Case studies for high voltage network development with respect to resonance conditions

T. Kuczek, T. Chmielewski, P. Oramus

Abstract- **This paper presents a case study of 400 kV network that was subjected to a comprehensive analysis performed in EMTP-ATP software. A part of 400 kV transmission network was investigated in 2016 in terms of possible resonance conditions with shunt reactors and transmission lines involved. Due to multiple configurations of close-by substations and overhead lines (OHL), dozens of scenarios had to be investigated, with main focus on switching events and faults. Circuit breakers' reclosing schemes that would allow to avoid any resonance conditions were determined.**

***Keywords*: resonance, shunt reactor, transmission line, reclosing**

I. INTRODUCTION

High voltage power systems are object of various analyses that are aimed to ensure safe and reliable operation as well as sufficient energy quality. The fundamental aspects that are being studied in system analyses are related to reactive power compensation, voltage stability, harmonics contamination and short-circuits. One of the crucial elements in terms of abovementioned aspects of power system operation are shunt reactors that are used for voltage regulation of long, unloaded transmission lines [1-4]. This is a consequence of rapid transmission system development that is based not only on overhead lines but also power cables that both require capacitive charging current compensation. As a result, the combination of transmission line capacitance and shunt reactor inductance forms an circuit that in certain conditions may be subjected to resonance oscillations. These oscillations (at the power frequency) are typically characterized with a voltage increase, that within few voltage periods may lead to damages of various equipment such as voltage transformers, surge arresters or circuit breakers [5-7].

This paper presents the approach to analytical calculations and computer simulations that are a tool to identify a potentially hazardous network configurations (in terms of resonance occurrence between transmission line capacitance and reactor shunt inductance). Moreover, the authors discuss the application of neutral grounding reactor (NGR) that is installed between shunt reactor neutral point and ground. Such solution influences the resonance frequency, which in turn may prevent the escalation resonance oscillations. Another benefit of NGR application is secondary arc current reduction that ensures a successful reclosing sequence [8-10].

II. RESONANCE TOPOLOGIES WITH SHUNT REACTORS INVOLVED

The most common configurations and events that trigger the resonance are the ones related to reclosing sequence. The reclosing mechanism (especially when circuit breaker can be operated independently) is beneficial in terms of power transfer. This is due to the fact that with single pole open conditions, about 50% of power can be still transmitted by remaining lines (phases) [8]. However, due to capacitive and inductive coupling the open phase voltage may increase drastically, leading to equipment damage. Furthermore, during an arc fault even after single pole opening the fault current still flows, it is so called secondary arc current. It sustains the electric arc [11-13], causing a difficulties in fault extinguishing and line reclosing. Persistent open phase conditions that may result in unbalanced network state which may trigger the resonance oscillations. It may also happen when failure of the circuit breaker occurs, and just one or two phases are open, instead of three. However, it concerns only those circuit breakers that are equipped with separate operating mechanism for each phase.

The following issues favor occurrence of resonance oscillations between the shunt reactor and the overhead line, as presented in Figure 1 [5]:

- level of compensation is within range of 60%÷100%,
- at least one phase is energized to the supply source,
- at least one phase is de-energized from the supply source.

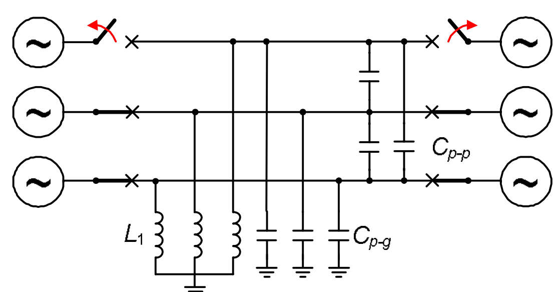

Fig. 1. General diagram for single-phase opening of OHL and shunt reactor: L_1 – main shunt reactor's inductance, L_N – NGR's inductance, C_{p-g} – phase-to-ground capacitance of the OHL, C_{p-p} – phase-to-phase capacitance of the OHL

Generation of resonance oscillations is possible for certain compensation degree *k*, which is dependent on phase inductance L_1 of the shunt reactor and positive sequence capacitance C_1:

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$$k = \frac{1}{\omega^2 \cdot L_1 \cdot C_1} \tag{1}$$

