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Article

Improvement of RVM Test Interpretation Using a Debye Equivalent Circuit

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- This paper is an extended version of our paper published in 6th International Advanced Research Workshop on transformers (ARWtr2019).

Abstract: The aim of this document is to present how the interpretation of the RVM (Recovery Voltage Measurement) test can be improved through the use of a Debye equivalent circuit. As it is described in the literature the interpretation of the RVM test requires expertise and if the transformer presents a high interfacial polarization it is not possible to diagnose it in detail. Debye model is proposed in this work for enhancing RVM interpretation. This model is based on an electrical circuit that includes basic R-L-C components, that allows two interesting features: on one hand, isolation physical effects can be separately represented and, on the other, the values of the R-C components can be calculated from the RVM response (L components are not used in this work as long as no magnetic field effects are taken into account). Thus, the different isolation effects that are indistinguishable merged in the RVM transient response can be split into different R-C branches, each one corresponding with a single (not merged) isolation effect. Finally, several case studies are presented, in which it is correlated a dielectric oil treatment carried out and the equivalent circuit changes.

Keywords: Debye model, dielectric properties, power transformers, spectroscopy, recovery voltage measurement (RVM), oil-paper insulation.

1. Introduction

In terms of cost, simplicity, efficiency and durability, oil paper insulation has been the most popular insulation used by industry for decades and will continue to be so, although this kind of insulation for specific applications such as mobile transformers, safety-sensitive transformers, those transformers on which large overloads or high temperatures are expected, in which it may be more advantageous to use other dielectrics, both solid and liquid.

For decades dielectric spectroscopy techniques (RVM, PDC and FDS) have assisted maintenance technicians to manage the transformers' dielectric condition. In 2002, Technical Brochure 254 "Dielectric Response Methods for Diagnostics of Power Transformers" [1] was published, focusing on the three spectroscopy methods mentioned above: RVM, PDC and FDS. It concluded that all three methods are sensitive to the same polarization and conduction phenomena in the transformers' dielectric, and that regardless of whether time or frequency domain measurements are used, mathematical modeling is necessary to understand the properties of an insulation system. The interpretation of the obtained results in these tests has been object of study being the FDS technique the one that has achieved the greater degree of development thanks to the development of its mathematical model.

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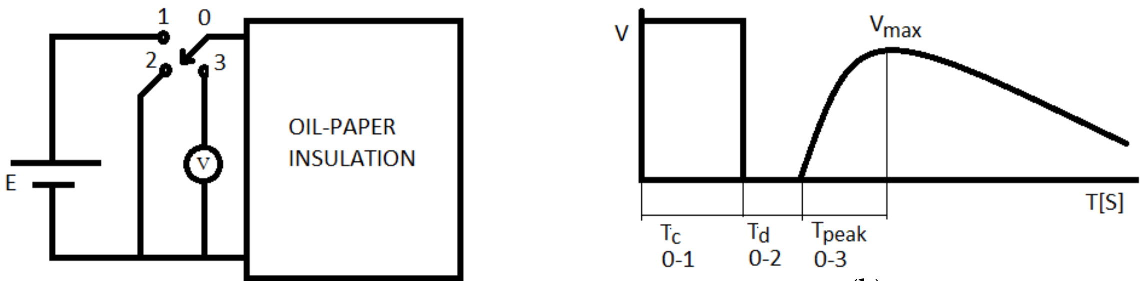
The aim of this article is to explain the way to obtain a good interpretation of the RVM test results by applying a mathematical model. To model a dielectric, one of the most commonly used model is known as "Debye Extended Model" [2]-[5], the method used by each of the authors to determine the parameters of the model varies, authors like [3] use genetic algorithms (GA) or like [4], [5] Particle Swarm Optimization (PSO) both very similar to find the optimal solution, in other cases assumptions and simplifications are used to solve mathematically the system and define the parameters of the model [6]. These methods result in a different number of branches and different time constants of these in each test.

Supported by a several case studies, it is shown how the different polarization branches of the equivalent Debye circuit vary, the transformers have been tested before and after carrying out an oil treatment, given that the effects of each treatment type on the dielectric are known, it is possible to correlate the change in the branches of the equivalent circuit with the removed contaminants in the dielectric.

The use of a model that has a fixed number of branches (14) and these in turn have a fixed time constant (value of the charging time used by the RVM test equipment for each) cycle allows a methodical evaluation running on every time the same sweep.

