Obtaining the parameters of an RC model to know the insulation condition of a distribution transformer

Obtención de los parámetros de un modelo RC para conocer la condición del aislamiento de un transformador de distribución

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Abstract

Because it is a topic of great interest in the study of the insulation system of oil immersed Transformers, methods have been sought to determine the moisture content and aging of the pressboard, paper and dielectric oil from Transformers, measuring the response of the dielectric materials, which are characterized by known polarization phenomena. One of these techniques is dielectric spectroscopy in the time domain, measuring the polarization-depolarization currents, with this the parameters of an equivalent RC circuit (Debye model) are determined. Using the Debye model (T. K. Saha, P. Purkait y F. Muller, 2005) and obtaining the polarization current through the insulation resistance test, the parameters to establish the condition of the transformer oil-paper insulation system will be determined, using exponential curve fitting of the data obtained from the insulation resistance test with the high vs. Low connection plus tank, the parameters of the time constant τ, the resistance R and the capacitance C of the equivalent circuit are obtained and with this information, the condition of the transformer insulation system is evaluated and decisions are made regarding maintenance actions.

Spectroscopy, Polarization, Depolarization, Resistance, Domain, Dielectric, Parameters

Resumen

Por ser un tema de gran interés en el estudio del sistema de aislamiento de los transformadores inmersos en aceite, se han buscado métodos para determinar el contenido de humedad y envejecimiento del cartón prensado, papel y aceite dieléctrico de los transformadores, midiendo la respuesta de los materiales dieléctricos, que se caracterizan por conocidos fenómenos de polarización. Una de estas técnicas es la espectroscopia dieléctrica en el dominio del tiempo, midiendo las corrientes de polarización y depolarizacion, con las cuales, se determinan los parámetros de un circuito RC equivalente (modelo de Debye). Usando el modelo de Debye (T. K. Saha, P. Purkait y F. Muller, 2005) y obteniendo las corrientes de polarización a traves de la prueba de resistencia de aislamiento, se determinarán los parámetros para establecer la condición del sistema de aislamiento aceite-papel del transformador, realizando ajustes exponenciales de los datos obtenidos de la prueba de resistencia de aislamiento con la conexión alta contra baja más tanque, se obtienen los parámetros de la constante de tiempo τ, la resistencia R y la capacitancia C del circuito equivalente; con esta información se evalúa la condición del sistema de aislamiento del transformador y se pueden tomar decisiones respecto a las acciones de mantenimiento.

Espectroscopia, Polarización, Depolarizacion, Resistencia, Domino, Dieléctrico, Parámetros

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Introduction

The transformer insulation system represents one of the most important components of the transformer.

Figure 1 75 kVA pad-mounted transformer insulation system

The dielectric materials of a distribution transformer, i.e. its insulation system, are affected by operating conditions, the environment, physical and chemical conditions, which alter the molecular structure of the dielectric materials of which it is composed; this can accelerate their ageing and the loss of dielectric properties when unfavourable conditions are combined.

In the presence of an electric field, a polarisation current develops due to the tendency of dielectric materials to align dipoles in the direction of the field. When the electric field is removed, the dipoles relax and return to their original state. In the transformer insulation system, each component dielectric material can have a different configuration with its neighbouring molecules. The response time of each group differs from one to another (T. K. Saha, P. Purkait and F. Muller, 2003).

The technical literature (S.M. Gubanski, 2002) considers in the response of insulating media, also called dielectrics, which in general are isotropic and homogeneous, the dielectric displacement vectors (electric flux density), the electric field E and the polarisation P are of equal direction and are interrelated by:

$$D = \varepsilon_0 E + P \quad (1)$$

The physical constant ε0 = 8.854e-12 As/Vm, is the vacuum permittivity.

The relationship between the dielectric displacement and the applied field is often and in general linear. The relationship can be expressed with a simple factor of proportionality ε_r.

$$D = \varepsilon_r \varepsilon_0 E \quad (2)$$

The factor ε_r is called relative permittivity and describes the dielectric properties of the medium. Therefore, it appears that the polarisation P must be proportional to the electric field E.

$$P = X\, \varepsilon_0 E = \varepsilon_0(\varepsilon_r - 1)E \quad (3)$$

This equation shows the linearity of the system, i.e. it shows the polarisation behaviour directly affected by the dielectric material under study. The quantity X is called the susceptibility of the medium.

