Journal of Energy

VOLUME 61 | 2012

journal homepage: http://journalofenergy.com/

C.J.G. Spoorenberg
SGB - Smit Transformers Nijmegen
c.spoorenberg@smit-trafo.nl

STATISTICAL ANALYSIS OF TEMPERATURE RISE TEST FOR INCREASED ACCURACY ON X- AND Y- EXPONENTS

SUMMARY

On a large number (> 50) of identical large power single-phase autotransformers ONAF temperature rise test have been performed as part of the customer specification. Part of the 24 hour test is a 125% overload for 8 hours. Based on this data one can statistically evaluate aspects as average value, standard deviation and correlation on many parameters.

Measurement tolerances have a large influence on the top oil exponent x and the winding exponent y. The calculation of x and y is determined by the ratio of two temperature differences due to a load difference, which can result in larger errors than expected.

In two transformers fibre optic (FO) sensors were installed in the common winding to measure the hot-spot, not only during steady state, but also during transient conditions. For ONAF cooling, a step increase of load takes a relatively long time before the oil flow reaches a steady state, as is described in the loading guide. The overshoot in the gradient between the hot-spot temperature and the top oil temperature is demonstrated and can influence the hot-spot gradient exponent z.

Based on the test results and a statistical simulation one can conclude that the normal tolerances in the temperature- and resistance measurements, result in a large standard deviation in the exponents x and y. Use of the exponents x and y, based on a heat run of one single transformer, should be handled with extreme care. In case of doubt, the use of the exponents given in the loading guide result in a safe margin when determining the overload capabilities of a transformer.

1. INTRODUCTION

The top oil exponent x (n in the IEEE standard [6]), the winding gradient exponent y (2.m in the IEEE standard [6]) and the hot-spot gradient exponent z determine the overloading capabilities of transformers as described in the standards ([1], [2] and [3]). Several published papers ([4] and [5]) present test data on these exponents for some large power transformers based on temperature rise tests. In this paper these exponents are determined for more than 50 large power transformers, all of the same identical design. Each transformer was subject to a 24 hour temperature rise test, consisting of a start with all coolers closed, then stabilizing at 100% load at ONAF which was followed with a 125% overload for 8 hours. Based on the large amount of test data, one can determine average value and standard deviation for the exponents and relate those to the standards. Based on a statistical theoretical simulation, taking into account all the tolerances on resistance and temperature measurement, the standard deviation on the factors x, y (and z) can already be explained.

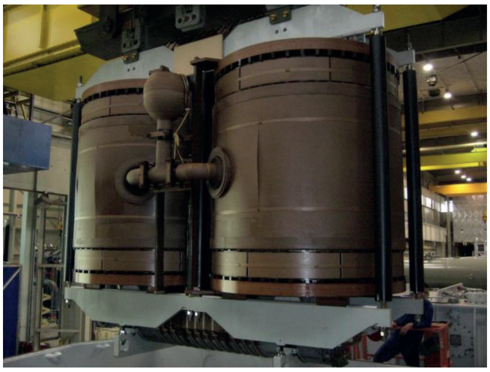
C.J.G. Spoorenberg, Statistical analysis of temperature rise test for increased accuracy on x- and y- exponents, Journal of Energy, vol. 61 (2012) Special Issue, p. 63-72

2. DATA ANALYSIS OF A LARGE NUMBER OF TEMPERATURE RISE TESTS OF TRANSFORMERS OF IDENTICAL DESIGN

In the time frame of about 5 years, between the end of 2005 and the beginning of 2011, temperature rise tests were performed on about 50 transformers of the same identical design. The test environment remained essentially the same within this time frame, although investments in air cushion transportation and repositioning the capacitorbank took place in 2008. Investments in new test equipment in 2007 for the resistance measurements increased the accuracy on the cooling down curve. From a statistical point of view the ambient and the test equipment did not change in this timeframe.

3. DESCRIPTION OF TRANSFORMER DESIGN WITH MAIN CHARACTERISTICS

The transformers are a 280 MVA - ONAF cooled single-phase autotransformers 500 / 230 kV with +/- 5% DETC on the HV side. The transformer is a two-leg design and the common- and the series windings are Smit disk windings with axial cooling channels.



Picture 1 Active part in lifting crane before putting into tank

Picture 2 Smit disk winding on vertical winding machine

3.1. Presentation of data and results.

The gradients are determined as the difference between average winding temperature and average oil temperature ([3] – 11 but also [1] – 7.7) and by the cooling down curve when cooling down to a constant value ([1] appendix C - Figure C3 with A_o is constant). The results of all test values, as an average value and the standard deviation as according the Gauss distribution, are summarized in a table 1. The design values are also presented for comparison reasons.

