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Short-term thermal stress of high voltage coil

***Abstract**. The main goal of this article is monitoring changes of partial discharge activity to the short-term thermal degradation of high voltage coil. Discharge activity is represented by statistical histograms ($H_{qmax}(\varphi)$, $H_{qn}(\varphi)$, $H_n(\varphi)$) from which are calculated descriptive operators (S_k^+, S_k^-, K_u^+, K_u^-). Comparing descriptive operators before and after thermal degradation could help get the information about condition of insulation system to the neural network.*

***Streszczenie.** Celem artykułu jest opis monitorowania relacji zmian w wyładowaniu niezupełnym w stosunku do krótkookresowego naprężenia termicznego. Porównując współczynniki opisujące wyładowanie przed i po naprężeniu termicznym można otrzymać informacje o warunkach izolacji. (**Krókookresowe naprężenie termiczne w cewkach wysokonapięciowych**)*

Keywords: high voltage coil, partial discharges, statistical operators, thermal degradation.
Słowa kluczowe: cewki wysokonapięciowe, wyładowanie niezupełne, naprężenia termiczne

Introduction

The insulation system is one of the most important parts of high voltage rotating machines. During the operation, insulation system is exposed to a number of different factors with adverse influence. Among these factors belong electrical, thermal, mechanical stress and ambient. Their actions lead to chemical and physical changes in insulation material. In the final merit it decreases the quality of the insulation system and increases the probability of failures by the electrical breakdown.

There are many different diagnostic methods for prevention the quality of the insulation system. One of the reliable non-destructive diagnostic methods is partial discharge measurement. It provides huge benefits in the form of one or more of the following [1]:

- It is truly predictive test, indicating insulation degradation in advance of the failure.
- It needs no use any over-voltages, thereby not exposing the tested equipment to higher voltage stresses than those encountered under normal operation conditions. Avoid unexpected in-service failures of the equipment and extend up-time between outages.
- Avoid unnecessary servicing and repairs of older equipment by maximizing the operating hours.
- Find a problem and remedy it before it has chance to fail the equipment.
- Find problems on new equipment which may still under warranty.
- Asses the quality of maintenance repairs and/or rewinds with before and after testing.
- Compare results from similar equipment to focus maintenance on those with higher levels of partial discharges.
- Identify specific failure mechanisms in the equipment to allow for corrective action prior to an outage.
- Improve the overall reliability of equipment.
- Accomplish all this while the machines remains in operation (On-line).

Partial discharge can be characterized as small electrical sparks that do not bridge the distance between two electrodes. It originates in strong inhomogeneous fields on electrodes with small curvature radius. Their presence indicates a looseness of coil in the stator slot, overheating or contamination of winding. In many cases, insulation degradation is relative slow process. The time between origin of the first partial discharges to failure can take order of years [2]. Quality of insulation system is high priority to hold machine in no-failures and reliable operation.

This article discusses about partial discharge measurements on high voltage stator coil, which was short-term thermal stressed. It monitors changings in partial discharge activity, shapes of phase resolved partial discharge patterns (histograms $H_{qmax}(\phi)$, $H_{qn}(\phi)$, $H_n(\phi)$). Moreover descriptive operators (skewness and kurtosis) were calculated for the purpose of minimizing phase resolved partial discharge patterns. This form provides information about shapes of the phase resolved partial discharge patterns in concentrated form and could be the appropriate input data to autonomous fault detection system of the insulation.

Experimental setup

The measured object was high voltage stator coil from asynchronous machine with the rated power P_n = 0,2 MW and with the rated voltage U_n = 6 kV. The main insulation of the measured object was created from thermosetting insulation Samicatherm 366.28 - mica–calcined tape amalgamated by epoxy asphalt by means of Resin Rich technology. Terminal slot parts of coil were not treated by semi-conductive coating as protection against surface discharges. The thermal class was F (155 °C).

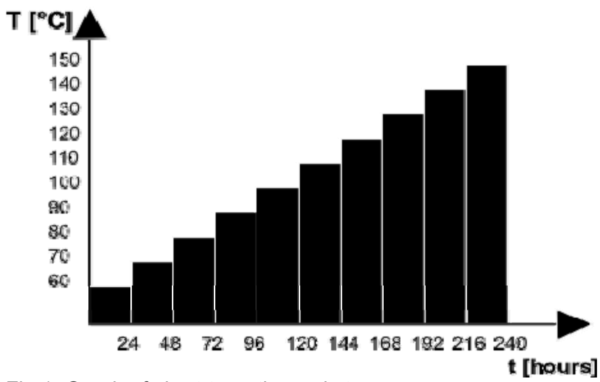

Fig.1. Graph of short-term thermal stress.

