Article

Influence of the Varnish Dilution on the Dielectric Breakdown of the Impregnated Electrical Insulating Paper

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Abstract: We investigated the dielectric breakdown of insulating paper for electric transformers impregnated with insulation varnish as a function of the amount of solvent added to the varnish. Six samples were prepared and impregnated with varnish at different dilutions and tested under a test voltage of 3000 V rms. The time for breakdown was recorded as a measure of the insulation power of the impregnated paper and data were analyzed using a statistical tool. Uncertainties related to the experiment were evaluated and quantified.

Keywords: electric transformer; insulating paper; varnish impregnation; dielectric breakdown; varnish dilution.

1. Introduction

Small dry transformers for electronic and electric purposes are built using paper as a means to insulate the windings from each other in the bobbin as well as to give insulation and mechanical strength for the wire layers in a winding [1]. The paper used is composed by almost pure cellulose, and sold under several brand names, the mostly known being “Presspahn“. Insulation paper is an organic material and cellular in nature, composed by almost 100% cellulose which is a highly hygroscopic material, and becomes conductive when moist [2]. In order to stabilize the insulation properties of the insulating paper, as well as the entire bobbin and windings, the entire transformer is subjected to drying in an oven or kiln in order to remove moisture, after that is immerged in electrical-grade insulating varnish. The varnish then fills up the tiny pores of the paper and the spaces between the wires, expelling the air trapped in these empty spaces. After a given time in immersion, the transformer is removed from the varnish tank, left to drain off the excess varnish and put back into the oven to finally cure the varnish. After curing, the varnish fills up all the empty spaces in paper and windings with a solid material that presents a dielectric strength higher than air, and prevents moisture from entering back to the windings and insulation paper, which in turn would degrade the reliability of the part and impair the insulation resistance between windings, moreover if the windings are subjected to a

high voltage difference. This is particularly important in mains-connected power transformers, since the secondary windings must be insulated from the primary winding in order to withstand a 3000 V, 60 Hz, 1 minute electric strength test according IEC 950 [3], for a mains voltage of 220 V AC. The test voltage must be applied between the primary and each one of the secondaries existent in the transformer, and the core and hardware as well, in order to ensure enough safety for the customer of the final equipment.

Paper is rated as class A insulation material, suitable for operation at 105 ºC maximum (40 ºC ambient, 55 ºC rise, 10 ºC hot spot gradient) [1]. Cellulose develops thermal decomposition at a noticeable rate at 100 ºC and at a very high rate at temperatures higher than 100 ºC [4]. Thus, for sake of maintain the paper insulation integrity during drying and varnish curing, processing temperatures must be kept at a maximum of 100 ºC. This fact precludes the use of oven-drying varnishes due the necessary curing temperature of 130-160 ºC for up to several hours [5]. Therefore, the varnish to be used in dry-type transformers must be of air-drying type, whose cure can be made at ambient temperature but is usually accelerated by using mild temperatures in the range of 50-80 ºC [5].

The varnish viscosity is controlled by adding a solvent or thinner in order to thin the varnish up and is adjusted before every impregnation process, since the solvent is highly volatile and evaporates from the impregnation tank either during the impregnation time or being poured in and out from the storage recipient. Varnish viscosity is a key parameter in the impregnation process, since the thicker the varnish, the longer the time necessary for complete, effective impregnation. Moreover, since the entire part is immersed on the varnish sometimes, the laminated core and the additional hardware might be varnished up altogether. The varnish bonds up the laminations one another, keeping the core as a single, solid unit which in turn contributes to reduce noise due to vibration and improves mechanical strength. Nevertheless, varnish can be deleterious for the part appearance; draining is made just leaving the part suspended by a mounting hole in order to allow the excess varnish to drip off from the part. The varnish leaves a shiny, neat appearance over the metallic parts indeed, but no control is made to ensure that the layer is even all over the surfaces. The varnish seems to have no drying-retardant compounds that are usually used in paints to provide time to the paint film to spread up evenly over a surface, but it seems to start to polymerize right after the solvent evaporates, once the part is removed from the varnishing tank. Thus, blobs, running marks and bubbles are often visible in finished units, which impair the appearance of the final product, moreover when the unit is intended to be painted. Not only the paint highlights any tiny surface imperfection due to the shiny finishing of the paint, but the own paint layer may result highly fragile if adhered in a varnish blob or running mark not completely cured.

