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Non-standard, High Frequency Power System Transients

Ebrahim Rahimpour, Álvaro Portillo, Bruno Jurišić

Summary — **A better understanding of the interaction between power transformers and reactors with the power system regarding high frequency transients is essential to improve equipment reliability in the presence of these types of transients. Operational experience has shown a substantial number of unexpected dielectric failures due to unknown causes that may be linked to this condition. This paper strives to give an answer about which overvoltages can appear in the power system and how their waveshapes differ from the standard test impulses. Transformers and shunt reactors are dimensioned to withstand standard impulses but during their operational lifetime they face many different overvoltages. In general, overvoltages in the power system are caused by switching or lightning. Depending on the network topology as well as the nature of the event that triggered overvoltages, their waveshapes differ. Such overvoltages may cause transformer failure even though the transformer or shunt reactor is adequately protected by the surge arrester. Such an event is recognized as internal resonance appearing inside a transformer as a result of interaction between the system and the transformer itself. Moreover, repetitive impulses are recognized as another event which can lead to inner insulation failure. To adequately evaluate the overvoltages that may occur at transformer terminals, it is necessary to measure or simulate overvoltage. Investigating the above-mentioned topic has been a part of the objectives of launching the CIGRE WG A2.63 »Transformer impulse testing«. The WG worked on the transformer impulse testing in three subgroups to study and analyze: A) High Frequency Power System Transients, B) Power Transformer Testing - Test Equipment and Techniques, and C) Transformer Transient Simulations and Dielectric Withstand of Transformer Insulation System. This paper summarizes investigations carried out under part A) High Frequency Power System Transients.**

Keywords — **Power transformers, reactors, power system transients, lightning impulse, non-standard overvoltage.**

I. Introduction

Overvoltages in the power network can be caused by lightning strikes to overhead transmission lines, circuit breaker switching operations and faults. Power transformers are exposed to such transient overvoltages during their operation. Transient overvoltages with a steep wavefront have an impact on dielectric stresses on the insulation of the first few winding turns. The number and amplitudes of overvoltages which stress the insulation depend on various parameters such as the lightning strike density in the area considered.

Power transformers are located behind the surge arrester in the direction of surge propagation. Therefore, the peak voltage of an incident wave arriving at transformer terminals is always limited by a surge arrester to its residual voltage. However, during a transient process in a busbar between the surge arrester and the transformer, many reflections occur, and as a result of that process the voltage at transformer terminals rises above the residual voltage of the surge arrester.

In general, it can be concluded that there is a variance between operating overvoltages and the standard impulse voltages (switching impulse SI, lightning impulse LI and lightning impulse chopped LIC) and it is important to compare transient overvoltage waveforms with the standard impulse voltages waveshapes.

Years of operational experience have shown several dielectric failures that were unexpected and whose causes remain unknown. They are likely connected to high frequency transients that appear in power systems due to interactions between power transformers/reactors & grid. In order to better understand and improve equipment reliability in such events, CIGRE has had some dedicated working groups on this subject. Each group has focused on a special topic and has made important contributions to achieving a broader understanding of this interaction.

First work on such phenomena from CIGRE and IEEE started in 1979. with a CIGRE Working Group WG 12. Another important work from CIGRE Joint Working Group JWG 33/13.9 and WG 12.11 appeared during the introduction of Gas Insulated Substations (GIS) during 1986-88 [1]. In 2001, CIGRE JWG A2/A3/B3.21 studied the electrical environment of transformers [2].

In Brazil, the topic of interaction of power transformers and reactors with the power system was studied, due to a significant number of dielectric failures with no clear cause. The report was presented in 2007 which led to CIGRE JWG A2/C4.39 that continued this work on an international scale that resulted in a CIGRE Technical Brochure TB in 2014. The follow-up was CIGRE JWG A2/C4.52 that dealt with transformer modelling topic [3].

The IEEE described similar issues, resulting in the publication of a guide called "C57.142-2010 IEEE Guide to Describe the Occurrence and Mitigation of Switching Transients Induced by transformers, Switching Devices, and System Interaction" which is currently in the process of revision [4].

A Task Force in IEEE has recently completed the "Investigation of the Interaction Between Substation Transients and Transformers

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in HV and EHV Applications", with a publication in 2021 [5].

In 2020 CIGRE started the WG A2.63 on power transformer impulse testing. One of the tasks for this new WG is to report on observations of high frequency transient phenomena in the power grid. This is the focus of TF1. The WG was divided into three parts A) High Frequency Power System Transients, B) Power Transformer Testing - Test Equipment and Techniques, and C) Transformer Transient Simulations and Dielectric Withstand of Transformer Insulation System. The current paper summarizes investigations carried out under part A) High Frequency Power System Transients. Chapter 2 introduces the measurement techniques used throughout the study and presents key equipment such as Transformer Monitoring Systems (TMS), together with validation guidelines in both the frequency and time domains. Chapter 3 investigates lightning and switching overvoltages through case studies, measurements, and simulations. The findings show that lightning waveforms are generally longer and less steep than standardized impulses, while switching overvoltages, arising from three different events: reactor or transformer switching, low capacitive currents or disconnector operations, display moderate amplitudes and widely varying frequency specter. Case-specific EMTP modeling for accurate transformer assessment is also described. Chapter 4 provides tools to compare real overvoltages with standardized tests (SI, LI), emphasizing that non-standard waveform shapes can lead to insulation degradation even at lower magnitudes. It outlines methods for assessment of overvoltage severity such as frequency domain severity factor (FDSF), time domain severity factor (TDSF), the Evaluation Method and the Voltage–Time Method. All of which help determine severity on inner or outer insulation. The paper ends with a final concluding section that synthesizes the main results and overall insights.

II. Measurement Techniques

Measuring transient phenomena, which are defined by their rapid dynamics, can be highly demanding, making a welldesigned measurement technique essential. To measure overvoltages in the power system, different measurement techniques are used, but overall the measurement system consists of a sensor, transmission device, data acquisition card and software used to analyze the measured signals. In general, CIGRE TB No. 836 [6] identifies 6 different types of sensor technology used to measure fast or very fast transients divided into two main categories: contact and non-contact sensor techniques. Contact sensor techniques include capacitive bushings and resistance-capacitance voltage dividers, while non-contact sensor techniques are electrotechnical electric field sensors in air insulated substations (AIS) and overhead lines (OHL), optical electric field sensors, embedded electrode sensors in gas insulated substation (GIS) and porthole sensors in GIS.

