INDIVIDUAL TEMPERATURE CORRECTION (ITC) FOR INSULATION RESISTANCE MEASUREMENTS

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INTRODUCTION

Safe operation of electrical power network relies on healthy electrical insulation of all of its components. In general the condition of insulation is unknown and appropriate periodic electrical testing is required to detect potential deterioration and avoid catastrophic failure of the given system.

The value of insulation resistance (IR) is strongly affected by the temperature of the material. The same material measured at a lower temperature can exhibit significantly higher resistance, and vice versa. Higher temperature leads to lower insulation resistance. Therefore, a direct comparison of values can only be done for the "base temperature", for example 20 °C [1,2], but other values can be also used as required [3,4].

However, in most cases IR measurements are done at the operating temperature of the given device, which could be significantly lower as well as higher than the ideal base temperature. For this reason temperature correction is required to make sure that meaningful conclusions can be drawn from the real measured values of IR.

Correction factors depend on the type of insulation. To facilitate and simplify corrections some average correction factors, for different insulation materials, have been developed over the years. Table 1 is an example of commonly used temperature correction factors for typical insulation systems used in rotating equipment and cables.

The temperature correction factors in the table are average values and describe the material under "normal" conditions. In reality the condition of an insulation material is unknown and the assumed temperature correction may not accurately reflect the actual insulation.

For instance, for rotating equipment Class A the IR at 50 °C differs by more than an order of magnitude as compared to 20 °C. Therefore, if the given device does not conform to the "average" value then the applied correction factor of 10.45 might lead to a significant error in the estimation of the IR value at 20 °C.

Generic correction factors can also be used for other parameters, like insulation power factor. However, these values were removed from the newer edition of the relevant standard C57.12.90-2010 with the following note [2]: "*Experience has shown that the variation in power factor with temperature is substantial and erratic so that no single correction curve will fit all cases.*" For this reason an individual approach to temperature correction is beneficial.

Table 1 Temperature correction factors for insulation resistance

	Rotating Equipment		Cables							
Temperature (°C)	Class A	Class B	Code Natural	Code GR-S	Performance Natural	Heat Resist Natural	Heat Resist Performance GR-S	Ozone Resist Natural GR-S	Varnished Cambric	Impregnated Paper
0	0.21	0.4	0.25	0.12	0.47	0.42	0.22	0.14	0.1	0.28
5	0.31	0.5	0.4	0.23	0.6	0.56	0.37	0.26	0.2	0.43
10	0.45	0.63	0.61	0.46	0.76	0.73	0.58	0.49	0.43	0.64
15.6	0.71	0.81	1	1	1	1	1	1	1	1
20	1	1	1.47	1.83	1.24	1.28	1.53	1.75	1.94	1.43
25	1.48	1.25	2.27	3.67	1.58	1.68	2.48	3.29	4.08	2.17
30	2.2	1.58	3.52	7.32	2	2.24	4.03	6.20	8.62	3.2
35	3.24	2	5.45	14.6	2.55	2.93	6.53	11.65	18.2	4.77
40	4.8	2.5	8.45	29.2	3.26	3.85	10.7	25	38.5	7.15
45	7.1	3.15	13.1	54	4.15	5.08	17.1	41.4	81	10.7
50	10.45	3.98	20	116	5.29	6.72	27.85	78	170	16
55	15.5	5			6.72	8.83	45		345	24
60	22.8	6.3			8.58	11.6	73		775	36
65	34	7.9				15.40	118			
70	50	10				20.3	193			
75	74	12.6				26.6	313			

INDIVIDUAL TEMPERATURE CORRECTION

The concept of Individual Temperature Correction (ITC) is based on the fact that electrical phenomena in electrical insulation follow power laws, so that appropriate scaling and similarity is preserved at different ranges of temperature and time intervals.

With increased temperature the dielectric response is quicker, which results in similar behaviour at higher frequency for AC excitation, or shorter time for DC excitation. In other words, the values change, but the general shape of the curves is preserved.

These effects can be described by an appropriate phenomenological approach based on the Arrhenius equation, which can be used for re-calculating (or correcting) the values measured at one temperature to some other temperature [5], [6].