Blobs and running marks are hard to cure because they represent a large volume of varnish concentrated in a small area, and the formation of a skin of cured varnish over a blob precludes the material underneath the skin to get contact with the air and thus polymerize completely. A considerable long time (up to two weeks) is demanded to cure a varnish blob or running mark completely; before this time, the material is soft and tacky and highly conformable under pressure. Although this sort of imperfections cannot be avoided completely due to the form as the impregnation process is performed and the complex shape of a transformer, their occurrence can be largely minimized by using varnish with low viscosity, which has more time to spread up over the surfaces

before starting to dry due to the evaporation of the solvent, thus avoiding spots of varnish accumulation which cause blobs and running marks.

The varnish used is delivered ready to be used in 900 mL and 5 L cans. The manufacturer states that the product should be used in pure form and solvent should be added "just when necessary", do not giving any further details [6]. From our experience, a thinner varnish could provide a neater appearance to the finished part, and its use would provide shorter impregnation and draining time as well. Not only the appearance would be improved, but there would be a gain in productivity, since impregnation plus draining time is a significant part of the total producing time of a transformer. Otherwise, the thinner the varnish, the lesser the solids per volume unit, and we suspect that the insulation properties would be impaired by thinning the varnish for a viscosity other than the one presented by the product in pure condition.

The aim of this work is to evaluate how the breakdown resistance of the insulation paper changes with the varnish viscosity, in order to attempt to establish the maximum amount of solvent that can be added to a pure varnish and still provide the insulation resistance required by IEC 950. The goal with this approach is to reduce the impregnation and drain time and improve the final appearance of the finished part.

2. Experimental Section

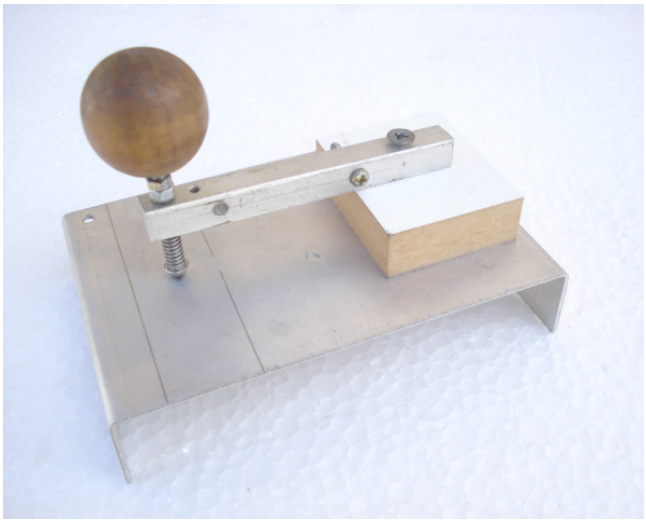
The experiment was performed by preparing samples of insulating paper impregnated with electrical varnish in different viscosities. Since is customary to express the amount of solvent to be added to a paint or varnish instead the actual value of viscosity to be achieved (in pascal-seconds or centipoises), we prepared five 100 mL samples of varnish to which we added to 10, 20, 30, 40 and 50 mL of solvent, resulting in samples diluted with 10% to 50% of solvent in volume. A sixth 100 mL sample of pure varnish was also separated. The varnish used was WEG Lacktherm 1333B, air-drying, polyester-base modified resin varnish [7] and the solvent was the recommended one Alquidic Diluent 1023 [7]. These products were acquired brand new in closed cans, and were opened just prior to the preparation of the samples. Varnish and solvent amounts were measured with volumetric pippetes and mixed and stored in airtight, closed containers, in order to keep the solvent evaporation to a minimum.

