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Monitoring of transient overvoltages on the power transformers and shunt reactors – field experience in the Croatian power transmission system

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Abstract

Power transformers and shunt reactors may be subjected to various dielectric stresses such as lightning and switching overvoltages. Since the exposure of equipment to overvoltages during operation and the overvoltage amplitudes are usually unknow, an on-line overvoltage transient recorder is used with the ability to sample, analyze and store transients at transformer terminals in real-time. In this paper, transient overvoltage monitoring system is presented. Overvoltages are measured on the outside measurement terminal of the shunt reactor and transformer bushing. Field experience regarding the application of monitoring system in Croatia is described including different cases of lightning and switching overvoltages. Lightning overvoltages recorded by monitoring system are correlated with data from the lightning location system (LLS). Switching overvoltages recorded on the shunt reactor are compared with numerical simulations in EMTP-RV software. Collected data about overvoltage stresses can be used as the basis for the assessment of the transformer and shunt reactor insulation condition and estimation of health index.

Keywords: Transient overvoltage monitoring system; lightning location system; lightning and switching overvoltages; power transformers; shunt reactors; EMTP-RV

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1. Introduction

Overvoltages are one of the often causes of faults and outages in the transmission power system. Magnitude and rate of rise of overvoltages due to lightning strikes on transmission lines is an important consideration for substation insulation and the strategy adopted for limiting these overvoltages. The transmission line faults caused by a lightning can be classified as a backflashover or a flashover due to the shielding failure. Both events cause overvoltages which travel towards the substation from the striking point. Attenuation due to high frequency nature of the lightning overvoltages is caused by corona losses and skin effect. Therefore, usually lightning strokes that are close to the substation are considered when assessing overvoltage protection requirements and the associated risk of failure of the substation equipment. Insulation faults on a transmission line in front of the substation can provoke short circuit currents with high magnitudes. In case of an insulator flashover, a surge with a very steep front is formed. It enters the substation and causes insulation stress especially on windings of power transformers and shunt reactors [1].

Modern LLSs report the location of the lightning impact and the lightning peak currents which are estimated from the measured electromagnetic field peaks. The available technology for detection and location of the cloud-to-ground (CG) lightning has significantly improved over the last decades. LLS data have the advantage of covering extended areas on a continuous basis [2]. Data from LLSs can be used only to determine if the fault, e.g. short circuit caused by an insulator flashover on the transmission line, was caused by the lightning. However, amplitudes and waveforms of the overvoltages at the power transformer terminals are usually unknown. For that purpose, an overvoltage transient recorder is used with the ability to sample, analyze and store transients in real-time.

Switching overvoltages during deenergization of the shunt reactor can impose a severe duty on both the shunt reactor and its circuit breaker due to current chopping that occurs when interrupting small inductive currents. Switching overvoltages can be dangerous for the equipment if the peak value exceeds the rated switching impulse withstand voltage of the shunt reactor. However, overvoltages resulting from the deenergization are unlikely to cause insulation breakdown of shunt reactors as they are protected by surge arresters connected to their terminals. The severity of the switching duty increases when single or multiple reignitions occur. Such flashovers create steep transient overvoltages on shunt reactor with the front time ranging from less than one microsecond to several microseconds and may be unevenly distributed across the winding. These steep fronted transient voltages are stressing the entrance turns in particular with high inter-turn overvoltages [3]. Switching transients on shunt reactor are measured by using the transient overvoltage monitoring system.

In this paper, transient overvoltage monitoring system for power transformers and shunt reactors is presented. Overvoltages are measured on the outside measurement terminal of the shunt reactor and transformer bushing. Field experience regarding the application of monitoring system in Croatia is described including different cases of lightning and switching overvoltages recorded on power transformers and shunt reactors. Data from transient overvoltage monitoring system are correlated with data from the LLS. Switching overvoltages recorded on the shunt reactor are compared with numerical simulations in EMTP-RV software. Collected data about overvoltage stresses can be used as the basis for the assessment of the transformer and shunt reactor insulation condition and estimation of health index.

2. Transient overvoltage monitoring system

Overvoltages in power network can be caused by CG lightning strokes, switching operations and faults. Power transformers and shunt reactors can be exposed to such transients during the operation. Transient overvoltages with steep wave front have an impact on dielectric stresses of the insulation of first few winding turns. The number and amplitudes of overvoltages which stress the insulation depend on various parameters such as the lightning stroke density in the considered area, since it determines how often the transformer is stressed by lightning overvoltages. Since the overvoltage amplitudes at transformer terminals are usually unknown, an on-line overvoltage transient recorder is used with the ability to sample, analyze and store transients in real-time. Collected data can be used as the basis for the assessment of the transformer insulation condition, especially if combined with other transformer data such as dissolved gas analysis (DGA). This fact was the driving force for upgrading the existing Končar (TMS) transformer monitoring system with transient overvoltage monitoring system. Overvoltages, as well as voltages, are measured on a measuring tap of corresponding bushing. The connection with the measuring tap shown in Fig. 1 (a) is accomplished with a specially designed adaptor while the link between the adaptor and impedance matching circuit is carried out with a coaxial cable. Transient overvoltage monitoring system installed on 100 MVAr shunt reactor is shown in Fig. 1 (b) [4].

Measurement of transients needs to be triggered by an external signal. Since only one of the eight input channels of the overvoltage acquisition module can be used as a trigger, in other words the trigger can be set only for one phase at a time, it was necessary to provide an additional signal that is used as a trigger for data acquisition. This signal shall trigger data acquisition if overvoltage occurs in any of the phases.

