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Off-line Partial Discharge Testing of Rotating Machines

Presenter : Charles Nybeck, PhD
Applications Engineer
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Auditor : Jeroen Goedertier
Service Engineer
Power Diagnostix

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Moderator

- Michael Fleischer
  - Digital Marketing Specialist

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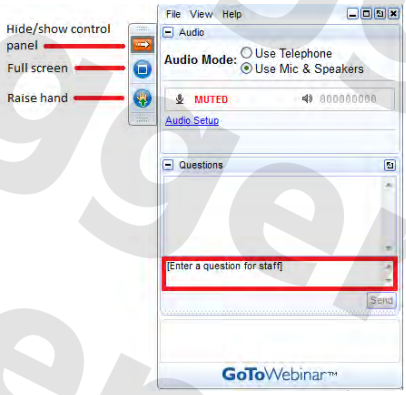
Q&A

- Send us your questions and comments during the presentation



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Today's Presenter and Panelists

Presenter

- Charles Nybeck
  - Applications Engineer

Panelists / Auditor

- Jeroen Goedertier
  - Senior Service Engineer

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Off-line Partial Discharge Testing of Rotating Machines

Charles Nybeck, PhD
Applications Engineer
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June 19, 2020

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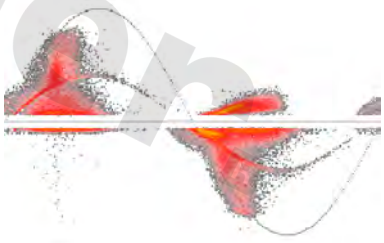
Presentation Outline

- Introduction: Partial Discharge on Rotating Machines
- Rotating Machine Insulation Systems
- Deterioration & Condition Assessment of Stator Windings
- Normative References
- Off-line PD measurements: General
- Typical Rotating Machine PD-patterns
- Offline RM-testing using ICM*system*
- Offline RM-testing using ICM*flex*
- Summary



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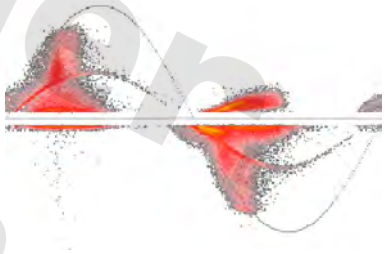

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Introduction – PD in Rotating Machines (1/3)

- Partial Discharge is a local insulation breakdown in a small portion of an overall insulation system
- PD causes a destructive high frequency current impulse and local heat
- Apparent charge decoupled at stator terminals
- Insulation will have a small amount of micro voids, as not all can be avoided
- Rotating machinery insulation materials are PD resistant

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Introduction – PD in Rotating Machines (2/3)

- Partial Discharges are inherent to rotating machine insulation systems and provide insight into the insulation systems condition
- Performance of new stator windings in terms of Partial Discharge rely on several factors
  - Insulation materials
  - System design
  - Applied processes
- TEAM-stresses under normal operation play a major role on the PD-behavior
- The severity gradation strongly depends on PD-location or discharge site

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Introduction – PD in Rotating Machines (3/3)

- Stator winding insulation systems can widely tolerate PD throughout their life
  - Monitor the development of PD activity
  - Determine if there is new PD activity
- Loss factor (tan δ) and off-line PD measurements are valuable tools for revealing winding deterioration
- PD-measurements offer the advantage of possibly detecting winding defects and fault mechanisms in an early stage
- Early detection allows intervening partial repair in an early stage and often avoids immediate rewinding

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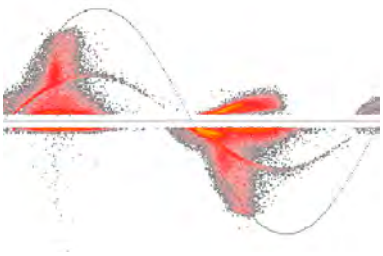

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Rotating Machine Insulation Systems

- Induction or generation under high voltages requires an stator winding insulation system offering sufficient dielectric strength under severe “online” stresses

- Main properties and functions of a stator insulation system are :
  - Introducing an insulated barrier
  - Ensuring optimal thermal conduction
  - Securing the copper conductors
  - Partial Discharge resistant for the intended life cycle
  - Thermal and mechanical stability
  - Protection against moisture and contamination insertion

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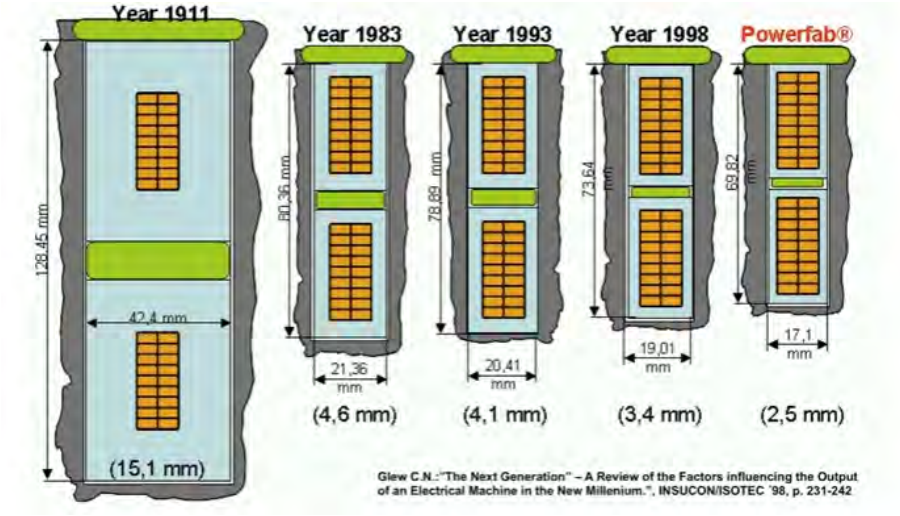
Evolution of the Main Insulation size



