

# IEEE Transformers Committee

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## *Dielectric Frequency Response (DFR) Task Force – Final Report*

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## DFR Task Force - Final Report

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### Summary and Recommendations

A review of the published literature on dielectric response methods as a means of evaluating the condition of the insulation systems shows a strong interest in the methods. There are numerous articles by various researchers that have been published in the public domain and elsewhere. In addition, CIGRE has commissioned at least two working groups that have investigated the technical and practical merit of dielectric response methods for transformer diagnostics and published reports on the topic. The literature demonstrates a sound technical underlying basis for the use of dielectric response for the assessment of the condition of insulation systems. The CIGRE work analyzed measurements of moisture in transformers in the field and compared them with moisture estimates from conventional methods. The general conclusion from that study was that when properly performed and interpreted, dielectric response methods provide information on moisture content in paper and pressboard in transformers that are more closely in line with direct Karl Fischer measurement than the use of moisture equilibrium curves.

A review of measurements on transformers performed by members of this task force and also of measurements reported in the open literature demonstrates the results of moisture estimation using Dielectric Frequency Response (DFR) is comparable to direct measurement using Karl Fischer titration on cellulose samples taken from transformers.

Commercial instrumentation for measuring DFR has been available on the market for over ten years. There are presently at least two equipment suppliers that make instruments for DFR measurements and provide software for modeling and analyzing measurements on transformers. These instruments have been successfully and reliably applied in different substation environments.

There are a few existing IEEE technical standards and CIGRE working group reports that also deal with the topic of moisture estimation in transformers. A summary of the relation of these documents to results of DFR analysis has been documented under Task 4 of this report. That section will provide useful reference material in the development of a guide for DFR measurement and analysis.

There are several issues related to the measurement and analysis of DFR that must be addressed if a guide is to be developed. These include the influence of low molecular weight acids on moisture estimation, oil condition, proper derivation of the x-y model parameters of the insulation system that is used to analyze the results and quality of the databases of moisture curves used for the analysis. High level assessments of the impact of these parameters are presented in the main body of this report, but a more in-depth treatment will be required in a guide.

At the Spring 2012 meeting of the TF, a motion was put forth to recommend the formation of a working group to develop a guide for measurement and analysis of DFR as means of estimating moisture in insulation of transformers. The motion passed unanimously. It was suggested that the Performance Characteristics Subcommittee (PCS), which currently owns this TF should perhaps transfer the topic to the Dielectric Tests subcommittee since the basis of this test is essentially power factor measurement over several frequencies. If a working group is authorized at the subcommittee level, the chairman recommended that Peter Werelius serve as the chairman of that working group. The TF can meet one more time under Peter's leadership to develop a Title, Scope and Purpose for the PAR and then constitute as a WG at the subsequent meeting.

George Frimpong, Ph.D.  
Chairman, DFR Task Force

## History

An IEEE Task Force has been convened to look further at the diagnostic test technique known as Dielectric Frequency Response (DFR).

The scope of the task force is presented here.

- a) Review existing practices of Dielectric Frequency Response measurement techniques, to determine:
  1. if the technique has technical merit
  2. if the technique is proven and commercially available
  3. if the technique IS (not "can be", but "is" already) a practical and useful tool for the industry
- b) Review the relationship of DFR measurements to existing projects or Standards.
- c) Determine whether sufficient interest and resources exist to develop an IEEE tutorial, paper, or guide.
- d) Prepare a report to the PCS chairman to address these issues, summarize the findings, and make recommendations on a course of action.
- e) If a further project is suggested, then define the intended Title, Scope, and Purpose for the PAR.

The scope was divided into four subtasks and assigned to different groups of members. The following are the reports from these groups.

## Task 2: Description of DFR Method

### *Measurement:*

Dielectric response measurement is an off-line testing technique that can be performed in time and frequency domains, to determine the moisture content of the transformer's solid insulation. The representation of dielectric response in the frequency domain is termed dielectric frequency response (DFR). The results can be displayed as capacitance and dielectric loss as a function of frequency or tangent delta (or power factor) as a function of frequency. The default test configuration is the UST (Ungrounded Specimen Test) measurement, in which the transformer's inter-winding capacitance ( $C_{HL}$ ) is measured, as this is where most of the paper and pressboard resides. Also, a UST measurement excludes influence of bushings and external creep currents that may influence the assessment. The dielectric response measurement uses the same preparation setup and execution procedure as traditional (50 or 60Hz) Capacitance (C) and Power Factor (PF) measurements as illustrated in Figure 1. In addition, the high voltage side insulation to ground ( $C_H$ ) and the low voltage side insulation to ground ( $C_L$ ) can also be measured.

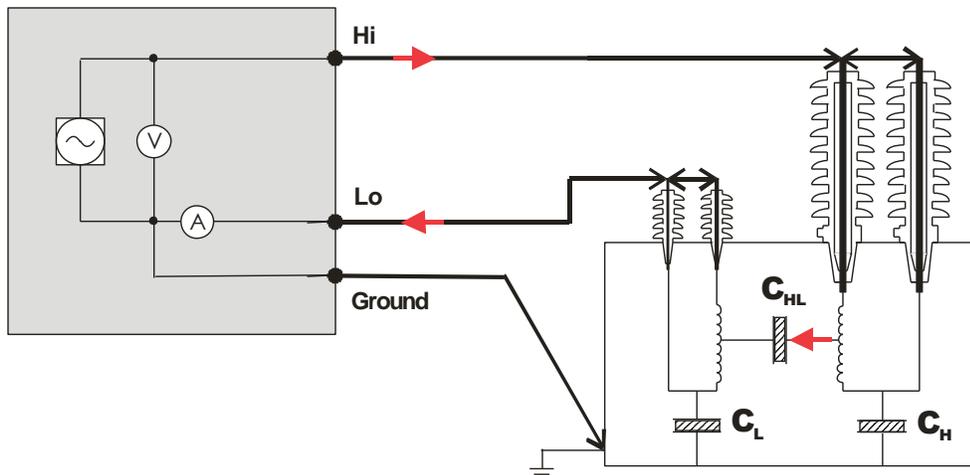


Figure 1 - DFR Test Set Connected to a Two-Winding Transformer

### ***Dielectric Frequency Response Interpretation:***

Analysis of the DFR signatures for moisture estimation relies on a database of dielectric response measurements of carefully prepared samples of oil-impregnated pressboard at known moisture levels and temperatures. For an insulation system consisting of oil and cellulose, both materials contribute to the DFR signature. In order to analyze the DFR signature of a transformer, the insulation system is modelled using the X-Y model considering the barriers and spacers within the insulation construction. The geometrical properties used in the X-Y model are calculated based on the relative amount of oil and cellulose material between the transformer windings. All the pressboard barriers and insulation paper is accumulated into one barrier that represents the X in the modeling. All the spacer sticks are accumulated into one stick with a width represented as Y in the model. The oil ducts form one oil duct which has a comparative thickness of 1-X and a width of 1-Y. Figure 2 illustrates the X-Y model for a typical core form power transformer insulation system.

