# *Characterization in Medium Voltage Stator Coils using Dielectric Frequency Domain Spectroscopy*


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***Abstract*—The Dielectric Frequency Domain Spectroscopy (FDS) is a widely used test to estimate the moisture content in power transformers. However, this diagnostic technique has potential to be utilized in different applications where the moisture level estimation is a critical parameter. In this paper, the FDS has been tested for moisture characterization in stator-winding coils. The main idea is being able to evaluate the moisture content during stator winding coil manufacturing. The laboratory test described in this paper has been carried out by moistened and de-moistened controlled laboratory tests, using FDS sweeps and measuring the moisture content by the coil weight.**



***Keywords—Rotating machines, Moisture, Frequency Domain Spectroscopy, Stator-Winding Coil, Dissipation Factor***


## I. INTRODUCTION

It is clear the importance of electric rotating machines for the industry and electrical transportation, these are the main equipment that impulse the economic development and are fundamental in almost every easement that modern society enjoy. To ensure, the continuity in the productive and transportation processes, each component of rotary machines should work correctly, and this requires an excellent design and fabrication method, as well as the proper execution of the maintenance tasks, that mandate includes, apparatus condition testing.

A good maintenance process allows, in most of the cases, not only to increase the uninterrupted working hours but also to decrease the extra maintenance outcomes avoiding worst damages, triggered by the initial fault that was not corrected on time [1]. These types of maintenance require investment, knowledge and adequate testing equipment that allows to perform continuous monitoring that inform the machine condition. When testing tools offer more information about the equipment condition, allowing to take accurate decisions such as the specific timing or place/piece to carry out a specific maintenance task, this technique is better known as Condition Monitoring (CM) [2]. There are plenty of applications in electric power systems components with advances in CM which brings deep machine state information; rotary machines are not the exception.

In rotary machines, there are multiple CM techniques for detecting windings, rotor and stator faults [3], however, there still are some harmful aspects, as moisture and humidity characterization, that are not covered by ay CM technique in this type of machines.

There are some recent research that focus on moisture and humidity phenomena in water-cooled windings of large rotary machines, as presented on the study of Humidity on dielectric response of Rotating Machines Insulation System [4], which focuses in testing the dielectric response in bar and coils varying the relative humidity in an electronically controlled environmental chamber. Reference [5] details an intrusive electronic device for detecting wet stator-windings in large machines with water-cooled windings; and others, focuses their research on the preservation of large motor and generators from weather [6].

In transformers, the moisture effects already have a condition monitoring tool which brings prompt analysis to determine moisture in pressboard and paper for oil-paper-insulated transformers as presented in [7] and is widely applied as shown in [8] and [9].

## II. BACKGROUNDS

In this section, the different existing dielectric assessment techniques are briefly described.

### *A. Traditional Dielectric Analysis Methods*

The traditional methods for insulation analysis are based on the dissipation factor measurement, as specified in the most relevant standards [10]. However, for stator-winding insulation analysis, these methods are limited only to specific points or small frequency ranges, which does not allow determining the root causes of insulation degradation.


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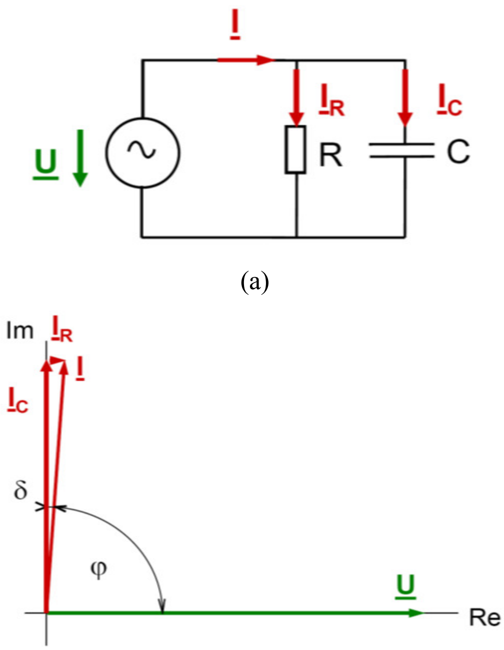


Fig. 1. Measurement scheme for determining creasing moisture content in the Coil (a) circuital scheme (b) Phasor diagram

