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# Use of Ester based Insulating Fluids in Power Transformers

For CIGRE NGN UK Meeting

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# Contents

- Why the industry is looking for alternatives to mineral oil?
- What needs to be studied in order to use ester based fluids as an alternative?
- AC dielectric strength /partial discharge characteristics – assess oils under the same conditions
- Breakdown under Lightning Impulse – pre-breakdown phenomena and what do they mean?
- Condition monitoring and diagnosis for incipient faults
- Conclusions

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# Introduction- transformer industry background

- Ester based fluids (synthetic and natural) - good biodegradability and high flash/fire points
- Electric Power Industry – high demand for reliability and safety
- Potentials for manufacturers to produce and utilities to operate “Environmentally Friendly” and “Low Fire Risk” power transformers
- Mineral oil, on the other hand, constantly goes through changes of chemical composition
- All in all, make the industry look for alternatives to mineral oil

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# Basic Properties of Insulating Oils

| Property | Unit | Gemini X | Midel7131 | FR3 |
|---|---|---|---|---|
| Density @ 20°C | $g/cm^3$ | 0.895 | 0.97 | 0.92 |
| Viscosity @ 40°C | $mm^2/s$ | 12 | 28 | 34 |
| Relative permittivity @25°C | | 2.2 | 3.2 | 3.2 |
| Volume resistivity@ 25°C | Ωcm | $51\times10^{12}$ | $12\times10^{12}$ | $20\times10^{12}$ |
| Acidity | mg KOH/g | 0.01 | <0.03 | 0.02 |
| Dielectric dissipation factor @ 90°C | % | 0.5 | <0.6 | 2 |
| Water solubility @ 20 °C | ppm | 55 | 2700 | 1100 |
| Pour point | °C | -40 | -60 | -20 |
| flashpoint | °C | 135 | 275 | 320 |

# Introduction-Impacts of Changes

- The Industry is extremely conservative, and rightly so, since electricity is such a commodity that failing to provide it will bring great detrimental impacts on society and economy.

- What needs to be studied in order to use ester based oils as an alternative?

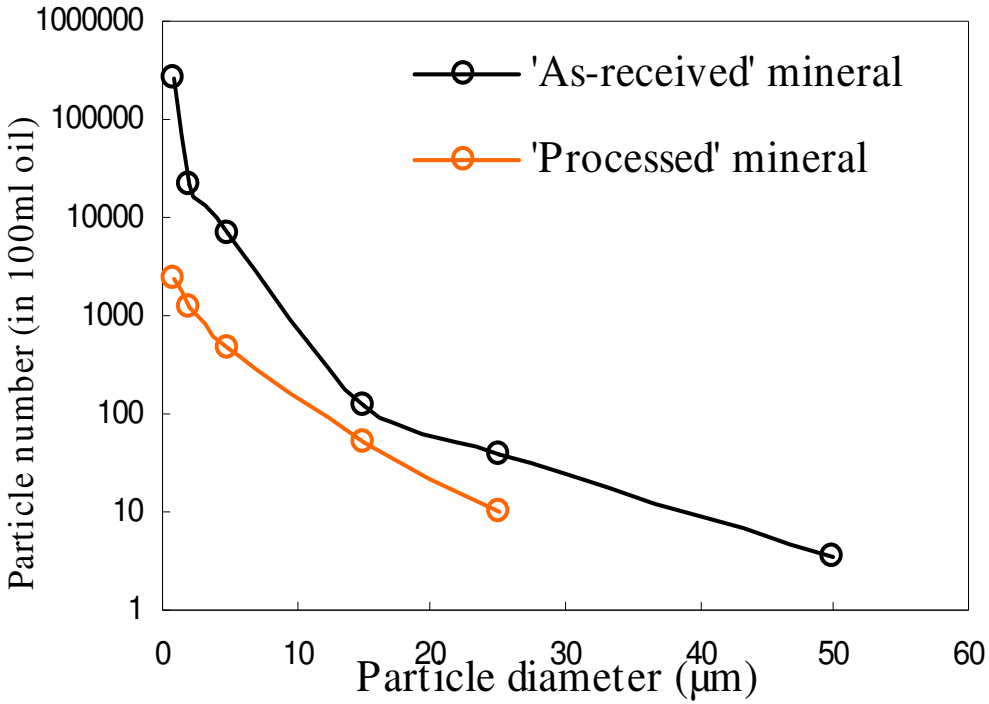
- R & D mainly focuses on
  - dielectric properties of ester based oil and oil / cellulose insulation structure, ageing performance and material compatibility tests,
  - with considerations of ester based oils' thermal /chemical properties,
- and their impacts on
  - Design / manufacture process, processing procedure and condition monitoring & diagnostics / post failure procedures

# AC Dielectric Strengths of Oils -1

- Breakdown voltage tests for insulating liquids under AC voltage
- Standard oil breakdown tester (VDE electrodes with distance of 1 mm / 2mm / 2.5 mm (IEC 60156, ASTM D1816)
- Tests under large oil gaps (volume effect – large electrode surface or / and long gap distance)
- Breakdown voltages are a distribution parameter in nature, needs applying statistical methods to extrapolate /predict the lower-probability breakdown voltage value for design /quality control use
- Highly sensitive to contaminations: - particles and water contents

