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Analysis of electromagnetic transients in secondary circuits due to disconnector switching in 400 kV air-insulated substation

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ABSTRACT

This paper describes the electromagnetic transients caused by disconnector switching in 400 kV air-insulated substation. Transient overvoltages in the secondary circuits of capacitor voltage transformer (CVT) have been calculated using the EMTP-ATP software. The transfer of electromagnetic transients through substation's grounding grid has been analyzed in order to determine the overvoltages at the terminals of protective relays located in the control (relay) room. The overvoltages in secondary circuits have been recorded during on-site test.

1. Introduction

Secondary equipment in HV substation is highly sensitive to transient electromagnetic disturbances due to the disconnector switching operations. Opening and closing of the disconnector produce electromagnetic transients with a very fast rate of rise. These transients can be particularly harmful to microprocessor-based electronic equipment located near the HV switching devices [1,2].

HV disconnectors have a negligible current interrupting capability ($\leq$0.5 A) which includes the capacitive charging currents of bushing, busbars, connective leads, very short lengths of cables and of the CVT [3]. Literature [4–6] related to capacitive current interruption by air-break disconnectors is sparse and a good overview is presented in [7]. A disconnector operates only after a circuit-breaker has already opened the corresponding switchyard section, which represents a capacitive load. When the slow moving contacts of a disconnector close or open, numerous pre-strikes or re-strikes occur between the contacts (Fig. 1).

These high-frequency phenomena are coupled with the secondary circuits as a result of various mechanisms [8–11]. Electromagnetic disturbances are transmitted to secondary circuits through stray capacitances between the high-voltage conductors and the grounding system, followed by the galvanic connection between the grounding system and the secondary circuits (Fig. 2). High-frequency transient current flowing in the grounding system generates potential differences every time when a strike occurs between the disconnector's contacts.

In case of large secondary circuits, the potential differences are in the form of longitudinal voltages between the terminal and the enclosure of the equipment. Depending on the type of secondary circuits and the way they are laid, differential voltages may also occur. Such a coupling mechanism has a special effect on the secondary circuits of instrument transformers, and particularly on the connected instruments, since these circuits are always directly connected to the grounding system. Another important factor which also has to be taken into account is the linking of these circuits through the internal capacitances of the instrument transformers.

This paper deals with transient overvoltages in the secondary circuits of CVT due to disconnector switching in 400 kV air-insulated substation. The transferred overvoltages in the secondary circuits were estimated in the designing process of high voltage substation. Recorded transients caused by disconnector switching in 400 kV substation are presented.

2. Modeling of 400 kV substation

Fig. 3 shows a part of 400 kV substation used for the analysis of the disconnector switching.

Switching the transmission line bay from the main to the auxiliary busbar system and vice versa was analyzed. In this case the CVT and the auxiliary busbars represent capacitive load which is switched by the disconnector in line bay. The transfer of electromagnetic transients through the substation's grounding grid has

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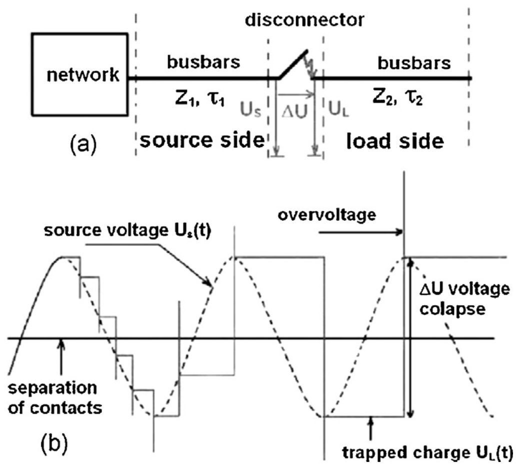

Fig. 1. Voltages associated with disconnector switching: (a) simple scheme of a substation; (b) voltage waveform on disconnector due to opening of the contacts.

