HIGH VOLTAGE ENDWINDING DESIGN OF LARGE HYDROGEN COOLED TURBO GENERATORS

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Abstract: Today there is a demand for the overall performance of high voltage rotating machines to be optimized, due to the increasing pressure on costs and space requirements. Because of size reduction in the design of generators, minimized distances between adjacent insulated bars or coils in the endwinding are required. Consequently, this area is a critical part of the machine regarding the corona phenomena. Hence the dependency of pressure and distance has to be investigated in detail for hydrogen cooled generators with negligible corona effects.

In this paper, the results of experimental investigations in air and hydrogen for various electrode configurations are presented. Metallic electrodes were covered with standard stator winding insulation material of different thicknesses commonly used in generators. The test vessel was designed for applications in a wide pressure range up to 0.5 MPa. Additionally, the adjustment of the gap distance with an accuracy of ± 100 µm was possible. To determine the corona inception and extinction voltage a PD measurement system according to IEC 270 standard was used. The discharges were monitored with acoustical (ultrasonic microphone) and optical (special UV camera) PD detection systems.

The outcome of this study indicates a very good correlation to the Paschen's Law in both investigated gases. On the basis of gas physics and previous investigations an increasing inception and extinction voltage for higher pressures and larger distance was expected. Experimental results confirmed this. Formulating a mathematical expression relating gap distance to the prescribed pressure and voltage is a topic for future work.

1 INTRODUCTION

The efficient design of generators, especially the end winding design of hydrogen cooled turbo generators, is the motivation for looking into the corona behaviour of different electrode-insulation configurations. Minimized distances between adjacent insulated bars or coils in the endwinding with negligible corona effects are key points in generator design.

As it has been known since the investigations of F. Paschen, the breakdown voltage for gas gaps between blank metallic electrodes is a function of the product of gas pressure and gap length [1], [2], [5], [6]. For generator design configuration with metallic electrodes coated with insulation material is more important but only a few authors explored the behaviour of such insulated electrode configurations (as in [3] and [4]). Obviously, depending on the specific test set-up (electrode material, insulation material, shape of electrodes, type of gas etc.) there is an analogy to Paschen's Law, but on the basis of the published results it is not yet possible to generalize the correlation.

Therefor we used a special design of metallic electrodes covered with standard insulation material used in generators.

While applying high voltage (a.c.) to the electrode-insulation set-up we recorded corona inception voltage (CIV) as well as corona extinction voltage (CEV). We compared our results with the well known Paschen curve for breakdown in hydrogen according to [6] and we made comparisons with the results of our previous research in air [7].

One purpose of this study was to determine the impact of varying pressure and gap length on the properties of our test configuration and to investigate the correlation between the classical Paschen's Law for breakdown and corona behaviour at specific conditions. We hypothesized that for hydrogen, a translation "blank metallic electrodes – insulated metallic electrodes" would be possible within a wide range of pressure and distance respectively as we already had shown for synthetic air [7].

2 PASCHEN'S LAW – BREAKDOWN IN GASES VS. PARTIAL DISCHARGES

The Paschen's Law (1) for gases expressing the dependence of the breakdown voltage (U_b) on the product of pressure (p) and electrode distance (d)

$$U_b = f\,(p.d) \qquad (1)$$

is valid only for non-insulated metallic electrodes and homogeneous field distribution. As it is worked out in [8] the Paschen curve shows an approximately linear progression over a quite wide range which seems to be adequate formulating an expression about analogy between gas breakdown and corona inception.

In the present case it is predetermined to monitor PD activity instead of breakdown events. Analogy and correlation between gas breakdown and corona inception and extinction voltage respectively (CIV, CEV) are therefor focal points in our research.

3 EXPERIMENTAL INVESTIGATIONS

Materials and methods within our experimental investigations were the same as for the previous tests under synthetic air. For reasons of comparison we did not change the setup since the completed experiments in synthetic air, therefor this section is kept short and it is referred to [8] for further information.

3.1 Test set-up

Our test set-up was built up at an high voltage testing field, where we installed a testing stand for 50 Hz a.c. voltages up to 50 kV (the high voltage rise speed was adjustable) and the necessary measuring equipment (voltage, PD, pressure, temperature).

3.2 Measuring Apparatus

To detect partial discharges we kept using an electrical partial discharge measurement system (ICMsystem®) as well as an optical detection system (CoronaScope™).

The applied voltage was measured with a standard digital voltmeter (rms) which we calibrated using a highly precise reference standard before.