Based on parameters of the OHLs (zero and positive sequence capacitances C_0, C_1) and shunt reactor inductance L_1 it is possible to calculate compensation degrees k_1 and k_2 (according to the formulas (2) and (3)), for which the resonance is possible during single-pole or two-pole opening of the circuit breaker. For such analytical calculations, the following assumptions have to be taken into account [5]:

- OHL is transposed,
- losses of the OHL and shunt reactor are neglected,
- mutual inductance of the shunt reactor is negligible,
- neutral of the shunt reactor is effectively earthed.

$$k_1 = \frac{1 + \frac{2}{3}\left(\frac{C_1}{C_0} - 1\right)}{\frac{C_1}{C_0}} \tag{2}$$

$$k_2 = \frac{1 + \frac{1}{3}\left(\frac{C_1}{C_0} - 1\right)}{\frac{C_1}{C_0}} \tag{3}$$

Induced voltages U_1 and U_2 at the open phases during single-pole or two-pole opening are related to compensation degree k as well as zero and positive sequence capacitances of the OHL:

$$U_1 = \frac{1}{\left|\frac{3 \cdot (1-k)}{1 - \frac{C_0}{C_1}}\right| - 1} \tag{4}$$

$$U_2 = \frac{1}{\left|\frac{3 \cdot (1-k)}{1 - \frac{C_0}{C_1}}\right| - 2} \tag{5}$$

Theoretically, induced voltages on open phases can reach values as high as dozens of the nominal voltage U_N. This is however just a mathematical effect, in the real networks these voltages are limited to approximately 2 pu due to presence of nonlinear components, such as iron cores of transformers, shunt reactors, voltage transformers, and surge arresters – which in fact, can be easily damaged by a long lasting 50 Hz resonance oscillations.

III. NGR – Neutral Grounding Reactor

For some special cases, where mitigation of resonance conditions or minimization of secondary arc current is required, so called neutral grounding reactors (NGRs) can be installed, in the neutral of main shunt reactor. They are manufactured as dry type, air-core reactors. Such inductor influences the zero sequence impedance of the whole system, as presented on the diagram in Figure 2.

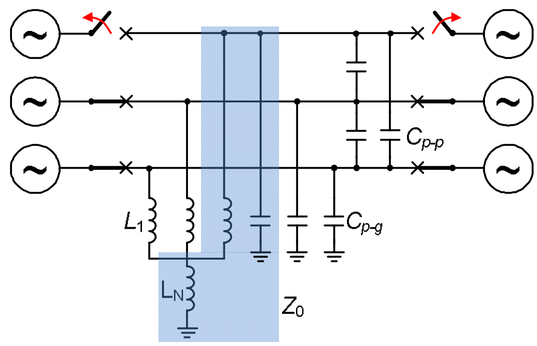

Fig. 2. De-energization of the faulted phase, NGR installed, L_1 – main shunt reactor's inductance, L_N – NGR's inductance, $C_{p\text{-}g}$ – phase-to-ground capacitance of the OHL, $C_{p\text{-}p}$ – phase-to-phase capacitance of the OHL, Z_0 – equivalent zero sequence impedance

There are several methods for NGR selection, and in any case, special precautions have to be taken into account, depending on the requirements of the customer and currently used reclosing schemes [5, 6, 13]. There are theoretical inclusions that allow to calculate minimal NGR's inductance required for resonance oscillations mitigation, as well as for full compensation of zero and positive sequence of the OHL's capacitance. Finally, secondary arc current shall be minimized in order to provide successful reclosing. Nonetheless, NGR's selection should be followed also by economical and technical analyses, and finally – by simulations, that allow to study multiple scenarios. The EMTP-ATP studies are shown in further part of this technical paper.

IV. EMTP-ATP Model description

A. General network layout

General layout of the network that was taken under study is presented in Figure 3. As shown in Figure 3, it consists of four subsystems (substations) connected by means of overhead lines with variable lengths (80 km, 115 km and 140 km). The base substation (named S/S 0) is the main point of interest, since there the compensating shunt reactor is installed. Devices such as transformers, surge arresters etc. are intentionally not shown on the diagram below, for better visibility reasons.

