Thompson-Lampard Theorem for Dielectric Characteristics Detection of Generator Stator Insulation

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Abstract. The insulation of large generator stator winding will be gradually aging in the long-term operation process. The traditional aging test method cannot accurately locate the non-penetrating local defects of winding. Interdigital electrode is widely used in the fields of environmental monitoring and food detection because of its excellent characteristics such as self-closing and unidirectional penetration, but it has not been popularized in the identification of generator insulation aging. The paper proposes an interdigital electrode structure based on the Thompson-Lampard theory. The electrode suitable for dielectric characteristic detection of stator winding, and the electrode structure is optimized by using the finite element method from the parameters of signal strength, sensitivity and penetration depth. With the help of optimising, the measuring accuracy of the electrode can reach 0.1 level. Then, the different moisture conditions of water-cooled generator and air-cooled generator are simulated to verify the feasibility that interdigital electrode can detect insulation moisture which is an important factor in accelerating insulation aging. Finally, the moisture depth detection results show that the electrode combination based on the Thompson-Lampard theory can be used to locate moisture depth accurately, it is of great significance for the prevention of insulation aging and the pre-diagnosis.

1. Introduction
The stator winding insulation of generators is subject to electric field, thermal stress, mechanical stress and external environmental influences during operation, and is inevitably damaged and gradually deteriorated during long-term operation. The trend of the material's dielectric constant, dielectric loss tangent and other parameters reflects the degree of insulation deterioration [1,2]. The traditional method of measuring the whole phase winding capacitance and dielectric loss factor to judge the deterioration of stator winding insulation cannot effectively test the non-penetrating local defects. The dielectric loss test of the whole machine is affected by the field temperature, humidity and electromagnetic interference. The result has a large deviation [3]. Measuring the local dielectric characteristics to accurately determine the insulation status of the specified location is an efficient sampling test method. Compared with the method of measuring the dielectric characteristics of the phase winding, the difficulty and destructiveness of the test are reduced, and the economy is improved.

The traditional method of using parallel plate electrodes or other improved electrodes to detect insulation is to make the electrodes and the conductor form an electric field. Such a structure will cause errors due to the change of the insulation thickness, and the measurement result will be affected by stray capacitance and edge effects, and it cannot measure the characteristics of the medium itself accurately [4]. Interdigital electrode can overcome the above adverse effects because of self-closing.
and unilateral penetration characteristics. It is now widely used in atmospheric environment monitoring [5], food safety testing [6], material flaw detection [7] and other fields, but it has not been popularized in the field of generator insulation diagnosis. Interdigital electrode sensors can be used as the application carrier of advanced technologies such as insulation dielectric spectroscopy, and have broad development prospects in the fields of insulation life diagnosis and sampling evaluation.

This paper constructs the interdigital electrode model based on the cross-capacitance theory proposed by Thompson-Lampard, uses finite element simulation software to design the electrode structure parameters and optimize the performance, verify the feasibility of insulation moisture detection, and finally propose a method for detecting insulation moisture depth. The interdigital electrode sensor based on the principle of cross-capacitance is suitable for the study of the local dielectric characteristics of stator insulation.

2. Capacitance measurement system based on the principle of cross capacitance

Thompson-Lampard theorem [8] proposes: In a conductive cylindrical shell with a cross-section S, two planes AC and BD with an angle of 90° divide the cross-section S into four parts, as shown in Figure 1. Under the influence of the electric field inside the shell, if the line of intersection between the plane AC and the section S is the symmetry axis of the section S, the capacitance per unit length between the opposite parts of the cylinder (β and δ or α and γ) is a fixed value as shown in equation (1). As shown. Using the Christoffel-Schwarz formula to transform the conductive cylindrical shell into conformal mapping, the infinite planar cylindrical capacitor system in the Cartesian coordinate system can be obtained as shown in Figure 2. Let the lengths of the β and γ planes be respectively b and a, the capacitance value between α and γ satisfies equation (2).