2. RVM Test Technique

The RVM (Recovery Voltage Measurement) test consists of carrying out several polarization and depolarization cycles in order to obtain an oil paper insulation polarization spectrum.



(a) (b)

Figure 1. (a) Wiring diagram for the three steps that the RVM test is divided; (**b**) voltage at insulation terminals for each step.

Each cycle consists of three steps:

1st A DC voltage is applied to both terminals of the dielectric to be tested during a T_c time. Terminals 0-1 connected in Figure 1(a).

2nd Both terminals of the dielectric are short-circuited during a time Td (usually this time is equal to $T_c/2$). Terminals 0-2 connected in Figure 1(a).

3rd The two terminals of the dielectric being tested are opened, measuring the voltage between the two terminals, the highest voltage reached V_{max} for that time T_c is recorded. Terminals 0-3 connected in Figure 1(a).

The measurement results are displayed by representing the maximum voltage obtained in each cycle with respect to the charging time of that cycle (Figure 2.). Depending on the equipment, the number of cycles to be carried out and the charging times may vary, the equipment used for this project uses 14 cycles with charging times between 0.1 and 819.2 seconds, each one being two times the previous one.

Table 1. Charging time sequence used in the 14 test cycles

Cycle	1	2	3	4	5	6	7	8	9	10	11	12	13	14

Charging time [s]	0.1	0.2	0.4	0.8	1.6	3.2	6.4	12.8	25.6	51.2	102.4	204.8	408.6	819.2

The result obtained in the test is evaluated graphically, based on the morphology of the curve obtained. For both the RVM and FDS techniques, algorithms have been developed that summarize the test result in a numerical value that can be a percentage of moisture, a conductivity or a time constant [7], although an evaluation that only observes these values is partial and it is recommended to evaluate the whole response.

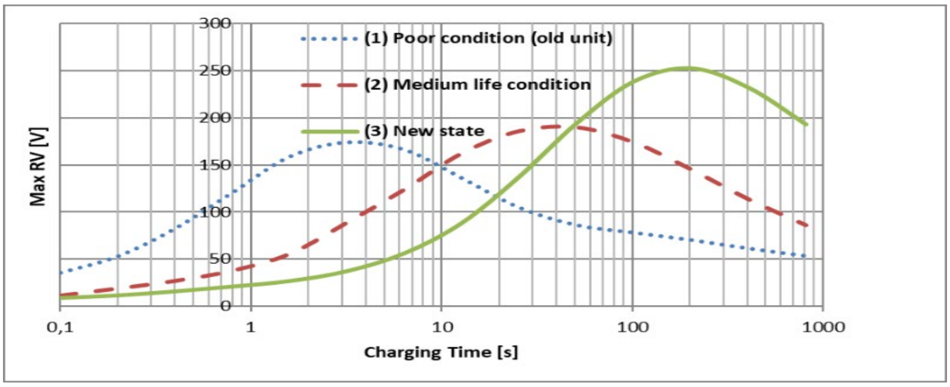


Figure. 2. Example of a graphical representation of a RVM test

In the case of RVM, different behaviors can be characterized. The traditional diagnostics has always been based on the value of the time constant [7], which is the charging time value for which the maximum recovery voltage value is reached and the decrease of the time constant value is interpreted as a degradation in the transformer condition, in the previous graph, the time constants would be (1)=3.2sg, (2)=40sg and (3)=204.8sg, although as indicated in CIGRÉ's Technical Brochure 254 [1]: *"Intermediate time constant values may exclusively show interfacial polarization effects, hiding other insulation characteristics"*, this fact can be considered an important factor that has penalized its acceptance in academic and industrial sectors.

3. Dielectric condition management

In terms of maintenance and transformer life management, monitoring and managing the liquid dielectric condition is the key factor. Transformer dielectric ageing causes the formation of paper and oil decomposition products and sub-products, these products and sub-products must be removed due to their presence catalyzes the ageing mechanisms themselves (Table 2).

To manage the life of the transformer the sequence to be applied must to be: monitoring the aging products of the transformer, removing the decomposition products and testing the transformer to validate the treatments performed.

3.1. Transformer aging, products and sub-products

The oil paper combination offers synergies such as the increase in the dielectric breakdown voltage of the whole 12kV/mm_paper + 40kV/mm_oil = (52)64kV/mm in comparison to the sum of the individual properties, there are also negative synergies such as the ageing products catalyze the insulation decomposition or the degradation of its insulation characteristics.

