Partial Discharge Measurements in HV Rotating Machines in Dependence on Pressure of Coolant

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The influence of the pressure of the coolant used in high voltage rotating machines on partial discharges occurring in stator insulation is discussed in this paper. The first part deals with a theoretical analysis of the topic. The second part deals with the results obtained on a real generator in industrial conditions. Finally, theoretical assumptions and obtained results are compared.

Keywords: partial discharges, stator insulation, high voltage rotating machine, phase resolved partial discharge analysis.

1 Introduction

Theoretical assumptions as well as practical experience of diagnostic measurements on high voltage cables, transformers or rotating machines show that if we intend to compare results, it is necessary to carry out all measurements with the same internal conditions (atmospheric humidity, ambient temperature, air pressure, etc.) for example, the influence of temperature on the loss dissipation factor of insulating system of high voltage equipment is well known. After measurements, it must be recounted to a temperature of 20 °C.

In technical and scientific literature, the influence of pressure on partial discharge measurement has not been handled very often. Because diagnosing high voltage rotating machines using the partial discharge method has become very popular, and our experience of partial discharge measurements has shown that the pressure of the coolant is a very important factor influencing the measurements, we consider it useful to deal with this matter more precisely.

2 Theoretical analysis

At normal temperature and pressure, gases are excellent insulators. In higher fields charged particles such as electrons or positive ions may gain sufficient energy between collisions to cause ionisation. Ionisation by electron impact is the most important process leading to breakdown of gases, because electrons usually gain higher energy than relatively slow atoms. This corresponds closely with the fact that the mean free path λ_m of electrons is longer than the mean free path of atoms $\lambda_{me} = 5.66\ \lambda_{ma}$ [1]. It can therefore be said that the effectiveness of ionisation by electron impact depends upon the energy that an electron can gain along the mean free path in the direction of the electrical field.

Considering only collisions by electrons, if λ_{me} is the mean free path in the field direction of strength E, then the average energy gained over a distance λ_{me} is

$$W = eE\lambda_{me}\ . \tag{1}$$

To cause ionisation on impact energy W must be at least equal or higher than ionisation energy W_I.

Collisions of particles in a gas are random events. Hence, a free path (which is defined as the distance molecules or particles travel between collisions [1]) is a random quantity and will have a distribution about a mean value. In the case of simple "ballistic" model the mean free path is given by

$$\lambda_m = \frac{1}{n\sigma_i}, \tag{2}$$

where n is gas density and σ_i is the collision cross-section of two particles.

According to the universal gas law $pV = NkT$ or $p = nkT$, where p is the gas pressure, $n = N/V$ (N is number of particles, V is volume) is gas density, k is the universal Boltzmann constant and T is an absolute temperature, we can evaluate n as follows:

$$n = \frac{p}{kT}\ . \tag{3}$$

Inserting (3) into (2) we can evaluate the mean free path as

$$\lambda_m = \frac{1}{\sigma_i}\frac{kT}{p}\ . \tag{4}$$

If the free path of particle $\lambda = \lambda_I$, where λ_I is the free path of a particle which at a certain level of strength E gains the ionisation energy W_I, from (1) it is possible to write

$$\lambda_I = \frac{W_I}{eE}\ . \tag{5}$$

The mean number of collisions caused by an electron per unit length is $1/\lambda_m$. This electron initiates α ionisations, where α is Townsend's first ionisation coefficient, defined as the number of electrons produced by an electron per unit length of path in direction of the field. Townsend's first ionisation coefficient can be evaluated as

$$\alpha = \frac{1}{\lambda_m} e^{-(\lambda_I/\lambda_m)}. \tag{6}$$

Coefficient α plays a valuable role in the process of multiplying of the free charge holders. According to (4), the mean free path (provided that the collision cross-section, gas density and temperature are constant) is indirectly proportional to the pressure of the gas. According to (5) we can say that λ_i is indirectly proportional to the strength of electric field E and we can write

$$\frac{\alpha}{p} = A e^{-\frac{B}{E/p}}, \tag{7}$$

where $A = \sigma_i / kT$ and $B = \sigma_i W_i / ekT$.

Equation (7) points to those physical quantities of the gas which interact with the ionisation coefficient α. The value α/p is mainly affected by the coefficient B that comprises ionisation energy W_i. The ionisation energy is different for each type of gas.

If we know the dependence of ionisation coefficient α on the strength of electrical field E and pressure of gas p, then according to the condition of self-sustained discharge we can derive an equation describing the inception breakdown voltage in a homogeneous electrical field which is dependent on gas pressure and the distance of the electrodes (Paschen's law)

$$U_{br} = f(pd). \tag{8}$$

In non-uniform electrical fields it is necessary to use generalized Paschen's law, the law of similarity of discharges in gas, which considers the geometry of the electrode set-up

$$U_{br} = f(pd, r/d). \tag{9}$$

Such a curve has its characteristic minimum $U_{br\ min}$ at the critical value $(pd)_{min}$. The minimum breakdown value is dependent on the material of the electrodes and the type of the gas.