If a given electric field E(t) is suddenly applied across a dielectric material, the contained free and bound charges will give rise to a current flow. The movement of the free charges represents the bulk resistivity of the materials, while the bound charges represent the dielectric being a sum of the displacement currents and the bias current. The total current density is given by:

$$j(t) = \sigma E(t) + \frac{\delta D(t)}{\delta t} = \sigma E(t) + \varepsilon_0[\varepsilon_r \delta(t) + f(t)]E(t) \quad (4)$$

The two asymptotic parts of the current j(t), are the instantaneous current density due to the capacitance of the component, ε0εrδ(t) (where δ(t) means the delta function) and the conduction current density due to the conductivity σ of the material respectively.

The current density due to the polarisation of the material is given by the dielectric response function f(t). It is therefore seen from the above equation that the conductivity σ, the instantaneous (high frequency) component of the relative permittivity ε∞ and the dielectric response function f(t), characterises the behaviour of the dielectric material in the time domain. It is worth mentioning that current measurements in the time domain can directly lead to the estimation or quantification of σ and f(t).

The step function, which is an exciter, must start at t=0. The function f(t) cannot be assigned instantaneously in application problems, at least one second is necessary which is a dynamic range measurement.

For all homogeneous material, the field strength E(t) is specified as an external voltage applied to the dielectric.

$$i(t) = C_0[\frac{\sigma}{\varepsilon_0}E(t) + \varepsilon_r \frac{dE(t)}{dt} + f(t)E(t)] \quad (5)$$

Co is the capacitance of the test equipment and εr is the relative permittivity of the test material.

The bias current in the dielectric can be obtained by the following equation if a step function is applied in the test with an exciter with Eo amplitude.

$$i_{pol} = C_0E_0[\frac{\sigma}{\varepsilon_0} + f(t)] \quad (6)$$

The Debye model (see figure 1) is used to model the response of the transformer isolation system, through an equivalent circuit of parallel branches containing series resistors and capacitors in each branch. These RC branches represent the dipoles which are randomly distributed and have the associated time constant:

$$\tau_i = R_iC_i \quad (7)$$

Where

Ri and Ci Relaxation parameters (resistance and capacitance).

The different parts of the insulation have unique relaxation parameters that depend on ageing and humidity.

There is also a conduction current due to the insulation resistance Ro; Co represents the geometrical capacitance of the insulation system.

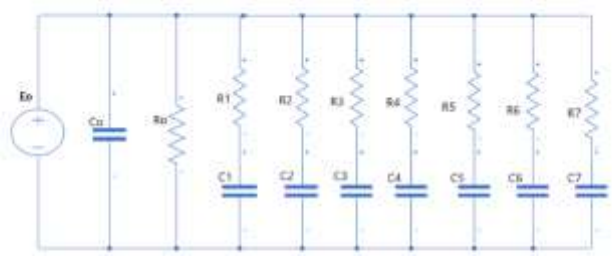

Figure 1 RC circuit, Debye model

The transfer function of the equivalent RC circuit.

$$\frac{I(s)}{E(s)} = \frac{1}{R_0} + sC_0 + \sum_{i=1}^{N} \frac{sC_i}{sR_iC_i+1} \quad (8)$$

Where Ro is the insulation resistance and Co is the geometrical capacitance of the elements; Ri and Ci are the resistance and capacitance of each branch representing the dipoles in the polarisation process and N the number of branches of the RC model.

The transfer function terms of this model can be identified in the branches containing parameters of the geometrical isolation of the elements. On the other hand, the terms of the transfer function corresponding to the insulation of the oil and paper.

$$\frac{I(s)}{E(s)} = FT_G + FT_{aceite} + FT_{papel} \quad (9)$$

The number of branches of the RC circuit in practical models varies from 6 to 10 (T. K. Saha, P. Purkait and F. Muller, 2003), thus, the time domain current equation is obtained for 7 branches of the RC model.

$$i(t) = \frac{E}{R_0} + \frac{E}{R}e^{\frac{t}{RC_0}} + \frac{E}{R_1}e^{\frac{t}{R_1C_1}} + \frac{E}{R_2}e^{\frac{t}{R_2C_2}} + \cdots + \frac{E}{R_7}e^{\frac{t}{R_7C_7}} \quad (10)$$

Obtaining the parameters and condition of the insulation system

The polarisation current will be obtained from the insulation resistance test, which is a routine test performed on the transformer among others that are carried out during preventive maintenance. Resistance values in Ohms are obtained from this test; the current is calculated for each value of the insulation resistance test.