The insulating paper used for the test samples was 0.25 mm thick Presspahn, which is customarily used to insulate windings one another in our production process. A new raw sheet of paper was cut in six 3 cm x 20 cm rectangles, and subjected to our standard impregnation cycle – 2 h at 60 ºC for drying, 30 min of immersion, 15 min of draining, 2 h at 80 ºC for curing. Ambient temperature was 21 ºC during these operations, which were performed in a row, in the same day. For impregnation, the paper samples were introduced into the varnish sample containers, where they become completely immersed in the liquid. To accomplish this, the rectangles were wrapped in spiral form, in order to fit inside the containers used. The containers were kept closed during impregnation time to avoid solvent evaporation. After impregnation, the paper samples were left to drain in vertical position for 15 min, in order to evaporate the solvent and put in the oven for curing the varnish. Presence of solvent during cure in oven could be a cause of varnish bubbles in the paper surface, indicating poor impregnation. After the curing time, the test samples were left to cool down in the ambient, protected from dust, for two days. This time is believed to be necessary in order to allow the test samples to absorb the natural

moisture present in the ambient air and thus reproduce the actual conditions existing inside a transformer. Since a transformer winding is not airtight, it is believed that the internal insulation, although “dry“, effectively carries a small amount of moisture, furnished by the ambient.

The electric strength test was performed using an Instronic HT-2.5/5E Hipot tester set to a test voltage of 3000 V rms. A chronometer was coupled to the internal relay that controls the voltage generator of the tester in order to allow the measurement of the elapsed time to break down the paper under voltage stress. *The variable of interest here is the elapsed time for rupture under a 3000 V rms applied voltage, as function of the varnish viscosity present in the paper sample*. The test voltage was applied to the paper samples using a special jig shown in Figure 1, comprising an aluminum base and a round tip probe which is compressed against the paper by a spring. The force exerted by the spring is just enough to compress the paper firmly, without create any damage to the surface of the paper.

Figure 1. Test jig used to apply the test voltage on paper samples.



The electric strength test was performed in different points along the central, longitudinal line of the paper samples. The measurements were performed selecting one paper sample and one point per time at random and extracting one measurement, until 10 valid measurements were extracted, performing a completely random experiment. This sampling size was determined by the available time of 6 hours to completely perform the test. Some measurements provided an abnormally short elapsed time (<1 s) and were discarded, because they were attributed to the presence of tiny flaws, pits and holes in the tested point of the paper. Paper is not a homogeneous material and these imperfections, if considered, would lead to measurements which are not representative to the actual insulation power of the paper itself. A lot of discussion can be conducted about how deleterious are these imperfections over the final insulation strength of electrical paper, but we will not to consider these arguments here. Ambient temperature was 19 ºC during the tests, which were performed all in the same day. After all, the measurements were tabulated and a variance analysis was performed.

3. Analysis of Uncertainties Associated to the Experiment

Although this experiment describes and utilizes processes whose repeatability in industry is rather rough and imprecise, an analysis of the uncertainties which occurred in the experiment is well in order, in order to give credibility to the results obtained here. From the start, basic cares were taken to ensure that any side effect or influence not related to the experiment had no effect over the results – airtight containers for the diluted varnish samples, brand new raw materials, operations performed in the same day under the same ambient temperature and humidity and so on.

The varnish dilution was performed using two different class A pippetes, one for the varnish (100 mL +/- 0.08 mL) and one for the solvent (10 mL +/- 0.02 mL). For each dilution, the varnish is measured first and drained into the container. Then the amount of solvent (in multiples of 10 mL) is measured and stored in a auxiliary container, after that it is admitted into the 100 mL pipette in order to wash off the varnish adhered to the internal wall of the pipette. This procedure avoids errors in the varnish amount due its rather high viscosity. The final percentage of solvent in a given varnish sample was evaluated using GUM method [8] and can be determined with a confidence level of 95% by

$$\%solv = \left(\frac{n}{10} + /- n * 2.49 * 10^{-4} \right) * 100 \tag{1}$$

where n is the number of 10 mL volumes of solvent added to the sample. By using Equation (1) the varnish dilutions taking in account the pipette uncertainties are shown in Table I :

Table 1. Percentage of solvent into the varnish samples

n	% nominal	% calculated, confidence level = 95%
1	10	10 +/- 0.0249
2	20	20 +/- 0.0498
3	30	30 +/- 0.0747
4	40	40 +/- 0.0996
5	50	50 +/- 0.1245

The elapsed time to breakdown was measured with a resolution of tenths of second. Since the timebase is precise within 10^{-9} seconds, the uncertainty associated to the time counter is not significant. There is a delay time associated to the start and stop operation due the mechanical relay, internal to the Hipot tester, which is rated as 20 ms by the equipment manufacturer. since this delay is added in both operations, they cancel each other in a first approximation. Any error due the start and stop delay time mismatch would be not significant for a resolution of tenths of second, however.

