Performance of Oil and Paper in Transformers based on IEC61620 and Dielectric Response Techniques

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ABSTRACT

This article demonstrates how to identify conduction and polarisation in oil and paper of a power transformer. In the first part, polarisation, which refers to deterioration products, are characterized at room temperature by the oil conductivity test according to the method in IEC61620. The results from more than 1,000 oil samples are discussed and acceptance criteria are included. The second part presents dielectric responses in time and frequency domain of transformers having different insulation conditions. It shows how to assess the condition of oil-paper interface and how to characterize the aging type of paper material.

Key words: Conductivity, Dielectric Response, Polarisation Depolarisation Current, Recovery Voltage, Dielectric Dissipation Factor, Capacitance Ratio, Moisture.

1. INTRODUCTION

1.1 Conduction and Polarisation in an oil-paper transformer

Like all other dielectric materials, oil as well as paper posseses two basic electrical properties – the ability to be polarized and in which an electrostatic field can exist. Polarisation and Conduction phenomena occur in every electrical insulating material. Problems in the dielectric are produced by the mechanism of one of these two. Polarisation takes place in all the molecules of a dielectric and causes chemical change or deterioration in the material (the term “deterioration products” will be used in this article). At the same time, conduction of a dielectric is often determined by the presence of impurities or contaminants (the term “contaminants” will be used in this article) and is not attributed to its basic substance.

In a transformer, contaminants are mostly moisture in the form of dissolved water or free water, but can be carbon dust, conducting particles or deposits, etc. Deterioration products are referred to polar molecules in oil (polar aromatics, polar compounds, etc), acid and non-acid type oxidation by-products in aged oil, by-products from discharges, thermal aging by-products in paper, etc. Moisture in the molecular level of solid insulation causes polarisation instead of conduction. This will be discussed later in section 3.

All transformers in the case studies have normal lives. They have no special illness such as electrical or thermal faults. We are going to talk about "normal aging" of oil-paper insulation.

1.2 The life and health of Insulating oil and diagnosis

The life of service-aged oil is mostly influenced by water (contaminants) and oxidation products (deterioration products). Most water in oil is in the dissolved state and its solubility increases with temperature. When the moisture in oil exceeds the saturation value, there will be free water precipitated from the oil. Free water in the area of high electric stress can easily cause the breakdown of insulation. States and solubility of water in oil-filled, high voltage equiment are discussed in [3]-[4].

Two main factors which cause oxidation products are oxygen and unstable hydrocarbon in the oil. Contaminants are the catalyst and electrical stress is the accelerator. This means oxidation aging of oil starts before energising a transformer as long as there is oxygen and the oil has low quality. For a sealed transformer where oxygen is kept low, the quality of oil is the most important factor in reducing the oxidation reaction. Oxidation products can be acid type and non-acid type.

Apart from oxidation products in aged oil, new oil can sometimes contain undesired compounds or polar molecules which are leftovers from the refinery process. These will be also called deterioration products in this article. The life of a new transformer will be adversely affected when low quality oil is used, even if the oil is new.

In the diagnosis of contaminants in oil, water content is mostly tested by Karl Fischer method though free water and some contaminants can be roughly checked by dielectric breakdown voltage test. Other special tests are particles count and metal analysis.

Deterioration products in oil are detected by Dielectric Dissipation Factor (DDF) which can be in the term of power factor (ASTM-D924 method), DDF or tan δ (IEC60247 method) or DDF & Conductivity (IEC61620 method), Interfacial tension (IFT) and Neutralization Number (or Acidity). The latter detects only the acid type molecules. DDF will be discussed more in section 2.

The conductivity of oil in the main duct between windings can be determined by some dielectric response techniques, which will be described in section 3.

1.3 The life and health of Insulating paper and diagnosis

Heat is the number-one enemy of insulating paper. Heat breaks the glycosidic bonds of the cellulose and shortens the Degree of Polymerisation (DP) of paper, which is the measurement of paper life. The products produced by overheating paper are CO, CO_2 and water. This means water in the pressboard or paper is not necessary transported from the oil. Water in insulating paper can bubble at the immediate change of load or a fault and cause the breakdown of the transformer. Oxidation products in oil can be accumulated at the surface of the pressboard and block the main ducts between windings. In this case, heat generated from the paper cannot be dissipated to the oil and finally the life of paper is shortened by overheating.