These methods are generally based on AC voltage injection and the measurement of the resistive insulation current $I_R$, and the capacitive insulation current, $I_C$ (see Fig. 1(a)). The phase shift between the applied voltage and the injected current ($\varphi$) gives an indication of the state of the insulation (see Fig. 1(b)). The main parameter to evaluate the insulation ($\tan\delta$) can be obtained by means of (1)

$$\tan\delta = \frac{I_R}{I_C} \tag{1}$$

Where

$$\delta = 90º \quad \varphi \tag{2}$$

*B. Frequency Domain Spectroscopy (FDS)*

As described in [7], insulation dielectric response can be tested in time or frequency domain, but also these techniques may be combined to improve measurement speed. A time domain current measurement is based on evaluating the charging and discharging currents of the insulation (Polarization and Depolarization Currents PDC) is especially fast for low frequencies measurements; contrary to FDS that works faster especially in high frequencies. If both techniques (FDS + PDC) are combined it considerably reduces the test duration compared to other existing techniques.

As detailed in [11], FDS applied to dielectrics involves a more complex calculation of the insulation level (2).

$$\tan\delta(\omega) = \frac{\varepsilon_r''(\omega)}{\varepsilon_r'(\omega)} = \frac{(\varepsilon''(\omega)+\sigma_0/\varepsilon_0\omega)}{\varepsilon_r'(\omega)} \tag{2}$$

Where $\varepsilon''(\omega)$ is permeability imaginary part, $\sigma_0$ is dc conductivity, $\varepsilon_0$ refers to the initial permittivity and $\varepsilon_r'(\omega)$ is permeability real part.

Using this technique allows:

- Detection of moisture contents in the insulation, because if moisture amount is changed, then there is a change in the dielectric properties and consequent change in Tangent delta measurement (dielectric response).
- Measuring in the same sweep: tangent delta, Capacitance, Impedance and power factor with the same instrument.

## III. Experimental Setup

The main purpose of this test is to characterize the moisture content in a Medium Voltage stator-winding coil (section A) using FDS.

For this goal, was developed a process that involves moisturize, weighing and de-moisturize more deeply explained section 0, but also was mandatory to build a mechanism to simulate the stator core for correct dielectric spectroscopy measurements as detailed in section B.

*A. Winding coil under test*

For the experiment was used a new non-impregnated medium-voltage motor-winding stator coil (Fig. 2). Further information of the stator winding is given in TABLE IV.

Fig. 2. Stator-Winding Coil under test

*B. Test Setup*

To represent the operating conditions of the coil inside the core slots a laboratory setup was developed. It was composed of a set of highly conducting iron profiles (see Fig. 3). The metallic elements were clamped to the stator coil with sufficient tightness to avoid air gaps (see Fig. 4).

Fig. 3. High conductivity "L" shaped steel profiles arrangement detail for Stator Core simulation for simulating the stator core for the coil

Fig. 4. Complete Stator-Core arrangement using metallic profiles and connecting both sides with a cable

This test setup is a proper simulation for a long-term non-operating Medium Voltage Rotary Machine, that may be susceptible of acquiring moisture due to water leaking or ambient humidity.

### C. Test Procedure

For make a moisture content characterization, and verify its repeatability making multiple tests, is necessary to have the possibility to perform FDS test with different water content in the same coil under test. For this reason, was developed a test which involves two phases, moistening and drying described as follows:

*a) Moistening phase*

After being initially weighted and performed FDS measurement, the coil was immersed in clean water employing a clean container, almost full of adequate volume and size for ensuring uniformity during the immersion. After the moistening, has been checked that the coil does have not been dripping, then weighted and performed FDS measurement again.

*b) Drying phase*

In this second phase, the coil was dried continuously using a special setup described in Fig. 5, performed with direct current injection though the coil, controlled by a variable voltage Source, then weighted and performed FDS measurement again. This phase is performed several times until the coil weight were near to the un-moisten coil weight.

To check the repeatability, this test procedure was repeated three times for comparing the tangent delta curve behavior and gradient and the moisture content in the coil.

In each phase, for each moisture stage the weighing has been executed with an electronic scale with decigram precision.

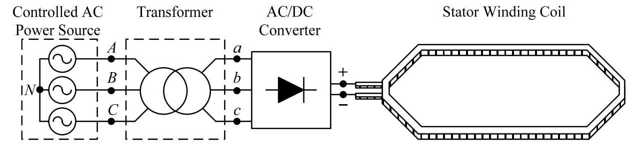


Fig. 5. DC current injection scheme for decreasing moisture content in the Coil

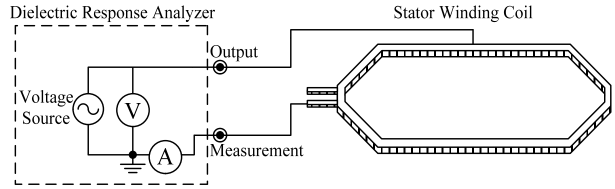


Fig. 6. Connection scheme for all FDS sweeps

### D. Instrument Characteristics

The Dielectric Response Analyzer used to perform the tests has a frequency range from 5μHz to 5 kHz with a up to 200 V in its variable voltage source. The main data of this equipment are enclosed in Table V in the appendix.

