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Statistical Analysis of Non-Standard Overvoltage Waveforms Measured at 220 kV Terminals of a Power Transformer

B. Jurisic, B. Filipovic-Grcic, T. Zupan and G. Levacic

***Abstract*--Power transformers are designed to withstand switching and lightning overvoltages which can occur in the power system. The knowledge about waveshapes of these events grows rapidly with the introduction of online transient monitoring systems. Consequently, it is important to compare standard test voltage impulses with the ones existing in the power system. In this paper, 123 measured overvoltages in 220 kV air-insulated substation are analyzed. The observed overvoltages are fitted using double exponential mathematical function. Function parameters are calculated using genetic algorithm. To compare measured signals with the standard ones, statistical analysis of their parameters is performed. Additionally, frequency domain severity factor is calculated for the observed signals.**

***Keywords*: Non-Standard Overvoltages, Lightning, Power Transformer, Statistical Analysis, Genetic Algorithm.**

I. INTRODUCTION

POWER transformers are designed to withstand switching and lightning overvoltages which can occur in the power system, according to the international standards [1]. Therefore, during transformer factory acceptance test, transformer insulation is subjected to different standard impulse waveforms [1], [2]. However, significant portion of transformer failures happen due to various overvoltages, according to the literature [3], [4]. These failures happen since overvoltages that exist in the power system differ from the standard impulse waveforms or the cause of the breakdown lies in the interaction between the power system and power transformers as in the case of resonance. Currently, there is an ongoing CIGRE WG A2.63 that deals with specifying new test impulse waveforms, taking into account new knowledge based on measurement results of different real-case system overvoltages. Different overvoltage waveforms that could exist in the power system, such as switching, lightning and very fast front overvoltage (VFTO) are given in the literature [5]. This paper presents the statistical analysis of an equivalent parameters of overvoltages measured across the 220 kV power transformer bushings during the period of 6 months. The main cause of observed overvoltages were lightnings. The monitored transformer unit is located in Croatia. Similar analysis has been made in China and Japan [6], [7].

In this paper, first the transient monitoring system, used to record overvoltage events is presented. Then, the equivalent parameters of measured overvoltages are presented in chapter 3. In chapter 4, frequency domain severity factor (FDSF) has been calculated for all observed overvoltages [3]. The overvoltages with FDSF higher than 1 are further discussed in chapters 4 and 5. Finally, conclusions are given in chapter 6.

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II. MEASUREMENT OF OVERVOLTAGES IN THE POWER SYSTEM

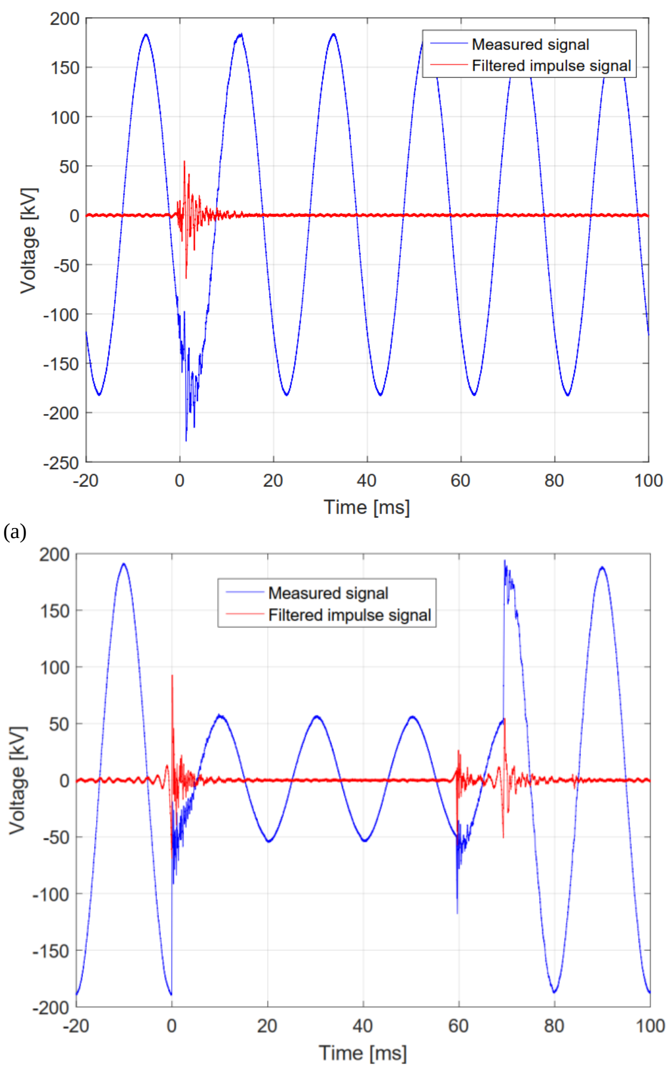
This chapter presents the transient monitoring system, used for online recording of overvoltages. The system measures voltages on a measuring tap of the transformer's high voltage bushing. It consists of specially designed adapter for the connection to the bushing measurement tap, measurement circuit including the matching impedance, capacitance divider, coaxial cables, acquisition unit and associated software [8]. 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 equipment starts logging 0.5 ms before the trigger). 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 [9], [10].