Figure 1. Conductive cylindrical shell structure diagram

Figure 2. Infinite Planar Cylindrical Capacitor System.

\[ C_0 = \frac{\log_2 \frac{a}{b}}{4\pi^2} \text{e.s.u} = \frac{\varepsilon_0 \varepsilon_r}{\pi} \ln 2 = 0.01954 \times \varepsilon_r \text{ (pF / cm)} \]  

where: \( \varepsilon_0 = 8.85418 \text{ pF/m} \) vacuum relative permittivity and \( \varepsilon_r \) is relative permittivity

\[ C\left(\frac{a}{b}\right) = \frac{\varepsilon_0 \varepsilon_r}{\pi} \ln \left(1 + \frac{a}{b}\right) \]  

When the following conditions are met, the plane γ width a is equal to Plane β width b, The unit length capacitance value between α and γ satisfies equation (1) [9]. When the capacitor system is placed in air medium, assume the capacitor length is 51.19cm, then the capacitance between planes α and γ is 1pF, and the sum of the upper and lower planes of the total capacitance is 2pF. Similarly, when the electrode structure is fixed, the relative dielectric constant of the measured medium can be deduced according to the measured capacitance.
3. Finite size interdigital electrode topology

3.1. Finite size planar electrode group

In order to topology the infinite planar cylindrical capacitor to a finite size, a finite-size planar electrode group is constructed. Each metal strip in the electrode group is a meta-electrode, and a sub-electrode is composed of one or several meta-electrodes. An electrode group contains four sub-electrodes, and the spacer sub-electrodes 1 (G1), driving sub-electrodes (H), spacer sub-electrode 2 (G2) and the sensing electrode (L) are arranged in this order.

Figure 3. Electrode group model established in finite element simulation software.

The finite element simulation model of the electrode group is established (as shown in Figure 3), and the structural parameters of the planar electrode group that meet the characteristics of the infinite planar cylindrical capacitor system are studied by adjusting the number of meta-electrodes that constitute each sub-electrode. According to the requirements of the cross-capacitance principle, the widths of the H sub-electrodes and G2 sub-electrodes are both \( x \). The width of the G1 sub-electrode and the L sub-electrode is set to \( y \) (corresponding to the \( \alpha \) and \( \delta \) parts of the infinite planar cylindrical capacitor system), the meta-electrode length is 51.19cm, the meta-electrode spacing is 0.05mm, and the meta-electrode thickness is 0.015mm. The copper (\( \varepsilon_r=1 \)) electrode made of material is placed in the air medium (\( \varepsilon_r=1 \)). An AC signal with a frequency of 1kHz and an amplitude of 1V is applied to the H sub-electrode, and the capacitance between the H electrode and the L electrode is measured. When \( x \) and \( y \) take different values, the variation trend of capacitance measurement error with the ratio of sub-electrode width is shown in Figure 4.

Figure 4. The influence of the width of the sub-electrode on the measurement accuracy of the interdigital electrode.

It can be seen from Figure 4 that as the ratio of the sub-electrode width increases, the measurement error of the interdigital electrode becomes smaller and smaller. Increasing the width of the meta-
electrode can improve the measurement accuracy to a certain extent. When the width of the L sub-electrode exceeds the width of the H sub-electrode 6 times, it can be considered that the measured value of the interdigital electrode is equal to the theoretical value of 2pF within the error range of 1%. In other words, when the width of L sub electrode in the electrode group is more than 6 times that of H sub electrode, the measurement characteristics accord with the theory of infinite planar cylindrical capacitor system mentioned above.

3.2. Interdigital electrode total electrode structure

When a single electrode group is used to measure the dielectric constant, the measurement signal strength is small, and the measurement accuracy is difficult to guarantee. In order to meet the measurement characteristics of the infinite planar cylindrical capacitor system, the effective utilization rate of some sub-electrodes is low \( y/x \geq 6 \), which does not meet the requirements for portability in practical applications. In order to improve electrode utilization and signal strength, fixing the sub-electrode width ratio to 1, and constructs the interdigital electrode total electrode by establishing a repeated electrode group.

When the sub-electrode width ratio is fixed to 1, the measurement error of a single electrode group is relatively large. Therefore, this section uses simulation analysis to study the influence of the number of electrode groups repeated on the measurement error. Taking the meta-electrode with a width of 1mm as the basic unit, the number of meta-electrodes constituting the G1, H, G2, and L sub-electrodes is the same \( y/x=1 \), and the other parameters are the same as the simulation above. The simulation test takes the number of electrode groups \( k \) and the width (number) \( x \) of the meta-electrodes as independent variables, and records the actual measured value of the total electrode capacitance and the theoretical value \( 2k \) (in air medium, the capacitance value of a single electrode group is 2pF, and \( k \) electrode groups is the error between \( 2k \) pF), and the error trend curve is shown in Figure 5.

