On-Line Insulation Diagnostics In Rotating Machines Without Pre-Installed Sensors Using Emi Analysis

Pavankumar Jaiswal • Aditya Korde
Diagnostic Technologies India Pvt. Ltd.

ABSTRACT

The reliability of high-voltage rotating machines is critical for sustainable industrial operations. On-line partial discharge (PD) monitoring of the insulation condition is rarely possible due to the lack of pre-installed sensors in most motors. This paper explores how EMI diagnostics can detect insulation degradation and arcing in motors and generators on-line, without the need for expensive pre-installed sensors.

In this paper, EMI fundamentals, testing methodology, sensor configurations, and data acquisition techniques are discussed. It also highlights practical case studies involving rotating machines, demonstrating how EMI signatures can be used to identify defects such as corona, arcing, insulation voids, and loose connections. EMI diagnostics, being an on-line and non-intrusive technique, allows condition assessment without shutdown, thus supporting predictive maintenance strategies and minimizing operational risks. The study concludes that EMI testing can enhance asset reliability, reduce unplanned outages, and support data-driven maintenance planning in modern power systems.

Keywords : EMI Diagnostics, Partial Discharge, Rotating Machines, Condition Monitoring, Insulation Degradation, Insulation Failure, Predictive Maintenance.

1. INTRODUCTION

One important factor in the operational reliability of high-voltage (HV) electrical equipment is the health of their insulation systems. Conventional diagnostic methods, including offline partial discharge (PD) testing, insulation resistance, and dielectric loss measurements, typically require equipment shutdown and may not effectively capture intermittent or evolving defects.

In many installations, especially older assets, the absence of permanently installed PD sensors makes continuous monitoring impractical. This limitation necessitates alternative diagnostic approaches that can be deployed without system modification.

Electromagnetic Interference (EMI) diagnostics provides a non-intrusive, on-line solution by capturing high-frequency signals generated due to electrical discharges within insulation systems. These emissions, spanning from a few kHz to several hundred MHz, carry critical information about insulation condition and defect characteristics.

2. FUNDAMENTALS OF EMI DIAGNOSTICS

EMI diagnostics is based on the frequency-domain analysis of damped high-frequency signals generated due to partial discharge or arcing activity within electrical equipment. These signals propagate through both conductive and radiative paths, enabling remote detection without direct electrical connection to the defect site. EMI associated with insulation defects originates from rapid transient current and voltage variations within the machine. These transients are governed by fundamental electromagnetic principles linking time-varying currents to radiated and conducted emissions.

2.1 Sources of EMI

Typical sources of EMI in HV equipment include:

- Partial discharge due to internal insulation defects
- Corona discharge in air-gaps or sharp edges
- Surface discharges due to contamination or moisture
- Arcing due to insulation failure or loose electrical connections
- Mechanical defects such as shaft seal rubs

2.2 Nature of EMI

- Broadband in nature
- Transient and repetitive
- Characteristic of specific defect types

A key advantage is that each defect produces a unique EMI signature, enabling differentiation between electrical and mechanical issues.

3. ELECTROMAGNETIC BASIS OF EMI IN ROTATING MACHINES

3.1 Transient Current Generation

Electrical discharges such as partial discharge or arcing involve extremely fast charge movement over very short time durations. The discharge current can be approximated as a pulse:

$$i(t) = I_0 e^{-t/\tau}$$

where:

- I_0 = peak discharge current
- τ = decay time constant (typically nanoseconds)

The key parameter governing EMI generation is the rate of change of current:

$$\frac{di}{dt}$$

Fast rise times (ns scale) produce very high $\frac{di}{dt}$, which directly leads to broadband electromagnetic emission.

3.2 Frequency Spectrum of Discharge Events

The characteristic bandwidth required to reproduce a transient with rise time is approximately

$$Bandwidth \approx \frac{0.35}{t_r}$$

based on first-order system response assumptions. Actual discharge spectra extend beyond this and depend on the physical discharge mechanism and propagation effects.

