Switching and Fault Transients of Unit Transformers of a Combined-Cycle Gas Turbine Generator

M. Kizilcay, S. Demmig

Abstract **– A new combined-cycle power plant is to be connected to a 110-kV grid through a power cable of approximately 2 km length. There are two options regarding circuit breaker (CB) use; either only one circuit breaker for each feeder will be installed at the substation, or an additional circuit breaker at the site of the power plant may be necessary. By means of digital simulations of switching and fault transients for various scenarios the system performance will be evaluated regarding the necessity of an additional circuit breaker.**

Keywords**: energization, ferroresonance, switching transients, fault, TRV, transient recovery voltage, EMTP-ATP.**

I. Introduction

A new combined-cycle power plant is to be connected to a 110-kV grid via cables with a length of approximately 2 km. There are three feeders in the 110-kV substation for the connection of the power plant, two of which are generator feeders with a generation of 230 MVA (gas turbine) and 125 MVA (steam turbine), respectively. The third feeder is connected to the service transformer with a power rating of 20 MVA. A generator feeder is shown in Fig. 1. The aim of the study is to analyze by means of computer simulations whether or not critical stress on equipment is to be expected due to switching and fault transients in the feeders when operating the CB at the substation because of the relatively long cables. To mitigate the expected stresses an additional CB shall be considered at the power plant site.

In this context several switching operations were studied by means of EMTP-ATP [1] simulations like energization of the unloaded unit transformers, opening of the feeders during steady-state or during inrush state of the transformers immediately after an energization, switching off immediately following a switching on operation due to a preceding fault in the feeders, unsymmetrical switching on and off due to a stuck CB pole. Additionally, the probability of the excitation of unit transformer winding resonances by the travelling waves in cables has been studied.

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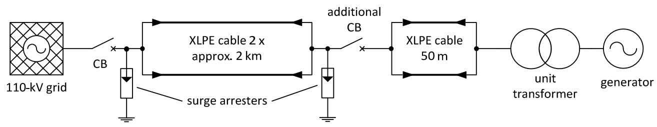

Fig. 1. 110-kV generator feeder

II. System Data and Simulation Model

A. System Data

The 110-kV grid is modeled in detail with all the 110-kV lines and two grid transformers 220 kV/110 kV connecting the 110-kV network to the 220-kV grid. Since the presentation of the simulation results in this paper will be confined to the generation feeder of the gas turbine unit (GT), only the data of the equipment in that feeder are given in Table 1. The computation results for the feeder of the steam turbine unit are similar to those of the GT generation feeder and are less critical. Phase-to-ground surge arresters (Fig. 1) are to be installed at both cable ends based on a lightning overvoltage study.

B. Simulation Model

The simulation model consisting of the two transformers supplying power from the 220-kV grid, the three feeders of the power plant and the remaining 110-kV overhead lines and cables in the network is shown in Fig. 2. In some cases the system load is also taken account. The loads are represented in a simplified manner by constant impedances at the 110-kV substations.

All lines and cables are modeled using Constant-Parameter Distributed Line (CPDL) model of EMTP-ATP.

The saturation of the unit transformer in the feeder of the GT unit is represented by a magnetization curve at the low voltage side based on the assumption that $L_{sat} \approx 1.0\, L_k$. L_{sat} is the inductance in the saturation region of the magnetization curve and L_k is the short-circuit inductance of the transformer at the low voltage side.

The modeling of the surge arresters is necessary to see their limitation of overvoltages and to observe their thermal stress in case of sustained overvoltages (i. e. ferroresonance). They are modeled in EMTP-ATP based on [3].