The correction factor used in an ITC algorithm is calculated with the following activation energy function:

(1) $$A(T_1,T_2) = e^{\frac{-E}{k_B}\left(\frac{1}{T_2}-\frac{1}{T_1}\right)}$$

where: E – material-specific activation energy (J), k_B – Boltzmann constant 1.3806488 × 10^{-23} (J/K), T_1 and T_2 temperatures (K) of interest.

The value of activation energy depends on the material and it is usually between 0.4 – 1.1 eV (1 eV = 1.60217657 × 10^{-19} J), with typical values of 0.4 – 0.5 eV for transformer oil and 0.9 – 1.0 eV for oil impregnated paper [7]. The activation energy function reflects the temperature changes as shown in Fig. 1.

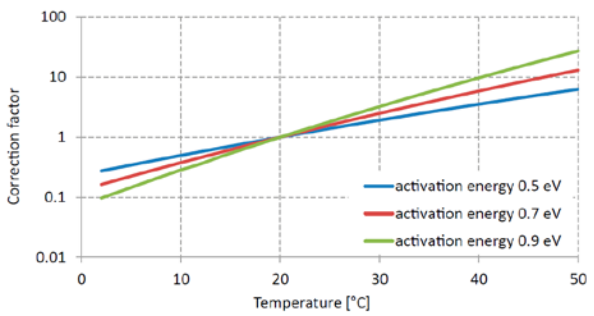

Fig. 1. Effect of activation energy on correction factor

TEMPERATURE CORRECTION IN FREQUENCY DOMAIN (AC)

ITC was first implemented in the frequency domain (for AC measurements). The technique was researched extensively and resulted with a Megger patent [8]. This method was developed and proved to be so reliable that it is now used in commercial products like the Megger IDAX 350 (Fig. 2), which utilises the so-called Frequency Domain Spectroscopy (FDS).

Fig. 2. IDAX 300 and IDAX 350 Insulation Diagnostic Analyzers [9]

With such equipment it is possible to measure the Dielectric Frequency Response (DFR), with typical tan δ curves as shown in Fig. 3.

As evident from Fig. 3, the general shapes of the curves are preserved at different temperatures, but the dielectric response is shifted proportionally to the temperature at which the measurement was taken. The higher the temperature the further the shift towards the higher frequencies.

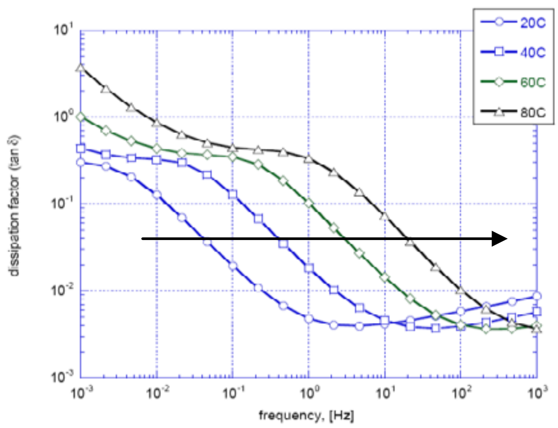

Fig. 3. Typical curves of tan δ vs. frequency. The arrow shows shifting of curves towards higher frequency at higher temperatures

Therefore, the measurement taken at a higher temperature can be re-calculated to a lower temperature with the help of equation (1) and the activation energy function shown in Fig. 1.

The curves are measured for the insulation of the particular device, hence accurate ITC is possible if the value of the activation energy was selected correctly.

A colloquial description of the method is sometimes given as "temperature is frequency and frequency is temperature" because the values change in a proportional way and it is possible to correct for change of temperature, as well as for the change for frequency.

TEMPERATURE CORRECTION IN TIME DOMAIN (DC)

The same concept of ITC can be applied to DC measurements. However, with DC it is not possible to sweep the frequency to produce the full curve. The only possibility is to apply a DC voltage, charge the insulation-under-test to the full voltage and record the changes in the current with respect to time. This will correspond to curves of instantaneous insulation resistance (IR), as shown in Fig. 4.