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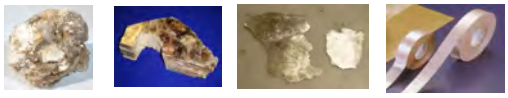
Today´s Insulation System

- Currently in use: the Epoxy – Mica system
- Epoxy-Resin: high-end low viscous thermosetting polymer
  - Breakdown strength: 20-26kV/mm (Paschen´s Law)

- Mica: a group name of silicate minerals
  - Generally Muscovite: $H_2KAl_3(SiO_4)_3$
  - Pure material: BDV 120-200 kV/mm
  - Mica based tapes: BDV 8-12 kV/mm



- After (proper) Curing
  - Excellent Dielectric stability
  - Moisture & contamination ingress protected
  - PD resistant unity (Not PD-free!)
  - Optimal thermal conductivity and mechanical stability

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Motor Diagram

Rotor Stator

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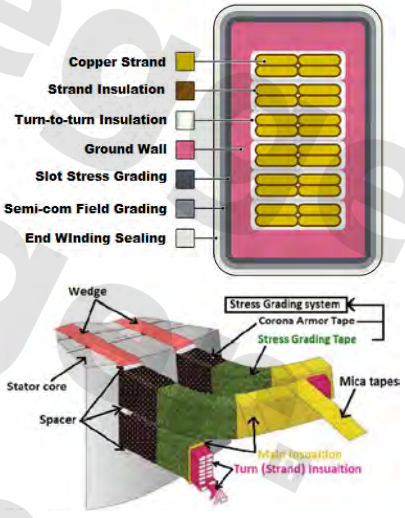
Stator Bar Design

- Conductor Insulation
  - Between strands or sub-conductors
  - Between turns
- Ground wall Insulation
  - Main Mica tape layers
  - Epoxy resin impregnated
- Slot stress grading layer
  - "Ground Electrode" for the straight part
  - Carbon loaded tapes – (linear surface resistance)
- Semi conductive field grading layer at the slot exit
  - Silicon carbide tape or paint layers
  - Non-linear surface resistance
- Overhang sealing tapes and or finishing paint layer



Ref: Ghassemi, Mona. (2019). Accelerated Insulation Aging Due to Fast, Repetitive Voltages: A Review Identifying Challenges and Future Research Needs. IEEE Transactions on Dielectrics and Electrical Insulation. 26. 1558-1568. 10.1109/TDEI.2019.008176.

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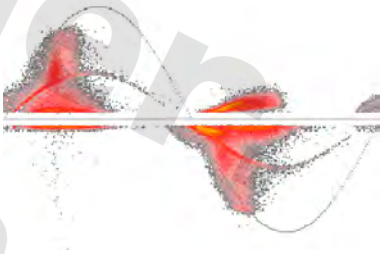

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Stator Winding Deterioration

- In service condition, stator windings are subjected to several stresses
- In the machines jargon often referred to as the “TEAM stresses”
  - Combined impact on the speed of deterioration
    - **T**hermal: overloading with consequent overheating (hot-spots)
    - **E**lectrical: uncontrolled electrical surface fields
    - **A**mbient: humidity - temperatures and or contamination
    - **M**echanical: vibrations, structural overhang resonance

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Stator Winding Deterioration

- Manufacturing inefficiencies, poor design and processing can enhance the impact of the common operational TEAM-stresses
  - Fast developing PD-behavior
- In case of “normal” gradual aging, the assumed life cycle a stator is up to 20 years
- However, a PD-fault mechanisms developing on a critical position within the winding may cause severe damage in only a couple of months
- PD-measurements are an excellent diagnostic tool in the philosophy of condition based maintenance (CBM)

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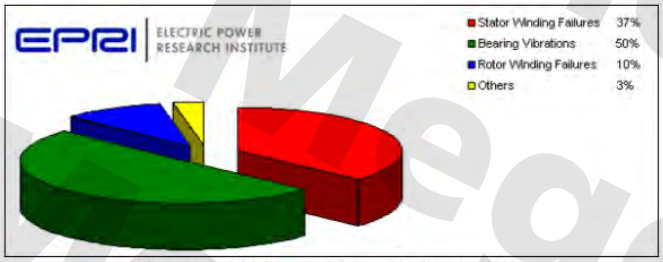
EPRI & IEEE Failure Studies



Analysis of 7500 machines (1983)

37% = stator winding related

Analysis of 3000 machines (1995)

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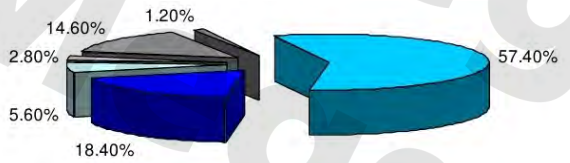
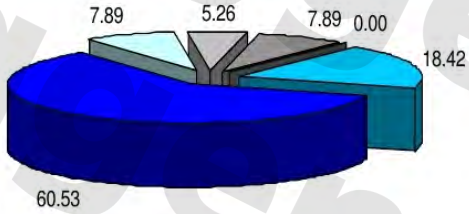
Failure Study: HV motors in the Petrochemical Industry (´99)

HV-Motors < 2MW



HV-Motors > 2MW



Bearing
Stator Windings
Rotor- Bars/rings
Shaft or coupling
External device
Not Specified