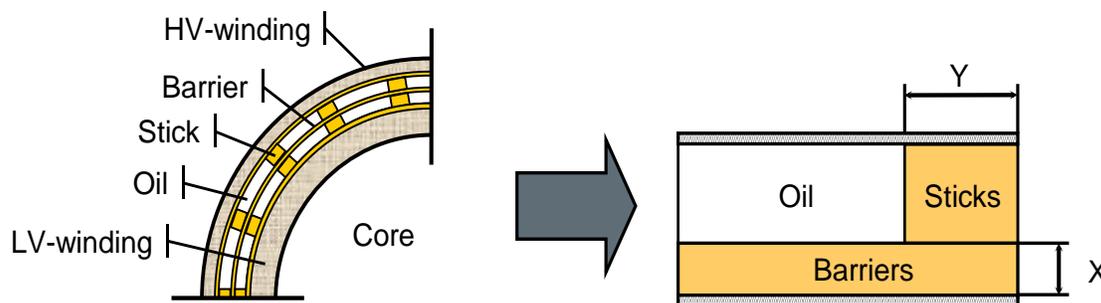


Figure 2 - Representation of the X-Y Model

The DFR signature itself is influenced by the geometry, oil conductivity; moisture and temperature (see Figure 3). The dielectric response of the insulation system under test is compared to the response of the modelled insulation system (taking into account the geometry, temperature and the database of measured samples) to estimate the moisture content and oil conductivity. It is noted that at lower temperatures, the response curve shifts to the left, and testing to lower frequencies may be required.

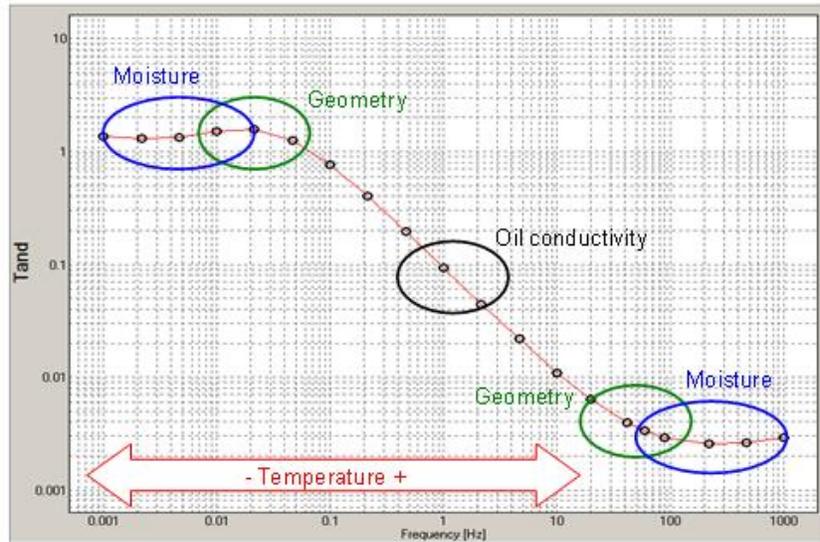


Figure 3 - Dielectric Behavior for Cellulose and Oil as a Function of Frequency

## Task 1: Literature Survey of DFR Topics

There are several articles that have been published relating to the use of DFR in transformer diagnostics. The list below is just a sampling of some of the more relevant papers and reports that would be useful if a guide were to be developed on the use of DFR for transformer diagnostics.

- **Measurement and modeling of dielectric response of composite oil/paper insulation**  
Frimpong, G. Gafvert, U. Fuhr, J. , Properties and Applications of Dielectric Materials, 1997., Proceedings of the 5th International Conference on , May 1997 , Vol. 1 , pp. 86
- **Modeling Of Dielectric Measurements On Power Transforms**  
U. Gafvert, G. Frimpong, J. Fuhr, CIGRE General Conference, Paris, 1998, Paper 15-103
- **Investigations into effective methods for assessing the condition of insulation in aged power transformers**  
Darveniza, M. Saha, T.K. Hill, D.J.T. Le, T.T., IEEE Transactions on Power Delivery, , Oct 1998 , Vol. 13 , Issue:4 , pp. 1214
- **Dielectric spectroscopy in time and frequency domain applied to diagnostics of power transformers**  
Gafvert, U. Adeen, L. Tapper, M. Ghasemi, P. Jonsson, B. , Proceedings of the 6th International Conference on Properties and Applications of Dielectric Materials, 2000. , 2000 , Vol. 2 , pp. 825
- **Estimation of Moisture in Cellulose and Oil Quality of Transformer Insulation Using Dielectric Response Measurements**  
G. Frimpong, U. Gafvert, M. Perkins, A. Fazlagic, Proceedings of the 2001 International Conference of Doble Clients - Sec 8-10
- **Diagnostic of power transformers in Sri Lanka application of dielectric spectroscopy in frequency domain**  
Ekanayake, C. Gubanski, S.M. Mularachchi, K.D. Fernando, M.A.R.M. , Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Conference, 2001. Proceedings , October 2001, pp. 593
- **Dielectric frequency response measurement as a tool for troubleshooting insulation power factor problems**

Perkins, M. Fazlagic, A. Frimpong, G., Conference Record of the 2002 IEEE International Symposium on Electrical Insulation, 2002 , April 2002 , pp. 162