Thermal aging products of insulating paper are detected by furans analysis, especially 2-Furfural (2-FAL). Dielectric response methods [5]-[7], either time or frequency domains, have become more popular in the determination of moisture in pressboard. The technique based on the time-domain measurement of both Polarisation and Depolarisation Current (PDC) can identify conduction and polarisation in dielectrics. Details are in section 3.

2. PERFORMANCE OF OIL BASED ON THE METHOD OF IEC61620

CIGRE TF 15.02.04 introduced IEC61620 which is the indirect method of determining DDF by the measurement of "conductivity" and "permittivity" of an insulating liquid under very low voltage stress and in short time duration. They demonstrated that the DDF using this method and the direct tan δ measurement using ac bridges are in perfect agreement. By IEC61620, the conductivity σ is the actual characteristic of the insulating liquid. Electron or hole conduction will never occur in the situation considered in this standard. The details of their work are in Electra 185, 1999 which concluded that the d.c. resistivity tested by the method in IEC60247 is not the characteristic of the liquid due to the high stress and long time voltage application of 1 minute.

In this section, the performance of oil in transformers is described through the test results of more than 1,000 oil samples from transformers in four countries in Asia-Pacific (90% of these oil samples are taken from free-breathing type transformers). 40.9% of these samples have σ > 5 pS/m, 36.3% have σ 1-5 pS/m, 7.9% have σ 0.5-1 pS/m, 13.6% have σ 0.1-0.5 pS/m and 1.2% have σ < 0.1 pS/m. These are the values at 20°C.

2.1 The independency of moisture-in-oil and oil conductivity based on IEC61620

While both moisture and oxidation products influence the oil resistivity tested by the method in IEC-60247, the conductivity of oil tested by this method is independent of moisture. as shown in Table I. This allows each problem to be solved correctly. Table I also shows the efficiency of each oil treatment method. Moisture which is tested by the Karl-Fischer method is better removed by vacuum dehydration. This can remove some volatile acids as well. Clay removes acid type oxidation products. The oil conductivity in combination with acidity (or Neutralization number) allows the non-acid type polar molecules or oxidation products to be recognized (see oil results of Tx-002 after the second treatment and Tx-003 after the first treatment).

Table I
Oil test results before and after treatment,
showing independency of moisture-in-oil and oil conductivity using method of IEC61620

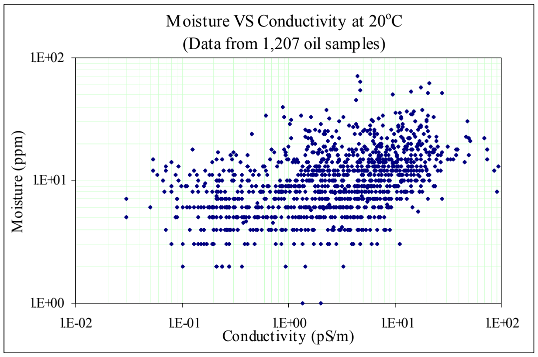
ID	Oil Condition	Oil temperature (°C) when sample is taken	Moisture-in-oil (ppm) (Karl-Fischer method)	Conductivity at 20°C (pS/m) (oil test: IEC61620)	Acidity (mgKOH/g
Tx-001	A	37.6	35	7.06	0.086
	C	40.0	37	1.30	0.029
	B + C	17.0	23	0.47	0.013
Tx-002	A	40.7	36	4.81	0.082
	C	39.7	37	1.54	0.019
	B + C	17.0	25	0.50	0.012
Tx-003	A	16.0	21	10.06	0.082
	B	10.0	10	7.88	0.080
	B + C	11.0	5	0.83	0.007
Tx-004	A	14.0	14	18.6	0.129
	D	9.0	7	19.5	0.128
	E	5	5	0.858	-

Note: A: Before treatment, B: after vacuum dehydration, C; after clay treat, D after on-line drying, E: after oil replacement

In spite of the independence of moisture and Conductivity (IEC61620) at 20°C as mentioned above, there are many in-service transformers which have problems with both moisture and deterioration products as shown in figure 1. The density of data (from 1,207 cases) in this figure is in the area of σ between 1.5-20 pS/m and moisture between 10-20 ppm. It can be seen from the chart that the moisture-in-oil in the majority of the transformers is not high since the majority of data belongs to those transformers which are operated at about 50% of their rating. Moisture of these transformers is stored in the insulating paper more than in the oil.

