Resonant Overvoltages in the 35 kV Compensated Network under Single-Phase Short-Circuit Conditions in the 110 kV Supply Network

Irina Drozhzhina, Ivan Naumkin, Alexandr Liske, Andrey Telegin

***Abstract*— It is shown in this paper that single-phase faults in a 110 kV supply network result in the occurrence of resonant overvoltages, which are dangerous for substation equipment at the 35 kV side where capacitive current compensation via Petersen coils is used. Along with the suppression of arcing, switching and ferroresonance overvoltages, the use of low-resistance neutral grounding in a 35 kV network also allows the damping of resonant overvoltages.**

***Keywords*: resonant overvoltage, Petersen coil, resistance neutral grounding, low-value resistor.**

I. Introduction

The following methods of neutral grounding are used in 110 kV networks:

- Solidly grounded neutral where transformer neutrals are connected directly to the earthing grid;
- Effectively grounded neutral where neutrals are solidly earthed in one group of transformers and isolated from the ground in another group (neutrals connected through opened disconnecting switches). It is important to note that there is the following restriction in this mode: in any switching configuration, the network should not include separate sections without solidly grounded transformers.

Partial or effective neutral grounding is commonly used in 110 kV networks to limit single-phase short circuits. For the same purposes, the neutral may be grounded through a reactor or resistor. If the short circuits are small enough, all transformers neutrals in the network are solidly grounded. Hereafter, only solid neutral grounding for a 110 kV network is considered.

At present, the following methods of neutral grounding are used in 35 kV Russian networks:

- Ungrounded (or isolated) neutral;
- Resonant grounding through an arc suppression coil (Petersen coil);
- Resistance grounding through a resistor;
- Combined neutral grounding with a parallel connection of a Petersen coil and a resistor.

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All hazardous conditions inherent to isolated-neutral distribution networks are well-known. Difficulties encountered in the operation of such distribution networks are related to the occurrence of arcing, switching and ferroresonance overvoltages. These problems are studied and described in special literature [1]. The behavior of resonant-grounded distribution networks is also well-studied [2]. Generally, the researchers used a standard approach where only a 6 – 35 kV network and its switching operations had been considered.

In this paper, we consider phenomena that occur in a 35 kV network under short-circuit conditions at the high-voltage 110 kV side of the transformer. Additionally, differences of processes observed in a 35 kV distribution network have been studied depending on the transformer type.

II. System Data and Modelling

A. System Data

The following versions of a 35 kV distribution network connected to the 110 kV supply network through a 110/35 kV transformer have been studied (Fig.1):

a) – Double-wound transformer, Yg/Yn, and

b) – Triple-wound transformer, Yg/Yn/D.

The 110 kV neutral is solidly grounded, whereas, the 35 kV side is grounded through a Petersen coil.

The 35/6 kV Yn/D transformers are supplied from the 35 kV busbars via cable lines. The 35 kV neutrals may be ungrounded (isolated) or grounded through a resistor.

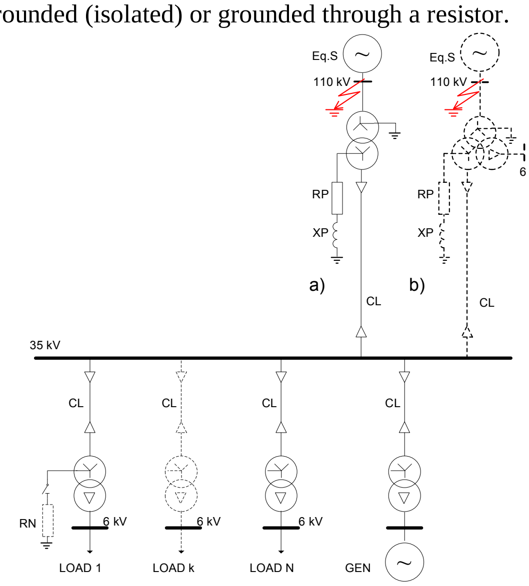

Fig. 1. Single-line diagram of a 110 – 35 kV network

Electromagnetic processes that occur in a 35 kV network under short-circuit conditions in the 110 kV supply network were studied using EMTP-RV [3] and MAES [4] software. MAES software is used because EMTP-RV does not contain a component "Triple-wound transformer" with available medium voltage neutrals (YgYnD) and only contains a "Triple-wound transformer" with solidly grounded neutrals (YgYgD). For the same circuits with double-wound transformers, both EMTP-RV and MAES give the same results.

