EVALUATION AND COMPARISON OF MEASUREMENT METHODS FOR DETERMINING THE ELECTRICAL POTENTIAL AT SURFACES BY USING THE EXAMPLE OF END CORONA PROTECTION CONFIGURATION

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Abstract: In this paper measurement methods for detecting the electrical potential along End Corona Protection (ECP) surfaces are compared and evaluated. The ECP consists of semiconducting material, which has the function to ensure a linear potential reduction along the surface. For the optimization of the ECP configuration presently two different measurement methods are applied. One is a compensation method based on a circuit bridge. As a second method, the potential is measured indirectly with an electro-optical miniature field sensor by determining the electrical field based on the pockels effect. For both methods, advantages and disadvantages referring to test setup, measurement range, and sensitivity are outlined.

1 INTRODUCTION

Compact stator end winding design of large turbine generators aims for the ideal total length of END CORONA PROTECTION (ECP). The function of the ECP is to ensure a linear potential reduction between Outer Corona Protection (OCP) and high voltage potential. The smallest possible length is limited basically by the effect of corona inception when the electrical surface field strength exceeds the dielectric strength of the ECP surface locally [1]. In order to determine the electrical field strength at the surface two different methods are compared, the measurement with an electro-optical field sensor and a bridge circuit called the compensation method.

However, until now both methods are restricted to narrow dynamic voltage range measurements and show measurement deviations between each other [2]. Therefore, further developments of the compensation method have to be done for extending test voltage and more accurate and sensitive measurement. The attention is focused on the exact balancing of the zero indicator bridge and exact positioning of the measurement points. Additionally, an optimized connection of the circuit bridge with the test setup is realized to minimize systematic errors. On the other hand an optimized setup is applied for measurements with the optical field sensor.
Based on the results the accuracy of the measurements is estimated and deviations are illustrated. Additionally the useful measurement ranges for both measurement methods are rated.

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2 TEST OBJECT – DESIGN AND SPECIFIC REQUIREMENTS

To compare the different measurement methods, an idealized test object is used, which models a real stator end winding of a large turbo-generator with axially symmetric configuration. The test object consists of an aluminium tube with outer diameter d = 60 mm, coiled with a compound material (resin rich, wet taped) of approximately 1800 mm length representing the main insulation and is provided with an OCP (dimension: 600 mm) in the centre section. A strap made of copper is located in the centre of the OCP and is connected with ground potential. Additionally the test object is fitted at both ends of the OCP with a symmetrically mounted end corona protection (ECP) system of 225 mm length (Figure 1). Both, OCP and ECP are provided with a non-conductive protective coating.

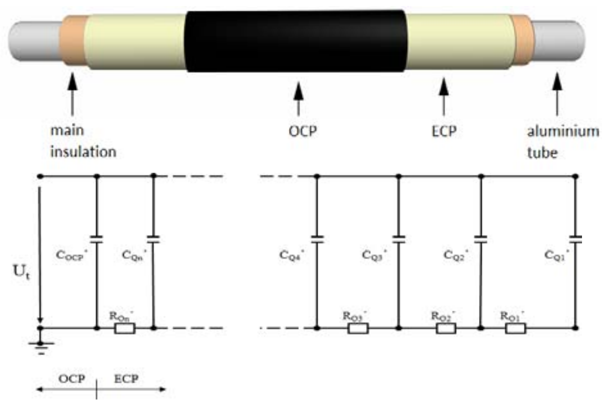

Figure 1: a) Schematic view of the test object with main insulation, Outer Corona Protection (OCP) and End Corona Protection (ECP); b) Equivalent Circuit Diagram

The ECP is realized by a resistive system with non-linear material mounted by various layers, which consists of coatings or tapes. As a result a decrease of the maximal electrical field strength should be realized. Because of the cylindrical setup, the typically used Inner Potential Protection (ICP) in stator winding bars is not applied.

3 THEORETICAL PRINCIPLES OF MEASUREMENT METHODS

3.1 Measurement of the surface potential with a bridge circuit

One well-known method for minimizing the local flow of charge carriers from the ECP surface is compensation system with bridge circuit [3][4]. The compensation is realized by an electrode, which is fixed at the surface of the ECP and which is connected with a zero indicator. The zero indicator consists of a capacitive divider and an electro-optical coupler, it operates at high potential. The detected voltage can be transmitted potential-free via optical fibre. With the help of an oscilloscope, both, voltage and phase are detected. For completely compensation voltage and phase must be in balance. This is realized by a compensation transformer, a separating transformer and a phase shifter (Figure 2).