2.2 DDF (IEC60247) at 90°C VS Conductivity (IEC61620) at 20°C

The high voltage stress based on the method in IEC60247 can sometimes cause the generation of new ionic charges. An increase in temperature increases the mobility of ionic charges and can increase the density of ionic charges from dissolved substance. So high temperature and high stress can modify the actual nature of insulating oil. There is no single value or single factor to describe the relationship of DDF at different temperatures in spite of the same test method applied, no matter it is aged oil or new oil. Nevertheless, figure 2 shows case studies of 1,066 oil samples tested by both test methods which reveals there is a relationship between DDF (IEC60247) at 90°C and conductivity σ (IEC61620) at 20°C.



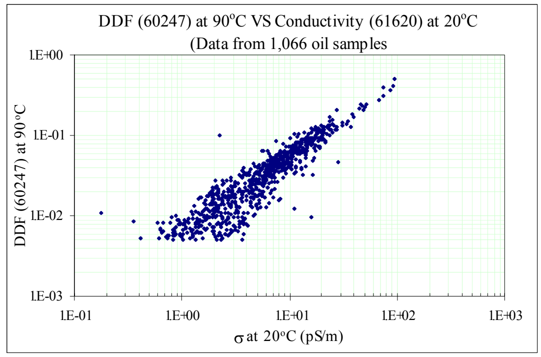


Figure 1 (left): Moisture in oil VS conductivity (IEC61620) at 20°C
Figure 2 (right): DDF (IEC60247) at 90°C VS conductivity (IEC61620) at 20°C

2.3 Deterioration products in oil

Figure 3 is the plot between acid number (Neutralization number) and conductivity (IEC61620) at 20°C. It proves that acids are not the only cause of high σ. When acid value is 0.01 mg KOH/g, oil conductivity can vary from 0.05 pS/m to the highest of 73.6 pS/m. High σ of oil can be caused by non-acid type oxidation products or other polar molecules in oil, which are leftovers from refinery process in the case of new oil. In our population, non-acid polar molecules in service-aged oil which caused very high σ are from on-load tap changers (e.g. discharges-by-products). Oil in OLTC is leaking directly into the main tank.

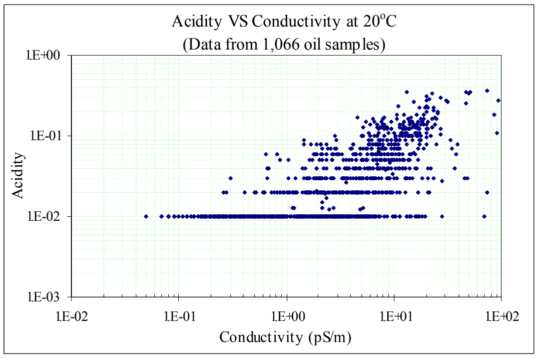
Table II shows examples of oil results from new and young transformers. NT-001 – NT005 have trouble with polar molecules in their new oil, σ can be as high as 16.39 pS/m. The good results of NT-006 – NT-009 are presented in the same table for reference.