Fig. 2 shows an example of an EMTP-RV calculation circuit.

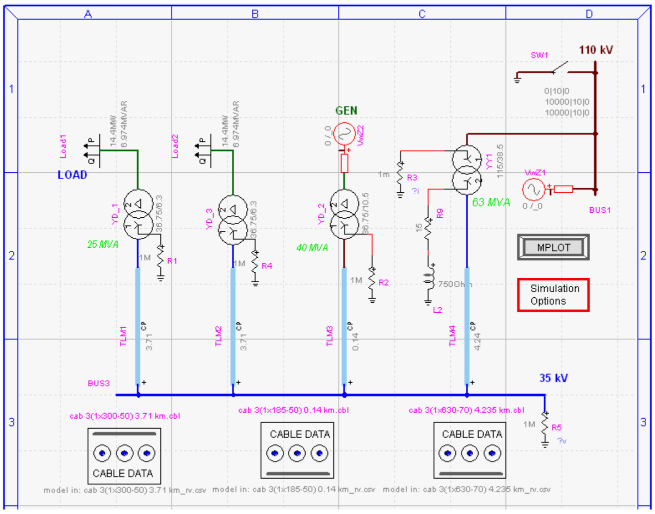

Fig. 2. EMTP-RV calculation circuit for a 110 – 35 kV network

The principal electrical parameters for the main components of the actual network configuration that is the object of study are reported in the Appendix.

B. Modelling

Consider a diagram of a resonant grounded network where the zero-sequence circuit has resonance conditions.

Develop a zero-sequence equivalent circuit in a 110 – 35 kV network (Fig. 3), where:

$\dot{Z}_{j,T1}$ (j=1,2,3) – impedance values of 110/35/6 transformer windings (j=1 for star-connected high-voltage windings with short-circuited neutral; j=2 for star-connected medium-voltage windings grounded through $\dot{Z}_{N,T1}$; j=3 for delta-connected low-voltage windings);

$\dot{Z}_{j,T2}$ (j=1,2) – impedance values of 35/6 transformer windings (j=1 for star-connected high-voltage windings grounded through $\dot{Z}_{N,T1}$; j=2 for delta-connected medium-voltage windings);

$\dot{Z}_{L,CL}$, $\dot{Z}_{C,CL}$ – cable line impedance values;

$\dot{U}_0$ – zero-sequence voltage.

Analysis of the circuit shown in Fig. 3 gives several preliminary conclusions. For example, it is clear that if the neutral of the T_1 transformer is ungrounded ($|\dot{Z}_{N,T1}|\to\infty$), the lower part of the circuit becomes isolated from $\dot{U}_0$; therefore, in any method of T_2 grounding including grounding via the Petersen coil, resonant phenomena will not occur in the 35 kV network in the case of a short-circuit at the 110 kV side. Impedance $\dot{Z}_{3,T1}$ of the third winding of T_1 provides a bypass for the resonant circuit (in this case, zero-sequence currents flow only in the windings). Therefore, the higher the $|\dot{Z}_{3,T1}|$ value, the less it will dampen the resonant voltages in the circuit. From here follows the difference between phenomena occurring in a 35 kV network when a 110/35 double-wound transformer is used, and when a 110/35/6 triple-wound transformer is used: in the case of a double-wound transformer, resonant phenomena will be more prominent[1].

