15
Power: 2728kVA
Own needs: 100kVA
Medium voltage 15750V; +/-5% (2x2,5%)
Low voltage 400/230V
Single phase to ground fault voltage U_z = 5%
Connection layout ZNyn11</td><td rowspan="2">Grunding choke
Type: ASR 2,5
Power: 2728kVA
Voltage ratio kV; 9,1kV
Range of stepless current regulation: 30–300A
Current transformer: 300/5A, 30VA, kl. 1FS5
Additional winding with voltage: 500V and 100V
Resistor type: SE 500/60, Un=500V, In=500A,</td></tr>
<tr><td colspan="6">Ground fault compensation current</td></tr>
<tr><td>[A]</td><td>300</td><td>263</td><td>225</td><td>273</td><td>150÷0</td><td rowspan="2"></td></tr>
<tr><td>Working time</td><td>2h</td><td>4h</td><td>8h</td><td>Continuous operation</td><td>Continuous operation</td></tr>
</table>

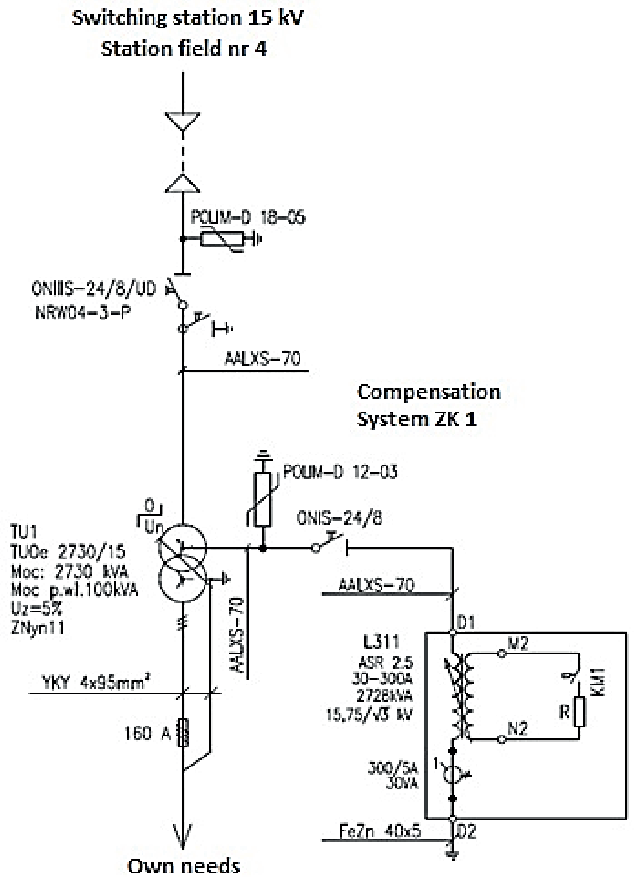

Fig. 14. Diagram of follow-up compensation for the bay 4 and 41 for both sections in 15 kV medium-voltage switching station

and SAIFI. The application of the cable lines on a large scale results in the growth of the value of grid capacity, and counterbalance to it is activation of inductance in the grid. The process of wiring of the medium-voltage grids affects the growth of single phase to ground fault currents and forces to apply new solutions of ground fault current compensation. Automation inside the grid can't be omitted, which by application of the switches in the medium-voltage cable connectors and in the overhead lines, allows to isolate a place of single phase to ground fault and apply an alternative grid configuration, for example, switching the part of the grid to supply from different main power supply station affects the change of the value of ground-fault capacity current in the stations covered by scheduled configuration.

An ideal solution for the purposes of constant and sometimes sudden changes of grid configuration and parameters is the application of the follow-up arc-suppression coils, which due to their structure and option of changing inductance using a regulator measuring current parameters of the grid, adapt to current needs.

Based on real data for 15 kV medium-voltage switching station, computational analysis for selected bays was presented. A computational method allows to determine capacity current for all lines connected to the switching station. Taking into account the changes of configuration of the medium--voltage grids caused by extension and particularly quick and unpredictable changes of configuration caused by remote switching, preparing many alternative models of operation of the switching stations is necessary. It forces to use prepared calculations and tune arc-suppression coils to configuration of the grid powered by the main power supply station. A quick and convenient way of tuning of an arc-suppression coil is follow-up compensation, which during sudden changes caused by weather conditions or the necessity of switching may tune compensation devices to actual work schedule of a medium-voltage grid powered by the main power supply switching station.

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