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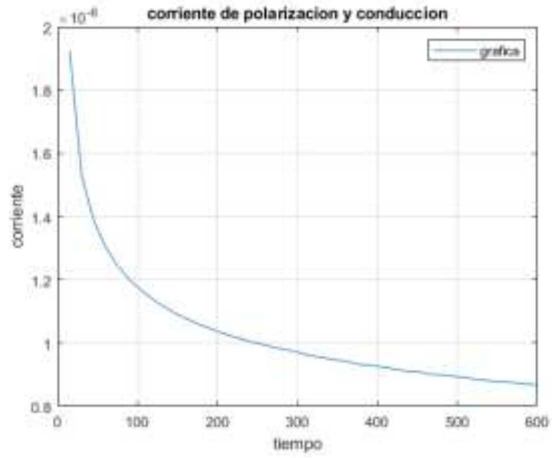
The insulation resistance test of electrical power transformers is one of the routine tests performed during preventive maintenance of electrical distribution transformers. This test consists of applying a direct current voltage to the transformer windings, connected in such a way as to determine the impedance of the oil-paper insulation system of the transformer, applying a direct current voltage, which causes a current to flow through the insulation system; identifying the displacement current due to the geometric capacitance of the insulation system, the dielectric absorption current that occurs due to the polarisation phenomenon of the dielectric materials and the conduction current that flows through the dielectric materials due to the moisture or dirt contained or degradation of their dielectric properties.

From the winding insulation resistance test, it will be possible to obtain the polarisation current and, using the Debye model, we will obtain the equivalent circuit parameters, making the exponential adjustment of the values; which will allow us to know the condition of the insulation system based on the parameters obtained and the characteristics of the graphs obtained.

In the insulation resistance test, with its test connection, a direct current voltage is applied for a certain period of time, and resistance readings are obtained for each time interval. In this way we will analyse and evaluate the response of the dielectric materials, calculating the bias current and the parameters of the Debye model (see Figure 1) which is used to model the response of the transformer insulation system.

Case 1: Insulation resistance test of the transformer as it is at present

With the impedance values obtained over 10 minutes, every 15 seconds, applying a voltage of 5000 V dc, ambient temperature of 21 °C, relative humidity of 40 %, the current is calculated, using Ohm's law.



Graph 1 Polarisation current
Source: Own Elaboration

With the calculated current values, we divide the data in 7 groups that represent the branches of the RC circuit, we make an exponential adjustment to obtain the parameter of the time constant τ. We start by considering that the value of the largest time constant corresponds to the longest time of the test, then we move on to the next group of values until the end. Thus the bias current can be expressed for all points at each part of the insulation with exponential functions of the type:

$$f(x) = A_i e^{\left(\frac{x}{\tau_i}\right)} \quad (11)$$

With the parameters obtained, the equation is parameterised and then we have the mathematical model with which the polarisation current can be determined and condition indicators can be established. As equation 10:

$$i(t) = \frac{E}{R_0} + \frac{E}{R} e^{\frac{t}{RC_0}} + \frac{E}{R_1} e^{\frac{t}{R_1C_1}} + \frac{E}{R_2} e^{\frac{t}{R_2C_2}} + \cdots + \frac{E}{R_7} e^{\frac{t}{R_7C_7}}$$

The second term in the equation corresponds to the instantaneous currents due to the component capacitance decreasing in seconds, so the term is eliminated and not considered for the current calculations for each branch.

For example, to calculate the current in branch 1, the longest set of time values of the 10-minute test is considered; the rest of the branches will have been saturated for these time values and only the conduction current and branch 1 terms are considered.

