A Dual Approach To Electrical Lubricant Testing

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18.09.2024

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Agenda

The Problem Of Electric Discharges In The Drivetrain

Electrical Lubricant Testing – Dual Approach

1 Static Tests (Constant Gap): Specification Of Lubricant
- Conductivity and Permittivity Measurement ($\kappa(\vartheta)$, $\varepsilon(\vartheta)$)
- High-Pressure Dielectric Test ($\kappa(\vartheta, p)$, $\varepsilon(\vartheta, p)$)

2 Dynamic Tests (Variable Gap): Assessment Of Lubricant Film
- Impedance Spectroscopy With A Lubricated Bearing
- Initial Breakdown & Discharge Distribution Test

Exemplary Test Results

Conclusions, Prospect & Discussion

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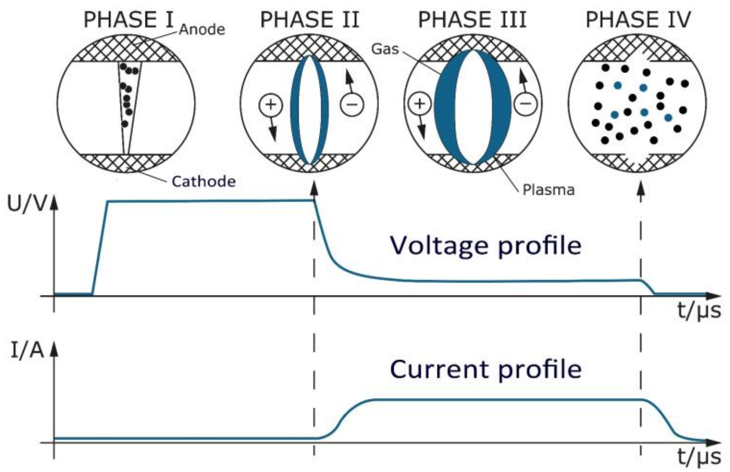
Introduction: The Problem Of Electric Discharge

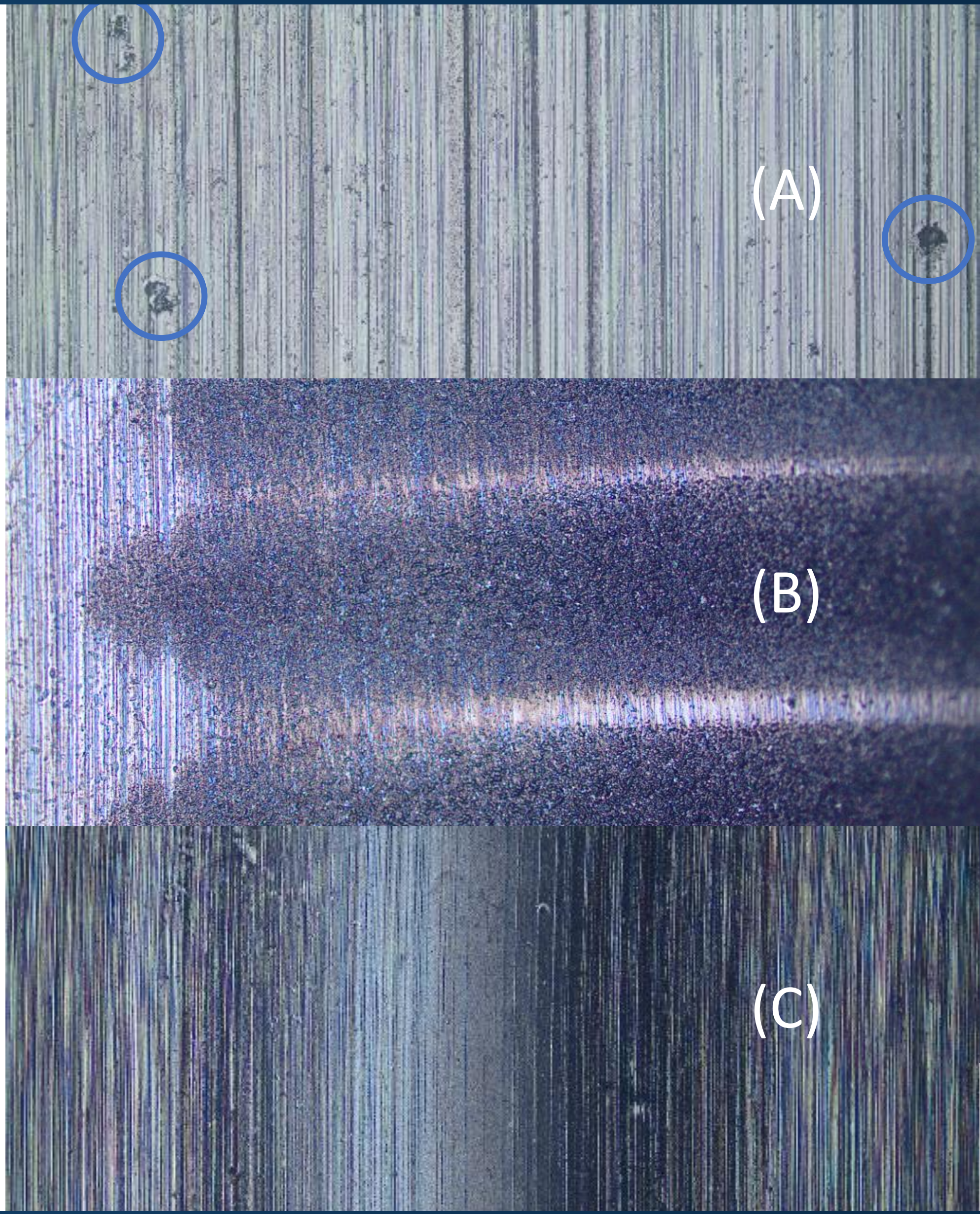
- Electrified drivetrains with inverter-controlled motors often have **parasitic current flow** in their mechanical contacts
- Mechanically proven machine elements are subjected to **additional electrical load** and stray currents
- Lubricants must be **tested electrically** and optimized to minimize damage to the electric drivetrain
- Not solely a problem of e-mobility: **40%** of wind turbine generator failures are related to discharge damages

Bearing Damage Through Electric Breakdowns

- Reaching the breakdown voltage will generate an **electric arc** through the lubricant film
- **100 mA** EDM currents are sufficient to create damage in the contacts
- The spark-erosive current flow will **damage the ball and the raceways** of both the rotating and stationary ring



- Typical raceway damage patterns: **craters** (A), **fluting** (B) & **grey frosting** (C)



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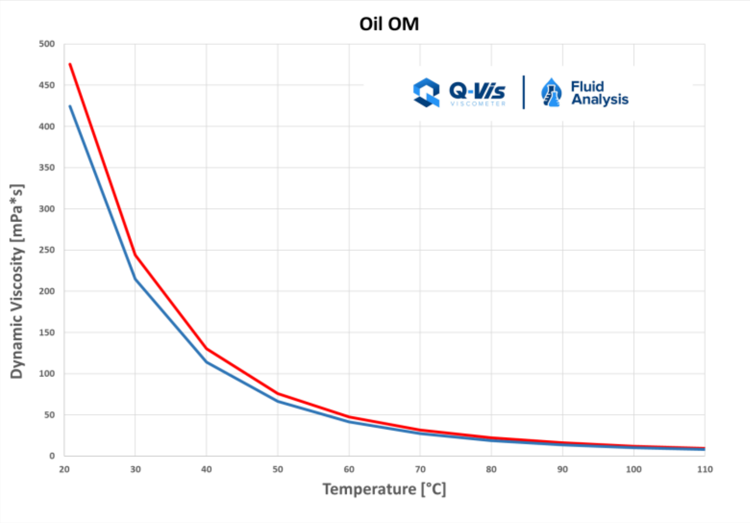
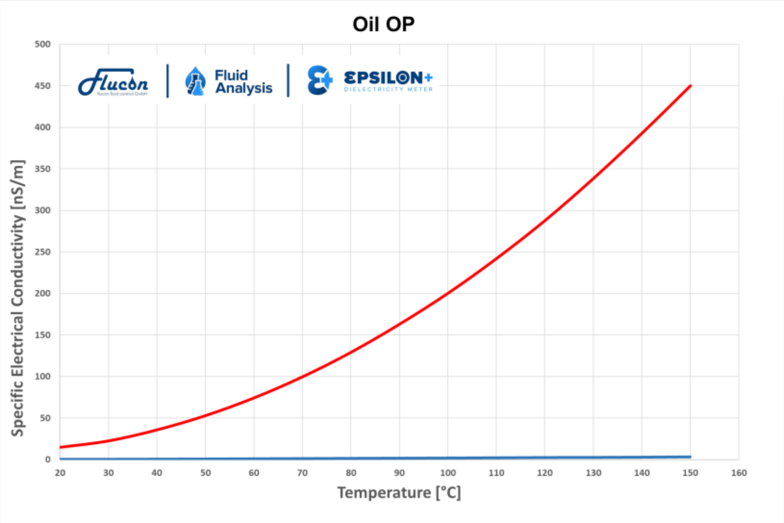
Electrically Caused Lubricant Degradation