![Figure 5. The influence of the width of the sub-electrode on the measurement accuracy of the interdigital electrode.](image)

Figure 5 shows that when the total electrode is composed of a group of electrodes (G1-H-G2-L), the measurement error is about 10% (the number of meta-electrodes has a small effect on the measurement error, and the error is reduced by about 0.02% for each additional electrode group.), as the number of electrode groups constituting the total electrode increases, the measurement accuracy increases rapidly. When the number of repetitions exceeds 10, the error trend slows down. It can be considered that the number of electrode repetitions is basically decoupled from the electrode measurement value. According to the above results, when the number of repetitions of electrode groups exceeds 10, the total electrode capacitance measurement value is equal to the theoretical calculation value within 1% error range. By increasing the number of electrode groups, the measurement accuracy can be further improved and the signal strength can be enhanced.
4. Detection of insulation local defects based on interdigital electrodes

4.1. Key parameter design of interdigital electrode

The simulation model of a single electrode group of the interdigital electrode structure is shown in Figure 6, where the ratio of the widths of the driving sub-electrodes, the sensing sub-electrodes, and the spacer sub-electrodes is 1:1:1 (the width of the meta-electrode is w, and the number of meta-electrodes is n); According to the electrode manufacturing process and common winding size, the electrode thickness is set to 0.015 mm, the electrode length is 40 mm, the electrode thickness is set to 0.015 mm, the electrode spacing is 0.05 mm, and the thickness of the substrate (relative dielectric constant $\varepsilon_m=4.5$) is h mm; the total electrode consists of 10 electrode groups.

![Figure 6. Structure model of interdigital electrode single electrode group](image)

![Figure 7. Finite element simulation model of interdigital electrode single electrode group.](image)

The study of electrode parameters of planar capacitive sensors usually analyses the signal strength, sensitivity, penetration depth and other indicators [6,7,10]. The signal strength is the sensor's output capacitance value $C_0$ in the air medium (dielectric constant is $\varepsilon_0$), and the sensitivity $S$ is the degree of change of the sensor's output capacitance value with the measured dielectric constant of the medium, expressed by equation (3). It can be seen from equation (3) that the trend of sensitivity is the same as the trend of signal strength. Set the tested materials to air ($\varepsilon_0=1$) and mica ($\varepsilon_s=6$). From the simulation results Table 1, it can be seen that the substrate thickness h and the width of the sub-electrodes (the width of the element is w, the number of the element n) do not affect interdigital electrode sensitivity (considering 1% measurement error). Because the cross-capacitance principle defines the ratio of the width of the sub-electrodes, the gold plating rate does not change when the width of the sub-electrodes changes. It can be seen from Figure 8 that when the number of element electrodes is 1 to 3, choosing a substrate with a thickness of 20mm and above can compensate for the difference in signal intensity caused by the different width of the sub-electrodes (initiating different penetration depths, see below).

$$S = \frac{C_s - C_0}{\varepsilon_s - \varepsilon_0}$$ (3)

| Meta-electrode width (mm) | Substrate thickness (mm) | Sensitive  | 1meta-electrode | 2meta-electrode | 3meta-electrode |
|--------------------------|--------------------------|------------|----------------|----------------|----------------|
| 0.5                      | 1                        | 0.7738     | 0.7737         | 0.7718         |
|                          | 30                       | 0.7736     | 0.7736         | 0.7717         |
| 1                        | 1                        | 0.7733     | 0.7736         | 0.7732         |
|                          | 30                       | 0.7732     | 0.7734         | 0.7733         |
| 1.5                      | 1                        | 0.7732     | 0.7733         | 0.7734         |
|                          | 30                       | 0.7732     | 0.7732         | 0.7735         |
The definition of sensor penetration depth [11] is equation (4). Set the measured material under the electrode to mica ($\varepsilon_r=6$), record the mutual conductance capacitance value of the sensing electrode during the process of increasing the thickness of the mica layer under the electrode from 1mm to 10mm, and convert the capacitance value into the electrode penetration depth according to the definition of penetration depth. The influence of the sub-electrode width on the penetration depth is shown in Figure 9. It can be seen from the figure that the penetration depth of the sensor is directly proportional to the width of the element electrode and the number of elements. The regression line equations of the number of element electrodes $W_1$, the width of element electrodes $W_2$ and the penetration depth $P$ are calculated by using the least square method, as shown in equation (5).

