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Session 2022

Statistical Analysis and Grouping of Measured Power Transformer Overvoltages

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SUMMARY

Nowadays, more and more renewable energy sources, together with power electronics are installed in the power networks worldwide. This leads to complex situations in the networks that have to be analysed and monitored. One of the main problems in such networks are the overvoltages that may cause failure of the equipment, in particular power transformers. Therefore, it is necessary to assess this problem with outmost care.

In this paper, a methodology for power transformer overvoltages management based on field measurements and advanced electromagnetic transients (EMT) modelling is presented. It consists of simulating overvoltages using detailed power network models, including the high frequency transformer models and continuous monitoring of overvoltage events at the places of interest in the power network. This work gives a framework for dealing with overvoltages in the power network that could be implemented by power utilities.

KEYWORDS

Power transformer, overvoltages, high frequency, EMTP, modelling, asset management, field measurements

1. INTRODUCTION

Modern power systems with high share of renewable energy sources (RES) and implementation of power electronic devices, such as DC lines, are more prone to transient events. Overvoltages can occur in the power network due to switching operations or can be caused by lightning activities. These overvoltages may cause failure of the components in the network, even though good practices of the insulation coordination were followed.

One of the critical system components is a power transformer. In the case of a power transformer failure, economic consequences can be several times higher than the cost of the transformer itself. Therefore, it is necessary to establish asset management system for such components. A crucial part of this system is to mitigate overvoltages as much as possible. Therefore, it is necessary to know the real types and severity of overvoltage events for a specific device, and to understand its response to them. In general, two approaches to evaluate the overvoltages that may exist at transformer terminals are possible.

The first one is to run simulations in EMTP-type software with detailed wideband transformer models [1]. Based on the results of simulations, one can determine the waveshapes of possible overvoltages. These waveshapes can be useful information for the transformer manufacturer, in order to produce the transformer that will not contain natural winding frequencies which are likely to be triggered by the overvoltages. In the case when natural frequency of the transformer winding is close to the main overvoltage frequency, internal insulation breakdown may occur due to the phenomenon called resonance. Moreover, these simulations can help to better design and dimension the equipment in the transformer bay. The problem with this approach is lack of transformer data, especially during the procurement process. For the transformers that are already in operation, transmission system operators can build its own transformer model based on measurements, also known as black box model.

Another approach is to continuously monitor overvoltages at the transformer terminals in the substation. This can be done by using the transformer monitoring system equipped with devices for monitoring of transients. Overvoltage monitoring can help in extending the knowledge of transients that occur in power networks, as these can significantly differ from the standard test impulses [2]. Such data can be used either in system planning phase or in defining the protection specification. By more thoroughly specifying the power transformer, it can be able to withstand possible nonstandard overvoltage waveforms that may occur at the particular position in the power network. On the other hand, adopting or installing better specified protection devices can help in eliminating potential equipment failures.

Both approaches lead to gathering more knowledge on overvoltages. This knowledge can be used in proper dimensioning of both the transformer and its protection devices, which can lead to better economic decisions and general increase in reliability. To maximize the level of knowledge on interactions between power transformer and the power networks, the best practice would be to use both of the presented approaches, EMTP simulations and transient monitoring.

One of the main goals of the currently active CIGRE WG A2.63 is to analyze whether the standard test impulse waveforms are enough to describe all the potential overvoltages that can occur in the power network. The paper is in line with the mentioned CIGRE WG, as it analyses the overvoltages measured at 220/110 kV substation through extended time period. Statistical analysis is done based on grouping of measured data, in order to compare the measured overvoltages with the standard ones. Genetic algorithm and energy equivalent method is used to find double exponential expressions that fits measured overvoltages. In that way, overvoltage waveform parameters, such as rise and tail time, can be more precisely compared with the standard ones.