The influence of the losses of the transformers on the temperatures can be neglected. The no-load loss has an average value of 56.8 kW with a standard deviation of 2.8 kW. The values for the load losses in tap 1 are 405 kW and 3.4 kW respectively. The resulting standard deviation on the total losses, might only contribute for a standard deviation of < 0.5 K on top oil rise and average winding rise.

Due to the two different loads (280 MVA and 350 MVA) during the temperature rise test, one is able to determine the value of the exponents x and y on each transformer (table 2). The x - exponent is calculated based on the top-oil rise and on the average oil rise . (see table 2) The average value of x is 0.78 (standard deviation 0.12) respectively 0.85 (standard deviation 0.1) and this corresponds well with the value of 0.8 according to the present standards.

There is a large difference in standard deviation between the y - exponent based on average winding – average oil and on the cooling down curve. The values of y between 1.4 to 1.5, based on cooling down curve, do not fully correspond with the value of 1.3 ([2] -table 5) in spite of the small standard deviation of 0.12 to 0.14.

The value of the y-exponent based on the average winding – average oil is much higher than 1.3 but the standard deviation is also very high (0.35 or 0.39). One may conclude that the value of the y-exponent, as determined by the tests, is not within the bandwidth of the IEC standard and [4] (see table 2).

Remark : Based on the Gauss curve, 68% of all test values are within a bandwidth defined by average minus standard deviation and average plus standard deviation. Also 95 % of all test values are within a bandwidth defined by average minus 2 x standard deviation and average plus 2 x standard deviation.

Table 1	Test data of more than 50 temperature rise tests.						
		280 MVA			350 MVA		
		Design values	average value	Standaard deviation	Design values	average value	Standard deviation
HV	Twinding shutdown		75.8	5.39		102.5	5.85
	Time constant		9.3	0.58		8.2	0.39
	Delta T winding-oil (curve)	15.0	14.7	0.53	20.9	20.7	0.63
	Delta T oil (curve)	35.7	38.5	2.25	53.3	55.9	2.43
	Delta T winding-oil		10.6	2.09		16.6	2.51
	Delta T oil		42.2	2.26		59.6	2.82
	Delta T-winding	50.7	52.8	2.34	74.3	76.2	2.69
LV	Twinding shutdown		78.3	5.00		105.3	5.51
	Time constant		9.2	0.76		8.0	0.54
	Delta T winding-oil (curve)	16.2	16.5	0.75	22.1	22.7	0.97
	Delta T oil (curve)	37.3	38.8	2.20	55.1	56.2	2.36
	Delta T winding-oil		13.0	2.19		19.3	2.68
	Delta T oil		42.2	2.21		59.6	2.79
	Delta T-winding	53.5	55.2	2.17	77.2	78.9	2.50
	Top oil rise	48.6	52.9	2.20	67.3	72.4	2.6

Table 2	exponents x and y of test data compared with IEC and ref [4]				
	IEC 60076 - 7	Average value	Standard deviation	Average value [4]	Standard deviation [4]
x - component average oil		0.85	0.12		
x - component top oil	0.80	0.78	0.10	0.71	0.05
y - HV	1.30	2.04	0.40	1.12	0.36
y - HV (curve)		1.52	0.14		
y - LV	1.30	1.79	0.35	1.12	0.36
y - LV curve		1.43	0.12		

The temperature rise test was performed according to IEEE standards [3] . The cooling down curve is measured after stabilization of the top-oil rise, but not necessarily immediately after that point in time. During switch off and resistance measurement one needs extra personnel and one wants to organize the temperature rise test in such a way that it fits convenient within the time schedule of the test department. This results in a large variation in time of the first switch-off after start of the temperature rise test and consequently explains a part of the large standard deviation in the top oil exponent x. (see figure 1). It is clear that there is a relation between the value of x and the time after switch off. Due to the relative large standard deviation, one can only make an estimate of this relationship. This is expressed in figure 1, including an estimated bandwidth of +/- 0.1, which complies with the standard deviation as according table 1.