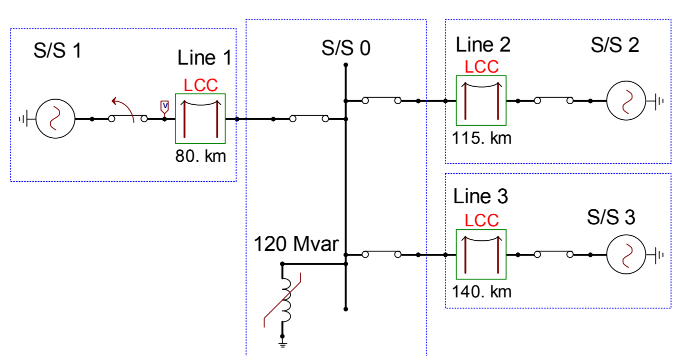

Fig. 3. Simplified general layout of the studied 400 kV network

B. Shunt reactor

The shunt reactor that is installed in S/S 0 is rated at 120 Mvar. Its rated data is presented in Table I. It was modelled in EMTP-ATP by means of lumped linear components (inductance, resistance) and also nonlinear magnetization characteristic in the form of flux-current curve, according to linearity guaranteed up to 130% of the U_N [14-16].

TABLE I
RATED DATA OF THE MAIN SHUNT REACTOR

Parameter	Value
Rated voltage	400 kV
Frequency	50 Hz
Nominal power	120 Mvar
Reactance	1333 Ω
Phase inductance	4.25 H
Linearity	up to 130% U_N
Vector connection group	YN
Total losses	210 kW

C. Overhead lines

In the present case, the overhead transmission lines are modelled as Bergeron types. This is allowable due the fact that the frequency of oscillations [16, 17] that are meant to be generated are in the range of 50 Hz, high frequency oscillations are out of concern in this case. Based on the provided dimensions below, EMTP-ATP calculates equivalent self and mutual resistance, capacitance and inductance of the line, using LCC module. Overhead line layout and phase wire's data is presented in Figure 4.

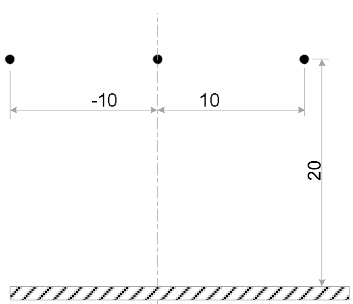

Fig. 4. Overhead line layout and phase wire's data

D. Grid equivalent network model

AC network was represented by a RLC equivalent circuit (Figure 4) tuned to resonant frequency of 2 kHz. The grid parameters were specified by the short-circuit power equal to S_k" = 40 GVA at ratios X/R = 10 and Z_0/Z_1 = 3 [16].

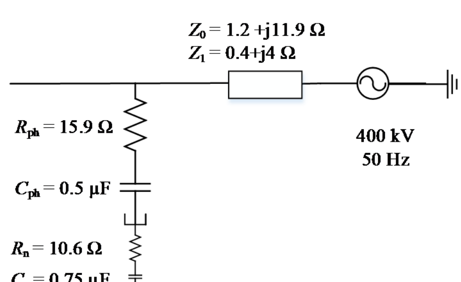

Fig. 4. Frequency dependent network equivalent diagram

The proposed system equivalent was based on the Thevenin circuit that includes both zero and positive sequence impedance Z_0 and Z_1 (LINESY_3 default component in EMTP-ATP library) complemented with RLC elements that compose the frequency dependent network equivalent with specified resonance frequency. This kind of approach was proposed by the IEC 60071-4 standard.

E. SF_6 circuit breaker models

The SF_6 circuit breakers (CB) that are installed in 400 kV substations were modelled in two separate ways. This was intended by necessity of investigation, if CB model may have any influence on the final simulation result. First model is simple one and it considers only grading capacitors (700 nF per phase) and the chopping current (20 A). The second model is more complex and is based on Cassie-Mayr equations that allow to include arcing phenomenon. The conductivity of the electric arc is modelled for two parts of the current, representing the electric arc behavior for both the high current (Cassie portion – eq. (5)), and for the low current conditions (Mayr portion – eq. (6)). The total arc resistance is given by (7), according to references [18, 19].

$$\frac{dg_c}{dt} = \frac{1}{\tau_c} \cdot \left(\frac{i_a^2}{u_s^2 \cdot g_c} - g_c \right) \tag{5}$$

where: g_c is arc conductance [S], τ_c = 0.8 μs – time constant of the arc [s], u_s = 2.35 kV – steady-state arc voltage [V], and i_a is arc current [A].

$$\frac{dg_m}{dt} = \frac{1}{\tau_m} \cdot \left(\frac{i_a^2}{P_0} - g_m \right) \tag{6}$$

where: g_m is the arc conductance [S], τ_m = 0.22 μs – the time constant of the arc [s], P_0 = 8.8 kW – the steady-state cooling power of the arc [W], and i_a is arc current [A]

$$r_{arc} = \frac{1}{g_{arc}} = \left(\frac{1}{g_c} + \frac{1}{g_m} \right) \tag{7}$$

where: g_c is the arc conductance for Cassie portion, and g_m is the arc conductance for Mayr portion.