Short-term thermal degradation was performed in the hot air dryer MLW TS 400. Measured object was exposed 240 hours at different temperatures. Temperature was continuously increased with step 10 °C per 24 hours from 60 °C to 150 °C (see Fig. 1).

Coil was measured five times before and after short-term thermal stress for purpose to reach more reliable results and better statistics.

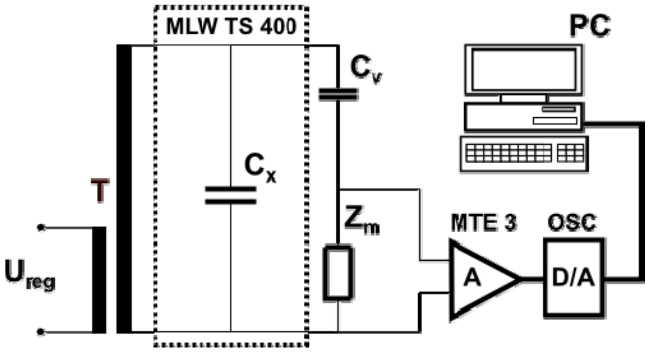

Fig.2. Scheme of experimental setup.

Principal setup is depicted on the Fig. 2. By means of voltage regulator U_{reg} and high voltage transformer T, high voltage was supplied to measured object C_x. Parallel to measured object were connected coupling capacitor C_v in series with measured impedance Z_m. Voltage drops caused by partial discharges were boosted in amplifier MTE3, digitalized in OSC and executed in personal computer PC.

Harsh edges of coil were homogenized by spherical electrode, thus excluded impact of corona discharges from high voltage side. Slot parts of coil were grounded by four strips of aluminium foil 1,5 cm from terminates of slot part's conductive coating. Measurements were done from voltage when stable partial discharges was captured to 6 kV with step 0,2 kV.

Theoretical Analysis

Measured data were stored in two files. The first file contained information about magnitude of apparent charges and the second given frequencies. Files were used for further processing by special program that created two dimensional plots - phase resolved partial discharges patterns - histograms H_{qmax} (φ), H_{qn} (φ) a H_n (φ) (see Fig. 3 - Fig. 5.).

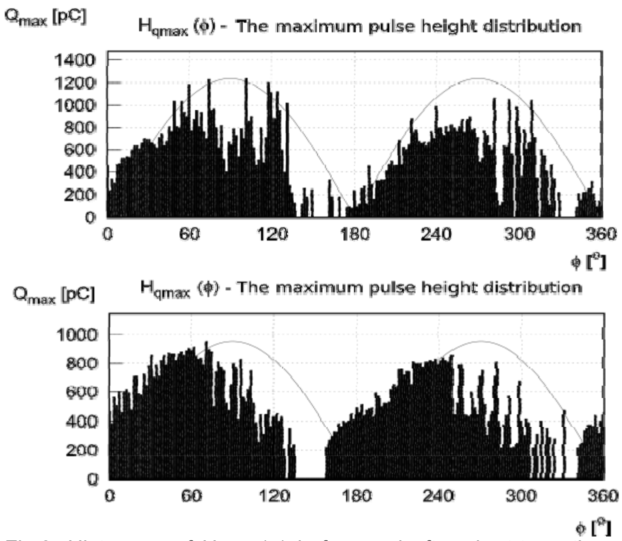

Fig.3. Histogram of H_{qmax} (φ) before and after short-term thermal stress at 6 kV.

Phase resolved partial discharge patterns of the maximal value and the mean value of the apparent charges and pulse count of frequencies - histograms H_{qmax} (φ), H_{qn} (φ) and H_n (φ) - were calculated by means of programme written in Octave.