- With each breakdown, oils and greases are locally subjected to **high temperatures** (> 10,000°C)
- Lubricant becomes **oxidized** and **discolored**
- Contamination with **soot and metallic wear particles**
- **Viscosity**, **lubricity** and **dielectricity** are often affected





▪ Before / ▪ After 24 H Breakdown Test

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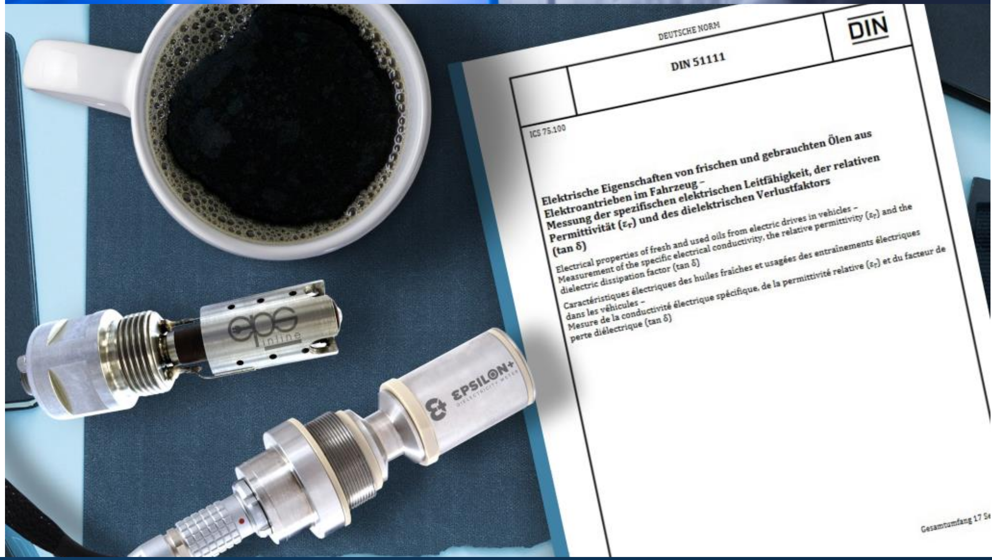
Key Factors For Electric Discharge Prevention

- Breakdown tendency of a lubricated electric drive depends on multiple important parameters:
- **Lubricant properties**
  - Viscosity & pressure-viscosity coefficient (affecting the film thickness)
- **Operating conditions**
  - Temperature
  - Speed
  - Load
  - Run time
  - Contact geometry & running smoothness (shaft concentricity, vibrations etc.)
- **New test methods are needed** for the assessment of future lubricants



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DUAL APPROACH

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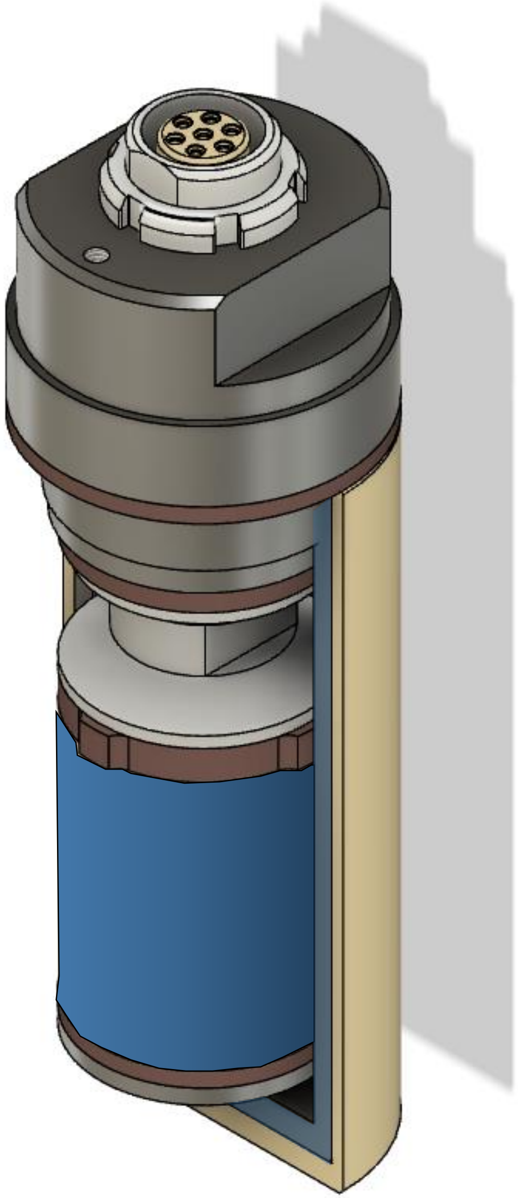
1 Static Electrical Lubricant Tests

- **Static test: constant electrode gap** (d = 1 mm)
- **Electrical characterization** of oils and greases in a tubular capacitor cell
- Measurement of the electrical fluid properties as functions of the temperature at variable frequency
  - **specific electrical resistivity** ρ (ϑ) & **specific electrical conductivity** κ (ϑ)
  - **relative permittivity** ε_r (ϑ)
  - **dielectric dissipation factor** *tan δ* (ϑ)

  @ 50°C, 100°C, 150°C

- New test standard for EPSILON+ Dielectricity Meter: **DIN 51 111:2024-02**
- Dielectricity should be specified in all lubricant data sheets!