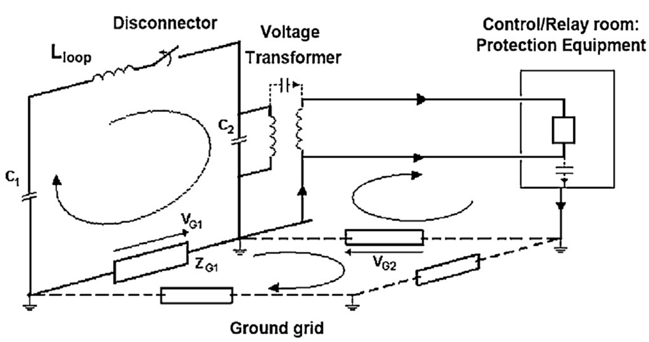

Fig. 2. Coupling mechanisms between HV and LV circuit.

been analyzed in order to determine the overvoltages at the terminals of protective relays located in the control/relay room. Fig. 4 shows the configuration of substation grounding grid between CVT and the relay/control room.

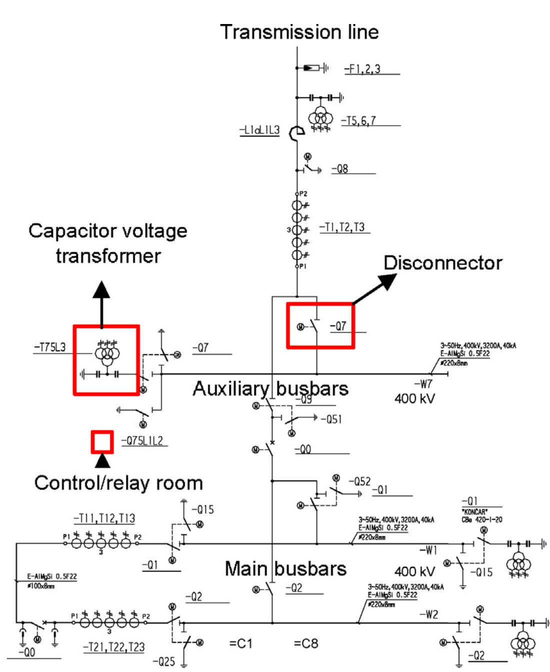

Fig. 3. A part of 400 kV substation used for the analysis of the disconnector switching.

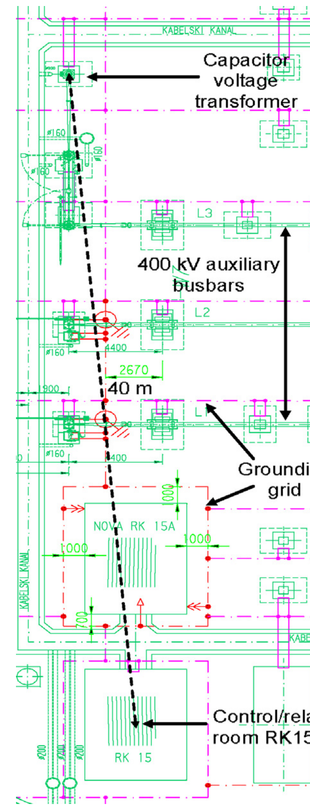

Fig. 4. Substation grounding grid between CVT and the control/relay room RK15A.

The model for the analysis of the disconnector switching in EMTP/ATP software is shown in Fig. 5. CVT in one phase was represented with the following elements [12,13]: two capacitors C_1 and C_2 connected in series on the HV side; compensating inductor (R_C, L_C, C_C); step-down transformer (primary winding R_P, L_P, C_P; secondary winding R_S, L_S, C_S); stray capacitance between primary and secondary windings C_{PS}; burden 4.6 VA (726 Ω). Stray capacitance between primary and secondary windings has a significant influence on the transient response of the CVT for frequencies above 10 kHz (Fig. 6).

The grounding mesh has been represented with the frequency dependent cable model (Fig. 7). The mutual coupling between grounding system components has been taken into account by treating them as different phases of a cable.

The relay room RK15A is located 40 m away from CVT. The parameters of the grounding system are shown in Table 1.

The electrical and geometrical parameters of the auxiliary busbar system are shown in Table 2.

The auxiliary busbar system was modeled with the frequency dependent JMarti model [14] and bus support insulators with capacitances to the ground [15].

The equivalent network from the "source side" of the disconnector has been represented by a voltage source and a short-circuit

Table 1
Parameters of the grounding system in 400 kV substation.