(a) (b)

Fig. 1. (a) Connection to measuring tap; (b) Transient overvoltage monitoring system (Končar TMS+) installed on shunt reactor

While overvoltages are acquired occasionally, voltages need to be measured continuously in order to detect changes of bushing capacitance. To accomplish this, continuous voltage measurement is performed with an additional analogue input module. The measuring range of the overvoltage acquisition module is ±15 V. In order to extend the overvoltage detection range to approx. $5 \cdot \hat{U}_{\mathrm{fn}}$ (where $\hat{U}_{\mathrm{fn}}$ equals to the peak value of the nominal phase voltage), it is necessary to dimension the capacitors of the matching circuit in a way that for the nominal voltage, the amplitude of the signal entering overvoltage acquisition module equals approximately 3 V. At the same time, the module used to continuously sample voltage signal has a measuring range of ±60 V. In order to optimally utilize both measuring ranges i.e. vertical resolution of both acquisition modules, signal conditioning was done in two stages as shown in Fig. 2.

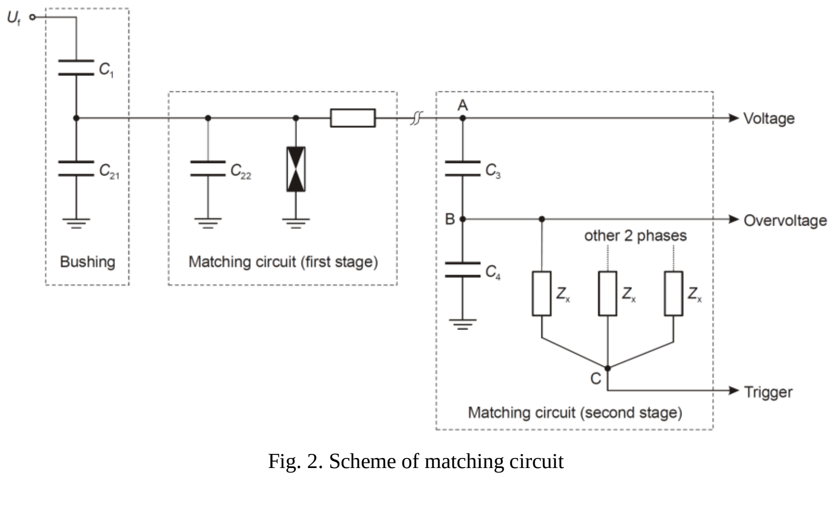


Fig. 2. Scheme of matching circuit

Besides signal conditioning, the second stage of matching circuit also implements solution for the triggering of overvoltage acquisition. The following was considered during design:

a) Capacitance of C_3 and C_4 needs to be selected to ensure that the potential of the node B is approximately 3 V when nominal voltage value $\hat{U}_{fn}$ is applied.
b) Capacitance of C_3 and C_4 must not influence significantly on the potential of the node A, i.e. total capacitance of C_3 and C_4 connected into series must be negligible in comparison to the capacitance of C_2 ($C_2 = C_{21} + C_{22}$). The input impedance of the voltage measuring module is 1 MΩ and it does not change the potential of the node A much.
c) Impedance of the condenser C_4 must be negligible at the lowest frequency (in this case system frequency of 50 Hz) to the input impedance of overvoltage module which is 1 MΩ.

The potential of the node C is used to trigger data acquisition when overvoltages occur. It is equal to 0 V as long as all the impedances Z_X are equal and the system voltage of all three phases balanced. In case of unbalance of three-phase system voltages, like it is the case when overvoltages occur, the potential of node C will not be equal to 0 V. In this way data acquisition will also be triggered in case of a voltage disturbance in electrical grid (transients) which not necessarily have the amplitude higher than the nominal voltage. After completion of the design of the Končar TMS+ prototype and successful testing in the high voltage laboratory of Končar Electrical Engineering Institute, a project was started to install the system on in-service power transformers. At the first stage project included installation of monitoring system on the two 150 MVA autotransformers in one 220/110 kV substation, one system for the two autotransformers 300 MVA and one shunt-reactor unit 100 MVAr in one 400/110 kV substation.

In this paper, two events recorded by transient overvoltage monitoring system are presented:

a) switching overvoltages recorded on the shunt reactor (U_r=123 kV, 100 MVAr) are compared with numerical simulations in EMTP-RV software.
b) lightning overvoltages recorded on the power transformer in 400/110 kV substation are correlated with data from LLS.

3. Transients caused by switching of three-phase shunt reactor

3.1. Model for calculation of switching transients in EMTP-RV

Transient overvoltage monitoring system is installed on shunt reactor with manufacturer's data shown in Table 1.

Table 1. Shunt reactor data.

Rated voltage	123 kV
Rated frequency	50 Hz
Reactive power	100 MVAr
Rated current	469 A
Core type	Three limb
Total losses (at 123 kV)	218 kW
Zero sequence impedance per phase	113.8 Ω

The calculation of switching transients requires an adequate modeling of the reactor's nonlinear flux-current curve. The nonlinearity is caused by the magnetizing characteristics of the shunt reactor iron core. Recorded RMS voltage-current curves obtained from manufacturer are converted into instantaneous flux-current saturation curves shown in Fig. 3 which are used in the nonlinear inductance model in EMTP-RV [5] and approximated with two segments (linear area A'-B' below knee of the saturation curve and saturation area B'-C').