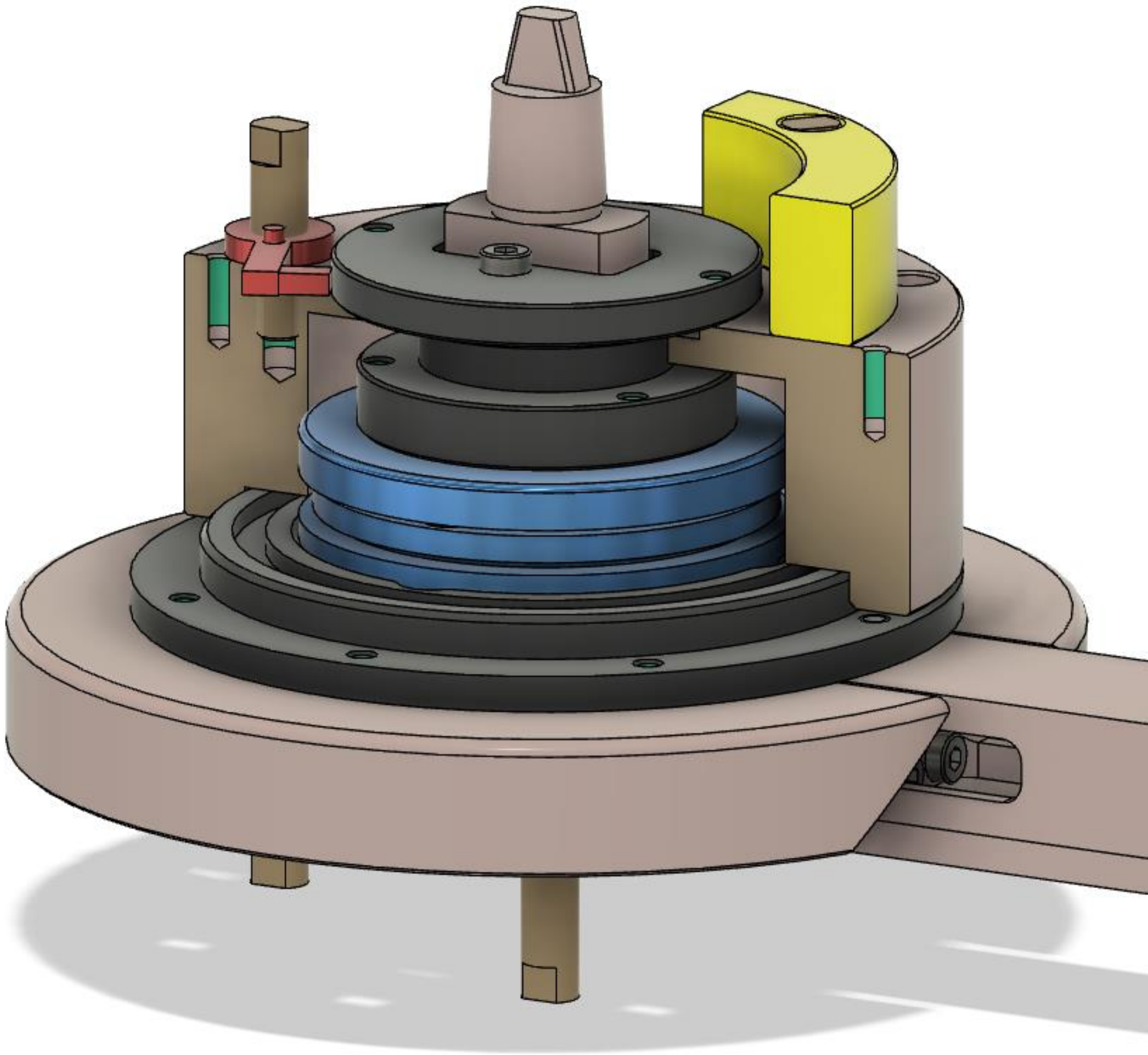


1 Static Electrical Lubricant Tests

- **High-pressure lubricant test** with special tubular capacitor (d = 1 mm)
- κ, ε_r & *tan* δ as substance-specific properties **up to 1.4 GPa** at variable temperature
- Additional **high-pressure viscometry** with a high-shear torsional transducer to determine dynamic viscosity η (ϑ, p) and pressure-viscosity coefficient α_p
- Validate dielectric results from the bearing with **Hamrock-Dowson's film thickness h_{min}**

2 Dynamic Electrical Lubricant Tests

- **Dynamic tests: variable electrode gap** (d ≙ h_{min})
- **Electrical characterization** of oils and greases in a controlled tribological contact of a lubricated test bearing
- Measurement of the **bearing impedance at variable frequency** and the **electrical breakdown tendency** as functions of the operating conditions
  - lubricant temperature
  - speed
  - axial load
  - voltage signal
- **NA 062-06-53-B** & **NA 062-06-53-C** standardization
- DIN draft procedure includes impedance spectroscopy at different operating points and breakdown tests



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2 Dynamic Electrical Lubricant Tests

- **Electrified tribometer "E-Lub Tester"** with automatic speed and load variation
- **Four-ball tester**-adapted bearing test cell with temperature control
- Uses type 51208 **thrust ball bearing** with 30 ml oil / 5 g grease
- Measurement of impedance (100 Hz – 10 MHz) and determination of **ohmic resistance R** & **capacitance C** for any operating point to assess the lubricating condition
- Measurement of the **initial breakdown voltage** U_{crit} for any operating point (non-damaging "Breakdown Finder" method)
- Determination of the **discharge distribution** at one operating point (damaging method)
- Adaptable for Falex Four-Ball, Hansa VKA four-ball tester or fully automated as Stand-alone unit by flucon GmbH

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Exemplary Tests – Lubricant Selection

Fluid Analysis | Q-Vis Viscometer | EPSILON+ Dielectricity Meter | E-Lub Tester Dielectric Tribometer			OM	GM	OP	GP
Substance Type			Mineral Oil	Mineral Grease (Base Oil: OM)	Polyglycol	Polyglycolic Grease (Base Oil: OP)
Rheology	Dynamic Viscosity	**η** [mPa*s] @ 80°C	18.9	18.9 (OM)	**87.1**	87.1 (OP)
		η [mPa*s] @ 80°C; 1 GPa	**10,164,000**	10,164,000 (OM)	1,545,000	1,545,000 (OP)
	Pressure-Viscosity Coefficient	α_p [1/bar] @ 80°C	1.32 E-03	1.32 E-03 (OM)	0.98 E-03	0.98 E-03 (OP)
Dielectricity	Specific Electrical Conductivity	**κ** [nS/m] @ 80°C	1.21	1.68	2.24	**2,238.00**
	Relative Permittivity	ε_r [ ] @ 80°C	2.222	2.727	**4.521**	**5.087**
	Dielectric Dissipation Factor	**tan δ** [ ] @ 80°C	0.196	0.221	0.178	158.164