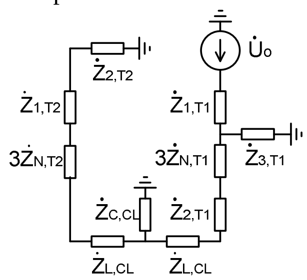

Fig. 3. Equivalent zero-sequence circuit

Consider the connection between 35 and 110 kV networks through a double-wound Yg/Yn transformer. First, we make a calculation for a very simplified circuit, then demonstrate how the values tend to change as the circuit complexity increases.

As a simplified circuit, consider a system under single-phase short-circuit conditions in the 110 kV network, where the 35 kV busbars have two outgoing feeders: one feeder supplies the considered distribution network through a 110/35 kV transformer, while the other feeder supplies the load through a 35/6 kV transformer. The 35 kV network is resonant grounded; thus, the 35/6 kV transformer neutral is isolated, and the 110/35 kV transformer neutral is grounded through the Petersen coil at the 35 kV side.

In order to achieve the complete compensation of capacitive current, inductance of the Petersen coil should comply with value [2]:

$$X_{P,b0} = \frac{1}{3b_{0,C}}, \qquad (1)$$

where $b_{0,C}$ is the total conductivity of zero-sequence cable line capacities.

Now, determine the frequency response of a 35 kV network where a purely reactive Petersen coil is connected with the inductance of $X_{P,b0}$ = 153.16 Ω calculated according to (1) in compliance with cable line parameters (Table A3). The result is shown in Fig. 4 (Curve 1).

Since the network includes resistances and other inductances, the $X_{p,b0}$ value determined as per (1) does not exactly correspond to the resonance at *f = 50 Hz*. $X_{p,b0}$ can be adjusted to match the resonance using the formula below:

$$X_{p,50} = X_{p,b0}\left(\frac{f_{b0}}{f_{50}}\right)^2. \qquad (2)$$

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1 Since two-wound transformers are not used in practice, calculations with the use of a such transformer have rather theoretical application.

The frequency response for connection of a purely reactive Petersen coil with an adjusted inductance value $X_{p,50}$ = 151.255 Ω is shown in Fig. 4 (Curve 2).

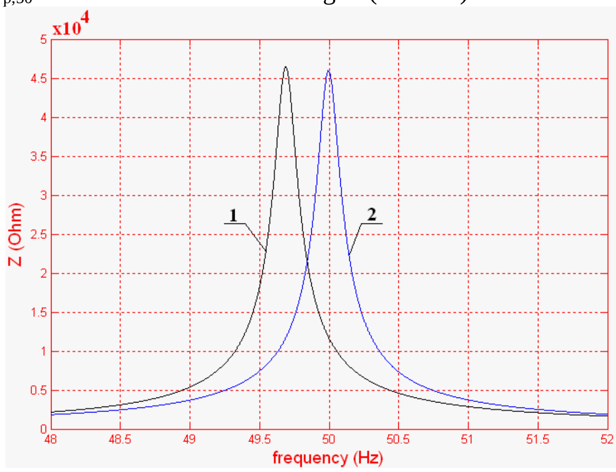

Fig. 4. Input impedance of a resonant grounded 35 kV network

Voltage at 35 kV busbars corresponding to neutral grounding through a Petersen coil with an inductance of X_p = 151.255 Ω is shown in Fig. 5.

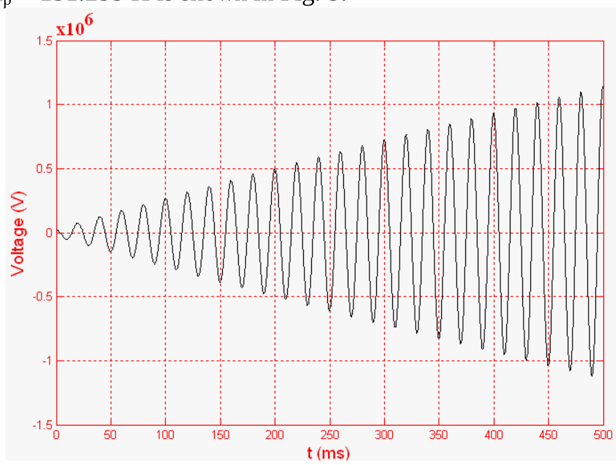

Fig. 5. Calculated 35 kV busbar voltage for Xp = 151.255 Ω

Owing to the high Q-factor of the circuit, the voltage at 35 kV busbars increases to extremely high values.