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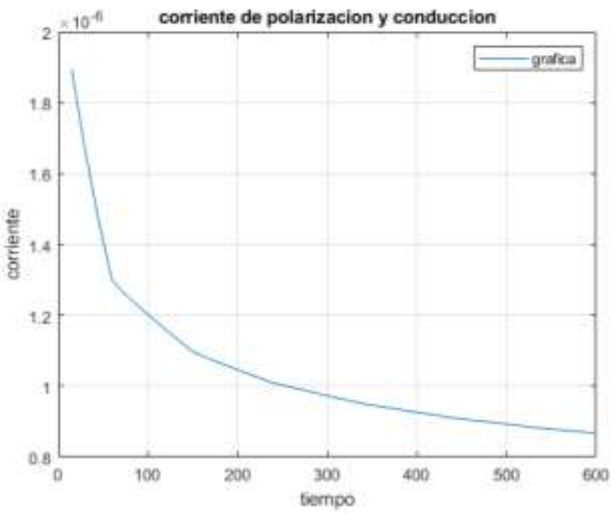
$$i(t) = \frac{E}{R_0} + \frac{E}{R_1} e^{\frac{t}{R_1 C_1}} \quad (12)$$

Obtaining the parameters Ri and Ci.

Branch	Ai [A]	τi [s]	Ri [GΩ]	Ci[nF]
1	1.01751E-06	3747.08	471.5	7.94
2	1.04721E-06	3102.3663	171.85	18.05
3	1.09257E-06	2318.6117	135.2	17.14
4	1.1539E-06	1611.0747	99.027	16.26
5	1.23613E-06	1026.5581	66.5	15.41
6	1.40736E-06	489.1234	33	14.81
7	2.08396E-06	96.4684	9.45	10.207

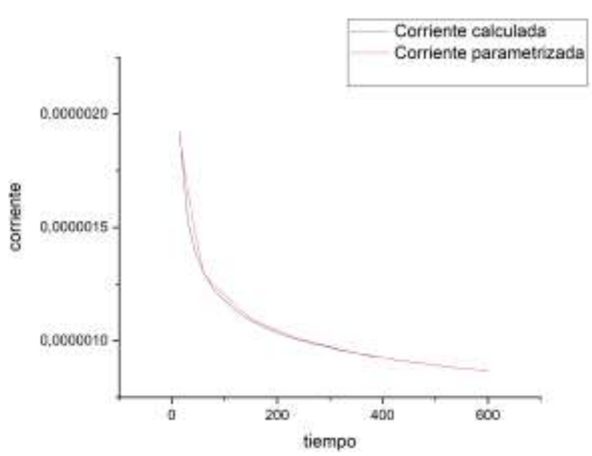
Table 1 Parameters resulting from the exponential adjustment of the initial condition

The values of the current for the rest of the branches are determined, and their values are obtained and plotted (see Figure 2).



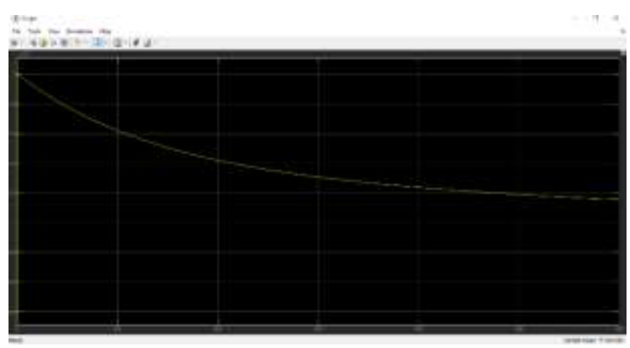
Graph 2 Polarisation currents, with the parameters of the RC equivalent circuit model
Source: Own Elaboration

Comparing the values obtained from the current obtained from the measurement of the insulation resistance and the current obtained from the parameters of the exponential function (see graph 3).



Graph 3 Comparison of the calculated currents and those obtained with the parameters of the RC equivalent circuit model
Source: Own Elaboration

Assigning the values of Ri and Ci of each branch in the equivalent circuit, we obtain the graph of the current (see Graph 4).



Graph 4 Currents obtained by substituting the values of R and C for each branch of the equivalent RC circuit

Analysing the values of the constant **τi** to establish the insulation condition. It is known that, if the constant is less than 100, it represents the oil condition. If one has a constant greater than 100, it represents the solid insulation condition (A. Baral and S. Chakravorti, 2014). As can be seen in Table 2, the branches from 1 to 6 represent the solid materials of the insulation system and with this information, their condición.