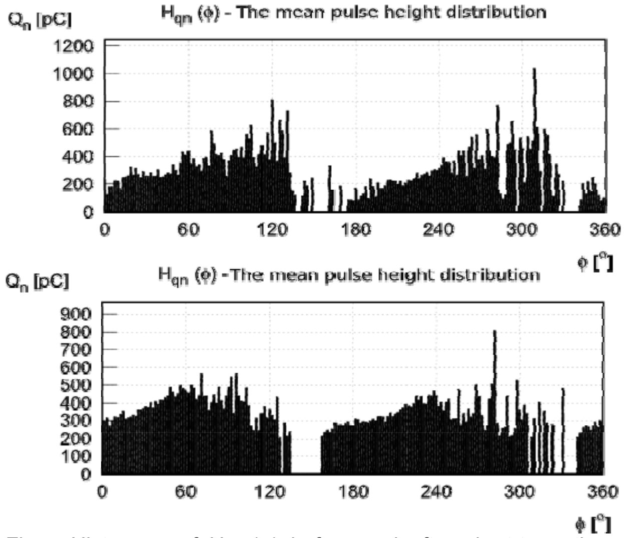

Fig.4. Histogram of H_{qn} (φ) before and after short-term thermal stress at 6 kV.

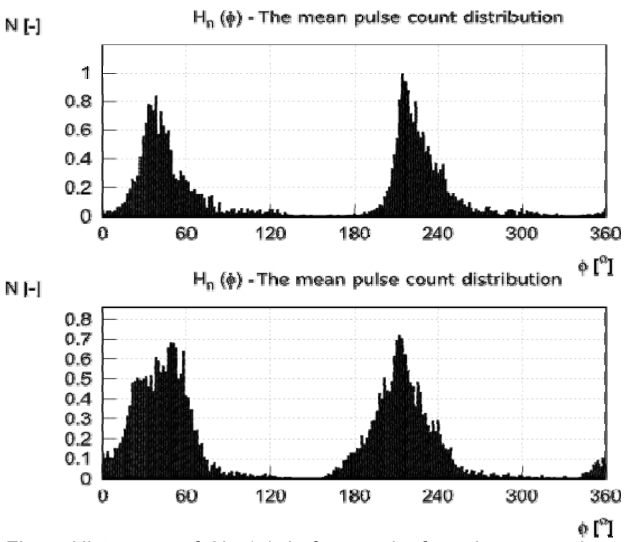

Fig.5. Histogram of H_n (φ) before and after short-term thermal stress at 6 kV.

Phase resolved partial discharges patterns H_{qmax} (φ), H_{qn} (φ) and H_n (φ) served to calculate the descriptive operators skewness S_k and kurtosis K_u that give information about their shape.

The skewness S_k is defined by means of the equation 1. It compares phase resolved partial discharges patterns H_{qmax} (φ), H_{qn} (φ) and H_n (φ) with the normal distribution and monitors whether is tilted to the right or left side than normal disribution.

$$S_k = \frac{m_3}{\left(\sqrt{m_2}\right)^3} = \frac{1}{n}\frac{\sum_{i=1}^{n}\left(q_i - \bar{q}\right)^3 n_i}{s^3} \tag{1}$$

The kurtosis K_u is defined by means equation 2. It compares phase resolved partial discharges patterns of H_{qmax} (φ), H_{qn} (φ) and H_n (φ) and monitors whether is flatter or sharper than normal distribution.

$$K_u = \frac{m_4}{\left(\sqrt{m_2}\right)^4} - 3 = \frac{1}{n}\frac{\sum_{i=1}^{n}\left(q_i - \bar{q}\right)^4 n_i}{s^4} - 3 \tag{2}$$

Reviewed of results

Tab. 1 and Tab. 2 show measured values of apparent charges – the maximal values, the frequencies and phase angle of its origination at voltage value 3,6 kV and 6,0 kV (five times before thermal stress and five times after thermal stress).

The partial discharge activity after short-term thermal stress at voltage level 3,6 kV reached higher maximal values of apparent charges. The maximal values before thermal stress varied in range from 1200 pC to 4000 pC. The average discharge activity was 3240 pC. After short-term thermal stress discharge activity increased. The maximum value of the apparent charge was in the range from 3500 to 12000 pC with the average value of 6100 pC.

Table 1. Table of measured value for voltage value 3,6 kV before and after thermal stress.

Before thermal stress				
U [kV]	Q_{max}[pC]	N [-]	φ^{+} [°]	φ^{-} [°]
	1200	0.01	50-70	230-270
	4000	0.5	40-70	200-270
3.6	4000	0.05	-	210-300
	3500	0.05	30-70	220-290
	3500	0.16	-	240-260
After thermal stress				
U [kV]	Q_{max}[pC]	N [-]	φ^{+} [°]	φ^{-} [°]
	12000	0.40	30-40	200-300
	4500	0.35	30-70	230-270
3.6	4500	0.40	30-80	220-300
	6000	0.04	-	230-250
	3500	0.27	30-70	230-270

Table 2. Table of measured value for voltage value 6 kV before and after thermal stress.