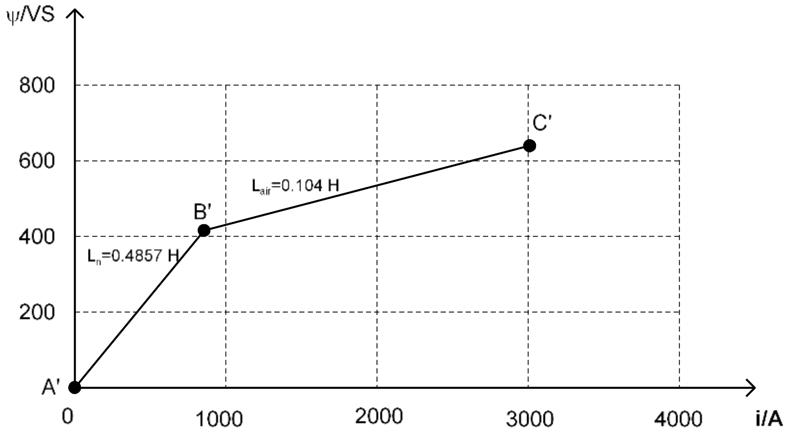


Fig. 3. Instantaneous flux-current saturation curve of shunt reactor

EMTP-RV model shown in Fig. 4 consists of equivalent 110 kV network, circuit breaker and shunt reactor bay.

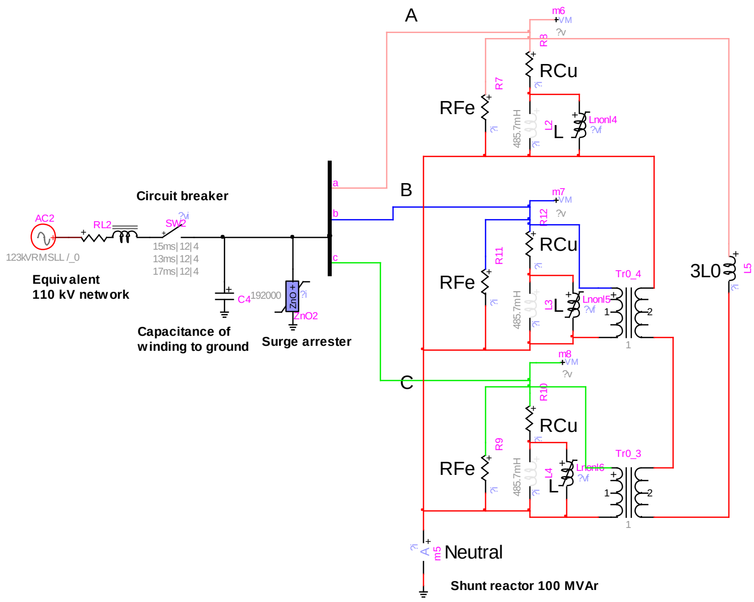
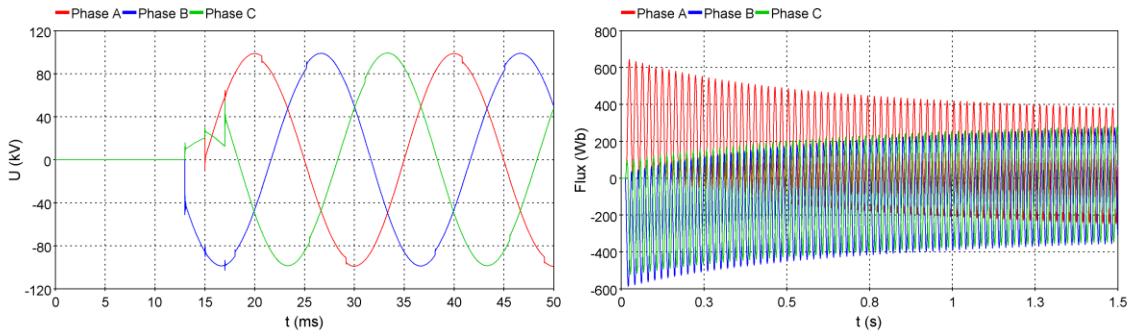


Fig. 4. Model in EMTP-RV

Each phase of a three-phase shunt reactor is modeled as a nonlinear inductance with serially connected resistance R_{Cu}=0.248 Ω, representing copper losses and parallel connected R_{Fe}=277 kΩ, representing iron losses. Magnetic coupling among the three star connected phases is represented with zero-sequence inductance L_0=0.362 H which provides a path for the zero-sequence current [6]. The equivalent 110 kV network was represented with positive (R_1=0.265 Ω, L_1=6.96 mH) and zero (R_0=0.216 Ω, L_0=5.68 mH) sequence impedances, determined from single-phase and three-phase short circuit currents. Metal-oxide surge arresters in shunt reactor bay with rated voltage U_r=192 kV are modeled by nonlinear *U-I* characteristic with respect to switching overvoltages.

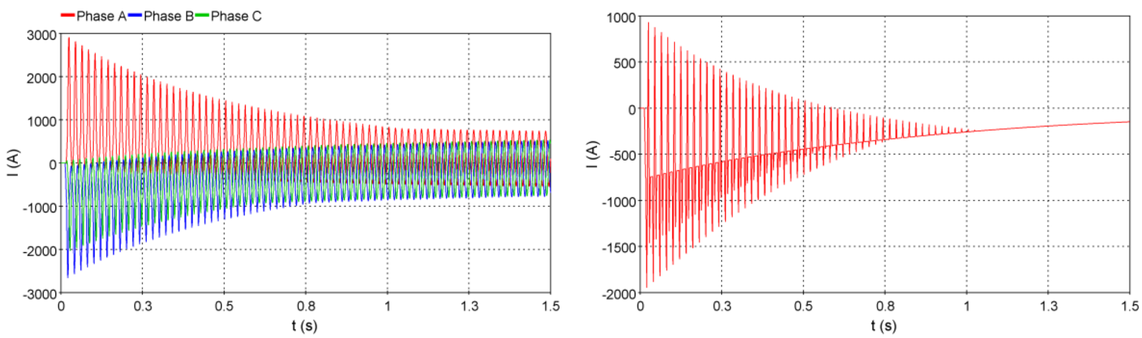
3.2. Simulation of uncontrolled energization

The actual magnitude of the inrush current due to shunt reactor energization is quite dependent on the range of linearity of the core and on the time instant of circuit breaker pole operation. Switching operations at unfavorable instants can cause inrush currents that may reach high magnitudes and have long time constants. In case when shunt reactor has a solidly grounded neutral, unsymmetrical currents cause zero-sequence current flow which can activate zero-sequence current relays. This may cause difficulties such as unwanted operation of the overcurrent relay protection [7]. The following instants of circuit breaker pole closing were considered: t_A=15 ms, t_B=13 ms and t_C=17 ms. Figs. 5 (a) and 5 (b) show shunt reactor voltages and magnetic flux, respectively. The highest inrush current occurs at an instant near the voltage zero-crossing in phase A, since it results with the maximum DC component of current.