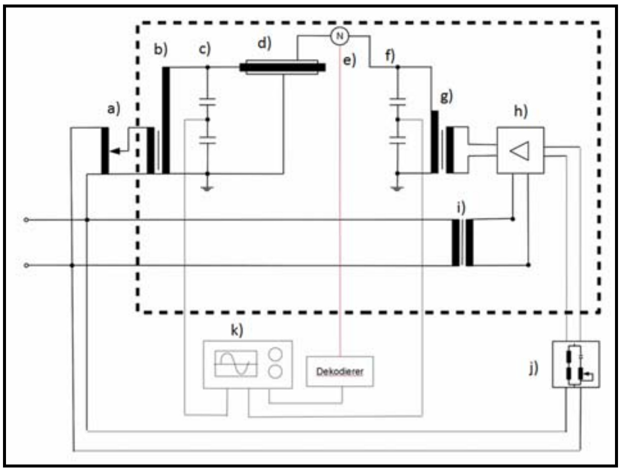

Figure 2: Schematic setup of the compensation method with a) adjustable transformer; b) test transformer; c) capacitive divider; d) test object with electrode; e) zero indicator; f) capacitive divider; g) compensation transformer; h) power amplifier; i) separating transformer; j) phase shifter within a shielding section

3.2 Measurement of the surface potential with an electro optical sensor

The application of an electro optical miniature sensor enables a direct measurement of the electrical field with relatively small influence on the test object environment. In comparison with the compensation method, which embodies a direct measurement of surface voltage resp. potential, the potential between two points φ_{12} is determined by the integral of electrical field E along the surface way as shown in (1) [5].

$$U_{21} = \Delta\varphi_{21} = \varphi_2 - \varphi_1 = \int_2^1 E\,dx \qquad (1)$$

The electro optical sensor works by using of the linear pockels effect, which causes a linear double refraction in optical anisotropic crystals. In detail the sensor consists of a reflective measurement setup: A super luminescence diode generates a light ray with a wavelength of λ = 818 nm, which is coupled in a polarising optical fibre. The polarised ray leads - after transforming the light in circular light - to a BTO (Bariumtitanyloxid) crystal, which rotates the light depending on the existing (one-dimensional) electrical field.

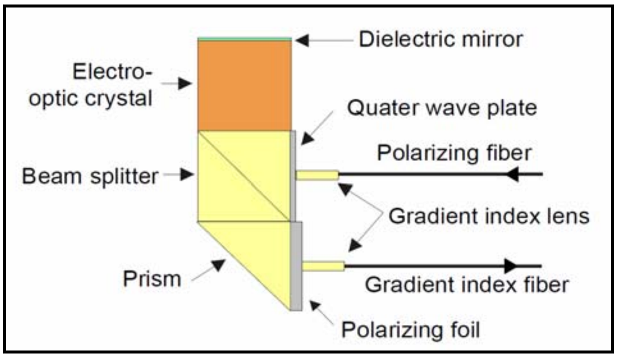

Figure 3: Schematic setup of the electro optical field sensor [6]

After reflecting the light at the end of the crystal with an dielectric mirror, the ray light passes a polarisation filter and a second optical fibre (Figure 3). A photo diode and a trans-impedance amplifier (R_{ampl}) transform the ray light (photo-current I_{photo}) to a proportional electrical signal U_{out}.

$$U_{out} = R_{ampl} \cdot I_{photo} \qquad (2)$$

The electrical voltage signal is – after being filtered by AC and DC signal – analysed. The effective electrical field is given through a normalisation of U_{AC} and U_{DC} multiplied with a calibration factor k.

$$E = \frac{U_{AC}}{U_{DC}} \cdot k \qquad (3)$$

In this way ray fluctuation caused by attenuation is minimized. The course of the electrical potential is calculated by the measurement of the electrical field at discrete positions and by use of the Riemann integral.

$$\varphi(n) = \sum_{i=2}^{n} \varphi(n-1) + \overline{E}(n) \cdot \Delta s \qquad (4)$$

The electrical field strength between two points is calculated using the mean values of the electrical field.

4 TEST SETUPS

For the test setups with the compensation method and optical field measurement according to a 100 kV high voltage test transformer, which is supplied by a 230 V ring transformer is used. All setups are build up in a shielded test laboratory [7].

