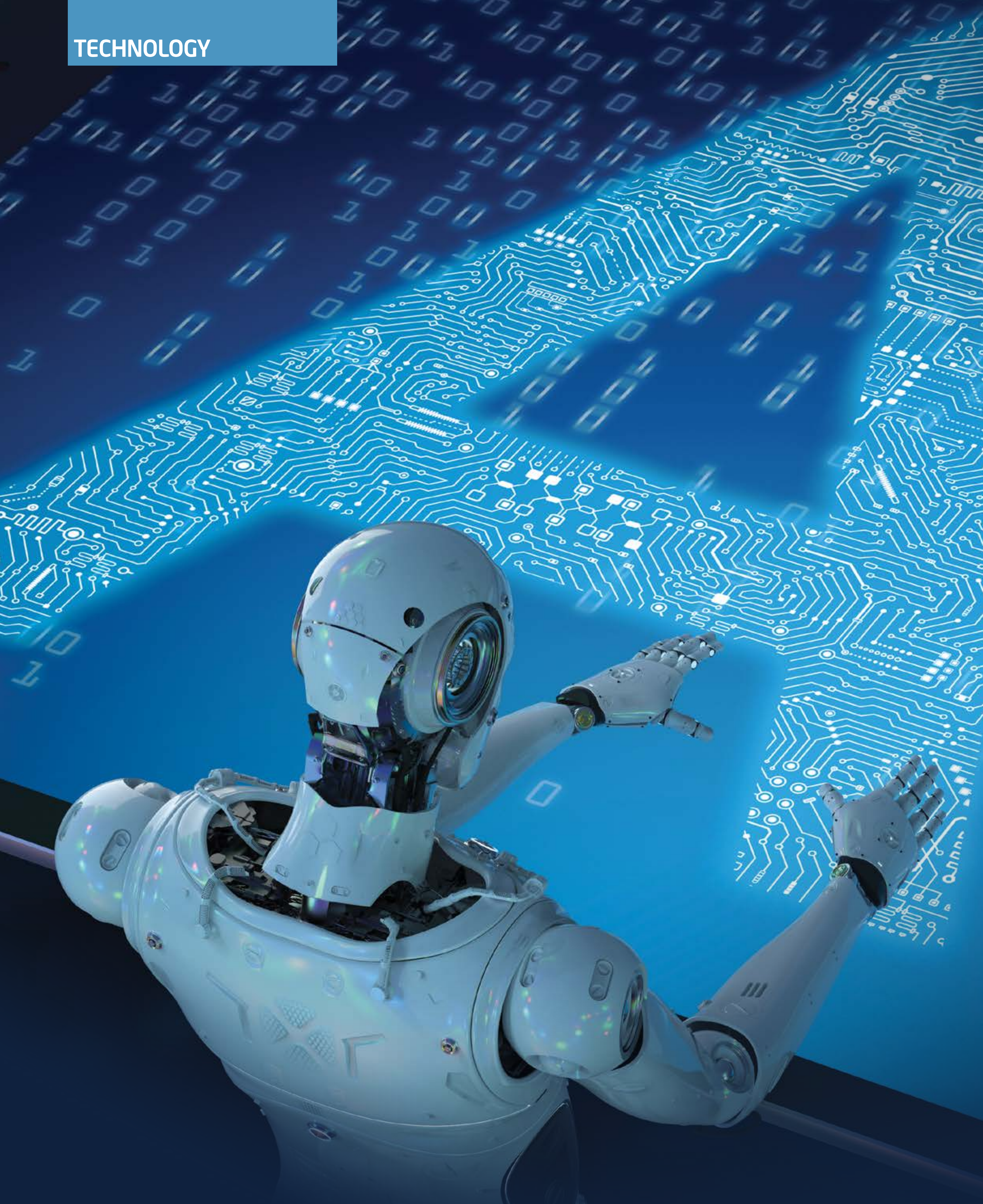

**The electrical power grid and the apparatus that support it are subject to continuous advancements in voltage and insulation levels, power throughput, efficiency, and economies of scale**

# Advanced online electrical testing in real time aided by electromagnetic signature analysis (EMSA) and artificial intelligence (AI) technology