Material	Copper wire
Specific resistance (Ωmm^2/m)	0.0169
Cross section (mm^2)	120
Soil resistivity (Ωm)	300
Burial depth (m)	0.8

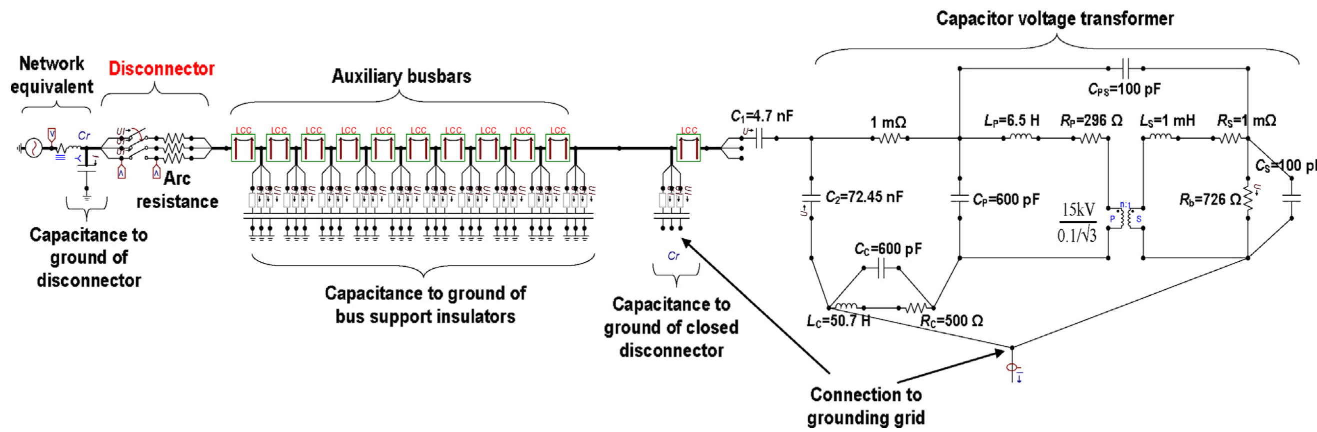

Fig. 5. EMTP-ATP model for analysis of disconnector switching.

impedances. Arc resistance of 2 Ω between the disconnector's contacts was assumed in simulations.

3. Calculation of overvoltages in secondary circuits due to the disconnector switching

A flashover in case of 2 p.u. voltage between opening contacts of disconnector as the worst theoretical case has been analyzed. In a real operation the flashover occurs at lower voltage differences and the corresponding overvoltages are lower. Figs. 8–12 show the calculation results in case of disconnector opening. When closing the disconnector the flashover was simulated at the voltage difference of 1 p.u. between the contacts.

The calculated overvoltage amplitudes in case of disconnector opening and closing are shown in Table 3.

Overvoltages on secondary side of CVT are lower than 1.6 kV which is the highest permissible value [16].

High frequency disturbances that occur in secondary circuits could disturb the normal operations of microprocessor-based electronic equipment. The transferred overvoltages increase with the decrease of CVT secondary burden. Fig. 13 shows the transferred overvoltage on CVT secondary for burden 1 VA in case of disconnector opening.

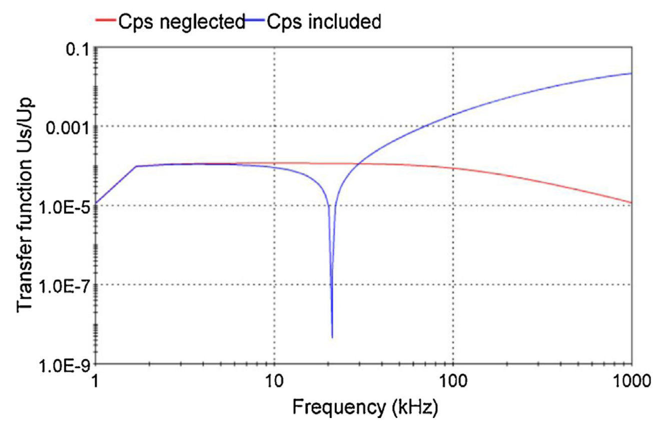

Fig. 6. Influence of stray capacitance C_{PS} between primary and secondary windings on CVT transfer function frequency response (calculated in EMTP).