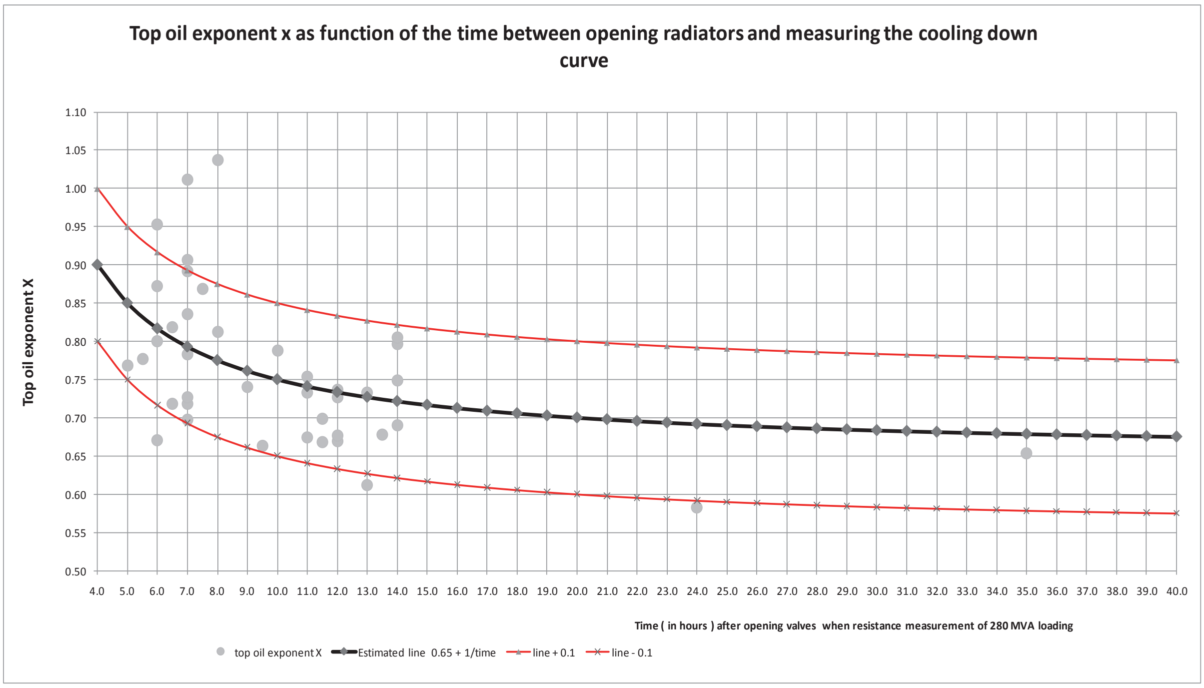


Figure 1 Top oil exponent x as function of time of switch off after opening cooler valves

As part of this investigation, the cooling down curve was measured twice for two transformers at 280 MVA. One time after stabilization, so about 8 hours after the start of the temperature rise test (280 MVA – first) and for the second time at the end of the 24 hour test (280 MVA – at end). In the latter case the 280 MVA load at the end lasted also about 8 hours after the shutdown of the 125% overload. The x exponents decrease of about 0.2 on average(see also figure 1). This is due the fact that at first shut down the temperatures are not fully stabilized starting from no load, although the it is according to the standards. At the shut down at the end, the temperature might also not be fully stabilized starting from a previous overload.

3.2. Temperature test with FO sensors.

In the loading guide ([2] – table 5) the exponents x and y are defined, but also the dynamics of the hot-spot over top oil, by the factors k11, k21 and k22. As part of this investigation, two transformers are equipped with some FO sensors. One transformer (serial number 3230146) had the normal temperature rise test and the sensors were placed in both LV and HV winding [8]. For the second transformer (serial number 3230204) the temperature rise test started with nominal current and all cooling in operation.

The two major aspects of investigation are:

- The hot-spot gradient exponent z, which determines the increase in hot-spot gradient to top-oil in the steady state situation, can be calculated out of the gradients at the different loads.
- The dynamic behavior of the hot-spot gradient to top-oil in the case of change of load, when there is no change in cooling. This overshoot in the gradient is described in figure 9 of reference [2] by the function $f_2(t)$.

The temperature rise test started with nominal current and all coolers and fans in operation and the FO sensors were only assembled in the LV windings, but also sensors were mounted at the outlet of the LV windings to measure the oil exit temperature. The temperature rise test started with 100% current and all cooling in operation, to measure the overshoot in the case a cold transformer is put in service at nominal load. Also in this case one is able to estimate the value for sensor 1 of about (34.5K – 0.0K)/(20.0K – 0.0K) = 1.7. The value for sensor 3 is 35.3K/19K = 1.85

This overshoot is related to the gradient of the sensor minus the average top oil temperature as measured at the cover of the tank by the sensors immersed in the oil.