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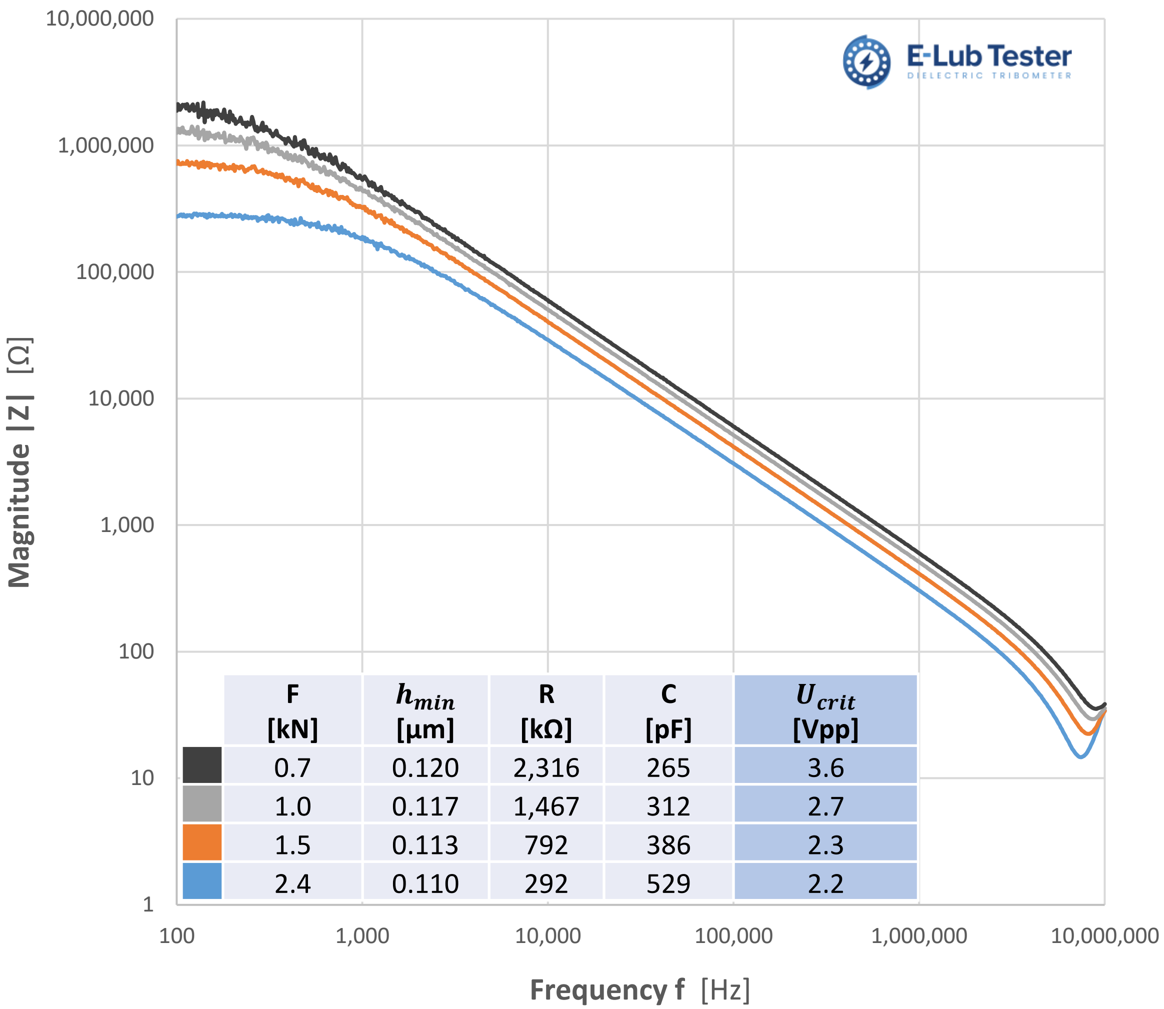
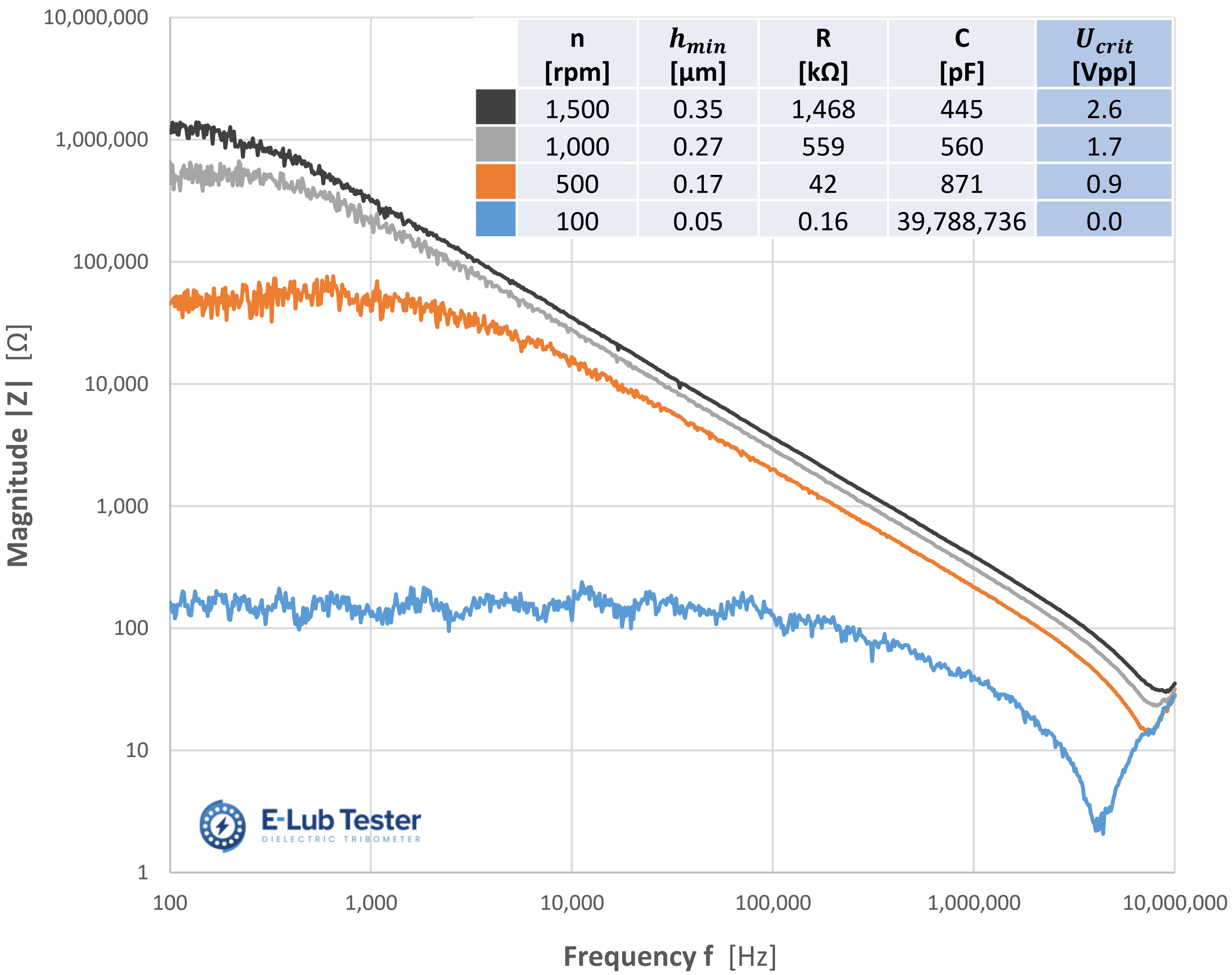
Exemplary Tests – Impedance Spectroscopy & Initial Breakdown Voltages

Load variation with OM @ {80°C | 1,000 rpm}



	F [kN]	h_{min} [µm]	R [kΩ]	C [pF]	U_{crit} [Vpp]
(dark grey)	0.7	0.120	2,316	265	3.6
(light grey)	1.0	0.117	1,467	312	2.7
(orange)	1.5	0.113	792	386	2.3
(blue)	2.4	0.110	292	529	2.2

Speed variation with OP @ {80°C | 2.4 kN}



	n [rpm]	h_{min} [µm]	R [kΩ]	C [pF]	U_{crit} [Vpp]
(dark grey)	1,500	0.35	1,468	445	2.6
(light grey)	1,000	0.27	559	560	1.7
(orange)	500	0.17	42	871	0.9
(blue)	100	0.05	0.16	39,788,736	0.0

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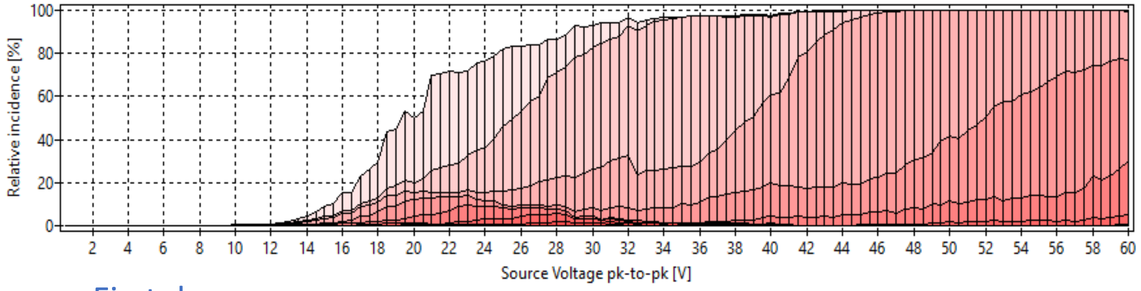
Exemplary Tests – Discharge Distribution Test @ {40°C | 1,000 rpm | 2.4 kN}

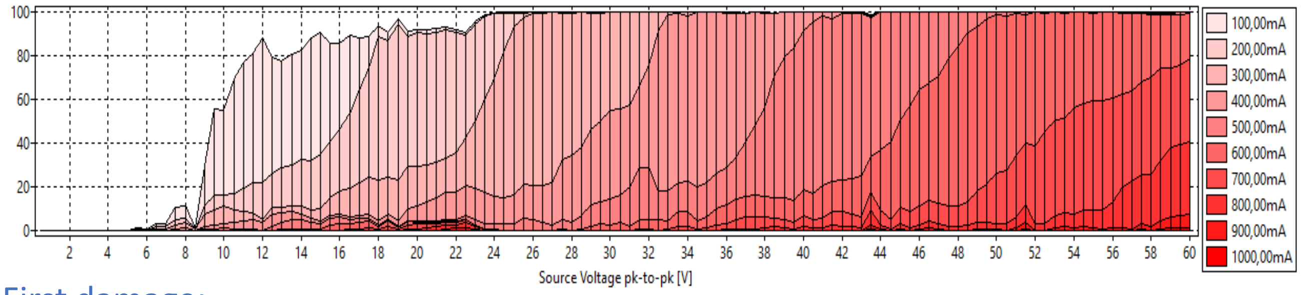
GM (h_{min} ≈ 0.44 µm)

GP (h_{min} ≈ 0.76 µm)