The influence of CVT secondary burden on the transferred overvoltage amplitudes is shown in Table 4. This analyzed example represents the "worst case" scenario.

In order to reduce the longitudinal voltage caused by high frequency transients, shielding and multiple grounding of secondary circuits are necessary.

Table 2
Electrical and geometrical parameters of auxiliary busbar system.

R_{in} (cm)	R_{out} (cm)	DC resistance (mΩ/km)	Height above ground (m)	Length (m)	Spacing between phases (m)
10.2	11	6.285	12.66	171.4	6

Table 3
Calculation results.

Disconnector switching operation	Closing	Opening
U_{max} on HV side of CVT	656.1 kV	985.6 kV
U_{max} on LV side of CVT	376.4 V	752.9 V
Impulse current I_{max} on CVT connection to grounding grid	691.1 A	1382.2 A
Grounding potential on CVT connection to grounding grid	719.7 V	1438.5 V
Grounding potential in the relay/control room RK15A	150.7 V	300.4 V

Table 4
Influence of burden on overvoltage amplitudes transferred to LV side of CVT.

CVT secondary burden (VA)	Disconnector closing (V)	Disconnector opening (V)
1	788.5	1577.1
2.5	553.8	1067.5
4.6	376.4	752.9

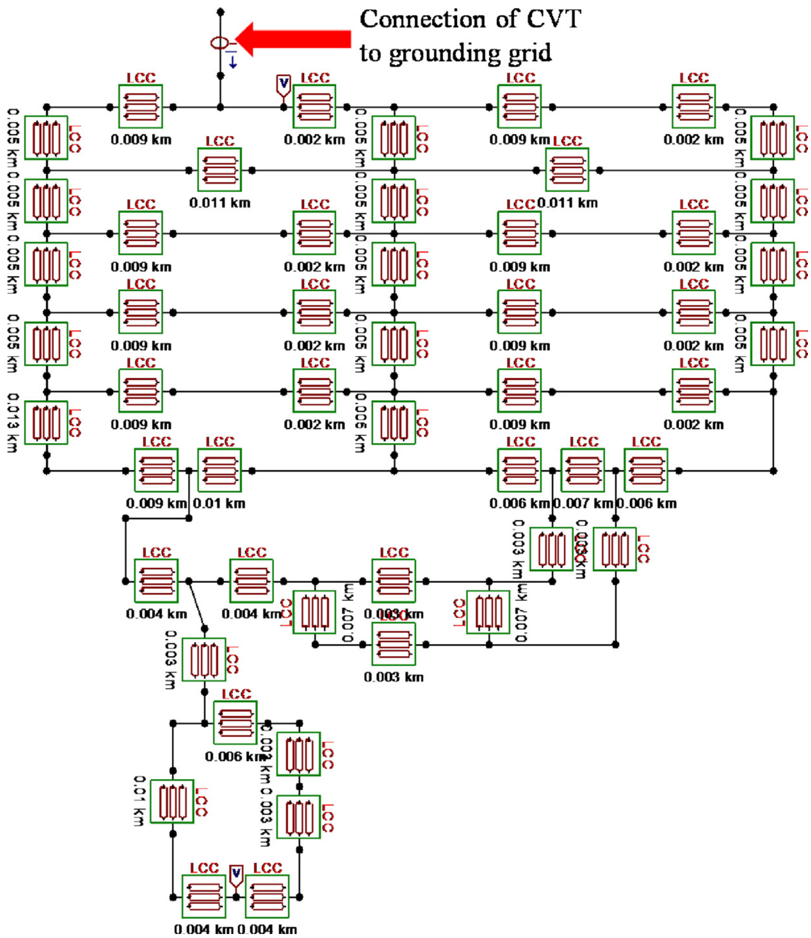

Fig. 7. A small part of substation grounding grid modeled in EMTP-ATP.

By applying the previously described approach it is possible to estimate the overvoltage amplitudes in secondary circuits in the designing process of high voltage substation.

4. Disconnector switching in 400 kV substation – on-site testing

On-site test circuit for measurement of transients caused by disconnector switching in 400 kV substation is shown in Fig. 14.