- **Dielectric Response Methods for Diagnostics of Power Transformers**  
Report of CIGRE Task Force D1.01.09, CIGRE Report #254, 2002
- **Some precautions for the field users of PDC measurement for transformer insulation condition assessment**  
Saha, T.K. Purkait, P. , IEEE Power Engineering Society General Meeting, July 2003 , **Volume : 4**
- **Calibrating the result of dielectric measurements on field aged power transformers using oil analyses and similar measurements on well-defined pressboard samples**  
C. Ekanayake, S. M. Gubanski, W. Hribnik and M. Fernando, Proc. of the Nordic Insulation Symposium, Tampere, 2003
- **Dielectric spectroscopy characteristics of aged transformer oils**  
Neimanis, R. Arvidsson, L. Werelius, P., Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Technology Conference, 2003. Proceedings, Sept. 2003, pp. 289
- **An attempt to correlate time & frequency domain polarisation measurements for the insulation diagnosis of power transformer**, Saha, T.K. Purkait, P. Muller, F., IEEE Power Engineering Society General Meeting, June 2004, pp. 1793
- **Dielectric response of oil-impregnated paper insulation: variation with humidity and ageing level [power transformer applications]**  
Linhjell D., Gafvert U., Lundgaard L.E., Annual Report Conference on Electrical Insulation and Dielectric Phenomena, CEIDP '04. Oct. 2004, pp. 262
- **Dielectric responses of new and aged transformer pressboard in dry and wet states**, Gielniak, J. Ekanayake, C. Walczak, K. Graczkowski, A. Gubanski, S., Proceedings of 2005 International Symposium on Electrical Insulating Materials, (ISEIM 2005)., June 2005 , Vol. 2 , pp. 386
- **Influence of geometric structure and material properties on dielectric frequency response of composite oil cellulose insulation**, Gafvert, U., Proceedings of 2005 International Symposium on Electrical Insulating Materials, (ISEIM 2005)., Kitakyushu, Japan, June 2005, Vol. 1, pp. 73
- **Sequential Comparative Study of Dielectric Response and Analyses of Oil and Paper from a Power Transformer Undergoing Repair**, J. Blennow , A. Dernfalk , K. Walczak , C. Ekanayake , P. Koestinger , L. Karlsson , U. Gäfvert , S. Gubanski , A. Bartnicki , Proc. 14th International Symposium on High Voltage Engineering, 2005, pp. 505
- **Field experiences with measurements of dielectric response in frequency domain for power transformer diagnostics**  
Blennow, J. Ekanayake, C. Walczak, K. Garcia, B. Gubanski, S.M., IEEE Transactions on Power Delivery, April 2006 , Vol. 21 , Issue:2 , pp. 681
- **Frequency response of oil impregnated pressboard and paper samples for estimating moisture in transformer insulation**  
C. Ekanayake; S.M. Gubanski; A. Graczkowski; K. Walczak; IEEE Transactions on Power Delivery, July 2006 , Vol. 21 Issue:3, pp. 1309 - 1317
- **Diagnosis of Moisture in Transformer Insulation - Application of frequency domain spectroscopy**, C. Ekanayake, Chalmers University of Technology, Göteborg, Doctoral Thesis ISBN/ISSN: 91-7291-727-X, Nr. 9851, 2006
- **Reliable Diagnostics of HV Transformer Insulation for Safety Assurance of Power Transmission System, REDIATool - a European Research Project**  
S. Gubanski, J. Blennow, I. Karlsson, K. Feser, S. Tenbohlen, C. Neumann, H. Moscicka-Grzesiak, A. Filipowski, I. Tatarski, CIGRE Conference, 2006, Paper D1-207
- **Improved Moisture Analysis of Power Transformers Using Dielectric Response Methods**  
M. Koch, S. Tenbohlen, M. Kruger, A. Kraetge, MatPost 07

- **Effects of moisture and temperature on the frequency domain spectroscopy analysis of power transformer insulation**  
Yew, J.H. Pradhan, M.K. Saha, T.K., IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, July 2008
- **Influence of the geometrical parameters of power transformer insulation on the frequency domain spectroscopy measurement**  
Pradhan, M.K. Yew, J.H. Saha, T.K., IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, July 2008
- **Investigations of Temperature Effects on the Dielectric Response Measurements of Transformer Oil-Paper Insulation System**  
Saha, T.K. Purkait, P., , IEEE Transactions on Power Delivery, Jan. 2008
- **DFR – An Excellent Diagnostic Tool for Power Transformer**  
P. Patel, M. Perkins, 2008 Weidmann Annual Diagnostic Solutions Technical Conference
- **Dielectric response of transformer insulation - comparison of time domain and frequency domain measurements**  
Jadav, R.B. Ekanayake, C. Saha, T.K., Conference Proceedings 2010 IPEC, Oct. 2010, pp. 199
- **Application of polarization based measurement techniques for diagnosis of field transformers**  
Ekanayake, C. Saha, T.K. Ma, H. Allan, D., IEEE Power and Energy Society General Meeting, July 2010
- **Dielectric Frequency Response and temperature dependence of power factor**  
Ohlen, M. Werelius, P., Conference Record of the 2010 IEEE International Symposium on Electrical Insulation (ISEI), June 2010 , pp. 1
- **Dielectric Response Diagnoses for Transformers Windings**  
Report of CIGRE Task Force D1.01.(TF 14), CIGRE Publication #414, April 2010
- **Study on Moisture in Oil-Paper Insulation by Frequency Domain Spectroscopy**  
Guo Wei Saha, T.K., Power and Energy Engineering Conference (APPEEC), 2011 Asia-Pacific , March 2011
- **Comparative Study of Dielectric Spectroscopy Measurements and Analyses of Oil and Paper Samples from a Power Transformer**  
J. Blennow, K. Walczak, A. Dornfalk, B. Garcia, A. Bartnicki, S. Gubanski, O. Samuelsson, U. Karlsson, Nordic Insulation Symposium - Nord-IS 05 - Trondheim, Norway, June, 2005, pp 35-38
- **Information within the Dielectric Response of Power Transformers for Wide Frequency Ranges**  
Michael Jaya, Thomas Leibfried, Maik Koch, Conference Record of the 2010 IEEE International Symposium on Electrical Insulation (ISEI), June 2010

### Task 3 – Validation/Verification

The table below provides a summary of measurements and analysis of dielectric response parameters performed on power transformers both in the factory and in the field having various years of service. The methods of validation were by taking samples of cellulose from the transformers or making moisture estimation from moisture in oil samples. Both positive and negative aspects of the dielectric methods are addressed. There is in general good agreement between the dielectric response measurements and Karl Fischer moisture titration on paper samples, but inconsistent agreement with moisture from oil samples.