For the electro insulating purposes of gases in high voltage equipments it is always valid that $(pd) > (pd)_{min}$. For this reason we can consider only the "right wing" of Paschen's curve. This means that when the pressure of the gas is going up (provided that distance d is constant), the mean free path of electrons λ_{me} shortens, which causes a decrease in their energy W, see Eqn.(1). This leads to an increase in the electric breakdown strength of the gas.

Surface discharges occurring on the interface of the gas-solid dielectric occur in cases when both normal and tangential components of the electrical field are present. According to [2], the type of insulating material does not essentially affect the discharge formation. For this reason the same laws that have been described for discharges in a gas are valid both for pure discharges in air and for surface discharges on the gas-solid dielectric interface.

3 Partial discharge measurements on a high voltage rotating machine

Off-line partial discharge measurements were made on stator windings of synchronous generator with stator insulation of thermal class F. Each phase was measured separately.

All measurements were carried out using a partial discharge detector with digital data recording. The testing voltage was increased gradually until the inception of partial discharges. At this voltage, the discharge data was recorded for the first time. Then the testing voltage was increased in 1 kV steps, up to the nominal phase voltage of 8 kV. The partial discharge signal was measured at each voltage level.

The first partial discharge measurement was performed when the pressure of the coolant (hydrogen) was 108.9 kPa. The inception voltage of partial discharges in each phase was

Phase	Inception voltage (kV)
L1	2.1
L2	2.8
L3	2.0

The next measurement was carried 6 month later. The pressure of the coolant (hydrogen) was higher – 196 kPa. The inception voltage of partial discharges in each phase was much higher then in the case of previous measurement.

Phase	Inception voltage (kV)
L1	6.0
L2	5.5
L3	5.5

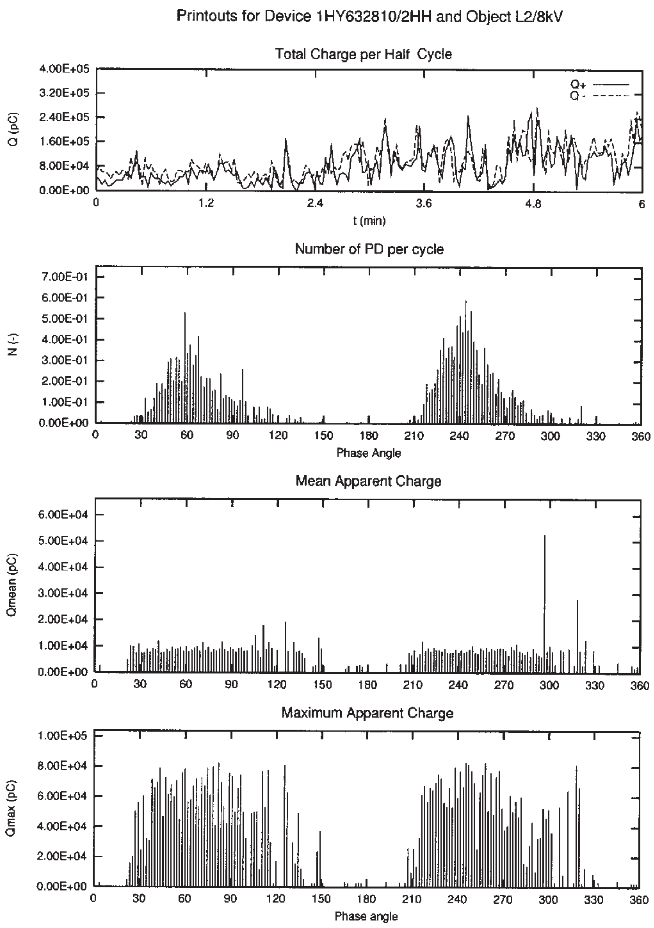

Fig. 1: Partial discharge fingerprints: $U_t = 8$ kV, pressure of coolant $p = 108.9$ kPa

Partial discharge phase analysis it can shows that at lower hydrogen pressure, (108.9 kPa), see Fig. 1, much higher values of apparent charge were obtained ($q_{max} = 80\ 000$ pC, $q_{avg} = 10\ 000$ pC) than when partial discharge measurements were performed at higher hydrogen pressure (196 kPa), see Fig. 2, where $q_{max} = 4\ 500$ pC, and $q_{avg} = 500$ pC. All the above mentioned apparent charge values are for a nominal phase voltage of 8 kV.