3.3 Test Vessel

The test vessel (Figure 1) containing the test electrodes (Figure 2) under a selected gas atmosphere has a volume of 80 dm3 and provides two inspection glasses. It is designed for a maximum operating pressure of 0.5 MPa (absolute value) and temperatures up to 110°C (the investigations were carried out at constant temperature of 25°C).

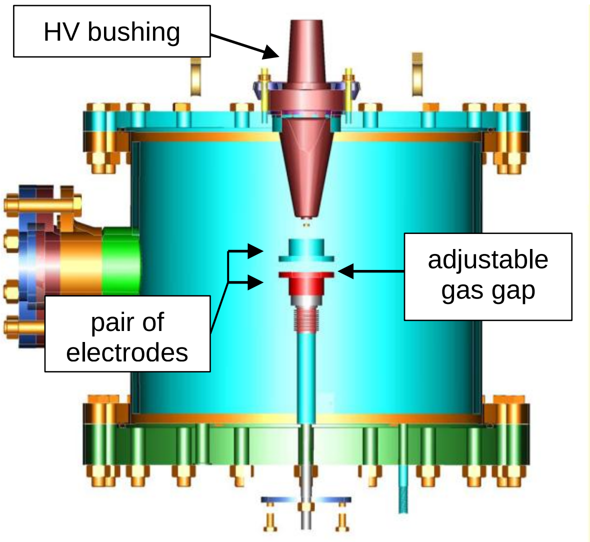

Figure 1: Schematic sketch of test vessel

At the top of the vessel there is a high voltage bushing connecting the fixed high voltage electrode whereas the ground electrode is mounted adjustable to set the gap length from zero to 10 mm. The test vessel is fitted with valves to fill and evacuate and to adjust the gas pressure from zero to 0.5 MPa.

3.4 Test Object

The test objects consist of metal electrodes covered with standard insulation materials as it is used for generator stator bars (Figure 2). During the experiments described in this paper we used insulation materials with a thickness of 6 mm.

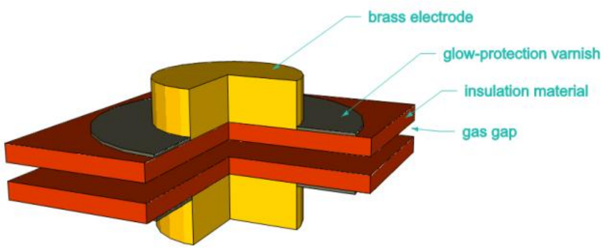

Figure 2: Schematic sketch of test electrode

In addition we plan to test some samples with different dimension of insulation thickness. The configurations field distribution is assumed to be quasi homogeneous.

3.5 Experimental methods

In order to identify an appropriate test procedure and moreover to get independent results for CIV and CEV respectively we did pre-test measurements where we varied a handful parameters. We increased the applied high voltage (about 300 Volt per second) until PD were detected. The so found corona inception voltage was kept on that level for a period of time (T_1 = 10 s). Subsequent to that the applied voltage was raised by a certain percentage (X = 10 %) and was maintained again for a period of time (T_2 = 30 s). Finally the applied voltage was decreased until no PDs were detected any more (CEV). After decreasing the voltage to zero Volt, recovery time (T_0 = 30 s) was given before increasing the voltage again. This was done to allow recombination and to let the gas stabilize itself. To allow statistical evaluation this basic procedure was repeated three times (Figure 3) using the previously chosen parameters.

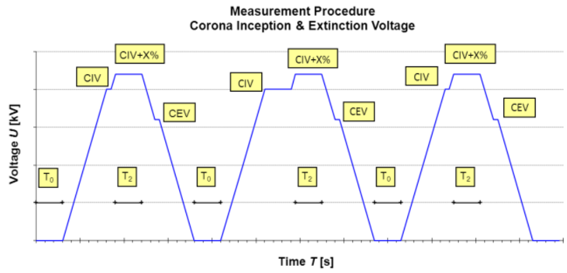

Figure 3: Principal of the measurement procedure

For every run PD-Level at CIV and CEV was determined, whereat the second rerun we recorded a 30 second phase resolved partial discharge sample at CIV-level.

3.6 Variation of Settings

As already mentioned we varied some of the parameters (Table 1) according to our previous experiments under synthetic air. The gap length was set from 1 mm to 10 mm and the applied pressure was in the range of 0.1 to 0.5 Mpa (1 to 5 bar).

Table 1: Variation of Parameters

Parameter	Value or Range
Temperature	25°C
Insulation thickness	2 x 6 mm
Gap length	1 – 10 mm
Pressure	0.1 – 0.5 MPa (1-5 bar)
Voltage	0 – 50 kV

4 RESULTS

Some of the obtained results are given in Figure 4 (totally applied voltage), Figure 5 (calculated gap related voltage) and Figure 6 (field strength at CIV). Regarding the totally applied voltage for hydrogen it can be seen that the corona behaviour of the test setup is analogical to the previous results under synthetic air.