The aim of this work is to explore the possible applicability of new insights that the statistical analysis of network transients can give the system operators, and how it can affect the insulation coordination at geographically different power network regions. In this paper, first the examples of high frequency transformer modelling, which is used to evaluate overvoltages using EMT simulations, is presented. Then, a monitoring of transient events in vicinity of a power transformer, installed in the network with high share of RES is presented. The results of long term overvoltage monitoring are analysed using statistics. As these two approaches are necessary inputs for successful power transformer asset management, directions for implementation of framework for overvoltage management based on field data and modelling are given in forth section. Fifth section gives the conclusions of this approach and work.

2. EMTP SIMULATION INLCUDING HIGH FREQUENCY TRANSFORMER MODELLING

In this section, a detailed EMTP modelling of the power network including high frequency transformer modelling is presented. The aim of this section is to provide an insight for a power utility on how to deal with simulation of fast overvoltages that includes detailed transformer models.

In general, to simulate fast and very fast transients in the power system, high frequency transformer models are needed [3]. High frequency components of such overvoltages are causing resonant behavior inside the transformer. As a consequence of this resonance, electromagnetic behavior of a transformer becomes complex and traditional transformer models are not suitable for its representation.

Wide-band transformer models are classified in four different categories, in accordance with the data they require for their construction and application: simplified models, Black Box models, White Box models and Grey Box models [4]. From the perspective of power utility, the only model, besides simplified ones, which can be used straightforwardly is the Black Box model. They are based only on the measurements that can be conducted at transformer terminals, using standard SFRA or VNA equipment [5], [6]. Measurements can be done both in the HV laboratory or on field. Only condition that has to be satisfied is to have a proper grounding which is satisfied both in the HV laboratory and in the substation.

Measuring on field requires more preparation as power transformer has to be deenergized and disconnected from the power network, which can be seen in Figure 1.

Figure 1. On field measurements of power transformer admittance matrix.

The admittance matrix for the particular 150 MVA 220/110 kV autotransformer unit has been measured on field and EMTP model is established based on the measurement results and fitting, which can be seen from Figure 2 [7], [8].

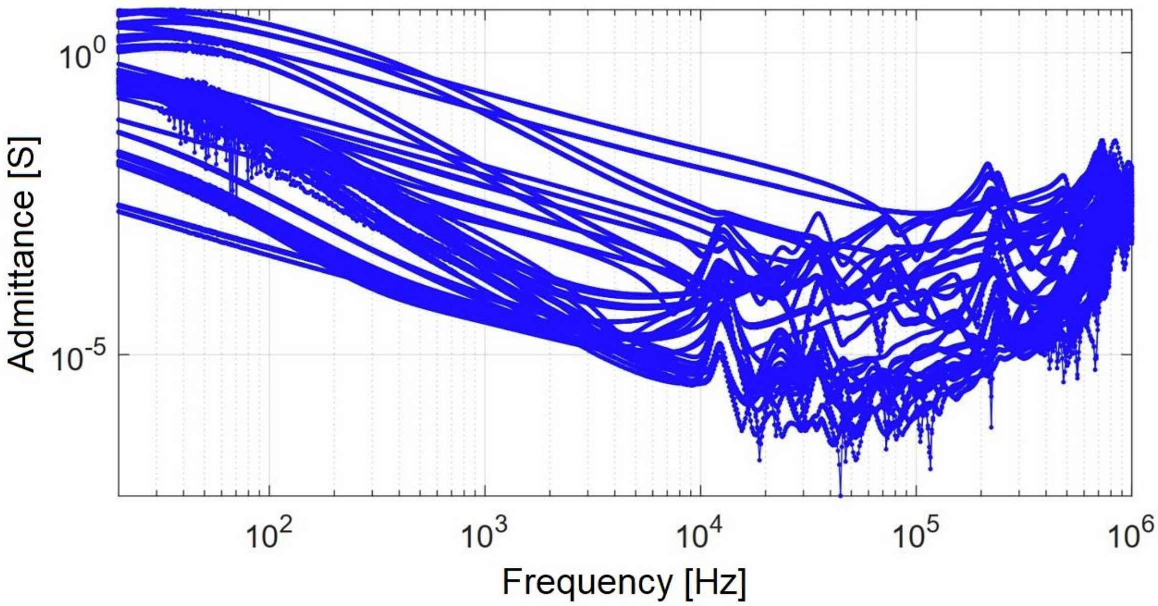

Figure 2. Frequency dependent admittance matrix coefficient for a 150 MVA transformer unit [9].

Once the model is established, it can be used in EMTP to simulate overvoltages [10]. An example of EMTP simulation of a lightning strike to a 220 kV overhead line tower, which led to flashover in phase B, following by the flashover in phase A, is given below. Observed transformer unit is located in the area with significant lightning activity and high soil resistivity due to the rocky mountain terrain [11]. Seven 110 kV and two double-circuit 220 kV overhead lines are connected to the substation with three autotransformer 220 kV/110 kV working in parallel.

Particular lightning strike was detected by the lightning location system, while SCADA detected double phase to ground short circuits, in phases A and B. Measured overvoltage amplitude, obtained from the installed transient recorder was approximately 320 kV, as can be seen from Figure 3. Waveshape of the overvoltages suggest that the fault, following the lighting strike, was double phase to ground fault in phases A and B.

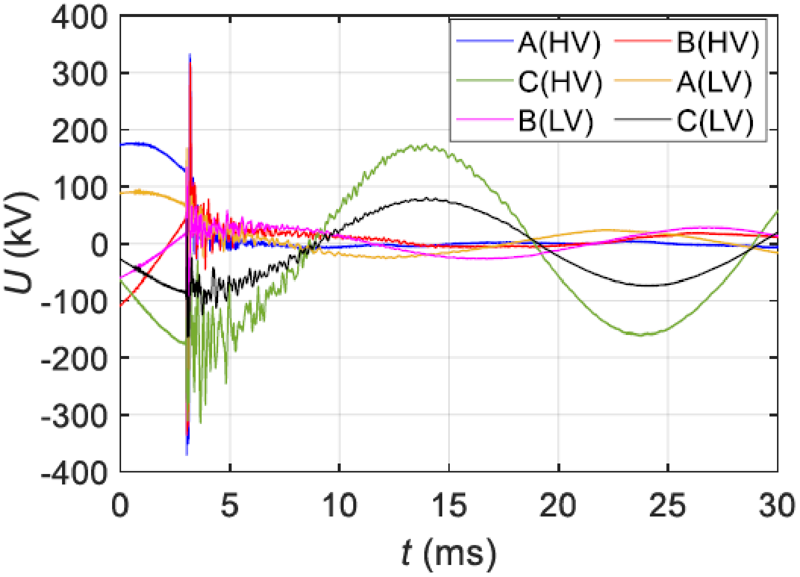

Figure 3. Measured overvoltages, by transient recorder, in the case of double phase to ground short circuit

In EMTP simulation, overvoltage is simulated as a lightning strike to the tower of the 220 kV overhead line. The overvoltage propagated to the 220 kV part of the substation, through the transformer to the 110 kV side as can be seen from Figure 4. Modelling includes detailed EMTP model of the substation as well as the overhead lines connected to the substation. Overhead lines, busbars and connections inside substation are modelled using frequency dependent line models [12]. Surge arresters are installed in every transformer bay (surge arresters with rated voltage U_r=198 kV are installed at 220 kV level and with U_r=108 kV at 110 kV level) [11] and are modelled using their voltage current characteristics while instruments transformers are modelled with capacitance to the ground. Corona attenuation was neglected because of short distance between lightning strike and substation.

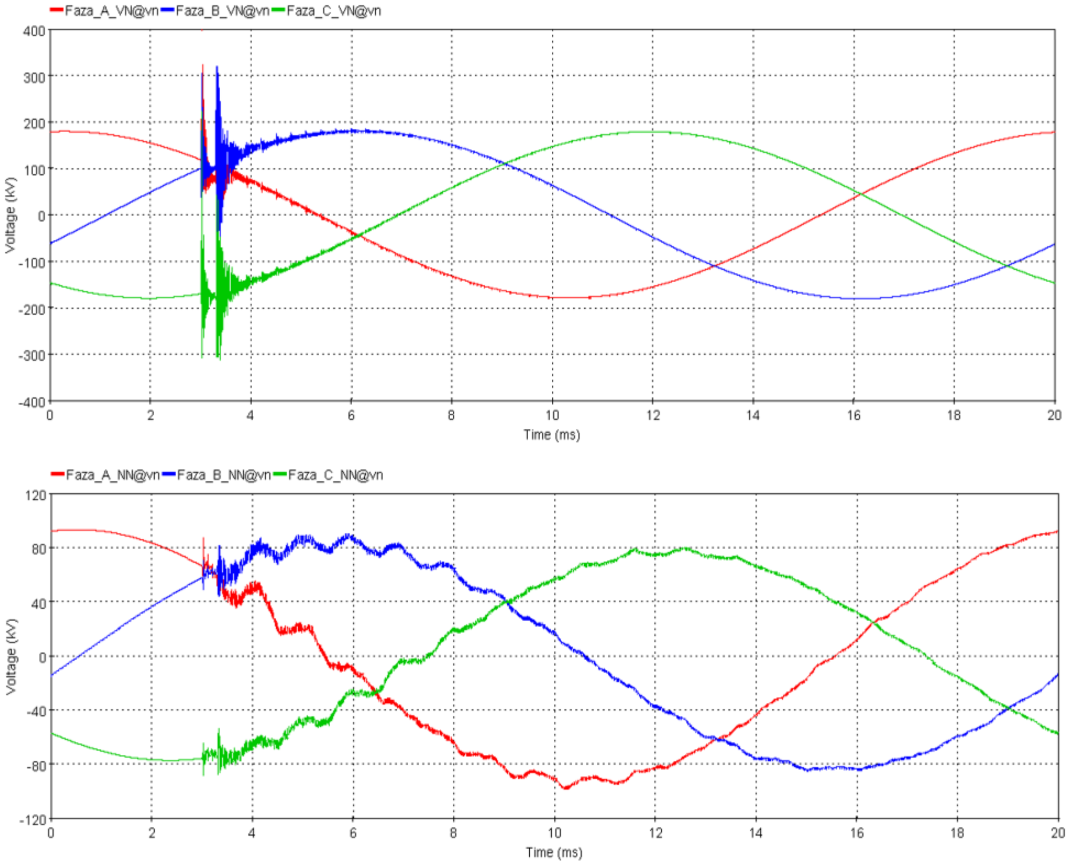

Figure 4. Simulated lightning overvoltages in EMTP using power network model together with detailed black box transformer model (upper figure – HV side, lower figure – LV side, red – phase A, blue – phase B, green – phase C).

Simulated overvoltages consist of lightning strike overvoltage and system response, which is quite complex due to numerous reflections inside the substation and between adjacent substations connected with 110 kV overhead lines. More specifics on modelling can be found in [10]. The amplitude of the simulated overvoltage is comparable to the measured ones while the oscillations following the initial overvoltage differ due to lack of damping in the model.

It is important to note that these models are not capable of simulating transformer inner behavior as they do not include any information on transformer inner geometry. These models can provide utilities with an idea of the overvoltages that can exist at the transformer terminals. It can be valuable when it comes to testing of the transformer and comparing the insulation stresses and safety factors to standard test impulses. To calculate safety factors on the inner insulation, white box models are needed. This part has to be done in cooperation with the transformer manufacturers.

3. CONTINUOUS OVERVOLTAGE MONITORING IN POWER NETWORK

This section shows another approach on how to evaluate overvoltage hazard in the power system. It consists of continuously monitoring overvoltages at different locations in the power system. Once the data is collected, it is possible to statistically analyze it, and obtain the geographical allocation and severity of overvoltages in the network [13]. In this section, a result of statistical analysis of overvoltage parameters, measured at 220/110 kV, 150 MVA autotransformer located in Croatian coastal area, is briefly reported. More about the used methodology can be found in [14]. In the section, the equipment for overvoltage monitoring is presented first, following by the results of statistical analysis.

The transient monitoring system measures voltages on a measuring tap of the transformer's high voltage bushing. It consists of specially designed adapter for the connection to the bushing measurement tap, with measurement circuit including the matching impedance, capacitance divider, coaxial cables, acquisition unit and associated software [15]. The system is continuously logging the transient overvoltage data with a high sampling rate. Since this results in a very large data set, the algorithm is set to only save a time frame of the measurements when the trigger detects a rise or an anomaly in the voltage. To accomplish this, continuous voltage measurement is performed with an additional analogue input module and two stage matching circuit is needed.

The embedded acquisition card is fast enough to capture data with a time resolution of 0.5 µs (when six different voltages are observed simultaneously), which is enough for transients containing frequency components lower than 1 MHz. The number of points recorded per event is 10^6, which leads to a total recording time of 500 ms per event. The system is already installed and operates on different locations in Croatian transmission system. The performance check of the system has been done in both frequency and time domain [10], [16]. In [16], the system was tested in the high voltage laboratory for SI, LI and LIC on 100 MVAr 220 kV shunt reactor, while in [10] the system was tested against the simulation results of transferred overvoltage, caused by lightning. The simulation included wideband black box power transformer model in EMTP.

The overvoltages are continuously measured in 220/110 kV substation, the same substation as in the example in the previous section. 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. The measured overvoltage waveshapes are bidirectional and differ from the standard test impulses. Therefore, the signal processing has to be made in order to compare the measured waveshapes to the standard ones.

Every observed overvoltage U(t) can be equivalented using the well know double exponential function:

$$U(t) \approx kA(e^{-\alpha t} - e^{-\beta t}), \tag{1}$$

where k, α and β are constants dependent on the wave shape of the observed overvoltage, while A is the amplitude. k is the function of α and β, while α is a function of tail time, t_h and β is a function of the front time, t_f. Front and tail time of the standard lightning impulse are specified in [17], 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.

In the paper, amplitude of the overvoltage is specified as the highest voltage peak value of the observed overvoltage, while the front time is calculated as the time from the signal trigger to the highest voltage peak value. Once these two parameters are specified, it is necessary to calculate a tail time. This parameter can be found using the energy method presented in [13]. Calculated statistical parameters and probabilities are given in Table 1.

Table 1. Statistical parameter of measured overvoltages.

Parameters	μ	σ^2	Geometric mean $\mu^* = e^{\mu}$	Geometric stand. dev. $\sigma^* = e^{\sigma}$
Amplitude [kV]	4.53	0.81	92.29	2.46
Front time [μs]	3.06	1.21	21.27	3.00
Tail time [μs]	5.05	0.17	156.44	1.52

Statistically derived overvoltage parameters can be used to check the severity of the overvoltages that arrive at power transformer terminals. These data incorporate specifics of geographic and electric location such as lightning activity in the area, problems with the grounding system, switching repetition, resonance problems, specific power network configuration, transformer interaction with the network, etc. In general, it can help utilities to choose insulation level specifically for the transformer unit and as an input for transformer manufacturer in order to make a design more persistent for a specific type of overvoltages. In addition, measured severe cases of overvoltage events can be investigated more closely with factors such as frequency domain severity factor (FDSF) [1].

4. FRAMEWORK FOR OVERVOLTAGE MANAGEMENT BASED ON FIELD DATA AND MODELLING

In this section, the explanation on how the power utilities can benefit from advanced EMTP simulation of overvoltages and from monitoring transients in the system is given. These two approaches are the input for the overvoltage management framework.

Term overvoltage management, at first, considers understanding of the different natures and causes of the overvoltages in the power system. Moreover, based on that knowledge, it considers overvoltage monitoring at critical points in the systems. Final and the most important point and meaning of the term is mitigation of overvoltages using appropriate measures.

Implementation of successful overvoltage management system in the power network can be done through several steps. First, it is necessary to detect critical parts of the network, that consist of specific network configurations, such as connections of long underground cables, connection points of renewable resources, connections of gas insulated switchgear (GIS), etc., or of specific geographical characteristics such as cost line, mountain ranges, rocky terrain, etc. Once the sites are detected, equipment for transient monitoring can be installed at those critical points. Meanwhile, the critical points have to be modelled in detail in EMTP, to be able to simulate overvoltages accurately enough. These simulations should include detailed black box models of power transformers, which consider measurements of frequency dependent admittance matrix.

Both transient measurements and EMTP models can provide input for overvoltage database, where data should be stored with time and geospatial marks. Having the database formed, it is possible to achieve the following: overvoltage map, statistics and sample test impulses, overvoltage mitigation measures and long-term system planning and maintenance input. The scheme of the framework is shown in Figure 5.

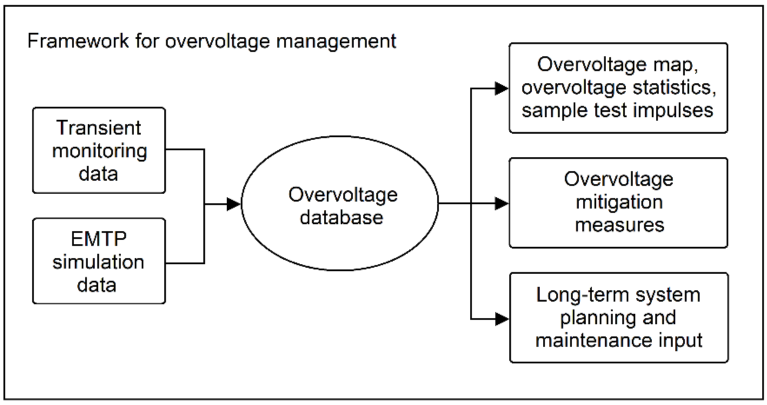

Figure 5. Framework for overvoltage management.

The outputs defined in the framework are related to overvoltage preview, mitigation and long-term planning and maintenance. Overvoltage preview gives a possibility in having an idea of the overvoltage severity in the network. This can be done using overvoltage maps. While the maps show the data spatially, statistics are used to evaluate the overvoltages at different network locations. At the end, the most severe overvoltage waveforms can be used as sample test impulses. Overvoltage mitigation measures consider actions to limit the overvoltages by changing network configuration, by installing additional surge arresters, by installing snubbers, filters, etc., if the data obtained from the database shows that the overvoltages are higher or more severe than the ones used to test the equipment. Long-term planning input considers more accurate specification of needed insulation levels for the high voltage equipment or going beyond standard insulation level and requiring equipment that is capable of withstanding nonstandard waveshapes, as explained in [18]. Overvoltage severity can be used as an input for asset management and intelligence condition monitoring [19].

5. CONCLUSION

The papers presents an integral approach to assessing and handling the specific overvoltages in the power network from the view point of the utility. It considers being able to use advanced EMTP models in order to simulate overvoltages that might appear at the transformer terminals. The results of the detailed EMTP simulation of a lightning strike, presented in the paper, showed good agreement with the measured transients in the power network. In addition, an example of the overvoltage statistics data has been shown for the same transformer unit.

In this paper two segments are detected as inputs for framework for overvoltage management: the overvoltage monitoring and the advanced overvoltage simulations in EMTP. Based on the inputs from these two, the one can have a clear picture about the specifics of the overvoltages that exist not only at the terminals of a specific power transformer but also at the particular substations within the possession of a power utility. Both of these segments are nowadays technically within reach of a modern power utility and can therefore be put into implementation.

Based on this approach and the gathered information it is possible to: have an information about overvoltages that exist in the system, provide overvoltage mitigation measures and improve long-term planning and maintenance of the equipment. All of this can lead to better economic planning and fleet management at the power utility level, and also contribute to increasing the reliability of the equipment and reducing its eventual down-time.

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