Before thermal stress				
U [kV]	Q_{max}[pC]	N [-]	φ^{+} [°]	φ^{-} [°]
	14000	0.12	50-70	210-260
	18000	0.80	40-70	180-260
6.0	25000	0.90	20-80	180-290
	18000	0.50	30-60	180-260
	19000	0.35	30-110	180-290
After thermal stress				
U [kV]	Q_{max}[pC]	N [-]	φ^{+} [°]	φ^{-} [°]
	23000	1.00	10-120	190-290
	8000	1.50	10-130	190-300
6.0	25000	1.40	20-70	180-290
	10000	0.03	-	230-250
	12000	2.30	0-130	180-320

The partial discharge activity at the voltage level 6,0 kV reached higher maximal values of apparent charges before short-term thermal stress. The maximal values of apparent charges varied in range from 14000 pC to 25000 pC. The average discharge activity before heat stress was 18800 pC. After short-term thermal stress discharge activity decreased. The maximum value of the apparent charge was in the range from 8000 to 25000 pC with the average value of 15600 pC.

On the Fig. 6 - 11 are depicted dependencies of descriptive operators skewness and kurtosis of H_{qmax} (φ), H_{qn} (φ) and H_n (φ) on applied voltage before and after short-term thermal stress. Due to fact that the discharge activity dominates at the negative half voltage cycle, dependencies of descriptive operators were displayed only for the negative half voltage cycle.

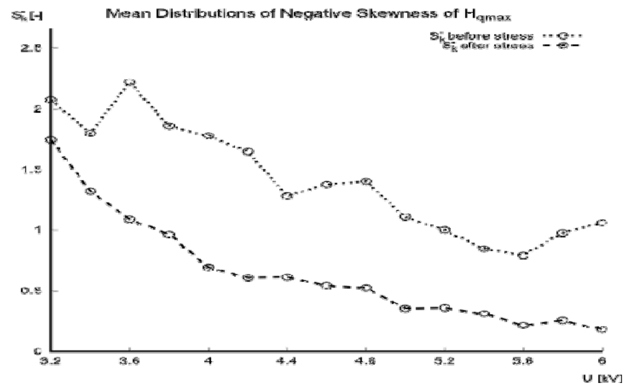

Fig.6. Arithmetical average of the skewness H_{qmax} (φ) for five measurements before and after short-term thermal stress.

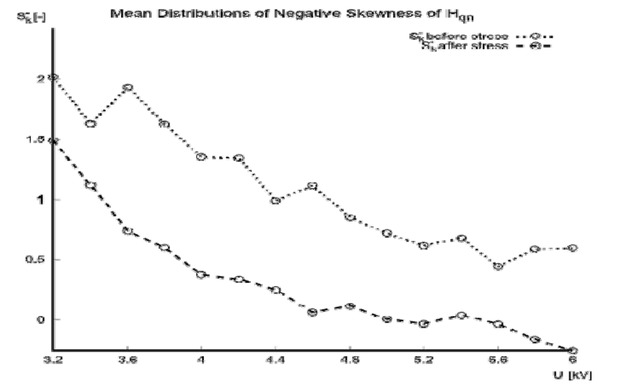

Fig.7. Arithmetical average of the skewness H_{qn} (φ) for five measurements before and after short-term thermal stress.

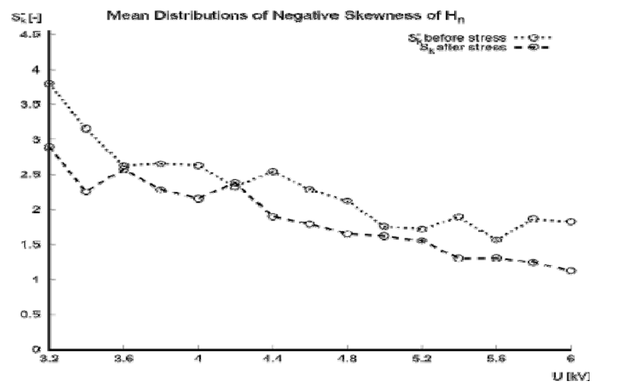

Fig.8. Arithmetical average of the skewness H_n (φ) for five measurements before and after short-term thermal stress.

