Study Committee D1

Materials and Emerging Test Techniques

Paper D1-PS2-11027

THERMAL FAULTS SIMULATION FOR ARAMID INSULATION IN LIQUID IMMERSED POWER TRANSFORMERS

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Motivation

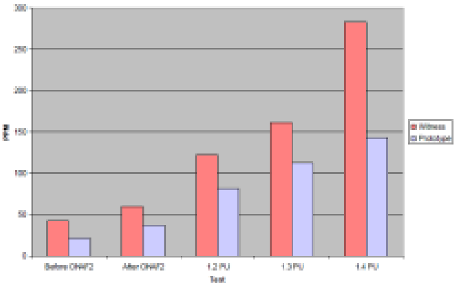
Identifying faults related to solid insulation is of utmost relevance in determining transformer condition. In case of cellulose, it is common to correlate insulating paper involvement in a fault with DGA. However, aramid paper (Nomex®) does not have a standardized or well-established methodology to characterize its involvement in a failure.

Traditional aging test methods are not able to simulate high temperature thermal failures. It is difficult to distinguish between compounds released by oil from those formed by solid insulation.

Approach

An “aging device” was built in which solid insulation can be heated up to 700 °C and oil is cooled to stay at relatively low temperature, i.e. <70 °C. Using this device allowed research to investigate chemical markers and dissolved gases released by aramid paper insulation degradation through the study at different insulation temperatures (from 170 °C up to 700 °C).

Test equipment developed for thermal fault modelling in liquid immersed insulation system: vessel with powerful water-cooling system + paper wrapped heating resistance



Example of test data comparing CO_2 generation in transformer with insulation system with aramid paper vs. cellulose paper (prototype unit with aramid paper)

Test program

The main parameters for the new study:

- Range of temperatures for heating resistance: 170 – 700 °C,
- Liquid temperature: <70 °C,
- Insulation type: DuPont™ Nomex® 926, 0.05 mm thickness (100% aramid paper for conductor insulation applications in liquid immersed power and distribution transformers),
- Liquid types: mineral oil and synthetic ester,
- For comparison purpose, aging at respective temperatures with insulating paper or without paper (liquid only).

Expected duration of test at different temperatures:

- Up to 1 440 h @ 170 °C,
- Up to 120 h @ 300 °C,
- Up to 120 h @ 500 °C,
- Up to 8 h @ 700 °C.

Types of analysis before/after aging:

- Dissolved gas analysis (DGA),
- Gas chromatography mass spectroscopy (GC-MS),
- Suspended particles investigation (analytical ferrography),
- Liquid physical chemical analysis, incl. power factor @25 °C.

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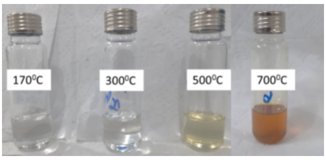
Test results

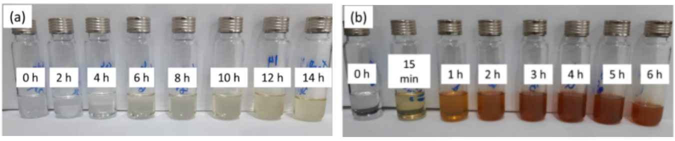
Actual tests performed in the 1st phase of test program

System	Aging temperature	Aging time	Oil analysis
MIO/aramid	< 150 °C and 300 °C	32 h (16 h at 150 °C + 16 h at 300 °C)	DGA, Interfacial tension, Acidity, Power factor at 25 °C, FTIR
	170 °C	16 h	
	500 °C	16 h	
	700 °C	6 h	
MIO blank	300 °C	16 h	

Appearance of aramid paper layers after tests at 170 °C, 300 °C, 500 °C and 700 °C.



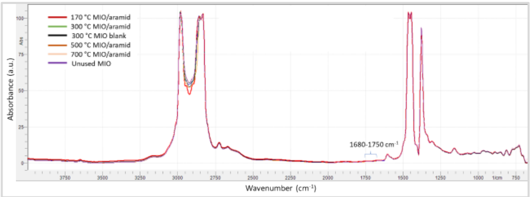
Appearance of oil in MIO/aramid test cells after completion of each test



Appearance of oil in MIO/aramid test cells versus time for tests at the highest temperatures (a) 500 °C; (b) 700 °C

Physicochemical analysis of unused oil and oil aged in MIO/aramid cells

Analysis	MIO	MIO/aramid		MIO blank	MIO/aramid	
	unused	170 °C (16 h)	< 150 °C – 300 °C (16 h)	300 °C (16 h)	500 °C (16 h)	700 °C (6 h)
Power factor at 25 °C (%)	0.003	13.1	11.4	2.9	0.02	22.2
Acidity (mg KOH/g)	0.01	0.01	0.01	0.01	0.01	0.01
Interfacial tension (mN/m)	46	46	44	37	40	47



