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Transformers with low degree of polymerisation of paper

ABSTRACT

Present observations indicate that the life of transformers with a degree of polymerisation of paper of 200 could be extended by several years without increasing their risk of failure due to the mechanical condition of paper, thus significantly reducing capital investment costs needed for their replacement.

KEYWORDS

power transformers, low degree of polymerisation (DP) of paper

Introduction

Abnormal faults are the main cause of failure of transformers in service as a result of transformer design (e.g., hot spots), manufacture (e.g., loose bolts), operation (through faults, overloading) or poor maintenance (e.g., high moisture, oxidised oil, leaking gaskets, corrosion, etc). Most electrical and thermal faults can be detected by dissolved gas analysis (DGA) in oil.

Paper insulation also slowly degrades during the life of transformers, more or less rapidly depending on their operating/loading conditions.
Owners of transformers with degraded paper are faced with a technical and financial dilemma:
- if they do not replace these transformers early enough, they risk unplanned failures, the cost of which may be very high, largely exceeding the cost of the transformer itself.
- if they replace them too early, even though they could still operate satisfactorily for several more years, this will markedly increase their capital investment costs.
Deciding on the optimum time to replace transformers with degraded paper depends very much on a correct evaluation of their risk of failure at various stages of paper degradation. Presently there is no agreement among transformer experts on this issue.

Degree of polymerisation of paper

The extent of paper degradation is represented by the degree of polymerisation or DP of paper.

New insulating paper has typically a DP of 1100 and a high tensile strength. This high initial tensile strength is needed to run insulating paper on the winding machines used to wrap it under tension around conductors without tearing it.

In transformers in service, DP decreases more or less rapidly, depending mainly on temperatures in the transformers and on other factors such as moisture, oxygen content and acidity of oil. The more degraded the paper is, the lower is its DP.

A DP of 200 is presently considered in the industry as the lowest value acceptable in transformers in service. It corresponds arbitrarily to paper having lost 60% of its initial tensile strength measured in the laboratory [1]. It has been assumed since the 1970s that below a DP of 200 paper is not able to withstand any more of the mechanical forces occurring in transformers, therefore that the transformers are going to fail imminently and have reached their 'end-of-life'. Another popular statement is that 'the life of the transformer is the life of paper'.

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The accuracy of these assumptions and statements, however, has never really been demonstrated in transformers in service.

Determination of DP of paper

DP of paper can be determined:
- either by direct measurement on paper samples taken from transformers removed from service (e.g., in the bottom, middle and top of windings), paper samples are dissolved in a solvent and the viscosity of the solu-

