Impact of Cellulose Degradation on Space Charge Dynamics and Conductivity of Synthetic Ester Liquid-Impregnated Kraft Paper Insulation

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SC A2 – PS1

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Background

- **HVDC links play a crucial role in achieving the UK ambitious Net-Zero target by reducing carbon emissions associated with electrical power generation.**
  - ✓ They can transmit bulk power over long distances with lower loses and costs compared to the AC systems.
  - ✓ They facilitate the integration of remote renewable energy sources located in the UK.
  - ✓ 'By 2030, 90% of the energy imported by UK interconnectors will be from zero carbon energy sources' according to national grid[1].

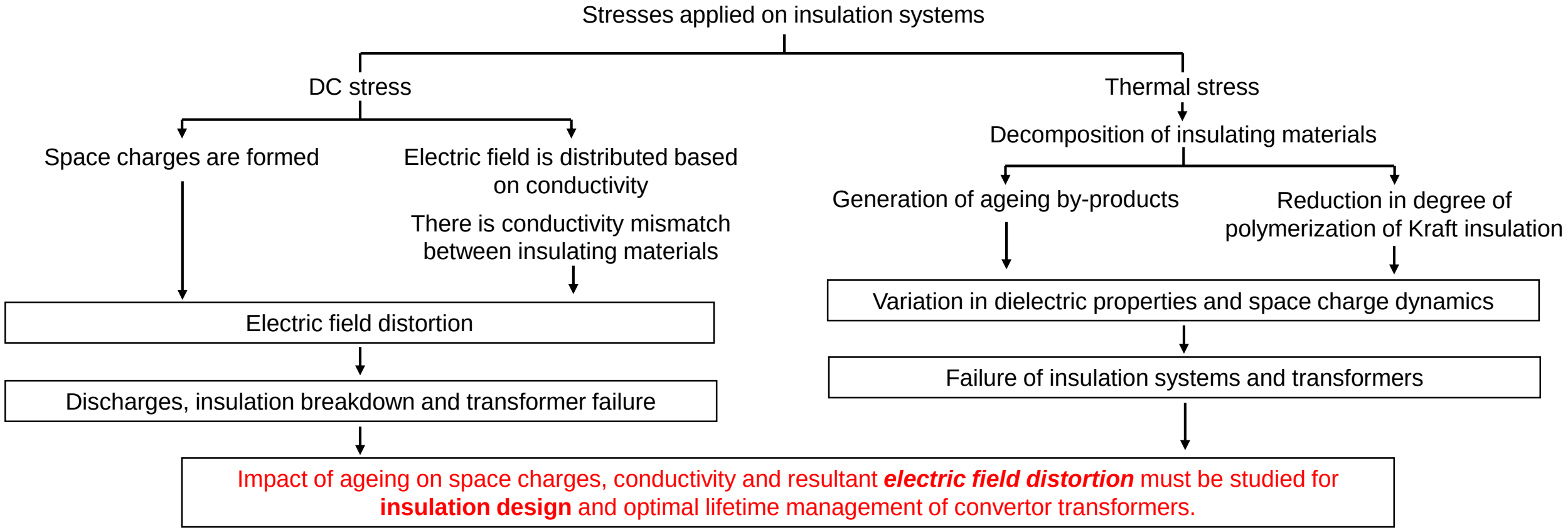
- **Converter transformers are key and expensive components of HVDC systems.**
  - ✓ Insulation system plays an essential role in maintaining their reliable and safe operation.
  - ✓ Mineral oil and cellulose paper/pressboard are commonly used as insulating materials.
  - ✓ Different from traditional AC transformers, the change of material properties over lifetime can greatly affect the criteria of converter transformer insulation design.

- **Ester liquids are becoming popular as environmentally-friendly alternatives to hazardous mineral oils.**
  - ✓ They have higher biodegradability and fire safety features.
  - ✓ They can slow down ageing process of paper insulation.
  - ✓ They have potential application in HVDC converter transformers.

[1] https://www.nationalgrid.com/national-grid-ventures/interconnectors-connecting-cleaner-future

Motivation

- **Dielectric and thermal failures have been the dominant causes for converter transformer failures over the past two decades[2].**



[2] L. Crowe et al., "HVDC LCC Converter Transformers – Converter Transformer Failure Survey Results from 2013 to 2020", Technical Brochure 859, Cigré, 2021.

Objectives

- **Main aim:**

  'Investigating the performance of ester liquid-impregnated Kraft paper under HVDC stresses and ageing with focusing mainly on the influence of cellulose degradation'

- **Objectives:**

1. Preparing aged Kraft papers of different Degree of Polymerization (DP) impregnated with fresh synthetic ester liquid and fresh mineral oil at dry conditions.