In addition to the overvoltages measured using transient monitoring system, the recorded events are compared with the data from the lightning location system and the data from the SCADA. Similar checks were done before and reported in [11].

III. STATISTICAL ANALYSIS OF OVERVOLTAGE PARAMETERS

In this chapter, a result of the statistical analysis of overvoltages measured on the 220 kV power transformer bushings, during six months period, are presented and compared to the existing values that can be found in literature [6], [7].

The overvoltages are continuously measured in 220/110 kV substation, located in the area with significant lightning activity and high soil resistivity due to the rocky mountain terrain. 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. 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]. 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.



(b)

Fig. 1. Observed voltages and filtered overvoltages.

To calculate the statistical parameters, first, the measured signals are converted to the frequency domain using FFT. Then the frequency content of the signal lower than 500 Hz is filtered by using an ideal filter. A signal is then converted back to the time domain using inverse FFT. Additionally, average filter is applied to the signal in order to filter measurement noise. Two examples of the signal filtering are given in Fig. 1.

In Fig 1.a, overvoltages did not cause short circuit fault, while in Fig 1.b voltage drop in the observed phase can be seen, which means that the short circuit fault occurred. The fault clearance duration is approximately 70 ms, i.e. time needed for the relay protection and circuit breaker to operate. In the case of multiple overvoltages during the same observed event, only the first overvoltage has been considered in the statistical analysis. Only the overvoltages of the phase with the highest amplitude are considered.

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

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

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 [2], 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.

For the purpose of this 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 [6]. However, in the reference [6] it is not clear how the values of α and β are related to the t_h and t_f. There are two possibilities to relate them:

- Using simplified relations (2) and (3), valid only when α << β and k≈1. To retain the correct amplitude, U_a relation (4) can be used. [12]
- Using genetic algorithm to calculate values of k, α and β according to the measured t_f and chosen t_h [13]