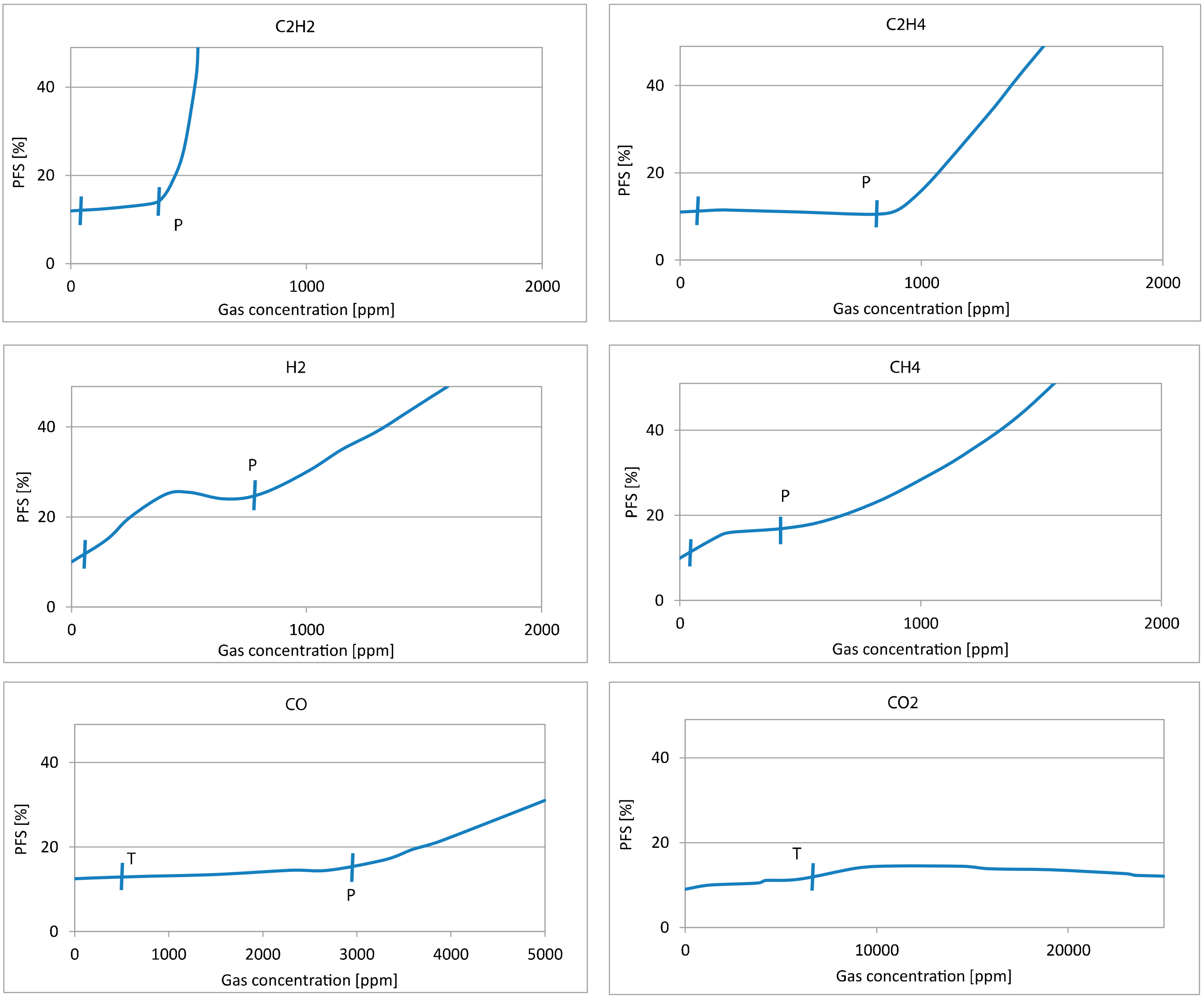

Figure 1: Probability of failure in service (PFS) vs. gas concentration

A large number of cases (more than 55) of transformers with DPs between 250 and 75 has been reported and still operating normally without failure. So far, no transformer failures due to mechanical failure of paper at low DPs have been reported

tion measured. The higher the viscosity, the longer the cellulose chains, the higher the DP and the mechanically stronger the paper. This, however, requires paper samples to be fully soluble in the solvent, otherwise measurements will falsely indicate a lower viscosity, lower DP and paper mechanically weaker than in reality.

- or by indirect measurement of paper degradation products in transformer oil:
- furans, using different models of DP vs furans content available in the literature.
- methanol [2].
- CO2 and CO2/CO ratio [3].

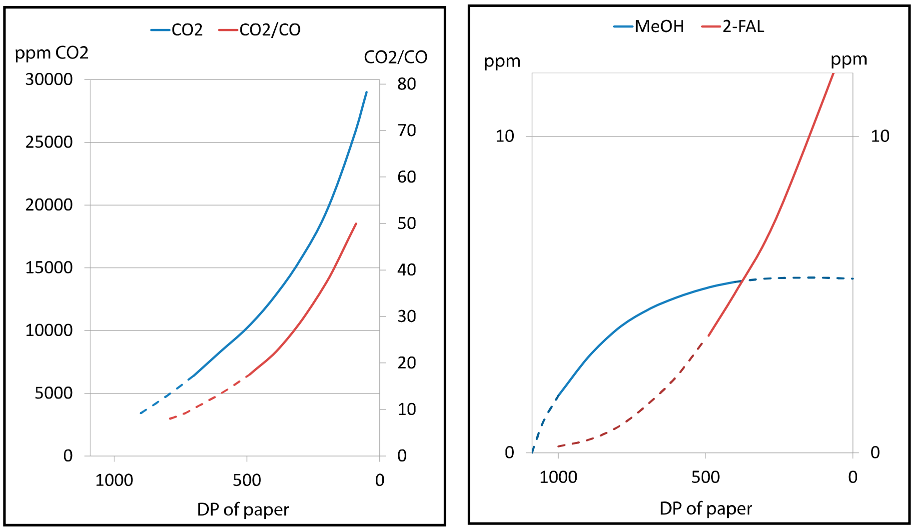

Figure 2: Typical correlations between DP of paper, CO2, CO2/CO, 2-FAL and MeOH

Risk of failure of transformers with low DPs of paper

It has been shown [4, 5] that even at very high concentrations of CO_2 the risk of failure of transformers in service is very low (Figure 1) in the absence of abnormal faults indicated by DGA.