The main insulation decomposition products are Water, CO and CO2, acids, furanics compounds and sludge or x-wax, these decomposition products have to be studied and monitored for the following reasons:

- They may affect the safe operation of the asset.
- Act as catalyzers of aging processes
- They are an indicator of the aging process and allow us to know the condition of the asset.

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Table 2 lists the aging processes that occur in a transformer, these processes don't occur separately and depending on the condition the rate of aging of each process will vary, although as it is possible to observe, the sub-products of a process catalyze itself and/or others, which makes it possible to close a loop.

Table 2. Paper ageing: processes, sub-products and catalysers

Process	Caused by	Sub-product	Catalyzed by
Hydrolysis	H2O	H2O + acids + sludge	acids
Oxidation	O2	CO/CO2 + H2O + acids + sludge	Metals such as Cu and Fe ions
Pyrolysis	Temperature >140ºC	CO/CO2 + H2O + acids + sludge	sludge

3.1. Dielectric fluids treatments

As a function of the substance or substances to be removed there is a series of treatments that can be applied, in this article we will limit ourselves exclusively to the treatments used on site, omitting the treatments that can be carried out in the factory with other techniques.

Basically it is possible to differentiate between two dehydration and/or drying and regeneration processes, the first dedicated to removing moisture from oil or from oil and paper and the second according to the IEC definition are focused on "removing or reducing soluble and insoluble polar contaminants from dielectric oil through chemical and physical processes".

3.1. Dielectric fluid treatment assessment

Oil physicochemical tests are usually used both to evaluate the oil condition and to evaluate the treatment quality, although it must be taken into account that only the condition of the dielectric fluid is being evaluated. Therefore, there are parameters such as the moisture in the paper or the interfacial polarization that cannot be evaluated, being later when the transformer returns to service when an abrupt increase in the value of dielectric losses of the oil or moisture contained in the oil can be observed.

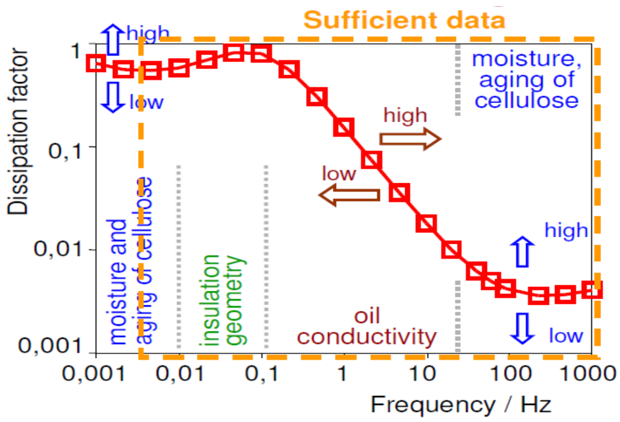

Figure 3. In FDS tests, the areas of influence of the different insulation parameters are well defined.

Dielectric spectroscopy techniques are complementary to physical-chemical tests and are capable of carrying out a full assessment of the condition of the paper and the oil paper interface (Figure 3.), FDS in the frequency domain and PDC and RVM in the time domain. Currently, the most well established technique is the FDS which, based on adjusting the response obtained to responses obtained using models, is able to carry out dielectric condition estimations with a high degree of precision.

4. Deriving Debye equivalent circuit from RVM test result

An algorithm developed in Octave has been used to calculate the value of the different components of the Debye equivalent circuit (Figure 4.), this circuit is composed of parallel branches which correspond to a physical meaning, R_g represents the conduction resistance of the dielectric, C_g

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represents the geometric capacity of the insulation system, and the successive RC branches, represent the different dielectric polarization mechanisms, the R_n*C_n is equivalent to the branch τ called time constant [2].

The parameters Cg and Rg are obtained from electrical tests such as conventional capacitance measurement techniques at power frequency and insulation resistance measurement at larger values of time. [2], [8]

The used model consists of 14 branches, with time constants τ similar to the charging times used by the RVM test equipment employed (Table 1). The capacitance of each of the 14 Cn branches represents the energy stored due to the different dielectric polarization mechanisms for each time constant. Rn is obtained by dividing τ of the corresponding branch (it is a prefixed value for each branch) by the value obtained of Cn for the corresponding branch, $R_n=\tau_n/C_n$. Other authors prefer to explain the variations in polarization mechanisms based on the variation of the resistance R of each polarization branch [9].