Branch	Ai [A]	τi [s]	Ri [GΩ]	Ci[nF]	Isolation
1	1.017E-06	3747.08	471.5	7.94	Solid
2	1.047E-06	3102.3663	171.85	18.05	Solid
3	1.092E-06	2318.6117	135.2	17.14	Solid
4	1.153E-06	1611.0747	99.027	16.26	Solid
5	1.236E-06	1026.5581	66.5	15.41	Solid
6	1.407E-06	489.1234	33	14.81	Solid
7	2.083E-06	96.4684	9.45	10.207	Oil

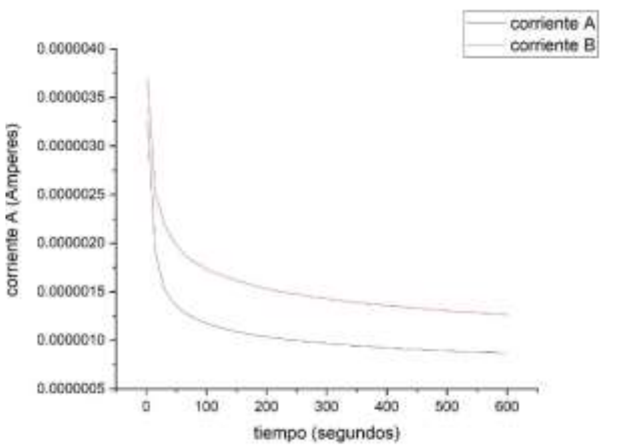
Table 2 Identification of the insulation system

In this way we identify the branches related to solid or liquid insulation and the parameters that define their condition.

Case 2: Transformer insulation resistance test with dielectric oil change

Now we create a condition to the transformer, changing dielectric oil in good condition for oil of low dielectric rigidity. The insulation resistance test is carried out with the high vs. Low tank connection.

By plotting the values of the polarisation currents, the following is obtained:



Graph 5 Comparison of the currents in initial condition and change of dielectric oil with low dielectric strength

The polarisation current describes a descending curve, but with higher values and the tendency is to continue descending, but after 10 minutes it does not approach the value of the initial case, with the dielectric oil with better dielectric rigidity. A table with the old values and the new values is displayed.

	Case 1			Case 2		
Branch	**τi [s]**	**Ri [GΩ]**	**Ci[nF]**	**τi [s]**	**Ri [GΩ]**	**Ci[nF]**
1	3747.08	471.5	7.94	2932.37	254.84	11.5
2	3102.36	171.85	18.05	2588.38	105.88	24.44
3	2318.61	135.2	17.14	2137.707	80.73	26.47
4	1611.07	99.027	16.26	1537.19	62.99	24.4
5	1026.55	66.5	15.41	954.187	41.35	23.07
6	489.12	33	14.81	531.68	22.9	23.11
7	96.46	9.45	10.207	129.15	8.5	15.19

Table 3 Comparison of case 1 and case 2 parameters

The resistance and capacitance values of each branch show the condition of the insulation system and allow actions to be taken to improve conditions. Resistance decreases and capacitance increases, these are the parameters that will be monitored to determine improvements in the insulation system.

Conclusion

Having obtained the parameters of the RC model, it is possible to know the condition of the insulation system and compare the before and after performing preventive maintenance to the transformer, through the parameters of the RC model.

Graph 5 shows the behaviour of the polarisation current for both cases, with parallel curves showing higher current values over time, indicating the condition of the oil-paper insulation system. The condition of the oil has an important influence on the condition of the insulation system, which can be significantly improved if a degassing and filtering process is carried out during corrective maintenance.

References

Chakravorti, A. B. (2014). *Prediction of Moisture Present in Cellulosic Part of Power Ttansformer Insulation using Transfer Function of Modified Debye Model.* Kolkata, West Bengal, India: IEEE.

S.M. Gubanski, P. B. (2002). Dielectric Response Methods for Diagnostics of Power Transformers. *CIGRE*, 42.

Tapan K. Saha, P. P. (2003). *Deriving an Equivalent circuit of transformers insulation for understanding the dielectric response measurements.* Australia-India: IEEE.