For example:

- $t_r = 10$ ns $\Rightarrow f_{max} \approx 35$ MHz
- $t_r = 1$ ns $\Rightarrow f_{max} \approx 350$ MHz

This explains why:

- Partial discharge and arcing produce broadband spectra extending into MHz ranges
- EMI systems detect signals well beyond conventional PD bandwidths

3.3 Electromagnetic Radiation Mechanism

According to Maxwell's equations, a time-varying current produces both electric and magnetic fields:

$$\nabla \times \mathrm{H} = \mathrm{J} + \frac{\partial \mathrm{D}}{\partial t}$$

i. e., the Curl of the Magnetic Field = Conduction Current Density (A/m^2) + Displacement Current Density

The displacement current term $\frac{\partial \mathbf{D}}{\partial t}$ becomes significant for fast transients, leading to radiated electromagnetic energy. The radiated electric field is proportional to:

$$E \propto \frac{dI}{dt}$$

Thus:

- Faster discharge events → stronger high-frequency emissions
- Arcing (high energy, fast rise) → wideband, high amplitude EMI

- Corona (slower, lower energy) → narrower spectrum

3.4 Conducted vs Radiated EMI Paths

EMI signals propagate through two primary mechanisms:

(a) Conducted paths – captured by Radio Frequency Current Transformer (RFCT) sensors

- Through stator windings
- Through cable shields
- Through grounding systems

(b) Radiated paths – captured by antennas

- Through air as electromagnetic waves
- Influenced by machine geometry

Both methodologies are used in rotating machines. The antennas work as sniffers to determine the approximate location of the EMI source, while the RFCTs are used to record the frequency data for reporting and trending.

3.5 Effect of Machine as a Transmission Network

A rotating machine cannot be treated as a lumped element at high frequencies.

Instead, it behaves as a distributed network with:

- Capacitance between windings and ground (C)
- Inductance of winding (L)
- Resistance of winding (R)

This forms a frequency-dependent transfer function for its Impedance (Z):

$$Z(f) = R + j\omega L + \frac{1}{j\omega C}$$

As a result:

- Different frequencies propagate differently
- Some frequencies are attenuated
- Others are amplified due to resonance

3.6 Resonance and Signal Distortion

When resonance occurs, EMI signals can be significantly amplified, and the measured amplitude may not represent actual discharge magnitude. Resonance occurs when:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

This explains:

- Why EMI amplitudes vary with sensor location
- Why absolute magnitude is unreliable
- Why trend analysis is preferred
- Why measurements must always be done in the same frequency bands

3.7 Measurement Interpretation – From Current to Measured Signal

EMI sensors such as RFCTs do not measure discharge current directly. Instead, they measure the high-frequency current flowing through the grounding or return paths. The measured voltage output of the sensor is related to the current by the transfer impedance of the sensor:

$$V(f) = Z_t(f) \cdot I(f)$$

where:

- $Z_t(f)$ = transfer impedance of the RFCT
- $I(f)$ = frequency component of current

Since both the machine and the measurement system exhibit frequency-dependent behaviour, the measured signal represents a filtered version of the original discharge event. As a result:

- Measured amplitude is not a direct measure of discharge magnitude
- Sensor location significantly affects measured signal
- Frequency content may be distorted due to propagation and resonance effects

This explains why EMI diagnostics relies on pattern recognition and trending rather than absolute magnitude comparison. This is different from IEC 60270 PD measurements, where results are in apparent charge (pC).

4. MEASUREMENT METHODOLOGY

4.1 Signal Acquisition in Rotating Machines

In practical applications, EMI signals are collected using 100 MHz RFCTs installed around either ground straps or power cables. This allows on-line non-invasive measurements without modification of the machine.

Fig. 1: Placement of RFCT to collect EMI data

4.2 Data Acquisition Method

Data is typically collected under normal operating conditions across a wide frequency spectrum. Careful selection of the time intervals is required, to ensure that data is captured when transient events are occurring. Advanced acquisition systems allow simultaneous capture of time-domain and frequency-domain signals.

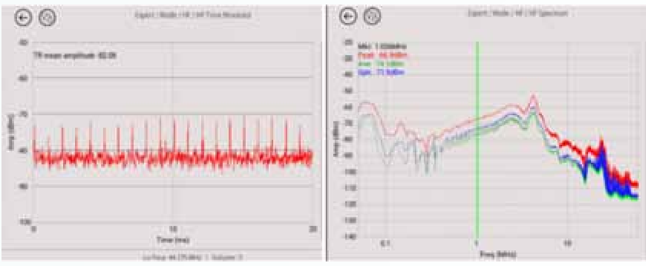


Fig. 2: Simultaneous time and frequency domain data

4.3 Measurement Best Practices

Each machine has a unique EMI fingerprint, which must be trended over time for accurate diagnostics. From field experience:

- Measurements should always be repeated from the same physical location
- Signal levels vary with machine loading conditions
- Baseline signatures should be established for each machine

4.4 Noise Mitigation

Industrial environments introduce significant electromagnetic noise from switching operations, communication systems, and external interference. Pattern recognition techniques are employed to distinguish genuine defects from noise.

5. SIGNAL ANALYSIS AND INTERPRETATION

A key insight from field measurements is that fault location/ type can be approximated from freq. distribution:

- Low to Mid Frequencies → Typically associated with winding-related issues

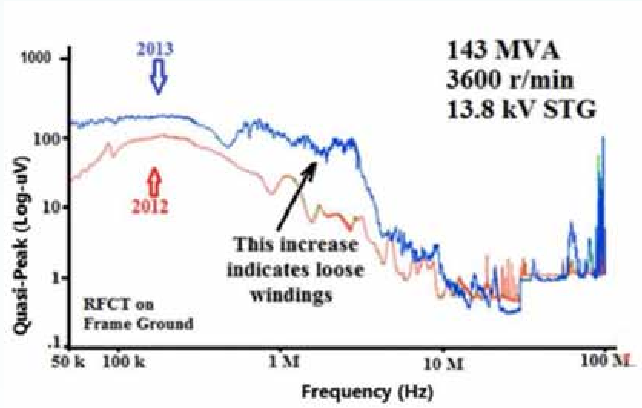


Fig. 3: Freq. spectrum showing loose windings

- High Frequencies → Usually linked to busbars, external disturbances, or connections

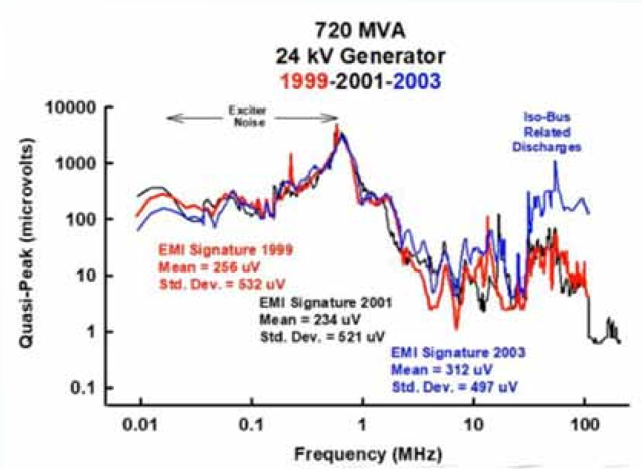


Fig. 4: Freq. spectrum showing bus related discharges

5.1 EMI Frequency Spectrum Analysis

Frequency-domain analysis of EMI signals provides insight into the energy distribution and nature of electrical discharges. Different defects produce different current waveforms, leading to distinct spectral characteristics:

Fault Type	Physical Mechanism	EMI Behaviour
Internal PD	Capacitive discharge in voids	Broadband, repetitive
Corona	Ionization in air	Narrowband, lower energy
Surface discharge	Leakage across contamination	Burst-type, mid-frequency clustering
Arcing	Sustained conduction path	Wideband, high energy, random

This frequency-based interpretation provides a first-level fault localization tool before detailed phase-resolved partial discharge (PRPD) or waveform analysis. By analyzing the frequency spectrum, it is possible to:

- Differentiate between discharge types
- Filter out external noise sources
- Identify dominant defect frequencies for targeted monitoring

PRPD is the method of plotting the amplitude of partial discharges vs. the phase angle (of the voltage) at which they occurred. It is the one of the most widely used methods of determining whether acquired high frequency signals are due to noise or discharges, and for determining the probable cause of the discharges.

5.2 Time-Domain Waveform Analysis

Time-domain analysis of EMI signals provides more insight into the nature and severity of insulation defects. Different faults produce distinct pulse shapes, repetition behaviour, and energy levels. These characteristics, when correlated with PRPD and frequency spectrum analysis, significantly improve diagnostic accuracy:

- Internal Partial Discharge: Fast rise time (nanoseconds), short duration pulses, damped oscillatory behaviour, repetitive pulses with similar magnitude.
- Corona Discharge: Low amplitude pulses, high repetition rate, uniform pulse shape, minimal oscillation.
- Surface Discharge: Irregular pulse shapes, varying amplitude, burst-type activity, moderate rise time with noise-like structure.
- Arcing: High amplitude pulses, random occurrence, wide pulse width variation, high energy impulsive spikes.

5.3 Fault Identification Matrix

A consolidated fault identification matrix based on PRPD patterns, frequency spectrum and time-domain waveform characteristics is presented in Table 1, enabling systematic classification of insulation defects.

Fault Type	Current Mechanism	PRPD Pattern	Frequency Spectrum	Time-domain Waveform	Field Interpretation
Internal PD	$\frac{\partial D}{\partial t}$	Symmetrical	Broadband (low–mid freq)	Damped pulses	Insulation voids in winding
Corona	$\frac{\partial D}{\partial t}$	Near voltage peaks	Narrowband	Small repetitive pulses	Air ionization
Surface Discharge	$\frac{\partial D}{\partial t} + J$ ($\frac{\partial D}{\partial t}$ is dominant)	Asymmetrical	Mid-frequency clustering	Irregular bursts	Contamination/ moisture
Arcing	$J + \frac{\partial D}{\partial t}$ (is J dominant)	Random	Wideband high energy	Large spikes	Loose connection/ severe fault
External Noise	-	No pattern	Discrete high-frequency peaks	Stable signals	Non-PD interference

Table 1: Fault Identification Matrix

6. APPLICATIONS

6.1 Rotating Machines (Motors and Generators)

- Detection of stator winding insulation degradation
- Detection of loose connections and arcing
- Detection of mechanical rubs
- Monitoring without the need for embedded sensors

6.2 Power Transformers

- Detection of insulation weaknesses and internal faults
- Identification of loose connections and localized heating

6.3 Switchgear and Cable Systems

- Detection of surface tracking and termination defects
- Assessment of insulation aging and contamination

7. CASE STUDIES

7.1 Loose cable in 205 MVA generator exciter

The following case study is adapted from published work by Timperley [1] and is included here to illustrate the application of EMI diagnostics to arcing in generator exciter circuits.

Two identical 205 MVA generators were tested as part of routine condition monitoring. Generator A exhibited stable and repeatable EMI signatures across the frequency spectrum. Generator B showed elevated signal levels, particularly in the lower frequency range of the measured spectrum.

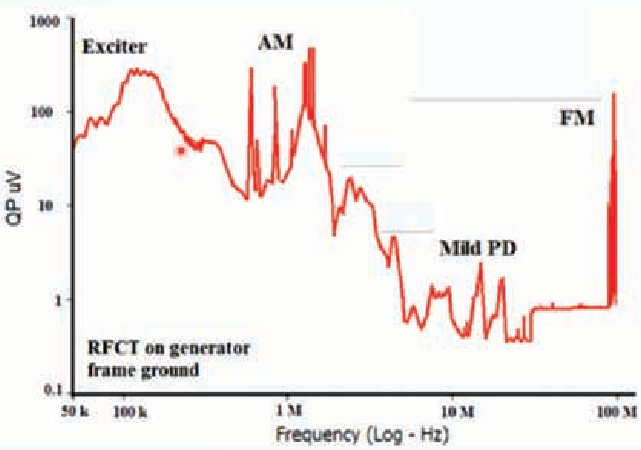
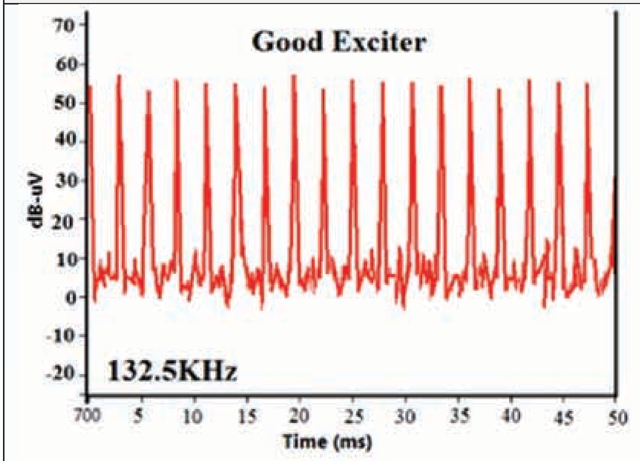


Fig. 5: Frequency spectrum showing elevated signals at lower frequency sweep

Time-domain waveform analysis revealed:

Generator A: Regular, periodic pulses corresponding to normal SCR firing activity within the exciter system.



Generator B: Irregular, high-amplitude impulsive signals with no consistent periodicity.

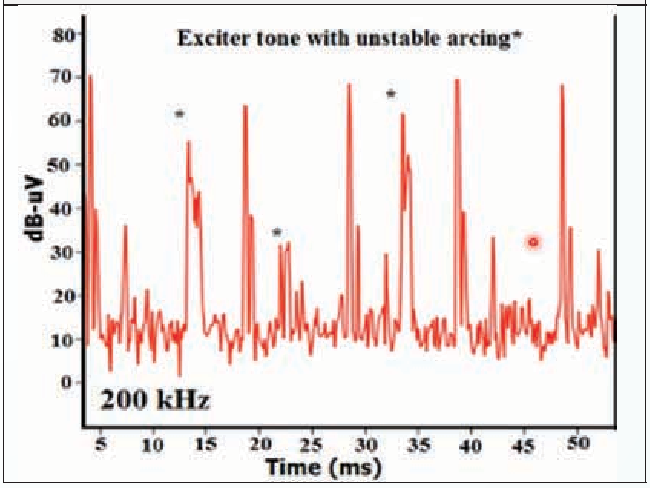


Fig. 6: Time waveforms showing regular & irregular pulses

Interpretation

The EMI behaviour observed in Generator B is characteristic of conduction-dominated discharge mechanisms:

- The high-amplitude, non-periodic pulses indicate intermittent conduction paths rather than capacitive discharge.
- The wider pulse widths indicate sustained current flow, consistent with arcing phenomena. Arcing introduces significant conduction current (), along with displacement

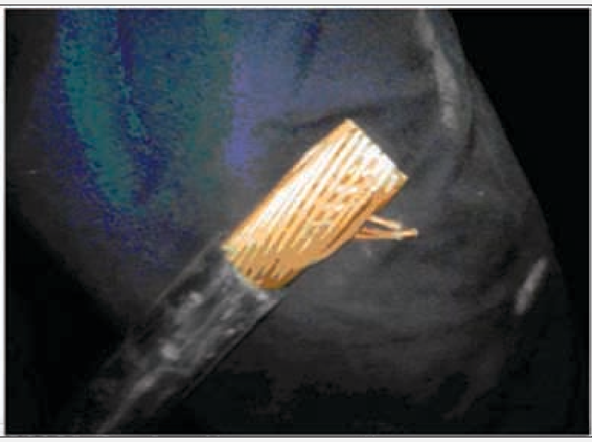
current components.

- In contrast, normal exciter operation (Generator A) produced repetitive and predictable waveforms.

Validation

Following EMI diagnosis, Generator B was inspected during a planned shutdown. One of the cables feeding the exciter was found to have a loose connection.

Generator B, healthy exciter connector



Generator B, loose exciter connector

Fig. 7: Generator B exciter connectors

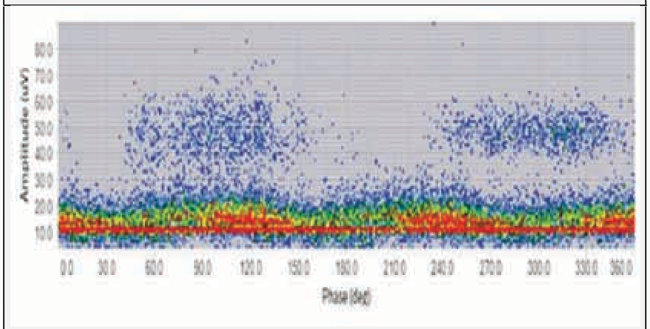
The observed EMI signatures correlated directly with the physical defect, confirming that:

- EMI diagnostics can effectively differentiate between normal operational signals and fault-induced emissions
- Arcing faults can be identified through waveform irregularity and broadband spectral characteristics

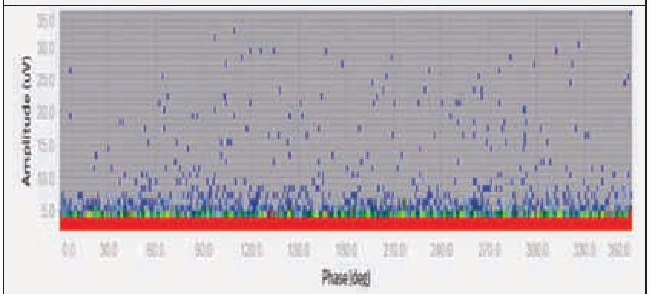
7.2 Insulation defect in 345 kW motor

EMI analysis was carried out on multiple induction motors as part of routine condition monitoring. Among the tested machines, the EMI signature of one motor exhibited a distinct pattern, as seen below:

Motor-1, 345 kW



Motor-2, 600 kW



Motor-3, 2080 kW

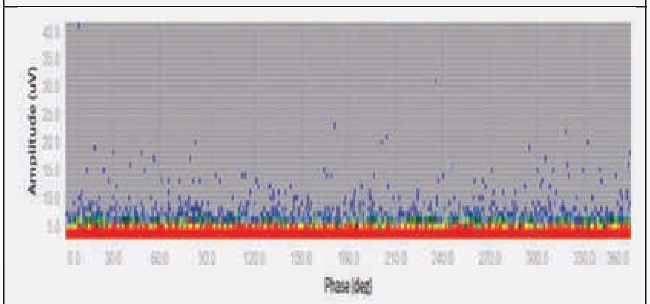


Fig. 8: EMI patterns on motors

Interpretation

The EMI characteristics observed in Motor-1 are indicative of insulation-related discharge activity:

- The presence of a repeatable phase pattern suggests phase-related discharge behaviour, consistent with internal insulation defects.
- The stability of the pattern suggests a persistent defect rather than transient noise.
- In contrast, Motors-2 and 3 exhibited no structured discharge activity, indicating healthy insulation condition.
- From an electromagnetic standpoint, insulation defects result in localized electric field intensification, leading to partial discharge activity dominated by displacement current.

Validation

To validate the EMI-based diagnosis and assess the severity of insulation degradation, the motors were de-energized, and tan delta & dielectric discharge tests were performed on them. The results are presented in Table 2:

Test	Motor-1, 345 kW	Motor-2, 600 kW	Motor-3, 2080 kW	Reco. Limit
Dielectric Discharge	5.3	0.7	0.3	< 2.0
Tan Delta	4.9%	0.9%	0.7%	< 1.5%
Tan Delta Tip-up	5.1%	0.6%	0.3%	< 1.0%
Capaci-tance Tip-up	11%	0.5%	0.3%	< 2.5%

Table 2: Off-line test results

The strong correlation between EMI, tan delta and dielectric discharge results confirms that EMI analysis can effectively differentiate between healthy and defective insulation conditions.

8. KEY PRACTICAL INSIGHTS

- On-line and non-intrusive testing
- No requirement for shutdown
- Applicable to assets without pre-installed sensors
- Each machine must be individually benchmarked
- Trending is more important than absolute values
- Frequency band analysis gives quick fault direction
- Reduced dependency on complex test setups

9. LIMITATIONS

- Sensitivity to external electromagnetic noise
- Requires expertise in signal interpretation
- Dependence on measurement setup and environment
- No existing standard

10. CONCLUSION

EMI diagnostics provides an additional diagnostic method for on-line condition monitoring of high-voltage rotating machines. The ability to detect faults such as insulation degradation, arcing, loose connections and rubs without requiring pre-installed sensors makes it especially valuable for existing assets. It should be noted that some of these may not be readily detected by conventional PD measurements, which is an added benefit.

Field case studies demonstrate that EMI analysis can reliably detect incipient defects, which can then be further diagnosed using standard off-line test techniques. This approach significantly enhances reliability, reduces downtime, and enables predictive maintenance in modern power systems.

ABOUT THE AUTHORS

Pavankumar Jaiswal is a Manager – Technical at Diagnostic Technologies India Pvt. Ltd., Mumbai. He holds a Bachelor's degree in Electrical Engineering and has over 9 years of experience in condition monitoring and diagnostic testing of electrical power equipment.

He has been involved in testing, analysis, and troubleshooting of motors, generators, transformers, cables, and switchgear across a range of industries. His experience includes on-site diagnostics, report analysis, commissioning support, and root cause failure analysis, with assignments carried out in India and overseas.

His work includes the application of techniques such as partial discharge, tan delta, LIRA, SFRA/DFRA, and EMI-based diagnostics, along with supporting client training and technical discussions.

Aditya Korde is the Managing Director of Diagnostic Technologies India Pvt. Ltd. and Diagnostic Technologies ME LLC. He holds a Bachelor's degree in Electrical Engineering and an MBA.

He has over 32 years of experience in electrical diagnostics, testing, and condition assessment of motors, generators, transformers, and cables. His work includes testing, repair, and overhauls of large rotating machines up to 300 MW, along with diagnostic testing across multiple industries in India and internationally.

He has been involved in the application of diagnostic techniques such as Electrical Signature Analysis, Acoustic Emission, Partial Discharge, and dielectric testing, and has contributed to commissioning and training activities for various diagnostic systems. He regularly participates in industry seminars and training programs related to condition monitoring of electrical equipment.

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AUTHORS BIODATA

Name	PAVANKUMAR JAISWAL
Date of Birth	05-10-1993
Qualification	BE (Electrical)
Designation	Manager – Technical
Present Organization	Diagnostic Technologies India Pvt. Ltd.
Field of Expertise	Condition monitoring and diagnostic testing
Landline /Mobile No.	+91 83568 36143
Email	pavan.jaiswal@diatech.in
Brief Profile (in 200 Words)	An electrical engineer with over 9 years of experience in condition monitoring and diagnostic testing of electrical power equipment. Involved in testing, analysis, and troubleshooting of motors, generators, transformers, cables, and switchgear across a range of industries. Experiences include on-site diagnostics, report analysis, commissioning support, and root cause failure analysis, with assignments carried out in India and overseas. Work includes the application of techniques such as partial discharge, tan delta, LIRA, SFRA/DFRA, and EMI-based diagnostics, along with supporting client training and technical discussions.

AUTHORS BIODATA

Name	ADITYA KORDE
Date of Birth	31-10-1971
Qualification	BE (Electrical), MBA
Designation	Managing Director
Present Organization	Diagnostic Technologies India Pvt. Ltd.
Field of Expertise	Overhauling, repair, condition monitoring and diagnostics, specializing in multi-technology correlation (MCSA, PD, vibration, and EMI) for rotating electrical assets.
Landline /Mobile No.	+91 98692 42761
Email	aditya.korde@diatech.in
Brief Profile (in 200 Words)	Aditya Korde began his career hands-on in the workshop, focusing on the overhauling and repair of large motors and generators up to 300 MW - operations he still actively oversees today. Over the past 30 years, he has evaluated more than 40,000 rotating machines globally. His core focus is the practical cross-validation of electrical signature analysis (ESA), partial discharge (PD), and vibration data - expertise that has led him to deliver specialized technical training for international companies like Framatome, Monitra, and b2HV. He also has extensive experience on diagnostic testing and residual life assessment of high voltage cables & transformers. His paper at ELROMA 2026 focuses on the application of EMI diagnostics, demonstrating how high-frequency measurements can be integrated with established testing methods to improve fault-detection accuracy in rotating electrical assets.