The FO sensors measuring the temperature gradient between top oil that exits the winding and the average top oil temperature have quite a similar behavior although positioned in different phases, but have a difference of several degrees. This also complies with figure 6 in reference [4].

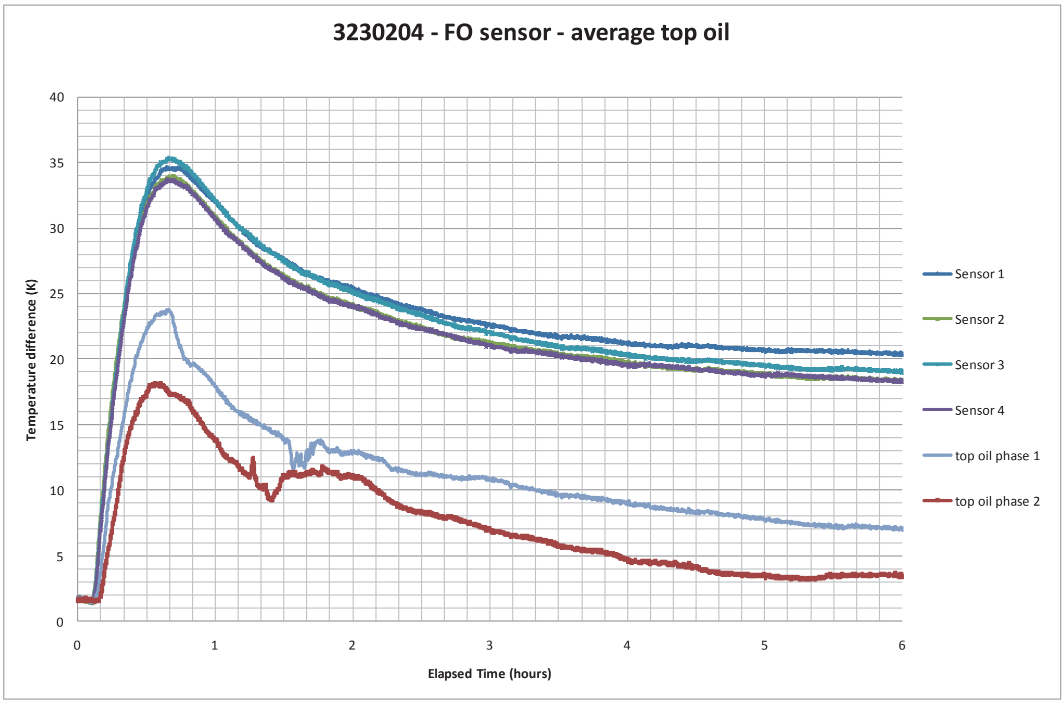


Figure 2 Temperature difference of FO sensors and averaged top oil.

4. INFLUENCE OF TOLERANCES ON THE EXPONENTS X AND Y DETERMINED BY STATISTICAL SIMULATION.

As a starting point one has the parameters to be measured and the tolerances on each parameter.

Tolerances are not only related to the accuracy of the test equipment, but also related to the test set up such as (accurate) location of the sensors for the ambient temperature, the bottom oil temperature and the top oil temperature. Some tolerances are also related to the test environment such as the positioning of the large power transformer within the test department laboratory and the steady state temperature condition of the transformer when the transformer is positioned, due to the “outside” ambient temperature. Some of these tolerances are more or less exact, but others have to be estimated. The combination of all these tolerances can be simulated by the using the statistical features of Excel.

4.1. Definition of parameters and their tolerances

For each parameter as defined in the IEC one can determine the measurement tolerance (table 3: column 2 until 17) and by using these tolerances and taking the average test values as input (table 1), one can simulate all the test values. The input parameters, which are measured data, are marked with a yellow colour.

The reference resistance has to be determined and is usually done in the factory with an tolerance in ambient temperature of +/- 0,5 ^{o}C (column 2 with reference = 13 ^{o}C). This cold resistance measurement has a tolerance of +/- 0,15% (column 3 with reference = 0.07183 Ω ([1] – 7.1.1.))

Warm resistance measurement after switch off has the same tolerance (resistance +/- 0,15% (column 4 with reference = 0.09074 Ω)).

The tolerance due to the extrapolation of in the cooldown curve for determining the winding temperature is estimated to be +/- 0.5 ^{o}C. (column 5 - [1] – 7.5.)