Table II
Oil test results of new and young transformers having bad oil (NT-001 – NT-005) and good oil (NT-006-NT-009)

Oil from transformer no.	Rating of transformer (MVA)	Age in service	Water content (ppm) ASTM-D1533 *[35 max]*	σ at 20°C (PS//m) IEC-61620	Acidity (mg KOH/g) ASTM-D974 *[0.03 max]*	IFT at 25°C (dynes/cm) ASTM-D971 *[40 min]*	DDF at 90°C IEC60247
NT-001	22	5 months	3	**5.03**	0.004	39.00	-
NT-002	13	0	3	**3.299**	0.003	39.7	-
	10	1 month	9	**3.644**	0.005	37.6	-
NT-003	13	3 months	3	**3.914**	0.005	37.6	-
NT-004	25	2 years	7	**5.50**	0.01	35.4	0.0177
NT-005	25	4 years	6	**16.39**	0.01	46.4	0.0483
NT-006	20	0	5	0.03	0.003	39.4	-
NT-007	20	1 month	3	0.03	0.001	41.0	-
NT-008	20	1 year	7	0.12	0.001	35.7	-
NT-009	20	1 year	3	0.10	0.001	39.0	-

2.4 2-FAL in oil VS Conductivity (IEC61620) at 20°C

Figure 4 shows the plot between 2-FAL, which are the products from thermal aging of paper, and oil conductivity. The transformers having $\sigma < 1$ pS/m are healthy, no matter what age they are. Those having σ 1–5 pS/m and 2-FAL > 200 ppb mostly have acceptable health in their middle age. But if σ 1–5 pS/m and 2-FAL < 200 ppb, likely they struggle at teenage. Those having $\sigma > 5$ pS/m includes transformers with the leakage of oil from on-load tap changers as mentioned in item 2.3. When discharges-by-products or oxidation-by-products accumulated in the oil ducts or at oil-paper interface, heat transfer will be very poor which result in paper overheating and very high 2-FAL.



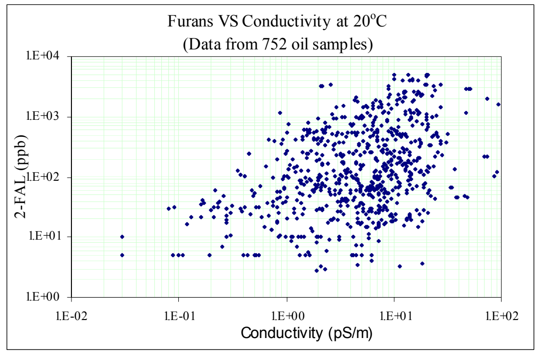


Figure 3 (left): Neutralisation number (or Acid number) VS conductivity (IEC61620) at 20°C
Figure 4 (right): 2-FAL VS conductivity (IEC61620 at 20°C

2.5 Suggested criteria of oil conductivity σ (IEC61620) at 20°C

When new oil is filled into a new transformer, σ of oil sample taken from the transformer can be more than 3 times higher than σ of the oil before filling depending on how well the transformer is prepared after the factory tests. Therefore, different criteria are given below.

New oil before filling into a new transformer	$\leq$ 0.05 pS/m
Oil in new transformer after oil filling	$\leq$ 0.1 pS/m
Service-aged oil after treatment or reclamation before refilling (sample taken from transformer, not treatment plant)	$\leq$ 0.5 pS/m

3. DIELECTRIC RESPONSES OF POWER TRANSFORMERS

The main purpose of the dielectric response technique is to determine the insulation system between the windings especially moisture in pressboard and σ of oil in the main ducts. In many cases of in-service transformers, the σ of oil in the main ducts is the same as σ of an oil sample taken from the main transformer tank and tested by the method of IEC61620. However, there are some cases when σ of oil in the main duct can be different from the result of an oil sample. The first case is a new transformer before it is energized and after the on-site oil filling. Case 1 in [13] is an example. The new oil filled into the transformer has low quality with σ 2.03 pS/m but σ in the main duct is 0.79 pS/m at 20°C. Another case is when oxidation products block the oil duct. The σ of oil in the main duct is higher than the majority of oil in the main tank. In addition, insulation to ground of each winding can be also assesed by dielectric response technique [13].

All the results of the dielectric responses presented in this article are obtained from PDC-analyser-1 MOD, which details are in [6]. This is based on time-domain PDC measurement but also provides time-domain evaluation results of Recovery Voltage polarisation spectrum and insulation resistance. It can also provide the frequency-domain evaluation results of Capacitance & Dielectric Dissipation Factor (DDF) or tan δ.