Reference: IEEE transactions on industry applications vol.35 N°3

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Stator Condition Assessment

- Failure root-cause investigations emphasize the importance of electrical and dielectric measurements
- A global recommendation for stator winding condition assessment:
  - Factory acceptance test (FAT) incl. offline PD and Tan Delta measurements as baseline reference
  - A first offline inspection 6-12 months after the commissioning
  - Further Off-line measurements every two years
  - Alternatively, permanent installation of coupling capacitors for online PD-measurements every 6 months combined with a full offline inspection every 4-5 years

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Stator Condition Assessment

- A typical scope for off-line stator winding inspections can be as follows:
  - Visual Inspection of the overhang and slot-exit
  - Winding resistance and inductance measurement
  - Surge test (if possible)
  - Insulation resistance and polarization index (PI) measurement
  - Optionally: DC step-voltage test
  - Optionally: Long duration polarization / depolarization test
  - Dielectric loss factor (tan delta) tip-up and capacitance test
  - Off-line Partial Discharge test
  - AC-high potential test (only after on-site repair such as e.g. re-wedging)

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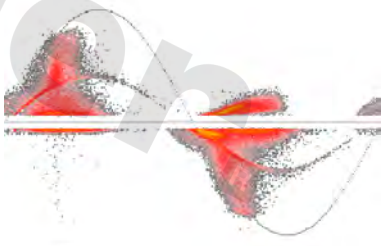

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Normative References

- There are currently no standards defining acceptance criteria for Partial Discharge testing on rotating machinery
- The lack of such criteria often causes endless discussions between owner and manufacturer after submission of test reports, even during factory tests
- An important difference between rotating machines and other applications is property to be PD-resistant versus other PD-free insulation systems
- Frequently asked questions on this subject are:
  - How much PD is now too much PD?
  - Defining acceptance criteria for a PD-resistant insulation systems?

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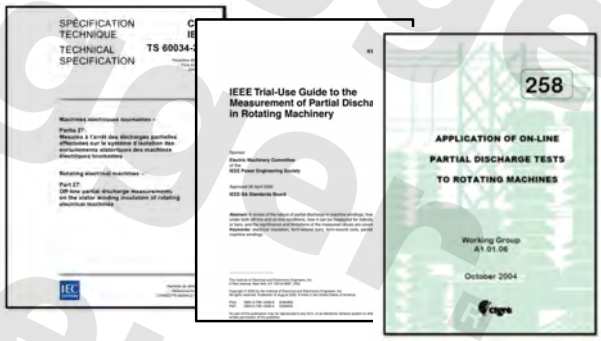
Normative References

- Main “horizontal” standard, i.e. the IEC 60270
- Technical specifications and guides from IEC, IEEE, Cigré, EASA and EPRI
  - Test circuits and procedures
  - Voltage application sequences
  - Test durations
  - PD-detection bandwidths
  - Calibration circuits
  - Typical PD-phenomena



- IEC600034-27, IEEE 1434-2014, Cigré ref.258 and ref.558, etc.

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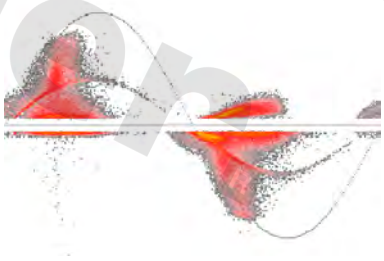

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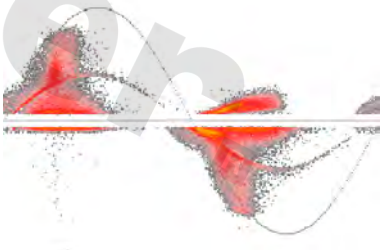
Off-line PD measurements: General

- Offline PD-measurements: Basics
- HFPD signal properties
- PD-measurement vs. Bandwidth
- Stator winding model
- Examples of machine PD-spectra
- PD-Calibration
- Recommended Test Circuits
- Procedure



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Offline PD-test: Basics

- The Motor or Generator is out of service, HV-supply cables or bus-bar system are disconnected and isolated
- Stator windings should be energized using an external “PD-free” high voltage source
- Measurement condition differ from normal operation
  - Cold conductor (no-load conditions)
  - Influence of environmental conditions (temperature, but mainly relative humidity)
  - Different electrical field distribution
- Reference measurement during factory acceptance test (FAT) and in-depth verification by periodical field testing
- Usually combined with visual inspections, loss/power factor & capacitance measurements, and DC insulation tests
- Excellent guidance for partial repairs

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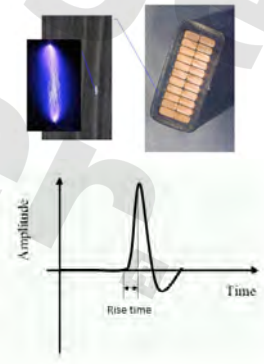
HFPD Signal Properties

- Internal activities within main insulation generally start as a gas discharge
- The electron avalanche causes a local high frequency current displacement
- At the discharge location, the HF-current impulse has a short rise time
- Under nitrogen (N) conditions, the rise time is typically in range of 1ns, translating into a bandwidth up to 350MHz
- However, a stator winding is a non-ideal high frequency conductor



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HFPD Impulse Properties

- The original PD-pulse properties will be affected by HF-effects such as attenuation, reflections, resonances, dispersion and radiation
- Basic understanding of the pulse propagation and bandwidth selection are essential for the measurement and the analysis
- The lower bandwidths are more prone to HF-noise, but offer the better coverage to detect PD in the entire winding
- Recommended detection bandwidth for offline testing: <1MHz (IEC60270)