(a) (b)

Fig. 5. (a) Shunt reactor voltages; (b) magnetic flux.



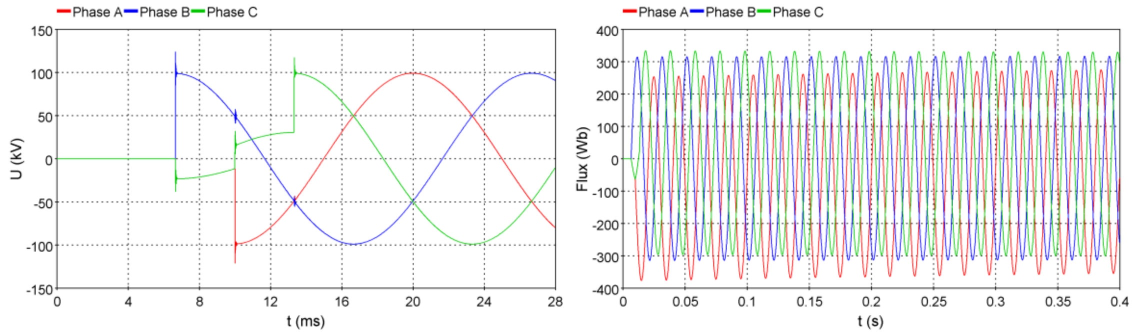
(a) (b)

Fig. 6. (a) Inrush currents: IAmax=2910.4 A (4.39 p.u.); (b) zero-sequence current, Imax=-1948.5 A (2.94 p.u.)

The conducted simulation showed that transient inrush current with amplitude of 4.39 p.u. and high DC component lasted for more than 1.5 seconds, as shown in Fig. 6 (a). Zero-sequence current shown in Fig. 6 (b) occurred in case of uncontrolled reactor energization because of asymmetry. This may cause the false operation of relay protection used for detecting single phase-to-ground faults.

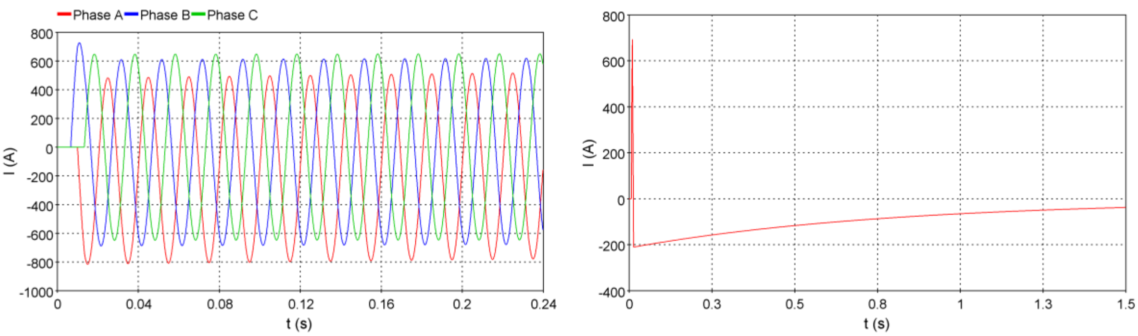
3.3. Simulation of controlled energization

Controlled energization at optimum instants of circuit breaker poles closing at peak voltages: t_A=10 ms, t_B=6.66 ms and t_C=13.33 ms is analyzed, as shown in Fig. 7 (a). The current in phase A shown in Fig. 8 (a) is slightly higher than in the other two phases, due to the appearance of the DC component, which was caused by initial magnetic flux in the core limb at the moment of energization. This initial magnetic flux is a part of a magnetic flux from the phase B, which was firstly switched on, as shown in Fig. 7 (b). The conducted simulation showed that the amplitudes and the DC components of inrush current and zero-sequence current are significantly lower in case of controlled switching. Zero-sequence current shown in Fig 8. (b) is significantly reduced compared to uncontrolled energization.



(a) (b)

Fig. 7. (a) Shunt reactor voltages; (b) magnetic flux.

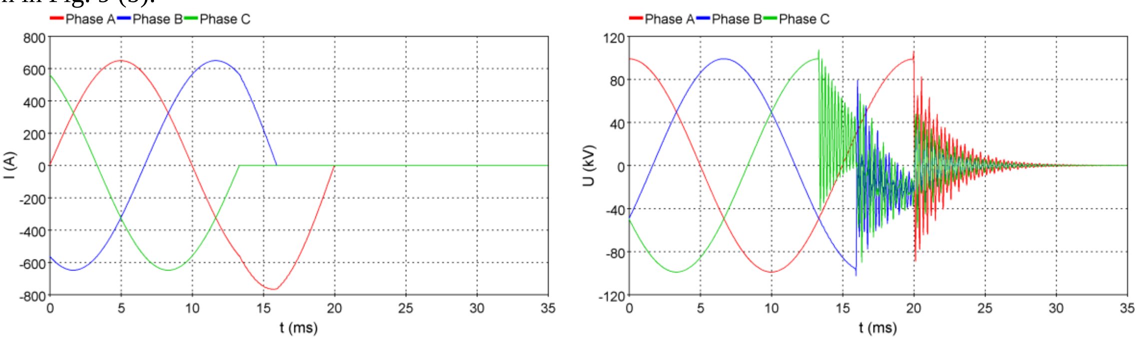


(a) (b)

Fig. 8. (a) Inrush currents: IAmax=-816 A (1.23 p.u.); (b) zero-sequence current, Imax=693.2 A (1.05 p.u.)

