PARTIAL DISCHARGE ANALYSIS FOR INSULATION SYSTEMS OF ELECTRIC ROTATING MACHINES WITH VARIOUS VOLTAGE STRESS

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ABSTRACT

High voltage insulation is loosing its quality during the operation of high voltage machines and generators. Degrading high voltage stator insulation is the main reason for sudden breakdown of stator windings. Partial discharge measurements can reveal a lot of defects in stator windings of high voltage rotating machines with operating voltage more than 3,3kV. Partial discharge monitoring provides reliable information necessary for basic maintenance of stator windings of motors and generators. Submitted paper deals with partial discharge measurements in stator windings during the increasing of applied voltage.

Keywords: *partial discharges, stator insulation, surface discharge, phase resolved partial discharge analysis*

1. INTRODUCTION

Insulation of high voltage rotating machines changes its properties due to acting of various operating factors: vibrations, high temperatures, heating and cooling cycles, operating voltage, overvoltages, pulse and dynamic loading [1], [2]. Influence of outdoor surroundings plays a valuable role at the deterioration of insulation, too, such as: moisture, chemical compounds, various types of radiations, impurities. Life time of insulation depends on intensity and duration of thermal, electrical and mechanical stresses.

The greatest influence on the insulation’s life time has temperature. Due to high temperatures, processes of thermal-oxidative destruction are present in high voltage insulation. These processes cause the decrease of mechanical strength, loss of elasticity and unlocking of fleet components, which is the reason for the creation of gas filled cavities in high voltage solid insulation [3].

2. INTERNAL AND SURFACE PARTIAL DISCHARGES

At the action of electrical field due to ageing of material, partial discharges occur in cavities in the volume of insulation – *internal discharges*. If protective surface coating is damaged, partial discharges can occur in stator slots or they can occur in the site of coil termination from stator slots – *surface discharges*.

Internal discharges are very dangerous for solid insulations because they damage all types of organic materials. Small cavities increase their volume and electric strength of material decreases. This fact can lead to complete breakdown of solid insulating material.

Electric stress of insulation depends on its thickness and amplitude of applied voltage. Partial discharges can occur in stator insulation of rotating machines with nominal voltage from 3,3 kV. The action of temperature leads to damage of binders and basic materials, vibrations cause the creation of cracks, gaps and layering of insulation. In damaged insulation, ionizing processes are present which leads to decrease of electric strength of insulation and its complete breakdown.

Surface discharges are present in various types high voltage equipment. Surface discharge processes depend on several factors:

- physical properties of the environment in which discharge takes place (gas, liquid),
- physical properties of solid dielectrics (permittivity, surface resistance, conductivity),
- distribution of electric field in the site between electrodes,
- direction of lines of force considering the surface of dielectric material,
- status of surface of solid dielectrics (polluted, sodden),
- type of voltage and time of operation.

In case of stator insulation of high voltage rotating machines, surface discharges can occur both in the stator slot and at the termination of the coil from the slot. Due to non-homogeneity of stator surface and surface of insulation, air filled gaps occur between them.

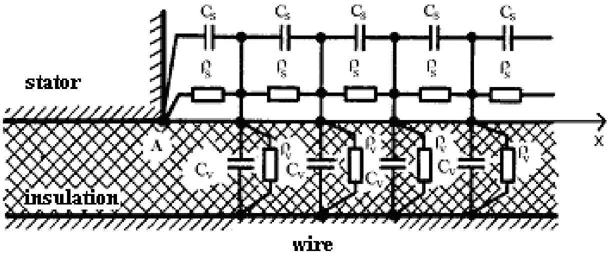

Fig. 1 The equivalent model of coil insulation in slot exit

Corona discharges originate in the place of maximal inhomogeneity of electrical field while increasing of applied voltage [4]. There are discharges on surface of insulation (so-called creeping discharges) at the next raising of test voltage. The length of creeping discharges grows with voltage increase and at certain voltage flashover on surface appears or breakdown occurs.

We use equivalent model of coil insulation in slot exit for determination of initial corona voltage according to Fig. 1, where

$C_v = \varepsilon_0\, \varepsilon_{rd} / d$ – capacitance of insulation surface in the face of wire,
$C_s = k\, \varepsilon_0\, \varepsilon_{rv}$ – capacitance among elements of insulation surface,
k – experimentally defined coefficient,
d – insulation thickness,
ε_{rd}, ε_{rv} – relative permitivity of insulation and air,
ρ_v – specific volume resistance of insulation,
ρ_s – specific surface resistance of insulation.