# AC Dielectric Strengths of Oils -2
## (particle counting before and after filtering)

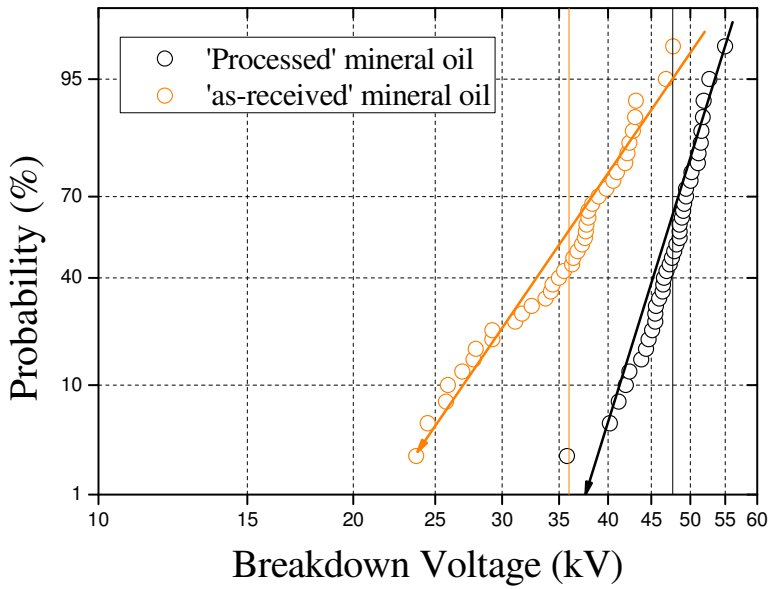
- 'as-received' new oil
- Processing through 2μm filtering device
- 'Processed' oil almost meets the CIGRE recommended 'clean' oil standard (100 ml oil has less than 300 particles of size > 5um)
- Using the same type of filtering device, ester based oils can be processed and reach the same clean standard – ester is more viscous and therefore requires a longer time without forced oil flow
- 'as-received' ester based oils are much 'cleaner' than mineral oil

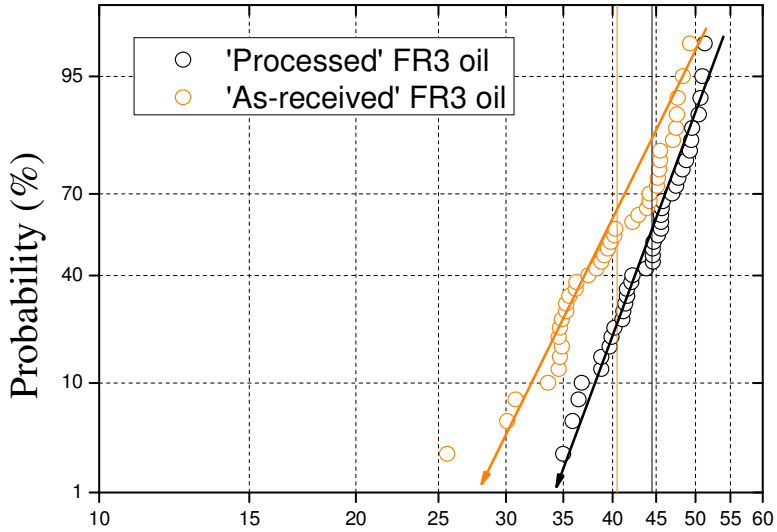



X. Wang and Z. D. Wang "Particle Effect on Breakdown Voltage of Mineral and Ester Based Transformer Oils", conference of electrical insulation and dielectric phenomena (CEIDP), October, 2008, Canada.

# AC Dielectric Strengths of Oils -3

## (breakdown voltages influenced by particle numbers )




- For mineral oil, breakdown voltages are more scattered when particles are present;
- The improvement of $U_b$ of ester based oil before and after processing is not significant, indicating new esters are much more 'clean' when leaving the factory, possibly due to good filtering process.

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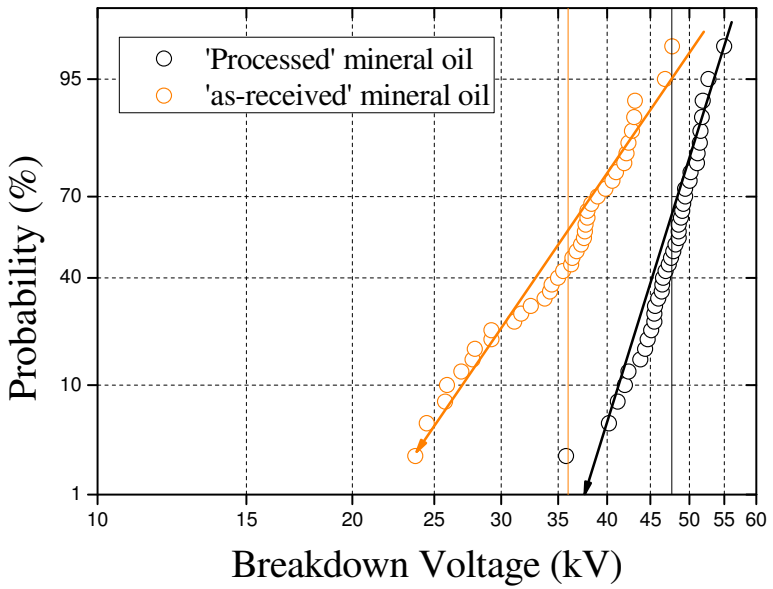
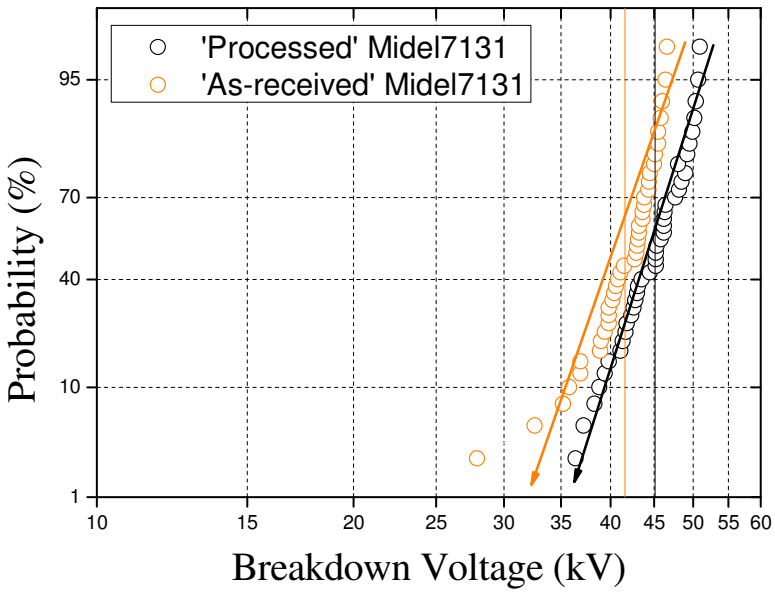
# AC Dielectric Strengths of Oils -4