## Introduction

Since its inception in the late 19th century, the electrical power grid and the apparatus that support it have experienced continuous advancements in voltage and insulation levels, power throughput, efficiency, and economies of scale. Yet throughout this period, the methods of dielectric testing have remained largely static and relatively unchanged. In recent years, however, the advancement of complex sensor technology, powerful computers, telecommunications, the internet, and Artificial Intelligence (AI) have set the stage for a quantum leap forward in the electrical testing of large power apparatus. A radical form of electrical testing has been under development for several decades and has proven itself as a welcome and worthy platform for advanced electrical system diagnostics. This testing is known by the acronym EMSA, which is the shortened version of Electromagnetic Signature Analysis. EMSA testing represents a major breakthrough in the field of electrical apparatus testing, as it is performed at power, with the apparatus or system undergoing testing remaining fully energized and loaded. Electrical system testing, while fully energized, represents a radical step-change in technological advancement, and it yields major gains in personnel safety, strategic operations, budgeting, forecasting, outage planning or outage deferment, and risk / reliability maximization. The availability of extremely powerful computing capabilities, high-bandwidth data transmission, and artificial intelligence allows for massive data set streaming and analysis in real-time, resulting in the ability to instantly monitor and analyze complex electrical apparatus. This radical improvement in testing and monitoring methodology allows for instant real-time analysis and notification of system anomalies and initiating faults long before they become a major concern for the owner / operator of the asset in question. Online EMSA testing represents a paradigm shift in how electrical testing will be performed in the future as it becomes adopted globally and accepted as a superior testing technology.

**The commercialization of EMSA has taken decades of dedicated engineering effort to fully develop this advanced technology for extremely accurate use in high-voltage electrical apparatus testing applications**

The commercialization of EMSA has taken decades of dedicated engineering effort to fully develop this advanced technology for extremely accurate use in high-voltage electrical apparatus testing applications. EMSA is the foundation of the fourth generation of electrical equipment testing and maintenance philosophy, which we identify as "knowledge-based maintenance." Another term used to describe this advanced approach is "actionable intelligence" necessary for strategic maintenance and operations.

The application of electromagnetic signature analysis technology for testing of high voltage electrical apparatus is performed as an online, non-invasive test that can detect a wide variety of defects in generators, bus systems, transformers, motors, switchgear, switchyards, and associated electrical system components. Trending data is not required, and maintenance recommendations can be provided on the very first test. EMSA data collection follows the international standard CISPR 16, which defines the characteristics and performance of equipment for the measurement of radio disturbance voltages and currents in the frequency range of 9 kHz to 1 GHz. The test equipment is very sensitive, and measurement accuracy is traceable to national standards. Historically speaking, the standard EMSA test is generally applied as a one-time test, typically performed on an annual basis. That method is now being superseded by full-time constant monitoring.

The development of a full-time electromagnetic signature analysis system has evolved directly out of the work and advancements that have been compiled over the past several decades doing EMSA testing. A vast repository of data has been collected and mined to identify and catalog a library of over 75 unique pre-failure conditions. This valuable information is used to assess the condition of electrical systems and apparatus and to form strategic knowledge-based operations and maintenance action plans.

The fulltime monitoring system contains much of the same equipment that is used when performing standard EMSA testing: namely, split-core current transformers for signal acquisition; a System Command Module (SCM) to receive and process the real-time data; and custom data analytics software called EMSA Diagnostics Software (EDS) for data analysis. The key difference between standard EMSA testing and the constant monitoring system is the frequency of testing. The standard EMSA test is a significant and vast improvement over any other testing available in the world today, has no rival, and is generally performed once per year. The constant monitoring system takes EMSA testing to a whole new level, and it is just what the name implies: standing watch, full-time, all the time, day or night, year-round. The equipment is permanently installed at the site, and all data is collected, processed and uploaded to the cloud in real time. The data is then processed for transmission to a Remote Command Center (RCC) for analysis, alarming when established system operating threshold parameters are met or exceeded. All data transmission is highly encrypted for total system security. The constant monitoring system has its own modem and communicates with the RCC using its own equipment and therefore does not need to piggyback on the host client's internet / intranet. This independent operation provides another measure of security in the sense that the systems cannot be hacked and then adversely affect the client systems.

## EMSA testing methodology

Electromagnetic Signature Analysis is a precise frequency domain measurement and identification of radio frequency energy that results from electrical partial discharge and arcing associated with system defects. EMSA data is collected from the placement of a single split core radio frequency current transformer (RFCT) around the power conduit, safety ground or neutral lead of the component being tested. No hot connection is required to any energized conductor, and no signals are introduced into the electrical system, making this an inherently safe testing process. The acquired radio frequency spectrum, or EMSA signature, is unique for each physical location, each apparatus, and each defect present within the electrical system.

EMSA diagnostics measure a broad spectrum of radio frequencies to allow the EMSA engineer to view various patterns at each frequency, including but not limited to corona, gap discharges, random noise and arcing. The first three are types of partial discharge, each with a unique pattern resulting from the specific defect or deterioration mechanism. The fourth pattern is arcing and is not measured by Partial Discharge Analysis (PDA) techniques. Arcing has a current flow and, by definition, is not a partial discharge. Arcing may be produced by a wide variety of mechanical defects such as a wiped bearing, loose electrical connections, transformer internal defects, isophase bus cracking, stator winding insulation failure, or broken rotor bars in an induction motor. Signals from radio stations and transients from power electronics are also measured and identified.