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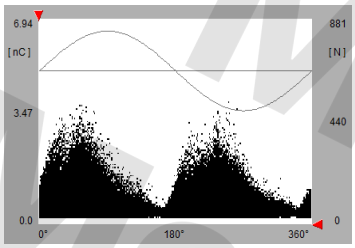
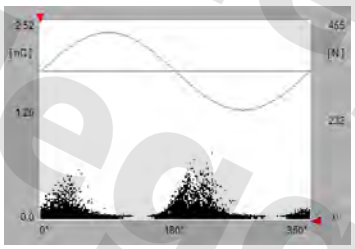
PD Pattern vs. Detection Bandwidth



40-800kHz (IEC60270)
1215697 Counts



2-20MHz
110843 Counts

20-200MHz
2270 Counts

- 1200kW – 6600V asynchronous motor with internal neutral connection
- New VPI impregnated stator winding
- Offline PD-measurement - 60s PD-pattern acquisition (coupling capacitor)
- Same test object and test voltage - different band pass filters

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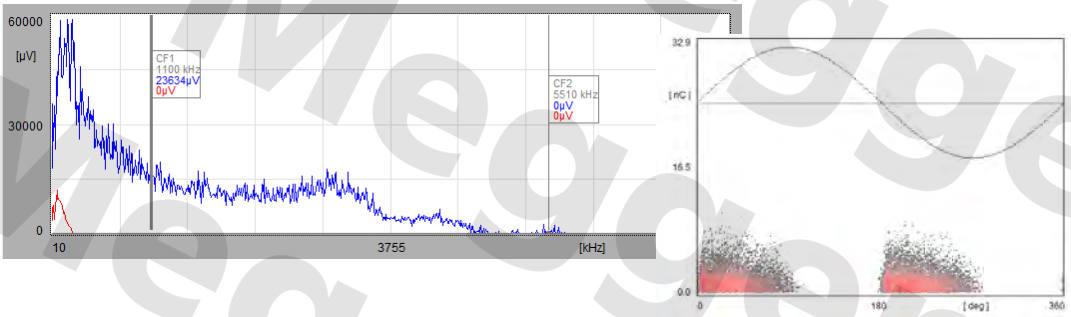
Example of an Off-line Signal Spectrum



- 800kW – 6000V asynchronous motor with internal neutral connection
- PRPD pattern reveals internal PD-activity in the main insulation (Ground Wall)
- Offline PD-measurement (conventional circuit acc. IEC60270)
- Available signal up to 5.5 MHz

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PD-calibration

- PD measurements are relative measurements and require a calibration (IEC60270)
- Compensation of the test circuit´s overall attenuation
- Injection of a calibration pulse with defined magnitude & magnitude adjustment of the signal response
- Strictly following the IEC60270, a calibration is valid only when using a bandpass filter

  $30kHz \leq f1 \leq 100kHz$ $f2 \leq 1MHz$ $100kHz \leq \Delta f \leq 900kHz$

- However, PDIX instruments support the principle of the so called quasi integration at higher frequencies as well

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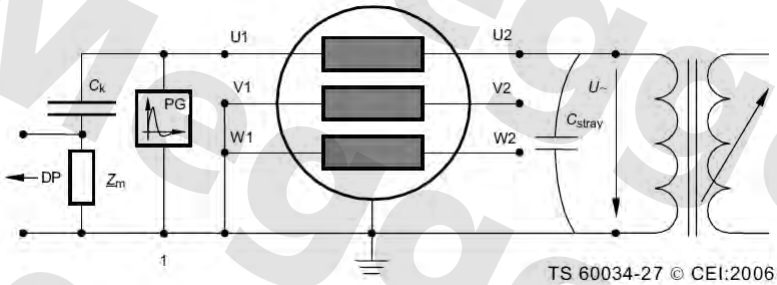
Offline Calibration Circuit



TS 60034-27 © CEI:2006

- Typical calibration levels for rotating machines (in IEC range /off-line): 500pC-10nC
  - Depending from winding to winding (slot length – capacitance)
  - Signal-to-noise ratio (SNR)
- Valid for the test setup in final arrangement, at a specific detection bandwidth and calibration magnitude

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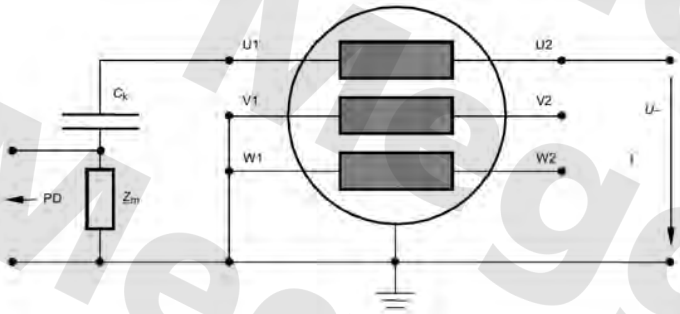
Recommended Off-line PD Test Circuits (1/2)



ID number	HV	Ground	C_K
E1.1	U1	V2W2	U2
E1.2	V1	U2W2	V2
E1.3	W1	U2V2	W2
E1.4	U1V1W1	-	U2V2W2

According to IEC TS 60034-27

- Motor or Generator windings with accessible neutral connection allow energizing of complete winding to ground and the individual phases to ground
- Measurements performed from line terminals (U1, V1, W1)
- Additional measurement from neutral for more in-depth inspection