4.1 The bridge circuit

The electrode configuration for contacting the surface of the test object bears a central challenge. The electrode has to be mounted adjustable along the surface and has to connect constantly without damaging the insulation. This is realized both mechanically and electrically by a cylindrical spring. The spring is connected by a dielectric retaining jig fixed on a rail system and with the zero indicator by use of a moveable measuring cable (Figure 4).

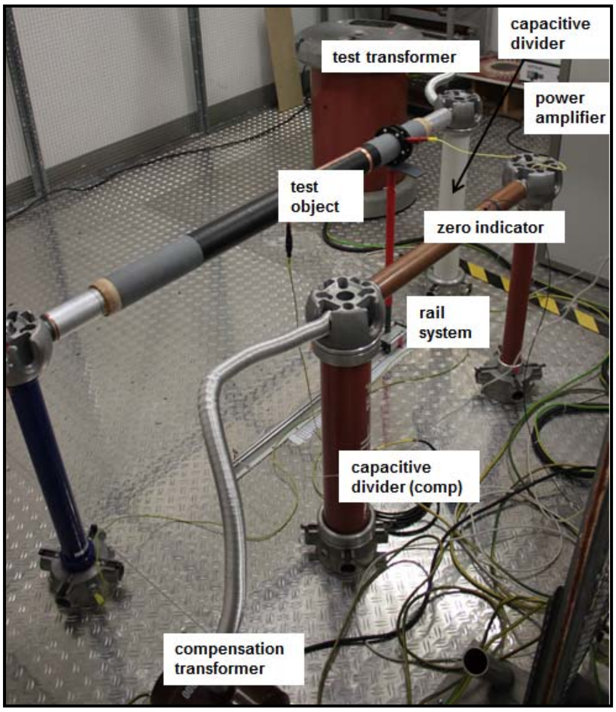

Figure 4: Test setup with bridge circuit

Due to the complex insulation of the test object, the applied phase shifter has to adjust the phasing to 90° inductive and 90° capacitive direction. The phase shifter and potentiometer is connected with a power amplifier and a 30 kV test transformer. The compensation voltage is measured by a capacitive divider. All sources (test voltage, compensation voltage, zero-indicator voltage, potentiometer voltage) are registered parallel with a 4-channel oscilloscope (Figure 5).

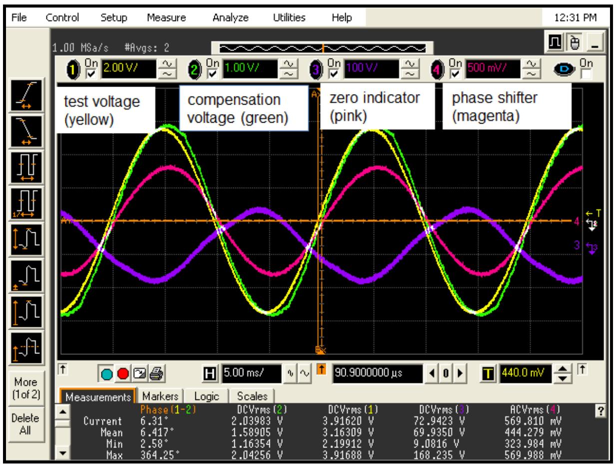

Figure 5: Screen shot of 4-channel oscilloscope during compensation measurement

The phase information is determined by detection between test and compensation voltage.

4.2 The electro-optical field sensor

The calibration of the electro-optical field sensor is realized by a defined electrical field strength, which is generated with a measuring spark gap.

To measure the electrical field strength at the surface of the ECP, the sensor is placed directly above the surface (1-2 mm distance between test object and sensor head). The sensor head is connected with a glass tube, which is applied on a tripod with a rail system (Figure 6).

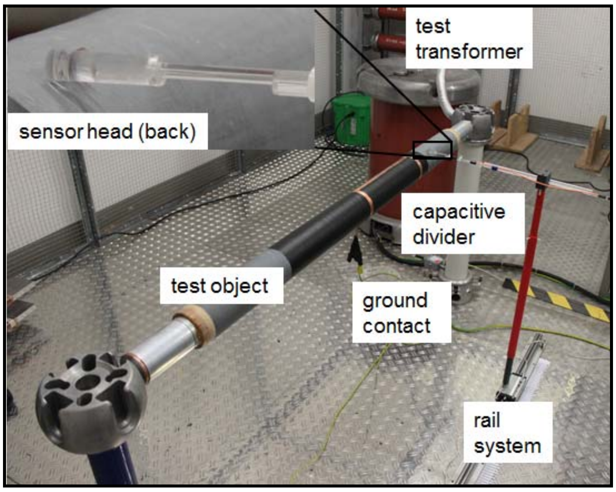

Figure 6: Test setup with electro-optical sensor

The rail system is moved during the measurement via two insulated ropes.