Ref #	Authors	Source	Method of validation <sup>1</sup>	Results
1	U. Gafvert, G. Frimpong, J. Fuhr	CIGRE General Conference, Paris, 1998, Paper 15-103	Quantitative analysis using a model based on linear dielectric response and comparing the model to the measured curve of a 700 MV generator step up transformer comparing the PDC and recovery voltage methods	Shown good agreement between the PDC and RVM methods. Verified the results of both PDC and ad RVM can be quantitatively modeled based on linear response method (+)
2	Gafvert, U. Adeen, L. Tapper, M. Ghasemi, P. Jonsson, B.	Properties and Applications of Dielectric Materials, 2000. Proceedings of the 6th International Conference on , Issue Date : 2000 , Volume : 2 , On page(s): 825	4 power transformers (1970). Tested FDS, PDC and RVM. Results compared against moisture concentration in oil	Described possible effects of noise on the measurement process. The tan δ values reflect the different oil conductivities but the moisture levels in the oil, deduced from Karl Fischer Titration seem unrelated to the moisture in the board deduced from the dielectric measurements. (-)
3	Ekanayake, C. Gubanski, S.M. Mularachchi, K.D. Fernando, M.A.R.M.	Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Conference, 2001. Proceedings , Issue Date: 2001, On page(s): 593, Meeting Date: 16 Oct 2001-18 Oct 2001	FDS test carried out on 105 transformers (0.5 up to 71MVA, 0 - 25 years of service) and comparison of measurements on a model rig of oil-paper insulation at 85, 65, 41 and 20°C. FDS before & after oil purification	Good agreement is achieved between the evaluations resulting from FDS measurements and from evaluations based on other analysis (electrical - chemical) (+)

<sup>1</sup> RVM – Recovery Voltage Method, PDC – Polarization and Depolarization Method, FDS – Frequency Domain Spectroscopy, DFR – Dielectric Frequency Response (same as FDS), KT – Karl Fischer Titration,

Ref #	Authors	Source	Method of validation <sup>1</sup>	Results	
4	Perkins, M. Fazlagic, A. Frimpong, G.	Electrical Insulation, 2002. Conference Record of the 2002 IEEE International Symposium on , Issue Date : 7-10 Apr 2002 , On page(s): 162	Shell form and core form transformers	DFR is applicable to detect: high core ground resistance problems, the amount of moisture in the insulation, chemical contamination of windings. Authors have found the DFR method to be more accurate than existing industrial methods, for example, dew point test and moisture/oil equilibrium method.	(+)
5	CIGRE Task Force D1.01.09 Task Force members: S.M. Gubanski (chair), P. Boss, G. Csépes, V. Der Houhanessian, J. Filippini, P. Guuinic, U. Gäfvert, V. Karius, J. Lapworth, G. Urbani, P. Werelius, W. Zaengl	Report of CIGRE Task Force D1.01.09, CIGRE Report #254, 2002	RVM, PDC and FDS on insulation model evaluation of thermodynamic moisture equilibrium between paper and oil and; oil conductivity. Summary of study cases in (National Grid Company) UK and (ABB & Vattenfall) Sweden. Tested 2mm Transformerboard Type T IV impregnated with Technol US 3000 mineral oil, SS electrodes, in an oil-filled glass vessel. Moisture % in aged samples measured by KFT. Study cases presented in Section 6 (Pancake model - Kraft thermo 70 + Nynas Nitro 10GBN and Shell Diala D, and UK, Sweden, Switzerland & Germany real transformers)	The results of this report confirm that the dielectric response measurements provide valuable information on the state of oil-paper insulation in power transformers, in particular the moisture content. Regarding the influence of geometry, it has an influence on the response but not as significant as the effect of the oil conductivity.	(+)
6	Neimanis, R. Arvidsson, L. Werelius, P.	Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Technology Conference, 2003. Proceedings , Issue Date: 23-25 Sept. 2003, On page(s): 289	FDS and 3-terminal cell for measurement on liquids with cell heater. Several oil samples were analyzed.	Relative permittivity defined to 2.2 in mineral oil, frequency dependence, activation energy and voltage dependence	(+)
7	Linhjell D., Gafvert U., Lundgaard L.E.	Electrical Insulation and Dielectric Phenomena, 2004. CEIDP '04. 2004 Annual Report Conference on , Issue Date : 17-20 Oct. 2004 , On page(s): 262	FDS on paper samples: Kraft paper, Munsjkjo Termo 70, Ø 76mm. Acidity and moisture content is measured on paper strips. Aging performed in glass jars 70g (dry weight) paper and 1.45 L of oil. Calculated amount of water was admitted and kept for 4 days at 45C, later impregnated with new dried degassed oil. Samples were tested for moisture in oil and paper by means of coulometric (electrochemical) KFT.	Apparently it is not the DP of the cellulose, but the presence of aging byproducts that influence the dielectric response. Results indicate that chemical oil analysis is required to be able to separate aging from humidity	(-)

Ref #	Authors	Source	Method of validation <sup>1</sup>	Results	
8	Gielniak, J. Ekanayake, C. Walczak, K. Graczkowski, A. Gubanski, S.	Electrical Insulating Materials, 2005. (ISEIM 2005). Proceedings of 2005 International Symposium on , Issue Date : 5-9 June 2005 , Volume : 2 , On page(s): 386	Paper samples 1.5mm thickness & 160mm Ø. After drying samples, those were left at the lab environment to absorb moisture from air. Weight changes were monitored. Immersed later in NYNAS Nytro 10 GBN. Fifteen samples with the same moisture intake were placed into one container. Thermal aging and DP sampling. Coulometric KFT using Metrohm 756 KF Coulometer instrument with 832 Thermoprep.	The results presented in this paper show the dependence of dielectric response of oil-impregnated pressboard on moisture content, temperature and aging. Difficult to distinguish between ageing by-products and water content	(+)
9	J. Blennow , A. Dernfalk , K. Walczak , C. Ekanayake , P. Koestinger , L. Karlsson , U. Gäfvert , S. Gubanski , A. Bartnicki	In Proc. 14th International Symposium on High Voltage Engineering, 2005, Page 505-	An old 40 MVA transformer was used; a comparison of FDS, KFT of paper samples and moisture in oil samples was performed at various stages: 1.) Day transformer removed from service, 2) eleven weeks out of service. 3.) After repair and short vapor phase, 4.) at retrofil and vacuum filtering of oil on site ,5) Transformer in service for 6 wks	The FDS method estimated moisture content in the paper insulation of 1.4 -2.4%, which compared well with the paper and pressboard of 1.0 to 2.5%. The moisture estimation in oil comparison with FDS is questionable due to temperature. The results using Oommen curves was high, however the temperature used was questionable, so author made an assumption on proper temp, and the moisture content was 2.4%,	(+)
10	Blennow, J. Ekanayake, C. Walczak, K. Garcia, B. Gubanski, S.M.	This paper appears in: Power Delivery, IEEE Transactions on , Issue Date : April 2006 , Volume : 21 , Issue:2 , On page(s): 681	FDS only. 3-ph 50/20kV, 40MVA transformer. Samples taken from different positions and tested KFT. Oommen's curves were used to estimate moisture content in blocks, the conductivity of the oil at different temperatures were derived from real measurements done in lab, dielectric response of pressboard for the given moisture at given temperatures were obtained from lab measurements and/or recalculated.	Different moisture distribution at different levels of the winding duct, good understanding of the factors that may influence the results and therefore also the interpretation of dielectric response measurements on power transformers in field conditions.	(+)