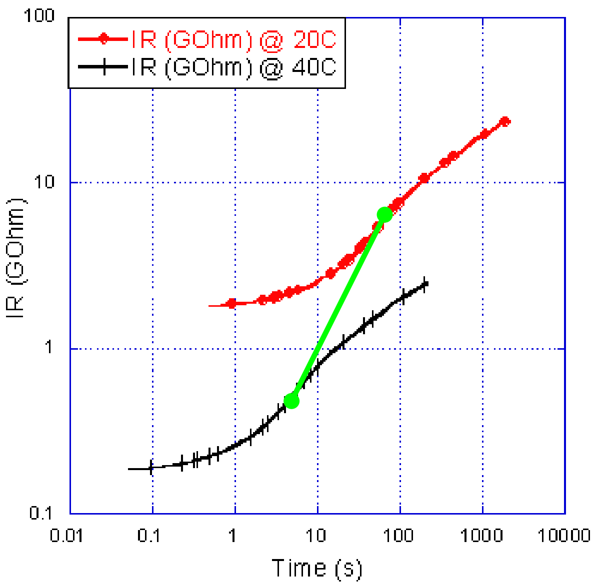

Fig. 4. Typical IR vs. time curves of the same insulation system at two temperatures

As evident from Fig. 4, with DC excitation the curves still have their shape preserved but they are clearly shifted horizontally as well as vertically. By utilising the properties of the energy activation function (equation (1) and Fig. 1) it is possible to re-calculate (that is to "correct") the values from the curve measured at one temperature to another temperature.

There is continued research and development of this method and the work resulted with another Megger patent [10].

With the 15 kV high-performance Megger insulation tester S1-1568 (Fig. 5) it is possible to stream instantaneous values via its USB port, for example one reading per second. Data similar to that shown in Fig. 4 can be produced.

Fig. 5. High-performance diagnostic insulation tester Megger S1-1568, 15 kV [11]

It is then possible to interpolate the intermediate values and the individual temperature compensation can be applied as described below.

In the first step the characteristic scaling value is calculated from equation (1). For example, for E = 0.90 eV, T_1 = 40 °C, T_2 = 20 °C the scaling value is 0.103.

Longer time at a lower temperature corresponds to a shorter time at a higher temperature. Let us assume that the value of interest is IR measured at 60 s at 20 °C. Therefore, as calculated above, the time needs to be scaled by 0.103 thus giving a time of 0.103 · 60 s = 6.2 s.
Then, the value measured at 6.2 s at 40 °C needs to be scaled by the reciprocal of the same scaling value.

Using values from Fig. 4 at 6.2 s and 40 °C this would correspond to IR = 0.6 GΩ. Therefore, dividing this value by the scaling coefficient will produce the corrected value of 0.60 GΩ / 0.103 = 5.8 GΩ at 20 °C and 60 s.

The same steps can be followed for each point on the curve, as can be appreciated from Fig. 4. Therefore, it is possible to use the re-calculated values to derive other corrected parameters, like for instance the Polarisation Index (PI), which is a ratio of IR measured at 10 minutes to that at one minute.

As mentioned above the IR curve measured at different temperatures is shifted vertically as well as horizontally. It is clear from Fig. 4 that the slope of the curve changes with time. Therefore, the values at specific time instances at different temperatures do not correspond to the same data points, and thus the value of PI is temperature dependent, even though in the past it was assumed not to be [12]. As evident from the data presented below this also applies even for simple systems, with single insulation.

IR values are strongly influenced by the temperature of the insulation system. This is clear from Fig. 4, but a better illustration for an old LV motor is shown in Fig. 6, measured for different temperatures at one minute and 10 minutes. By employing the temperature correction method (with activation energy E = 0.78 eV) the variation in IR values can be corrected and in this case the maximum deviation does not exceed 6% and for most points it is less than 3% from the actual value *measured* at 20 °C.