According to [6], the transient measurement requirements include uncertainty of the scale factor, bandwidth, sampling rate, vertical resolution, measuring range, storage capacity, triggering mode, minimum interval for continuous triggering, and time synchronization. Depending on the application (slow, fast, or very fast front overvoltages) different values of each parameter are proposed [6]. By applying one of the previously mentioned techniques and meeting the specified conditions, it becomes possible to reliably monitor the actual phenomena occurring in the network. Extensive experience of continuous monitoring of transients in the power system shows that the measured data can be correlated with the lightning location system (LLS) data and with the SCADA events [7]. Transient recorder can be part of a transformer monitoring system (TMS), as shown in Fig. 1. The monitoring system needs to have the ability to sample, store and analyze transients in real-time. Data collected from the system can be used as the basis for the assessment of the transformer insulation condition.

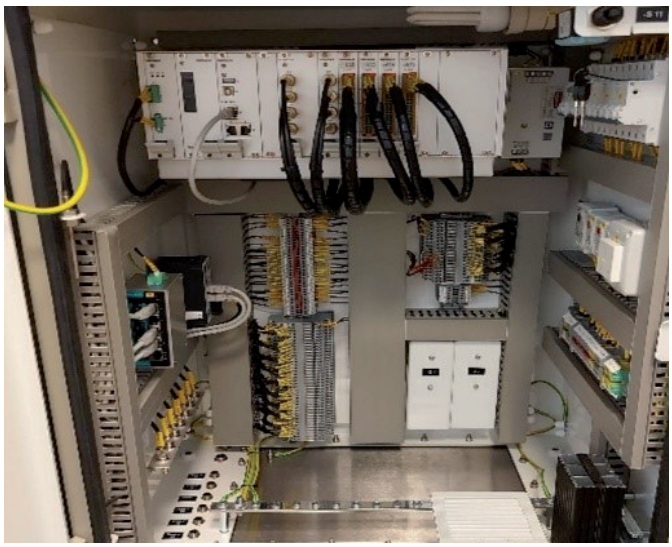

Fig. 1. Transient overvoltage monitoring system installed at power transformer as a part of transformer monitoring system [7].

One of the most common approaches is to measure voltage transients across the bushing measurement taps of power transformers or reactors [8]. A special bushing tap adapter and a measuring impedance need to be designed to accurately transfer the overvoltage amplitude and shape from the high to the low voltage side. Prior to its installation the system must undergo a performance check. There are two approaches to evaluating the equipment's performance: frequencydomain analysis and time-domain analysis. In the case presented here, both verification methods have been carried out. The system was validated in frequency and time domains using network analyzers and impulse tests on a variable shunt reactor, confirming accuracy up to 1 MHz with minor errors at higher frequencies. Test set up is shown in Fig. 2 and the frequency response is shown in Fig. 3. From Fig. 4 and Fig. 5. It can be seen that the TMS accurately measures the standard test impulses. The only exception being fast oscillations after chopping during LIC shown in Fig. 6. This is, however, expected since the inductances in the measuring circuit of the monitoring system are limiting the steepness of the signal and causing a slight error at higher frequencies. It is also important to note that all the impulses are observed on the same reactor phase (L2) and that the multiplier remained constant throughout the testing. This means that all the events captured with the transient recorder are linear with voltage showing its applicability not only for a wide frequency range, but for a wide overvoltage amplitude range as well.

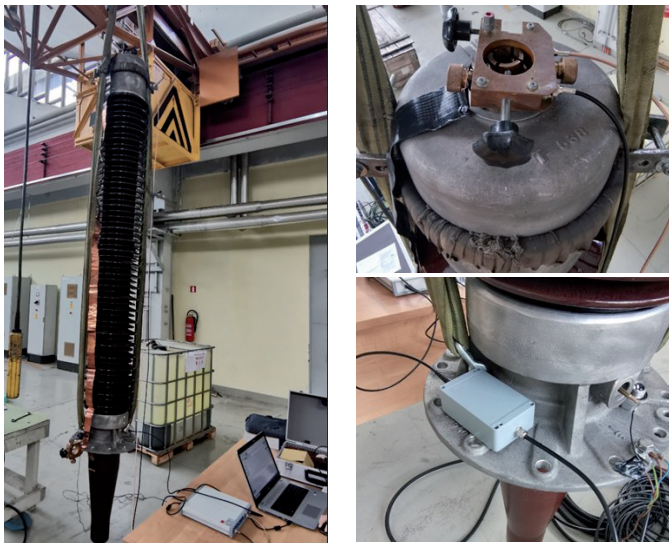

Fig. 2. Electrical circuit configuration for frequency response check of the transient measuring system [9].

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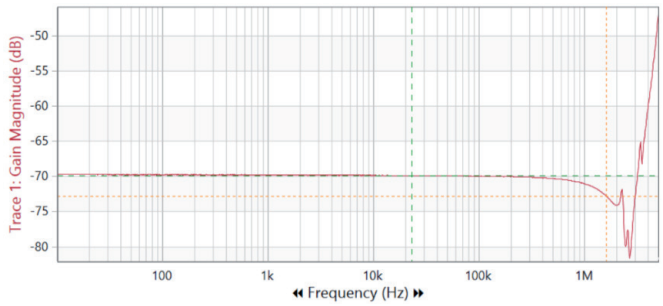

Fig. 3. Frequency response of the transient measurement system [9].

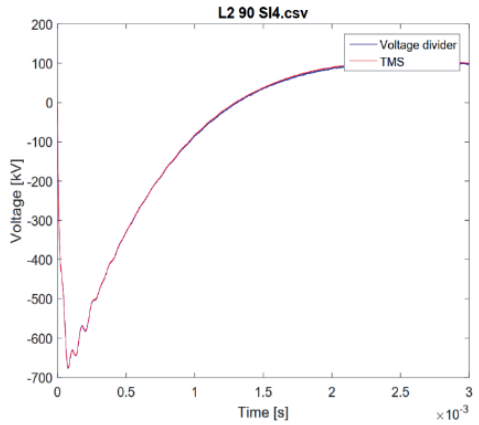

Fig. 4. SI waveform comparison [9].

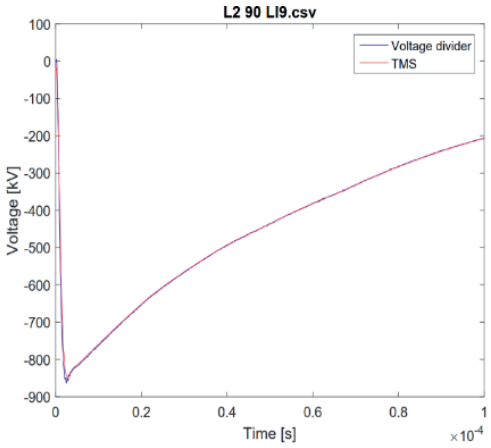

Fig. 5. LI waveform comparison [9].