3.1 Conduction and polarisation by time-domain PDC measurement results

During PDC measurement, the polarisation current (I pol) consists of conduction current caused by conduction phenomena (or contaminants) plus absorption current caused by polarisation phenomena (or deterioration products) while the depolarisation current (I depol) consists of absorption current only. When the insulation is dry, I pol & I depol will be nearly equal at about one-tenth of the charging time. This is how the technique identifies conduction and polarisation in dielectrics, although the values of moisture in pressboard and σ of oil in the main duct are determined by the PDC software. PDC magnitude depends on capacitance, design & geometry and the insulation condition.

Figure 5 shows the PDC measurement results of transformers in various insulation conditions. The charts 5.1 - 5.6 are from the tests on the transformers T1-T6 filled with oil while the charts 5.7 - 5.9 are from T4-T5, T7-T8 without oil. Details are in Table III.

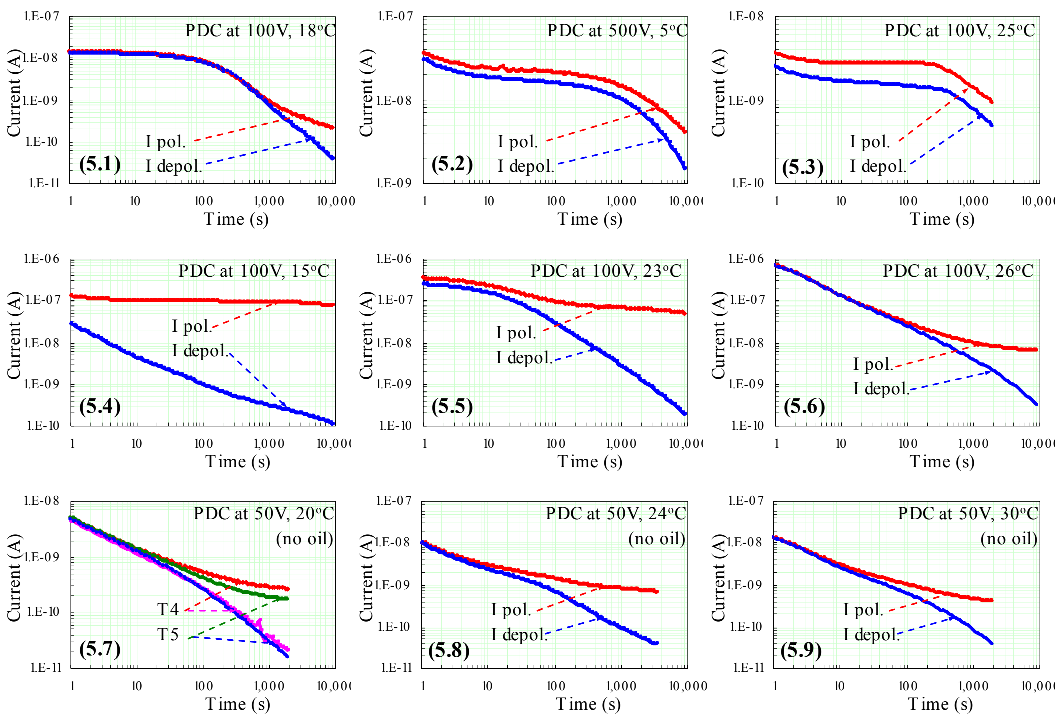


Figure 5: PDC measurement results of transformers in different aging condition
Charts 5.1–5.6 are from the measurement of transformer filled with oil (multi-layer oil-paper)
Charts 5.7-5.9 are from the measurement of transformer without oil (Homogeneous)

3.1.1 PDC measurement on a transformer filled with oil

For the test on transformer filled with oil, the initial current refers to the condition of oil while the current at longer time refers to the pressboard condition. The area of oil-paper interface is the area where the current shape changes the major slope (or knee) which in many cases is between 60-600 seconds (1-10 minutes). This depends on the design and can be much longer in many cases, especially for a large transformer such as T2 in the chart 5.2.

In case of very high moisture in the insulation system such as T4 in chart 5.4, the area of oil-paper interface cannot be seen from the PDC shape.