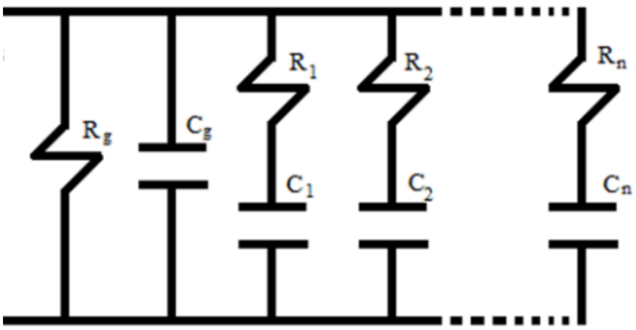

Figure 4. Debye equivalent circuit

The algorithm developed use as baseline data Vmax value obtained in the RVM test for each of the 14 cycles and C_g, R_g obtained from conventional electrical tests. Using this initial data, it calculates a first vector with 14 C_n, the particularity of this vector is that it is composed of the values of C_n for which a Debye equivalent circuit of a single branch of polarization (time constant τ_n) fits with the $Vmax_n$ value of the corresponding cycle. The following steps form a loop in which the response is simulated, the error is calculated with respect to the measured value and if any one of the branches error is greater than 0.5%, the vector value of each component of the C_n vector is recalculated proportionally to its error (Figure 5.).

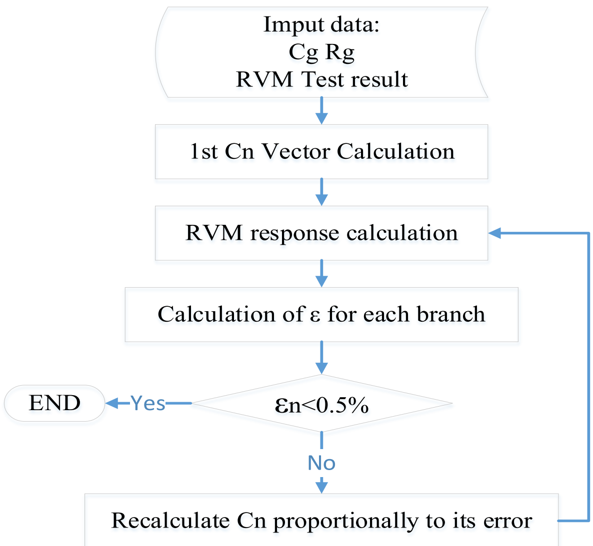

Figure 5. Flowchart of the algorithm for determination on Cn vector parameters

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It is proposed to establish that only certain branches are sensitive to the removal of specific compounds present in the oil (moisture, X-wax, polar compounds). Using tests carried out before and after dielectric oil treatment, and based on the knowledge of the removed compounds from the oil, it is possible to correlate the compounds with those polarization branches that are sensitive to their presence.

5. Equivalent circuit model interpretation

When in a transformer there is only one dominant polarization mechanism, such as in the case of a new transformer, where in theory the time constant is only a function of the quality of the drying process, only a single maximum is observed. In cases in which the mechanisms of polarization are several but their dielectric response is sufficiently spaced in time, two or more maximums are observed in the response without a strong interaction between them. However, there are many cases in which the time constants of the different polarization branches are close to each other, and it is in these cases in which one effect overlaps the other and therefore the interpretation of the RVM test results is more difficult.

The following simulation will simulate a RVM spectrum composed by three polarization branches in which the values of Ci and Ri of the intermediate branch will be varied in all but in the fourth simulation. In the intermediate regions from 30 to 300 seconds the effects of oil-paper interfacial polarization [10] can be observed. In the fourth simulation (RVM4), an important variation of the value of the third polarization branch will be carried out to show the low sensitivity of the system when the interfacial polarization is predominant.