To determine the winding temperature rise (column 7 - [1] – 7.6) one has to subtract the ambient temperature, as measured by sensors at the half height of the coolers and the ambient air temperature at the inlet of the fans. ([1] – 7.1.1) The ambient air temperature has a tolerance of +/- 1^{o}C .

Remarks regarding the ambient temperature and the test method

- One of the main starting points is that the ambient temperature is a constant value, but during a temperature rise test on a large power transformer the ambient temperature changes also. The amount of change is influenced by such factors as the power(loss) input, the relative size of the transformer to the size of the laboratory and whether the laboratory has forced air ventilation in operation or not. The change in ambient temperature will have some time delay on a change of the average oil, which will affect the results with respect to the temperature rises.
- Temperature rise tests are sometimes performed in winter time and sometimes in the summer, so when comparing results one has to realize that the ambient temperatures are not the same for the tested transformers.
- The test has to last until the steady state is reached, as being when the variation of the top oil temperature rise is below 1 K during a consecutive period of 3 hours. ([3])
- The short circuit test method for the temperature rise test ([1] - 7.2.2.) in a test department of a transformer factory can only be a simulation of the operation conditions at site.

For practical reasons the bottom oil temperature is defined as the temperature of the oil returning from the cooling equipment. (see [1] – 7.3.2). The bottom oil temperature (column 8 [1] – 7.3.2) is measured by a thermocouple placed at the return headers of the coolers, the thermocouple must be thermally insulated from the ambient temperature. The tolerance of measurement is +/- 1^{o}C but one also has to introduce an assembly tolerance, because the sensors are not assembled in the exact same way on every transformer. This assembly tolerance is taken as +/- 2^{o}C at 280 MVA load. This relative tolerance in the oil temperatures due to location and assembly of the sensors does not change when this transformer is tested at a different load. (marked orange in table 5)

Remark : The same applies for the oil that enters the cooling equipment, which is not prescribed in [1]. but required for calculation of average oil as defined in [3]. (coolin (column 9))

Top oil temperature (column 13 – [1] – 7.3.1) is measured by one or more sensors immersed in the insulating liquid at the top of the tank , or in pockets in the cover and the same tolerances apply for the top oil sensor as the bottom oil thermocouples. To determine the temperature rises, one has to subtract the ambient temperature, as in the case of average oil rise (column 11 – [1] – 7.4) and top oil rise (column 14– [1] – 7.4)

The hot-spot temperature is set with a reference of 93.7 ^{o}C at 280 MVA and the error is +/- 1^{o}C. The hot-spot temperature (column 15 – [1] – 7.8.2) and hot-spot temperature rise (column 16 – [1] – 7.8.2) can be determined. The maximum reading shall be taken as the hot-spot winding temperature. In the case of several fibre optic sensors that are assembled close together, one can correct for the offset of the individual sensors. Before the start of the test the temperatures should all be the same and one may calibrate each sensor to that average value. In that way one compensates for the different tolerances among the sensors and the corresponding channels in the measurement equipment. The maximum difference between sensors before start of the test was about 1.5 ^{o}C

Remark : The average oil in the simulation is defined as top oil minus 0,5 * temperature drop over the cooler [3] and the basic starting point is that the average oil temperature in the cooler is the same as the average oil temperature in each winding.

4.2. Simulation results according [3].

In this section the IEEE definition of gradient winding – oil is according reference [3] – 11), while in the next section (4.3) the definition is according to reference [1] - annex C. By using Excel one can simulate the tolerance by using the function ASELECT(), as in following line.

*Tcold = Tcold(reference) +2*Tcold(tolerance)*(ASELECT()*(0-1)+1)- Tcold(tolerance)*.

For each parameter, if applicable, one can apply this function and each row in a spreadsheet simulates one transformer temperature rise test. In this way one can calculate in each row the hot-spot factor. At the end of the 50 rows the average value and the standard deviation of each parameter are calculated by Excel (as a check of input for some parameters).