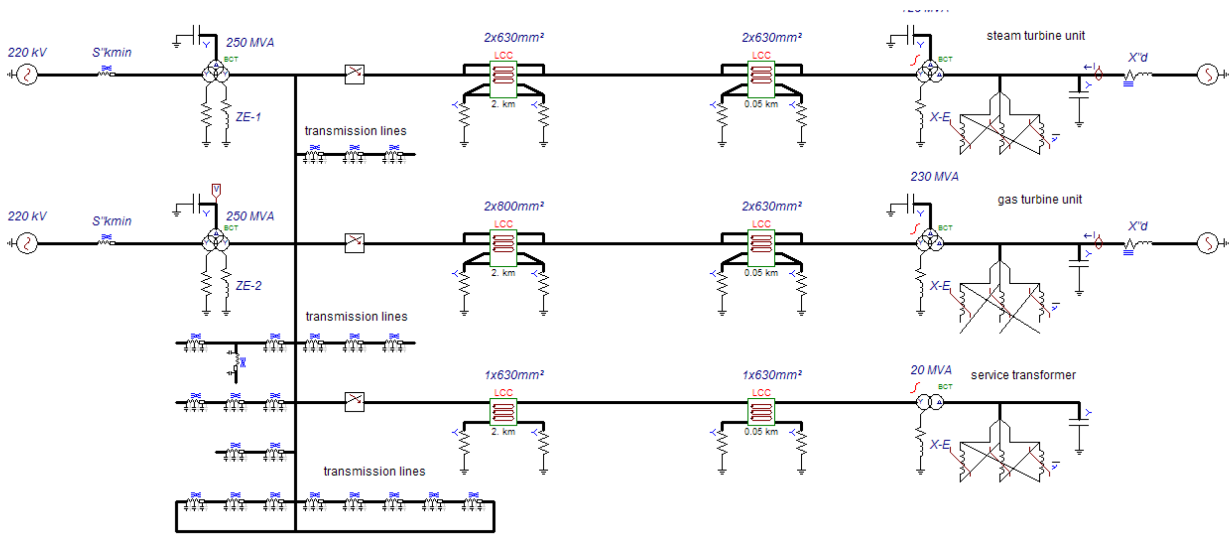

Fig. 2. Complete simulation model of the studied 110-kV system excluding surge arresters and loads generated using ATPDraw [6]

TABLE 1
ELECTRICAL DATA OF THE STUDIED SYSTEM

- Source network:	
voltage (rms)	220 kV
short-circuit power	4.85 ... 5.92 GVA
$R_{(1)}/X_{(1)}$	0.11 ... 0.17
$X_{(0)}/X_{(1)}$	approx. 1.0
$R_{(0)}/R_{(1)}$	approx. 1.1
- 220-kV/110-kV transformers (2x):	
vector group	YNyn0d5
rated voltage of the windings	231 / 115.5 / 10.5 kV
rated power of windings	250 / 250 / 83 MVA
impedance voltages (1-2) / (1-3) / (2-3)	15.9 / 13.9 / 6.7 %
grounding reactor of the neutral point (110 kV)	43 Ω
- Unit transformer (gas turbine unit):	
vector group	YNd5d5
rated voltage of the windings	122.5 / 16.5 / 11.2 kV
rated power of windings	230 / 230 / 20 MVA
impedance voltages (1-2) / (1-3) / (2-3)	15 / 15 / 19 %
grounding reactor of the neutral point (110 kV)	60 Ω
- Gas turbine (GT) generator:	
rated power	230 MVA
rated voltage	15.75 kV
sub-transient reactance	15 %
- 110-kV feeder XLPE cable (gas turbine unit):	
double cable per phase	N2XS(FL)2Y 1 x 800 RM/50
length	1.6 ... 2 km
pos.-sequence impedance	(0.042 + j0.163) Ω/km
zero-sequence impedance	(0.582 + j0.169) Ω/km
capacitance core-sheath	191 nF/km
- metal-oxide surge arresters (phase to ground):	
rated voltage	132 kV
nominal discharge current	10 kA
energy absorption capacity	1056 kJ

III. SIMULATION RESULTS

The computations of switching transients focus on

- energization and de-energization of the feeder in normal operation
- energization and de-energization with unsymmetrical switching by the CB (one CB pole is stuck)
- disconnection of the feeder by a malfunction of the protection immediately after energization
- disconnection of the feeder due to a fault in the feeder.

A. Energization of the GT Generator Feeder

Regular energization of the GT feeder with the unloaded unit transformer does not cause any critical stress on the equipment, when the three CB poles close synchronized within an acceptable period of time (pole spread). If a CB pole is stuck (i. e. does not close) and the CB closes in two-phases, ferroresonance with severe overvoltages occurs in the still open phase of the feeder [4]. Fig. 3 shows phase-to-ground voltages in the feeder at the terminals of the unit transformer. The surge arresters are not taken into consideration in this computation. When the surge arresters as shown in Fig. 1 are taken into account in the model, the phase-to-ground voltages are limited to maximum 245 kV by the surge arresters as shown in Fig. 2, but surge arresters of the unconnected phase C is likely to be destroyed thermally in a relatively short period of time (229 ms) after energization (see Fig. 5). This time is too short to apply a protective measure against destruction of the surge arresters. A second CB at the power plant site would help to avoid this overvoltage stress, when at first step the CB at the substation will be closed, while the second CB at the power plant site is open. At second step the generator can be synchronized with the 110-kV grid at the HV side of the unit transformer by closing the second CB.

Another option to reduce the stress on the surge arresters following an energization with a stuck CB pole would be to temporarily short-circuit the neutral point reactor of the 110-

kV winding of the unit transformer during energization. Time duration until thermal overstressing could be extended this way to 4.8 s. This value is estimated by linear extrapolation of the rate of energy absorption of the surge arresters.

It should be added that by using a CB at the power plant site, the excitation of unit transformer winding resonances by travelling waves in the cables following an energization of the feeder at the substation can be avoided.

B. Opening of the GT Generator Feeder

Three-phase de-energization of the GT feeder by opening the CB at the substation with the generator in operation or switched off (unloaded unit transformer) does not cause any critical stress on equipment.

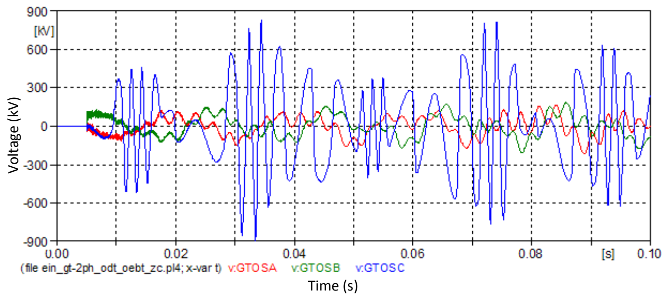

Fig. 3. Phase-to-ground voltages at the terminals of unit transformer in case of two pole closing of the CB at the substation (stuck CB pole in phase C). No surge arresters in the feeder.

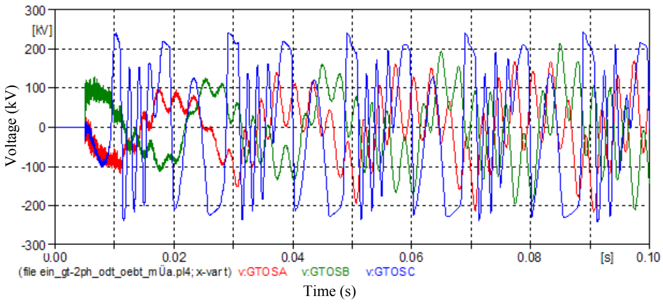

Fig. 4. Phase-to-ground voltages at the terminals of unit transformer in case of two pole closing of the CB at the substation (stuck CB pole in phase C). Surge arresters in the feeder are taken into consideration as shown in Fig. 1

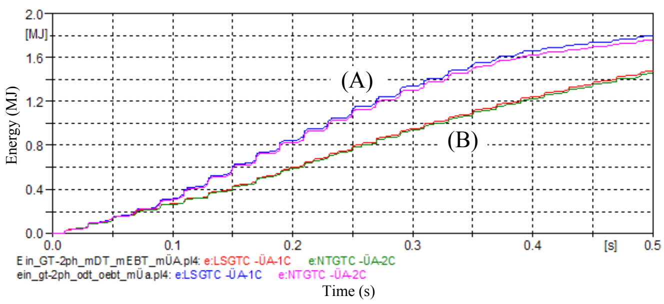

Fig. 5. Energy absorption of the surge arresters of phase C in case of two pole closing of the CB (refer to Fig. 4 for phase-to-ground voltages)
Feeders of the steam turbine unit and of the service transformer are: (A) not energized; (B) energized before energization of the GT feeder

If one CB pole sticks while the other two poles open with the generator switched off, then again ferroresonance occurs in the feeder because of the unloaded unit transformer in connection with the 110-kV grid. Waveforms of the phase voltages at the terminals of the GT unit transformer in case of two-phase opening of the CB are shown in Fig. 6, 7 and 8. Surge arresters in the feeder are not taken into consideration in the model to show uninfluenced waveforms. This case is not as severe as two-pole closing described in section 3.1. The overvoltages do not attain high values compared to Fig. 3. The surge arresters would also be stressed thermally due to sustained ferroresonance phenomenon, but the time period to reach thermal limit is expected to be approximately 9 s. This value is estimated by linear extrapolation of the energy waveform.

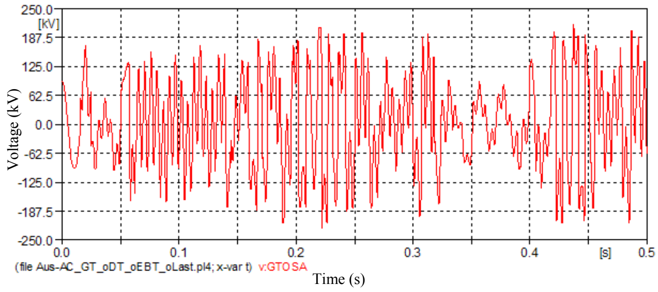

Fig. 6. Phase-to-ground voltage in phase A at the terminals of the unit transformer in case of two pole opening of the CB at the substation (stuck/closed CB pole in phase B)

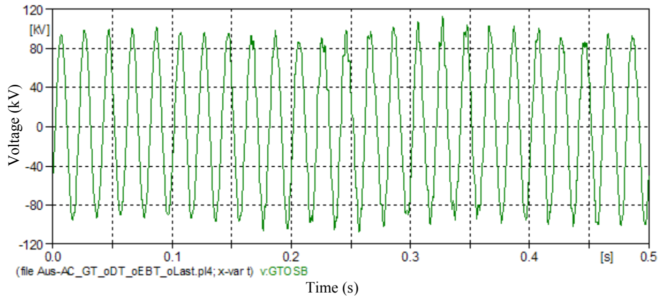

Fig. 7. Phase-to-ground voltage in phase B at the terminals of the unit transformer in case of two pole opening of the CB at the substation (stuck/closed CB pole in phase B)

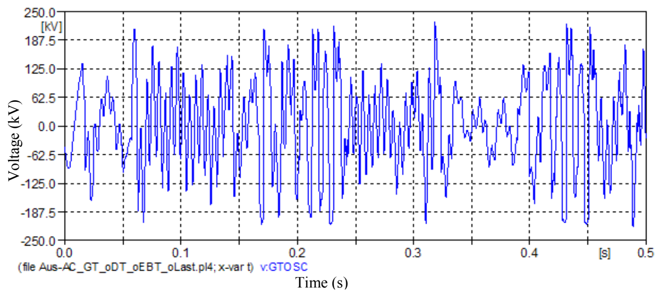

Fig. 8. Phase-to-ground voltage in phase C at the terminals of the unit transformer in case of two pole opening of the CB at the substation (stuck/closed CB pole in phase B)

Much more severe overvoltages are expected, when the GT feeder is disconnected by the CB in two poles (third pole is stuck) as a result of malfunction of the protection immediately after the energization. Figures 9 and 10 show the waveforms of the CB current (phase A does not open) and phase-to-ground voltages at the terminals of the unit transformer, respectively. After the simulation started, the feeder is energized and at $t = 0.1$ s the CB interrupts inrush current of the unit transformer in two poles (phase B and C). The surge arresters of the feeder are not included in this computation. When surge arresters are included, the thermal overstressing limit is reached approximately in 0.8 seconds.

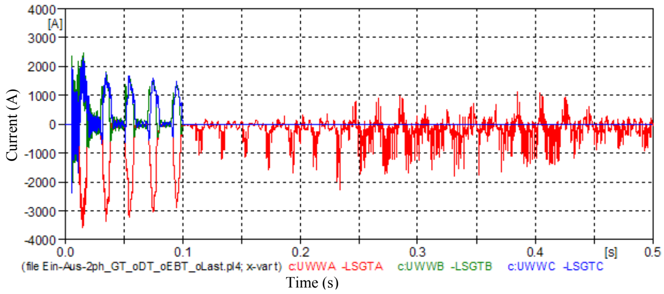

Fig. 9. CB current waveforms during energization of the GT feeder (inrush current of the unit transformer) and after the interruption of the inrush current in two phases (B and C) at around $t = 0.1$ s

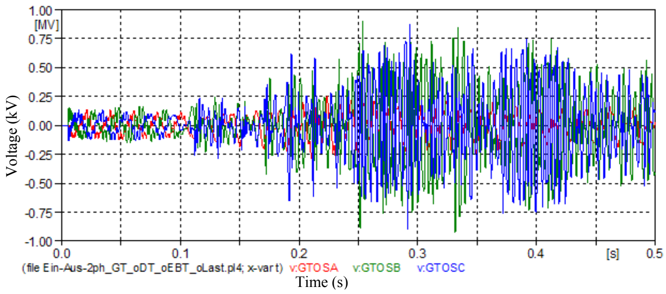

Fig. 10. Phase-to-ground voltages the terminals of the unit transformer in case of energization of the GT feeder and subsequent two pole opening of the CB at the substation (stuck/closed CB pole in phase A) at around $t = 0.1$ s

C. Switching Transients of the Faulted Feeder

1) Three-Phase Fault

When a fault occurs in the feeder, the fault will be cleared by opening of the CB at the substation. During opening transient recovery voltage (TRV) waveform across the CB poles may cause the malfunction of the CB, i.e. restriking of the CB pole [5]. In case of a three-phase short-circuit in the GT feeder the maximum short-circuit current amounts to 12.2 kA. The rated short-circuit breaking current of the CB is specified to be 31.5 kA. According to [2] test duty T60 applies for the selection of the standard values of the prospective TRV, which is represented by a four parameter envelope. Thereby the first-pole-to-clear-factor k_{pp} is to be known for the CB of the GT feeder. It has been determined by means of steady-state calculations with EMTP-ATP as $k_{pp} = 1.49$. The prospective TRV envelope (see Fig. 11) is represented for the calculated k_{pp} and rated voltage $U_r = 123$ kV by the following four parameters [2]:

$$u_1 = 113\ \text{kV}, \quad t_1 = 38\ \mu\text{s}, \quad u_c = 226\ \text{kV}, \quad t_2 = 228\ \mu\text{s}.$$

The TRV obtained by the ATP simulation of a three-phase fault just behind the CB in the GT feeder and the prospective TRV for the test duty T60 according to [2] are compared in Fig. 12. The prospective TRV envelope is computed dynamically by a MODELS routine by adjusting its starting time to the CB pole opening moment.