2. Measuring conductivity using Polarization-Depolarization Current (PDC) method.

3. Measuring space charges and evaluating electric field distortion using Pulsed Electro-Acoustic (PEA) technique.

4. Investigating the correlations between conductivity, space charges and electric field distortion.

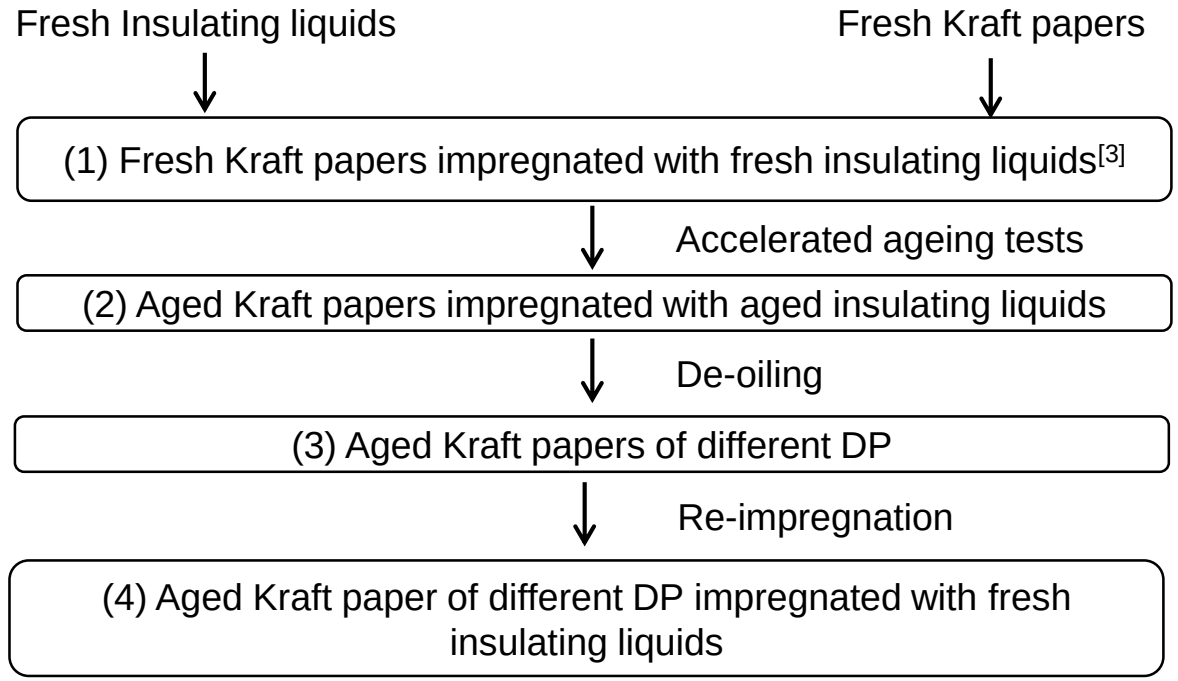
Experimental procedure

Experimental procedure

1. **Preparing aged Kraft papers impregnated with fresh synthetic ester liquid and fresh mineral oil at dry conditions:**

Table 1: Materials used in this study.

Material	Description
Kraft Paper	Thermally non-upgraded from Weidmann (400 μm thickness and 1.15 kg/m^3 density).
Synthetic ester	MIDEL 7131.
Mineral oil	Nytro Gemini X.



[3] J. Dai and Z. Wang, "A Comparison of the Impregnation of Cellulose Insulation by Ester and Mineral oil," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 15, no. 2, pp. 374-381, 2008.

Experimental procedure

2. Volume conductivity measurement using Polarization-Depolarization Current (PDC) method:

- ✓ A three-electrode test cell connected to a KEITHLEY 6517B current measuring device in accordance with CIGRE TB 646[4] and IEC 62631-3-1[5].