## (breakdown voltages influenced by particle numbers )

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# AC Dielectric Strengths of Oils -5

## (breakdown voltages influenced by particle numbers )

### Breakdown voltages & distribution parameters of oils

| | 'As-received' oil | | | 'Processed' oil | | |
|---|---|---|---|---|---|---|
| | Mineral | FR3 | Midel 7131 | Mineral | FR3 | Midel 7131 |
| Mean breakdown voltage, (kV) | **36.0** | **40.5** | **41.6** | **47.7** | **44.5** | **45.1** |
| Lowest breakdown voltage, (kV) | **23.8** | **25.6** | **27.9** | **35.8** | **35** | **36.2** |
| Highest breakdown voltage, (kV) | **48.9** | **49.9** | **48** | **58.2** | **53.1** | **53.3** |
| Standard deviation, (kV) | 6.3 | 5.8 | 4.5 | 4.1 | 4.56 | 4.3 |
| Coefficient of variation | 17.5% | 14.3% | 10.5% | 8.6% | 10.3% | 9.7% |

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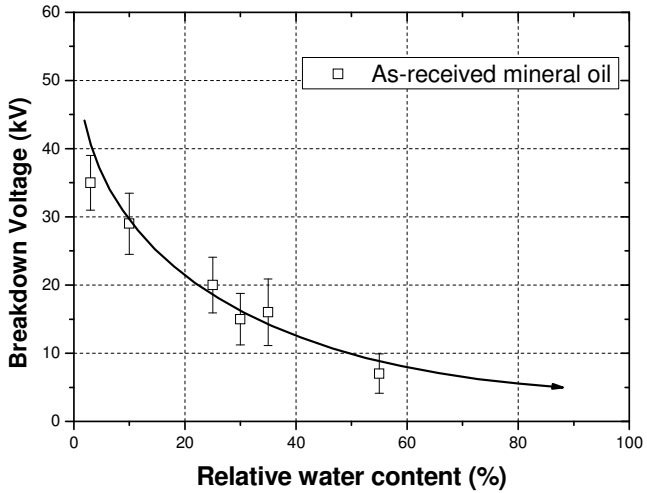
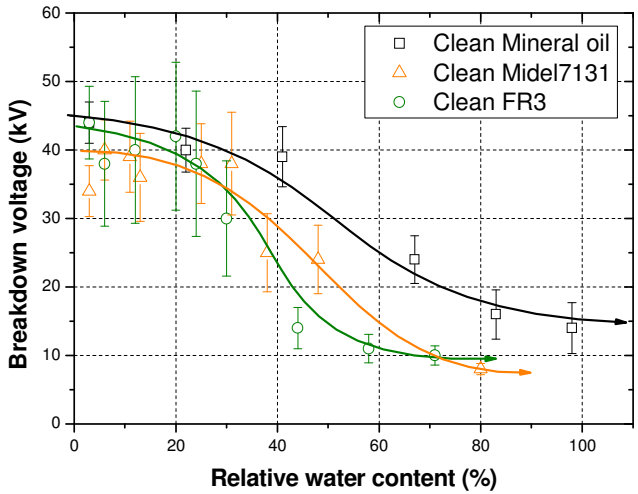
# AC Dielectric Strengths of Oils -6

## (assessing oil under the same condition)

- Mineral oil and ester based oils have good dielectric strength, in terms of breakdown voltages, Mean breakdown voltages of 'clean' 'dry' oils are comparable, standard deviations which represents the scattering range of breakdown voltages are also similar for three oils

- As water saturation levels are different, moisture effect should be assessed as relative humidity (RH), and if is 'clean', mineral oil and ester based oils are having good and change-little breakdown voltages for moisture contents less than 30% RH.

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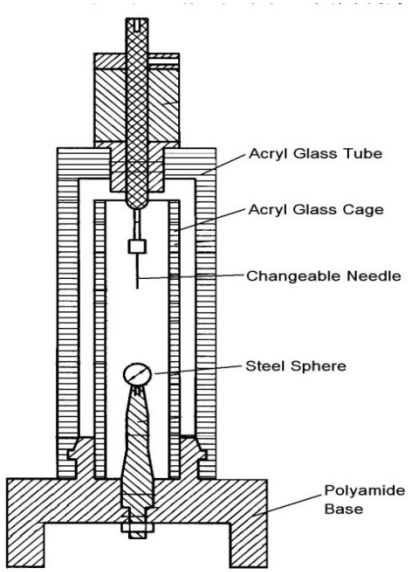
# AC Dielectric Strengths of Oil Impregnated Paper-7