FTIR spectra of oil after each test (Fourier transform infrared spectroscopy)

Findings from oil testing

- The different values measured for power factor might indicate some contamination of the oil at respective temperatures.
- The acidity showed no change for any of the tests.
- The changes in interfacial tension are not relevant.
- The oil was not oxidized, which was confirmed by FTIR analysis. (Fig. 7 shows the oil FTIR spectra with no absorbance for wavenumbers in the range 1680-1750 cm^{-1}, which are related to carbonyl compounds formed during oil oxidation.)

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DGA for "MIO/aramid" test at 170 °C

Gas/Time	0 h	2 h	4 h	6 h	8 h	10 h	12 h	14 h	16 h
H_2	39	29	10	34	39	23	34	40	30
CH_4	0	1	0	0	0	0	0	0	0
C_2H_4	0	0	0	0	0	0	0	0	0
C_2H_6	0	0	0	0	3	0	0	0	0
C_2H_2	0	0	0	0	0	0	0	0	0
Diagnostic code	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal
CO_2	408	372	384	303	412	234	236	243	225
CO	1	1	1	1	1	1	2	2	1
CO_2/CO	**408**	**372**	**384**	**303**	**412**	**234**	**118**	**122**	**225**
C_3H_8	1	2	2	3	2	0	0	0	0
C_3H_6	1	6	7	7	7	11	11	11	11
C_3H_6/C_3H_8	**1.0**	**3.0**	**3.5**	**2.3**	**3.5**	-	-	-	-

DGA for "MIO/aramid" test at 700 °C

Gas/Time	0 h	15 min	1 h	2 h	3 h	4 h	5 h	6 h
H_2	35	504	1463	1783	2702	2393	2123	1765
CH_4	0	2173	9281	13047	15854	16869	15878	14717
C_2H_4	0	10695	38153	48867	54111	58596	59025	56458
C_2H_6	0	2164	5212	6357	7443	8675	10009	10230
C_2H_2	0	157	860	1528	2175	1879	15878	1276
Diagnostic code	Normal	HTTF	HTTF	HTTF	HTTF	HTTF	HTTF	HTTF
CO_2	343	2764	1487	824	495	360	278	246
CO	0	77	38	20	15	11	10	7
CO_2/CO	-	**36**	**39**	**41**	**33**	**33**	**28**	**35**
C_3H_8	0	325	498	646	722	736	997	1006
C_3H_6	0	80314	166558	175720	177431	176968	169081	170264
C_3H_6/C_3H_8	-	**247.1**	**334.5**	**272**	**245.7**	**240.4**	**169.6**	**169.2**

CO_2/CO levels and ratios at different temperatures

Gas	Aging temperature (°C)			
	170	300	500	700
CO_2	225	993	741	246
CO	1	23	20	7
CO_2/CO	**225**	**43**	**37**	**35**

Results discussion

- Bulk oil temperatures have always been kept <70 °C; hence, we can assume that the DGA was indication of the simulated incipient faults in aramid insulation.
- In case of tests with aramid insulation, it is possible to observe thermal fault diagnostics for tests at 300 °C and above. For the 170 °C test diagnostics yield no fault.
- Observed levels of carbon dioxide and CO_2/CO ratios indicate that aramid thermal degradation generates higher amounts of CO_2 and lower CO when compared to typical oil/cellulose insulating systems.
- The propylene/propane ratio increases for higher test temperatures. It shows large amounts of these gases in thermal degradation of aramid. (Propylene and propane are not commonly included in the analysis of conventional insulation systems based on cellulose and mineral oil.)
- It could be expected that at the highest test temperatures some free gases were generated. Because of the open vessel used for the testing, these gases were not collected nor analyzed in this research program.

Conclusions

- The incipient faults detection based on simulation tests developed in this project can become a useful tool in diagnostics for condition assessment of power transformers with aramid-based insulation systems as per IEC 60076-14 or IEEE Std. C57.154.
- Novel approach and complexity of fault modelling at high temperatures up to 700 °C creates a lot of difficulties.
- High levels of CO_2 and C_3H_6 (propylene) seem to indicate thermal degradation of the aramid paper at high enough temperatures; however, a model for the chemical mechanism has not yet been established and will require further studies to be carried out.
- Detailed recommendation for diagnostic criteria cannot be given at this first attempt of DGA analysis.
- Further studies must continue in various liquids (esters) to generate more comprehensive conclusions.