The applied voltage was measured using the analog voltmeter existing in the Hipot tester. The manufacturer states an uncertainty of +/- 1% of full reading. Since the reading is 3000 V in a 5000 V

scale, the uncertainty of reading is 5/3 * 1% or 1.67% (+/- 50 V) which is well suited for the present test, considering that the test voltage is mains-derived and subject to slight deviations during a test. As a matter of fact, is quite difficult to adjust the test voltage to the exact value of 3000 V rms, due mains fluctuation. Although these fluctuations were out of control, the test voltage did not depart more than +/- 100 V (½ division on scale), as read on the voltmeter. Therefore, although the results reflect the effect of voltage test fluctuation, this fluctuation is considered a second-order effect and has not been considered on this experiment.

4. Results and Discussion

The elapsed time between application of the test voltage of 3000 V rms and the paper breakdown are tabulated on Table 2.

Table 2. Measured time to breakdown at 3000 V rms.

Dilution	Pure	10%	20%	30%	40%	50%
Time (s)	905.6	149.6	143.5	5.5	7.3	22.5
	518.2	334.3	55.0	24.4	6.5	31.9
	302.4	169.7	745.8	26.9	42.1	29.6
	1113.6	465.3	359.9	16.3	50.9	5.1
	986.2	44.9	11.3	10.2	7.8	10.3
	697.3	39.7	16.4	54.0	47.2	4.0
	639.8	262.5	1293.2	13.4	3.6	9.7
	292.7	63.4	14.7	123.7	4.3	2.6
	1804.1	58.6	150.4	6.8	2.7	7.4
	535.3	39.1	17.0	49.1	5.4	14.3

Data analysis was performed using single-factor ANOVA EXCEL tool, whose results are presented in Table 3.

Table 3. ANOVA analysis log for data on Table 2.

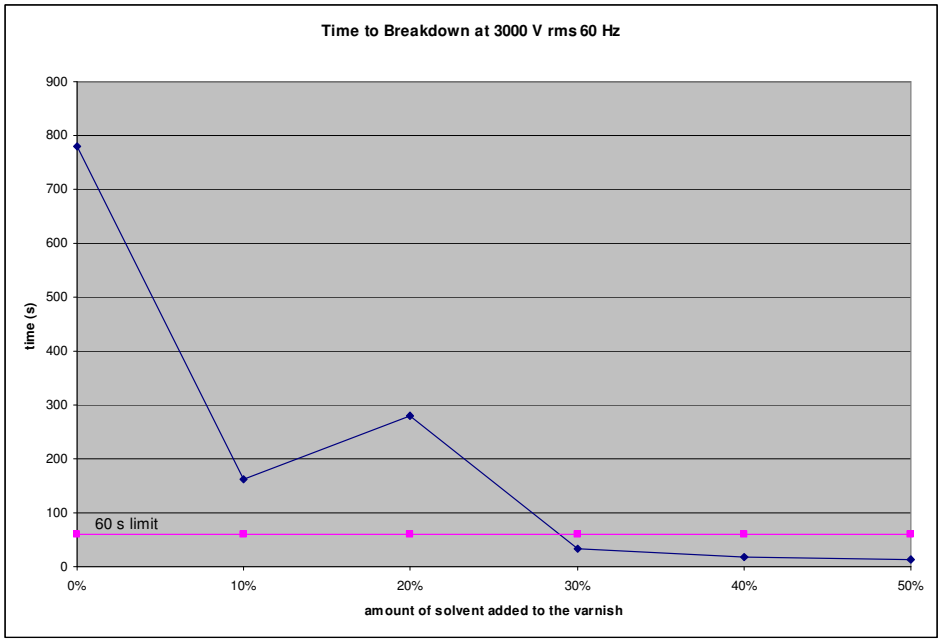
ANOVA: Single Factor					
SUMMARY					
Groups	*Count*	*Sum*	*Average*	*Variance*	*Std Dev*
pure	10	7795.2	779.52	204315.2	452.0124
10%	10	1627.1	162.71	21797.12	147.6385
20%	10	2807.2	280.72	179690.4	423.8991
30%	10	330.3	33.03	1295.938	35.99914
40%	10	177.8	17.78	406.0062	20.1496
50%	10	137.4	13.74	113.3716	10.64761

