Journal of Energy

VOLUME 69 Number 3 | 2020 | Special Issue

journal homepage: http://journalofenergy.com/

Overvoltages & Transients Identification In On-line Bushing Monitoring

Wieslaw Gil[1], Wiktor Masłowski[1], Przemysław Wronek[1]
[1]Mikronika sp. z o.o. Poznań, Poland
E-mail: wieslaw.gil@mikronika.com.pl

***Abstract*—Overvoltages and transients are sometimes recognized as the cause of bushings' rapid failure. This fact is confirmed by the studies published at the 2018 CIGRE session. They can also initiate dangerous resonance phenomena in transformer windings. The identification of very fast overvoltages characterized by high dynamics of voltage changes, so-called "transients", is difficult due to the limited frequency response of station voltage transformers. However, the bushing monitoring systems, based on the so-called "voltage method" can be used for this purpose successfully. There are several running bushing monitoring systems based on this method in Poland. The transients' events are registered together with their oscillographs in Transformer Monitoring Systems (TMS). The overvoltage statistics are also performed to support service procedures. The TMS are integrated with station systems, which greatly increases the possibility of overvoltages' phenomena analyzing.**

***Index Terms*—transients, overvoltages, on-line bushing monitoring, voltage method**

I. SWITCHING DISTURBANCES AND TRANSIENTS IN STATIONS‘ INFRASTRUCTURE

In 2015, CIGRE working group WG A2.37 published the brochure 642 [1], which presented statistics of overvoltages' and transients' impact on bushings installed in reactors and power transformers. The influence on bushing insulation of high-speed transients 1/50µs was also one of the topics discussed during the CIGRE session in Paris, in August 2018.

Overvoltages arising as a result of switching phenomena, lightings, groundings and other power failures in power lines affect the transformers' and reactors' bushings and winding insulation. The voltage values during such disturbances can reach voltage levels comparable to the test values for these devices.

During switching disturbances, very fast resonance waveforms featuring rise times even below 1 µs and multi thousand voltage changes are sometimes occurring. This undoubtedly causes partial discharges occurrence. They can also be the reason for particularly dangerous resonances in the transformer windings, which can lead to the winding insulation damage and internal short circuits [2]. Therefore, overvoltages can shorten bushing lifetime or even induce their rapid failures. They degrade insulation condition of a transformer or a reactor. Atmospheric lightings cause a different problem and their impact should be effectively limited by properly designed stations' lightning protection.

Therefore, it is necessary to monitor the fast overvoltages and transients occurrence in the power grid, assess their impact on the infrastructure condition and take remedial measures. However, identification of disturbances is problematic. The stations' voltage measuring transformers feature a limited frequency response, typically up to 50 harmonics. It is sometimes possible to transfer a signal up to 10kHz, but it is not enough for transients.

Identification and recording of fast overvoltage disturbances like transients, set a technical challenge. Input filters, measuring transducers and parameterized recorders triggers must be adapted to identify and record fast disturbances.

The data connected with network disturbances have a high economic significance. It can be used to improve the asset management but also to provide relevant information in resolving warranty or other disputes. Therefore, data protection and establishing the secure access rules to the collected statistics in the TMS can set a big challenge.

Fast overvoltages and assessment of their impact on bushing durability and reliability are rising an increasing interest, supported by statistics of occurring failures. At several power stations of Polish Transmission Operator PSE S.A., on-line bushing monitoring modules were installed [3]. They are identifying and recording voltage disturbances, including fast transients, caused by station switching operations and those reaching these stations from external lines as well.

Such modules were also installed in TMS in newly launched power plants. They enable phenomena identification caused by disturbances in circuit breakers operation and assessment of their impact on the bushing condition.

The authors profusely thank the Employees of PSE S.A. and Operation of Power Plants. They shared waveforms & registrations presented in this work. It should also be noted, that the presented data is for reference only and do not relate to any specific equipment or time

II. VOLTAGE METHOD

The measuring principle of the mentioned systems is based on the so-called voltage method of on-line bushing monitoring [4]. The method has not been widely used due to difficulties with accurate measurement of phase angles of voltage vectors at the bushing measuring taps. This resulted in an inaccurate tgδ estimation. Recently, these problems have been overcome by taking into consideration momentary line voltage asymmetry and synchronizing the measurement time. The advantages of this method are also confirmed by the results of analyses considering the possibility of measuring the higher harmonics of line voltages in bushing monitoring systems [5]. The capacitive probes installed in the bushings' taps make the basic component of the measuring system, as shown in Fig. 1. The measuring principle of this probe is illustrated in Fig. 2