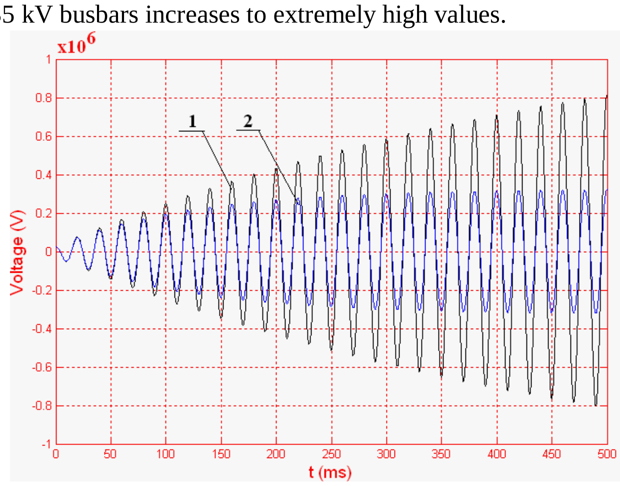

Fig. 6. Calculated 35 kV busbar voltages for Xp = 151.255 Ω, Rp = 1.5 Ω (1) and Rp = 7.6 Ω (2)

Arc suppression coils (Petersen coils) used in practice are not perfect. Resistance of a Petersen coil winding can be evaluated because its typical Q-factor values are known to be in the range of X_p/R_p = 100…20; hence R_p = 1.5…7.6 Ω.

Figure 6 shows 35 kV busbar voltage waveforms for extreme values R_p = 1.5 Ω and R_p = 7.6 Ω.

As shown in Fig. 6, the determined resonant overvoltage value is impermissible even for R_p=7.6 Ω (overvoltage ratio equal to 5.6 p.u.).

Within the practical implementation of the resonant grounding mode, over-compensation is recommended (inductive current, $X_p = 0.95 \cdot X_{p,50}$), while under-compensation is impermissible (capacitive current, $X_p=1.05 \cdot X_{p,50}$). Fig. 7 shows voltage waveforms for both cases (Petersen coil resistance R_p=7.2 Ω and R_p=7.9 Ω, respectively).

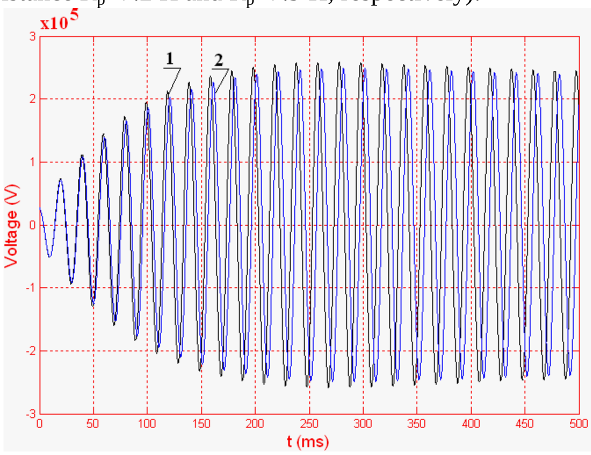

Fig. 7. Calculated 35 kV busbar voltages for over-compensation (1) and under-compensation (2) of capacitive current

On a practical level, both cases are indistinguishable from one another; the overvoltage ratio is approximately 4.5 p.u.

Then, a more complex circuit with a higher number of loaded feeders connected is considered.