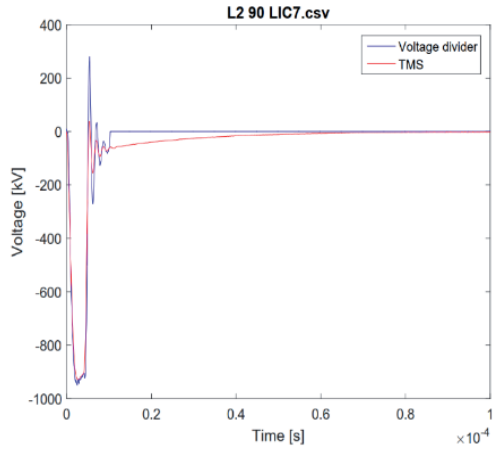

Fig. 6. LIC waveform comparison [9].

III. Field Measurements and Simulations

The measured overvoltages recorded using the previously described measurement technique can be used to analyze lighting and switching events. This chapter will be divided into two parts, the first one related to lightning measurements and simulations, while the second one related to switching events.

A. Lightning Events

Lightning strikes are the main cause of power outages. This motivated TSO to install transient recorder as a part of TMS systems in different substation in Croatia [10]. The brief layout of the 220/110 kV substations and transmission lines is shown in Fig. 7.

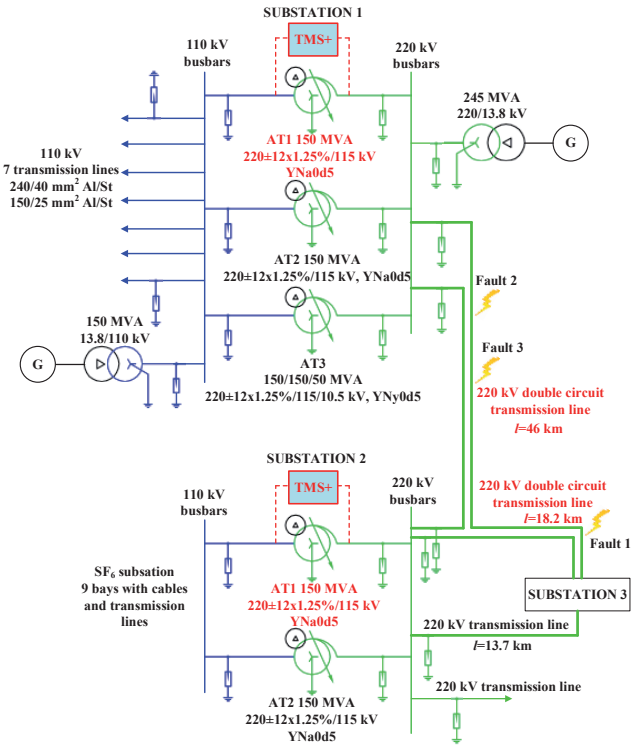

Fig. 7. Layout of 220/110 kV substations with two installed TMS systems [10].

In the continuation an example of recorded overvoltage is presented. This particular overovoltage is caused by a lightning strike to a 220 kV transmission line, connecting substations 2 and 3 and causing insulator flashover in two phases. Transients recorded during the event by TMS installed in substations 1 and 2 are shown in Fig. 8 and Fig. 9.

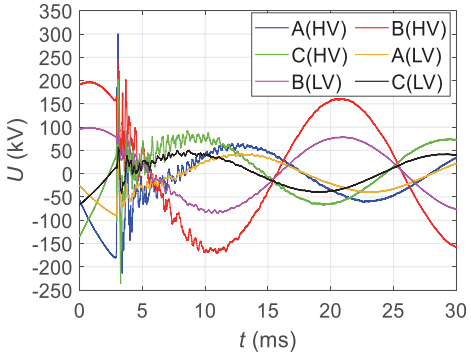

Fig. 8. Transient overvoltages recorded in substation 1 [10].

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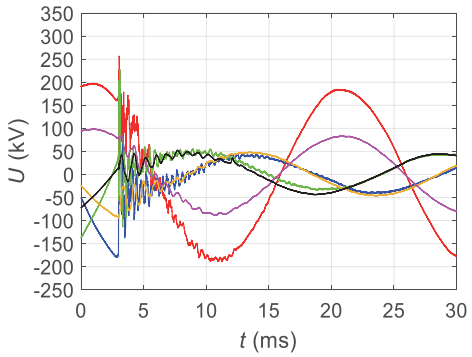

Fig. 9. Transient overvoltages recorded in substation 2 [10].

The recorded transients are time-correlated with a lightning strike which is detected by LLS (lighting location system). Lightning strike with current amplitude of 115 kA occurred and hit the tower of 220 kV transmission line connecting substations 2 and 3, at a distance of 11.2 km from substation 2 and 7 km from substation 3. At the same time, SCADA system detected double phase to ground fault in phases A and C, following the auto-reclosure operation of circuit breakers in the line bays in substations 2 and 3. Although substation 2 is closer to the fault location compared to substation 1, overvoltages in substation 2 are lower due to network topology.

Transient overvoltage waveforms can be extracted from the recorder data using the high-pass finite impulse response (FIR) filter. High-pass filter is used to obtain only high frequency components and to remove low-frequency and powerfrequency components from measured waveforms. Lightning overvoltage waveforms obtained after filtering out lowfrequency components from measurements are shown in Fig. 10 and Fig. 11. Waveforms from Fig. 10 and 11 were transformed to the frequency domain using the fast Fourier transform (FFT) and calculated frequency spectrum is shown in Fig. 12 and Fig. 13. Overvoltages observed in the power network differ from the standard 1.2/50 μs lighting impulse as they have oscillatory behavior and dominant frequency components in the range from 1 to 30 kHz [10].

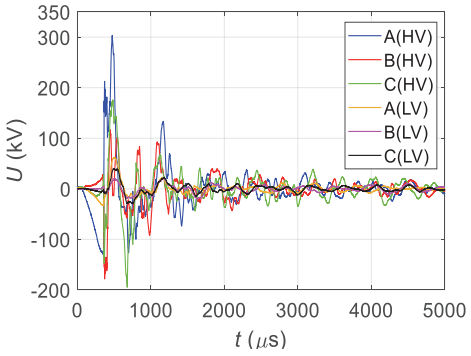

Fig. 10. Lightning overvoltages in substation 1 after filtering [10].