ANOVA					
Source of Variation	*SS*	*df*	*MS*	*Fcalc*	*Ftab*
Treatment	4382495	5	876499.1	12.90177	1.376
Error	3668563	54	67936.35		
Total	8051058	59			

The value for $F_{tabulated}$ was taken from an F-distribution table, using $df_{numerator} = 5$ and $df_{denominator} = 54$. There is no row for this last figure, so we interpolate the value using adjacent values. Comparing values for $F_{calculated} = 12.90177$ and $F_{tabulated} = 1.376$ and since $F_{calculated} > F_{tabulated}$ we conclude that *the time to break down the insulating paper under a test voltage of 3000 V rms does vary in a significant fashion as the varnish dilution is changed.*

Based on data from Tables 2 and 3, we can plot a graph showing the behavior of time to breakdown and varnish dilution, as shown in figure 2:

Figure 2. Time to breakdown as a function of amount of solvent added to the varnish.



We can see that pure varnish provides the higher time to breakdown and this parameter has strong correlation with the amount of solvent added to the varnish. Although there is a large variation on this parameter between 0% (pure) and 30%, we can see that the critical amount of solvent which is able to produce an impregnated paper able to withstand 3000 V rms for 1 minute is about 28%. There is an anomalous peak at 20%, which can be attributed to the fact of a more fluid varnish can penetrate more easily among the paper fibers and provide a better impregnation compared to 10% and 30%. A varnish with 10% of solvent do not penetrates so easily, and one with 30% does not have enough solids to fill the empty spaces in the paper. A further investigation should be made about this subject.

Notwithstanding the mean results do indicate that a reasonable amount of solvent could be added to the pure varnish an still provide enough insulation, data on Table 2 present a large amount of points where the minimum time was not achieved, for samples with 10% and 20% of solvent added. The only

sample that was able to withstand consistently the test voltage was the one impregnated with pure varnish and, even so, measurements from some test points were discarded as explained before.

The residue histograms were also evaluated, and are presented in figures 3 to 8.

Figure 3. Residue histogram for the sample with pure varnish.

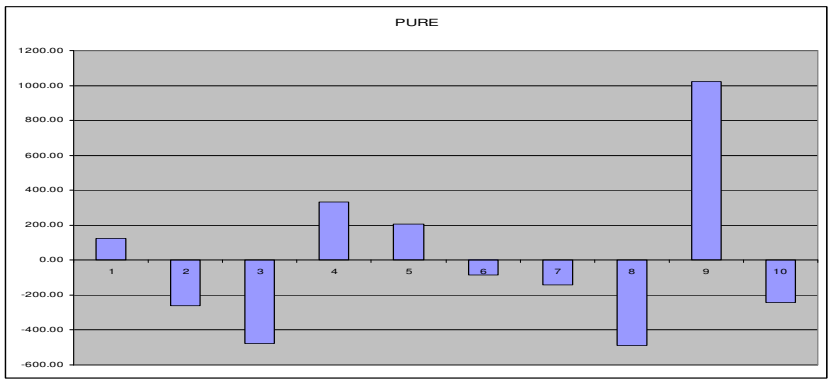


Figure 4. Residue histogram for the sample with 10% solvent.

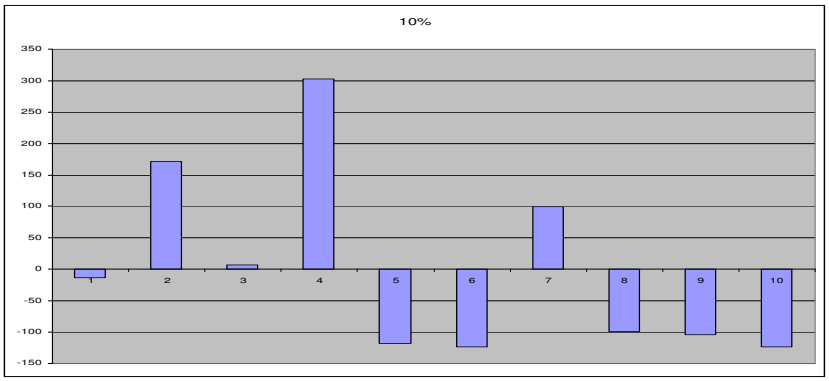


Figure 5. Residue histogram for the sample with 20% solvent.

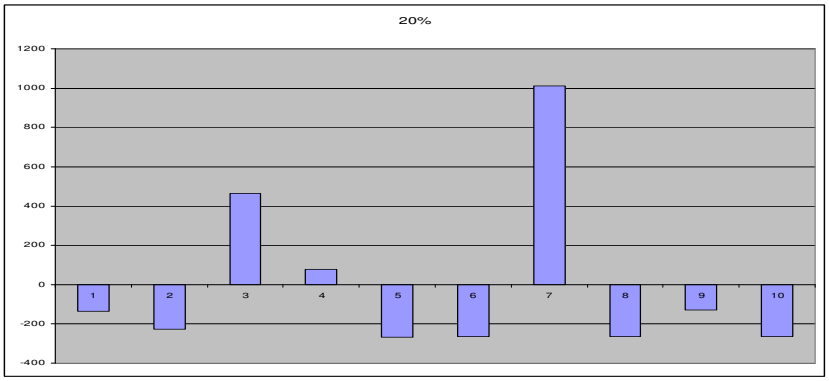


Figure 6. Residue histogram for the sample with 30% solvent.

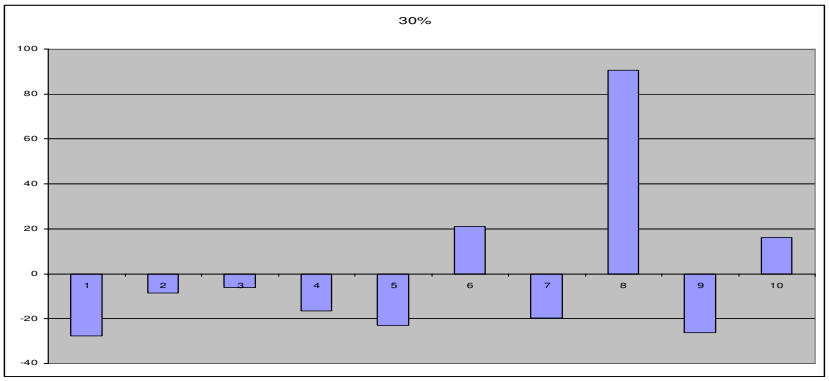


Figure 7. Residue histogram for the sample with 40% solvent.

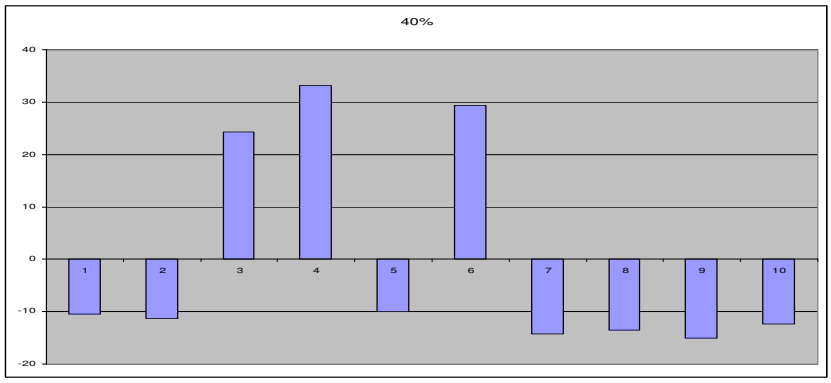
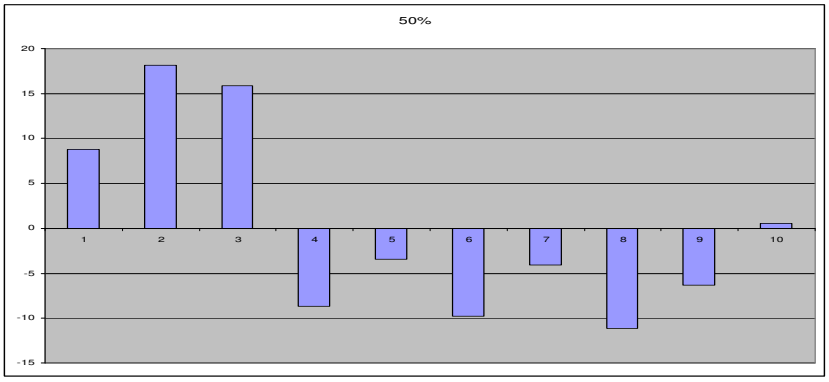


Figure 8. Residue histogram for the sample with 50% solvent.