For 5 feeders according to (1), we obtain $X_{P,b0}$ = 62.45 Ω. After being adjusted by (2), $X_{p,50}$ = 60.42 Ω (variation within 3%). Comparative voltage waveforms for two-feeder and five-feeder resonant circuits ($R_p = X_{p,50}/20$ Ω in both cases) are shown in Fig. 8.

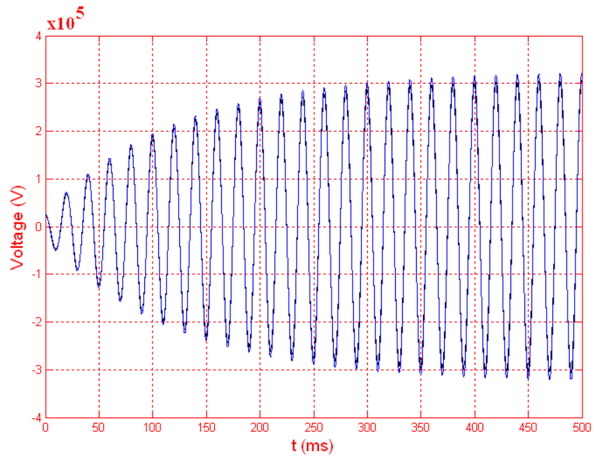

Fig. 8. Calculated voltages for two-feeder and five-feeder resonant circuits

The difference in 35 kV busbar voltage waveforms between two-feeder and five-feeder circuits is within 5%. When calculating using $R_p = X_{p,50}/100$ Ω, this difference increases to 28%.

Finally, consider the calculation results of resonant overvoltage values in a 35 kV network where a triple-wound 110/35/6 kV transformer is used (Fig. 1,b). Figure 9 shows calculated 35 kV busbar voltage waveforms for double-wound (110/35 kV) and triple-wound (110/35/6 kV) transformers with Petersen coil parameters of X_p = 151.255 Ω; R_p = 0 Ω.

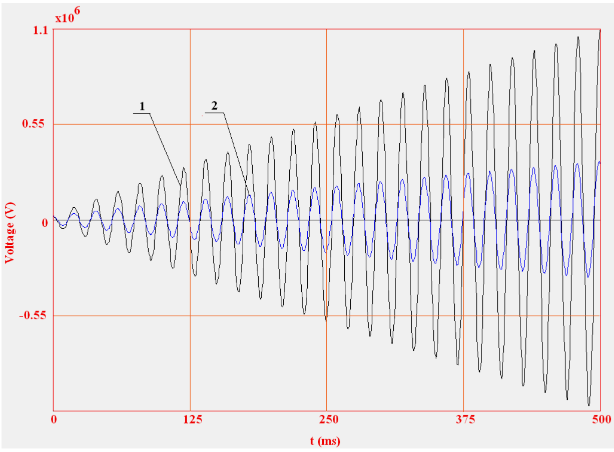

Fig. 9. Calculated 35 kV busbar voltages for Xp = 151.255 Ω, Rp=0 Ω
1 – for a double-wound 110/35 kV transformer;
2 – for a triple-wound 110/35/6 kV transformer

As predicted in the network study above (Fig. 3), the third 110 kV winding has a damping effect on the value of 35 kV busbar voltage. The third winding is still unable to change the behavior of resonant overvoltages (their growth up to significant values).

If active losses in the Petersen coil are taken into account (R_p=1.5…7.6 Ω), 35 kV busbar voltage values will decrease (Fig. 10).