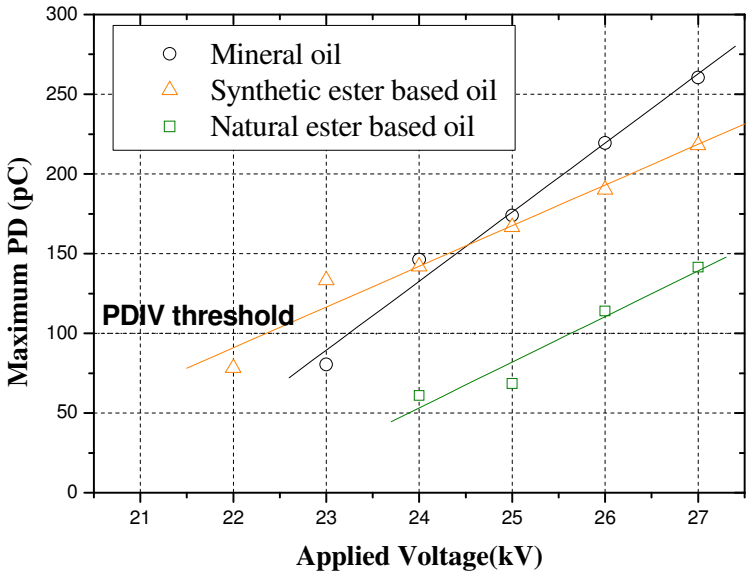
| Oil type | Mineral oil | FR3 | Midel 7131 |
|---|---|---|---|
| Average breakdown voltage $\mu$ (kV) | 16.3 | 15.9 | 15.1 |
| Standard deviation $\sigma$ (kV) | 1.1 | 1.5 | 1.0 |
| Average breakdown strength (kV/mm) | **63.7** | **62.0** | **58.8** |

- **Paper for Layer type windings, 0.25 mm thick and 0.76 g/cm3**
- **40 breakdown tests on paper samples, they follow normal distribution well,**
- **Mineral oil and ester impregnated papers have comparable breakdown strength**
- **Paper breakdown is attributed to discharge in oil pores. As a oil-cellulose composite system, oil in pores acts as a weak link, initiates discharges in oil pore and induces paper breakdown.**

# Partial discharges in mineral oil and ester based fluids

- Partial discharge under AC voltages indicates localised insulation defects, manufacturers endeavour to design/manufacture discharge free transformers
- Partial discharge phenomenon in oil and insulating fluids: PD inception voltage (PDIV), and PD pattern (Q-N-Φ)

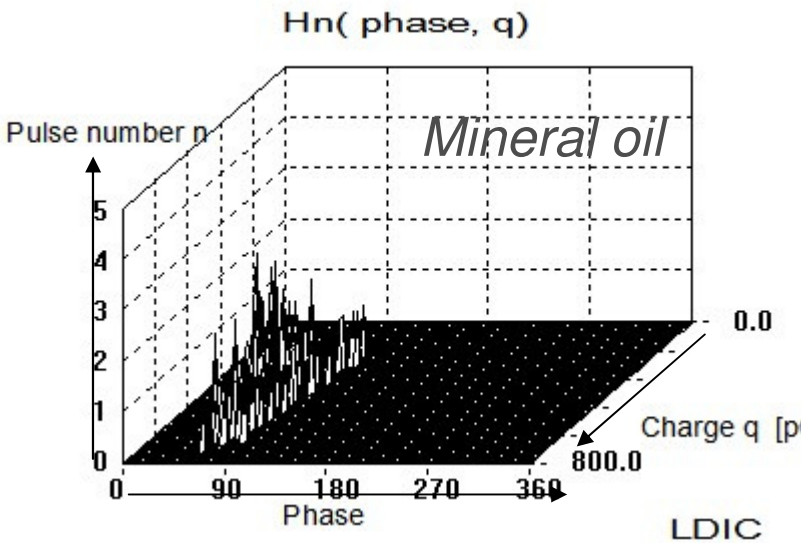


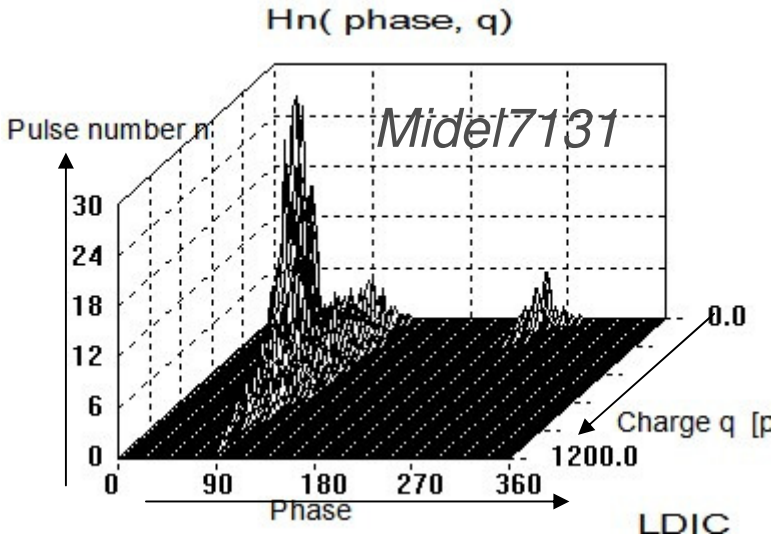




| Oil Type | PDIV (kV) |
|---|---|
| Nytro Gemini X | 23.2 |
| FR3 | 25.6 |
| Midel7131 | 22.3 |