Figure 2 shows the gap that can occur in the slot, adjacent to the coil surface, since the coil is undersized.

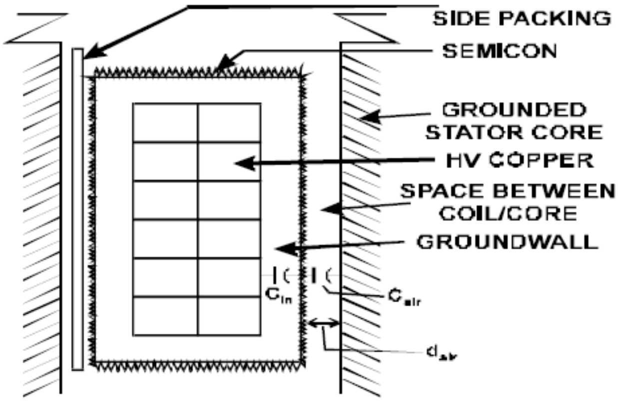

Fig. 2 Gap that can occurred in the slot [5]

A surprisingly large percentage of the applied voltage will appear across the air gap. If the electric stress (E = V/d) in the air gap exceeds 3 kV/mm, PD will occur, at least in an air-cooled machine. This PD will eventually erode a hole through the groundwall, causing failure. Discharges on the coil/bar surface are sometimes referred to as slot discharge, since they can be seen in the slot. Under practical conditions, most stators rated 6 kV or more will experience this PD on the coil/bar surface [5].

The height of surface non-homogeneities can be from hundreds to tenths millimetres. Intensity of electrical field in the gap (E_m) is higher than the average value of electric strength of insulation due to the difference of permitivities of air and solid dielectrics:

$$E_m = \frac{\varepsilon_{rd}}{\varepsilon_{rv}} E_{str} \tag{1}$$

where E_m is intensity of electrical field in air filled slot, $E_{str} = U/s$, where s is the distance between electrodes, ε_{rd} is permittivity of dielectrics and ε_{rv} is permittivity of air.

At the stator termination is the intensity of electrical field even higher. For that reason, partial discharges occur in these sites. Discharges at the stator termination are the source of photons that causes the increase of the coefficient of secondary ionisation. Moreover, partial discharges create space charge influencing electric field in electrode surroundings [6], [7]. This fact contributes to the occurrence of discharges along solid dielectrics.

Three main stages can be observed at partial discharge process occurred on the surface of dielectrics at the slot termination. When increasing voltage, corona discharges occur first in the site of the highest intensity of electrical field. Discharges have streamer-like character (first stage). Next increasing of voltage is following by leader-like spark discharges (second stage of discharge process) occurred on the surface of dielectrics. Temperature in leader channel is 6500 K, average velocity of channel is 10^4-10^5 ms^{-1}. With the increase of tested voltage, the length of surface discharges increases. If the length reaches the some value l_p (where l_p is the distance between two electrodes) complete breakdown across the surface of dielectrics occurs (third stage).

Inception voltage of corona discharges U_k and surface discharges U_{kl} are characterized by Toepler's relations valid for AC voltages of industrial frequency [8]:

$$U_k = K_k / C_{pov}^{0,45} \tag{2}$$

$$U_{kl} = K_{kl} / C_{pov}^{0,45} \tag{3}$$

where K_k, K_{kl} are coefficients determined experimentally, C_{pov} is specific surface capacity.

For the arrangement with $C_{pov} > 0{,}25.10^{-8}$ Fm^{-2} it is possible to write:

$$C_{pov} = \frac{\varepsilon_0 \varepsilon_{rd}}{d} \tag{4}$$

where

ε_{rd} - permitivity,
d - thickness of dielectrics.