E-Lub Tester
DIELECTRIC TRIBOMETER

All Currents

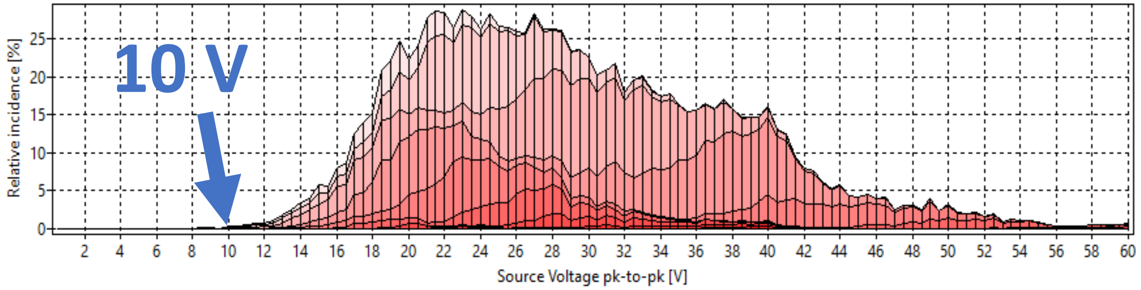


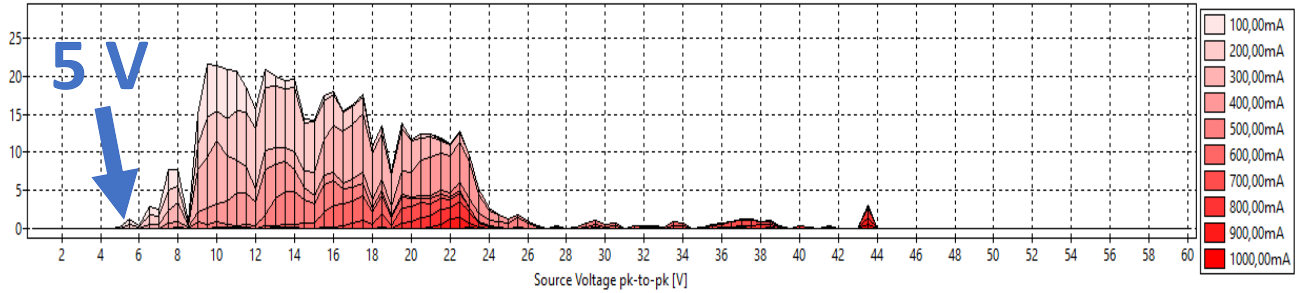


First damage:

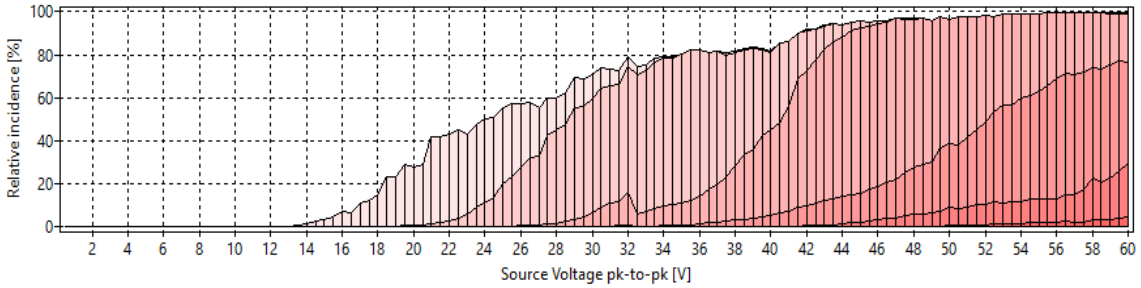
First damage:

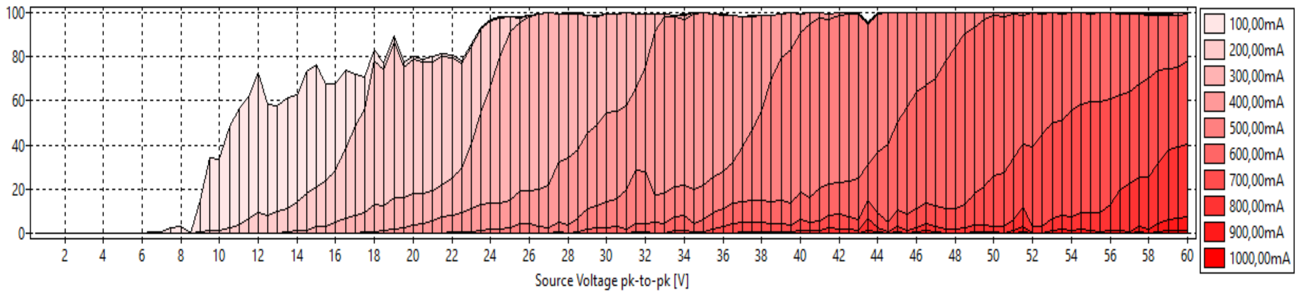
EDM Breakdown





Ohmic





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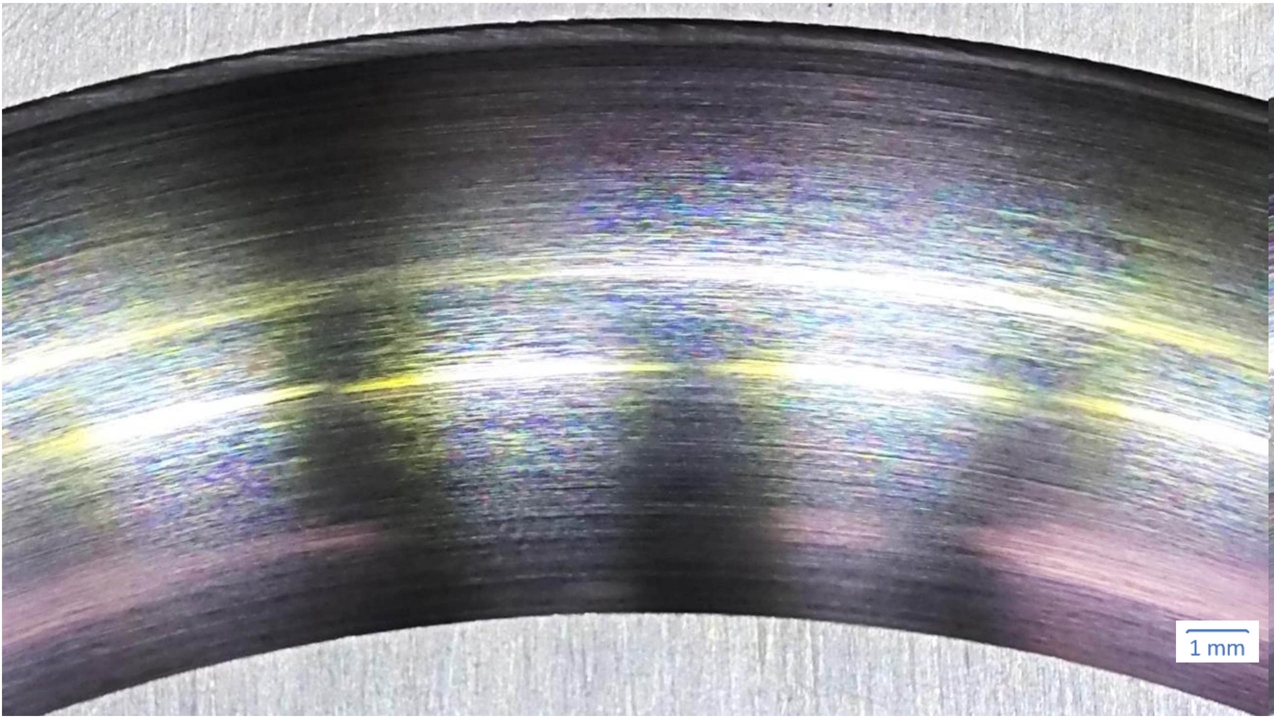
Exemplary Tests – Damage Comparison After 24-Hours Of Breakdown Testing

Raceway of stationary ring after 24-hour test with GP @ {40°C | 1,000 rpm | 2.4 kN}