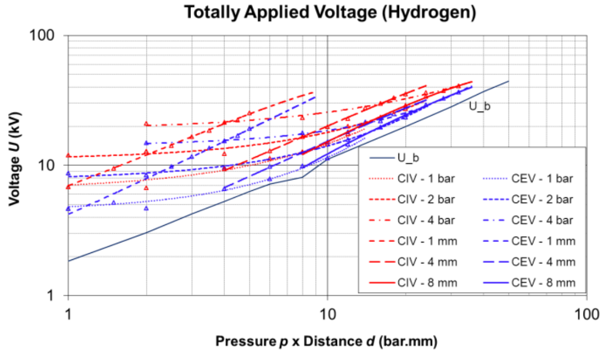

Figure 4: Totally applied voltage (CIV) compared to the Paschen curve (Ub) for Hydrogen at 25°C [6]

The gap related voltage we calculated again following (2) as it is described in [7].

$$U_{gap} = \frac{U_{total} \cdot d}{d + 2 \cdot a \frac{1}{\varepsilon_r}} \qquad (2)$$

U_{gap} .... gap related Voltage (calculated) *
U_{total} .... totally applied voltage (measured) *
d .... gap in mm (distance between insulated electrodes)
a .... thickness of insulation material mm
ε_r .... relative permittivity of the insulation material (dependency of temperature or pressure are disregarded)
* .... U stands for CIV or CEV either in V

Both the hydrogen and the synthetic air values for the gap related voltage are given in Figure 5. It is obvious that the curves for CIV and CEV respectively for hydrogen show similarity with the corresponding air curves. As supposed the values for hydrogen correlate with the classical Paschen's Law within the regarded range of parameters.

Throughout all the experiments the previously noticed scattering of measuring results [7] could be observed and is referred to non-deterministic but random effects of gas discharges.

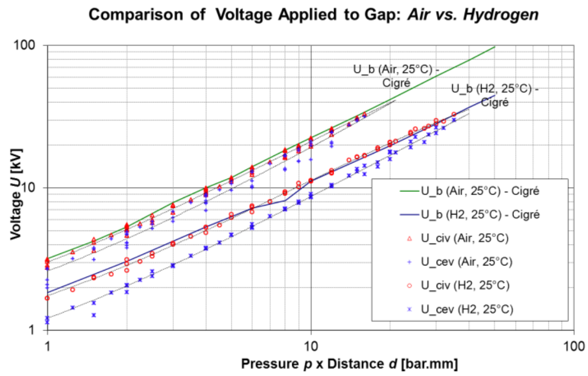

Figure 5: Calculated values for CIV (gap related voltage) compared to the Paschen curve (U_b) for Air and Hydrogen [6]

Regarding the field strength at CIV for synthetic air and hydrogen respectively (Figure 6) the similar corona behaviour can be seen. The curves (each for constant value of pressure) seem to have asymptotical character with increasing gap length.

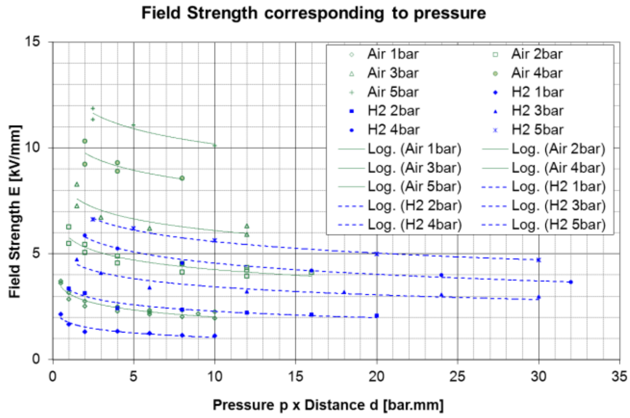

Figure 6: Field Strength at CIV over p.d-product corresponding to certain values of pressure

5 CONCLUSION

On the basis of gas physics and according to the previous tests our experiments indicate a very good correlation to the Paschen's Law in both investigated gases (synthetic air and hydrogen) at 25°C. Experimental results confirmed the expectations for increasing inception and extinction voltage for higher pressures and larger distance using insulated electrodes.

Continued experimental investigations with some modified electrode configurations as well as formulating a mathematical expression relating gap distance to the prescribed pressure and voltage are topics for future work.

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