3.4. Simulation of shunt reactor de-energization

When interrupting small inductive currents, the medium used for arc extinguishing will develop fast increase of the residual column resistance, and abrupt current interruption before its natural zero crossing occurs. Release of energy stored in the reactor inductance will cause the electromagnetic transients that lead to the switching overvoltages. Fig. 9 (a) shows circuit breaker currents in case of controlled de-energization of shunt reactor. For small inductive currents, the cooling capacity of the circuit breaker dimensioned for interrupting short-circuit currents is much higher in relation to the energy dissipated in the electric arc. This leads to the chopping of small inductive currents before the natural zero crossing and produces high frequency overvoltages on shunt reactor shown in Fig. 9 (b).



(a) (b)

Fig. 9. (a) Shunt reactor currents; (b) shunt reactor overvoltages

3.5. Waveforms recorded by transient overvoltage monitoring system

The circuit breaker contact timing is controlled to avoid reignitions that can lead to breaker failures. The breaker is controlled so that its contacts will part just after a current zero. As the contacts continue to open they draw out electric arc that will extinguish less than a half-cycle later at the next current zero. When the arc is extinguished, the contacts are sufficiently separated, which provides the maximum dielectric strength. This enables the circuit breaker to successfully withstanding the recovery voltage and prevents occurrence of reignition or restrike.

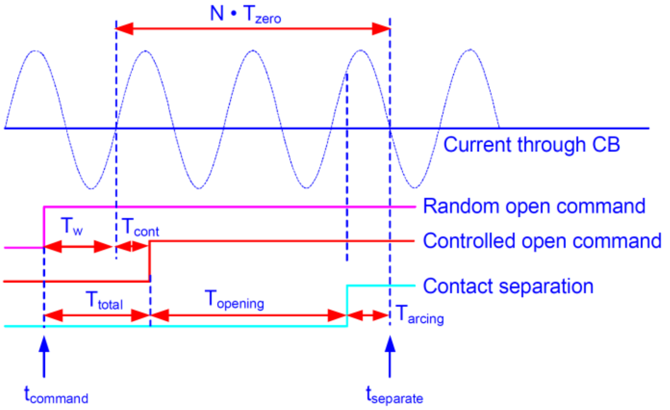


Fig. 10. Controlled opening sequence

Fig. 10 shows the timing sequence for controlled opening of circuit breaker [8]. The control command is issued randomly with respect to the phase angle of the reference signal at an instant $t_{command}$. The randomly received opening command is delayed by the controller by some time T_{total}, which is the sum of an intentional synchronizing time delay T_{cont} and a certain waiting time interval T_w. T_{cont} is calculated with respect to a relevant zero crossing which is a function of the opening time $T_{opening}$, and by the target phase angle of the time instant of contact separation $t_{separate}$. Accurate control of $t_{separate}$, which is the instant of contact separation, with respect to the next current zero at which arc extinction occurs, effectively defines the arcing time T_{arcing}. The mechanical opening time $T_{opening}$ is the time interval from energization of the breaker trip coil to the start of breaker contact separation.

Switching overvoltages recorded during controlled deenergization of shunt reactor are shown in Fig. 11. The overvoltage amplitudes and frequency of oscillations on shunt reactor coincide well with simulation results from EMTP-RV, as shown in Fig. 9 (b).

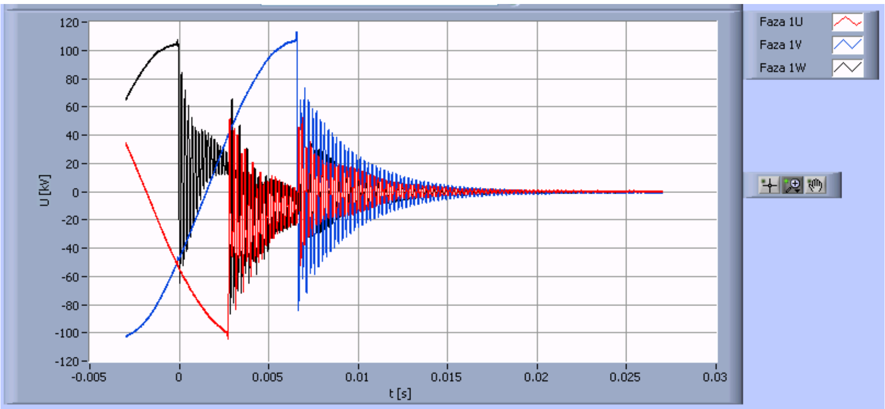


Fig. 11. Switching overvoltages recorded during controlled deenergization of shunt reactor

In case of uncontrolled switching, typical reignitions occur producing steep overvoltages on shunt reactor. Switching overvoltages on shunt reactor recorded during uncontrolled deenergization and energization are shown in Figs. 12 and 13, respectively.