$$t_f = 3.243/\beta \tag{2}$$

$$t_h = 0.693/\alpha \tag{3}$$

$$U_a = U_{max}/(e^{-\alpha * t_{max}} - e^{-\beta * t_{max}}) \tag{4}$$

$$t_{max} = \log\left(\frac{\alpha}{\beta}\right)/(\alpha - \beta) \tag{5}$$

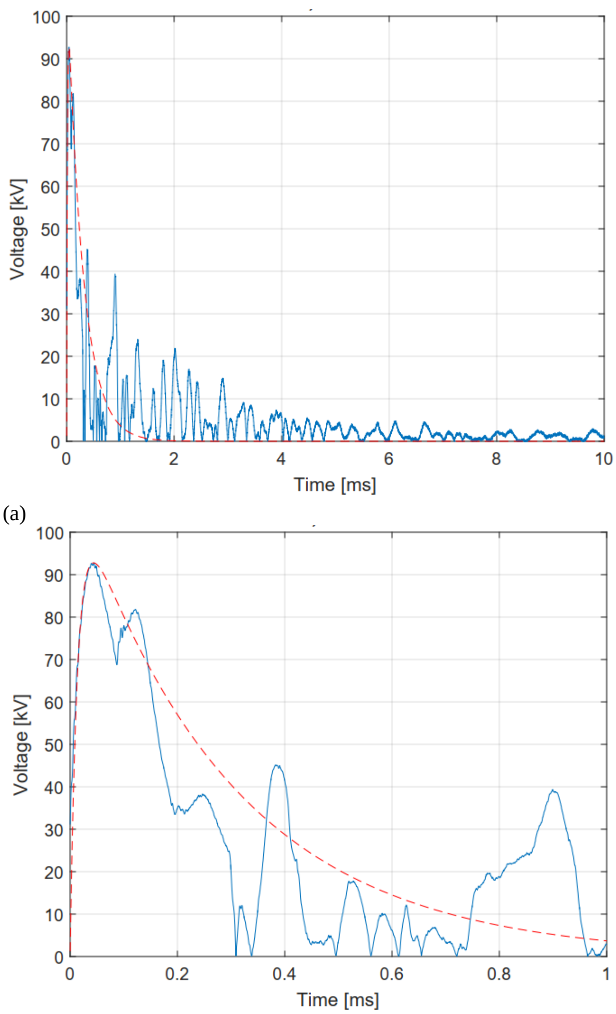
The energy method considers the integral of the observed overvoltage value squared, eq. (6) and comparing it to the integral of the overvoltage described using the expression (1) squared, eq. (7):

$$\int_0^{t_i} U(t)^2 dt, \tag{6}$$

$$\int_0^{t_i} \left(k * A * (e^{-\alpha t} - e^{-\beta t})\right)^2 dt, \tag{7}$$

where t_i is the integration time which is set to 10 ms. The method is iterative and the condition to finish is difference between integrals (6) and (7), which is set to be less than 5 %.

An example of signal comparison, measured and fitted, using the genetic algorithm for mathematical fitting and the energy method to calculate t_h is given below. Allowed fitting error for parameters t_f and t_h, when finding the coefficients of double exponential function using genetic algorithm, is set to 5 % in order to limit processing time.



(a)

(b)

Fig. 2. Example of absolute values of measured (full curve) and fitted signal (dotted curve), using double exponential; (a) is the full signal length; (b) is a detail of the signal during the first millisecond.

For around 20 % of the observed waveshapes, it was not possible to describe them accurately enough using double exponential expression (eq. (1)), since their t_f and t_h values are too close to each other. These waveshapes are excluded from further statistical parameters calculation.

Three different double exponential waveshape parameters can be observed statistically: amplitude, front and tail time. In Fig. 3-5 distribution of waveshape parameters in terms of probability density function estimate is shown. It is assumed that parameters X are distributed according to the log-normal law, $X \sim \text{Log-normal}(\mu, \sigma^2)$ [6]. Log-normal distribution is described using the log-normal probability density function $f(x)$, eq. (8):

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln(x)-\mu)^2}{2\sigma^2}}, \tag{8}$$

where μ representes mean value and σ^2 stands for variance. These parameters are estimated using the maximum likelihood estimator, using expressions (9) and (10):

$$\mu = \frac{\sum_k \ln x_k}{n}, \tag{9}$$

$$\sigma^2 = \frac{\sum_k (\ln x_k - \mu)^2}{n}, \tag{10}$$

where n is the number of observed overvoltages. In the case of the events analyzed in this research, n is equal to 98.