## IV. RESULTS

The tests were made 3 times, that consists in humidification and drying cycles, as detailed in 0,. The principal goal for repeat the process was to check that was a repeatability test.

TABLE I. TEST NO. 1 MOISTEN PROCEDURE AND RELEVANT RESULTS

| *Moistening Duration: 2 hours Moisture Acquired: 39.6 g* | | | | |
|---|---|---|---|---|
| ***Heating No.*** | ***Time [h]*** | ***Voltage [V]*** | ***Current [A]*** | ***Moisture Content [g]*** |
| 1 | 2.0 | 1.4 | 18.3 | 13.6 |
| 2 | 2.5 | 1.6 | 25.0 | 12.7 |
| 3 | 2.0 | 2.1 | 30.0 | 12.4 |
| 11 | 3.0 | 4.4 | 72.0 | 2.0 |
| 12 | 2.0 | 3.5 | 62.5 | 1.7 |
| 19 | 3.0 | 4.4 | 63.0 | 0.9 |
| 20 | 6.0 | 4.7 | 65.4 | 0.6 |
| 21 | 2.0 | 4.8 | 66.0 | 0.4 |
| 22 | 4.0 | 4.6 | 63.5 | 0.3 |

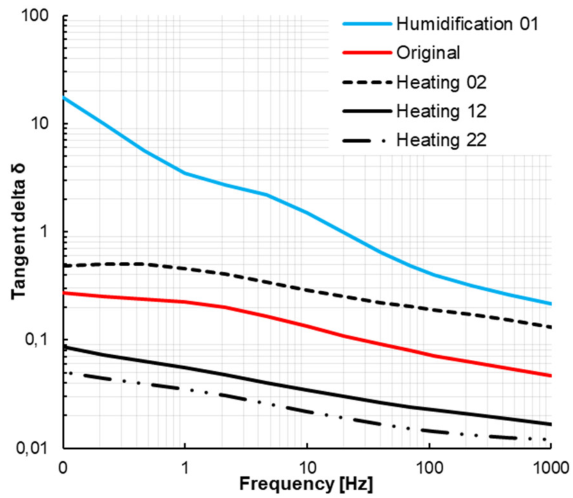


Fig. 7. Dissipation Factor (delta tangent) in some relevant moisture stages in Test No. 1, including the original tangent delta measurement.

TABLE II. TEST NO. 2 MOISTEN PROCEDURE AND RELEVANT RESULTS

| *Moistening Duration: 2 hours Moisture Acquired: 39.6 g* | | | | |
|---|---|---|---|---|
| ***Heating No.*** | ***Time [h]*** | ***Voltage [V]*** | ***Current [A]*** | ***Moisture Content [g]*** |
| 24 | 0.50 | 1.50 | 33.5 | 39.5 |
| 27 | 0.50 | 2.40 | 50.0 | 29.1 |
| 28 | 0.50 | 4.59 | 58.5 | 20.4 |
| 29 | 0.50 | 4.26 | 65.0 | 4.9 |
| 30 | 0.50 | 4.14 | 62.0 | 2.6 |
| 31 | 1.00 | 4.24 | 62.5 | 1.3 |
| 32 | 2.00 | 4.60 | 58.5 | 0.7 |
| 33 | 2.50 | 4.75 | 66.7 | 0.2 |
| 34 | 1.00 | 4.20 | 59.0 | 0.0 |

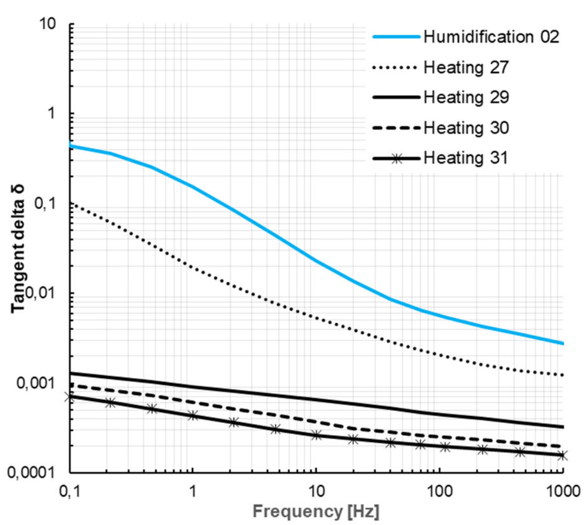


Fig. 8. Dissipation Factor (delta tangent) in some relevant moisture stages in Test No. 2