Dependencies of the skewness on applied voltage of the H_{qmax} (φ), H_{qn} (φ) and H_n (φ) (see Fig. 6 - 8) showed that individual values are higher before short-term thermal stress. Higher values of skewness indicate tilted to right side and with increasing voltage titling change to left side.

However, the directive transition from right to left side before short-term thermal stress is similar to after short-term thermal stress.

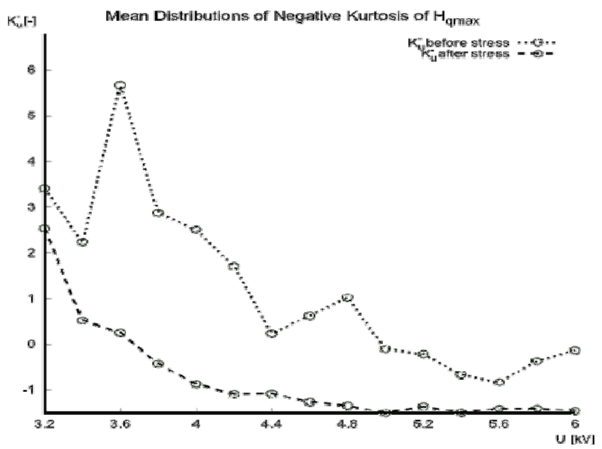

Fig.9. Arithmetical average of the kurtosis H_{qmax} (φ) for five measurements before and after short-term thermal stress.

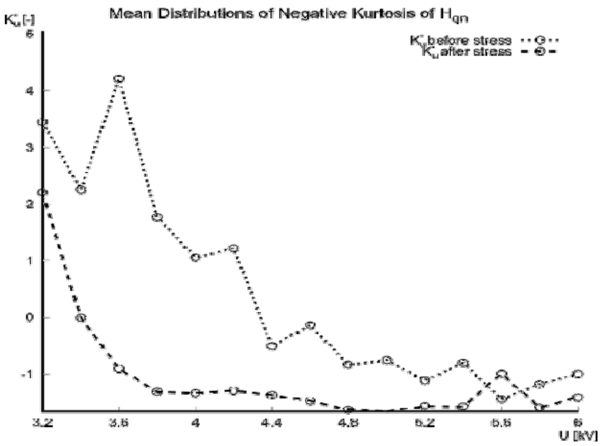

Fig.10. Arithmetical average of the kurtosis H_{qn} (φ) for five measurements before and after short-term thermal stress.

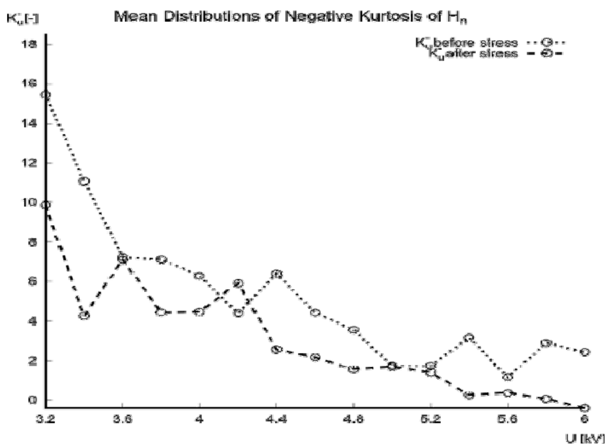

Fig.11. Arithmetical average of the kurtosis H_n (φ) for five measurements before and after short-term thermal stress.

Dependencies of the kurtosis on applied voltage of the H_{qmax} (φ), H_{qn} (φ) and H_n (φ) (see Fig. 9 - Fig.11) showed that individual values are higher before short-term thermal stress. Higher values of kurtosis indicate sharper shape of histogram. But with increasing of applied voltage values of kurtosis dropped down – histograms became flatter.

Conclusion

The results of partial discharges measurements show following facts. The moderate increasing of discharge activity after short-term thermal stress at the rated voltage 3,6 kV, but accentuated decreasing discharge activity at the voltage value 6,0 kV. The descriptive operators skewness and kurtosis of the histograms H_{qmax} (φ), H_{qn} (φ) and H_n (φ) before short-term thermal stress reached higher values. It shows on sharper right-side skewness. After short-term thermal stress descriptive operators changed to lower values - the shape of histograms H_{qmax} (φ), H_{qn} (φ) and H_n (φ) became flatter and tilted to the left side.

The influence of short-term thermal stress at the view of partial discharge activity can be supposed as positive. The higher temperature caused curing and insulation became more complex.

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