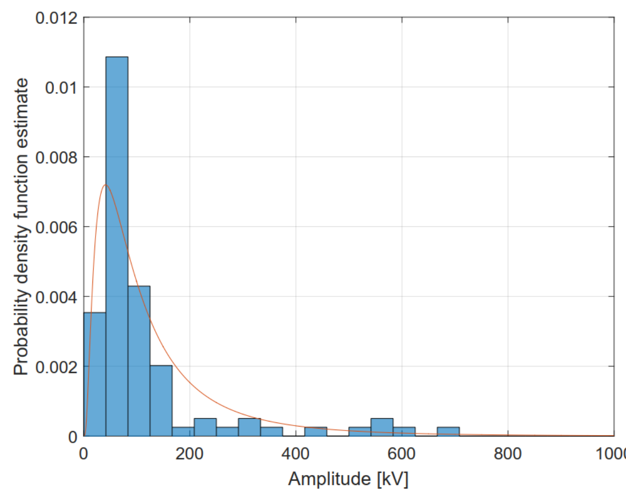


Fig. 3. Amplitude distribution.

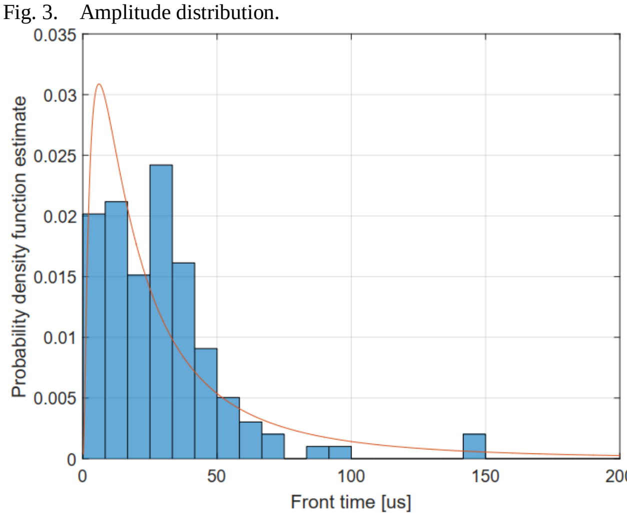


Fig. 4. Front time distribution.

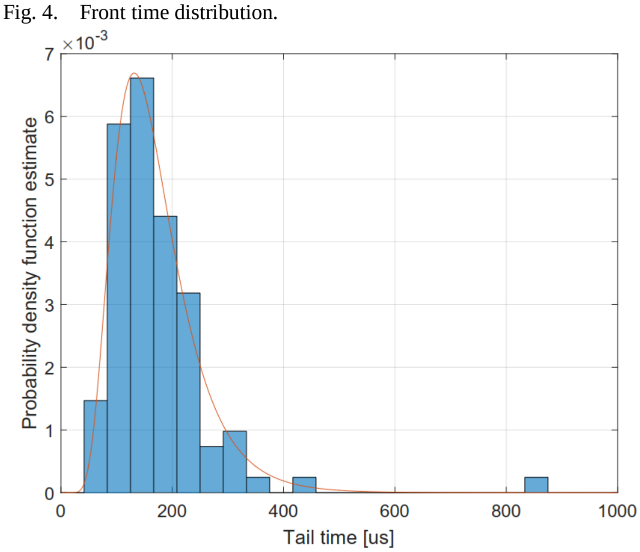


Fig. 5. Tail time distribution.

Probabilities for log-normal distribution are calculated using cumulative distribution functions, eq. (11):

$$F_X(a) = \frac{1}{2}\left[1 + erf\left(\frac{\ln(a) - \mu}{\sqrt{2}\sigma}\right)\right], \quad (11)$$

where a is the value of X for which the probability to be less or equal to is calculated and erf stands for the error function. Calculated statistical parameters and probabilities are given in Tables I and II respectively. Given values are compared to the values from references [6] and [7].

TABLE I
CALCULATED STATISTICAL PARAMETERS.