Ref #	Authors	Source	Method of validation <sup>1</sup>	Results
11	S. Gubanski, J. Blennow, I. Karlsson, K. Feser, S. Tenbohlen, C. Neumann, H. Moscicka-Grzesiak, A. Filipowski, I. Tatarski	CIGRE Conference, 2006, Paper D1-207	<b>a. DFR on model samples:</b> FDS on precise and reliable data from well controlled oil impregnated samples of pressboard and paper. Pressboard samples 1.5mm thickness & 160mm Ø. Paper samples 60µm and 160mm Ø. Sample preparation included: drying, moisturizing, impregnation with transformer oil and in some cases thermal aging. Transformer oil NYNAS Nytro 10 GBN. Five groups of samples were kept in containers for 6 months. <b>b. Measurements on Model transformer:</b> Measurements performed with Coulometric KFT (as per IEC 60814). Test with RVM, PDC and FDS. <b>c. Field Measurements:</b> 80 transformers in Europe, 17 in Sri Lanka. <b>d. Units sent for repair:</b> paper & pressboard samples were collected from different areas and analyzed with KFT	Results of the investigations performed allow believing that the dielectric response measurements, when properly performed and interpreted, providing more accurate information on moisture content in paper and pressboard in transformers that the use of conventional equilibrium curves. Moisture estimation based on dielectric response measurements, as well as on KFT analysis of oil samples in combination with the use of the equilibrium curves, yield similar results as the direct KFT analyses of paper samples, if appropriate temperature values were used. (+)
12	M. Koch, S. Tenbohlen, M. Kruger, A. Kraetge	MatPost 07	Comparative study among RVM, PDC and FDS. Used pancake Model with constant 1% moisture, measured at paper and pressboard at 160°C. Oil type Shell Diala D ( $\sigma=1.57$ pS/m) and later 25 year old aged transformer oil ( $\sigma=16.5$ pS/m)	Commercial software for PDC and FDS are able to compensate for the influences of insulation geometry, insulation temperature and oil conductivity. RVM method too simplistic. Generated new data pool and new device. (+)
13	Saha, T.K. Purkait, P.	This paper appears in: Power Delivery, IEEE Transactions on , Issue Date : Jan. 2008	Pancake Transformer model consisting of 3 windings insulated with oil and cellulose. Geometric detail of model is presented. PDC and RVM tests were performed.	Interpretation of RVM and PDC test results still remains a difficult task as it is influenced by insulation ageing condition, geometry of insulation, moisture content, and also operating temperature. On site test results presented in the paper indicate the necessity of careful understanding of the effect of temperature on the dielectric response measurement for correct analysis and interpretation. (-)

Ref #	Authors	Source	Method of validation <sup>1</sup>	Results	
14	P. Patel, M. Perkins	2008 Weidmann Annual Diagnostic Solutions Technical Conference	DFR (FDS) only. 1-ph, 2W GSY transformer producing combustible gases Hydrogen and Acetylene. Electrical tests	New patented software detected abnormality on the HV to ground path. Performed internal inspection on HV H1 bushing shield. Shielding tube was loose and did not provide proper contact. Performed on-site repair. Fixed unit put back to service.	(+)
15	Jadav, R.B. Ekanayake, C. Saha, T.K.	This paper appears in: IPEC, 2010 Conference Proceedings , Issue Date: 27-29 Oct. 2010, On page(s): 199	Three sets of pressboard samples (density 1.21 g/cm <sup>3</sup> ) with 0.2%, 1.8% and 2.3% moisture level were prepared. Response measurements taken at 40, 60 and 80C.	PDC and FDS have significant impact on moisture and temperature. It is observed that almost similar level of accuracy can be achieved while calculating DC conductivity from both methods.	(+)
16	Ekanayake, C. Saha, T.K. Ma, H. Allan, D.	Power and Energy Society General Meeting, 2010 IEEE , Issue Date : 25-29 July 2010	FDS with X-Y model and PDC on 2 groups of transformers 3 in Sri Lanka and 1 AT in Australia. Testing before and after oil refurbishment	The presented quantitative analysis of FDS response through X-Y model shows that geometrical parameters and oil conductivity is always interlocked. Comparison of the results from PDC and FDS shows that estimated moisture content from both techniques are not equal but reasonably close. The study shows the ability of polarization techniques to identify the status of transformer insulation through appropriate quantitative and qualitative analyses.	(+)

Ref #	Authors	Source	Method of validation <sup>1</sup>	Results
17	Ohlen, M. Werelius, P.	Electrical Insulation (ISEI), Conference Record of the 2010 IEEE International Symposium on , Issue Date : 6-9 June 2010 , On page(s): 1	Temperature variation on different paper samples, transformers and bushings. Measured 60Hz PF values at different temperatures vs. new individual temperature correction algorithm validated.	Advantages of DFR (FDS): Capability of performing ITC of 50/60Hz DF/PF, capability of estimating moisture in cellulose, dissipation factor/power factor at operating temperature, and to investigate increased dissipation factor in power components. (+)
18	Guo Wei Saha, T.K.	Power and Energy Engineering Conference (APPEEC), 2011 Asia-Pacific , Issue Date: 25-28 March 2011	Analytical. FDS vs. calculated response is $\pm 10\%$ .	The expression of moisture content is effective. (+)
19	J. Blennow, K. Walczak , A. Dernfalk, B. Garcia, A. Bartnicki S. Gubanski, O. Samuelsson, U. Karlsson	Nordic Insulation Symposium - Nord-IS-05 - Trondheim, Norway, June 13-15, 2005	FDS performed on a 19.5/6.8/6.8 kV 40 MVA transformer. Results compared with oil and paper samples (KFT)	FDS measurements gave more accurate estimates of moisture levels than the estimates based on oil analyses and equilibrium curves when compared to the paper samples taken from the unit and moisture estimated by KFT. (+)

## **Task 4 – DFR Relation to Existing Standards and IEEE Documents**

This section is a review of existing IEEE, IEC and CIGRE documents that may have some relation to the diagnostic approach of DFR method.