Table 3 Statistical simulation based on gradient winding - average oil (IEEE)																			
280 MVA		Measurement tol.of resistance in %											Input parameters						
		0.15	0.15				Tolerance due to assembly of sensor												
	Tolerances in degrees and Ohms (calculated on basis of % tolerance						2.0	2.0				2.0							
	0.5	0.000108	0.0001361	0.50	2.5		1.0	1.0				1.0		2.0					
	Reference values of temperature and resistance																		
	13	0.07183	0.09074		23.0		53.1	73.7				75.7		93.7		1.35			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Columnnumber		
Nr	Tcold	Rcold	Rwarm	Twinding	Tambient	Winding rise	Bottom oil	Coolin	Average oil	Average oil rise	Gradient winding to oil	Topoil	Topoil rise	Thotspot	Hotspot rise	Hotspot factor			
	θ1	R1	R2	θ2	θa	θw = θ2	θb	θc	θom	Δθom	g	θo	Δθo	θh	Δθh	H			
	°C	Ω	Ω	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C				
1	13.5	0.07187	0.09081	79.7	22.8	56.9	50.6	74.8	64.3	41.4	15.5	76.4	53.5	95.5	72.7	1.24			
2	12.7	0.07176	0.09074	79.3	24.6	54.7	51.8	75.6	63.6	39.0	15.7	75.5	50.9	91.9	67.3	1.05			
49	12.5	0.07176	0.09063	78.6	23.5	55.0	52.1	75.8	64.2	40.6	14.4	76.0	52.4	92.6	69.0	1.15			
50	13.1	0.07190	0.09084	79.4	20.6	58.9	53.0	74.7	65.9	45.4	13.5	76.8	56.2	94.4	73.8	1.30			
Average	13.06	0.07	0.09	78.92	22.70	56.23	52.94	73.70	65.57	42.88	13.35	75.95	53.26	93.64	70.95	1.34			
St. Dev.	0.30	0.00	0.00	0.45	1.47	1.48	1.38	1.39	1.40	2.02	1.45	1.08	1.70	1.13	2.06	0.15			
%	2.27	0.09	0.08	0.57	6.46	2.64	2.60	1.88	2.13	4.72	10.83	1.42	3.19	1.21	2.91	11.04			
350 MVA																			
Tolerances in degrees and Ohms (calculated on basis of % tolerance)																			
	0.5	0.000108	0.0001478	0.50	2.5		2.23	2.32				2.73		2.0					
	Reference values of temperature and resistance						1.0	1.0				1.0							
	13	0.07183	0.09855		27		60.6	85.9				99		124		1.29			
Nr	Tcold	Rcold	Rwarm	Twinding	Tambient	Winding rise	Bottom oil	Coolin	Average oil	Average oil rise	Gradient winding to oil	Topoil	Topoil rise	Thotspot	Hotspot rise	Hotspot factor	**x**	**y**	**z**
	θ1	R1	R2	θ2	θa	θw = θ2	θb	θc	θom	Δθom	g	θo	Δθo	θh	Δθh	H			
	°C	Ω	Ω	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C				
1	13.5	0.07187	0.09842	105.5	28.8	76.7	57.1	87.4	85.4	56.6	20.1	100.6	71.8	124.3	95.4	1.18	**0.72**	**1.17**	**0.95**
2	12.7	0.07176	0.09850	105.5	28.0	77.5	58.5	87.3	84.0	56.0	21.5	98.4	70.4	122.6	94.6	1.13	**0.80**	**1.39**	**1.73**
49	12.5	0.07176	0.09858	106.0	29.2	76.8	59.3	87.8	85.2	56.0	20.8	99.5	70.2	124.9	95.6	1.22	**0.72**	**1.66**	**1.91**
50	13.1	0.07190	0.09850	105.9	28.0	77.8	59.5	86.0	87.8	59.7	18.1	101.0	73.0	123.3	95.3	1.23	**0.64**	**1.31**	**1.07**
Average	13.1	0.07184	0.09855	106.0	26.9	79.2	60.4	85.8	86.6	59.8	19.4	99.4	72.5	124.0	97.1	1.28	**0.76**	**1.68**	**1.49**
St. Dev.	0.30	0.00006	0.00008	0.47	1.52	1.52	1.56	1.52	1.55	2.22	1.58	1.05	1.71	1.13	1.78	0.10	**0.09**	**0.29**	**0.36**
%	2.27	0.09	0.08	0.45	5.67	1.92	2.59	1.77	1.78	3.72	8.18	1.06	2.36	0.91	1.84	7.53	**11.81**	**17.43**	**23.98**

Remark :If one makes a second statistical simulation, the results vary a little. A population of 50 might be considered large in the power transformer business, but is not a large number for a population in the world of statistics

4.3. Comparison of statistical simulation and test results.

The main comparison is on the standard deviation of the exponents x and y and it is focused on the two different methods to determine the winding – oil gradient (see table 4)

Table 4 Comparison of exponents based on test data and statistical simulation

	IEEE definition with gradient winding - average oil				**Cooling down curve to constant value**			
	Simulation		**Testresults**		**Simulation**		**Testresults**	
	x	**y**	**x**	**y (LV+HV)**	**x**	**y**	**x**	**y (LV+HV)**
Average	0.76	1.66	0.78	1.86	0.82	1.57	0.78	1.46
St. Dev	0.08	0.29	0.10	0.37	0.11	0.14	0.10	0.13

The starting point of the simulation are the average values of the tests, so it is logical that test results and simulation comply very well, but the large standard deviation in the simulation is the outcome of all the tolerances.