Table 3. Parameters used for simulation (colored parameters are those which vary)

Parameter	RVM 1	RVM 2	RVM 3	RVM 4	Branch time constant τ [s]
Cg [F]	2.6e-09	2.6e-09	2.6e-09	2.6e-09	NA
Rg [Ω]	22e6	22e6	22e6	22e6	
C1 [F]	1.e-08	1.e-08	1.e-08	1.e-08	τ1=1.6 s
R1 [Ω]	1.6e8	1.6e8	1.6e8	1.6e8	
C2 [F]	1.e-06	2.e-07	5.e-06	5.e-06	τ2=80 s
R2 [Ω]	8e7	4e8	1.6e7	1.6e7	
C3 [F]	1.e-06	1.e-06	1.e-06	5.e-06	τ3=400 s
R3 [Ω]	4e8	4e8	4e8	8e7	

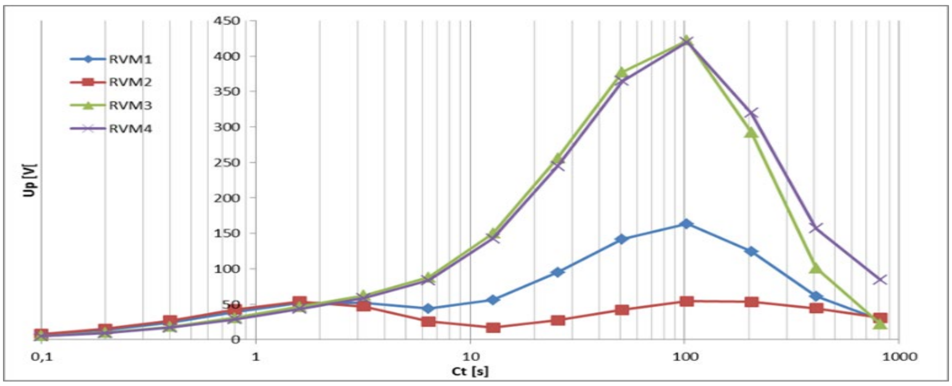

Figure 6. RVM1 C2=C2 R2=R2; RVM2 C2=C2/5 R2=R2*5; RVM3 C2=C2*5 R2=R2/5; RVM4 C2=C2*5 R2=R2/5 C3=C3*5 R3=R3/5

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The authors of Task Force 15.01.09 of CIGRE concluded in their article that: *an absolute maximum in the mid spectrum range indicates a high influence of "interfacial polarization" between oil and paper or between oil and pressboard in the ducts.*

As shown in figure 6, both absolute and relative maximums of the RVM2 spectrum are affected by changes in C2 and R2 until no relative maximums can be differentiated. As it has been mentioned, this change in the branches corresponding to intermediate times can be attributed to the "interfacial polarization" of a composed insulation.

For the interpretation of the results it is important to observe that the effects of the interfacial polarization are much more important on the branches with high times, because even when the value of C2 is not very high, the peak of branch 3, that would have been expected to be located in the area around 400 seconds, is displaced to 100 seconds.

It can also be inferred that the interpretation of a RVM curve in cases where interfacial polarization phenomena exists should be limited to evaluating this polarization, the time constant not corresponding either to the oil or the paper condition value.

6. Case studies

Over the last few years, many tests have been carried out on real transformers before and after the different oil treatments, so it has been possible to correlate the different treatments and the compounds they remove from the oil with the change in the value of the capacitance of each of the 14 branches of the equivalent circuit.

It solves the problem of the results interpretation expressed in the already mentioned Technical Brochure 254 of Cigre [1]: *"Intermediate time constant values may exclusively show interfacial polarization effects, hiding other insulation characteristics"*. It can be observed in case 3 in particular, that it is much more accurate to interpret a Debye equivalent circuit than to use the RVM test response.

6.1. Case 1: Transformer on which a drying process has been carried out

Table 4. Transformer characteristics.

Characteristic	Value
Year of manufacture:	1986
Voltage [kV]	132/21.5
Power [MVA]	40
Dielectric fluid	Mineral oil uninhibited
Oil mass [Kg]	13000

The transformer contains an important amount of water (Table5), so it is necessary to apply a procedure of reconditioning and active part drying, It consists of heating the oil by circulating it through the treatment equipment so that the hot oil heats the active part, once the active part is heated the oil is drained and vacuum is applied to the tank, the combination of vacuum and a 80ºC temperature causes that the water contained in the paper evaporates, this evaporation causes the cooling of the active part so it is a process that requires several cycles.