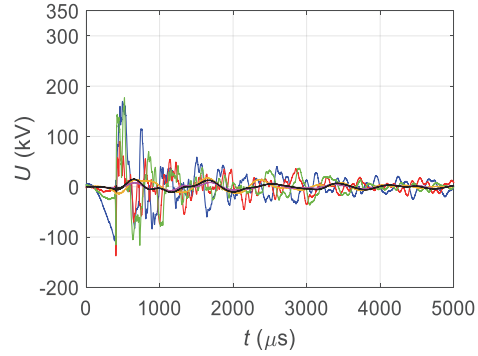

Fig. 11. Lightning overvoltages in substation 2 after filtering [10].

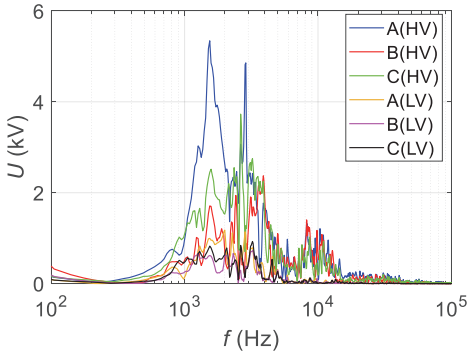

Fig. 12. Frequency spectrum of lightning overvoltages recorded in substation 1 [10].

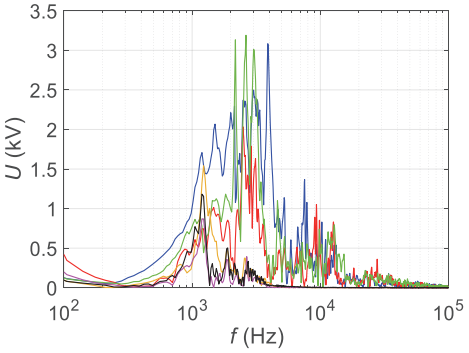

Fig. 13. Frequency spectrum of lightning overvoltages recorded insubstation 2 [10].

To simulate such high frequency events in EMTP-RV, wideband transformer models are required. The transformers are modelled using a black-box model, with more details given in [8]. The model must be validated for each transformer unit as the model is quite complex. This is usually done using low-voltage measurement results of transferred overvoltages, which are conducted in a high voltage laboratory. From the results, it can be concluded that transformer black-box wideband model can calculate the overvoltages which are transferred from the HV to the MV side of the transformer in this specific configuration accurately enough [8].

Once a validated transformer model suitable for simulating transients is available, it becomes possible to analyze various phenomena in the network and study the interaction between the transformer and the rest of the system. A simplified scheme of the substation modelled in EMTP, with AT3 being equipped with a TMS device with a transient recorder, is given in Fig. 14.

Comparison of measured and simulated transferred overvoltage provides accurate results in terms of overvoltage amplitude in phases U and V, as shown in Fig 15. The difference between waveshapes can be explained by complexity of a model and lack of modelling data.

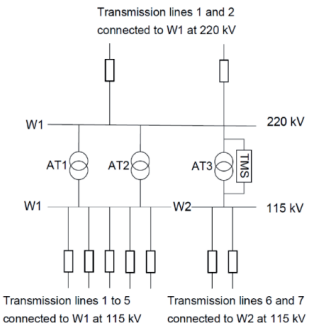

Fig. 14. Simplified scheme of the observed 220/115 kV substation [8].

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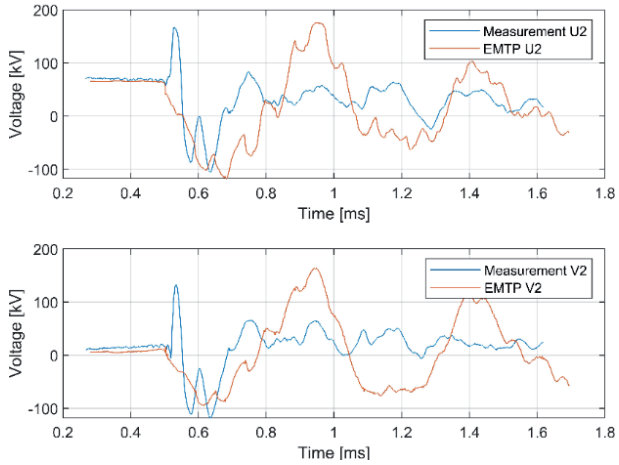

Fig. 15. Comparison of measured and simulated transferred overvoltages [8].

Statistical analysis of non-standard overvoltage waveforms measured at 220 kV terminals of a power transformer were calculated by converting the signals to the frequency model using FFT, then filtering out frequencies under 500 Hz using an ideal filter and finally converting the signal back to the time domain using inverse FFT. The observed events have occurred from May 2020 until October 2020 and include a period of the year with most severe lightning activity. Total number of recorded events is 123, which includes switching, lightning and other type of overvoltages that occurred during the observation period. Most of the events are overvoltages caused by lightning and most of them did not cause insulation failure.

Three different double exponential waveshape parameters can be observed statistically and are shown in terms of probability density function estimate: amplitude (Fig. 16), front (Fig. 17) and tail time (Fig. 18). Statistical analysis yielded the geometric mean values that are equal to 92.29 kV for the amplitude, 21.27 μs for the front time and 156.44 μs for the tail time. These numbers are compared to values from references [11] and [12]. From the probabilities of overvoltage parameters of front time and amplitude, it can be seen that the standard lightning impulse parameters are on the safe side for at least 95% of the observed overvoltages. This, however, must be carefully observed as the possibility for the impulse that is not covered by the standards is not negligible and has to be discussed further.

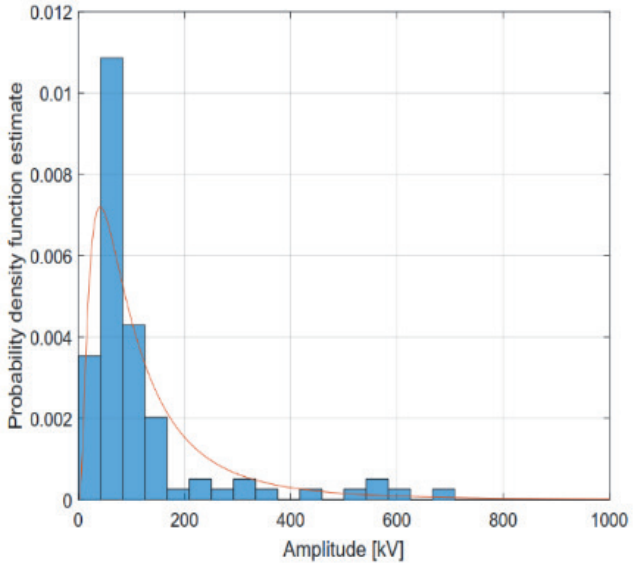

Fig. 16. Amplitude distribution [8].