3.1.2 PDC measurement on a transformer without oil

The measurements on transformers without oil allow the actual aging type and aging condition of insulating paper to be assessed. A new transformer can be tested before oil filling. There is an opportunity to test an in-service transformer without oil during the major refurbishment after the oil is drained. The test voltage in this case of a transformer without oil shall not be higher than 100V (in order to avoid occurrence of partial discharges).

Moisture in pressboard in the case of a transformer without oil (Homogeneous) means moisture in the molecular state (distributed inside the material by diffusion) [3], which causes "polarisation" and influences the absorption current. Thus, it increases both I pol. and I depol. Surface humidity or free water influences the conduction current in I pol.

T4 and T5 are twins with different extreme conditions before refurbishment (chart 5.4 for T4 and chart 5.5 for T5). Paper drying reduced moisture in pressboard of both units to 3%, But the tank of T4 was wet so I pol of T4 in the chart 5.7 is higher than I pol of T5.

Overheating in the LV ground insulation of T7 causes the bending shape of I depol in the chart 5.8 at about 100 s. Surface humidity is also observed from I pol in the same chart.

For T8 in chart 5.9, the high initial current with slight bending of the PDC shape refers to the oxidation products at the surface of the paper after the oil was drained.

In conclusion, the shape of the depolarisation current during the very low voltage application determines the characteristic of the insulating paper.

Table III
Details of the transformers, charts and dielectric response results

Transformer description	PDC chart no.	DDF chart no.	C ratio chart no.	Recovery voltage chart no.	Insulation system analysed	Moisture in pressboard (% wt.)	σ of oil in main duct at 20°C (pS/m)
T1: 20 MVA, new, not yet in service	5.1	-	-	-	HV-LV	1.0-1.5	0.71
T2: 180 MVA, age 26	5.2	-	-	-	HV-LV	2.0	0.18
T3: 20 MVA, new, 1 day after oil filling	5.3	-	-	-	HV-LV	0.5	0.06
T4: 20 MVA, age 28	5.4	6.1	6.4	7.1	HV-LV	>> 4.9	3.80
T5: 20 MVA, age 28 (a twin of T4)	5.5	6.1	6.4	7.1	HV-LV	4.0	17.7
T6: 100 MVA, age 32	5.6	6.2	6.5	7.2	HV-LV	2.5-3.0	30.53
The twins **T4** and **T5** after refurbishment, but before oil refilling. Case 2 of [13].	5.7	6.3	6.6	7.3	HV-LV	3.0	-
T7: 25 MVA, age unknown, tested after the oil was drained. A case of paper overheating.	5.8	-	-	-	LV-G	3.0	-
T8: 25 MVA, age 36, tested after the oil was drained. A case of high σ of oil before draining.	5.9	-	-	-	LV-G	2.5	-

3.2 Evaluation of DDF and Capacitance (C) Ratio from PDC measurement results

In figure 6, the top row presents the DDF results while the bottom row presents the C ratio (the ratio of capacitance at corresponding frequency to capacitance at 50 Hz). Both DDF and C ratio are evaluated from the PDC measurement results of figure 5. Details are in Table III. Oxidation products at the oil-paper interface influences the maximum DDF. The higher the frequency that maximum DDF appears, the worst condition the oil-paper interface is. In chart 6.1, maximum DDF of T5 is at about 0.05 Hz while maximum DDF of T4 is at about 0.005 Hz, so T5 has much more problems with oxidation products than T4. The transformer T6 in the chart 6.2 is one of the worst. Both polarisation and conduction increase the magnitude of DDF.

Polarisation causes an increase in C ratio while conduction does not. Moisture in the molecular level of insulating paper causes polarisation but free water, surface humidity or dissolved water causes conduction. Chart 6.4 presents C ratio in two worst conditions. T4 had extremely high moisture in pressboard before refurbishment and T5 had extremely high oxidation products especially the acid type. Each had very high C ratio at that time in spite of different shapes. Though T6 before refurbishment had much higher σ of oil than T5, the oxidation products were mostly non-acid type. The C ratio shape of T6 in chart 6.5 is also different from T5 in chart 6.4.