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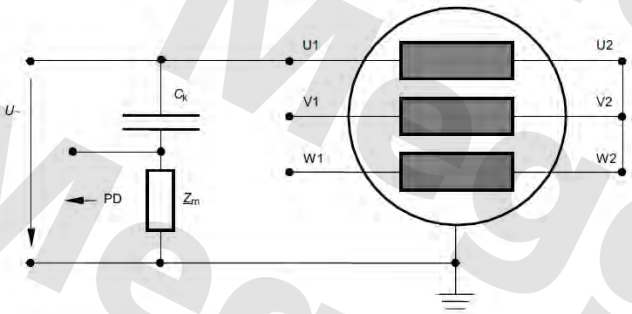
Recommended Off-line PD Test Circuits (2/2)



According to IEC TS 60034-27

ID number	HV	Ground	C_K
Accessible star point			
E2.1	U2V2W2	-	U1
E2.2	U2V2W2	-	V1
E2.3	U2V2W2	-	W1
E2.4	U1V1W1	-	U2V2W2
Inaccessible star point			
E2.5	V1	-	U1
E2.6	W1	-	V1
E2.7	U1	-	W1

- Stator windings with internal star point (neutral) connection allow energization of the complete winding
  - (phase-to-ground)
- It is highly recommended to perform measurements at each individual winding terminal

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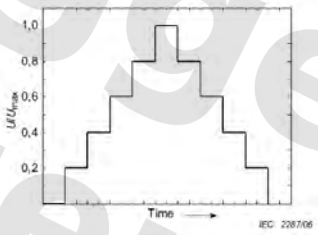
Off-line Test Procedure

- Insulation resistance and polarization index measurement show acceptable results
- Use a test circuit according to the suggested diagrams (INT/EXT star-point) and calibrate the setup
- Conditioning of the of winding at rated voltage (2-3min) prior to the PD-measurement (re-calibrate if needed)
- Recommended voltage application sequence
  ΔU = 20% of U_N (up to Un)



- Monitor partial discharge inception (PDIV) and partial extinction (PDEV) voltages
- Acquire a phase resolved partial discharge pattern (PRPD) for minimum 30-60s
- Monitor the discharge magnitude accurately while raising the test voltage and do not hesitate to suspend the testing in case of uncertainties or unsafe conditions

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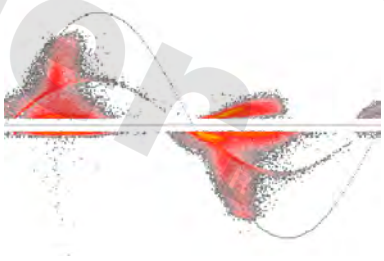

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Classification of Rotating Machine PD

- Internal Discharge Activities
  - Delamination's Micro voids
  - Thermal aging
- End Winding (overhang) Discharges
  - Surface dischargesBar-to-Bar activity
  - Vibrations
- Slot Discharges
  - Wedge problems
  - Inadequate impregnation
- Slot-exit Discharges
- External high frequency disturbances

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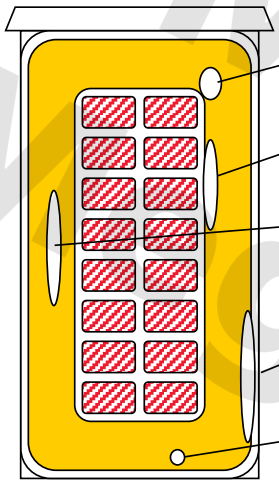
Stator Coil Cross Section



1) Higher Electrical Field on the corners

2) Conductor bound delamination

3) Internal delamination

4) Ground Wall Delamination

5) Internal micro voids

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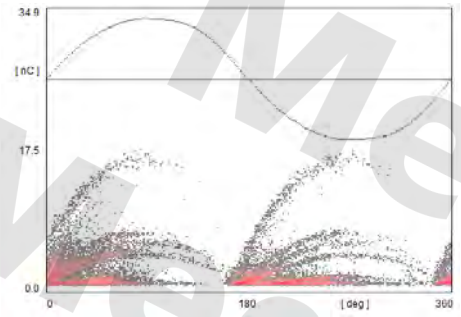
Spherical Void Discharge



Main Pattern Properties:

- Symmetrical pulse distribution
- Multiple (countable) voids
- Low availability of a starting electron
- Line type pattern (sine shaped clusters)
- Unipolar acquisition

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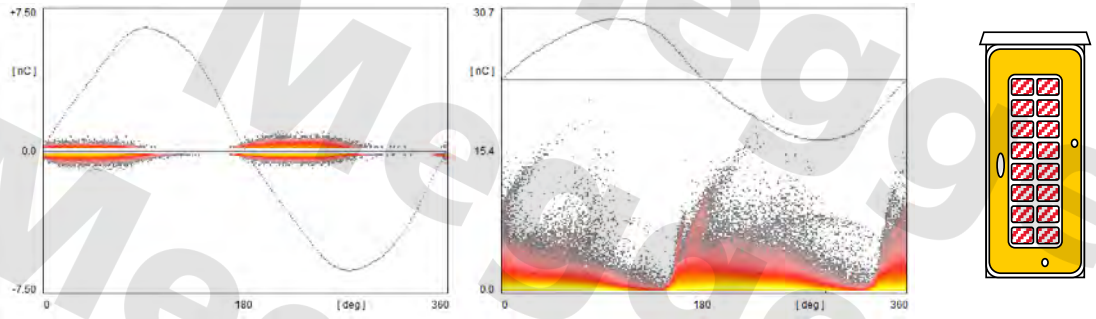
Internal Delamination: Early Stage