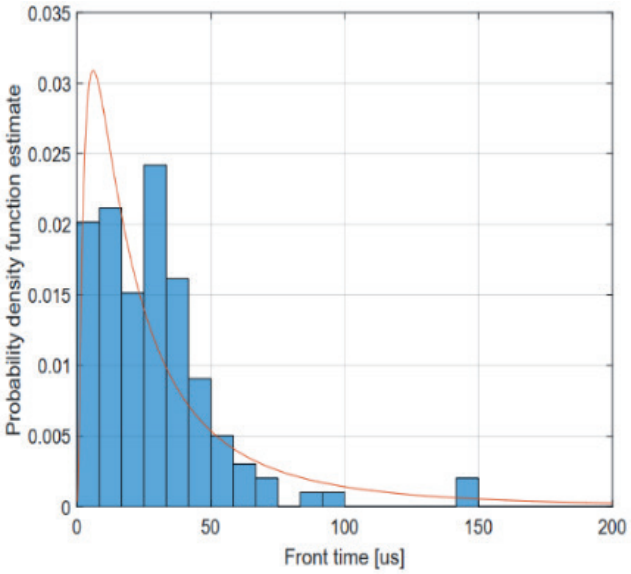

Fig. 17. Front time distribution [8].

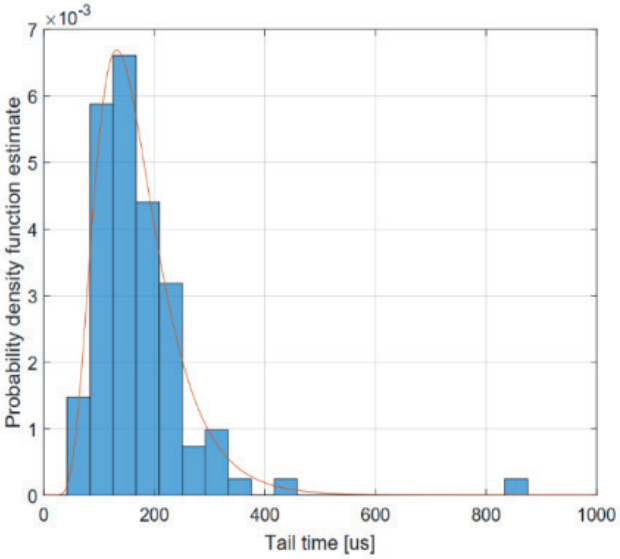

Fig. 18. Tail time distribution [8].

As non-standard overvoltages in the power system are mostly oscillatory, it is necessary to observe frequency spectrum of the measured signals in order to determine some severe cases. A calculated FDSF, which compares transient voltages with standard impulse tests in the frequency domain, is shown in Fig. 19 for all observed overvoltages. Fig. 20 shows cumulative envelope of observed overvoltages. FDSF is higher than one for only five out of 123 observed overvoltages indicating that these overvoltages might be potentially dangerous for the transformer. It should also be mentioned that these overvoltages did not cause any permanent damage to the power transformer.

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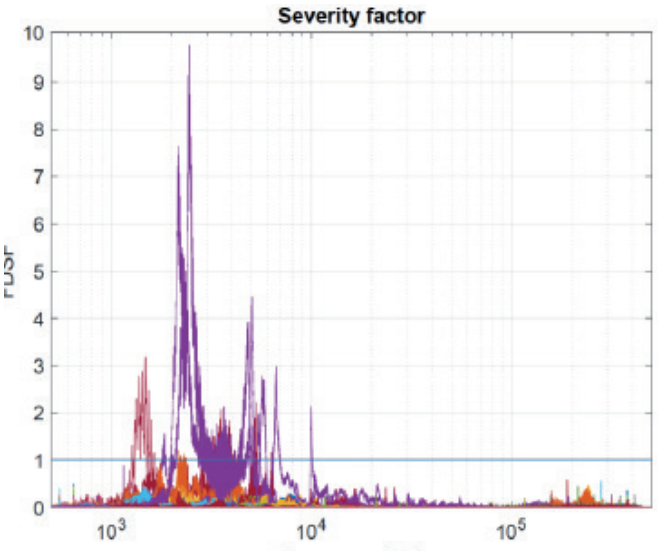

Fig. 19. FDSF calculated for observed 123 overvoltages [8].

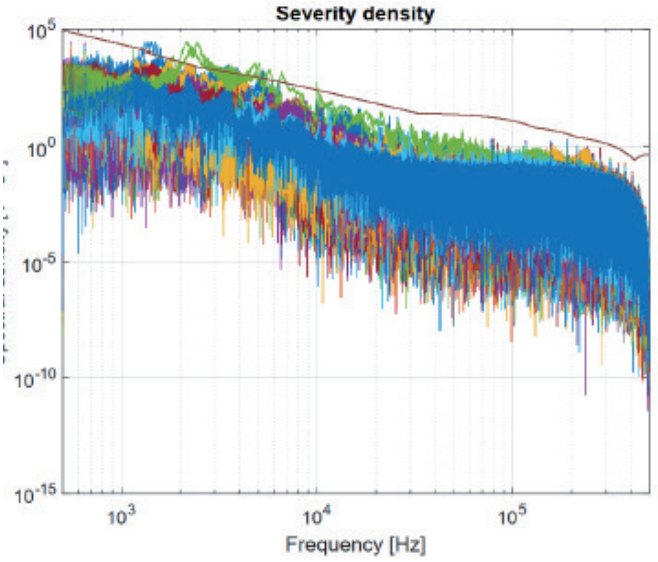

Fig. 20. Cumulative envelope of frequency energy spectrum [8].

B. Switching Events

Three different switching transients are identified: reactor/power transformer switching transients, switching off low capacitive currents and disconnector switching. These transients present different characteristics when compared to the standard impulses causing the dielectric stress on the insulation that may be higher than expected. The following case studies cover some switching events commonly performed in system operation and the generated transients.