Table 2: Testing parameters of conductivity measurement

Parameter	Specification
Applied electric field	1 kV/mm
Electrification time	6000s
Temperature	Room temperature (20°C)

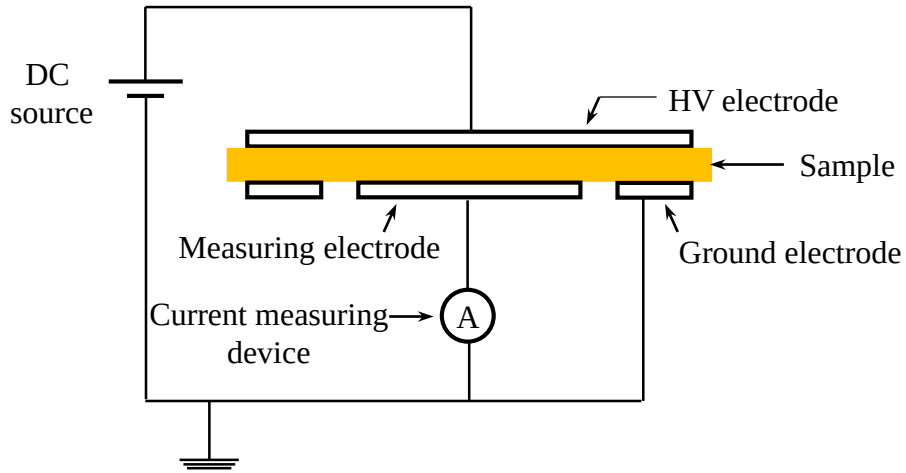


Fig.1: A schematic diagram of volume conductivity measurement system

[4] CIGRE Technical Brochure 646, HVDC transformer insulation: oil conductivity, Working Group JWG A2/D1.41, 2016.

[5] IEC 62631-3-1:2023, Dielectric and resistive properties of solid insulating materials - Part 3-1: Determination of resistive properties (DC methods) - Volume resistance and volume resistivity - General method, IEC, 2023.

Experimental procedure

3. Space charge measurement using Pulsed Electro-Acoustic (PEA) technique:

✓ A system was built in accordance with IEC/TS 62758 [6].

Table 3: Testing parameters of space charge measurement

Parameter	Specification
Applied electric field	20 kV/mm
Electrification time	60 minutes
Temperature	Room temperature (20°C)

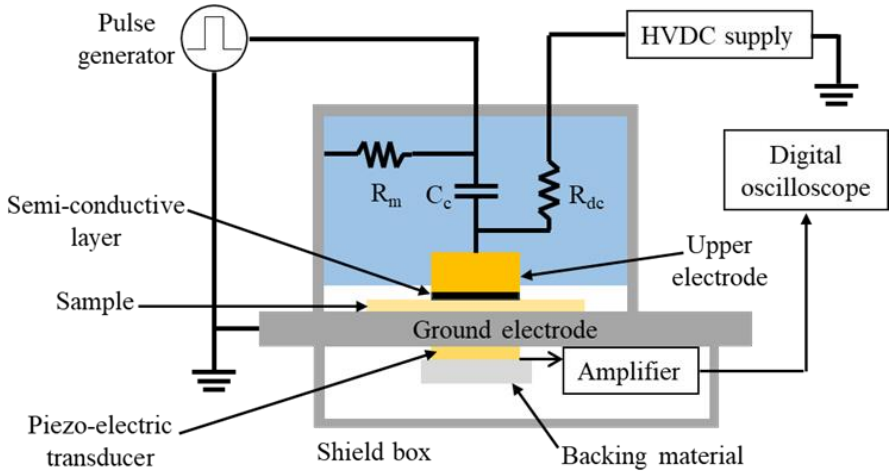


Fig. 2: A schematic diagram of a PEA system

[6] IEC/TS 62758: Calibration of space charge measuring equipment based on pulsed electroacoustic (PEA) measurement principle, IEC, 2012.

Experimental results

Experimental results

- **Comparison of Kraft paper ageing in synthetic ester liquid and mineral oil:**
  - ✓ DP measurements were carried out according to IEC 60450[7].
  - ✓ Ester liquid slowed down the degradation process of Kraft paper.

Table 4: Degradation in DP of Kraft paper aged at 130°C

Ageing period (days)	Aged in Synthetic ester	Aged in Mineral oil
0	950	950
7	829	746
14	611	595
28	506	400

Table 5: Degradation in DP of Kraft paper aged at 150°C

Ageing period (days)	Aged in Synthetic ester	Aged in Mineral oil
0	950	950
2	832	788
4	739	662
8	596	503
16	453	332

[7] IEC 60450:2004, Measurement of the Average Viscometric Degree of Polymerization of New and Aged cellulosic electrically insulating materials, IEC, 2004.