Main Pattern Properties:

- Symmetrical pulse distribution
- High availability of starting electrons
- Generally high repetition rate
- Left: expectation of a new stator
- Right: combination of delamination(s) and voids

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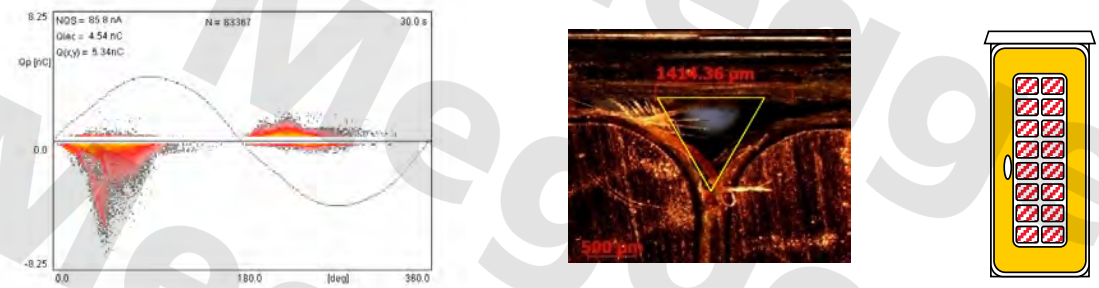
Conductor-Bound Delamination



Main Pattern Properties:

- ASymmetrical pulse distribution for both cycles
- Dominant positive cycle
- Delamination at inner conductor circuit
- Normal Ageing: frequent load cycling (e.g. pump storage stations)

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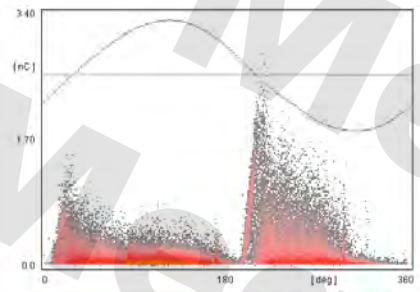
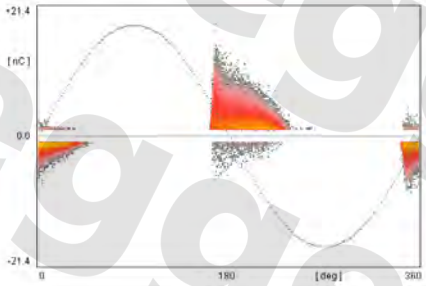
Ground Wall Delamination: Slot Discharge





Main Pattern Properties:

- ASymmetrical pattern with dominant negative cycle
- Strongly load dependent
- Delamination at the slot corona prevention layer
- Consequent high Ozone (O_3) generation causing “collateral damage”

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Consequences of Ozone

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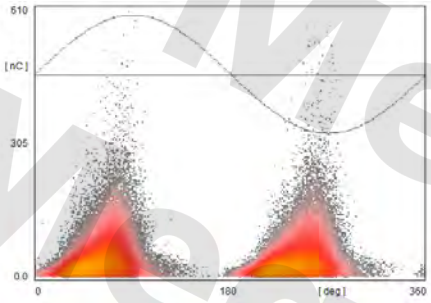
End Winding Surface Discharges



Contaminated Overhang:

- Similar Pattern for both half cycles
- Often a triangular configuration
- Maximum PD-magnitude (90° & 270°)
- Strongly voltage dependent discharge magnitude

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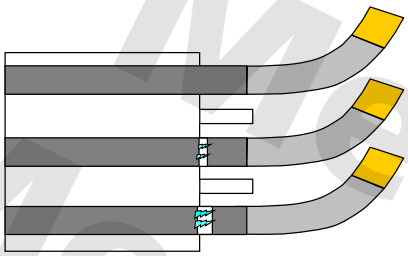
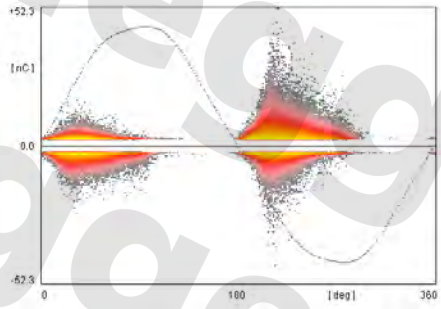
Slot-exit Discharge





Common Defect Mechanism with Global VPI Insulation Systems:

- Thermal & Mechanical causes small surface cracks
- Initial Stage: Surface Discharge
- Detection magnitudes ~10-50nC
- Superficial cracks develops to a growing gap due to the erosion by PD

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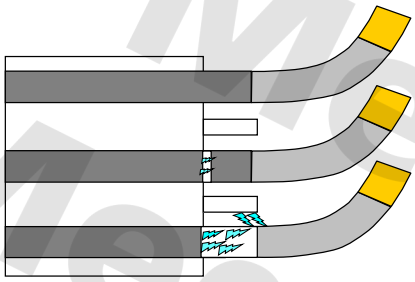
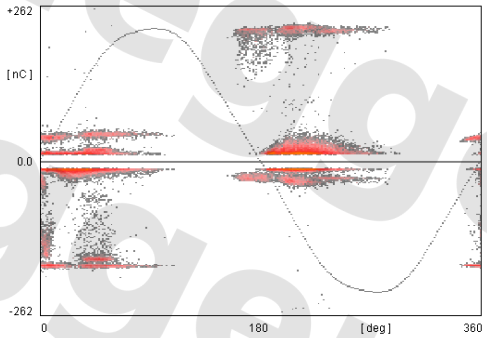
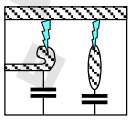
Slot-exit Discharge