...without replicated shaft voltage

...with **22 Vpp** replicated shaft voltage

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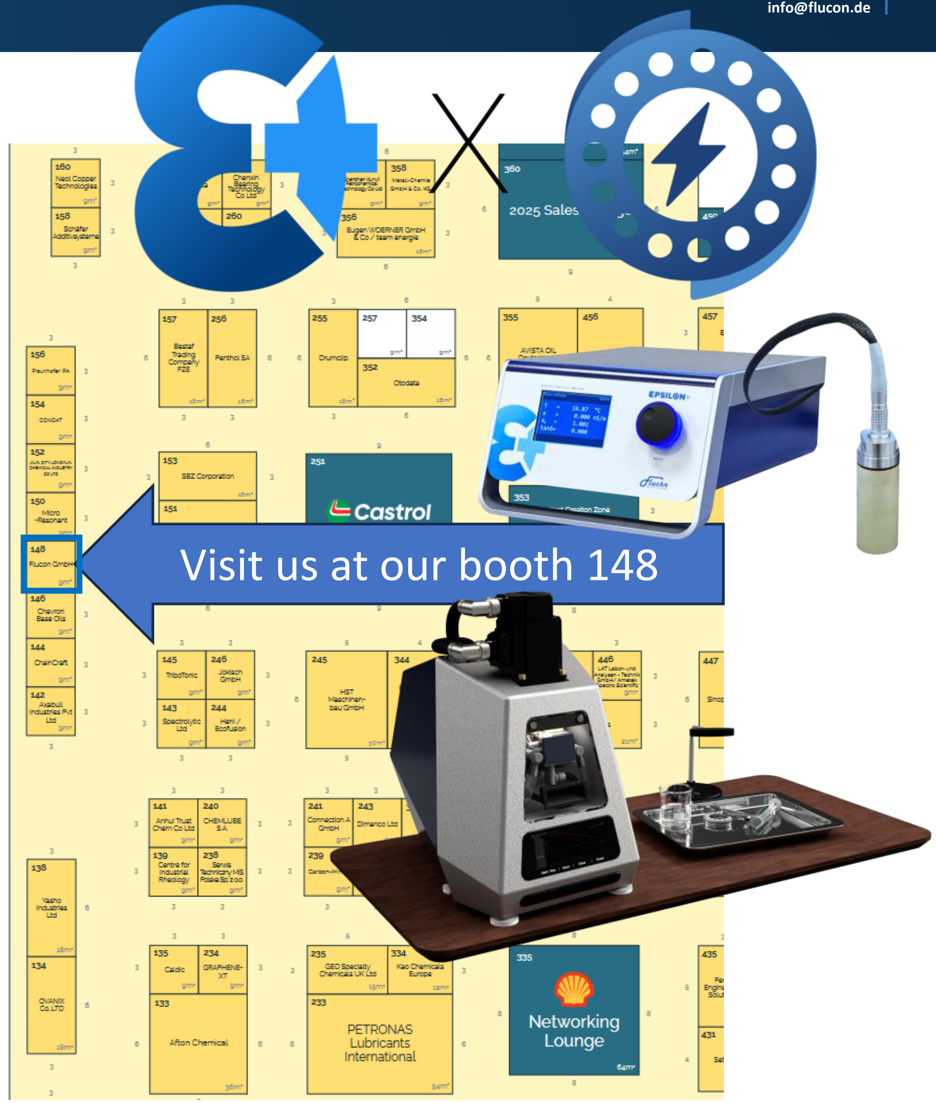
Conclusions & Prospect

- **Shaft voltage causes electrical breakdowns** through tribological contacts that damage machine elements and lubricants
- **New test methods are needed** to prevent or minimize electric discharges in the drivetrain
- Impedance (R & C) values can be fully interpreted only when the **electrical lubricant properties** are known
- Oils and greases should be analyzed and **specified in regard to their dielectricity** (e.g. through DIN 51 111 method)
- **Electrified tribometry** allows us to replicate operating conditions of electric drivetrains and investigate the lubricant film and its breakdown tendency
- Tomorrow’s lubricants can then be developed with an **optimized conductivity and dielectric strength** for the relevant operating conditions



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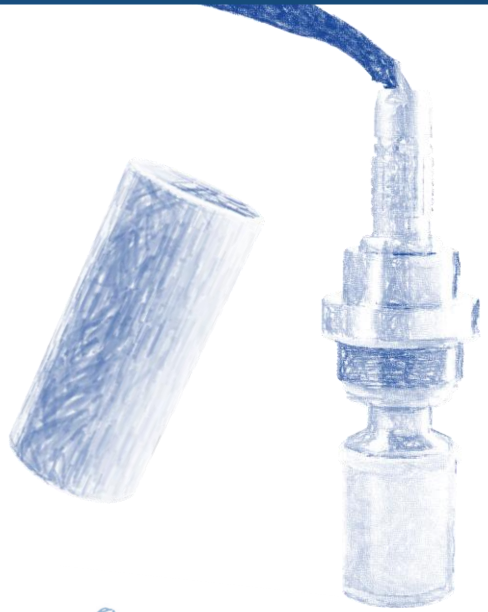
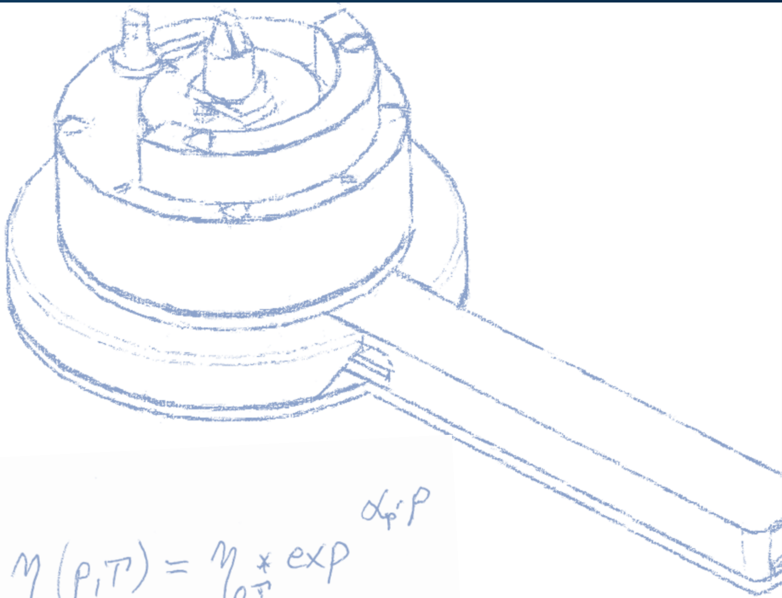


$\underline{Y} = \frac{1}{\underline{Z}}$

$\tan\delta = \frac{Re\{\underline{Y}\}}{Im\{\underline{Y}\}} = \frac{\kappa}{2\pi \times f \times \varepsilon_0 \times \varepsilon_r}$



Thank you.
Any questions?

$\eta(p,T) = \eta^*_{0,T} \exp^{\alpha_p \cdot p}$

$\varepsilon = \varepsilon_0 \times \varepsilon_r$

$\rho = \frac{1}{\kappa}$

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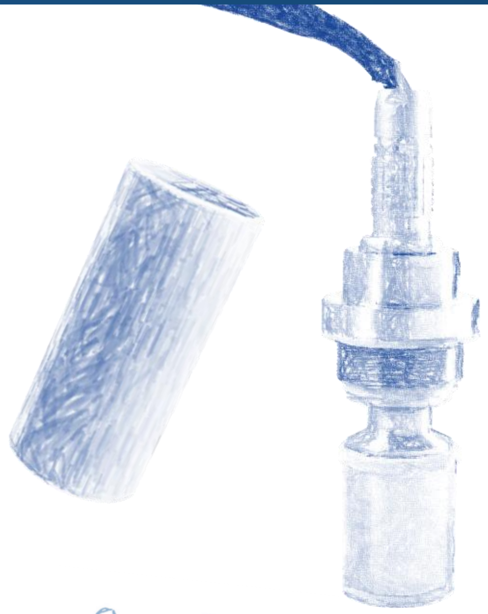