V. SIMULATION RESULTS

A. Scope of work

There are several goals of this technical paper, not only limited to resonance identification in the 400 kV network. Also influence of modelling techniques on possible resonance generation was checked, and it refers to used circuit breaker type model. Issue such as overhead lines configurations (namely the vertical and horizontal positioning of phase wires) and their length are out of scope in this technical paper, since they are already defined and fixed in the system under study. Moreover, these issues were already well described in other technical papers and guidelines, such as [5] and [6].

B. Resonance identification – network configuration

This subchapter shows the identification process of forbidden network configuration that can lead to resonance conditions. The resonance can be possible only for specific range of OHL's compensation degrees. It was calculated (eq. (2) and eq. (3)) that the factors k_1 and k_2 (compensation degrees for 1-phase open and 2-phase open conditions) are equal to 87% and 74%, respectively. Analytically calculated (eq. (4) and (5)) induced voltages are shown in Figure 5, and resonance regions are in line with mentioned k_1 and k_2 factors. Summary for all possible configurations is shown in Table II. Configurations that are highlighted in red are characterized with compensation degrees close to factors k_1 and k_2, hence can be considered as probably prone to resonance. NGR is not included herein – thus the neutral of shunt reactor is effectively earthed.

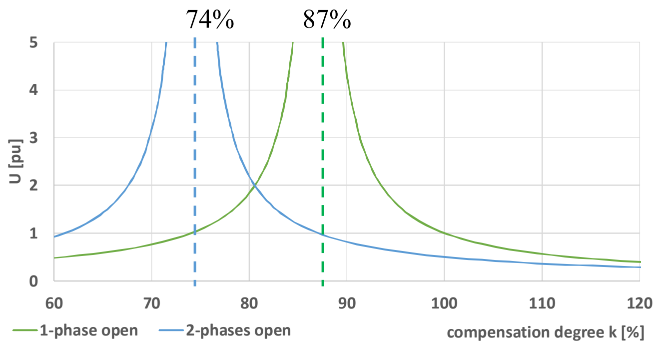

Fig. 5. Induced voltages with respect to compensation degree k

TABLE II
ANALYTICAL IDENTIFICATION OF RESONANCE CONDITIONS (WITHOUT NGR)

Configuration	Total OHL length [km]	k [%]	k1 [%]	k2 [%]
OHL 1 only	80	266	87	74
OHL 2 only	115	185	87	74
OHL 3 only	140	152	87	74
OHL 1 and 2	195	109	87	74
OHL 1 and 3	220	96	87	74
OHL 2 and 3	255	83	87	74
OHL 1, 2, and 3	335	63	87	74

Based on above presented calculations it can be said that the resonance conditions are possible only when the shunt reactor is de-energized simultaneously with 2 or 3 OHLs. Such configurations must be treated as forbidden. Obviously, they are of low level of probability, nonetheless – must be defined. Example of network configuration leading to resonance is presented in Figure 6, they are highlighted in red in Table II.

The analytical calculations were verified by means of EMTP-ATP simulations (Figure 7 and 8). Circuit breaker was opened at the time instant $t = 0.02$ s (on simplified CB model in this chapter). Single- and two-pole opening was shown, according to cases listing in Table II. In the studied case resonance oscillations are generated only in low probability cases, where shunt reactor is de-energized simultaneously with 2 or 3 overhead lines. These must be considered as forbidden, since may lead to damage of substation equipment [5].