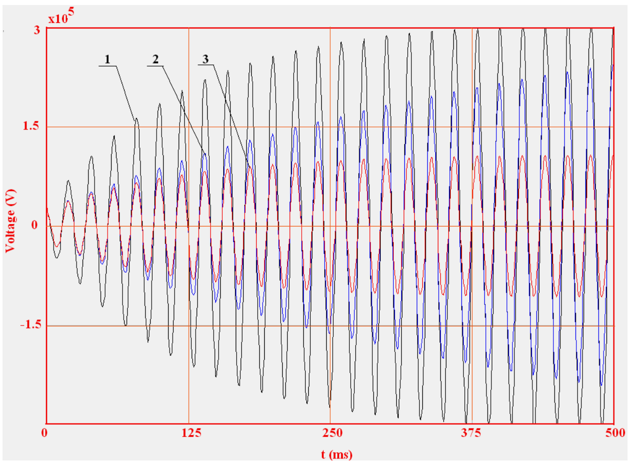

Fig. 10. Calculated 35 kV busbar voltages for Xp = 151.255 Ω
1 – for a double-wound 110/35 kV transformer, Rp=7.6 Ω;
2 – for a triple-wound 110/35/6 kV transformer, Rp=1.5 Ω;
3 – for a triple-wound 110/35/6 kV transformer, Rp=7.6 Ω

Figure 10 shows calculated 35 kV busbar voltage waveforms for a triple-wound transformer with a high Q-factor Petersen coil with R_p = 1.5 Ω (waveform 2 with an overvoltage ratio 4.2 p.u.) and a low Q-factor Petersen coil with R_p = 7.6 Ω (waveform 3 with an overvoltage ratio 1.9 p.u.). For purposes of comparison, waveform 1 obtained for a double-wound transformer with a Petersen coil having R_p = 7.6 Ω is shown (see also Fig. 6).

Therefore, the occurrence of unacceptable resonant overvoltages at 35 kV busbars under single-phase short-circuit conditions in the 110 kV supply network is possible for considered network parameters, transformers and Petersen coils.

C. Resistance neutral grounding

Until recently, almost all **Russian** 35 kV networks have been operated with an isolated or resonant grounded neutral. Currently, however, there is a trend in the distribution networks to transition to resistance neutral grounding. This transition is to a considerable extent a result of the mass implementation of XPLE cables.

In ungrounded networks with overhead power transmission lines, single-phase-to-ground conditions could persist for a long time **without** interrupting the line until the maintenance team arrived to clear the fault. The aforementioned ability of transmission lines to operate under single-phase-to-ground conditions without tripping was a prerequisite for the high reliability of power supply.

In XPLE cables, single-phase-to-ground fault leads to insulation burning and transition to the short-circuit mode (double-phase and then three-phase). Therefore, in the event of single-phase-to-ground fault, XPLE cables should be immediately disconnected by relay protection. Resistance neutral grounding enables the relay protection selectivity to be significantly increased, as the active current from resistors flows exclusively in the line affected by a single-phase fault.

A significant role in the change in the neutral grounding mode belongs to smart grids, a new concept in the development of smart electrical networks. Smart Grid principles are aimed at the minimization of consumer losses that can be provided by the resistance neutral grounding mode [5].

For elimination of resonant overvoltages, it is proposed to connect low-ohmic resistors to some of 35/6 kV transformers. If 35/6 kV transformers with neutral terminals are not available, resistors should be connected to the 35 kV busbars through grounding transformers with zigzag (Z)-connected windings.

Figure 11 shows calculated voltages determined at 35 kV busbars for configurations considered above at X_p = 151.255 Ω, R_p = 1.5 Ω, i.e. for double-wound 110/35 kV (1) and triple-wound 110/35/6 kV (2) transformers, but where the 35/6 kV transformer neutral is grounded through an active resistance R_N = 100 Ω.