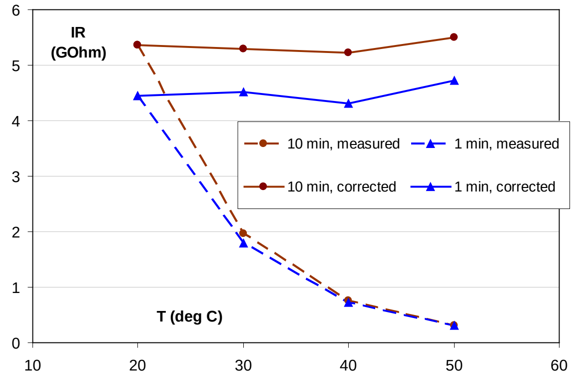

Fig. 6. IR for a motor at one minute and 10 minutes, values as measured and corrected

The PI values calculated from these curves are shown in Fig. 7. This quite old motor had a fairly low value of PI at 20 °C, but the PI values noticeably decrease at elevated temperatures. Therefore, the variation in PI can be also corrected with the method of individual temperature compensation.

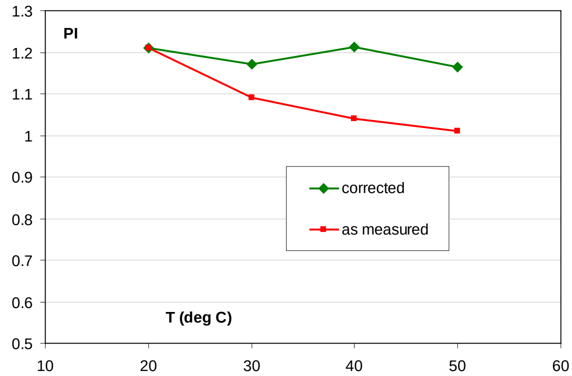

Fig. 7. PI as measured and corrected (see Fig. 6)

Another example is shown in Fig. 8. The measurements were done on a single-phase dry transformer and it is clear that the PI values are also significantly affected by the elevated temperatures with PI = 1.35 at 40 °C, which would indicate that the state of the insulation is “questionable” [3].

However, after applying temperature correction the calculated value is PI = 3.05, which would indicate that the insulation is “good”.

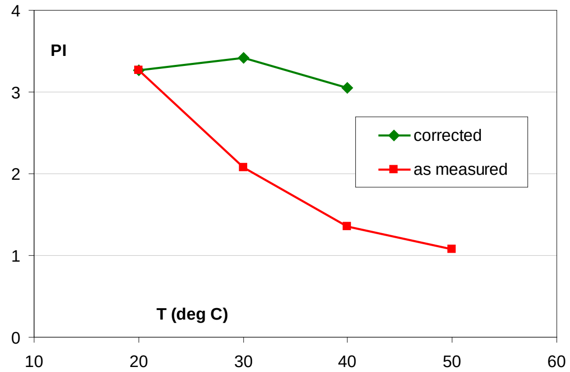

Fig. 8. PI for a dry transformer

Similar results were also produced for a bushing in a good condition (clean, etc.) with reference point at room temperature. At 22 °C the PI value was measured as 2.0, but at 43 °C it was only PI = 1.5.

After applying temperature compensation with the activation value of 0.9 eV (for oil-impregnated paper) the corrected values was 2.0, which is the same as *measured* at 22 °C.

Correction coefficients in Table 1 are listed only for certain numbers so this would require interpolation for the real temperature of 43 °C and such linear interpolation may introduce additional errors.

For example, the actual value of insulation resistance at 22 °C at 60 s was 18 TΩ. At 43 °C this value dropped to 3.2 TΩ. By using the correction method described in this paper the recalculated value was 17 TΩ, which is within 6% of the actual measured resistance. However, using the values from the table would give only 13 TΩ which is inferior in terms of both the insulation resistance as well as the polarisation index measurements.

Fig. 9 shows examples of several correction coefficients defined by different approaches. It is clear that the values can differ significantly.