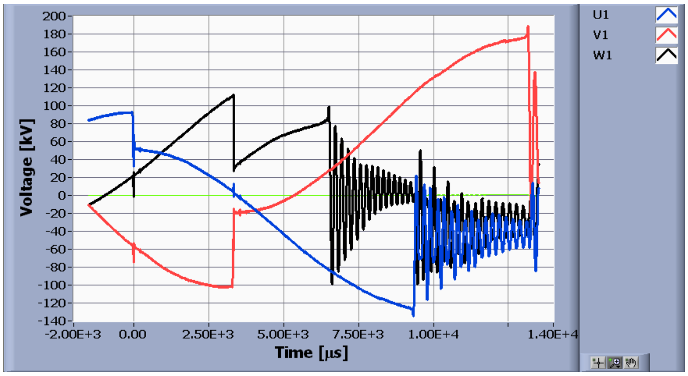


Fig. 12. Switching overvoltages recorded during uncontrolled deenergization of shunt reactor

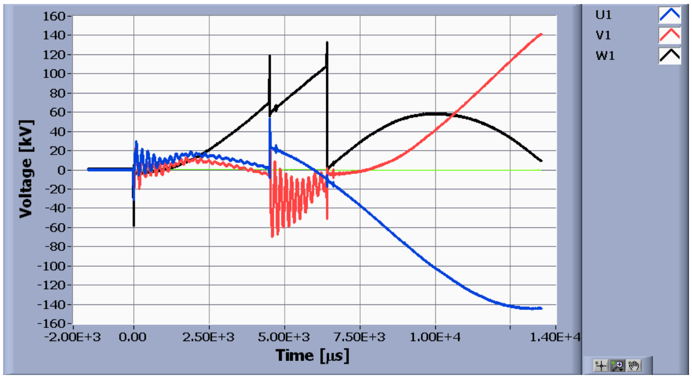
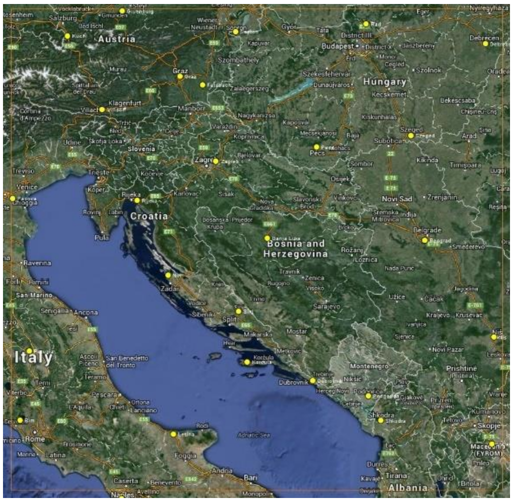


Fig. 13. Switching overvoltages recorded during uncontrolled energization of shunt reactor

4. Lightning location system

At the end of 2008, a LLS was established as part of the LINET network, covering a wide area of the Croatian territory. LINET is a modern LLS with a network of more than 125 sensors covering most of Europe. Fig. 14 (a) shows LINET sensors in Croatia and its neighbouring countries.



(a)

(b)

Fig. 14. (a) LINET sensors in Croatia and its neighbouring countries; (b) field antenna and a GPS receiver

LLS measures the VLF/LF frequency spectrum of electromagnetic waves which lightning strokes emit. The measurement of magnetic flux is carried out through highly sensitive sensors shown in Fig. 14 (b), which are arranged across the area with spacing of around 150 to 250 km. Since the electromagnetic emission of the lightning spreads at the speed of light, it reaches the sensors at different points in time. Although the difference is in the order of micro-seconds, the exact calculation of the original emission location of the lightning stroke is possible. The data measured by every single sensor is transmitted to a central server. The exact geographical position for all the lightning strokes measured is calculated and stored in a database. This measurement method is also known as the “time-of-arrival” method [9]. Main features of LLS are:

- ability to detect and locate the total atmospheric discharge with same locating error for inter-cloud (IC) and CG discharges;
- great accuracy in location of both IC and CG discharges of low current amplitude;
- new 3D technique for a reliable discrimination of IC and CG discharges;
- altitude reports for IC discharges and locating accuracy up to 100 m.

Application of LLS in power system control of Croatian transmission system operator enables lightning activity tracking and time-spatial correlation with incidences (faults, automatic re-closures, outages) registered by the relay protection system [10]. Also, it is possible to obtain the lightning statistics from LLS database. To enable the utilization of lightning data in power systems, customized software is developed. The functional demands on software are divided into two sets of functionalities. The basic functionalities are related only to LLS data to provide new knowledge that can be utilized in power systems. Advanced functionalities are related to interconnections with other systems and the use of additional data sources.

Basic functionalities:

- visualization of real time lightning activity maps with alarm function;
- analysis, reports and historical lightning activity visualization using interactive maps;
- lightning statistics calculation and generation of wide area lightning density maps.

Advanced functionalities:

- spatial correlation between lightning data and alarm zones around geographically represented power system objects (overhead lines, substations, power facilities, etc.);
- generation of high resolution lightning density maps inspecting alarm zones around the overhead lines;
- real-time correlation between lightning activity and events registered by the protection equipment (distant protection relays), gathered through the SCADA system.

5. Lightning overvoltages recorded on 300 MVA power transformer in a 400/110 kV substation

Transient overvoltage monitoring system is installed on two 300 MVA power transformers in 400/110 kV substation. Overvoltages recorded by one of the installed transient overvoltage monitoring systems are shown in Fig. 15. Two overvoltages are recorded with a time span Δ*t*=18 ms. Fig. 16 shows a detailed overview of the recorded overvoltages from Fig. 15 (time spans marked with red).