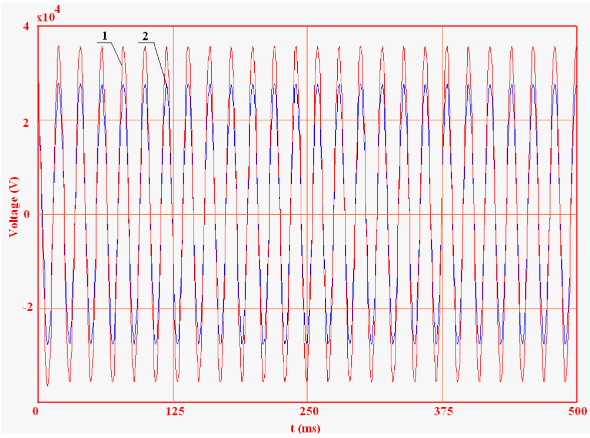

Fig. 11. Calculated 35 kV busbar voltages for Xp = 151.255 Ω, Rp = 1.5 Ω where the 35/6 kV transformer is grounded through RN = 100 Ω for:
1 – double-wound 110/35 kV transformer;
2 – triple-wound 110/35/6 kV transformer

As can be seen from Fig. 11, for any type of a transformer used, the presence of a resistance in the zero-sequence circuit of the 35 kV network allows the efficient damping of resonant overvoltages, which cannot be achieved by merely increasing the Petersen coil resistance. The influence of resistors on damping resonant overvoltages is considered as another beneficial factor in addition to the advantages of resistance grounded networks listed above.

III. Conclusions

1. Single-phase short circuit conditions in the 110 kV supply network result in the occurrence of resonant overvoltages, which are dangerous for substation equipment at the 35 kV busbars connected to the supply network through a 110/35 kV transformer with Yg/Yn windings or a 110/35/6 kV transformer with Yg/Yn/D windings, where capacitive currents are compensated by Petersen coils.

2. For practical use, it is recommended to thoroughly study the processes in 35 kV resonant grounded distribution networks with respect to emergency conditions not only in the 35 kV network, but also in the 110 kV supply network to avoid the occurrence of resonant overvoltages.

3. Along with the suppression of arcing, switching and ferroresonance overvoltages, the use of low-resistance neutral grounding in a 35 kV network further allows the damping of resonant overvoltages that occur in a 35 kV network under single-phase short circuit conditions in the 110 kV supply network, as well as the selective detection and automatic tripping of the faulty feeder.

IV. Appendix

1. Parameters of the equivalent 110 kV system. These parameters are determined by short-circuit current values. If the values of the busbar single-phase $I^{(1)}$ and three-phase $I^{(3)}$ short-circuit currents are known, the calculation of system inductances for known single-phase $I^{(1S)}$ and three-phase $I^{(3S)}$ short circuit current contributions from the equivalent system is made using the following equations:

$$X_{1S}=\frac{U_{ph}}{I^{(3S)}}=\frac{63.5kV}{6.3kA}=10\ \Omega;, \qquad (A.1)$$

$$X_{0S}=X_{1S}\frac{3-2\frac{I^{(1)}}{I^{(3)}}}{3\frac{I^{(1S)}}{I^{(3S)}}-2\frac{I^{(1)}}{I^{(3)}}}=10\cdot\frac{3-2\cdot\frac{25}{30}}{3\cdot\frac{4.9}{6.3}-2\cdot\frac{25}{30}}\ \Omega=20\ \Omega \qquad (A.2)$$

where X_{1S}, X_{0S} are positive- and zero-sequence inductances;
U_{ph} is busbar phase-to-ground voltage.

2. Transformer parameters. Transformer parameters are determined using the following equations.

For double-wound transformers:

$$U^{j}_{ph}=\begin{cases}U^{j}, & \text{delta connection winding};\\ U^{j}/\sqrt{3}, & \text{star connection winding};\end{cases};$$

$$S_{ph}=S_{rated}/3;\quad u^{H}_{\kappa}=u^{L}_{\kappa}=u_{\kappa}/2;\quad P^{H}_{k}=P^{L}_{k}=P_{k}/2;$$

$$L_{j}=\frac{1}{n}\frac{u^{j}_{\kappa}}{100}\frac{(U^{j}_{ph})^{2}}{S_{ph}\omega};\qquad R_{B}=\frac{1}{n}\frac{P^{j}_{k}}{10^{3}}\frac{(U^{j}_{ph})^{2}}{(S_{ph})^{2}};\qquad (A.3)$$

$$j=H,L.$$

where S_{rated} is rated transformer power, MVA;
U^{H}, U^{L} are operating voltages of high-voltage (H) and low-voltage (L) windings, kV;
u_k is short-circuit voltage, %;
P_k is short-circuit resistance losses, kW;
n is number of similar parallel transformers;
ω is synchronous frequency, 1/s.