$$\underline{Y} = \frac{1}{\underline{Z}}$$

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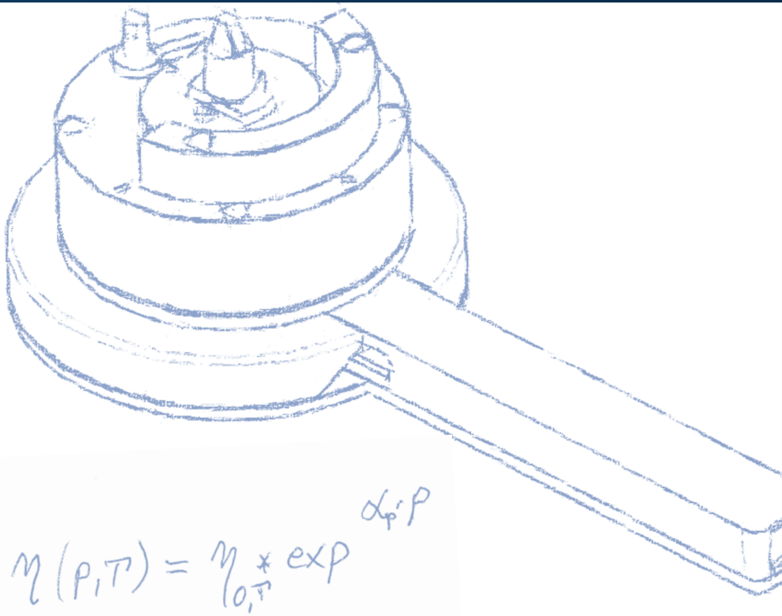


Annex

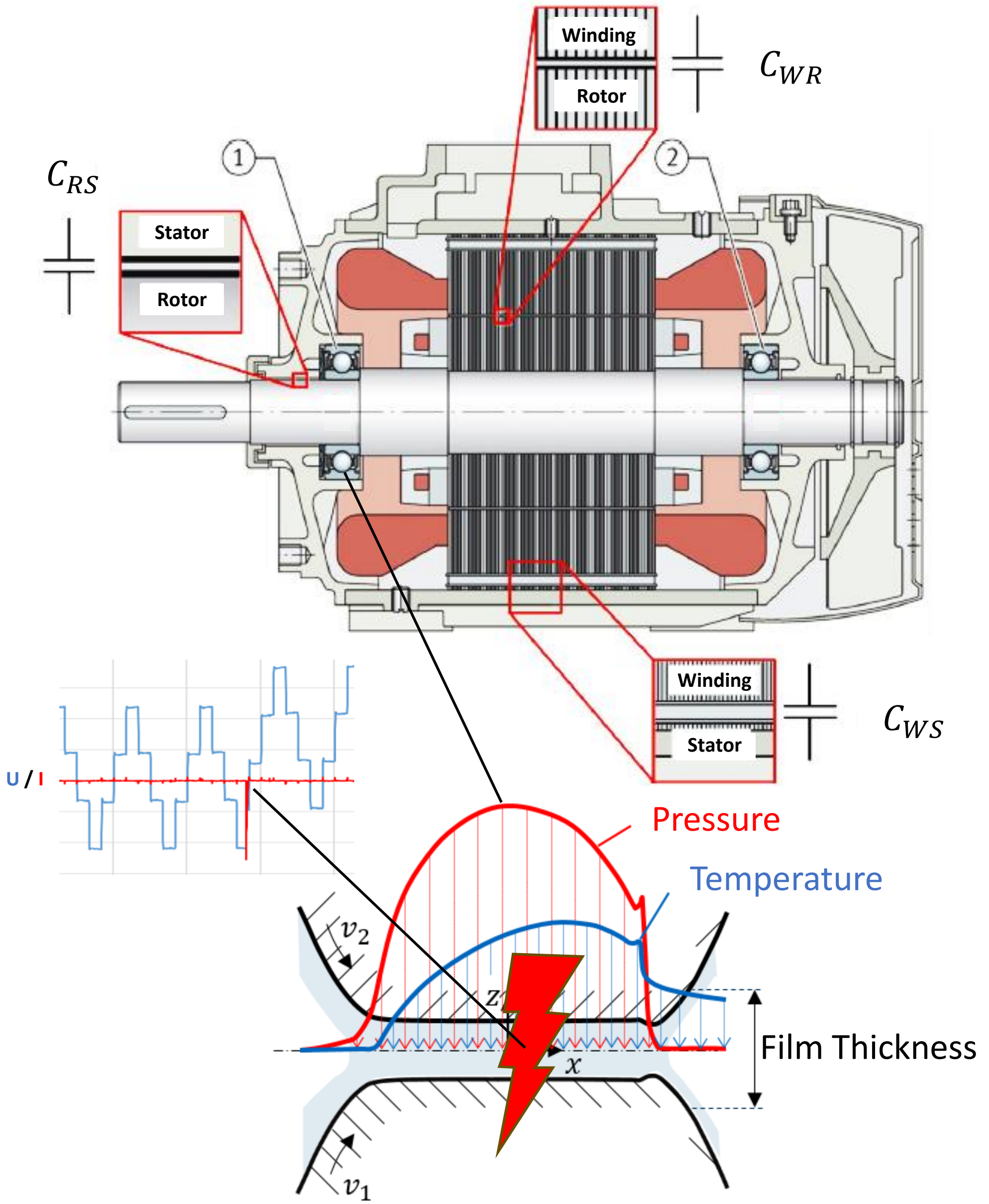
$$\eta(p,T) = \eta_{0,T} * \exp^{\alpha_p \cdot p}$$

$$\varepsilon = \varepsilon_0 \times \varepsilon_r$$

$$\rho = \frac{1}{\kappa}$$

How Discharges Occur In The Electric Drivetrain

- **Capacitive coupling** of rotor, stator and motor windings
- **Potential difference** between shaft (rotor) and housing (stator) is present in the bearings
- Shaft voltage must be taken into account when operating inverters with **high switching frequencies**
- When the critical field strength is exceeded **discharge currents** flow **through the insulating lubricant film** (EHD contact)
- Similar to Electric Discharge Machining (EDM), these **high-energy breakdown events** cause **structural damage** to the metallic components and to the lubricant in the gap



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Grey Frosting but as a larger image