We can see that the residues appear to follow some kind of tendency, despite all the care spent in making a random experiment. There is no other explanation for the fact other than the influence of the mains voltage, which was uncontrolled during the experiment. Some further investigation is needed in order to assess the influence of mains voltage in greater detail.

4. Conclusions

With this experiment, we concluded that the insulation power of electrical paper impregnated is dependant of the amount of solvent added to the insulation varnish employed. Pure varnish provides the highest dielectric breakdown properties, and the addition of even minute amounts of solvent degrades this parameter, although up to 28% of solvent in volume can be added to the pure varnish and still provide an impregnation that withstand the insulation test for 220 V AC. However, the only impregnated paper that withstands consistently the test voltage is the one impregnated with pure varnish. Thus, for sake of safety and reliability, pure varnish is the only material to be used and any addition of solvent should be avoided unless for restoring its original viscosity.

Paper itself is a non-homogeneous material and contains a lot of imperfections which cause points of premature rupture under voltage, even impregnated with pure varnish. From this experiment, we conclude that paper must not be used alone as insulation between primary and secondary in a power transformer, and among windings in general, and should be replaced by other materials. Polyester insulation tape has been used as primary and reinforced insulation in switch-mode power supply transformers, and this trend may be followed for power transformers. However, dielectric constant of polyester is higher than paper, and its use in audio transformers can lead to an increase in the winding self capacitance, with deleterious effects in the high-frequency audio response. Compound materials comprising a paper sheet covered by a polyester film are available in the market and may be a good choice for primary-to-secondary insulation in audio transformers. In both cases, paper may be used for winding interlayer insulation, where the electric stress demands are less stringent. The combined use of polyester or compound materials and paper as insulation materials can allow the use of a diluted varnish with all its benefits to the production process and to the product itself, without jeopardize its quality and reliability.

5. Appendix – Deduction of Equation 1

Deduction of Equation 1 follows:

$$\%solv = \frac{Vs}{Vv} * 100 = \frac{n * V_{PIP\_10\_mL}}{V_{PIP\_10\_mL}} * 100 \tag{2}$$

$$u_{\%solv} = \sqrt{u_{Vs}{}^2 + u_{Vv}{}^2} \tag{3}$$

$$u_{n*PIP\_10\_mL} = \frac{\partial \%solv}{\partial V_{PIP\_10\_mL}} * u_{PIP\_10\_mL} = \frac{n}{V_{PIP\_10\_mL}} * u_{PIP\_10\_mL} \tag{4}$$

$$u_{PIP\_100\_mL} = \frac{\partial \%solv}{\partial V_{PIP\_100\_mL}} * u_{PIP\_100\_mL} = -\frac{n * V_{PIP\_10\_mL}}{V_{PIP\_100\_mL}{}^2} * u_{PIP\_100\_mL} \tag{5}$$

$$u_{PIP\_10\_mL} = \frac{0.02}{\sqrt{3}} = 0.011547 \tag{6}$$

$$u_{PIP\_100\_mL} = \frac{0.08}{\sqrt{3}} = 0.046188 \tag{7}$$

$$u_{n*PIP\_10\_mL} = \frac{n}{100} * 0.011547 = n * 1.1547 * 10^{-4} \tag{8}$$

$$u_{PIP\_100\_mL} = \frac{n*10}{10000} * 0.046188 = n * 4.6188 * 10^{-5} \tag{9}$$

$$u_{\%solv} = \sqrt{\left(n * 1.1547 * 10^{-4}\right)^2 + \left(n * 4.6188 * 10^{-5}\right)^2} = n * 1.245 * 10^{-4}, k = 1 \tag{10}$$

$$u_{\%solv} = n * 2.49 * 10^{-4}, k = 2 \tag{11}$$

Plugging values for *Vs* and *Vv* in Equation 2 and adding the result of Equation 11 we get:

$$\%solv = \left(\frac{n}{10} + /- n * 2.49 * 10^{-4}\right) * 100 \text{ , k = 2} \tag{12}$$

Conflicts of Interest

The author declares no conflict of interest.

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