For triple-wound transformers:

$$\begin{cases}U^{j}, & \text{delta connection winding}\\ U^{j}/\sqrt{3}, & \text{star connection winding}\end{cases}$$

$$S_{ph}=S_{rated}/3;\quad P^{HL}_{k}=P^{ML}_{k}=0{,}8P^{HM}_{k};$$

$$u^{H}_{k}=0{,}5(u^{HM}_{k}+u^{HL}_{k}-u^{ML}_{k});\qquad P^{H}_{k}=0{,}5(P^{HM}_{k}+P^{HL}_{k}-P^{ML}_{k});$$

$$u^{M}_{k}=0{,}5(u^{HM}_{k}+u^{ML}_{k}-u^{HL}_{k});\qquad P^{M}_{k}=0{,}5(P^{HM}_{k}+P^{ML}_{k}-P^{HL}_{k});\qquad (A.4)$$

$$u^{L}_{k}=0{,}5(u^{HL}_{k}+u^{ML}_{k}-u^{HM}_{k});\qquad P^{L}_{k}=0{,}5(P^{HL}_{k}+P^{ML}_{k}-P^{HM}_{k});$$

$$L_{j}=\frac{1}{n}\frac{u^{j}_{k}}{100}\frac{(U^{j}_{ph})^{2}}{S_{ph}\omega};\qquad R_{j}=\frac{1}{n}\frac{P^{j}_{k}}{10^{3}}\frac{(U^{j}_{ph})^{2}}{(S_{ph})^{2}};$$

$$j=H,M,L,$$

whereby the same notation as in (A.3) is used, except that:
U^{M} is operating voltage of medium voltage winding, kV;
$u^{HM}_{k}, u^{HL}_{k}, u^{ML}_{k}$ are sort-circuit voltages for windings H-M, H-L, M-L, %;
P^{HM}_{k} is short-circuit resistance losses for H-M windings, kW.

Calculated transformer parameters are shown in Tables A1 and A2.

TABLE A1.
DOUBLE-WOUND TRANSFORMER PARAMETERS

S_{rated}, MVA	U_H, kV	U_L, kV	u_k, %	P_k, kW	L_H, H	R_H, Ω	L_L, H	R_L, Ω
63	115	38.5	10.5	245	0.035	1.22	0.004	0.14
40	36.75	10.5	11.5	170	0.0062	0.215	0.0005	0.018
25	36.75	6.3	9.5	115	0.0082	0.373	0.00024	0.011

TABLE A2.
TRIPLE-WOUND TRANSFORMER PARAMETERS

S_{rated}, MVA	U_H, kV	U_M, kV	U_L, kV	$P_{k,HM}$ kW	$u_{k,H}$, %	$u_{k,M}$, %	$u_{k,L}$, %	
63	115	38.5	11	310	10.5	17	6.5	
$P_{k,H}$, kW	**$P_{k,M}$, kW**	**$P_{k,L}$, kW**	**L_H, H**	**R_H, Ω**	**L_M, H**	**R_M, Ω**	**L_L, H**	**R_L, Ω**
155	155	93	0.0702	1.55	0	0.174	0.0004	0.0085

2. Cable line parameters

TABLE A3.
CABLE LINE PARAMETERS FOR EQUAL POSITIVE- AND ZERO-SEQUENCE PARAMETERS

Mode	Length, km	R, Ω/km	X, Ω/km	b, µS/km
0	12.06	0.100	0.187	81.681
1	12.06	0.100	0.187	81.681
0	10.84	0.0464	0.172	109.956
1	10.84	0.0464	0.172	109.956

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