Reactor/power transformer switching transients are analyzed first. It is common practice in extra-high voltage systems to perform power reactive control by means of installing shunt reactors. A reactor switching off operation may generate high frequency overvoltages due to arc reignitions in the circuit breaker, depending upon the specific moment at which the switching takes place. These high frequency transients may stress the high voltage bushings as well as internal parts of the reactor winding insulation leading to premature failures. In this case study of overvoltages caused by prestrike in the circuit breaker while switching variable shunt reactor 242 kV, 25-100 MVAr are presented [13].

The closing of the breaker poles at the near peak value of voltage to limit the energization currents might however generate switching overvoltages due to contact gap pre-strike inside high voltage circuit breaker. The prestriking arc may then be interrupted at or near a current zero, depending on the rate of change of current as it passes through the current zero. If interruption does occur, the dielectric strength will recover until the voltage across the breaker contacts overcomes again the dielectric strength of the decreasing gap. The process may be repeated several times until the contacts touch, and numerous high frequency current zeros can occur. SF6 circuit-breakers are generally unable to interrupt high frequency current, and usually only a single prestrike transient occurs when switching normal loads. However, in some cases more than one prestrike may occur during closing an SF6 circuit breaker under certain conditions, such as energization of shunt reactor.

Switching overvoltages shown in this chapter are recorded by TMS during energization/de-energization of variable shunt reactor (VSR) 242 kV, 25-100 MVAr. Switching overvoltages recorded at terminals od VSR during the energization are shown in Fig. 21. Initial time of energization with overvoltages caused by prestrikes inside SF_6 circuit breaker are shown in Fig. 22 (zoomed part from Fig. 21).

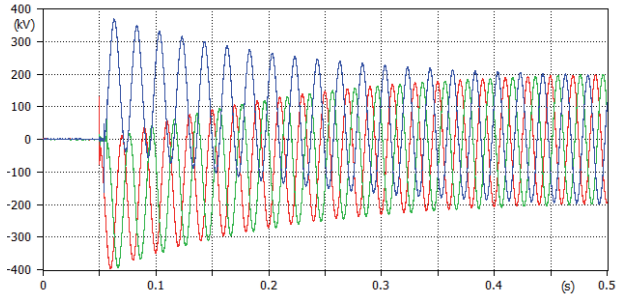

Fig. 21. Overvoltages at terminals of VSR during the energization.

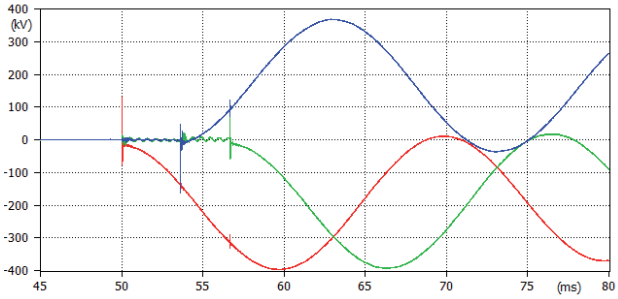

Fig. 22. Initial time of energization with overvoltages caused by prestrikes inside SF6 circuit breaker.

Fig. 23 shows overvoltages caused by circuit breaker prestrikes in phase A (zoomed part from Fig. 22).

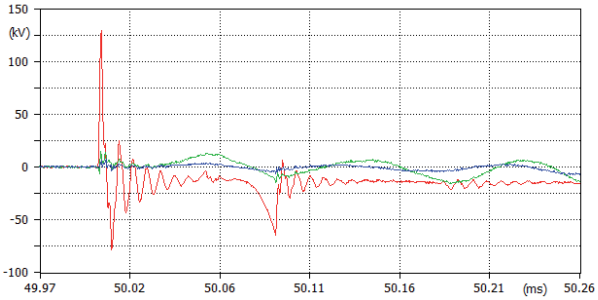

Fig. 23. Overvoltage caused by circuit breaker prestrikes in phase A (red).

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Another case study deals with energization and de-energization of a power transformer [14]. When the cable line is energized together with the generator step-up (GSU) transformer, the voltage at the input terminals of GSU transformer has an oscillatory waveform, as shown in Fig. 24. The frequency is determined primarily by the length of the switched cable line. Under certain conditions it can be comparable to the natural oscillation frequencies of GSU transformer HV winding, which determines the possibility of resonant overvoltages inside HV winding that could potentially be dangerous for its longitudinal insulation. Standard switching and lightning impulse tests have different waveforms and cannot exactly reproduce the longitudinal effects on insulation of the transformer HV winding caused by re-reflections of electromagnetic waves in cable lines.

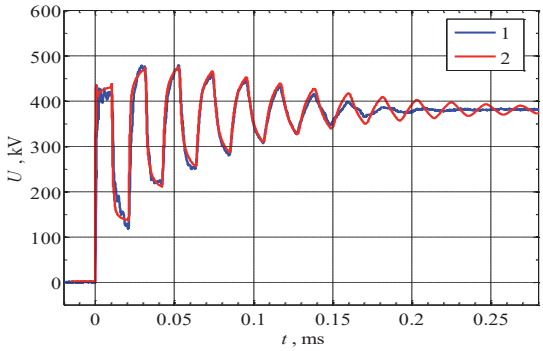

Fig. 24. Measured (1) and calculated (2) voltage waveform at the phase B terminal of HV winding of GSU transformer T4 [14].

Capacitive currents are encountered in the following cases:

- Switching of capacitor banks, no-load cables, no-load transmission lines or filter banks by HV SF6 or vacuum circuit breakers
- Switching of capacitive charging currents of bushing, busbars, connective leads, very short lengths of cables and of the capacitor voltage transformer by HV disconnectors in AIS and GIS substations.

The representative case of interrupting small capacitive currents is switching off the compensation capacitor banks with a vacuum circuit breaker (VCB), due to VCB re-ignitions.

Last switching event analyzed is disconnector switching. The process of extinguishing the electric arc by SF6 resulting from switchgear maneuvers generates very fast transient overvoltages (VFTO). These overvoltages have a very high frequency spectrum on the order of tens of MHz, and high rates of voltage variation (*dV/dt*) which may not be represented by transformer standard dielectric tests. The cumulative effect of these maneuvers can cause a drop in the insulation supportability of the windings and can also cause possible internal resonances and amplifications. The transients generated by the disconnector switches of GIS substations are very fast transients characterized by a high content of frequencies above 1 MHz. These predominant frequencies are not represented with the same energy in the standard waveforms.

The amplitudes of the switching transients are not high and are within the specified standard impulses voltage levels, but their frequency spectrum may differ significantly from the standardized dielectric impulses. Some dielectric failures of transformers and reactors have been reported in the literature with unknown causes. Those may be due to these switching transients or due to their cumulative stress on the insulation.