5 EVALUATION

The measurements with both methods are realized with two different test voltages:

$$1.\quad \frac{\hat{U}_{t1}}{\sqrt{2}} = 10kV; \qquad 2.\quad \frac{\hat{U}_{t2}}{\sqrt{2}} = 20kV$$

To get a steady-state condition at the test object, the test voltage is applied several minutes before starting the test sequence and is realized under standard conditions. The first measurement point is set at the crossover OCP/ECP (x = 0 mm).

5.1 Results with the bridge circuit

The following diagram shows the potential curve for both test voltages by the compensation method (Figure 7).

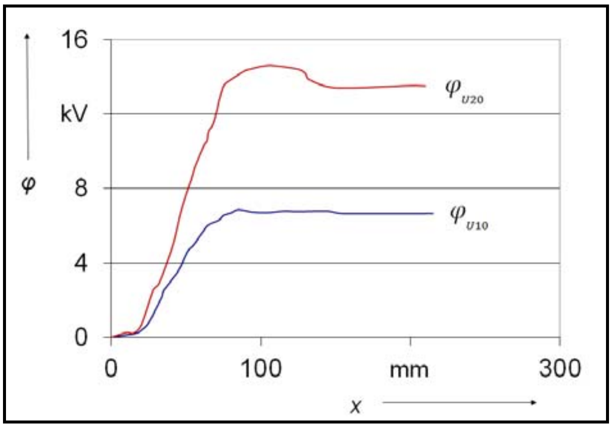

Figure 7: Potential curves with the bridge circuit for test voltages U_{t1} = 10 kV and U_{t2} = 20 kV

It is obvious, that the potential increases at the beginning of the ECP for both voltages. The highest values are given for U_{t1} = 10 kV after x = 93 mm, for U_{t2} = 20 kV at x = 118 mm with approximately 70 - 75 % of test voltage value. Subsequently the potential attenuates slightly till the end of the ECP. A reason could be seen in an influence by the working electrode, which should be located on the equipotential line resp. causes a electrical field distortion at the surface of the test object. Consequently - especially if the electrical field is unknown - a measuring inaccuracy is given.

5.2 Results with the electro-optical field sensor

For the calibration an electrode gap of d = 50 mm is chosen. Several test voltages are applied to ensure the linearity in a dynamic voltage range.

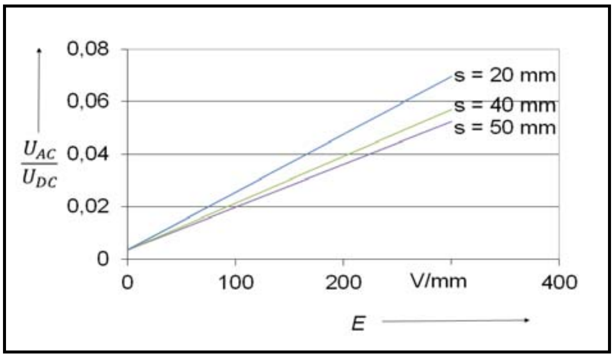

Figure 8: Calibration plot with electro-optical field sensor for different distances to the electrodes

Figure 8 shows calibration plots, which display the approximately linear trend between the applied electrical field and measured voltage with photo diode and amplifier. The plots present a regression line with error margins for each point. The linearity is within a measurement error less than 5 % between *E* = 20…350 V/mm. However, quadrature axis component and distance to the electrodes are influencing the signal strength. Therefore the distance between the electrodes and the angle between electrical field and sensor are varied for matching the factor k.

The following diagrams show both, the potential curve and the electrical field strength (tangential, radial and total) for both test voltages with the electro-optical field sensor (Figure 9, Figure 10).