# Partial discharges in mineral oil and ester based fluids

Part 1: Partial Discharge Phenomena under AC voltages



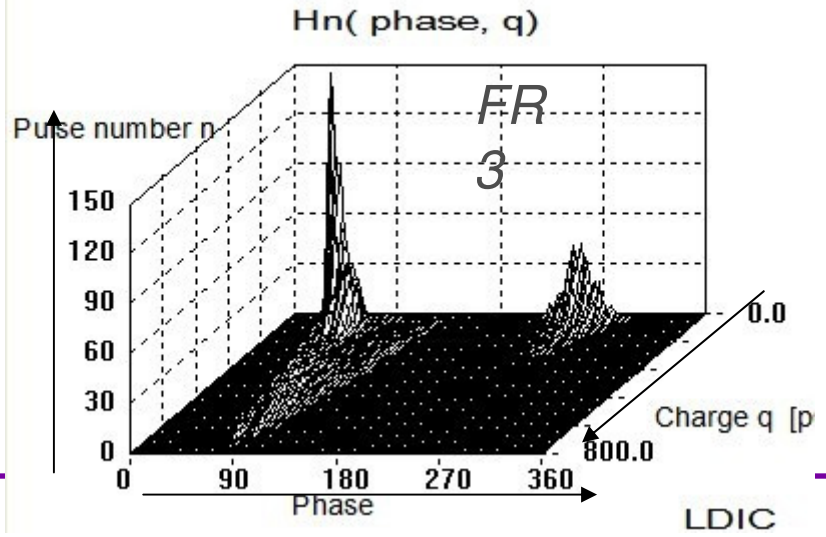




Amplitude: similar

Intensity (PD number):

ester fluids > mineral oil

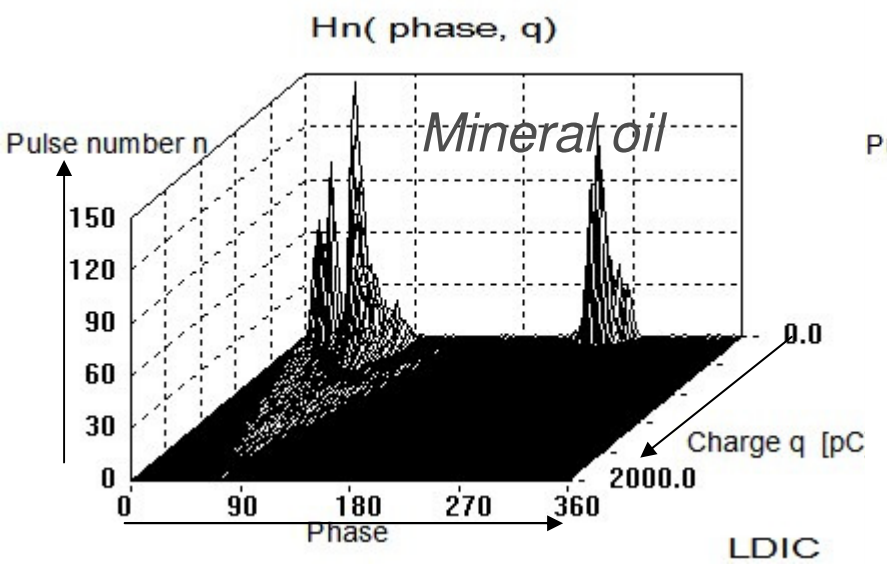
Negative PD (PD appearing in negative half cycle) occurs in ester oil

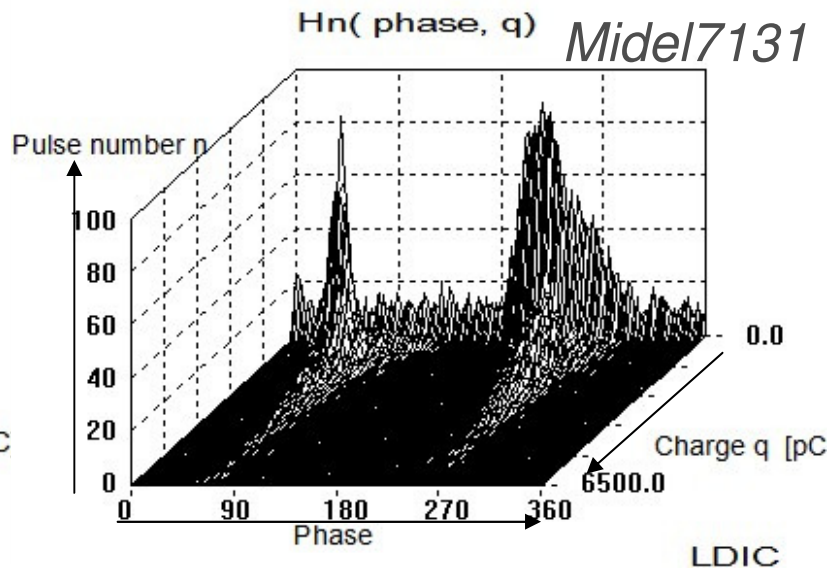



**Q-n-Φ at 2 times PD inception voltage**

# Partial discharges in mineral oil and ester based fluids

Part 1: Partial Discharge Phenomena under AC voltages



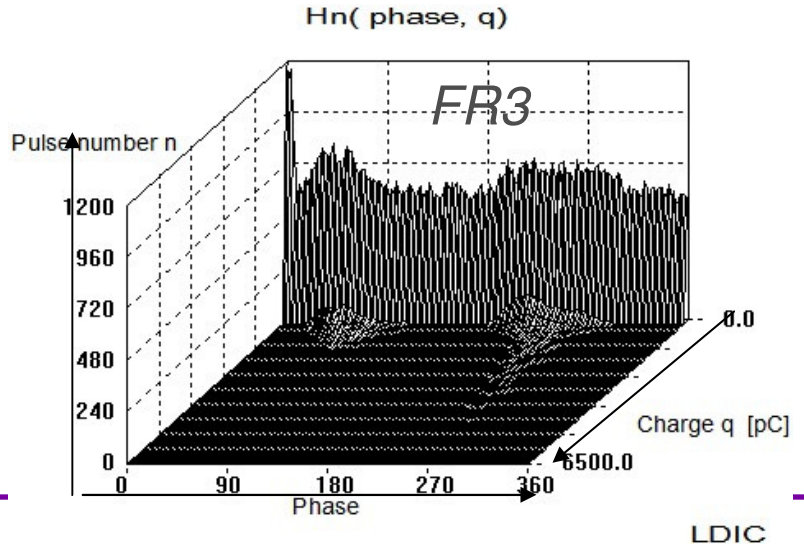

Amplitude: Ester > mineral oil

Intensity (PD number):