It has also been shown [6] that there is a strong correlation between high values of CO_2, CO_2/CO ratios and furans and low DPs of paper. The typical curves of Figure 2 indicate the general trends observed. In practice, there is often a large dispersion of individual values around these curves. Figure 2 shows that CO_2 and furans (2-FAL) are more sensitive than methanol (MeOH) to detect DPs < 400.

Since the risk of failure at high concentrations of CO_2 is very low, the risk of failure at low DPs is also likely very low. This is supported by a large number of reported cases (> 55) of transformers with DPs between 250 and 75 and still operating normally without failure. These cases have been compiled for CIGRE WG47 and are indicated in Table 1. Most DP values in Table 1 were measured directly with paper samples and from high values of furans. When paper samples were taken from different places in the transformer, only those with the lowest DPs are given in the Table 1. In the 4 cases where DPs were only estimated from furans, the models used were not indicated.

In the few cases from Table 1 that failed, transformer failure was not due to mechanical failure of paper but to other reasons (dielectric failure of paper, high humidity, corrosion, etc). So far, no transformer failures due to mechanical failure of paper at low DPs have been reported.

Table 1: Cases of transformers with low DPs of paper

DP	Company	Date	Number of Transformers	Comments
150-220	NTPC (IN)	2006-2013	5	No failure on account of low DP
87	Alliant (US)	2009	1	No failure
	HQ (CA)	2010	Several	Has never seen a failure because of low DPs
	EDF (FR)	2010	Several	Has never seen a failure because of low DPs
150	ERDF (FR)	2011	1	Survived external short circuits, transport
140	FKH (CH)	2011	1	No failure due this low DP in windings
100	TjH2b	2011	Several	No failure
<200	VPDiagnose (SW)	2011	Several	No failure
100-250	Hydro One (CA)	2011	25	5 failed, but for other reasons (high moisture, rusting, leaks
100	NL	2012	1	No failure
75	Transfo Services (FR)	2012	1	No failure (2-FAL = 13 ppm)
<100	Ameren (US)	2013	1	No failure (2-FAL = 14 ppm)
280	Sonelgaz	2013	3 +	Moved several timeswithout reclamping
150	Austr/ NZ	2013	Several	No failure
250	EDF (FR)	2013	1	Failure occurred in paper with DP 400/ 600, not 250
200	EIMV (SL)	2013	1	No failure
<100?	NZ	2013	1	Darkened paper, no failure, 10,845 ppm CO_2
170	HQ (CA)	2014	At least 1	No failure
175	EDF (FR)	2014	1	Dielectric failure of overheated paper, not due to the low DP
145	Elma (IT)	2014	2	No failure (in Congo)

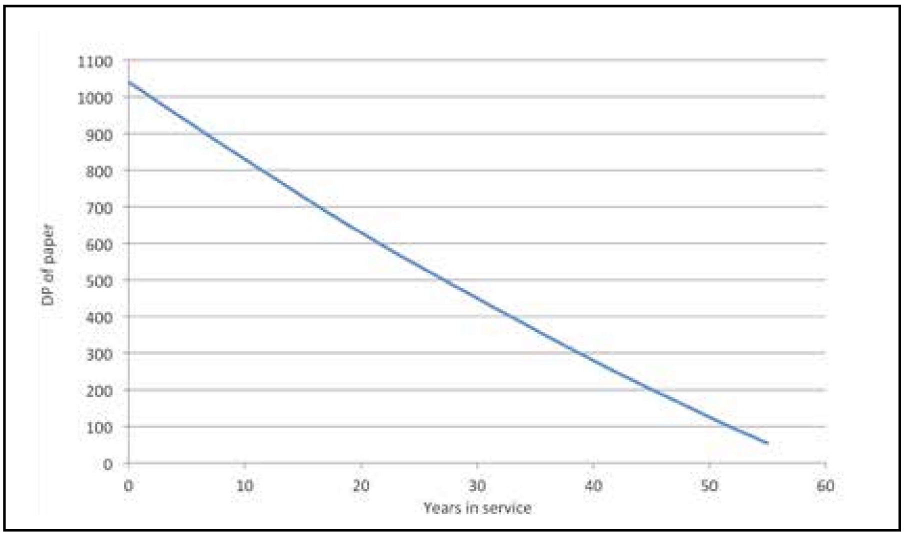

Figure 3: Typical decrease of DP of paper vs years in service (utility transformer)

Table 1 indicates that the risk of failure of transformers with DPs between 250 and 75 is quite low, even when subjected to external short circuits or transported (otherwise the transformers would have failed), and not very high as generally mentioned. Using a DP limit of 100 or 75 would therefore be more realistic than the present 200.