IV. Overvoltage Waveshape Comparison with Standard Tests

As shown in the previous chapters, there is a variance between real operating overvoltages and the standard impulse voltages (SI, LI, LIC) and it is important to compare it. Different methods for waveshape comparison will be discussed hereafter.

The Frequency Domain Severity Factor (FDSF) compares transient voltage on the transformer terminals and the standard impulse tests (SI, LI, LIC) applied on the same terminals in the frequency domain [15]. This comparison gives an analysis of the amplitudes for different frequency components. The FDSF approach is not directly linked to the internal stresses inside the transformer, because it is a comparison of external voltages and thus should be used in combination with other methods. It can be used for a wide range of transformer types, e.g. dry-type transformers and oil-immersed transformers with different liquids.

According to the method described in [15], FDSF can be determined as the ratio between the spectral density of the measured overvoltage and the spectral density of the standard lightning waveform used for testing transformers. It considers the frequency content of the overvoltages measured in the substation and compares it to the frequency content of the voltage waveforms for which the transformer had been tested. The FDSF factor should be less than 1 to ensure that the stress arising in the system is less severe for the transformer insulation system than the standard lighting waveform for the particular transformer. An example of such graph is shown in Fig. 25.

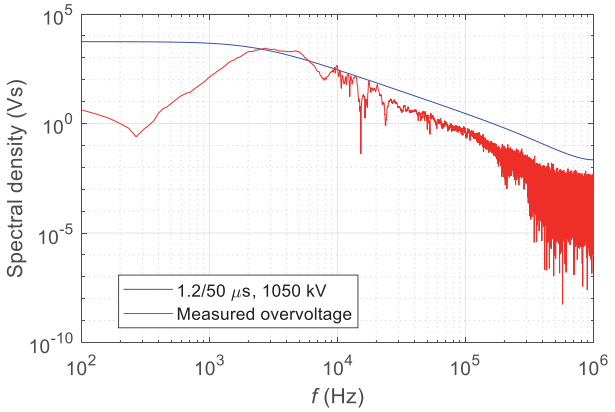

Fig. 25. Spectral density of measured overvoltage and standard lightning impulse waveform 1.2/50 μs, 1050 kV [15].

Time Domain Severity Factor (TDSF) is used as a tool for assessing power system overvoltage severity for transformer insulation compared with the severity of standard dielectric tests. It is introduced in [16] and is defined as (1).

$$TDSF = \frac{\Delta V_{max}}{\Delta V_{env}}; \quad (1)$$

where ΔV_{max} is the maximum voltage drop between disks along the winding due to the considered transient event, and ΔV_{env} is the maximum voltage drop between disks along the winding for all standard dielectric tests. TDSF considers internal voltage distributions inside the transformer windings. This approach is more applicable for the assessment of transient overvoltage severity. Fig. 26 shows the TDSF curve according to (1) along the HV winding of a WEG singlephase transformer, whose full design is given in TB No. 904 published by JWG A2/C4.52, during a simulation of a

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resonance condition initiated by a single-phase to ground fault on the supplying overhead line. The distance between the short circuit location and the transformer happens to be such that the frequency of oscillations in the line is close to the first natural frequency of the transformer HV winding [17].

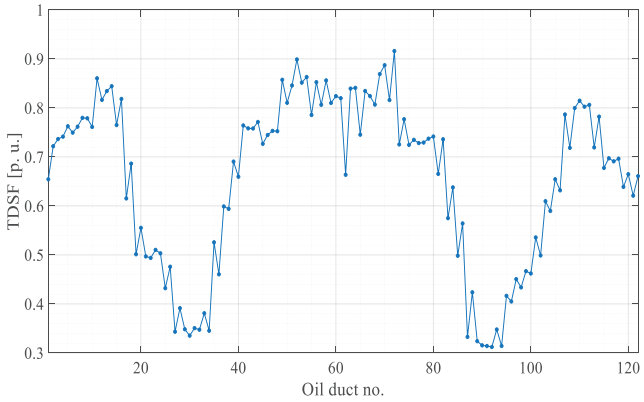

Fig. 26. TDSF along HV winding of the transformer during the resonance condition [17].

The Evaluation Method, according to IEC 60071-2:2018, is another approach to compare a transient overvoltage with the standard lightning impulse test. However, due to its limitations this approach should also be used in combination with other methods. In terms of transient overvoltage, five representative voltage shapes were defined, measured and analyzed during lightning events and disconnector switching at UHV substations. These five types are:

- Waveform A: A pulse-shape
- Waveform B: A steep front shape with a flat tail time
- Waveform C: A damped oscillation with a frequency between 0.4 MHz and 1.0 MHz for transformers. The crest value occurs at the first period of oscillation
- Waveform D: A damped oscillation with a frequency between 0.4 MHz and 1.0 MHz for transformers. The crest value occurs at the second period of oscillation
- Waveform E: A superimposed damped oscillation with two different frequencies.

Voltage-Time Method (Energy Method) compares the overvoltage waveshape with the standard test impulses based on the double exponential equation [11]. The method fits the overvoltage with the double exponential equation based on its energy. It can be used to find a waveshape that is feasible to produce in high voltage laboratories with the same amount of energy as the actual overvoltage waveshape and/or to analyze big amount of measured overvoltage data using statistical analysis [18].

Every observed overvoltage *U(t)* can be described using the well know double exponential function given in (2).

$$U(t) \approx kA(e^{-\alpha t} - e^{-\beta t}); \quad (2)$$

where k, α and β are constants dependent on the waveshape of the observed overvoltage, A is the amplitude, k is function of α and β, α is a function of tail time *th* and β is a function of the front time *tf*.

The front and tail times of the standard lightning impulse are specified in [19], respectively, as 1/0.6 times the interval T between the instants when the impulse is at 30% and 90% of the peak voltage value and the time between the virtual origin and the instant when the test voltage curve decreases to 50% value. This method is validated by comparison with the disruptive effect (DE) method [11].

Volt-time method has been used on the of overvoltage measured at the transformer terminal during the service, where it is substituted with double exponential approximation as it can be seen from Fig. 27.