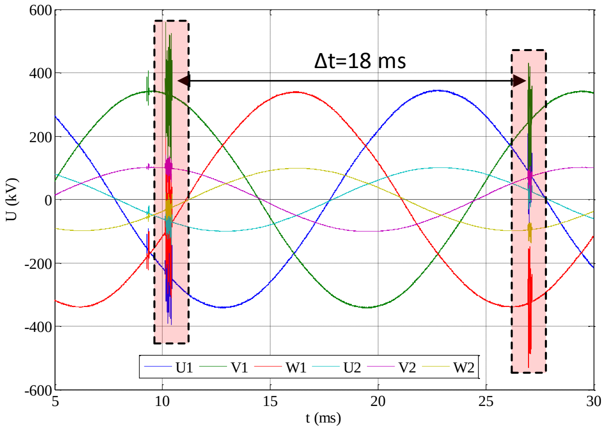
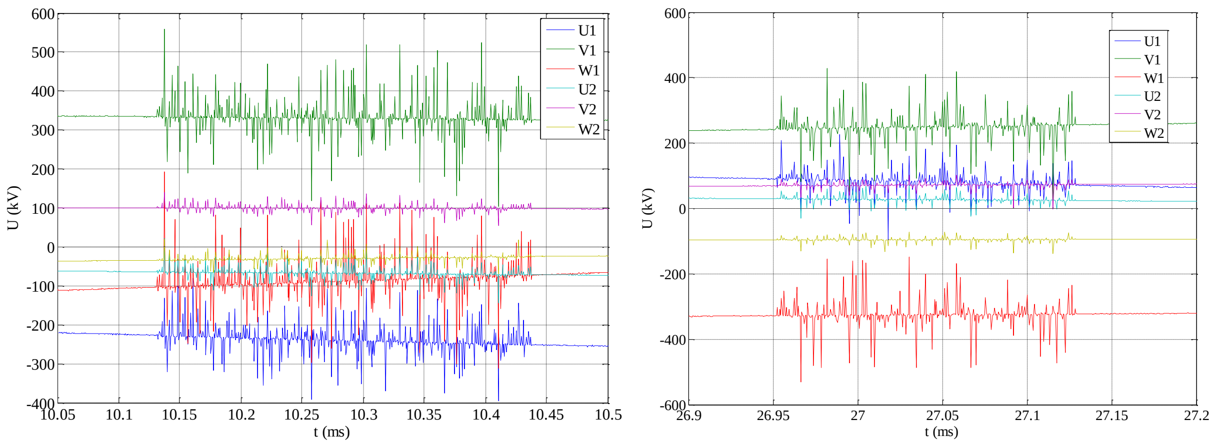


Fig. 15. Overvoltages recorded on power transformer 400/110 kV



(a) (b)

Fig. 16. Detailed overview of recorded overvoltages shown in Fig. 15: (a) first recorded overvoltage; (b) second recorded overvoltage

Numerous overvoltages like those shown in Fig. 15 were also recorded during the same day. Information from SCADA system indicated that there was no switching of circuit breakers at the instant of the recorded event. The data obtained from LLS for the day in which overvoltages were recorded are shown in Fig. 17. There was very high lightning activity in Croatia and neighbouring countries.

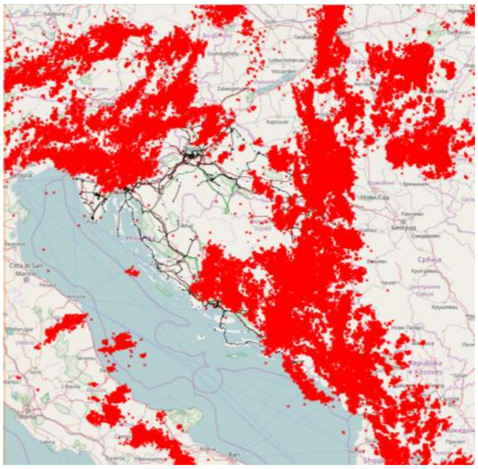


Fig. 17. Lightning activity (CG strokes) in Croatia and neighboring countries for the day in which overvoltages were recorded

A total of 247803 CG lightning strokes were detected with cumulative amplitude distribution shown in Fig. 18.

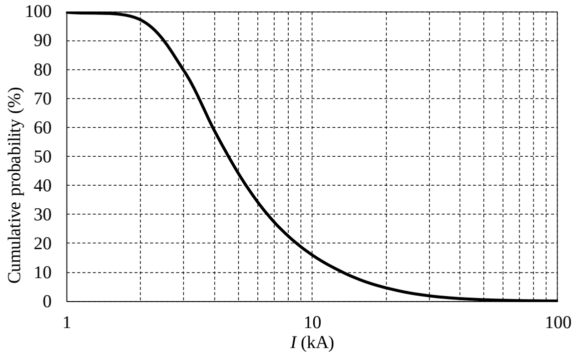
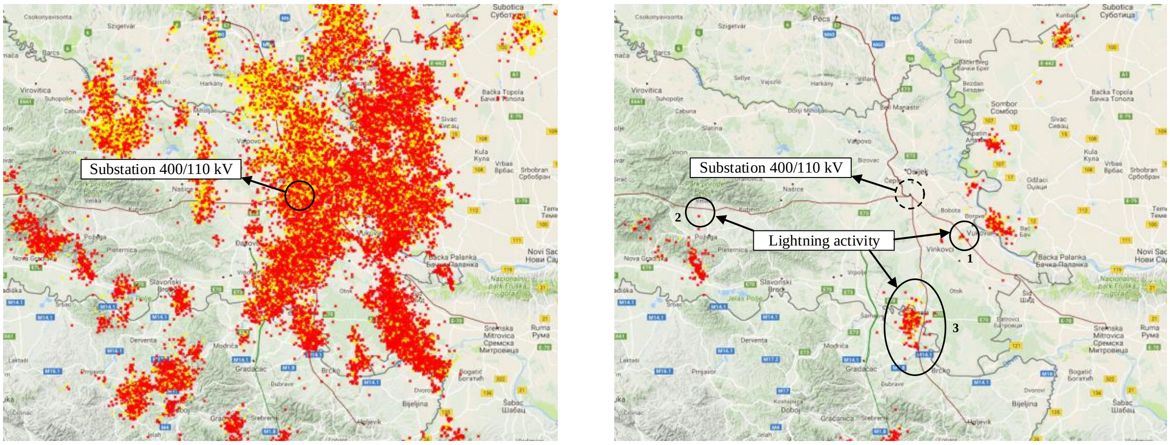