\[
\frac{C_r - C_o}{C_{max} - C_o} \times 100\% = 97\%
\]

\[
P = 1.9 \times W_1 \times W_2 - 0.15 \times W_2 + 0.03 \times W_1 + 0.28 \quad \text{(mm)}
\]
row of insulated thin-wall high resistance nickel alloy vent pipe is placed in the middle. [13], in order to meet the needs of stator bars of different structures, the electrode length is 40mm under the premise of ensuring the signal strength. The detection depth of the sensor should match the insulation thickness of the winding. The main insulation thickness $\delta_i$ (single side) of the generator with a rated voltage of 18kV in China is about 5.3mm according to equation (6) [13]. According to equation (5), the number of sub-electrodes should be three. It is composed of element electrodes with a width of 0.8mm.

$$\delta_i \geq 0.24U_n + 1 \quad \text{(mm)}$$

In summary, taking the stator bar insulation of a water-cooled generator with a rated voltage of 18kV as the detection object, the electrode parameters of the stator insulation local detection based on the principle of cross-capacitance are as follows: the total electrode is composed of 10 electrode groups, and the sub-electrodes consist of three meta-electrodes with a width of 0.8mm, a length of 40mm, and a thickness of 0.015mm (as shown in Figure 9). The metal electrode will be fixed on a substrate with a thickness of 20 mm.

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4.2. Simulation analysis of insulation moisture detection

This section takes insulation moisture as an example, and analyses the principle of insulation defect detection based on interdigital electrodes. Generators with different cooling methods are mainly affected by moisture for different reasons. The surface of solid insulation medium of air-cooled generator is exposed to air. When entering shutdown state from operation state, the interior of air-cooling chamber absorbs external air due to thermal expansion, and the insulation absorbs water in the air, resulting in moisture [14]. For the generator with direct water cooling of stator winding, the reason is the leakage of water from the gap of hollow copper strand wire in the water joint box due to poor welding [15].

The finite element method is used to simulate the moisture condition of the insulation. The unilateral insulation of the stator winding is set to 5mm thick and divided into 5 layers evenly, numbered 1 to 5 from top to bottom, as shown in Figure 11. By sequentially replacing the medium from mica ($\varepsilon=6$) to water ($\varepsilon=80$) in each layer, the process of damp degradation of the insulation is simulated, and the damp condition is detected using the interdigital electrode form proposed in Section 4.1. For air-cooled generator, the outside of the insulation gets moisture due to the absorption of moisture in the air, while for water-cooled generator, the inside of the insulation gets moisture due to poor welding.
Figure 12 shows the trend of the measured value of the interdigital electrode sensor under different moisture conditions. It can be seen that the interdigital electrode sensor can be used to detect the fault characteristics of the insulation damp.

4.3. Study on detection method of insulation moisture depth.

According to the existing conclusions, when the sub electrode width ratio of two interdigital electrode sensors is same, the relative permittivity measured between the induction electrode and the driving electrode in the same medium is same (the measured capacitance is converted into the relative permittivity by equation (1)), which is independent of the specific value of the sub electrode width. With this characteristic, a detection method for locating the moisture depth of insulation is proposed in this section.

The two cases that the inner side of the insulation is first affected by moisture due to poor welding and the outer side of the insulation is first affected by moisture due to absorption of moisture in the air are discussed respectively. Three groups of interdigital electrode sensors are used to simulate and test the capacitance value of the insulation. The only variable of the three groups of electrodes is the number of meta-electrodes constituting the sub-electrode (the meta-electrode width is 0.8mm). The other electrode parameters are the same as those set in Section 4.1, and the electrode width variables are set as follows

- Electrode A: each sub-electrode is composed of one meta-electrode;
- Electrode B: each sub-electrode is composed of two meta-electrodes;
- Electrode C: each sub-electrode is composed of three meta-electrodes.

Theoretically, the relative dielectric constants of electrodes A, B and C measured in the same dielectric are the same, but the detection depths of the three groups of electrodes are different. According to equation (4), the detection depths of electrodes A, B and C are 1.71mm, 3.26mm and 4.81mm respectively. The simulation diagram of insulation moisture depth detection is shown in Figure 13. The mica insulation board with a thickness of 1cm is used ($\varepsilon = 6$) The upper part of the is
divided into 5 layers (No. 1 ~ 5), and the mica material is replaced with water from layer 1 to layer 4 (internal moisture) or layer 5 to layer 2 (external moisture) (ɛ= 90), respectively use three electrodes with different detection depths to detect the moisture depth of the test object.

Figure 13. Simulation diagram of insulation moisture depth detection.