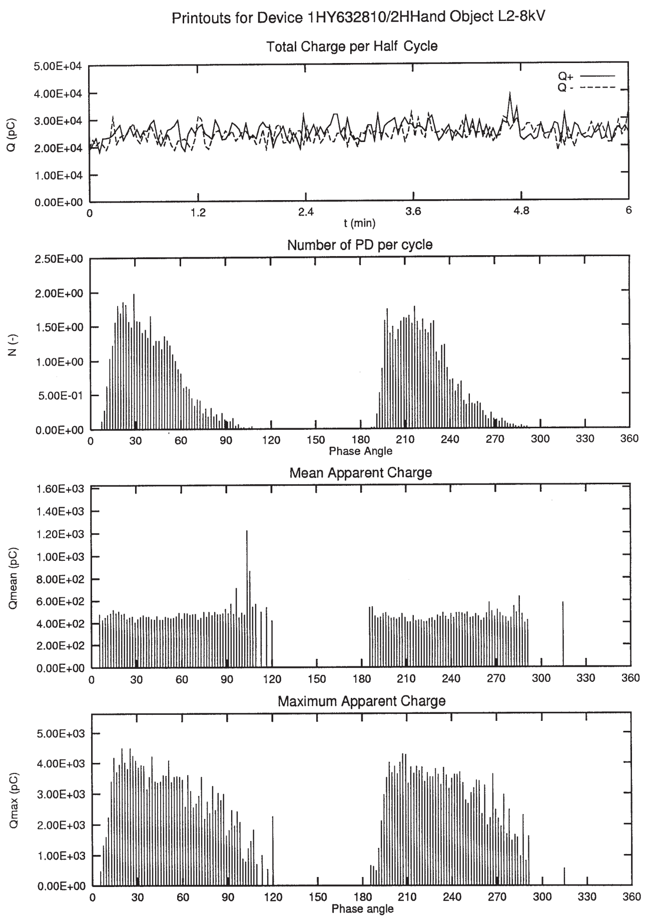

Fig. 2: Partial discharge fingerprints: $U_t = 8$ kV, pressure of coolant $p = 196$ kPa

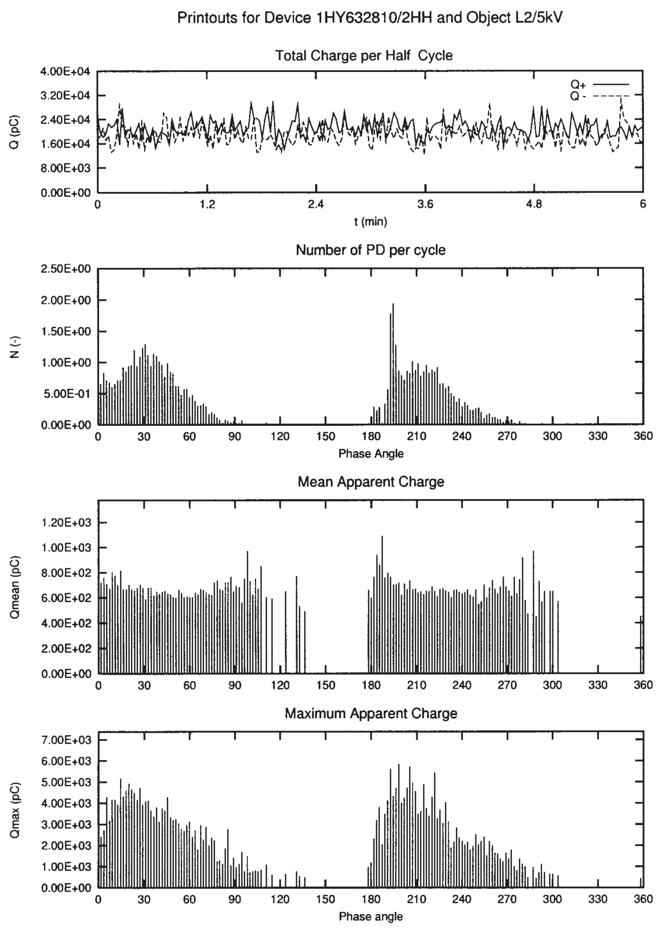

Fig. 3: Partial discharge fingerprints: $U_t = 5$ kV, pressure of coolant $p = 108.9$ kPa

On the other hand, very similar phase distributions to those obtained at coolant pressure of 196 kPa at the testing voltage of 8 kV were measured in the first case at lower coolant pressure at a testing voltage of 5 kV, see Fig. 3.

4 Conclusion

Both theoretical assumptions and partial discharge measurements on real stator insulation in high voltage rotating machines have shown that the coolant pressure value significantly affects both the inception voltage of partial discharges and their apparent charge values. For transparency in the process of evaluating the results, it is therefore necessary to perform partial discharge measurements in high voltage rotating machines with coolant at the same pressure.

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