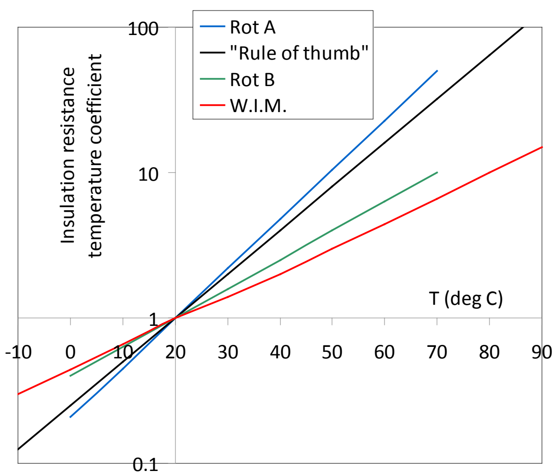

Fig. 9. Example of correction coefficients defined by different publications (W.I.M.: Winding insulation and maintenance [13])

FURTHER WORK AND SUMMARY

The corrected curve shown in Fig. 8 does not show the PI value corrected from 50 °C. This is because the higher the temperature the shorter the time required for measurement. In this particular case the measurement at 50 °C called for a sub-second data, which was not available from the given set of measurements, so the calculation could not be done. All measurements were done under controlled temperature conditions, which require a very long time and cannot be easily repeated.

Therefore, the measurement system must be designed in such a way that allows for accurate measurement of values immediately after application of the DC excitation voltage. This leads to two difficulties. Firstly, the system represents certain capacitance, which must be quickly charged to the final voltage at which the measurement can be taken. Until the voltage is stable the capacitive and polarisation current components are different from the steady-state condition and thus cannot be reliably used in the calculations.

The second difficulty arises from analogue electronic filters usually employed for facilitating measurements of very small currents (nA and below). The time constants associated with these filters must be such as to allow for accurate measurement of the sub-second data.

Another practical issue is the fact that any DC offset in the system-under-test, or in the measurement device, could lead to inaccurate measurements. For example, corona discharge is pronounced in negative half-cycle, which results with an asymmetrical current and thus with some equivalent DC offset. Such effects must be taken into account to make sure measurements are accurate.

As a final comment, this paper focused only on single-insulation devices. For more complex systems it is possible to extend the analysis with the so-called XY model [14]. It is then possible to handle individual correction for oil-filled transformers, which by definition comprise oil and oil-impregnated paper, with respectively lower and higher activation energy.

In fact, the XY model is already implemented for the ITC method under AC excitation [9].

The DC method will continue to be developed and it will be implemented in the future Megger insulation testers, so that the method will be available to the operators as an automated operation.

REFERENCES

[1] P. Werelius, M. Ohlen, “Using Dielectric Frequency Response Measurements to Determine Dissipation Factor Temperature Dependence in Power System Components”, GCC CIGRE, Qatar, 2010

[2] D. Robalino, P. Werelius, M. Ohlen, J. Cheng, “Dielectric Frequency Response Measurements and Dissipation Factor Temperature Dependence”, ISEI 2012, Puerto Rico

[3] “A stitch in time”, The complete guide to electrical insulation testing, Megger, 2006

[4] Testing solid insulation of electrical equipment, Vol. 3-1, Facilities Instructions, Standards, And Techniques, Bureau of Reclamation, US Department of the Interior, 1991

[5] D. Robalino, Individual temperature compensation, Transformers Magazine, Vol. 2 (3), 2015, p. 42

[6] A. Helgesson, “Analysis of Dielectric Response Measurement Methods and Dielectric Properties of Resin-Rich Insulation During Processing”, KTH Stockholm, 2000

[7] P. Werelius, M. Ohlen, Dielectric frequency response and temperature dependence of dissipation factor, TechCon Asia-Pacific, 2009

[8] P. Werelius, M. Ohlen, System and method for power system parameter measurement, Patent US8428895, 2013

[9] IDAX 300/350 Insulation Diagnostic Analyzers, Data sheet, Megger, 2013

[10] P. Werelius, M. Ohlen, A. Purton, Method and device for determining power system parameters, Patent SE537145, 2015

[11] S1-568, S1-1068, S1-1568 Insulation Resistance Testers, Data sheet, Megger, 2016

[12] H. Penrose, A review of polarization index and IEEE Std. 43-2000, Electrical Construction and Maintenance, 2004

[13] K.C. Agrawal, Industrial Power Engineering Handbook, Newnes Power Engineering Series, 2001

[14] CIGRE TB 445, Guide for Transformer Maintenance