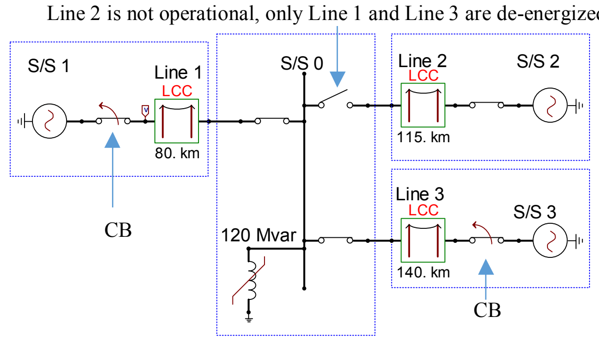

Fig. 6. Example of network configuration leading to resonance (OHLs 1+3)

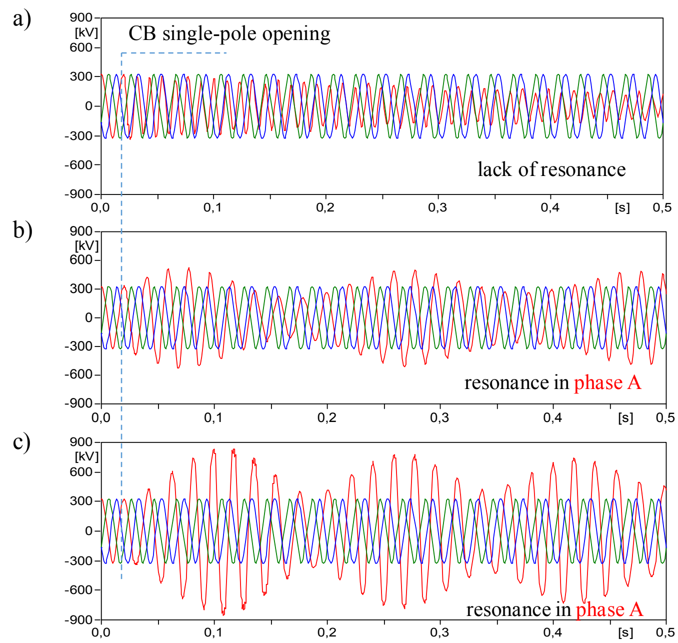

Fig. 7. EMTP-ATP simulation, single-pole opening of shunt reactor and OHL; various combinations: a) OHL 2, b) OHLs 1+3, c) OHLs 1+2+3

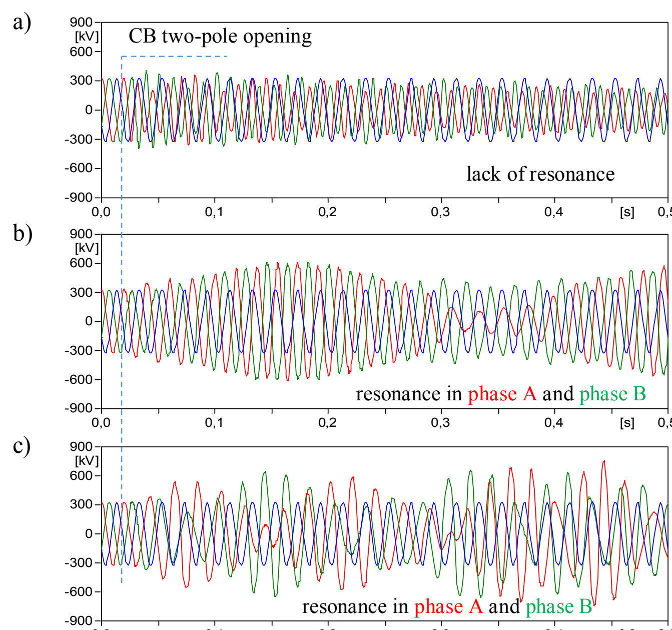

Fig. 8. EMTP-ATP simulation, two-pole opening of shunt reactor and OHL; various combinations: a) OHL 2, b) OHLs 1+3, c) OHLs 1+2+3

As can be seen in Figures above, resonance conditions are possible only for unbalanced system, so during single- or two-pole opening of the CB. The induced voltages on open phases are within range of 1.5 pu to 2.1 pu. This is crucial result, since such 50 Hz overvoltages exceed the allowable limits for installed surge arresters: maximum continuous operating voltage (MCOV = 1.16 pu) and temporary overvoltages (TOV) – 1.7 pu for 1 second and 1.6 pu for 10 seconds [20]. Long lasting oscillations could lead to surge arresters failure.

C. *Influence of CB model on transient response*

The idea was to check if the CB model can have any influence on transient response of the system or on the resonance conditions during the opening operation. Normally, this is a major issue for high frequency studies such as breaking of the inrush current, or multiple arc re-strikes [21-23]. The result of the 1-phase opening operation with Cassie-Mayr CB model is presented in Figure 9.

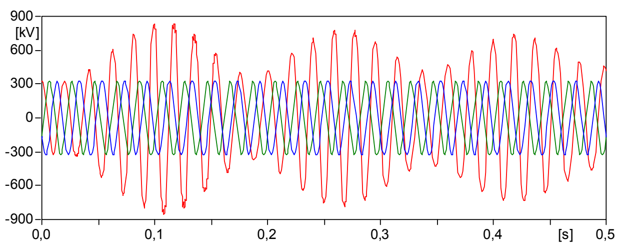

Fig. 9. EMTP-ATP simulation, single-pole opening at t = 20 ms of shunt reactor and OHLs 1+2+3, Cassie-Mayr model used for CB modelling

As can be seen in Figure 9, the influence on the result is marginal and it can be compared with Figure 7c. The maximum peak value differs by less than 0.1%, and is a result of a linearly rising resistance inserted into the circuit. Nonetheless, it has no effect on possible resonance conditions, since LC values of the CB are several orders smaller when compared to inductance of the shunt reactor and capacitance of the OHLs.

D. *Selection of the NGR*

The reasoning on possible resonance conditions is very often supported by additionally required calculations, which are related to selection of appropriate ratings of the neutral grounding reactor (NGR). Its first role is to shift the resonance frequency of the system far from k_1 and k_2 factors (for 1-phase open and 2-phase open conditions). Second role, not least, is to minimize the secondary arc current, which flows in the faulted phase even after disconnection of this phase by the circuit breaker. This is a result of the inter-phase coupling of phases of the overhead lines. The issue is significant, since it can lead to unnecessary prolonged reclosing delay. There are several ways of NGR sizing, and in this case, the main goal was to minimize the secondary arc current.

Typical NGRs are manufactured without the iron core, so they are linear in the entire region of operation. Even if the theoretical calculations suggest some value, also technical, economical and manufacturing factors have to be taken into account. Hence, in most cases NGRs are in the range of 10% to 30% of power of the main shunt reactor.

In the present study case, it as non-typical situation, since the shunt reactor is not installed directly on the OHL, but on the substation busbars. It was decided to run multiple simulation runs that would allow to determine the minimum secondary arc current, in the function of inductance of the NGR (Figure 10).

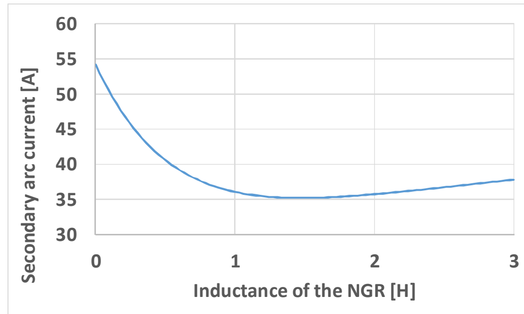

Fig. 10. Secondary arc current in the function of NGR's inductance with main shunt reactor rated at 120 Mvar

According to eq. (8) the NGR shall be sized at $L_N = 2.22$ H in order to achieve minimization of the secondary arc current.

$$L_N = \frac{L_1}{3} \cdot \left(\frac{\frac{C_1 - C_0}{C_1}}{k - \frac{C_1 - C_0}{C_1}} \right) \tag{8}$$

However, as it was described in the introduction, this equation excludes the inductive reactance of the line, as well as shunt reactors nonlinearities. Moreover, in practice such large NGRs are not used. As can be seen in Figure 10, in this particular case 30% NGR (approximately 1.3 H) provides satisfactory results which is in line with practical applications.

VI. Conclusions

This paper should be treated as a technical study case that shows the entire process of 400 kV network development that was done in 2016. Due to complicated grid and installation of new compensating shunt reactor, extensive analytical calculations as well as EMTP-ATP simulations had to be conducted, for multiple configuration of the studied network.

It was shown that the resonance conditions are possible only for certain, unusual network configurations, namely:

1. Single-pole or two-pole opening,
2. Simultaneous de-energization of two or three overhead lines and shunt reactor.

Based on the studied, forbidden switching operations were identified, which will allow to avoid generation of unfavorable conditions leading to 50 Hz resonance oscillations that would result in failure of the substation equipment, especially surge arresters. Moreover, it was proposed to install neutral grounding reactor NGR (as an optional solution) in order to decrease the secondary arc current. It can be added that conducted analytical calculation are in line with EMTP-ATP simulations, and numerical models were prepared according to international standards and guidelines provided in references.

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