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
Front time Sima et. all [6] [μs]	3.04	1.05	20.84	2.78
Front time Okabe [7] [μs]	-	-	5.9	-
Tail time [μs]	5.05	0.17	156.44	1.52
Tail time Sima et. all [6] [μs]	5.29	0.87	198.10	2.54
Tail time Okabe [7] [μs]	-	-	36	-

TABLE II
CALCULATED PROBABILITIES OF PARAMETERS.

Parameters	95 % probability	50 % probability	5 % probability
Amplitude [kV]	20.96	92.29	406.30
Front time [μs]	3.49	21.27	129.50
Front time Sima et. all [6] [μs]	3.87	20.84	112.32
Tail time [μs]	78.97	156.44	309.89
Tail time Sima et. all [6] [μs]	42.81	198.12	916.96

It can be seen that the values are in agreement with the values given in the literature [6], where the results are given for lightning overvoltages observed in 110 kV air-insulated substation in China. Differences in tail times can be explained due to the different integration time and fitting technique of double exponential or due to the different substation arrangement. Literature [7] provides different statistical parameters, for direct lightning surge waveforms measured at 500 kV substation in Japan.

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, has to 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.

IV. FREQUENCY DOMAIN SEVERITY FACTOR

As non-standard overvoltages in the power system are mostly oscillatory, it is necessary to observe frequency spectrum of the measured signals. In this chapter a calculation of FDSF and the dominant frequencies is done for all the observed overvoltages.

FDSF compares the frequency spectrum of the measured waveshape with the impulse test waveshape envelope [3]. If the factor has value higher than 1, it means that transformer is not tested for such waveshapes. It is important to note that even though the transformer has not been tested for the particular waveshape, it does not mean that it is not capable to withstand that waveshape. Transformer manufacturers have extended experience in transformer manufacturing and their insulations are designed to operate for several decades, which means that they have safety factors included in the insulation design.

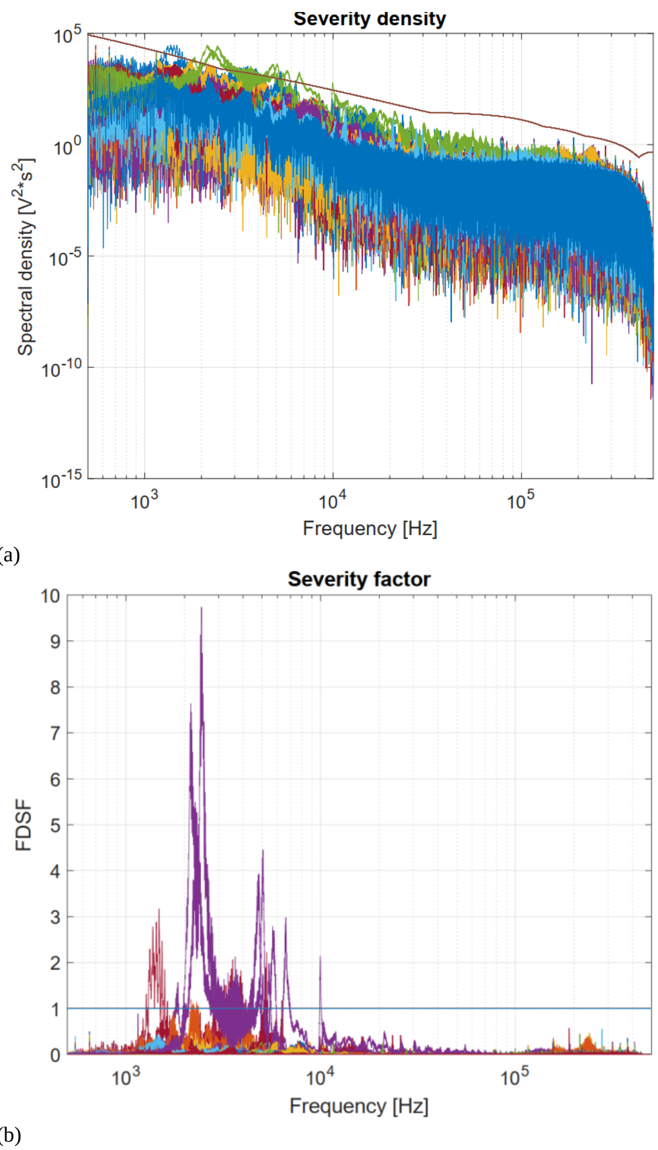


Fig. 6. Frequency energy spectrum (a) and FDSF (b) calculated for observed 123 overvoltages.

In Fig. 6 a frequency energy spectrum and the FDSF are given for all of the observed overvoltages. Envelope for the calculation of FDSF is calculated for 220 kV transformer with test voltages equal to: 1050 kV (full lightning impulse), 1155 kV (chopped lightning impulse), 850 kV (switching impulse) and 460 kV (applied voltage), i.e. highest values for the equipment with 245 kV nominal voltage level according to IEC Standard [1]. Frequency spectrum and FDSF are given for the frequency range from 500 Hz up to 500 kHz.

From Fig. 6, it can be seen that only five out of 123 overvoltages have FDSF higher than 1 and at frequencies lower than 10 kHz. It is important to note that these overvoltages did not cause any permanent damage to the power transformer.

Impulses with FDSF higher than one are analyzed further using data from SCADA and lightning location system. Four out of five analyzed overvoltages are caused by lightning activity. These cases can be correlated using time logging. Only one analyzed overvoltage did not cause insulator flashover on overhead line and consequently a short circuit. All the observed insulation failures were temporary. An example of insulation breakdown fault followed by three phase short circuit to the ground has been shown in Fig. 7. From the figure, it can be seen that the first overvoltage originated from lightning and it did not cause any failure. Then, the second lightning caused the insulation breakdown and consequently the three-phase short circuit to the ground. Approximately 60 ms after the fault, circuit breakers operated and cleared the fault. 260 ms after the fault clearance automatic reclosure happened.

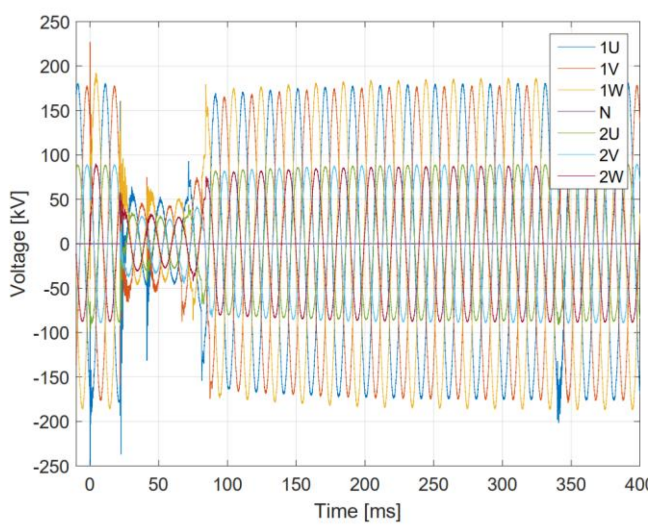


Fig. 7. Overvoltage caused by lightning activity followed by three phase short circuit.

The details of the waveshapes captured by transient measurement system can help in better understanding of the overvoltages and their occurrence at the particular point in the power system.

From frequency spectrum, the main oscillation frequency can be extracted as the frequency at which the observed signal's energy spectrum is highest. Distribution of the main oscillation frequency is shown in Fig. 8. It can be seen that most of the observed overvoltages have this frequency in the range up to 10 kHz (similar as in [6]) while some of them have it in the range from 180 - 380 kHz.

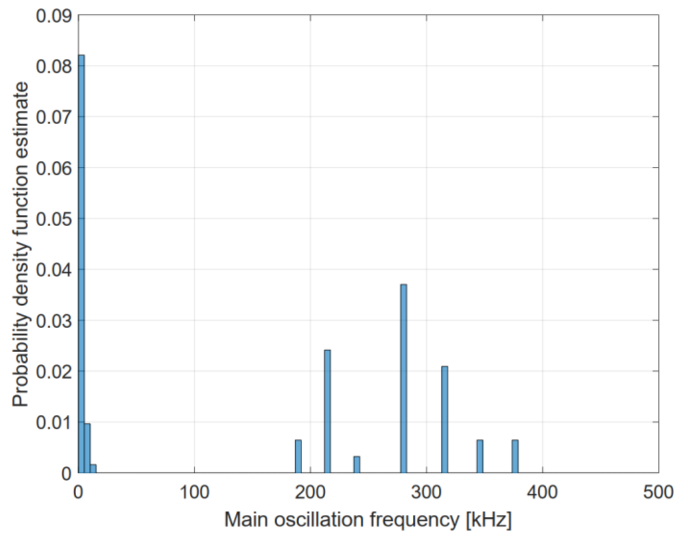


Fig. 8. Distribution of the oscillation main frequency.

V. Discussion

The bidirectional shape of the measured overvoltage signals is observed in this paper which is similar to research [6]. The reason for such waveshape are the reflections between different parts of the substation and transmission line. Statistical parameters of the overvoltage waveshapes that enter the substation and occur at transformer terminals differ from the test impulse parameters, specified in the standards. Most likely overvoltage to occur, in the observed cases, has longer front and tail time than 1.2/50 µs wave. This, however, does not mean that the overvoltage stresses on internal transformer insulation that occurs in the power system are neither lower nor higher than the ones in the case of standard 1.2/50 µs wave.

The oscillatory waveshape caused by electromagnetic wave reflections has relatively low dominant frequency, which can be close to the natural frequency of the transformer winding and can cause internal resonance. Therefore, it is necessary to monitor and measure such overvoltages and to analyze its frequency content. This can be done using FDSF, as shown in the paper. The disadvantage of FDSF is that it cannot provide information about the local dielectric stress inside the transformer. To calculate these voltages, it is necessary to use detailed white box transformer models [14]. Consequently, it can be used just as an indication that the transformer is stressed with overvoltages for which it was not tested and that it may fail because of it. One additional information that can be extracted from the frequency spectrum of the observed overvoltages is the oscillation's main frequency. This frequency should not be close to the transformer's winding natural frequency as it may cause internal resonance.

VI. Conclusions

With the advancement of online transient monitoring systems, the knowledge about overvoltage waveshapes that exists in the power system grows rapidly. This knowledge is important in order to reduce the transformer failure rate through better transformer specification and insulation coordination as well as for detecting the problems in the power system due to local system specifics such as resonance frequency.

In the paper, the measured overvoltages at 220 kV terminals of power transformer are presented. Overvoltages are measured during a six-month period in the area with high lightning activity and high value of ground resistance. In total, 123 overvoltages are observed and analyzed. Most of the measured overvoltages are bidirectional and oscillatory due to reflections between different parts of the power system.

Measured overvoltages are filtered and fitted using double exponential mathematical function. Rise time and amplitude are taken directly from measurement results, while tail time is calculated using energy method as explained in the paper. Double exponential coefficients are found using genetic algorithm. 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. This is in line with the values from [6]. It is shown that for at least 95 % of the observed overvoltages, standard lightning impulse 1.2/50 is on the safe side, if amplitude and front time are observed. These findings have to be carefully interpreted as the possibility for the impulse that is not covered by the standards to exist is not negligible.

In addition, frequency domain severity factor (FDSF) is calculated for each measured overvoltage. It is shown that five out of 123 overvoltages have FDSF higher than 1 in the range up to 10 kHz. Main oscillation frequency is calculated as well and for most of the observed waveforms this frequency is in the range up to 10 kHz, which coincides with FDSF.

In the future analysis, it is planned to further expand the number of the measurements taken into account for statistical analysis and to find the correlation between different parameters, i.e. amplitude and front time or front and tail time.

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