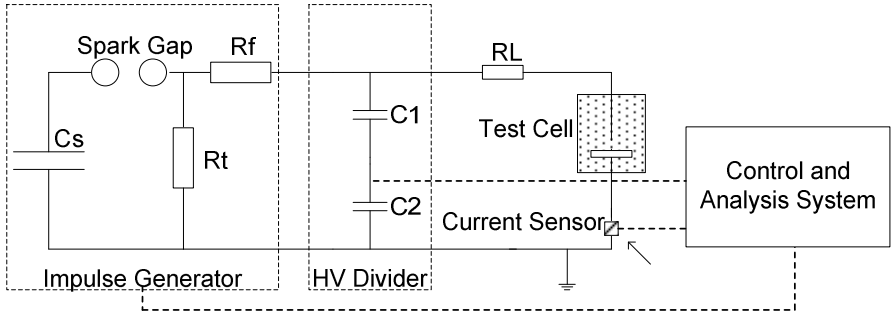
ester > mineral oil

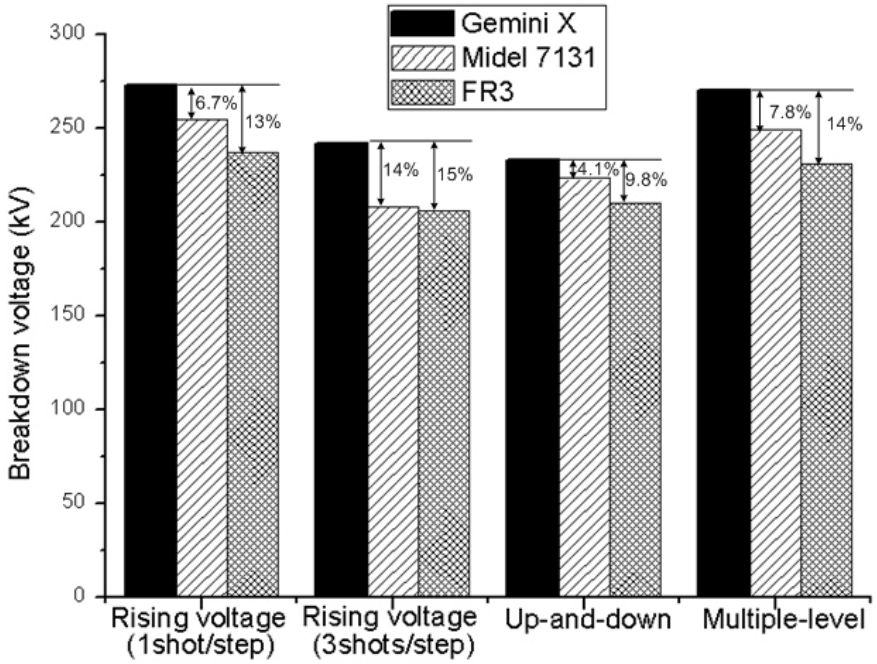
Negative PD occur in mineral oil, with small amplitude, while in Ester negative PD amplitude >= positive PD amplitude

**Q-n-Φ at 3 times PD inception voltage**



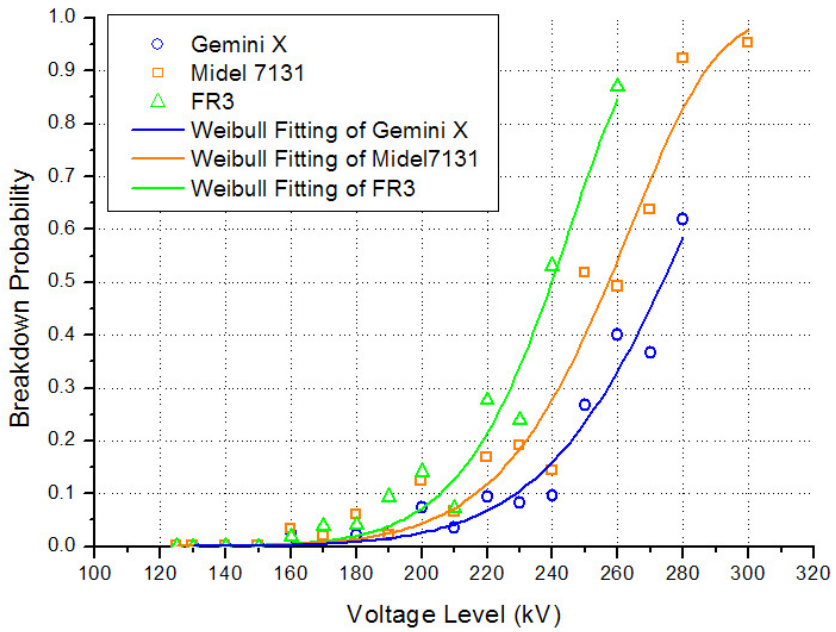
# Lightning breakdown voltages for 3.8mm sphere-sphere electrodes




- Standard ASTM electrodes for LI: 3.8mm oil gap with 12.5mm diameter sphere electrodes,
- Homogenous field,
- Various voltage applying method,
- 50% breakdown voltage: ester fluids lower than mineral oil by <= 15%