Fig. 18. Cumulative amplitude distribution of CG lightning strokes

LLS can detect multiple-stroke flashes where every stroke is represented by individual set of data (current amplitude, discharge time, location, etc.). CG flashes consist of one or several strokes coming in very short temporal intervals and close spatial proximity. The common method for grouping stroke data into flashes is to use the thresholds for maximum temporal separation and maximum lateral distance between successive strokes. For this purpose, an algorithm was developed to group lightning strokes into flashes (assessment of the lightning stroke multiplicity) in order to determine the current probability distribution of the first and subsequent CG strokes. The multiplicity is calculated for a maximum temporal separation of 200 ms and a maximum lateral distance of 2 km between successive strokes [11].

In order to check if the recorded event corresponds to overvoltages caused by lightning stroke to 400 kV transmission lines entering the substation, a more detailed analysis was conducted. Lightning activity around 400/110 kV substation in the time span of ± 3 hours from the recorded event is shown in Fig. 19 (a) and time span of ±15 minutes is shown in Fig. 19 (b). CG lightning strokes are marked red, while yellow ones correspond to IC strokes.



(a) (b)

Fig. 19. Lightning activity in the vicinity of 400/110 kV substation: (a) time period ± 3 hours; (b) time period ±15 minutes

Since the measurements from the transient overvoltage monitoring system were not GPS time synchronized, lightning strokes within the time span of ±15 minutes are considered. Three potential areas of lightning activity in the vicinity of the 400 kV transmission lines, that could cause overvoltages recorded on the power transformer, are determined. In the area 1, a lightning flash consisting of two strokes shown in Fig. 20 with the temporal separation of 18 ms is detected, which coincide with time Δt between two overvoltages recorded on power transformer. Lightning flash, that probably caused lightning overvoltages recorded on the power transformer, occurred on 400 kV transmission line at distance of 25.8 km from the substation.

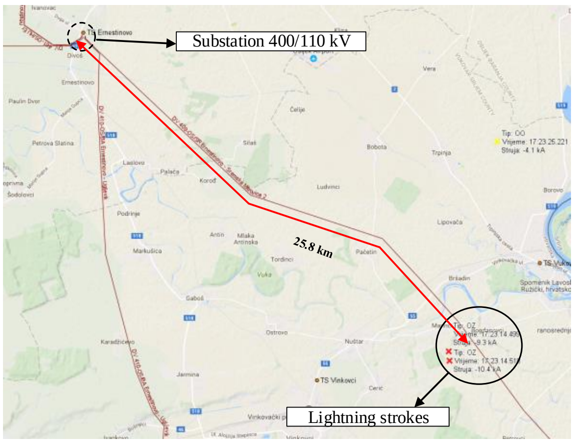


Fig. 20. Lightning strokes that probably caused lightning overvoltages recorded on the power transformer

Parameters of registered lightning flash are shown in Table 2.

Table 2. Parameters of registered lightning flash consisting of 2 strokes

Type	Date	Time	Lightning current amplitude (kA)	Locating error (m)
CG	26.6.2016.	17:23:14.499	-9.3	32
CG	26.6.2016.	17:23:14.517	-10.4	91

Lightning strokes shown in table 2 could hit directly the phase conductors or the shield wire on the transmission line. Lightning strokes near transmission line can induce overvoltages on phase conductors. In order to determine the most probable scenario in considered case, a detailed analysis including simulation of lightning overvoltages should be done as in [12] but such analysis is beyond the scope of this paper.

6. Conclusions

The main reasons involved in the transformer operation failure include ageing, deterioration, or damage of different internal or external components of the transformer such as the insulation system, load tap changer, windings, tank and bushings. Factors leading to such damage can be age-based factors, such as the reduced dielectric strength of the insulation system due to insulation contamination. Other factors are mainly due to the electrical, mechanical and thermal stresses due to external short circuits, incipient faults, transient switching, lightning strikes and excessive overloading. Having these factors identified, the utility company can predict the probability of failure and remaining life-time using formulated probabilistic models.

In this paper, a field experience regarding the application of transient overvoltage monitoring system in Croatia is described, including different cases of lightning and switching overvoltages recorded on power transformers and shunt reactors. Lightning overvoltages recorded on power transformer are successfully correlated with data from the LLS. Cumulative amplitude distribution of CG lightning strokes show that according to data from LLS there is a significantly higher probability of lightning strokes occurrence with lower current amplitudes, compared to CIGRE data provided in [13]. This difference is caused by sensitivity of LLS which can detect multiple CG strokes with low current amplitudes. This means, there is a higher probability of lightning stroke hitting phase conductors of transmission line, which is important for overvoltage protection and insulation stress of substation equipment. Switching transients recorded on the shunt reactor are compared with results of numerical simulations in EMTP-RV and good matching is achieved. Different cases of uncontrolled and controlled switching operations are shown and results including inrush currents and switching overvoltages are discussed.

Collected data about amplitudes and duration of overvoltage stresses on power transformers and reactors can be used for the assessment of the insulation condition, which is important for estimation of probability of failure and assessment of health index. Correlation between data from transient overvoltage monitoring system, LLS and SCADA will be applied in future work for analysis of different kinds of events in the transmission power system, such as faults on transmission lines and equipment failure.

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