Based on this limit of 100 or 75 and on typical curves of decrease of DP vs. years in service (Figure 3), the life of transformers with a DP of 200 could be extended by 6 to 8 years for utility transformers, and 3 to 4 years for industrials, with no significant increase in their risk of failure due to the mechanical condition of paper in the absence of abnormal faults indicated by DGA.

The horizontal scale in Figure 3 will vary depending on transformer operating conditions and for industrial transformers.

Behaviour of paper with low DPs in transformers

Table 1 indirectly indicates that paper with DPs between 250 and 75 still provides adequate mechanical and insulating barrier between winding turns. Also, that paper between turns is not submitted to strong tensile forces but rather to compression forces, even when submitted to external short circuits (as also observed at ABB US).

No significant decrease in clamping pressure on windings has been observed at low DPs of paper, indicating that the decrease in thickness of paper at low DPs is more than compensated by the increase in thickness due to higher moisture in degraded paper.

Paper with a DP of 200 to 30 has the visual aspect of paper but turns brown to dark (Cargill US [7]). For instance, in Figure 4, paper has a DP of 270 on HV turns and

Figure 4: Example of paper with low DPs

Based on the limit of 100 or 75 and on typical curves of decrease of DP vs. years in service, the life of transformers with a DP of 200 could be extended by 6 to 8 years for utility transformers, and 3 to 4 years for industrials, with no significant increase in their risk of failure

Figure 5: Example of transformer coil with degraded paper

170 on LV turns. Other examples of transformers with degraded paper operating without failure are indicated in Figures 5 to 7.

Paper with a DP < 30 is black and cracks into pieces or powder impregnated with oil acting as a binder. Such paper, composed of very short cellulose fibres, provides mechanical barrier between turns only as long as oil is not removed from it by transformer treatments such as vapour phase drying or de-sludging with hot oil spray.

In some cases, paper with a low apparent DP has been observed to be surprisingly difficult to cut from windings, possibly because of cross-linking reactions between short fibres and degradation products of cellulose (the main component of paper), which become insoluble in the solvent used for DP measurements in the laboratory. This phenomenon is under investigation in Algeria.

Conclusion

– Based on present observations, transformers with DPs of paper between 250 and 75 and with no abnormal faults indicated by DGA still operate normally without failure, even when subjected to external short circuits and transported.

– A DP limit of 100 could therefore be more realistic than the present limit of 200.

– This would allow the life of utility transformers with a DP of 200 by several (~ 6) years to be extended and would significantly reduce capital investment costs for companies having to renew their fleets of transformers based on DP criteria.

– Transformers with DPs > 250 are still far from their end of life and do not need to be replaced.

– In case of transformers with very low DPs of paper it is preferable not to remove the oil and not to use vapour phase drying, since oil acts as a binder.

– This article represents only the point of view of its author.

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Figure 6: Example of transformer turns with degraded paper

Figure 7: Example of cooked paper

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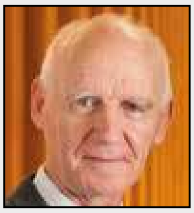

Dr Michel Duval obtained a B.Sc. and PhD. in chemical engineering in 1966 and 1970, and has worked for IREQ (Hydro-Quebec, Canada) since 1970. He has made significant contributions in 3 mains fields of R&D: dissolved gas-in-oil analysis (DGA), electrical insulating materials and lithium-polymer batteries.

In the field of DGA, Dr Duval is well known for his «Triangle method» of DGA interpretation, used worldwide. He has developed the use of gas-in-oil standards and participated in the development of the «Hydran» on-line monitor for hydrogen in oil. Dr Duval has established the levels of gas formation observed in various types of electrical equipment. He has been the Convenor of numerous IEC and CIGRE working groups and the principal author of several IEC international standards and CIGRE Technical Brochures on DGA. He is also very active in several IEEE working groups.

Dr Duval holds 16 patents and is the author of more than 100 scientific papers and standards. He is a Fellow at the Chemical Institute of Canada, a Life Fellow of IEEE, and the recipient of IEC and CIGRE Awards and of the IEEE Herman Halperin Electric Transmission and Distribution Award for 2012.