### ***IEEE C57.12.00- 2000, Standard General Requirements for Liquid-Immersed distribution, Power, and Regulating Transformers***

This standard is a basis for the establishment of performance, limited electrical and mechanical interchangeability, and safety requirements of equipment described; and for assistance in the proper selection of such equipment. This includes electrical, mechanical, and safety requirements for liquid-immersed distribution and power transformers, and autotransformers and regulating transformers; single and polyphase, with voltages of 601 V or higher in the highest voltage winding.

Table 19 in this document is for routine, design, and other tests for liquid-immersed transformer. It lists insulation power factor and winding insulation resistance as standard tests. The relationship of these two test methods to DFR is such that they are all used in some way to find moisture in an insulation system.

### ***IEEE C57.12.90-2006, Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers***

Methods for performing tests specified in IEEE Std C57.12.00TM-2006 and other standards applicable to liquid-immersed distribution, power, and regulating transformers are described.

Section 10 in the standard provides guidelines for performing insulation power factor and resistance measurements. The notes state “experience has shown that the power factor is helpful in assessing the probable condition of the insulation when good judgment is used. And the insulation resistance of electrical apparatus is of doubtful significance compared with the dielectric strength. It is subject to wide variation in design, temperature, dryness, and cleanliness of the parts.” These techniques could be construed to have the same intent as performing DFR.

### ***IEEE PC57.91/D9 -2010, Draft Transformer Loading Guide***

This guide provides recommendations for loading mineral-oil-immersed transformers and step-voltage regulators with insulation systems rated for a 65 °C average winding temperature rise at rated load.

Relationship info; Appendix A discusses two indirect methods, RVM and Moisture Equilibrium Curves for the assessment of moisture in paper insulation in transformers.

### ***IEEE C57.100-1999, Standard Test Procedure for Thermal Evaluation of Liquid-Immersed Distribution and Power Transformers***

This test procedure is intended to give a direct evaluation of the thermal aging characteristics of the composite insulation system of a liquid-immersed distribution or power transformer.

Possible relationship info: In Annex A there is a brief statement about the use of the Karl Fischer method to determine minimum moisture content with regards to sealed tube aging test procedure.

### ***IEEE C57.106-2006, Guide for Acceptance and Maintenance of Insulating Oils in Equipment***

The intent of this standard is to assist the power equipment operator in evaluating the serviceability of oil received in equipment, oil as received from the supplier for filling new equipment at the installation site, and oil as processed into such equipment; and to assist the operator in maintaining oil in serviceable condition.

Relationship info; discussion on Percent Saturation of Water in Mineral Oil, which ultimately will affect the condition of the insulation system

***IEEE PC57.143, Draft Guide for Application of Monitoring Equipment for Liquid-Immersed Transformers and Components***

This guide covers identification of the key parameters that can be monitored for obtaining an indication of the condition of liquid-immersed transformers.

Relationship info; listed as possible reference for determining insulation condition. Did not review, copy not available at time of report

***IEEE PC57.152/D5 (March 2012 rev.)-2011, (IEEE 62) Draft Guide for Diagnostic Field Testing of Fluid Filled Transformers, Regulators and Reactors***

This guide describes diagnostic field tests and measurements that are performed on fluid filled power transformers and regulators.

Relationship info; several sections devoted to offline test techniques used for transformer insulation assessment. ANNEX G is dedicated to DFR.

***IEEE TC Task Force on Moisture Estimation in Transformer Insulation***

This paper is mainly concerned with methods of moisture estimation in transformer insulation in operating transformers. Extensive list of list of selected publications found in the literature on moisture effects in transformer paper insulation

Relationship info; discussion of “Instruments for measuring power factor are widely used in the field. It will be shown that power factor measurements used to estimate moisture form part of the broader dielectric spectroscopy methods”

***Further references – Non IEEE***

IEC 60076-1, Power transformers – General Requirements, 2000

IEC 60247, Measurement of relative permittivity, dielectric dissipation factor and DC resistivity of insulating liquids, 2007

IEC 60422 – Mineral insulating oil in electrical equipment – Supervision and Maintenance Guidance, 2005

IEC 60814, Insulating liquids - Oil-impregnated paper and pressboard determination of H<sub>2</sub>O by automatic coulometric Karl Fischer titration, 1997

IEC 61620, Determination of Dielectric Dissipation Factor by Measurement of the Conductance and Capacitance, 1998

ASTM D1533 – Standard Test Method for Water in Insulating Liquids by Coulometric Karl Fischer Titration

***CIGRE Brochure 254, Report of TF D15.01.09, Dielectric Response Methods for Diagnostics of Power Transformers, 2002***

This report summarizes the work performed by TF 15.01.09 and presents conclusions regarding the state of the knowledge on the applicability of direct test methods. The intent is to determine moisture content and ageing of the pressboard and paper more directly by measuring the effects of moisture on electrical properties.

### **Cigre Brochure 349, Report of Working Group A2.30, Moisture Equilibrium and Moisture Mitigation within Transformer Insulation Systems, 2008**

Relationship info: This brochure describes the physical processes and mathematics of moisture ingress, migration and equilibrium in transformers.

### **Cigre Working Group D1.01 (TF 14), Report 414, Dielectric Response Diagnoses for Transformer Windings, 2010**

In this report the continuation of the work performed by CIGRE Task Force D1.01.14 – Dielectric Response Diagnoses for Transformer Windings – is summarized by presenting hands-on guidelines for performing dielectric response measurements on power transformers. The work described concentrates on diagnosing the moisture content in transformer insulation system.

### **Cigre Working Group A2.34, Report 445, Guide for Transformer Maintenance, 2011**

This guide was been prepared to help transformer users define and apply best practice for transformer maintenance.

Relationship info: Extensive references detailing recommendations for transformer life management. Section 5 in particular discusses Electrical Measurement Methods for On-Site Transformer Diagnosis.