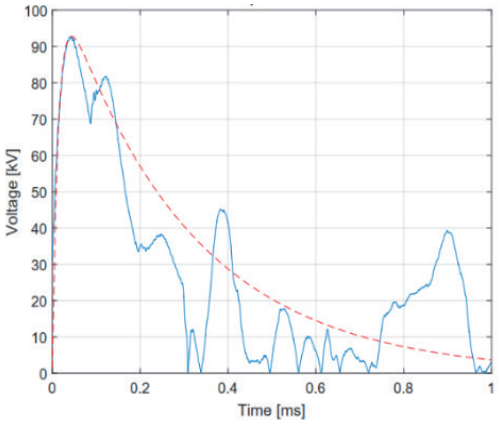

Fig. 27. Example of absolute values of measured (full curve) and fitted signal (dotted curve), using double exponential equation [11].

V. Conclusion

Considering ongoing changes in power systems driven by climate impacts, increases in renewable energy, and broader application of HVDC technology, transformers and shunt reactors are exposed to a growing range of complex transient overvoltages. Ensuring that power system equipment, especially oil-paper insulation, can withstand these stresses throughout decades of operation remains a critical requirement for system reliability. Recognizing this, CIGRE has established several working groups to better understand the interaction between high-frequency transients and transformer dielectric behavior.

The investigations carried out within CIGRE WG A2.63, part A, show that the waveshapes of real lightning and switching overvoltages differ significantly from standardized LI and SI impulses. These deviations include longer and less steep lightning waveforms, oscillatory components, and high-frequency content arising from switching interactions. All of these can intensify dielectric stress, excite internal resonances and lead to unexpected failures even when surge arresters are properly installed. The results confirm that accurate evaluation requires a combination of high-bandwidth measurements and detailed EMTP simulations capable of representing complex power system geometries.

The study highlights that comparing real transients to standard test impulses using tools such as FDSF, TDSF, the Evaluation Method and the Voltage–Time Method can provide valuable insight into insulation vulnerability. None of these techniques are fully sufficient alone, however, when used together, they allow a more realistic estimation of stresses on both internal and external insulation.

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VI. References

[1] E. E. Henriksen, "Study of Very Fast Transient Overvoltages in Transformers (VFTO)," ELECTRA, no. 179, pp. 13–23, Aug. 1998.

[2] CIGRE Working Group A2/A3/B3.21, "Electrical Environment of Transformers - Impact of Fast Transients," Electra, no. 208, Feb. 2005.

[3] CIGRE Technical Brochure No. 902, "High-Frequency Transformer and Reactor Models for Network Studies - Part C: Grey Box Models. JWG A2/C4.52," Electra, no. 328, Jul. 2023.

[4] "IEEE C57.142 IEEE Guide to Describe the Occurrence and Mitigation of Switching Transients Induced by Transformers, Switching Device, and System Interaction," 2010.

[5] J. McBride et al., "Investigation of the Interaction Between Substation Transients and Transformers in HV and EHV Applications," IEEE Transactions on Power Delivery, vol. 36, no. 3, pp. 1768–1774, Jun. 2021, doi: 10.1109/TPWRD.2020.3014595.

[6] CIGRE C4 WG C4.45, "CIGRE Technical Brochure No. 836, Measuring techniques and characteristics of fast and very fast transient overvoltages in substations and converter stations," 2021.

[7] S. Keitoue, I. Murat, B. Filipovic-Grcic, A. Zupan, I. Damjanovic, and I. Pavic, "Lightning caused overvoltages on power transformers recorded by on-line transient overvoltage monitoring system," in 2nd South East European Regional CIGRE SEERC Conference, Kyiv, Ukraine, 2018, pp. 1–11.

[8] B. Jurišić, T. Župan, G. Plišić, B. Filipović-Grčić, G. Levačić, and A. Xemard, "On site measurement and simulation of transferred lightning overvoltages through power transformers," in Lecture Notes in Electrical Engineering, Opatija, Croatia, 2020. doi: 10.1007/978-981-15-56005_13.

[9] T. Župan, B. Jurišić, I. Murat, B. Filipović-Grčić, S. Goglia, and G. Levačić, "Fleet Asset Management Opportunities Arising from Transient Monitoring of Power Transformers and Shunt Reactors," Journal of Energy - Energija, vol. 69, no. 4, 2020, doi: 10.37798/202069453.

[10] B. Filipović-Grčić, B. Jurišić, S. Keitoue, Filipović-Grčić. D, and A. Župan, "Analysis of Overvoltages on Power Transformer Recorded by Transient Overvoltage Monitoring System," in 5th International CIGRE Colloquium "Transformer Research and Asset Management," Opatija, Croatia, 2019.

[11] W. Sima, X. Lan, Q. Yang, and T. Yuan, "Statistical analysis on measured lightning overvoltage surges in a 110 kV air-insulated substation," IET Science, Measurement & Technology, vol. 9, no. 1, pp. 28–36, Jan. 2015, doi: 10.1049/iet-smt.2013.0235.

[12] S. Okabe, J. Takami, T. Tsuboi, G. Ueta, A. Ametani, and K. Hidaka, "Discussion on standard waveform in the lightning impulse voltage test," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 20, no. 1, pp. 147–156, Feb. 2013, doi: 10.1109/TDEI.2013.6451353.

[13] S. Keitoue and B. Filipovic-Grcic, "Operating experience with a transient overvoltages monitoring system installed on power transformers and shunt reactors," in 1st Conference of Nacional Committee CIGRE Kosovo, Pristina, Kosovo, 2019.

[14] V. S. Larin, "High-frequency overvoltages in power plants main circuits. Part 2. Transients when the cable line is turned on," Energetik, vol. 11, pp. 23–28, 2022, doi: 10.34831/EP.2022.42.52.003.

[15] JWG A2/C4.39, "CIGRE Technical Brochure No. 577A, Electrical Transient Interaction Between Transformers and the Power System, Part 1- Expertise," 2014.

[16] X. M. Lopez-Fernandez and C. Alvarez-Marino, "Induced transient voltage performance between transformers and VCB. severity factors and case studies," IEEE Transactions on Power Delivery, vol. 30, no. 3, 2015, doi: 10.1109/TPWRD.2014.2352112.

[17] JWG A2/C4.52, "CIGRE Technical Brochure No. 900, High-Frequency Transformer and Reactor Models for Network Studies - Part A: WhiteBox Models," 2023.

[18] B. Jurisic, B. Filipovic-Grcic, T. Zupan, and G. Levacic, "Statistical analysis of non-standard overvoltage waveforms measured at 220 kV terminals of a power transformer,," Electric Power Systems Research, vol. 197, p. 107318, Aug. 2021, doi: 10.1016/j.epsr.2021.107318.

[19] "IEC 60060-1, High voltage test techniques - Part I: General definitions and test requirements," 2010

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