Final Stage:

- Semi-con field grading looses contact to the grounded core
- Consequent floating potential activity
- Visible arcs to the pressure fingers
- Extraordinary detection magnitudes of above >100nC



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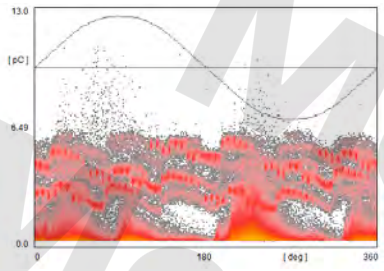
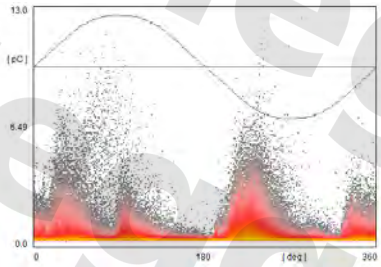
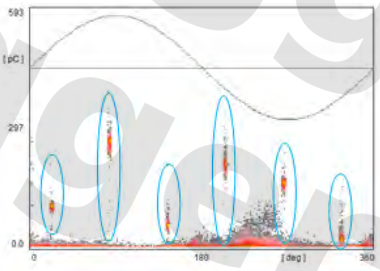
High Frequency Interference

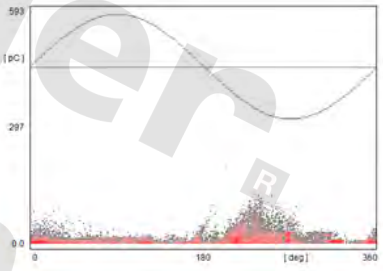




Frequency converter
HF-disturbance

Excitation Noise





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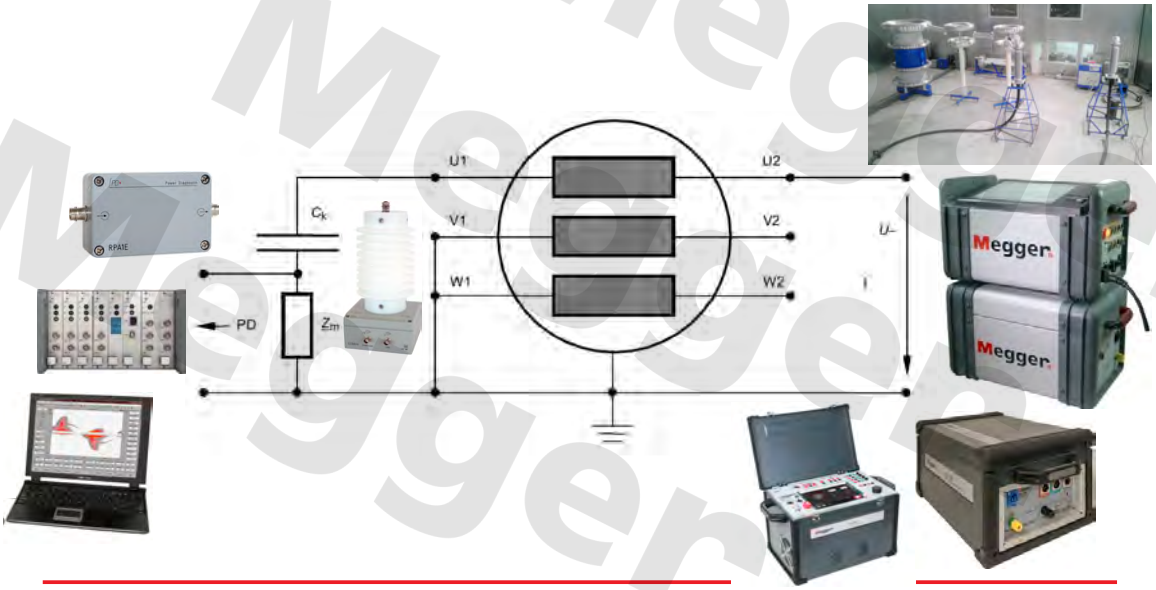
Test Setup



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Test Setup

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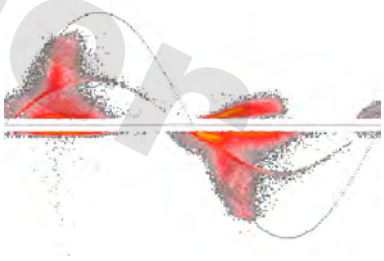
Presentation Outline

- Introduction: Partial Discharge on Rotating Machines
- Rotating Machine Insulation Systems
- Deterioration & Condition Assessment of Stator Windings
- Normative References
- Off-line PD measurements: General
- Typical Rotating Machine PD-patterns
- Offline RM-testing using ICM*system*
- Offline RM-testing using ICM*flex*
- Summary



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ICM*system* (Generation 5)

- Advanced PD-detection system and analysis tool
- Simultaneous real time acquisition on up to 10ch
- Integrated spectrum analysis up to 10MHz (BW: 9kHz/300kHz)
- Time domain analysis
- Measurements with AC and DC voltages
- Advanced (SC/MC) control software
- High Resolution PRPD-Pattern (16-bit)
- Powerful Suppression Tools
- Input sensitivity <0.02pC
- IEC 60270 compliant
- Field and factory environment

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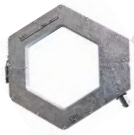
ICM*system*: Configuration for Rotating Machines

Decoupling

- Capacitive couplers (e.g. CC25B/V)

- HFCT (e.g CT100)