Experimental results

- **Impact of cellulose ageing on conductivity, space charges and electric field distortion:**

Table 7: Ester liquid-impregnated Kraft paper (ELIP)

Ageing condition	Conductivity	Total amount of space charges	Electric field distortion
First stage (DP ≈ 950:750)	*Decreased*	*Increased*	*Increased*
Second stage (DP ≈ 750:600)	*Increased*	*Decreased*	*Decreased*
Third stage (DP > 600)	*Decreased*	*Increased*	*Increased*

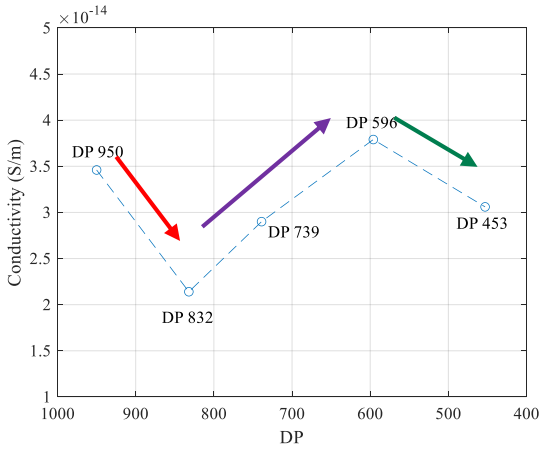


Fig. 3: The change in conductivity of ELIP of different DP.

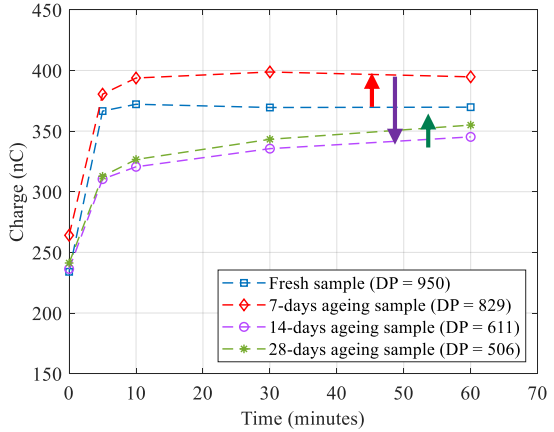


Fig. 4: The change in total amount of space charges in ELIP of different DP.

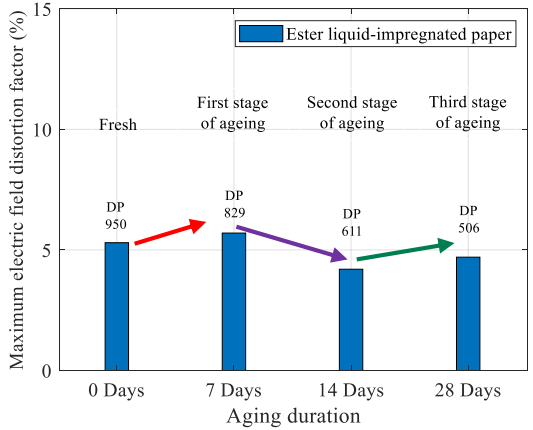


Fig. 5: The change in electric field distortion in ELIP of different DP.

✓ *Change in conductivity and space charges with ageing affect electric field distortion.*

Experimental results

- **Impact of cellulose ageing on conductivity, space charges and electric field distortion:**

Table 8: Mineral oil-impregnated Kraft paper (MOIP)

Ageing condition	Conductivity	Total amount of space charges	Electric field distortion
First stage (DP ≈ 950:750)	*Decreased*	*Increased*	*Increased*
Second stage (DP ≈ 750:600)	*Decreased*	*Increased*	*Increased*
Third stage (DP > 600)	*Increased*	*Decreased*	*Decreased*

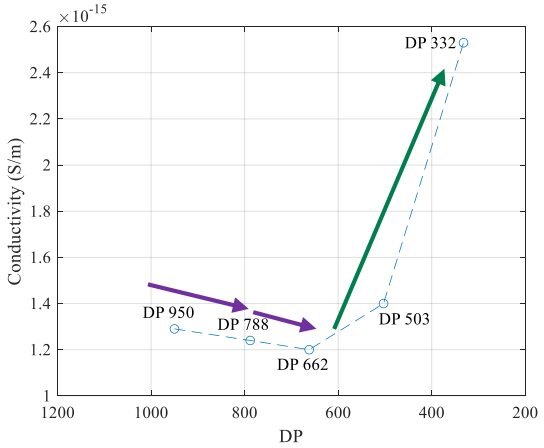


Fig. 6: The change in conductivity of MOIP of different DP.