# Lightning withstanding voltage at low breakdown probability




| Oils | | Gemini X (kV) | Midel 7131 (kV) | FR3 (kV) |
|---|---|---|---|---|
| Weibull Fitting | scale | 283.47 | 265.78 | 246.98 |
| | shape | 10.47 | 10.97 | 12.29 |
| Breakdown Probability | 50% | 273.72 | 257.05 | 239.73 |
| | 1.0% | 182.70 | 174.78 | 169.86 |
| | 0.1% | 146.57 | 141.64 | 140.79 |

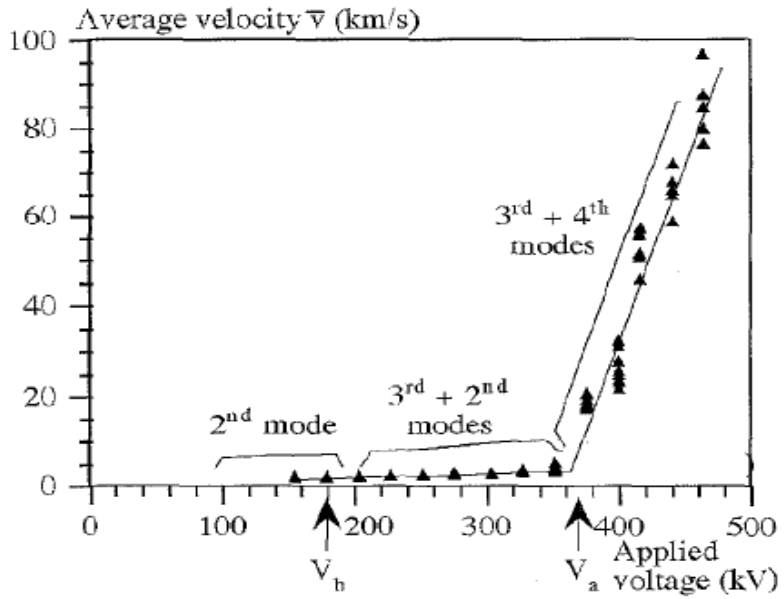
**Conclusion (3.8mm sphere-sphere, 1.2us/50us Standard LI):**

**Breakdown Voltage (50%):**
**ester <=15% lower than mineral oil**

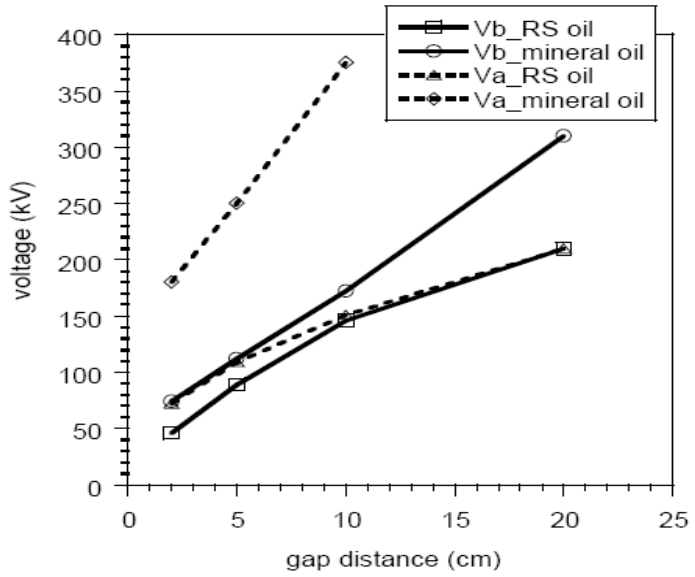
**Withstanding Voltage (@0.1% BP)**
**ester 3% lower than mineral oil**

# Breakdown under Lightning Impulse for Long Gaps

**Average velocity and streamer mode vs. applied voltage in mineral oil[1]**




**Breakdown and acceleration voltages vs. gap distance of mineral oil and rape-seed oil [2]**




- **Advanced research on oil breakdown under impulse voltage considers pre-breakdown phenomena and streamer propagation velocity [1] and [2]**
- **Tests were done under a long oil gap, point-plate electrode configuration – highly divergent field**
- **Mineral oil and one of the rape seed oil behave differently under impulse voltages**
- **Design may need to consider how to use this information – ?**


- [1] O. Lesaint & G. Massala, "Positive streamer propagation in large oil gaps: experimental characterization of propagation modes," *Dielectrics and Electrical Insulation, IEEE Transactions on,* vol. 5, pp. 360-370, 1998.
- [2] O. Lesaint & C.Tran Duy, "Streamer Propagation and Breakdown in Rape-seed Oil at High Voltage," *Conference 2008 ICDL Keynote,* 2008.

# DGA and Key Gas Indicators for Faults in Mineral Oil

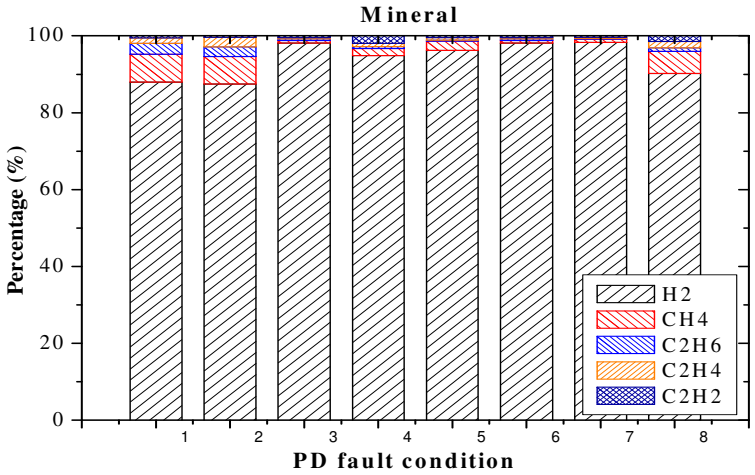
**Types of fault : - thermal fault (overheating), partial discharges and arcing**