## **Off-Line Electrical Tests**

To date there are several off-line electrical diagnostic test techniques that can be used to provide some indication of the moisture content in an insulation system:

- **Power factor/dissipation factor performed at 50/60 Hz and at voltages up to 12 kV:** AC dielectric-loss and power-factor test is applied to electrical insulation of high-voltage apparatus using various test equipment. This test is recognized as an effective method for locating defective insulation. Power factor is the ratio of dielectric loss to charging volt-amperes. Losses are typically the result of deterioration of the dielectric material and contamination of the system with moisture being one of the prime sources.
- **Recovery or return voltage method (RVM):** This is an automated DC test in which one winding is repeatedly charged and discharged to determine what charge time results in the greatest recovered voltage. The dominant time constant, so determined is claimed to be simply related to the amount of dryness in the solid insulation once test temperature has been taken into account.
- **Polarizing/depolarizing current (PDC):** The polarizing/depolarizing current (PDC) test is a simpler DC test in which charging and discharging currents are measured over a long period, up to 10,000 seconds. Up to about 2-3,000 seconds the current versus time curves for charging and discharging are similar and influenced mainly by oil condition, while at longer times the two curves diverge and are influenced more by solid insulation dryness.
- **Dielectric frequency response (DFR) also known as Frequency domain spectroscopy (FDS):** The frequency domain spectroscopy(FDS) / dielectric frequency response (DFR) technique is an AC test which essentially measures insulation tangent delta / power factor over a wide frequency range (from 1,000 Hz down to as low as 0.1 mHz). Over a mid range of frequencies the dielectric response characteristic is a simple straight line, with power factor increasing as frequency decreases, whose position is determined by oil condition (resistivity). At higher and lower frequencies the shape of the maximum and minimum in the characteristic is determined by solid insulation moisture content and insulation geometry.
- **Insulation Resistance:** One of the various indirect methods which rely on the measurement of some electrical parameter which is dependent on moisture content is DC insulation resistance. This is usually the

ratio of values for two different test times, ‘polarization index’, typically 1 and 10 minutes. These measurements are well established for solid insulation systems, for instance in generators, however for the oil-paper insulation systems of large transformers such measurements are influenced primarily by oil condition (resistivity) rather than solid insulation dryness

- **Direct measurement:** Obtaining paper samples from an operating transformer is considered risky and it requires de-energization and exposure of the coils. It is suggested that the accessible sample areas may not be truly representative of the insulation system.

## On-line Measurements

In addition to off-line electrical measurements, there are now on-line sensors that monitor **Relative Saturation (RS)** levels in the oil. One method, uses an On-Line Monitoring System to gain an understanding of this dynamic situation by using moisture sensors that measure the relative saturation (% RS) of moisture in the oil, combined with systems that measure and compute temperatures such as top and bottom oil temperature and the winding hot spot temperature (via fiber-optic probes). Taking into account the time constants to achieve moisture equilibrium between the oil and paper interface, the amount of water in paper, relative to the hotspot temperature, can be estimated.

## DFR Analysis Issues That Should be Considered in a Guide

There are a number of issues pertaining to dielectric frequency response that require further study. This work should enhance our understanding of the phenomena, helping to avoid erroneous interpretations of the test data. Presently, these issues include, but not limited to, the following:

**Influence of ageing by-products. It is known today that certain kinds of acids impact the dielectric response, making transformer insulation appear wetter than it actually is.**

This effect is reported in [2] and shown in Figure 1 for pressboard. The total acid content in each of the tests was 0.4 mgKOH/g (the highest suggested limit for continued use of service aged mineral oil is 0.20 mgKOH/g for voltage class  $\leq 69$ kV according C57.106). Light acids have a preference for the paper in the ratio of 100:1, while the heavy acids remain predominantly in the oil. The aging rate of cellulose is impacted by the presence of moisture and acids. A method that is sensitive to both should give the user info that may be more useful in estimating the aging rate than just moisture alone.

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<sup>2</sup> D. Linhjell, L. Lundgaard and U. Gäfvert, “Dielectric Response of Mineral Oil Impregnated Cellulose and the Impact of Aging”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 14, No. 1, pp. 156-169, February 2007

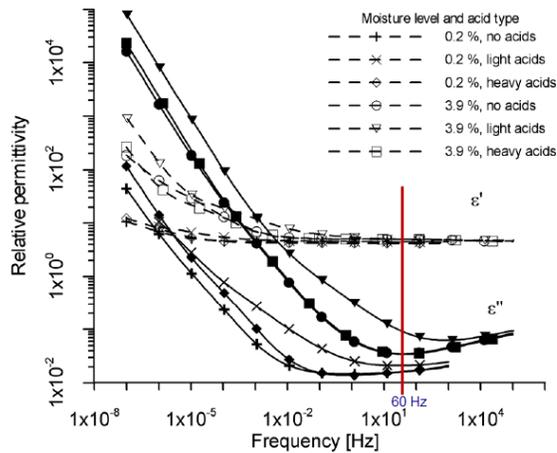


Figure 4 - The Effect of Acids on Pressboard with 0.2% and 3.9% Moisture

A summary of the findings of the authors is as follows:

- The effect of acids is somewhat similar to the effect of water and comes in addition to the effect of water
- The presence of light acids have the effect of higher moisture content of the cellulose
- The presence of heavy acids have no effect on the moisture measurement determined by DFR curves
- A high level of acidity of the paper (2-10 mgKOH/g) is needed to give the same effect as 1% humidity. Note that 2 mgKOH/g or more acidity in paper occurs only towards the “end of life” of the paper.
- The work indicates that fairly high concentrations of carboxylic acids are needed to make a significant contribution to the dielectric response of cellulose
- It is important to note that as expected, the same effect of acids also affects the power factor measurement at power frequency (see Figure 4)

The influence of acids and its impact on the DFR results should be considered if a guide is developed for the method.

**M. Lachman:** In reference [1], the statement "The work indicates that fairly high concentrations of carboxylic acids are needed to make a significant contribution to the dielectric response of cellulose" is based on evaluating samples with just one value of the neutralization number, i.e., 0.4 mgKOH/g. As oils with 0.4 mgKOH/g are rarely found in service, it may be prudent to avoid making definitive statements as to the level of acids at which the moisture results become affected until the influence of low concentrations of acids on the dielectric response of the cellulose is explored.

**Influence of testing under transient temperature conditions.** As the transformer is cooling down, selecting the value for the temperature correction becomes a considerable challenge. The lack of a well-reasoned methodology for temperature selection will result in an erroneous estimation of the moisture content.

The issue with transient temperature conditions was relevant in earlier instruments that took a few hours to complete a measurement. There are instruments available now that can complete a measurement in about 30 minutes. The temperature of the insulation is not expected to change by any significant amount in that time. A guide can put limitations on the maximum amount of time required to perform a measurement to avoid such an influence and also on proper estimation of the temperature of the insulation system.

**M. Lachman:** The 30 min test duration probably implies 1 mHz as the lowest test frequency (and not 0.1 mHz that was assumed in formulating the issue); this certainly changes things. Perhaps, a reference to steady-state thermal conditions would still be useful since, if someone is testing after the unit has just been de-energized, the change could still be (for example) 2-4°C. However, if testing goes down to 0.1 mHz (in the frequency domain), the caution about the thermal stability is definitely warranted.