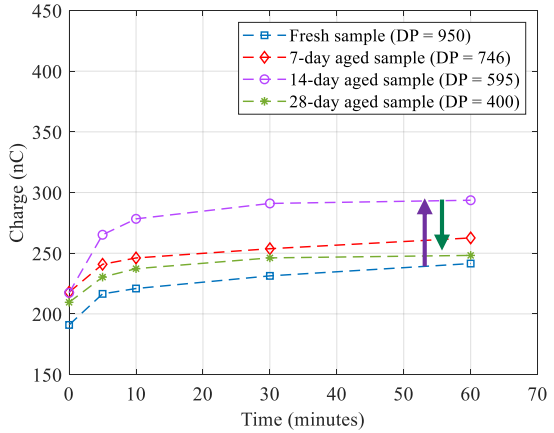


Fig. 7: The change in total amount of space charges in MOIP of different DP.

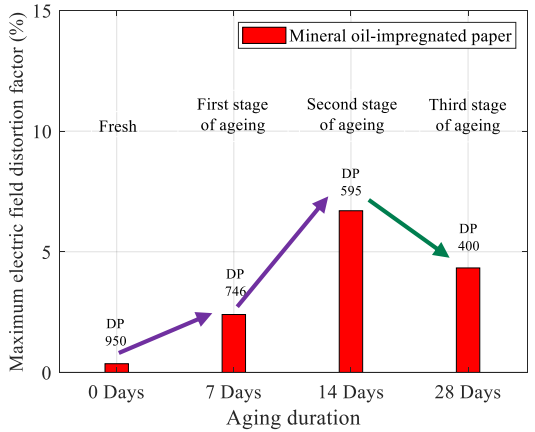


Fig. 8: The change in electric field distortion in MOIP of different DP.

✓ *Change in conductivity and space charges with ageing affect electric field distortion.*

Experimental results

- **Impact of cellulose ageing on electric field distortion:**
  - ✓ Electric field distortion factor was calculated in each sample as follows:

$$E_{distortion} = \frac{E_{max} - E_{applied}}{E_{applied}} \times 100$$

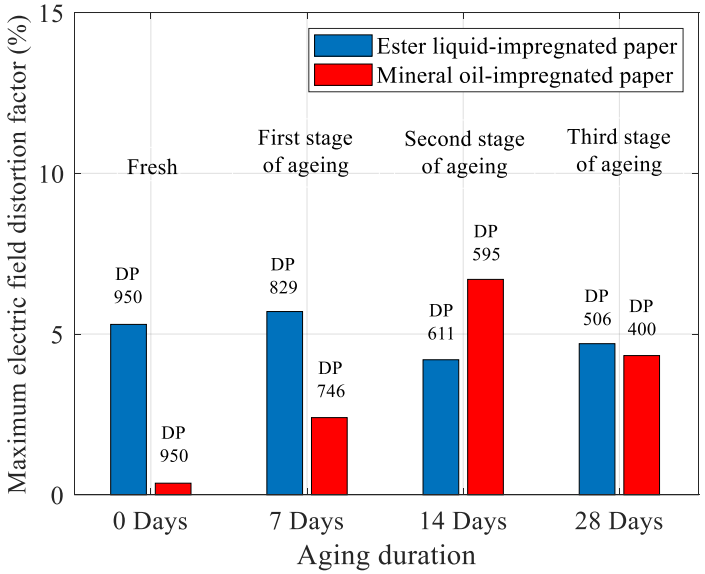


Fig. 9: The variations in electric field distortion factors in Kraft papers of different DP impregnated with synthetic ester liquid and mineral oil

- ✓ Electric field distortion factor in fresh ELIP was higher than that in fresh MOIP.
- ✓ Electric field distortion factor increased remarkably in MOIP with ageing and became higher than that in ELIP at Second stage of ageing.
- ✓ Electric field distortion factor was consistent in ELIP with ageing.
- ✓ Electric field distortion under fresh and aged conditions must be considered in insulation design.

Conclusions

<u>Ageing of Kraft paper in different insulating liquids</u>

- The degradation of Kraft paper aged in ester liquid was slower than in mineral oil at the same temperatures. ⇒ ✓ Ester liquid can slow down the ageing process of Kraft paper.

<u>Impact of cellulose ageing on electric field distortion</u>

- Fresh ELIP showed higher Electric field distortion under HVDC. ⇒ ✓ Higher safety margin must be considered in insulation design of ELIP.
- Electric field distortion in MOIP increased remarkably with ageing. ⇒ ✓ Impact of ageing must be considered in insulation design of MOIP.
- Electric field distortion in ELIP increased slightly with ageing. ✓ ELIP can provide better life-long performance.

<u>Correlation between space charge dynamics and dielectric properties</u>

- Change in conductivity and space charges with ageing affect electric field distortion. ⇒ ✓ Electric field distortion resulted from space charges and conductivity mismatch under fresh and ageing conditions must be considered in designing the insulation systems by choosing an appropriate safety factor to prevent insulation failure.

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Thank you!

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