The Figure 14 shows simulation results, if the inner side of the insulation is damped first, under the condition of 1mm ~ 2mm damp (damp defects appear within 4mm below the electrode), electrode A and B cannot obviously measure the change of damp depth due to the limitation of detection depth, The change rate of measured value of electrode C (theoretical detection depth 4.81mm) began to increase; as the moisture depth increased to 3mm (moisture defects appeared within 2mm below the electrode), both electrode C and electrode B (theoretical detection depth 3.26mm) could detect the change of moisture depth; electrode A had the narrowest electrode width, and the theoretical detection depth was 1.71mm. In the simulation, when the moisture depth increased to 4mm (i.e., there is a damp defect 1mm below the electrode), the measured capacitance reflects the change of damp depth

For the case that the outer side of the insulation is damped first (see Figure 15, right), when the upper surface of the insulation is damped by 1mm, the relative dielectric constant measured by electrode a is much larger than that of electrode B and electrode C, because the proportion of the damped part within the detection range of electrode A (1.71mm) is large, while the proportion of the dry part within the detection range of electrode B and electrode C is large. When the damp depth exceeds 2mm, the proportion of the damp part within the detection range of electrode B (3.26mm) increases, and the measured value increases significantly; when the damp depth reaches 4mm (basically covering the detection depth of each electrode), the measured values of electrodes A, B and C are basically the same.

Figure 14. Measured value of electrodes with different widths to changes in insulation moisture depth. (moisture from the bottom)
According to the above characteristics, a detection method for the depth location of insulation defects is proposed: multiple groups of interdigital electrode sensors with different sub-electrode widths are selected according to the thickness of the tested object. The moisture depth can be judged according to the different measured values. The specific steps are as follow:

Step 1: judge whether damp from bottom or from top

Judge by the measured value of electrode A (with minimum sub-electrode width): When the measured value of electrode A is the maximum value among the groups of electrodes, it indicates that the top is moisture first;

When the measured value of electrode A is the minimum value measured among the groups of electrodes, it indicates that the bottom is damped first.

Step 2: for the case that damp from bottom

- \( \varepsilon_{\text{electrode A}} \approx \varepsilon_{\text{electrode B}} \approx \varepsilon_{\text{electrode C}} \): the moisture range exceeds the detection range of electrodes A, B and C;
- \( \varepsilon_{\text{electrode A}} \approx \varepsilon_{\text{electrode B}} < \varepsilon_{\text{electrode C}} \): the moisture range is between the detection range of electrode B and electrode C;
- \( \varepsilon_{\text{dry}} \approx \varepsilon_{\text{electrode A}} < \varepsilon_{\text{electrode B}} < \varepsilon_{\text{electrode C}} \): the moisture range is between the detection range of electrode A and electrode B (the relative dielectric constant value of the dry insulation can be obtained before the generator is put into operation);
- \( \varepsilon_{\text{dry}} < \varepsilon_{\text{electrode A}} < \varepsilon_{\text{electrode B}} < \varepsilon_{\text{electrode C}} \): the damp depth is within the detection range of electrode a.

Step 3: for the case that damp from top

- \( \varepsilon_{\text{electrode A}} > \varepsilon_{\text{electrode B}} > \varepsilon_{\text{electrode C}} \): the damp range accounts for the main part of the detection range of electrode a;
- \( \varepsilon_{\text{electrode A}} \approx \varepsilon_{\text{electrode B}} > \varepsilon_{\text{electrode C}} \): the damp range accounts for the main part of the detection range of electrodes A and B;
- \( \varepsilon_{\text{electrode A}} = \varepsilon_{\text{electrode B}} = \varepsilon_{\text{electrode C}} \): the damp depth accounts for the main part of the detection range of electrode C;

5. Conclusion

Based on the Thompson-Lampard theorem, an interdigital electrode is proposed. The electrode parameters are optimized from the perspective of measurement accuracy, signal strength and sensitivity. The electrode structure is suitable for the detection of local dielectric characteristics of insulation which measuring accuracy can reach 0.1 level.
The trend of insulation dielectric constant measured by interdigital electrode can be used as the basis for judging insulation moisture. A detection method for the depth location of insulation defects is proposed: the insulation thickness of generators with different voltage levels is different, and multiple groups of interdigital electrode sensors with different sub-electrode width are selected for measurement based on the insulation thickness. According to the difference of measured values, the moisture direction and moisture depth can be diagnosed.

To achieve carbon peak and neutrality targets, for the expired generators that meet the energy efficiency index and complete the ultra-low emission transformation, the "life extension" operation is an important way to optimize the stock under the condition of ensuring the safety of the equipment. Interdigital electrode detection technology based on Thompson-Lampard theorem is of great significance for the evaluation of generator life extension operation such as insulation state detection and aging diagnosis.

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