Pre-processing

- <1MHz (IEC-60270) RPA1e
- Wideband (20MHz) RPA1H

Acquisition

- ½ 19inch ICM*system* (2ch)
- ½ 19inch ICM*system (4ch)*

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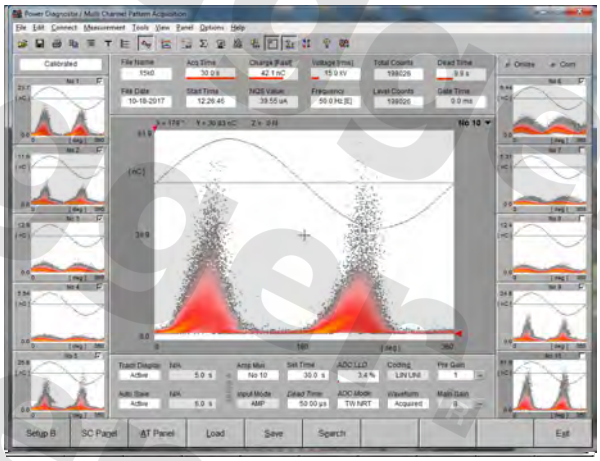
ICM*system*: Software

Misc. Panels and Visualizations

- Single Channel Acquisition (SC)
- Multi channel Panel (MC)
- Spectrum Analysis
- Trending Functionality
- 16-bit PD-pattern
- Statistic Analysis Panel
- Time Domain (DSO)



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ICM*system:* Setup Impressions

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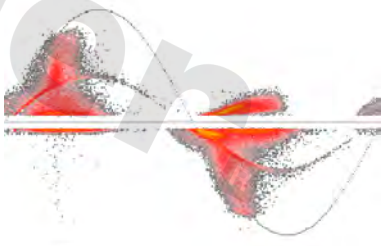

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ICM*flex*

- Measurement System for Partial Discharge (PD), Dielectric Loss Factor (Tan δ) and capacitance
- Unique design with Acquisition box on HV-potential
- Power frequency synchronization (20-510Hz) & VLF
- Plug and play setup incl. high voltage line filter
- User friendly control software with reporting functionality
- Optional step-by-step guide
- Bluetooth or Fiber optic communication
- Battery operated (up to 12h)
- IEC 60270 compliant
- Ultimately suited for Routine field and factory testing

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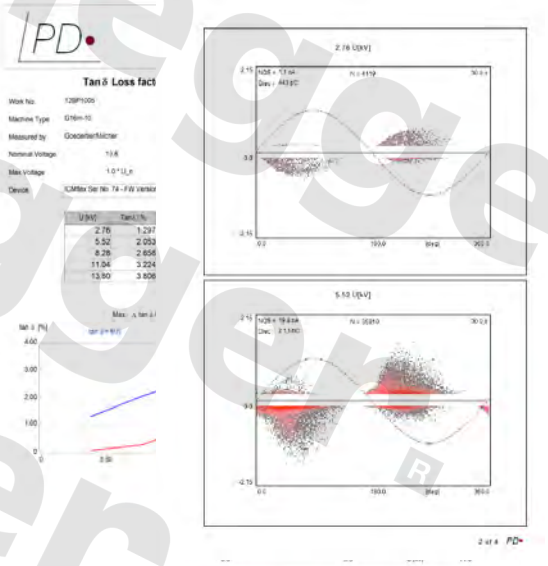
ICM*flex:* software

- Control Software:
  - All-in-one operation panel
  - Advanced recording mode (Tan δ & capacitance acquisition)
  - Supports two and three dimensional PD acquisition
  - Multiple simultaneously updated Graphs
  - Trending vs. Time and voltage functionality
  - Export data format (.xls, xlsx, pdf)
  - Semi-automatic report generation



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ICM*flex:* Setup Impressions

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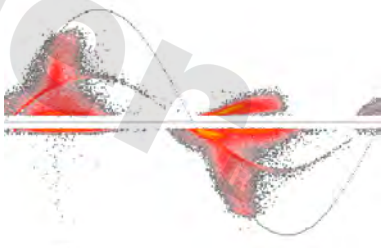

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Summary

- Stator winding insulation system are PD-resistant and widely tolerate PD-activity for several years of operation without being the root-cause of failure
- Dielectric measurements are as important as monitoring of vibrations
- Partial detection on rotating machinery is a matter of trending and comparing actual results with available reference data – there are currently no acceptance criteria defined
- Sufficient care must be taken with the bandwidth selection, calibration procedure and correct selection of recommended measurement circuits
- Analysis of the phase resolved partial discharge pattern (PRPD) provides essential information about the ongoing type of partial discharge, and the concerned location
- Off-line measurements serve as an in-depth verification after manufacturing, during the first months of operation, and during major maintenance outages. Moreover, they are an excellent to be used for partial repairs

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Thank You

IPD by Megger Power Diagnostix Systems

Thank you for your attention!

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Survey and Contact Information

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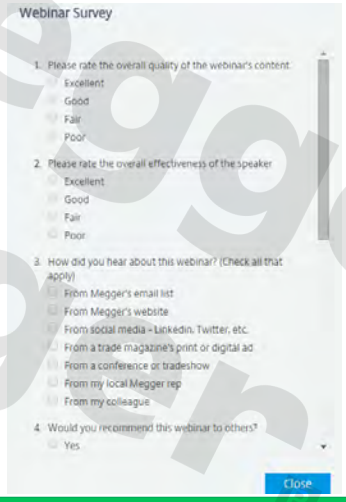

Please help us improve by filling out the survey after the webinar ends

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Questions?

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