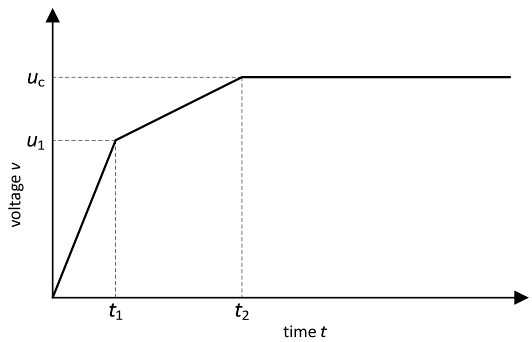

Fig. 11. Four-parameter prospective TRV envelope [2]

Since the TRV obtained by the simulation cuts the prospective TRV for the first pole opened, this may cause a problem for the CB. The TRV is affected by the system load, but it may not be considered as a measure because the load is fluctuating. The solution would be to select a CB with a higher rated voltage.

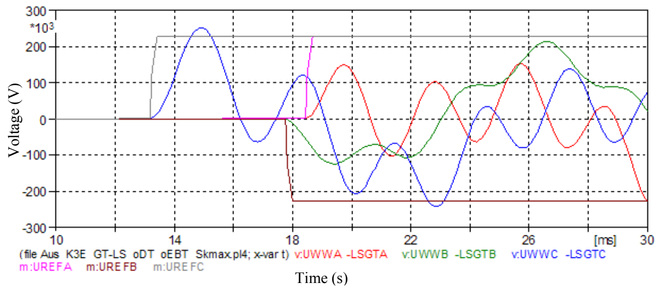

Fig. 12. Computed and prospective TRV (four-parameter representation) for each CB pole during interruption of the current of a three-phase short-circuit in the GT feeder

2) Single-Phase Fault

The fault current of a single-phase fault in the GT feeder is expected to be 2.44 kA, relatively low due to neutral point earthing of the 110-kV system by reactors to limit the single-phase-to-ground fault current. This implies a test duty T10 for a 31.5-kA-CB according to [2] for the CB pole to clear the inductive fault current. The other CB poles interrupt capacitive currents of the sound phases. Hence the prospective TRV for the capacitive current switching should be applied for those CB poles. For the capacitive switching current test, as an alternative to using test circuits, switching tests may be performed with following parameters of the prospective TRV [2]:

$$u_c = 2 \cdot u_{test} = 2 \cdot 1.7 \cdot \sqrt{2} \cdot \frac{U_r}{\sqrt{3}} = 342\ \text{kV} \ \text{ with}$$

$$U_r = 123\ \text{kV}\,; \ \ t_2 = 8.7\ \text{ms}$$

$$u_1 = 0.02 \cdot k_{af} \cdot u_{test} = 4.78\ \text{kV} \ \text{ with}$$

$$k_{af} = 1.4; \ \ u_{test} = 171\ \text{kV}\,; \ t_1 = 56\ \mu\text{s}$$

where k_{af} is the amplitude factor.

The worst-case of the TRV is obtained in case the unit transformer is unloaded and no load in the 110-kV grid is taken into consideration. The surge arresters in the GT feeder limit phase-to-ground voltages, but the thermal stress is rather uncritical. Fig. 13 shows the waveforms of phase voltages at the terminals of the GT unit transformer. The waveforms of the TRV obtained by the simulation and prospective TRV's for inductive and capacitive switching are shown in Fig. 14. According to Fig. 14 the prospective TRV envelope specified by line segments (yellow and cyan curves) for capacitive switching currents is cut in the amplitude as well as due to the steepness of the TRV obtained by the simulation. The TRV of the faulty phase A remains below the prospective TRV envelope.

An additional CB at the power plant site would help to have the TRV due to capacitive swithing current under control. The opening times of the two CB's in the same feeder can be controlled, so that the CB at the power plant site opens first and the CB at the substation opens with sufficient time delay.