3.3 Evaluation of Recovery voltage polarisation spectrum from PDC measurement

The results of the Recovery voltage polarisation spectrum are evaluated from the PDC measurement results. Details of transformers are in Table III. The charts 7.1 and 7.2 in figure 7 give the conclusion that the first peak of Recovery Voltage polarisation spectrum is more influenced by moisture in pressboard than σ of oil in the main duct. The oil in T6 (chart no. 7.2) containing extremely high oxidation products (σ 30.53 pS/m) has the first peak of recover voltage polarisation spectrum at charging time 2.8 seconds (> 1 second) while the highest moisture in pressboard of T4 has the first peak at < 1 second (chartno. 7.1). In chart 7.3 for the case of T4 and T5 without oil, surface humidity slightly decreases the maximum recovery voltage.

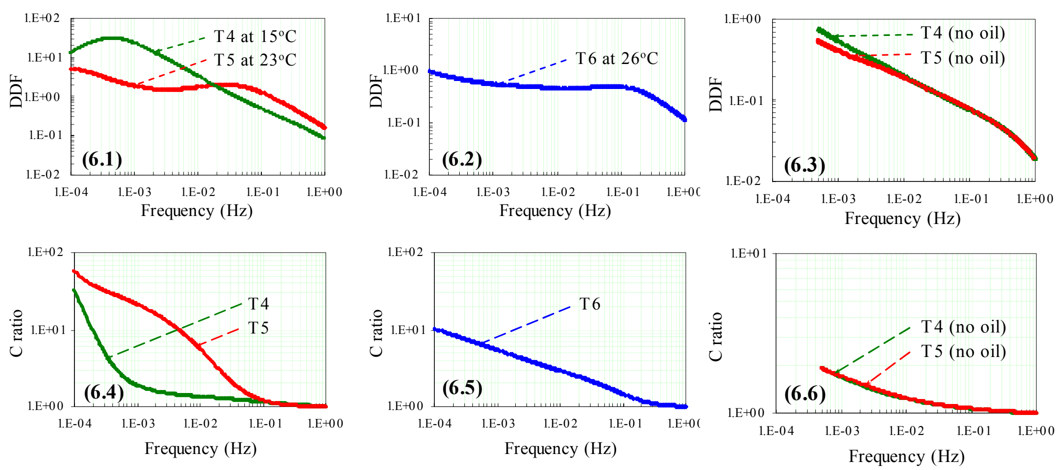


Figure 6: PDC Evaluation results of DDF (top row) and C ratio (bottom row)

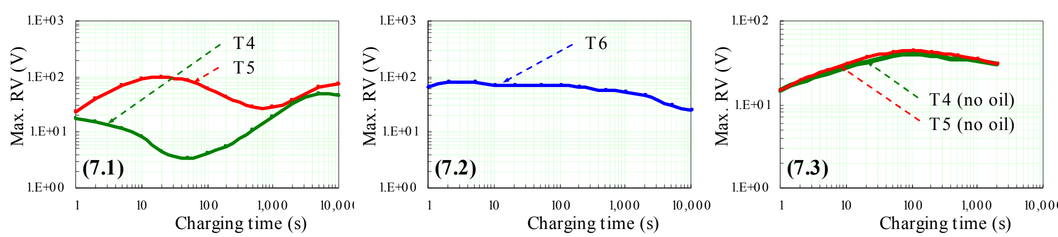


Figure 7: PDC Evaluation results of Recovery voltage polarisation spectrum at charging voltage 500 V

4. CONCLUSION

The characteristic of an insulating oil sample is determined accurately at room temperature by the test method in IEC61620. High voltage stress and high temperature can modify the actual characteristic. The deterioration products, both acid type and non-acid type, influences the conductivity tested by this standard, but not the moisture or contaminants. Criteria for new oil and in-service oil are suggested.

Moisture in pressboard and σ of oil in the main ducts are determined by the dielectric response techniques, which also give information about the insulation at the interfaces.

Conduction and polarisation of insulating paper are identified by the shape of both polarisation current and depolarisation currents when testing the transformer without oil. However, it is the depolarisation current which characterizes the aging type of the insulating paper as long as the voltage stress is very low.

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