5. EFFECT OF UNCERTAINTY ON X AND Y EXPONENT ON THE HOT SPOT TEMPERATURE RISE IN CASE OF OVERLOAD

The consequences of the uncertainty in values of the exponents x and y on the overload capability of a transformer needs to be determined. As a first step one has to determine if the x and y exponent, as based on the test results, are correlated or can be treated as independent variables. By using the function CORRELATIE in Excel one can determine the correlation (Table 5)

Table 5 Correlation between exponents and correlation with opening of coolers

	x - exponent top oil	y - **HV**	y - **LV**	Time after opening coolers
Top oil rise 280 MVA	NA	NA	NA	0.44
Top oil rise 350 MVA	NA	NA	NA	-0.04
x - exponent top oil	1.00	0.05	0.05	-0.47
y - **HV**		1.00	0.85	-0.18
y - **LV**			1.00	0.07

Based on the previous results , these correlation coefficients are not that surprising. There is a correlation between the top oil rise at 280 MVA and the x-exponent with the time after opening the coolers, but is also clear from Figure 1. There is no correlation with the top oil rise at 350 MVA and the time after opening of the coolers, which is expected because the overload is always fixed at 8 hours and this measurement is made a long time after start of the heat run test.

There is also no correlation between the x-exponent and the y-exponents of LV and HV, so they can be treated as independent parameters for determining the overload capability. There is a large correlation between the y exponents of LV and HV.

Based on the value of the x- and y – exponent, one can determine the hot spot temperature rise as a function of the load factor K (Figure 3). To compare the different results, the average values at 100% load are used as a starting point for comparison.

The overload curve based on the loading guide [2] IEC (x=0.8 and y = 1.3) can be compared with the final values of the temperature rise tests (x = 0.65 as based on figure 1 and y = 1.9 as average values of LV and HV in Table 2) and the difference between both curves is very limited.

In the case one would test only one transformer, one has to take into account the uncertainty in these exponents. Two overload curves are calculated, one based on the average values **minus** the standard deviation (see Table 2) and one on the average values **plus** the standard deviation.

The overload curve of this single transformer would be between the two dashed lines. Based on that one may conclude that by using values as determined during a temperature rise test, the overloading will most likely more limited as based on IEC, which means that during operation the hot spot temperature rise will not be exceeded, but there is a possible risk that this is not the case.

Remark : As a reminder, one has to consider that a temperature rise test is performed in the tap position with the highest losses, but the tap position is not taken into account in the loading guide. In the case of plus/minus regulation this will have a large impact. The hot spot factor is considered as a constant but it depends on the tap position and can be different for the main windings.