According to Toepler, experimentally determined coefficients are: $K_k = 1{,}1.10^5$, $K_{kl} = (10 - 13{,}5).10^5$. Relations (2) and (3) can be written then as:

$$U_k = 8{,}23 \left(\frac{d}{\varepsilon_{rd}} \right)^{0,45} \tag{5}$$

$$U_{kl} = 74{,}8 \left(\frac{d}{\varepsilon_{rd}} \right)^{0,45} \tag{6}$$

Dependence of the length of surface discharges l_{kl} on factors introduced by Toepler is given below:

$$l_{kl} = K C_{pov}^2 U^5 \left(\frac{dU}{dt} \right)_{\max}^{0,25} \tag{7}$$

If surface discharge reaches the opposite electrode ($l_{kl} = l_p$), complete breakdown across the surface occurs at $U = U_p$. From (4) and (7) it is possible to derive the value of breakdown voltage as:

$$U_p = K_p l_p^{0,2} \left(\frac{d}{\varepsilon_{rd}} \right)^{0,4} \tag{8}$$

where K_p = 57.5 for AC voltage of industrial frequency (experimentally determined value).The author presents his main ideas, mathematical formulations and their derivation. This part should be accompanied by exact references.

3. PARTIAL DISCHARGES DETECTED ON HIGH VOLTAGE COILS AT INCREASING OF TESTING VOLTAGE

From relations describing inception voltage of surface discharges it is possible to see the dependence of inception voltage on the thickness of insulating material and its permittivity. Moreover, increasing voltage causes the change of discharge activity. There are differences of partial discharge behaviour of internal, slot or surface discharges.

6kV coil of electric rotating machine was used during partial discharge measurements. The coil was inserted into stator slot. High voltage was applied to the coil and stator was earthed. Tested voltage was increasing until occurring first partial discharges. Discharge activity was checked using acoustic detector simultaneously.

Phase resolved partial discharge analysis was applied on partial discharge signal. Final results at particular values of testing voltage are given in Fig. 3 – 6. First internal discharges (in cavities) occurred at the testing voltage of U_t = 3 kV with maximal discharge magnitude q_{max}=77 pC (see Fig. 3).

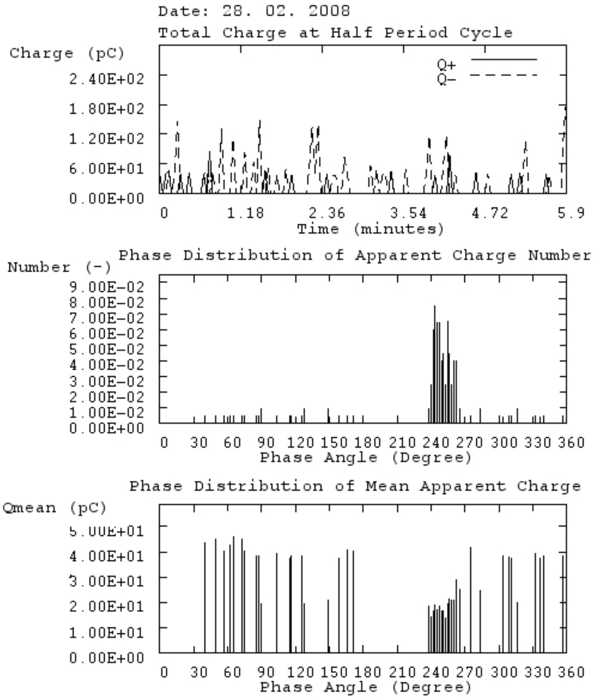

Fig. 3 Internal discharges in cavities occurrence

Corona discharges have started at testing voltage U_t = 3.6 kV, their maximal discharge magnitude was 770 pC (see Fig. 4).

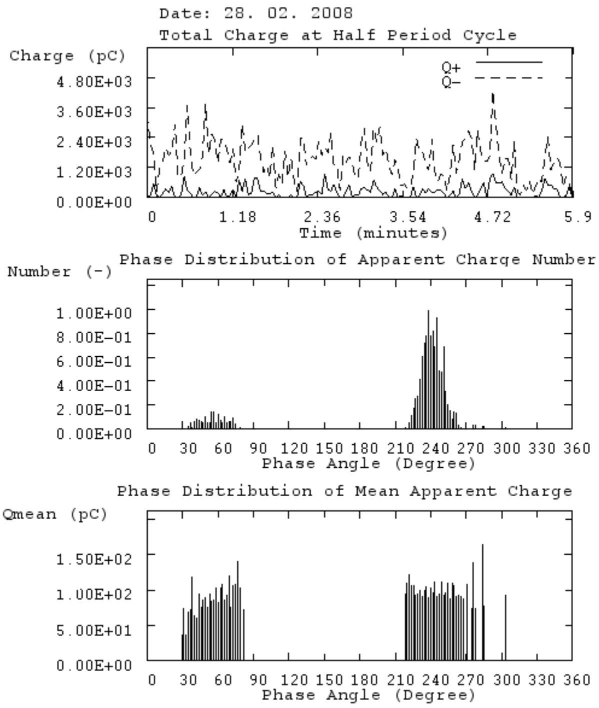

Fig. 4 Corona discharges occurrence

At further increasing of testing voltage (U_t = 2,3 kV), surface discharges occurring at the slot termination. Their maximal discharges magnitude are raised up to q_{max}=2500 pC (see Fig. 5).