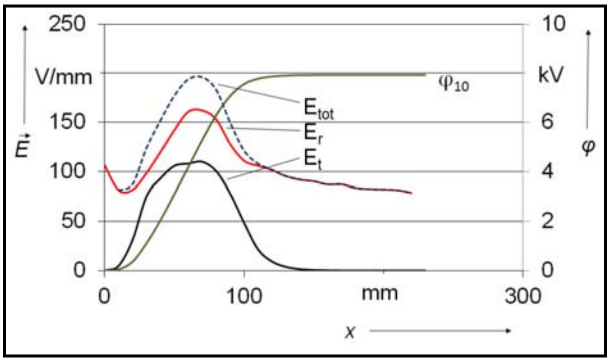

Figure 9: Potential curve and electrical field strength (tangential, radial and total) for U_{t1} = 10 kV with the electro-optical field sensor

The highest field strength gradient is located in the forward sector of the ECP and increases until x = 70 mm for U_{t1} = 10 kV and until x = 90 mm for U_{t2} = 20 kV.

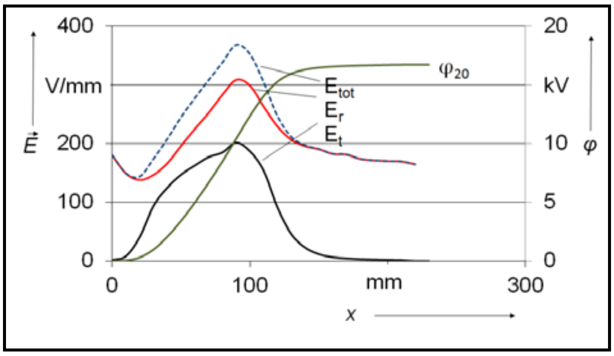

Figure 10: Potential curve and electrical field strength (tangential, radial and total) for U_{t2} = 20 kV with the electro-optical field sensor

The electrical field in radial direction has a similar trend as the tangential one with higher values. Due to a faster decrease of the tangential field (till zero) at the end of the ECP the total radial and total electrical field agree completely in the last sector.

5.3 Comparison of both methods

To compare the results of both methods the measurement series are shown in the following diagram (Figure 11).

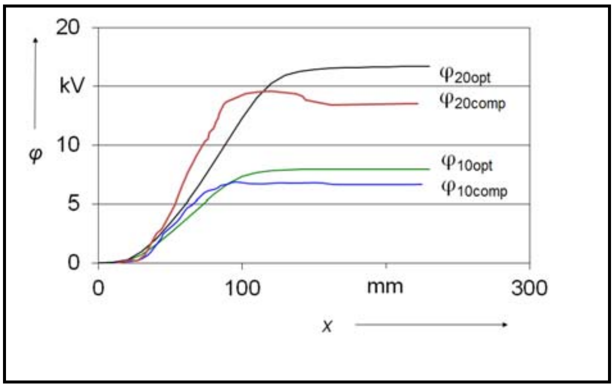

Figure 11: Comparison of potential curve for both measuring methods with applied test voltages

At the beginning of the ECP (0 mm < x < 70 mm) there is a good conformity of both methods with both test voltages. However, the bridge circuit is yielding a higher gradient in the first sector of the ECP. Due to (3) the potential rises with the electro-optical method smoothly and achieves the maximum at the end of the ECP. Based on the slight falling of the curve for the compensation method, the maximal deviation is given in the center of the ECP resp. at the end of the ECP.

In both cases there is a rest voltage drop in the sector of the main insulation (after the ECP section).

6 SUMMARY AND CONCLUSION

The applied methods can be seen as suitable measuring methods for experimental qualification of ECP functionality in this particular case and in general to determine the electrical potential or electrical field strength at surfaces of insulation configurations.

A visible advantage of the usage of the electro-optical field sensor is a simplified setup. For the qualification of ECP functionality it makes sense to get direct information about the electrical field. This is given by the physical background of the sensor based on the pockels effect. For extreme low resp. high electric field strength (E < 50 V/mm, E > 600 V/mm) the required accuracy is restricted and the electrical stability is not given anymore. Furthermore a strongly inhomogenous field and measurements close to electrodes influence the signal.

For the determination of the electric potential the bridge circuit is approved as a practical measurement method. The advantage is the theoretical wide measurement range. A high sensibility is given by a well-functioning zero indicator with ensured contacting of the test object. A disadvantage can be seen in the more complicated setup, e.g. all applied instruments have to be designed against overvoltage and the phase shifter and potentiometer have to guarantee a wide range and a high accuracy.

7 REFERENCES

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