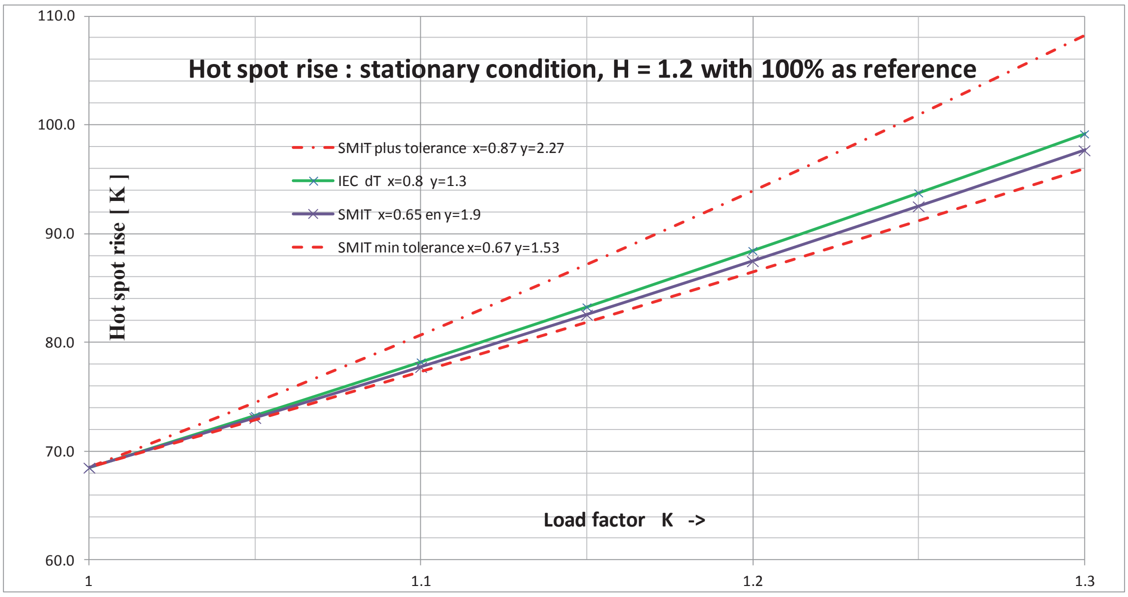


Figure 3 Comparison of hot spot temperature rise based on IEC and test results

There is always a lot of discussion on the values of the x- and y-exponent to be used. The variation on the value of the x-exponent is limited . There is a large variation on the value of y-exponent, but one has to consider that this is only related to the gradient of the winding to the oil. By making a numerical example, one can see quite clear the consequences on variation of the exponents.

Example
Starting point at 100% load
Top oil rise : 53 K
Gradient hot spot to top oil : 16 K

Difference in top oil rise at 130% load (neglecting no-load losses) in the case of x=0.65 compared to 0.8

$53 * ((1.3^2)^{0.65} - (1.3^2)^{0.8}) \approx -6$ K

Difference in gradient hot spot to top oil at 130% in the case of x=1.9 compared to 1.3

$16 * (1.3^{1.9} - 1.3^{1.3}) \approx 4$ K

6. CONCLUSIONS

The exponents x, y and z as determined by temperature rise test have as basic requirement that a steady state thermal situation has to be achieved before one makes the measurement. In the case of large power transformers with ONAF cooling, this will require a temperature rise test at nominal load taking at least 12 hours after ending the restriction by opening of the valves and in addition more than 6 hours in the case of the overload.

The exponents x, y and z are based on the difference of two temperature rise measurements. Also is each temperature difference based on two measured values with each it's own tolerance. This results in a large inaccuracy.

By performing a lot of temperature rise tests on "identical" transformers, one can statistically determine the average value and standard deviation of the oil-exponent x and winding exponent y. This will create a solid base to determine the exponents so that transformers can be loaded according the specification.

Simulation of the temperature rise test (by Excel) with all their tolerances regarding:

- test environment,
- test setup,
- test sequence
- test equipment

C.J.G. Spoorenberg, Statistical analysis of temperature rise test for increased accuracy on x- and y- exponents, Journal of Energy, vol. 61 (2012) Special Issue, p. 63-72

explain the large standard deviation in the x- and y-exponent as determined by the temperature rise tests.

Based on the current practice, regarding

- the length of temperature test,
- the available, highly accurate, test equipment
- available test environments at transformer factories, an improvement by a smaller value for the standard deviation on the x- and y-exponent will not be expected.

The exponents x , y and z can be determined during a temperature rise test of one single transformer. Due to the large inaccuracy, there is a possible risk that the use of these exponents will result in unacceptably high temperatures during overload. It is therefore recommended to use only the values according to the standard in that case.

REFERENCES

[1] IEC 60076-2 2011 - 02 Power Transformers – Part 2:Temperature rise for liquid immersed transformers

[2] IEC 60076 – 7, 2005-12 Power Transformers – Part 7 : Loading guide for oil-immersed power transformers

[3] IEEE C57.12.90 – 2006 Test Code for Liquid Immersed Distribution, Power and Regulating Transformers

[4] H. Nordman, O. Takala: Transformer Loadability Based on Directly Measured Hot-Spot Temperature and Loss and Load Current Exponents.Cigre 2010 A2_307_2010

[5] Norman, H; Hiironneieme, E; Pesonen, A.J.: Determination of hot-spot temperature rise at rated load and overload.Cigre 12-103 , 1990

[6] IEEE Standard C57.91:1995, IEEE Guide for loading mineral-oil-immersed transformers.

[7] J. Jaspar; C. Spoorenberg: Practical aspects of determining the hot-spot factor TJH2b conference Warwick UK 2011

[8] C. Spoorenberg: The statistical analysis of temperature rise test for increased accuracy on x- and y-exponents TJH2b conference Chicago USA 2012