Wieslaw Gil, Wiktor Masowski, Przemysaw Wronek, Overvoltages & Transients Identification In On-line Bushing Monitoring, Journal of Energy, vol. 69 Number 3 Special Issue (2020), p. 20–24
https://doi.org/10.37798/202069340

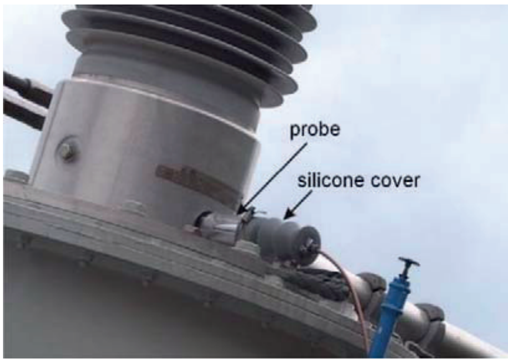


Figure 1: The probe installed in bushing measuring tap

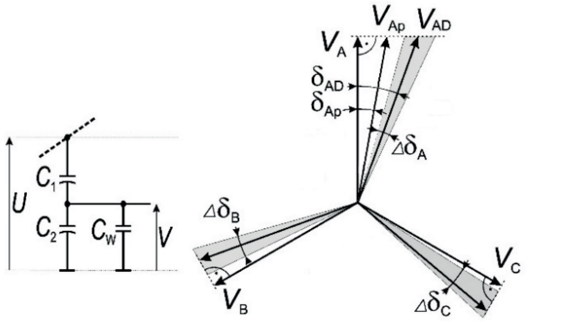


Figure 2: The capacitive probe operation principle and relative *tgδ* assessment

The C_w capacitor shown in Fig. 2 and the capacity C1 form a capacitive divider of the line voltage U supplied to the bushing. This capacitor is selected in connection with the voltage V at the measuring tap, which should amount to about 20 VAC. For example, the C_w = 800nF is selected for probes installed in 110kV bushings. The C_w capacitor, installed inside the probe together with overvoltage protection systems shall have a very good temperature stability.

Knowing the linear voltage module U, which is measured by the reference transducer and the capacitance C_w in the voltage module V, measured by the specialized converter, allows to assess the C1 capacitance. The tgδ assessment with the use of the relative voltage method is based on a precise measurement of the position and relative angle changes of individual phase voltage vectors. The current values of the angles are determined on this basis. It is assumed that in the phase in which phase angle changes have occurred, the dielectric properties of the bushing have also been changed. Then, the current tgδ coefficient is based on the new phase angle evaluation.

In the example shown in Fig. 2, the triangle of voltage vectors V_A, V_B, V_C, measured at the measuring taps of individual phases *A*, *B*, *C*, illustrates their initial position. Assuming, that a change had happened in the dielectric properties of the bushing phase *A*, then the V_A vector took a new V_{AD} position, which is determined by the angle δ_{AD}. The change of this angle was set in relation to the angle δ_{Ap}, resulting from the value of $tg\delta_{Ap}$ - measured after the installation of the TMS. The fluctuations $\Delta\delta_A$, $\Delta\delta_B$, $\Delta\delta_C$ of phase voltage vectors, caused by phase voltage asymmetry are also illustrated.

The voltage method, in addition to the C1 and tgδ factor assessment, allows the identification and recording of instantaneous values as well as RMS waveforms of overvoltages affecting the bushing. The V_A, V_B, V_C voltage vector modules are directly available in the measurement system, so they can be registered and archived in the bushing monitoring module along with other bushing parameters.

III. ON-LINE BUSHING MONITORING

The devices and structure of on-line bushing condition monitoring is presented in Fig. 3. Voltage signals from the measuring probes are connected to the Monitoring Module which performs required calculations and local data storage. The basic function of the installed equipment is to determine accurately the value of C1 capacitance and the value of the dielectric tgδ losses factor of the bushing in which the probe is installed.

For this purpose, the reference values of the measured relevant phase voltages from the Reference Unit are transmitted to the Monitoring Module by the IEC 61850 communication protocol. The work of both units is synchronized to GPS signal. The bushing capacity is determined with absolute uncertainty up to 1pF. The algorithm implemented in the Monitoring Module corrects the calculation errors resulting from a phase voltage asymmetry and estimates tgδ changes with absolute uncertainty 0.05%.

It is worth to comment, that the tgδ is an unnamed value in range 0,002 to 0,015 for not degraded high voltage bushings, depending on the manufacture technology. Traditionally, for convenience, it is expressed in arbitrary “percentage” units, after multiplying by 100. In this convention, the above typical values are from 0.2% to 1.5% respectively. The 'conventional percentage unit' has been used for many years in IEEE standards as well as in numerous articles. "Percent" values are also often used in bushings test reports. For this reason, it is justified to provide in this article an absolute uncertainty values, also in “percent”, discussing the quality of the tgδ coefficient measurements.

The principle presented in Fig. 3 is modified in power plants applications. The reference voltages U_A, U_B, U_C are connected directly to the Monitoring Module, where voltages from the bushing probes are also measured. This is possible due to relatively small distance of voltage transformers from the measuring system installation. Thanks to such solution, the equipment structure is simplified and the tgδ is determined with absolute uncertainty better than 0,05%.

Scaling of the measurements plays a very important role in the presented solution. It is performed after the equipment installation and the application of voltages. Then, the deviations resulting from the voltage vectors phase shifts in voltage transformers are compensated. The indication differences resulting from the C_2 capacitance influence and the C_w capacitors deviations from their nominal values are also trimmed automatically.

Station disturbances are characterized by high variability and dynamics. To trigger overvoltage recording, a threshold input with configurable hysteresis was implemented in wide measuring range. The change detection mechanism functions also in a parallel way. The voltage change is identified as a fast voltage disturbance when the programmable thresholds conditioning the triggering of the recording are exceeded or if the voltage change has the appropriate speed.

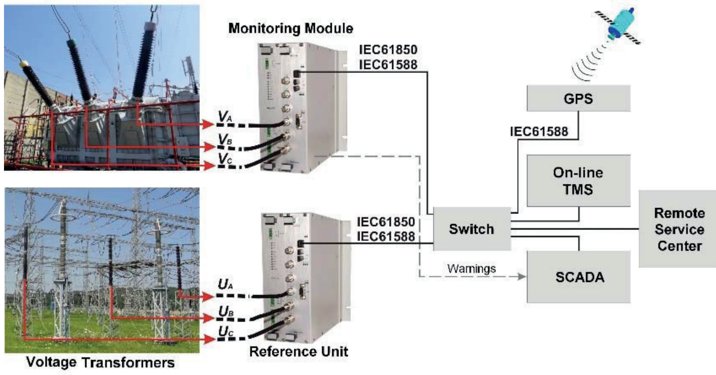


Figure 3: Structure of on-line bushing monitoring

TABLE I. RECORDER THRESHOLD FOR VARIOUS BUSHING NOMINAL VOLTAGES

Input signal & thresholds [kV]	**Busihing nominal voltage [kV]**		
	110	**220**	**400**
Signal range	280	560	1000
Detecting and recording threshold	140	279	488

Information about the surges along with information about the time of their occurrence is transmitted on-line to TMS as events with the transients oscillograph recordings and RMS waveforms in the COMTRADE standard files. Possible warnings and alarms created by TMS are directed to the SCADA station system. Expert access to the collected data in the monitoring server is possible from the Remote Service Center or through website secured mechanisms

IV. IDENTIFIED AND REGISTERED DISTURBANCES

Fig. 4 shows a recording example of a shortage disturbance that occurred on a 400kV line. A voltage peak exceeding 500kV triggered the recording after reaching the 488kV phase voltage. Subsequent oscillations and rapid voltage changes are placed on the first harmonic waveform.

Recently, bushing monitoring modules have been launched along with the identification and registration of overvoltage in newly built power plants in Poland. They give the opportunity to identify and thus eliminate the occurrence of dangerous phenomena, that may have a negative impact on the operation of block and reserve-start transformers. Fig. 5 shows an example of recording of switching overvoltage and resonance phenomena recorded on bushings when closing a 400kV circuit breaker during a put in operation.

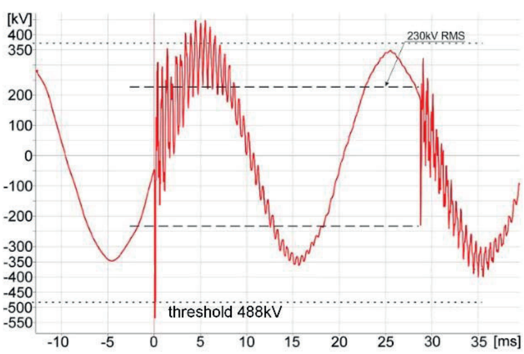


Figure 4: Shortage disturbance on 400kV line

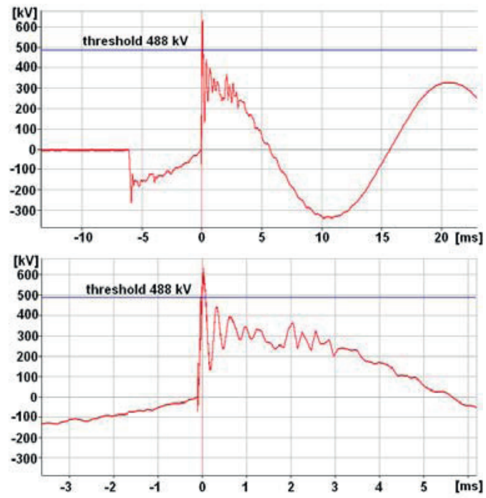


Figure 5: Switching overvoltage on 400kV line

Fig. 6 shows overvoltages caused by asynchronous switching of the 400kV line circuit breaker. A lightning discharge is probably a cause of the "transients" disturbances which are shown in Fig. 7. Nonlinear waveforms, visible in the initial phase in both above registrations, consist of many several hundred kilohertz oscillations. They significantly exceed the 500kV level and overlap the harmonic components. Oscillations of this type can generate partial discharges in bushings and transformer solid insulation. They are visible after enabling the "zoom" function in the program visualizing the recorded waveforms. A TMS analyzer of graphic images is used to observe and analyze these disturbances.

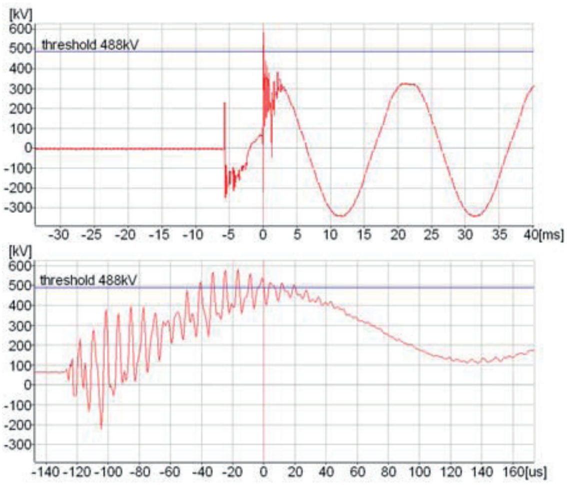


Figure 6: Asynchronous switching of the 400kV line

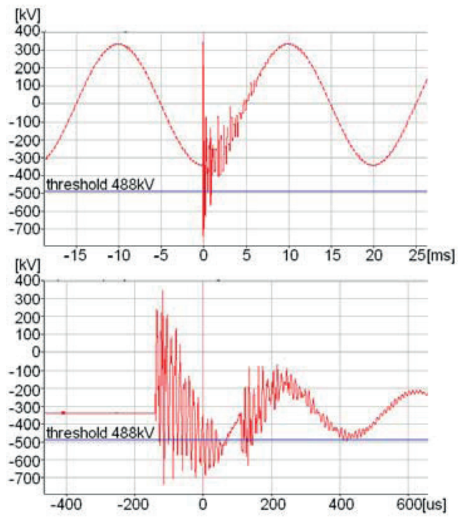
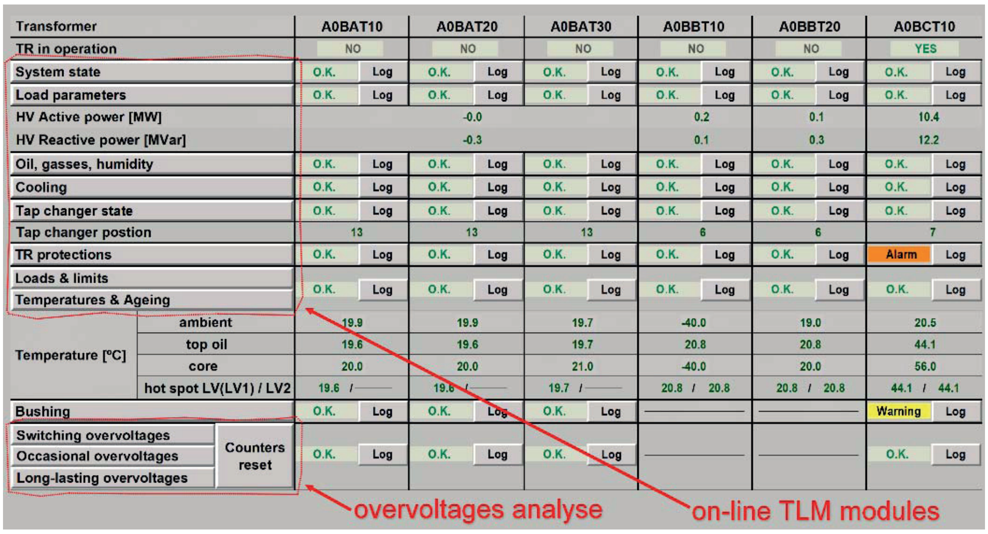


Figure 7: Transient overvoltage in 400kV line.

V. OVERVOLTAGE ANALYSES

The overvoltage identification and evaluation module should function as one of the TMS on-line modules. Such solution allows to correlate the collected statistical information about overvoltages and transients with other monitored parameters. It may be the data connected with partial discharges and related to the discharges gasses occurrence as well as rapid changes in capacitance C_1 of the bushing.

Fig. 8 shows the solution to this problem in the TMS of block transformers in the newly built power plant. The operation of the overvoltage analysis module can be verified on the main system screen. If necessary, individual overvoltage counters and waveforms can be analyzed and detailed reports can be performed. Any data analysis can also be obtained. The analysis can combine for example, recorded transients with data from the bushing monitoring module, as well as the moisture and gas in oil analyzer.



Transformer		A0BAT10	A0BAT20	A0BAT30	A0BBT10	A0BBT20	A0BCT10
TR in operation		NO	NO	NO	NO	NO	YES
System state		O.K. Log	O.K. Log	O.K. Log	O.K. Log	O.K. Log	O.K. Log
Load parameters		O.K. Log	O.K. Log	O.K. Log	O.K. Log	O.K. Log	O.K. Log
HV Active power [MW]		-0.0			0.2	0.1	10.4
HV Reactive power [MVar]		-0.3			0.1	0.3	12.2
Oil, gasses, humidity		O.K. Log	O.K. Log	O.K. Log	O.K. Log	O.K. Log	O.K. Log
Cooling		O.K. Log	O.K. Log	O.K. Log	O.K. Log	O.K. Log	O.K. Log
Tap changer state		O.K. Log	O.K. Log	O.K. Log	O.K. Log	O.K. Log	O.K. Log
Tap changer postion		13	13	13	6	6	7
TR protections		O.K. Log	O.K. Log	O.K. Log	O.K. Log	O.K. Log	Alarm Log
Loads & limits / Temperatures & Ageing		O.K. Log	O.K. Log	O.K. Log	O.K. Log	O.K. Log	O.K. Log
Temperature [ºC]	ambient	19.9	19.9	19.7	-40.0	19.0	20.5
	top oil	19.6	19.6	19.7	20.8	20.8	44.1
	core	20.0	20.0	21.0	-40.0	20.0	56.0
	hot spot LV(LV1) / LV2	19.6 /	19.6 /	19.7 /	20.8 / 20.8	20.8 / 20.8	44.1 / 44.1
Bushing		O.K. Log	O.K. Log	O.K. Log			Warning Log
Switching overvoltages / Occasional overvoltages / Long-lasting overvoltages	Counters reset	O.K. Log	O.K. Log	O.K. Log			O.K. Log

Figure 8: Overvoltage analysis in TMS

Overvoltages evaluation is carried in the implemented systems out. There are several types selected, as shown in Fig. 8. When an overvoltage from a given range is identified, then the value of the corresponding counter is increased. Overvoltages exceeding the threshold level parameterized for the assumed power network are identified. A distinction is made between overvoltages of less than 50μs duration and overvoltages of 50μs to 200 ms duration - so-called switching overvoltages. Overvoltages with a duration between 200ms and 1sec and between 1 sec and 10 sec are classified as temporary. Overvoltages with a duration exceeding 10 seconds are included in the category of long-term overvoltages.

Fig. 9 shows a solution for transients monitoring used in bushing monitoring modules, implemented in newly built power plants. Overvoltages for power output transformers, i.e. BAT10, BAT20, BAT30, cooperating with generators and for the BCT self-needs autotransformer have been collected.

Wieslaw Gil, Wiktor Masowski, Przemysaw Wronek, Overvoltages & Transients Identification In On-line Bushing Monitoring, Journal of Energy, vol. 69 Number 3 Special Issue (2020), p. 20–24
https://doi.org/10.37798/202069340

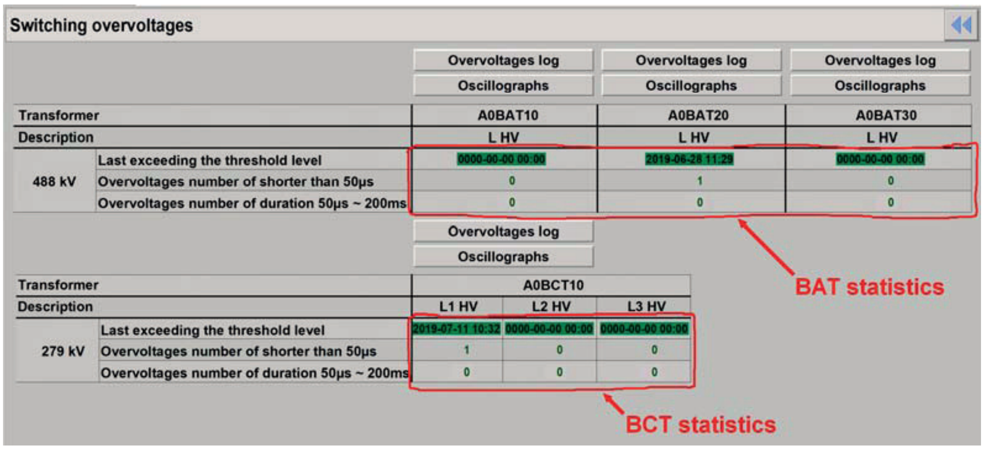


Figure 9: Switching overvoltage statistics

The system allows to create and analyze statistics of selected overvoltages, an overvoltage event log together with the time of occurrence of individual phenomena and individual disturbance oscillograms. The time of events such as exceeding the level of lightning protection, tgδ warning level, value of capacitance C_1 and other parameters are also recorded.

TMS with an installed overvoltage monitoring module can record and analyze overvoltages and transients on transformers and reactors which are caused not only by any switches at the station, but also those resulting from external disturbances. Therefore, overvoltage assessment should be able to determine the direction of disturbances. The implementation of an event registration mechanism for such disturbances gives the opportunity of system integration with other station systems, including the power quality assessment.

VI. CONCLUSIONS

Bushing on-line monitoring systems, based on the so-called voltage method, identify and record overvoltages, including transient overvoltages.

Identification, recording and analyses of overvoltages should form another functional module of the on-line TMS. It facilitates the performance of analyses and finding relationships between fast overvoltages and signals regarding, for instance, bushings, moisture & gas in oil analyzer and partial discharges.

The shape and level of recorded transient analysis can provide information on the status of lightning protection functioning at the station. Correlation of overvoltage events with changes in bushing insulation rates can provide valuable information in on-line bushing monitoring systems.

On-line bushing monitoring modules should collect statistical information regarding the type and size of overvoltages. Such information may support the decision about service performance, changes of operating conditions or the component replacement. However, access to this information is subject to special security protection and restrictions due to potential economic and legal significance. The above information may be crucial in the analyses of causes of failures and in the settlement of warranty disputes.

VII. REFERENCES

[1] CIGRÉ WG A2.37, "Transformer Reliability Survey", Brochure 642, Paris, 2015.

[2] E.Anderson, J.Karolak, J.Wiśniwski, "Internal Overvoltages in Transformer Windings", Przegląd Elektrotechniczny, ISSN 0033-2097, r. 90 Nr 1/2014.

[3] W.Gil, W.Grzybowski, P.Wronek, "The Expert Transformer Monitoring System in Substation Structure",International Conf. on High Voltage Engineering, ICHVE 2010, New Orleans, 11-14 Oct.2010, publ. IEEE Xplore, ISBN 978-1-4244-8283-2.

[4] Stirl T., Skrzypek R., Tenbohlen S., "On line condition monitoring and diagnosis for power transformers their bushings, tap changer, and insulation system", CMD 2006, Changwong, Korea.

[5] S.Tenbohlen, C.Kattmann, T.Brugger,…"Power Quality Monitoring in Power Grids focusing on Accuracy of High Frequency Harmonics", C4-122, CIGRE 2018, Paris.