TABLE III. TEST NO. 3 MOISTEN PROCEDURE AND RELEVANT RESULTS

| *Moistening Duration: 2 hours Moisture Acquired: 39.6 g* | | | | |
|---|---|---|---|---|
| ***Heating No.*** | ***Time [h]*** | ***Voltage [V]*** | ***Current [A]*** | ***Moisture Content [g]*** |
| 35 | 0.35 | 4.5 | 70.3 | 11.2 |
| 36 | 1.00 | 4.23 | 61.3 | 0.9 |
| 37 | 1.00 | 4.1 | 60.3 | 0.5 |
| 38 | 2.00 | 4.3 | 62 | 0 |

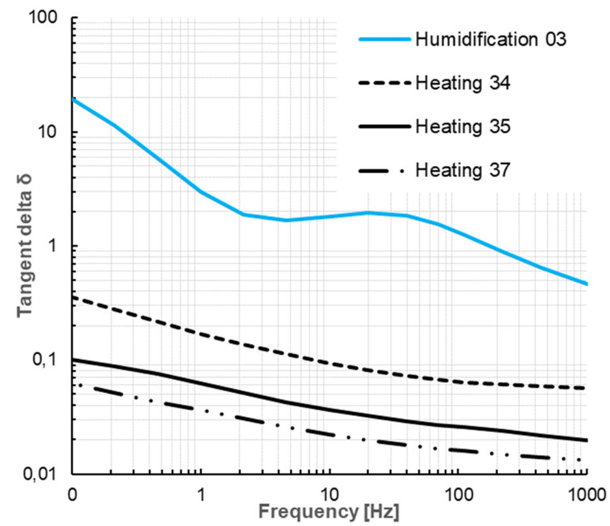


Fig. 9. Dissipation Factor (tangent delta) in some relevant moisture stages in Test No. 3

As has been seen in each figure of these results, the higher the moisture content, the higher the tangent delta for each frequency value. Other interesting result, is that in very moisten dissipation factor measurements (>20 g) shows a high curve gradient, especially notorious between 0.1 and 50 Hz.

## V. CONCLUSIONS

It has been demonstrated that the dissipation factor behavior, indirectly measured with the Dielectric Response Analyzer using FDS technique, is repeatable and allows characterize the amount of humidity present in a medium voltage winding coil.

It has been tested the FDS accuracy for measuring very small moisture quantity, the results show that this equipment can detect variations below decigrams.

The curve gradient, especially before 50 Hz, allows to determine the moisture level of the coil because the results shows that the bigger the gradient the higher the moisture content.

Measurements under 0.1 Hz were unshown in tangent delta figures, are not able to determine the moisture amount because in this range they do not follow any pattern.

## VI. FURTHER WORKS

Given the results of this project, there are some ideas to continue this line of research:

- Test moisturized specific zone of the coil to try to locate the moisturized zone.
- Continue with a full impregnated medium voltage coil and compare the results with this paper results.
- Test this technique with full winding arrangement and analyze it´s capability to characterize a full winding and or locate the moisturized coil, developing a method for easily a reliable weight measuring this full winding.

## APPENDIX

TABLE IV. STATOR WINDING COIL UNDER TEST DESCRIPTION

| ***Reference.*** | ***Unit*** | ***Value*** |
|---|---|---|
| Motor Output | kW | 650 |
| Power Factor | | 0.89 |
| Frequency | Hz | 50 |
| Voltage | kV | 6 |

TABLE V. DIELECTRIC RESPONSE ANALYZER

| ***Reference.*** | ***Unit*** | ***Value*** |
|---|---|---|
| Measuring and recording technique | - | FDS and PDC |
| Voltage | Vpeak | ±200 |
| Max. Continuous output current | mApeak | 50 |
| Min/Max. frequency | µHz/kHz | 5/5 |
| Resolution | - | $10^{-5}$ |
| Accuracy<br>1 mHz <f<100 Hz<br>f< 1 mHz and f>100 Hz | <br>%<br>% | <br>1+3 x $10^{-4}$<br>2+5 x $10^{-4}$ |
| Manufacturer/Model | Omicron/Dirana | |


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