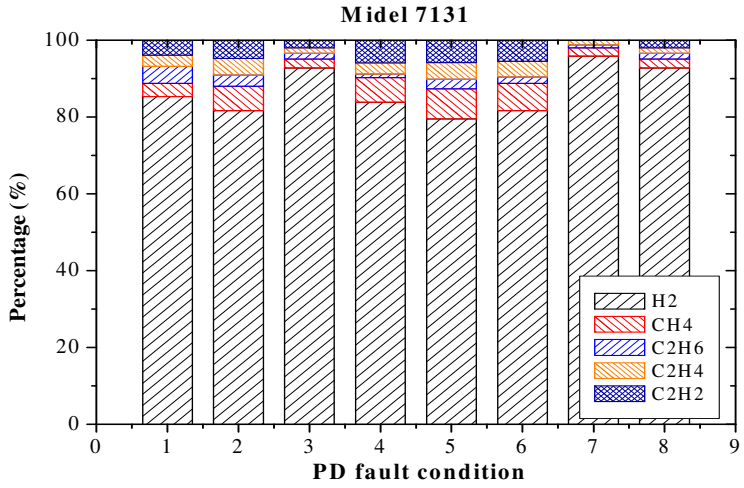
| Key gas | Fault type |
|---|---|
| $H_2$ | Partial Discharge |
| CO | Overheating of Cellulose |
| $C_2H_2$ | Arcing |
| $C_2H_4$ | Overheating of Oil |

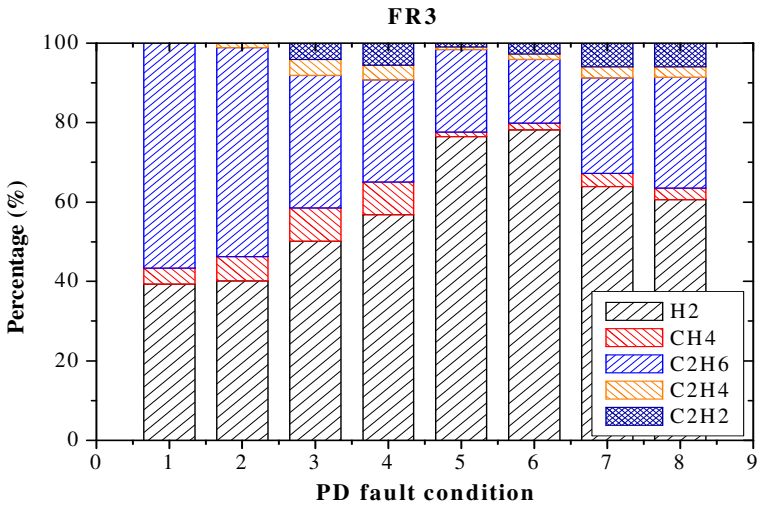
# DGA and Partial Discharges for Ester based Fluids

1: 200pC 30 minutes 2: 300pC 30 minutes
3:500pC 30 minutes 4:1000pC 30 minutes
5: 500pC 15 minutes 6: 500pC 30 minutes
7: 500pC 45 minutes 8: 500pC 60 minutes

H2 is the key gas for Mineral and Midel 7131
H2 + C2H6 are key gases for FR3



# Condition Monitoring Techniques - DGA

- **Thermal stability tests and DGA results for oils at 90°C**
- **Natural ester generated more ethane <- molecular structure dependent**

| Gas (ppm) / Oil type | Mineral oil | MIDEL 7131 | FR3 |
|---|---|---|---|
| $H_2$ | 72 | 23 | 500 |
| $CH_4$ | 10 | 4 | 7 |
| $C_2H_6$ | 2 | 0 | 120 |
| $C_2H_4$ | 2 | 1 | 2 |
| $C_2H_2$ | 1 | 1 | 0 |
| CO | 797 | 595 | 141 |
| $CO_2$ | 3541 | 2365 | 1413 |
| TCG | 885 | 624 | 769 |

# Condition Monitoring Techniques - DGA

- Arcing tests with laboratory DGA

| Oil | Sample | $H_2$ | $CH_4$ | $C_2H_6$ | $C_2H_4$ | $C_2H_2$ | CO |
|---|---|---|---|---|---|---|---|
| Mineral | Headspace | 8 | 2 | 0 | 0 | 0 | 4 |
| | Port | 148 | 33 | 7 | 69 | 336 | 5 |
| MIDEL 7131 | Headspace | 8 | 9 | 1 | 5 | 15 | 18 |
| | Port | 103 | 7 | 2 | 23 | 106 | 37 |
| FR3 | Headspace | 2152 | 105 | 5 | 179 | 723 | 533 |
| | Port | 139 | 9 | 1 | 38 | 174 | 28 |

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# Conclusions

- Transformer designs can take esters as alternatives to mineral oil, subject to taking account of their characteristics,
- Research on esters, always taking mineral oil as a benchmark, promote more understanding on ester based fluids as well as mineral oil
- Do not forget that designed stresses are always lower than dielectric strengths of insulating materials and structure,
- Ester based oil filled transformers and reactors are in use at 132 kV and 245 kV voltage levels,
- Design, manufacturing and operating experiences will be gained.
- More R & D activities are envisaged in the future, particularly on ester based oil performance under transients and condition diagnostic criteria.

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# Thank You For Your Attention