Switching of CVT T25L3 on main busbars has been performed with disconnector Q2L3. CVT secondary is connected to the equipment in the relay room with 66 m long measuring cable. The measurements of overvoltages in secondary circuits have been conducted in the relay/control room RK403 with digital storage oscilloscope (DSO), 500 MHz, 1 GS/s. Transients due to disconnector opening and closing have been recorded.

4.1. Disconnector closing

Figs. 15 and 16 show overvoltages at the end of the measuring cable in the relay room due to disconnector closing.

Figs. 17 and 18 show overvoltages on grounded cable sheath due to disconnector closing.

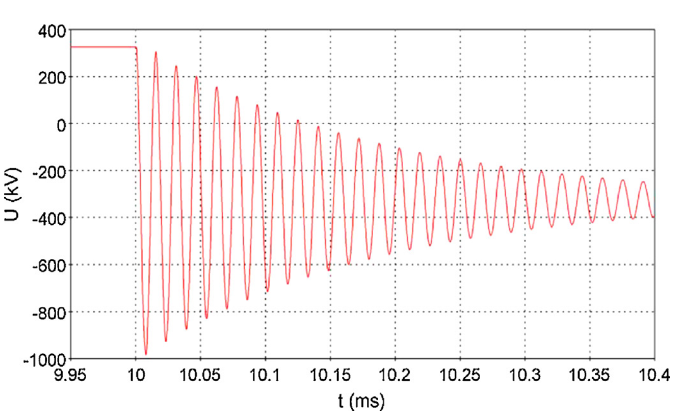

Fig. 8. Overvoltage on HV side of CVT.

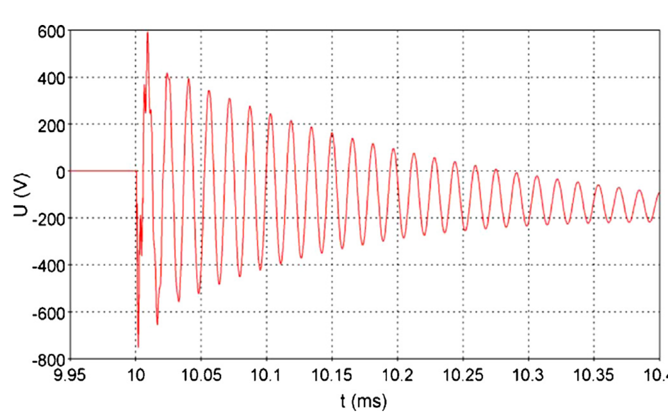

Fig. 9. Overvoltage on LV side of CVT.

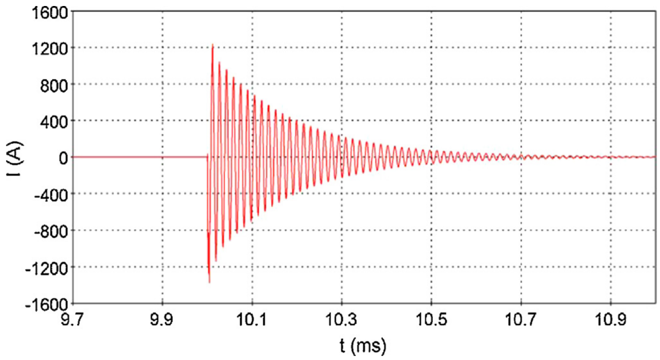

Fig. 10. Current through connection of CVT on grounding grid.

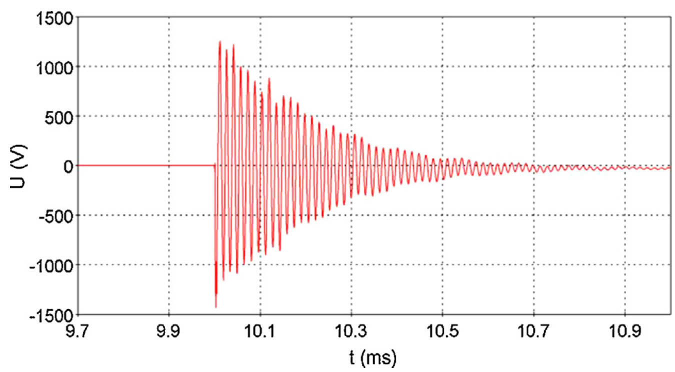

Fig. 11. Grounding potential on CVT connection to grounding grid.

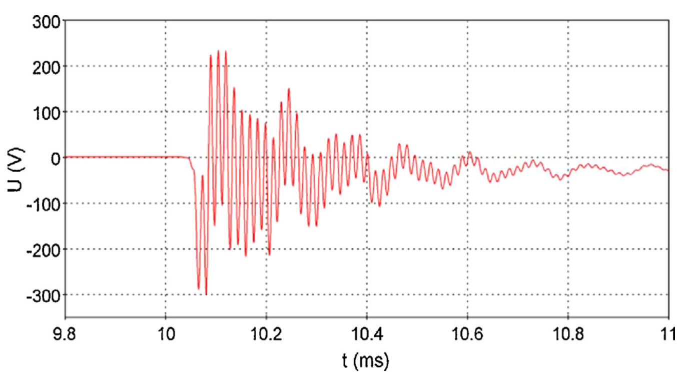

Fig. 12. Grounding potential in relay/control room RK15A.

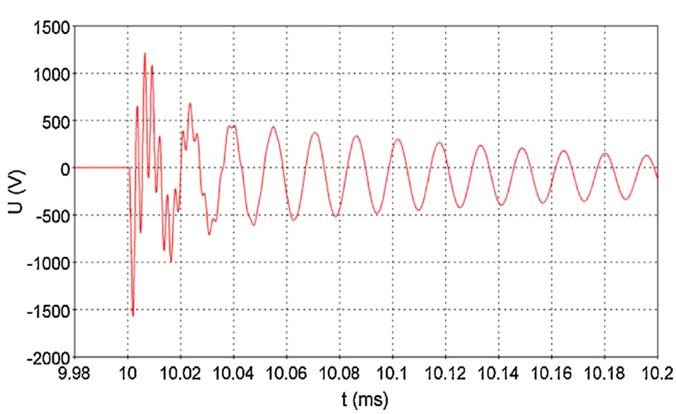

Fig. 13. Overvoltage on LV side of CVT in case of disconnector opening – burden 1 VA.

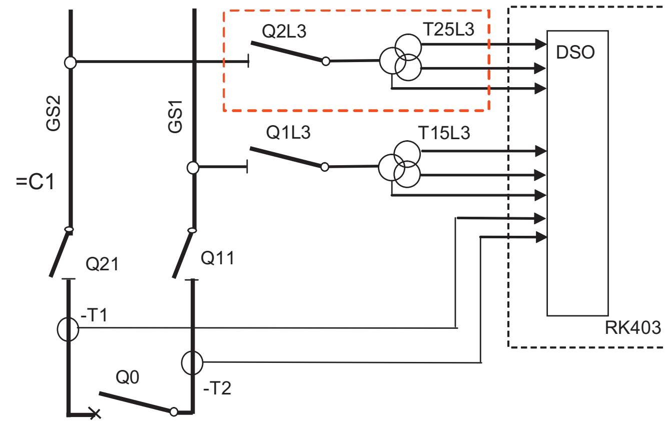

Fig. 14. On-site test circuit for measurement of transients caused by disconnector switching.

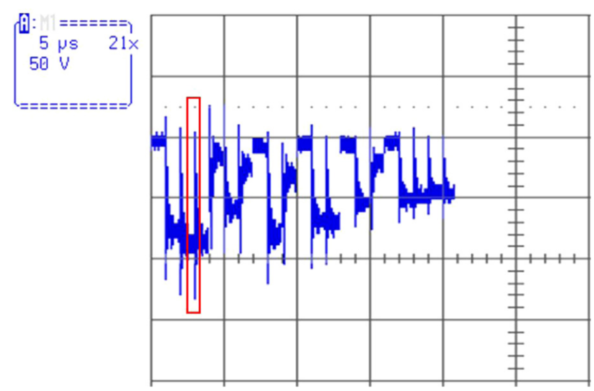

Fig. 15. Overvoltages at the end of the measuring cable in the relay room due to disconnector closing.

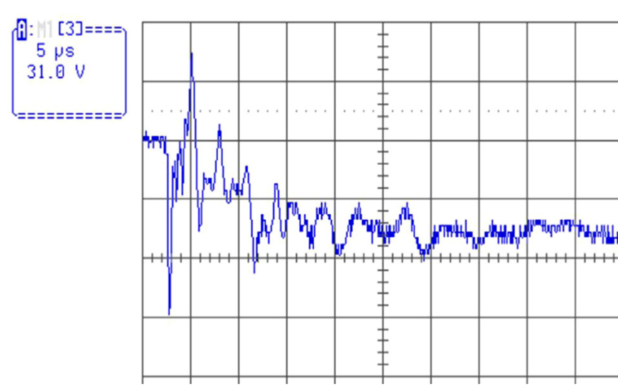

Fig. 16. Overvoltage caused by single flashover marked red in Fig. 15. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Numerous flashovers between disconnector contacts (21 recorded) cause high frequency overvoltages on grounded cable sheath.

4.2. Disconnector opening

Figs. 19 and 20 show overvoltages at the end of the measuring cable in the relay room due to disconnector opening.

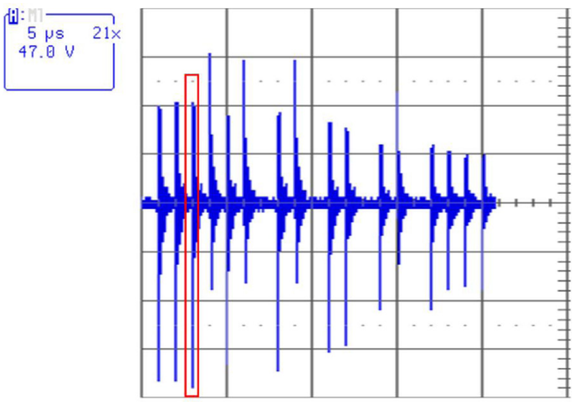

Fig. 17. Overvoltages on grounded cable sheath due to disconnector closing.

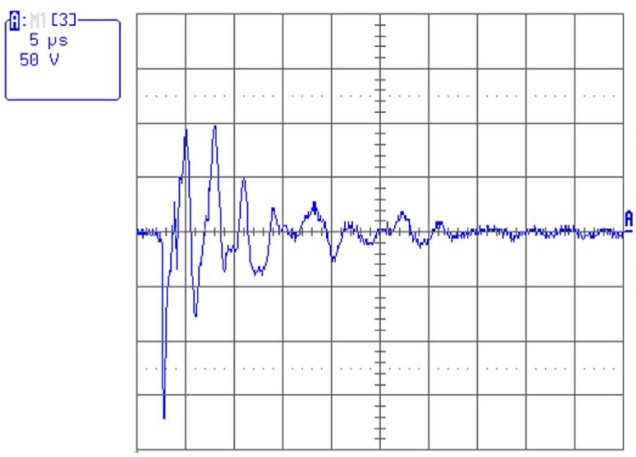

Fig. 18. Overvoltage caused by single flashover marked red in Fig. 17. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

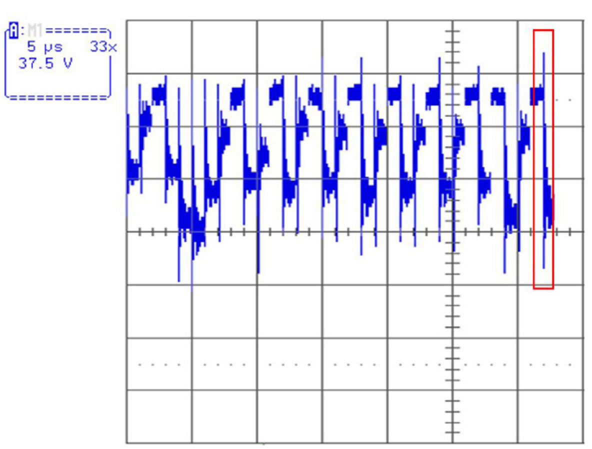

Fig. 19. Overvoltages at the end of the measuring cable in the relay room due to disconnector opening.

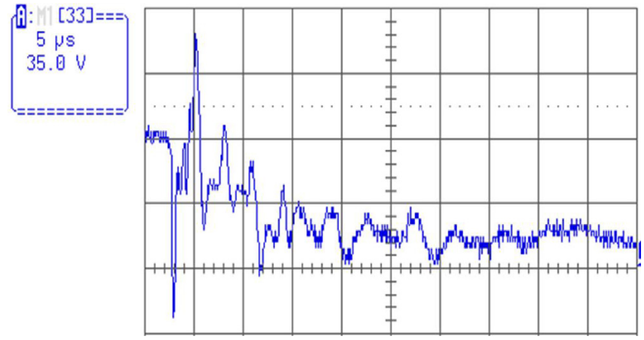

Fig. 20. Overvoltage caused by single flashover marked red in Fig. 19. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

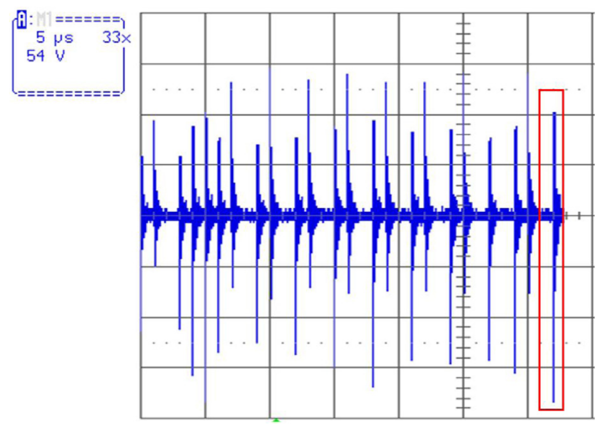

Fig. 21. Overvoltages on grounded cable sheath due to disconnector opening.

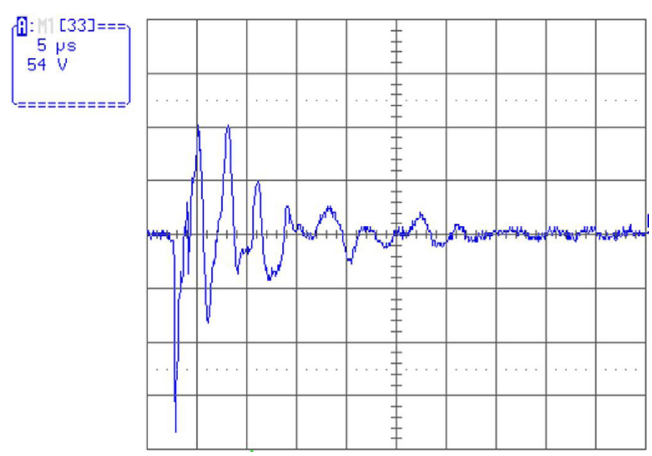

Fig. 22. Overvoltage caused by single flashover marked red in Fig. 21. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Figs. 21 and 22 show overvoltages on grounded cable sheath due to disconnector opening. Measured overvoltage amplitudes in secondary circuits are lower than 200 V, which is well below permissible value of 1.6 kV. The dominant frequency of overvoltages is around 350 kHz.

5. Conclusion

The opening and closing of the disconnector produce electromagnetic transients with a very fast rate of rise, which in some cases could be particularly harmful to secondary equipment located near the HV switching devices. Special attention should be paid to overvoltages transferred to the secondary circuits.

The transferred transients in the secondary circuits have been estimated in the designing process of high voltage substation. The transfer of electromagnetic transients through substation's grounding grid has been analyzed in order to determine the overvoltages at the terminals of protective relays located in the control/relay room. Peak values of transferred overvoltages increase as secondary burden decreases. Stray capacitance between CVT primary and secondary windings has significant influence on the transient response at high frequencies. This parameter is of primary importance in the frequency range of 10 kHz–1 MHz.

On-site tests performed in test operation of a real substation have demonstrated that the amplitudes of measured transferred overvoltages were not critical in the case of disconnector switching the CVT.

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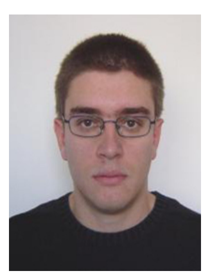

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