**Influence of oil condition. Uncertainty introduced by relying on models to estimate the conductivity of the oil should be evaluated. It appears, today, that there is a definite need to test the oil separately to know precisely the oil conductivity. This is especially relevant for aged oil. Furthermore, testing of oil will provide information required to address the influence of ageing byproducts.**

It is recommended to measure the conductivity of the oil and to use the measured value in the analysis if other parameters are not known, for example the geometry. If the conductivity is measured from a sample at room temperature, it is important to correct to the temperature of the DFR measurement for the analysis. The conductivity of the oil can be measured directly in the field using the DFR equipment and an appropriate oil test cell.

**M. Lachman:** The X-Y model is a non-linear equation requiring four important input variables: X, Y, moisture and oil conductivity. A fitting algorithm is used to determine a combination of these variables that best fits the measured response from the transformer. The criterion used to determine the best fit is the minimum error. There might be more than one combination of the variables: X, Y, moisture and oil conductivity that would produce similar errors. Since our objective is exclusively to find the moisture then it is necessary to reduce to a minimum the number of variables in the combination. Therefore, even when geometry inputs are known, it is still essential to measure the oil conductivity allowing the algorithm to find the minimum error relying only on the moisture variable.

**Influence of transformer design differing from x-y model. The most frequent example is when sticks on various insulation tubes (serving as part of the inter-winding insulation) do not line up to create a continuous path assumed by the x-y model.**

The X-Y model of transformer insulation used in DFR analysis requires three geometric parameters: X is the ratio of the aggregate thickness of pressboard to total width of measured insulation duct in the radial direction; Y is the ratio of aggregate width of pressboard sticks to total length of the perimeter of the duct being measured; the third parameter is the geometric capacitance of the duct (i.e. capacitance assuming the gap is filled with air). None of these parameters require the sticks to be lined up radially in a row. The model applies even to the more complex duct insulation structure in a shell form transformer. A guide should address the issue of how to derive the X, Y and geometric capacitance from design data and how to use them in the analysis. Also a table should be provided of typical values in case design data for the transformer is not available.

**M. Lachman:** It is fully appreciated that the pressboard sticks are not involved in the calculation of the X parameter. Hence, whether the sticks are lined up or not has no impact on X. The reason for raising this issue was based on much of the literature on the subject showing the sticks lining up. Therefore, your suggestion to include an educational discussion in the guide will be quite useful.

**Influence of moisture curve library. If the moisture content is determined by finding a best match in a library of curves of samples with known moisture content and oil condition, the quality and credibility of these curves is a factor requiring further discussion and, potentially, standardization.**

One of the tasks in producing a guide should be to address the different tools used to make DFR analysis in an attempt to guide the user in which tool to use. This task should try and validate the methods that are available presently in the industry. Some of the key parameters that influence the databases of moisture characterization that are used in tools for analysis of DFR measurements that should be addressed in the guide are:

- **Density of the pressboard material.** High density pressboard generally gives higher permittivity and loss than low density pressboard. Regular Kraft paper has a response that is somewhere between those two. So the material used for the database must be specified and should match generally the material used in the ducts of the transformer being measured.
- **Type of surface treatment** – the mesh-like pattern on pressboard surfaces create valleys on the surface that trap small pockets of oil. The presence of these oil pockets affects the desired response of the pressboard material. To eliminate this influence, it is important that the surface of pressboard samples used to generate the materials database be machined smooth so as to eliminate the peaks and valleys.
- **Deviations in Karl Fischer titration** – the inherent deviations in the Karl Fischer measurement used as benchmark for the samples in the database will propagate to the results of DFR analysis.

As a comparison, the standard direct measurement of moisture in paper samples via Karl Fischer titration can have the variations shown in Figure 5<sup>3</sup>. Similar variations may be expected in DFR measurements. The reporting of moisture content by DFR analysis may need to be reported as a range to take into account the likely deviations due to the effects of parameters mentioned in this section.

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<sup>3</sup> M. Koch, S. Tenbohlen, J. Blennow, I. Hoehlein - “Reliability and Improvements of Water Titration by the Karl Fischer Technique”, 15th International Symposium on High Voltage Engineering, ISH07, Ljubljana, Slovenia, 2007, p. 427.

**Karl Fischer Measurement on Kraft Paper Samples  
Round Robin among 7 Labs in 4 European Countries**

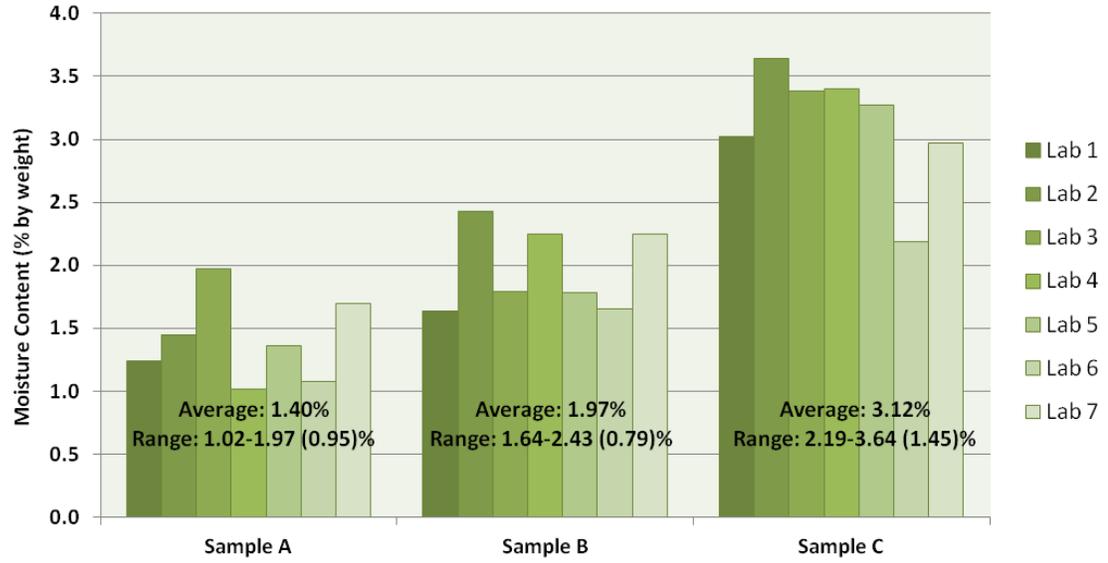


Figure 5 - Moisture Content of 3 Samples of Paper Measured by 7 European Laboratories

M. Lachman: Fully agree.