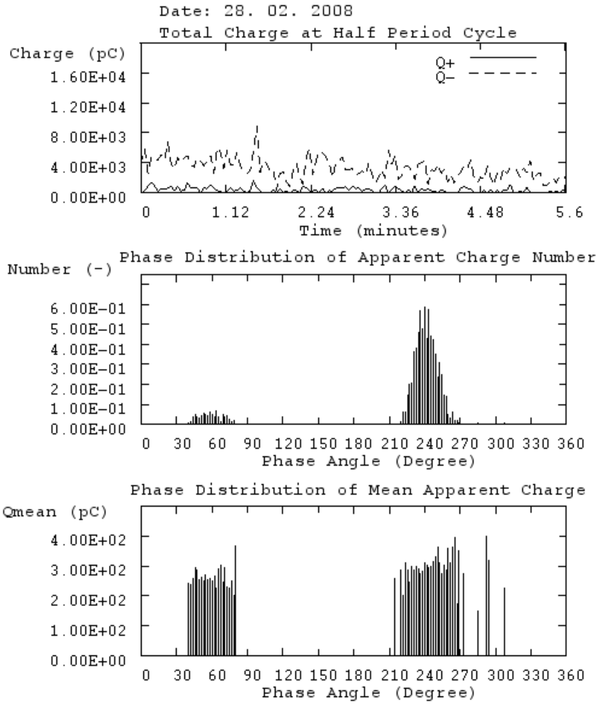

Fig. 5 Surface discharges occurrence

At nominal voltage U_t = 6 kV, partial discharges were observed in the whole slot (see Fig. 6). Maximal magnitude of partial discharges increased up to 6300 pC. The discharges with this magnitude could damage of insulating surface of high voltage coils.

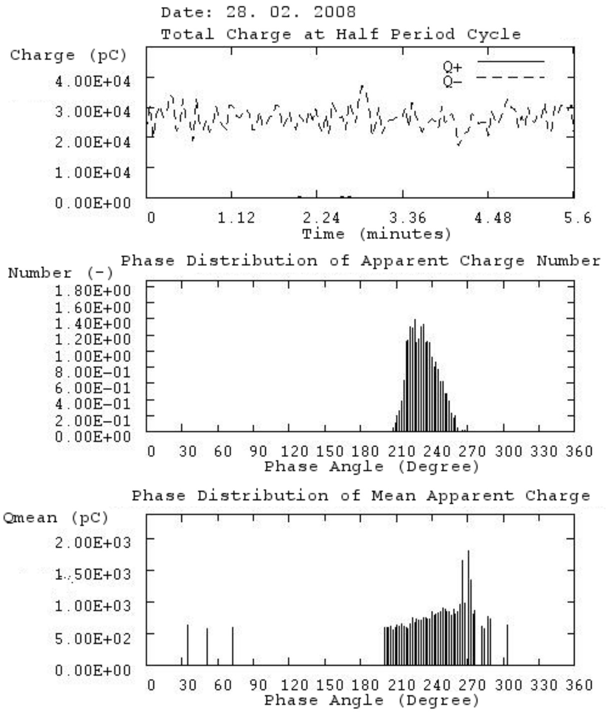

Fig. 6 Damaging discharges occurrence

Because of the highest magnitudes of slot discharges, it is impossible to detect internal and surface discharges at the nominal phase voltage. For that reason it is necessary to start measurement from inception voltage and then increase voltage step by step until its nominal value.

4. CONCLUSIONS

Partial discharge measurements performed in dependence of applied testing voltage seems to be very useful and progressive in the diagnostics of the state of stator insulation of high voltage rotating machines [9]. According to obtained results it is possible to determine the state of degrading insulation system. This method enables to reveal very dangerous internal discharges, which usually are at nominal values of testing voltage undetectable.

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