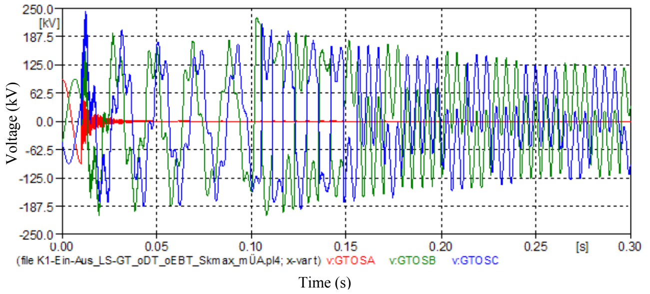

Fig. 13. Phase-to-ground voltages at the terminals of the GT unit transformer in case of a single-phase-to-ground fault (phase A) in the feeder. The feeder is opened approximately 100 ms after the fault inception.

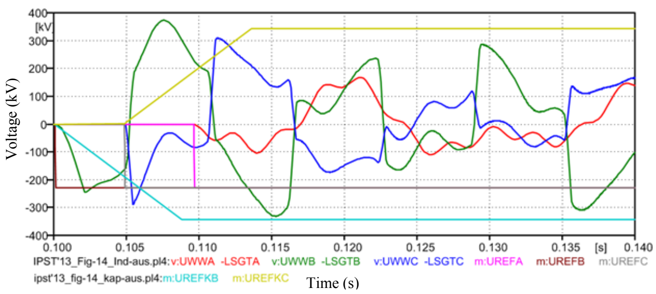

Fig. 14. Computed and prospective TRV for each CB pole during interruption of the current of a single-phase-to-ground fault in the GT feeder

When the GT generator is in operation while the single-phase fault occurs in the 110-kV GT feeder, no critical TRV waveform is expected across the CB at the substation, even with no additional CB at the power plant site.

IV. Conclusions

In this paper the likely impacts of switching operations on the performance of a 110-kV system are presented for a new generator feeder to connect a gas turbine generator (230 MVA) to the 110-kV grid. The feeder consists of a double XLPE cable with a length of approximately 2 km. A circuit breaker (CB) is installed at the substation to switch the generator feeder. To mitigate the expected stresses an additional circuit breaker shall be considered at the site of the power plant.

Critical sustained overvoltages are expected in the feeder with the unloaded unit transformer in case of unsymmetrical energization and de-energization by the circuit breaker at the substation, when one circuit breaker pole remains stuck, i.e. the closing and opening occur only with two-poles. In this case ferroresonance arises in connection with the nonlinear magnetizing inductance of the unloaded transformer and the cable capacitance. The surge arresters will be thermally overstressed in those cases within relatively short time. Installation of an additional circuit breaker at the power plant site would help to avoid that ferroresonance phenomenon, when the second CB is used to synchronize the generator at the HV side with the 110-kV grid.

Another subject of this study was the transient recovery voltage (TRV) across the circuit breaker poles during opening of the CB. When a three-phase short-circuit occurs in the generator feeder, the TRV of the first opening pole attains higher amplitude than the prospective TRV envelope specified by [2]. In this case a circuit breaker with a greater rated voltage should be selected.

In case of a single-phase fault in the feeder with the unloaded unit transformer the TRV across the CB poles of sound phases has a higher rate of rise and much larger amplitudes compared to the prospective TRV envelope for capacitive current switching, when the fault is cleared by opening the CB at the substaion. The additional CB at the power plant site would help to have the TRV due to capacitive swithing current under control. The opening times of the two CB's in the same feeder can be controlled, so that the CB at the power plant site opens first and the CB at the substation opens with sufficient time delay.

It should be added that by using a CB at the power plant site, the excitation of unit transformer winding resonances by travelling waves in the cables following an energization of the feeder at the substation can be avoided.

V. References

[1] EMTP-ATP: ElectroMagnetic Transients Program, version Alternative Transients Program, development and copyright by Canadian/American EMTP User Group, West Linn, Oregon, USA (http://www.emtp.org).

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