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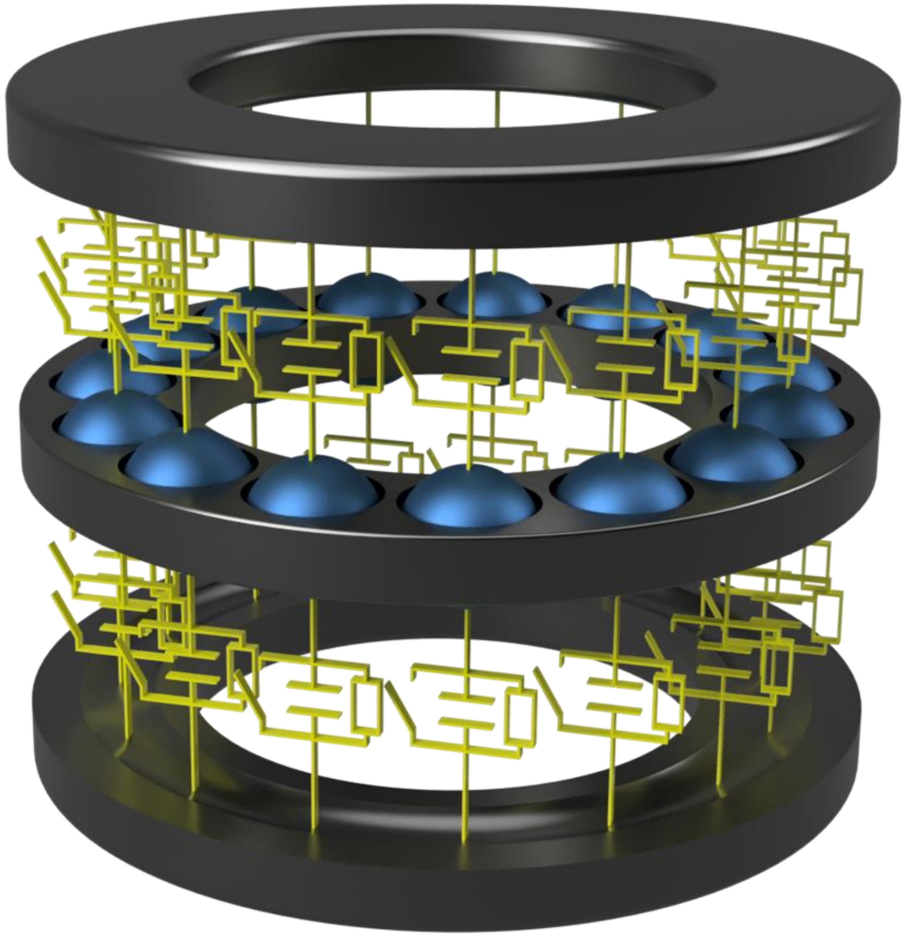
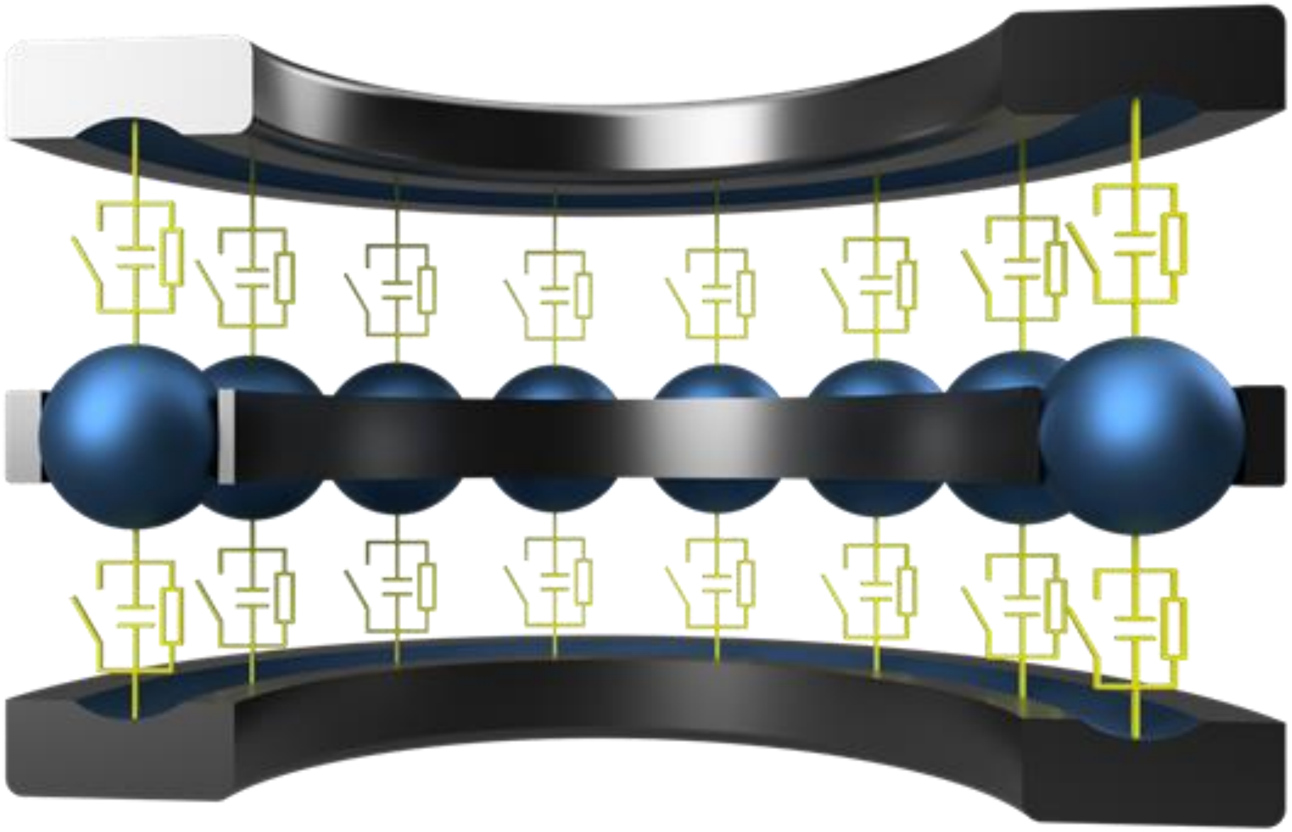
Impedance Measurement w/ Lubricated 51208 Thrust Ball Bearing





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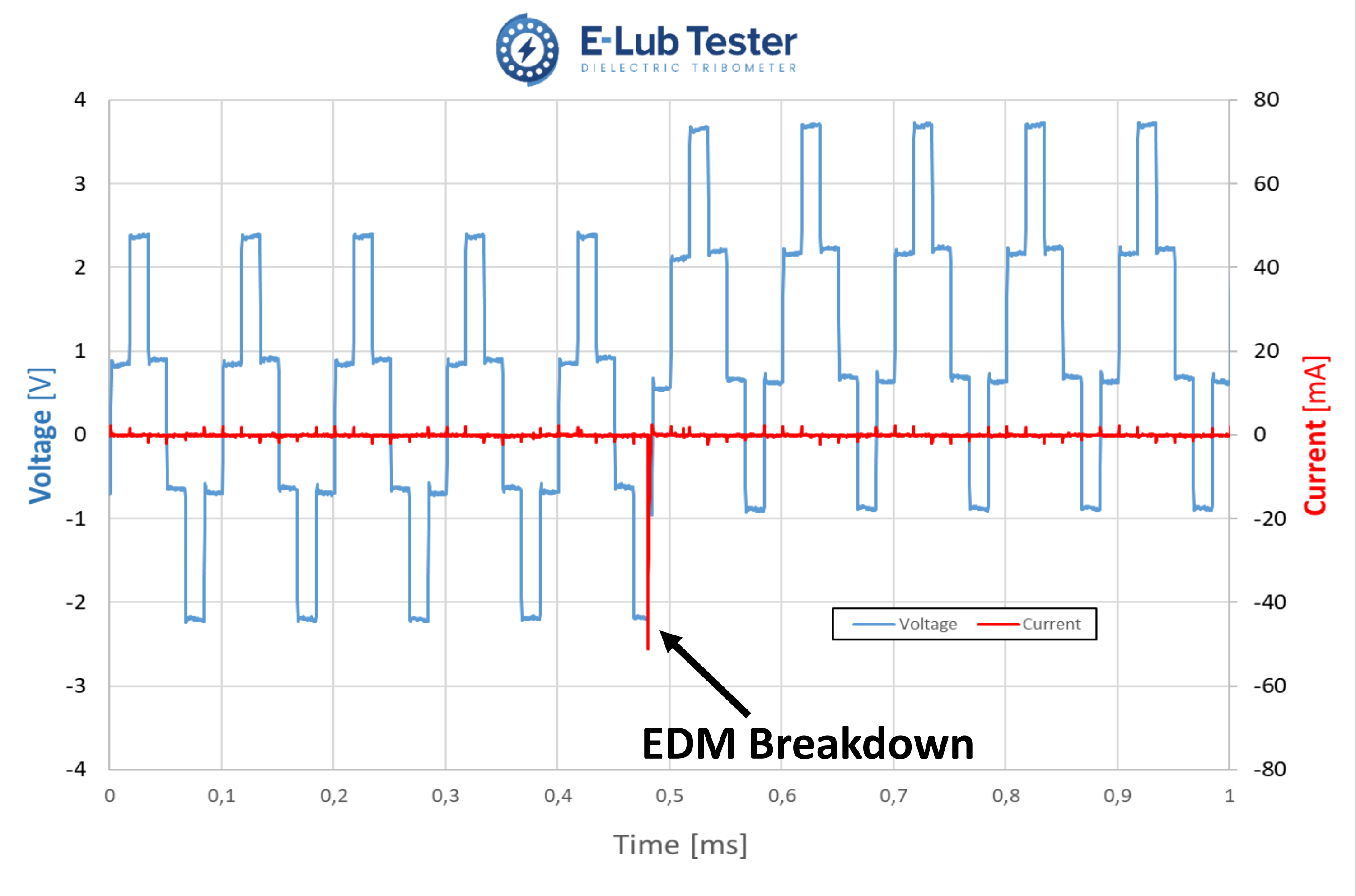
Initial Breakdown Test (Reversible Method At Multiple Operating Points)



"Breakdown Finder" algorithm: