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Fleet Asset Management Opportunities Arising from Transient Monitoring of Power Transformers and Shunt Reactors

SUMMARY

Power transformers and shunt reactors are strategic assets for every system operator and their downtime should be kept as low and controlled as possible. During their multi-decade service life, they are regularly exposed to transient overvoltages. These situations stress their insulation systems and can cause accelerated deterioration and aging. Since the shapes of these overvoltages are usually unknown, an additional approach to assessing the health index can be realized using monitoring systems with transient recorders. Analyzing the transient overvoltages using frequency domain severity factor, a quantification of additional stress on the transformer's/shunt reactor's insulation can be given. This can help in assessing the current state of the insulation system and can lead to more advanced fleet asset management.

KEYWORDS

transformer transient monitoring system, overvoltage stress, frequency domain severity factor, health index estimation, fleet asset management

INTRODUCTION

Power transformers and shunt reactors are subjected to various dielectric stresses during their service life [1]. These stresses are always caused by external factors such as switching operations or atmospheric discharges. Such repeatable stresses cause insulation degradation of the high voltage equipment which can consequently lead to their failure [2]. Since power transformers and shunt reactors are strategic assets in transmission and distribution network, their unplanned downtime can cause substantial financial loss. Therefore, it is necessary to monitor these transient events within a transmission system and possibly assess their long-term impact on installed strategic equipment.

As the transients that occur in the power network differ from the standardized test impulses, monitoring systems can be used to broaden the knowledge about the waveshapes and amplitudes of the overvoltages that can occur in the network and stress the units in the grid. This is in line with the current discussions within the CIGRE about the nonstandard waveshapes for the impulse testing. High frequency transformer models can help in evaluating the impact of nonstandard impulse waveshapes on the transformer or reactor insulation, especially in the case of the units already installed in the power network.

In this paper, a brief overview of the existing transformer transient monitoring systems is given first. Then a validation of the transient monitoring system with the measurements done in the high voltage laboratory for various voltage levels and shapes is shown. Finally, the possibilities of transient monitoring system in transformer fleet asset management is addressed using the Frequency Domain Severity Factor (FDSF).

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TRANSFORMER TRANSIENT MONITORING SYSTEM

Monitoring systems are installed across numerous locations around the globe. All modern-day systems should have, apart from the measured quantities, the algorithms for parameter estimation and trend comparison of current values with the predictive models. Monitoring the transformer transients is currently the state of the art of advanced transformer monitoring systems.

Extensive experience of continuous monitoring of transients in the power system shows that the measured data can be correlated with the lightning location system data and to the SCADA events [3]. Moreover, the data collected from the transformer fleet can be used to assess the real conditions in the power network and to help in deciding the equipment parameters and coordinating the insulation level for the future power transformers and reactors that will be installed at the same or similarly stressed nodes in the network. It is possible to take into account the observed transients when assessing the health index of the transformer which has an impact on network reliability. This can, in turn, lead to technically successful and economically sound fleet asset management.

A common approach is to measure voltage transients across the bushing measuring taps of power transformers or reactors [4]. A special bushing tap adapter and measuring impedance need to be designed in order to accurately transfer the overvoltage amplitude and shape to the low voltage side. This needs to be valid for the whole frequency range of interest, which is usually up to 1 MHz for the air insulated substations. Currently, several commercially available transformer monitoring systems that are capable of measuring and recording transient activities exist. In this paper, Končar TMS+ system was used. The most recent versions of such system can record transients at up to 16 channels with the sample rate of 4.5 MS/s and recordings up to 7 seconds long.

PERFORMANCE CHECK OF TRANSIENT MONITORING SYSTEM

In this chapter a verification of the transient monitoring system has been described. The verification has been done both in frequency and in time domain. Furthermore, the real case overvoltage examples from the real power network are presented.

Verification of System in High Voltage Laboratory

In order to be certain that the high-to-low voltage bridge does not influence the measured overvoltage signals, the frequency response of the measurement circuit needs to be checked. This was done using the vector network analyser Omicron Bode 100. The voltage ratio between the high voltage bushing connection and the bushing test tap needs to be as linear as possible for the frequencies of interest.

The object under test was Končar OTF 1050/245 kV bushing with C_1=326 pF and C_2=362 pF. The measurement configuration (bushing, bushing test tap, connection of coaxial cables to the top of the bushing, measuring impedance of TMS+ system connected to the test tap) and the measured results are shown in Figures 1 and 2, respectively. As expected, the frequency response of the test circuit remained stable until 1 MHz.

Figure 1: Electrical circuit configuration for frequency response check of the Končar TMS+ measuring system.

Once the validation of the measuring device has been done in the frequency domain, it is necessary to validate the whole transient monitoring system on the real transformer or shunt reactor. For the purpose of this paper, a 100 MVAr 220 kV variable shunt reactor (VSR) is used as a test object. Insulation level of the reactor is SI 750 kV, LI 950 kV, LIC 1045 kV, AC 395 kV, U_m 245 kV.

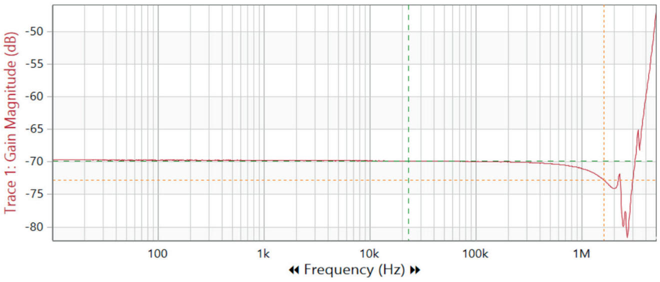


Figure 2: Frequency response of the Končar TMS+ measuring system.

During the lighting impulse test of the shunt reactor, the voltages are observed in parallel using the transient monitoring system in addition to measurements done using the voltage divider as is normally done in the high voltage laboratory during the impulse testing. The test sequence consisted of several different switching, lightning and chopped impulses (SI, LI and LIC) with different voltage amplitudes [5], [6]. In continuation, the comparison between signals measured using voltage divider and the transient monitoring system is shown.

Figure 3: TMS+ system (a) installed in a 100 MVAr 220 kV VSR (b).

From Figures 4-6, it can be seen that the transient monitoring system accurately measures the standard test impulses, with the exception of the fast oscillations after chopping during LIC. This is expected since the inductances in the measuring circuit of the monitoring system are limiting the change rate of the signal thus causing the slight error at higher frequencies. It is important to note that all the impulses are observed on the same reactor phase L2 and the multiplier remained constant throughout the test. 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.

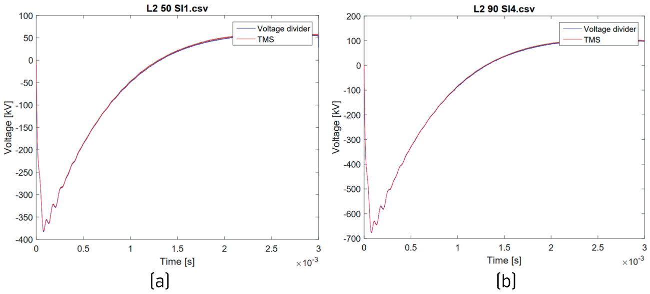
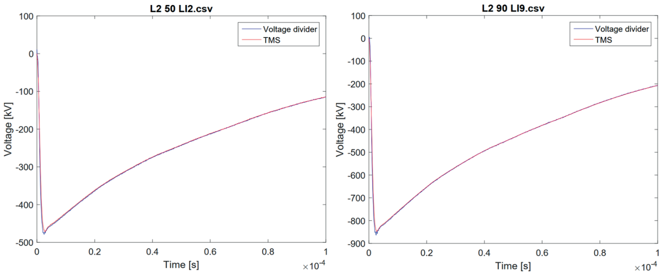
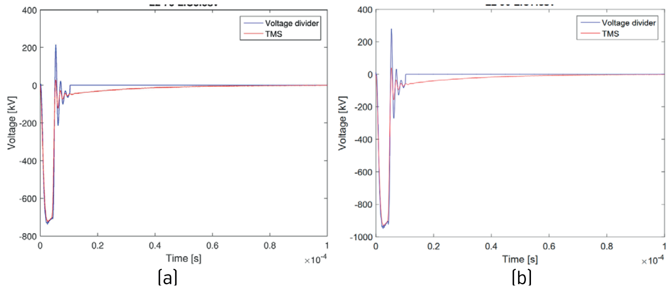


Figure 4: SI waveform comparison - voltage divider vs transformer monitoring system: (a) SI 50 %, (b) SI 90 %.



[a] [b]

Figure 5: LI waveform comparison - voltage divider vs transformer monitoring system: (a) LI 50 %, (b) LI 90 %.



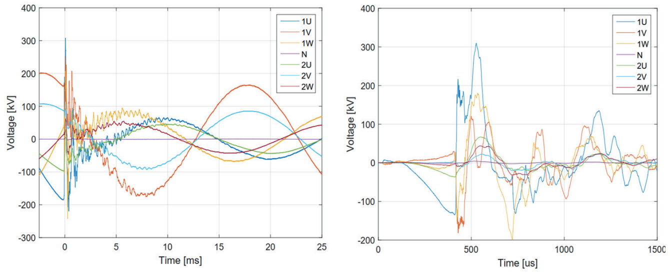
[a] [b]

Figure 6: LIC waveform comparison - voltage divider vs transformer monitoring system: (a) LIC 70 %, (b) LIC 90 %.

Real Case Overvoltage in the Power Network

Generally, overvoltages in power network can be caused by lightning strikes to overhead transmission lines, circuit breaker switching operations and faults. Power transformers can be exposed to such transients during their operation. Overvoltages with steep wave front have an impact on dielectric stress of the transformer's insulation. This can manifest either on the first few windings' turns or, in the case of the internal resonance, the voltage can build up locally inside the winding. The number and amplitude of overvoltages which stress the insulation depend on various parameters, such as the lightning strike density in the considered area, since it determines how often the transformer could be stressed by lightning overvoltages. Since the overvoltage amplitudes at transformer terminals are usually unknown, an on-line overvoltage transient recorder is used with the ability to sample, analyze and store these transients in real-time.

In this paper, three different cases of the overvoltages observed on bushings of a 220/110 kV 150 MVA transformer unit are shown. In Figures 7 and 8, phases are labeled as U, V and W, and "1" and "2" correspond to HV and LV sides, respectively. As the transformer unit is situated in the area with high ground flash density, all three overvoltages were caused by the lightning strikes. In the case 1, double phase to ground fault occurs in the phases U and W as shown in Figure 7 (a) [7].

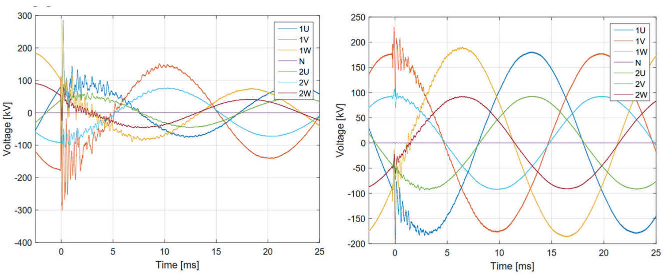


[a] [b]

Figure 7: Transient overvoltages at HV and LV terminals of power transformer – case 1: recorded signals (a) and signals after applying high-pass FIR filter (b).

For further analysis of the impulse signal or usage of the signal in EMTP simulations, it is necessary to filter the impulse from the 50 Hz data. For this, high-pass FIR filter can be used. Applying this filter removes the low frequency and power frequency components of the measured signal [8]. Lightning overvoltage waveforms for the presented case 1, obtained after filtering out low frequency components from measurements, are shown in Figure 7 (b).

Two more cases are observed in this paper and shown in Figure 8. Case 2 represents a double-phase to ground short-circuit on transmission line while case 3 remained without the fault. It is important to note that the overvoltages observed in the power network differ from the standard 1.2/50 μs impulse as they have oscillatory behavior and dominant frequency components in the range from 1 to 30 kHz [7].

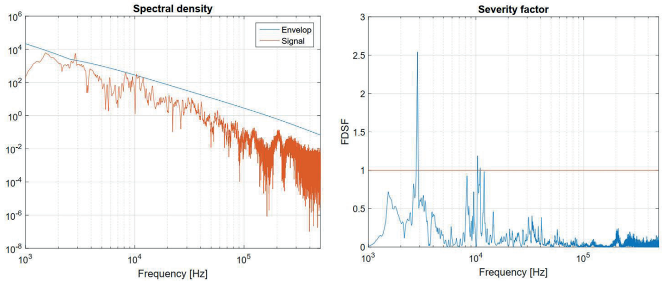


[a] [b]

Figure 8: Transient overvoltages recorded at HV and LV terminals of power transformer – case 2 (a) and case 3 (b).

FREQUENCY DOMAIN SEVERITY FACTOR (FDSF)

In this chapter a Frequency Domain Severity Factor (FDSF) has been explained. It is introduced in order to compare the real impulses with the standard test impulses over the wide frequency band. According to the method described in [2], [9], FDSF is defined as the squared ratio between the spectral density of the measured overvoltage and the spectral density of the standard lightning impulse 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 voltage waveforms for which the transformer had been tested. The ratio is squared in order to compare the energies of the overvoltages [10]. The FDSF factor should be less than 1 to ensure that the stresses arising from a particular event occurring in the system will be adequately covered by dielectric tests performed in the high voltage laboratory.



[a] [b]

Figure 9: (a) Spectral density (in $[V^2s^2]$) of measured overvoltage versus standard LI and SI; (b) FDSF of the measured overvoltage – case 1.

In the example of the transient observed at 220 kV side of the transformer, the envelope is formed (by taking the maximum) using 100/1000 μs switching and 1.2/50 μs lightning impulses [2] with the amplitude of 850 kV and 1050 kV respectively. Three overvoltages are compared for the FDSF. Prior to the factor calculation, the low voltage signal components were removed as already explained.

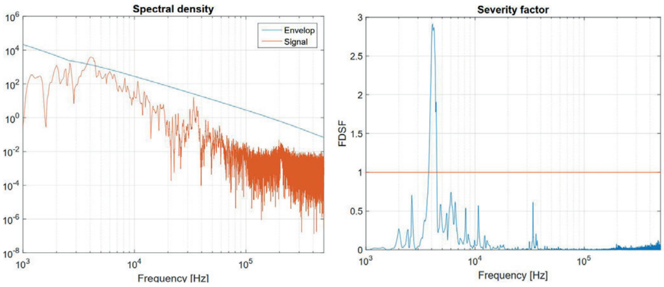
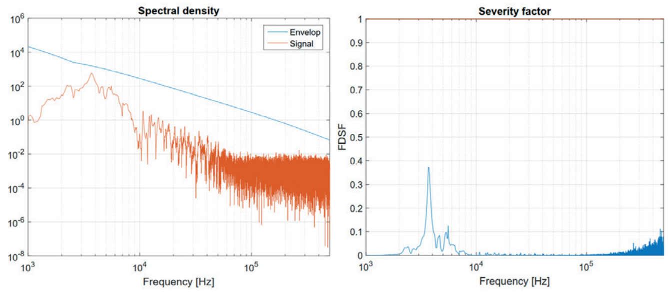


Figure 10: (a) Spectral density (in $[V^2s^2]$) of measured overvoltage versus standard LI and SI; (b) FDSF of the measured overvoltage – case 2.



[a] [b]

Figure 11: (a) Spectral density (in [V^2s^2]) of measured overvoltage versus standard LI and SI; (b) FDSF of the measured overvoltage – case 3.

FDSF exceeds 1 in two out of three observed cases meaning that at these frequencies the electrical stress on the transformer insulation is higher than expected. It also means that transformer tests performed with standard switching and lightning waveforms does not cover adequately low frequency stresses at the range of few kHz. Further step would be to analyze the internal resonance of the transformer windings and to see how these waveforms affect the inner insulation of the winding itself. In some cases of the internal resonances, winding can be endangered if the FDSF exceeds 1.

In general, the FDSF can be used both for design review with regards to incoming transients and in the analysis of failures. When combined with online monitoring, it can also be used as an indicator of increased transient risks for a power transformer.

CONCLUSION

Fleet asset management should have relevant and accurate information when it comes to planning and deciding with regards to strategically important assets such as power transformers and shunt reactors. For that purpose, monitoring systems play an important role since they can collect and process all the relevant data in real time so a quick and factual decision can be made.

Today's state-of-the-art monitoring systems have transient recorders installed in order to have an insight into transformer's/shunt reactor's behavior during such conditions. It is very important to measure transient overvoltages on transformer terminals and to record such events. This can help in assessing an overall condition of an object's insulation system throughout its service years.

Moreover, these effects can be included as input parameters for the health index estimation. This can, in turn, lead to more insight in the current state of the transformer/shunt reactor which will help in decision-making and asset management on the fleet level.

The future investigations in this field can consider correlating the data from the transient recorder with SCADA and LLS systems in order to group the overvoltages by type as well as doing the statistical analysis of amplitudes, frequency spectrum and FDSF of registered events. This can be extended to comparison of non-standard waveforms with equivalent ones in order to develop the method for assessment of the transformer insulation degradation caused by overvoltages.

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