Table 5. Oil physicochemical parameters

	Water [ppm]	DF @90ºC [%]	Interfacial Tension [mN/m]	Colour
After	2	5.1	20.2	4
Before	11	4.6	19.5	4

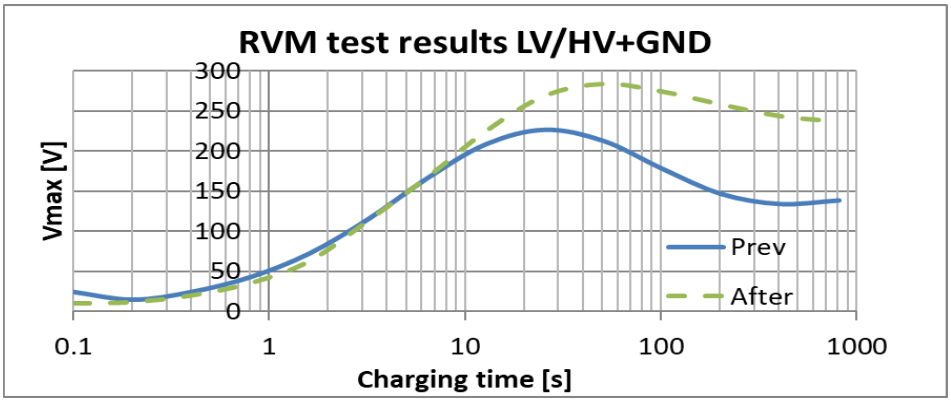

Figure 7. RVM test result

RVM test results (Figure 7.) can be interpreted as a positive treatment, slight displacement of the time constant, (absolute maximum of the curve) indicates an improvement and an increase of the maximum voltage indicates a higher insulation resistance [2], [7].

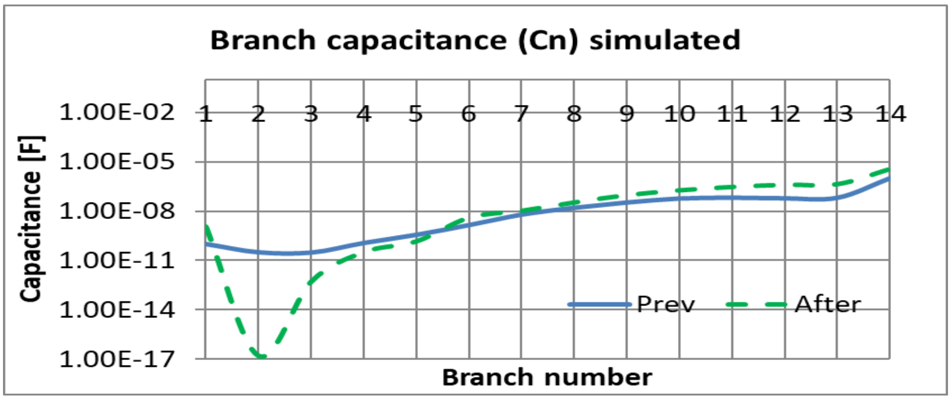

Figure 8. Cn values obtained in the simulated model

In the case of using the equivalent circuit's 14 branches condensers capacitance, it can be appreciated (Figure 8.) how before and after the treatment the branches beyond the nº 5 have not changed, this means that all those mechanisms of polarization with time constant higher than 1.6 seconds (branch 5 and above) are not modified after a drying, it being inferred that the time constant of the water is around 0.2 seconds (branch 2).

6.2. Case 2: Transformer on which a regeneration process has been carried out (without drying it)

Table 5. Transformer characteristics.

Characteristic	Value
Year of manufacture:	1970
Voltage [kV]	45/15.75
Power [MVA]	12
Dielectric fluid	Mineral oil uninhibited
Oil mass [Kg]	7800

In this case the transformer oil showed a dielectric loss factor of 13% and a water content of 7 ppm before the treatment. For this reason, only an oil regeneration process was carried out without drying the oil, which means that polar compounds and particles were removed, but no drying procedure was carried out. The process was carried out while the transformer was in service in order to maximize its effectiveness. The oil is pumped several times through Fullers earth which absorb the polar compounds. The last step is to add inhibitor compounds to the oil.

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Table 6. Oil physicochemical parameters

	Water [ppm]	DF @90ºC [%]	Interfacial Tension [mN/m]	Colour
After	5	1.8	31.8	4
Before	7	13.3	14.5	5.5

In this case it is possible to evaluate the results of the RVM test according to the traditional interpretation and infer that the polar compounds which causes interfacial polarization have been eliminated, [2], [7], [11]. The removal of polar compounds is deduced based on the decrease of the dissipation factor, the increase of the interfacial tension value, and in a smaller degree the decrease of the colour value (The decrease in color is due to the elimination of polar and non-polar particles). Nevertheless, as it is described in the literature, the response of an insulation affected by a strong interfacial polarization mechanism will overlap the rest of the polarization mechanisms, and the diagnosis should be limited to reflect the presence of this component.

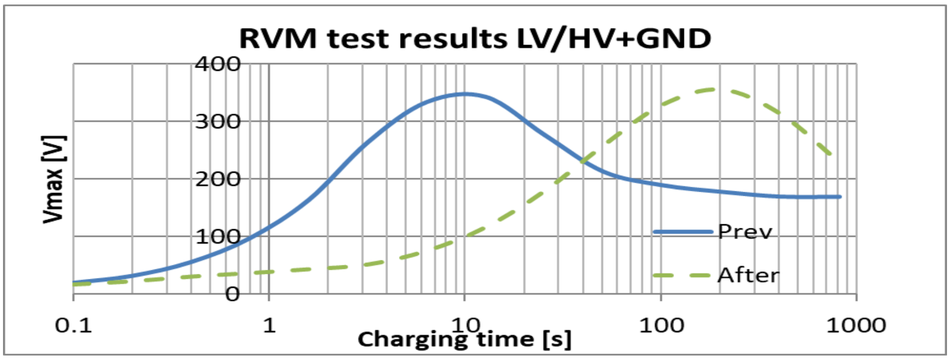

Figure 9. RVM test result, the pre-treatment test curve shows the typical pattern of a dielectric affected by interfacial polarization.

Once the extended Debye model is applied, it can be observed (Figure 10) how the branches between 1 and 5 show only a slight variation in the same way as the branches from 12 to 14, so it can be concluded that the polar products and contaminants extracted during regeneration respond to the time constants of the branches between 6 and 11.

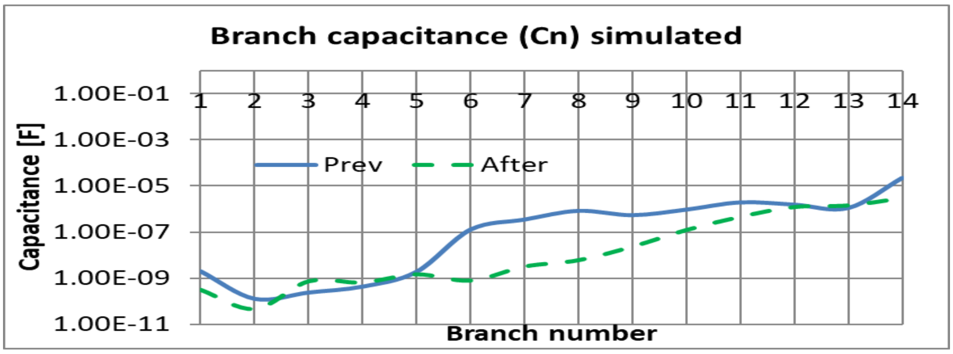

Figure 10. Cn values obtained in the simulated model

6.3. Case 3: Transformer affected by interfacial polarization on which a drying process has been carried out

Table 7. Transformer characteristics.

Characteristic	Value
Year of manufacture:	1978
Voltage [kV]	132/21.5
Power [MVA]	40
Dielectric fluid	Mineral oil uninhibited
Oil mass [Kg]	20000

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In this case, the results obtained in the transformer showed a high water content of 26 ppm, and the dielectric loss factor is not very high 3.3% so the most appropriate treatment is the drying of the transformer.

Table 8. Oil physicochemical parameters

	Water [ppm]	DF @90ºC [%]	Interfacial Tension [mN/m]	Colour
After	9	4.1	22.9	4
Before	26	3.3	21.8	4

The transformer contains an important amount of water, so it is necessary to apply a procedure of reconditioning and active part drying, It consists of heating the oil by circulating it through the treatment equipment so that the hot oil heats the active part, once the active part is heated the oil is drained and vacuum is applied to the tank, the combination of vacuum and a 80ºC temperature causes that the water contained in the paper evaporates, this evaporation causes the cooling of the active part so it is a process that requires several cycles.

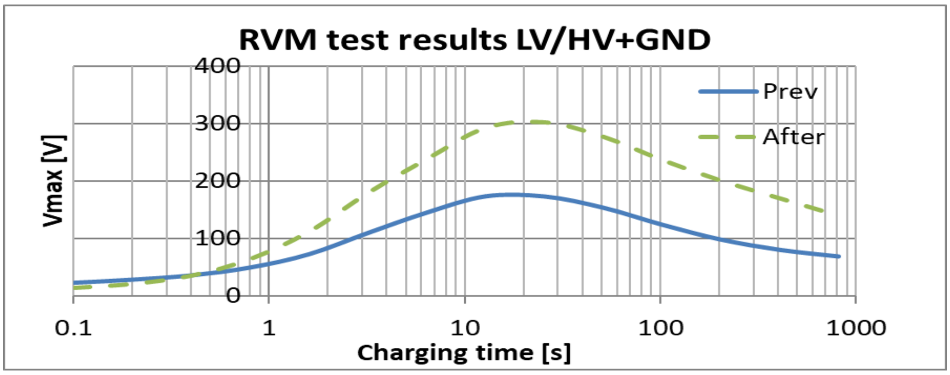

Figure 11. RVM test result. Both tests show interfacial polarization, the effect of removed moisture is not possible to appreciate.

It can be appreciated that, although the oil did not have a high dielectric loss factor, the diagnosis both before and after the treatment (Figure 10.) must be, and only can be, that the transformer is affected by interfacial polarization. The surface of the coils is probably heavily contaminated with adhering particles, particles that have not been suspended in the oil, therefore the dielectric losses of the oil are not high. This situation, given that the treatment carried out was not designed to remedy it, has been maintained in both tests, with the problem that it is not possible to determine whether the water has been eliminated or not.

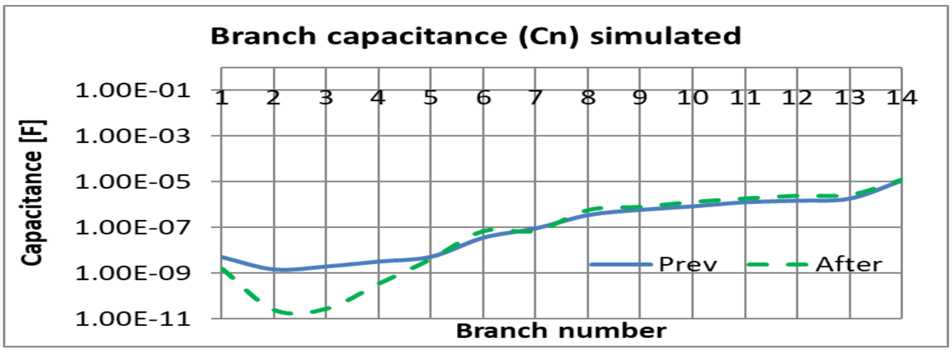

Figure 12. Cn values obtained in the simulated model

In the case that the Debye equivalent circuit is used, it can be observed parallelisms with the exposed in the cases one and two presented. It can be seen (Figure 11.) that as a result of the drying treatment carried out, the capacitance of the condensers of branches 1 to 4 has decreased, while the rest of the branches remain unchanged. Attention should be paid to branches 6 to 11, which have not changed as the compounds responsible for interfacial polarization have not been removed

This case is representative of the improvement in diagnostics resulting from the use of the Debye equivalent circuit, in this case the use of the traditional representation of the RVM test shows that it has no sensitivity to variations in moisture content as there is an overlapping effect of interfacial polarization.

7. Conclusions

In this document it has been described the different compounds that can contaminate the transformer's oil-paper insulation system, and how the correct evaluation of the contents of these contaminating substances allows to determine in a much more efficient way the treatment to be carried out.

The literature [1] shows that, although all the methods commonly used to evaluate the condition of transformers are capable of identifying the same polarization mechanisms, each technique has its own weaknesses, in the case of the RVM technique, shows insensitivity to all polarization mechanisms in the case of very strong interfacial polarization. Using a Debye equivalent circuit to model the dielectric according to the different polarization branches, it showed a higher sensitivity.

The use of a Debye equivalent circuit to characterize the different species present in the dielectric system has been shown to be a useful tool, the effects of the different species can be delimited allowing to carry out an individualized assessment.

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