The levels of electromagnetic signal output are determined by the software-driven algorithms to match the Quasi-Peak (QP) Detector's (electrical signal analysis measurement device) outputs as specified in the CISPR standard. Comparison between assets is improved by calculating both the mean and standard deviation of the QP levels.

In the event that the EMSA testing reveals any signals that indicate a potential problem, the EMSA engineer analyzes the specific signals in detail to assess the issue and the region of the apparatus causing the problem. The EMSA engineer will then walk the system down using a highly sensitive handheld device to precisely identify the location of a problem. Higher values indicate stronger PD and arcing at the source. Trending these values is a valuable methodology used to detect minor changes over the various tests over time.

EMSA diagnostics have been successfully performed on high voltage electric power systems since 1980. EMSA technology has been proven with over 10,000 successful field tests on more than 500 different designs with over 75 types of defects and conditions identified, catalogued, and verified. Countless hidden defects and ongoing issues have been identified on operating apparatus that would have otherwise gone unnoticed. Clients avoid preventable disasters and catastrophic failures of their valuable electrical assets with this advanced critical technology.

## Constant monitoring technology

The hardware and software are constantly monitoring the system(s) to which they are assigned. Suppose the monitoring system detects a new anomaly that is deemed significant (e.g., a signal that is outside of established parameters for normal operation). In that case, the system will issue an alert indicating that is immediately exported to the Remote Command Center (RCC) via the cloud and is analyzed by qualified professional staff at the RCC and / or at any other location around the world. The anomaly is observed in real-time and evaluated. If the anomaly appears to indicate a potential problem, the engineer will analyze the signal and notify the client immediately and discuss the nature and severity of the anomaly. If the anomaly appears significant or critical, a walkdown of the equipment is recommended and performed at the client's site in order to walk the system down with a highly sensitive handheld electromagnetic measuring device to measure the radiated EM activity that is detected by the constant monitoring system. This process is used in conjunction with the constant monitoring system to further identify and pinpoint each defect location. This handheld device measures the EMSA signals radiated from each component or system defect and allows an EMSA engineer to listen to the radio noise generated from these defects to determine their relevance and precise location.

## How EMSA and constant monitoring systems work

The EMSA testing system and the constant monitoring system are, in essence, very sophisticated electrical signal analysis systems consisting of proprietary hardware, software, and data analytics.

**Electromagnetic Signature Analysis is a precise frequency domain measurement and identification of radio frequency energy that results from electrical partial discharge and arcing associated with system defects**

The EMSA test system and the constant monitoring system both intercept signals from all types of high-voltage electrical apparatus, including motors, generators, transformers, isophase bus, circuit breakers, switchgear, and other similar equipment.

The signals are always present during operations. A device called a split-core Radio Frequency Current Transformer (RFCT) is applied to capture the signals, as shown in Figure A.

This current transformer is designed to open to facilitate placement around electrical power conduits, neutral wires, ground bus, or other similar associated components (Figure B). The RFCT is then closed over the conduit or other component. The signals that are passing through the component are intercepted through induction.

A shielded triaxial cable is used to take the signals from the RFCT to the System Command Module (SCM). The signals are processed and then analyzed on a personal computer in the field in the case of EMSA testing. The setup for EMSA testing is shown in Figure C. The yellow-colored device is a small handheld portable receiver for detecting electromagnetic interference in the apparatus being tested. This receiver (Figure D) is used to precisely locate the area of an apparatus that is exhibiting a problem by capturing radiated signals through propagation.

A shielded coaxial cable is used to take the signals from the RFCT to the System Command Module (SCM). This SCM contains a very powerful computer contained in a milled anodized aluminum housing. The housing is roughly the size of a personal laptop computer and also contains a communications modem.

**The EMSA testing system and the constant monitoring system are, in essence, very sophisticated electrical signal analysis systems consisting of proprietary hardware, software, and data analytics**


Figure A: RF current probe

**Installing a monitoring system that identifies trouble in the form of arcing and partial discharge while at powered operations is a huge step forward, and the ability to intercept faults and catastrophic failures is a game changer**

The signals are processed in the field and exported via the communications modem through data centers and into the cloud. The data is immediately received at the RCC but can also be accessed anywhere in the world for immediate analysis by a qualified EMSA engineer.

The installation of a full-time monitoring system that enables the identification of troubles in the form of arcing and partial discharge while at powered operations is a huge step forward in the industry. The ability to intercept faults and catastrophic failures is a game changer. This powerful real-time system analysis and fault detecting capability have never before been available. The advent of extremely powerful computers and high-speed data transmittal makes it possible. The development of the constant monitoring system presents a technology that forms the foundation for "knowledge-based" operations and strategic maintenance plans. The use of a constant monitoring system provides the asset owner with "actionable intelligence", which enables strategic planning for maintenance and reliable operations.

The use of a powerful EMSA based constant monitoring system, utilizing a full-time, around-the-clock monitoring technology, is at the very forefront of energized,


Figure B: Radio Frequency Current Transformer (RFCT)

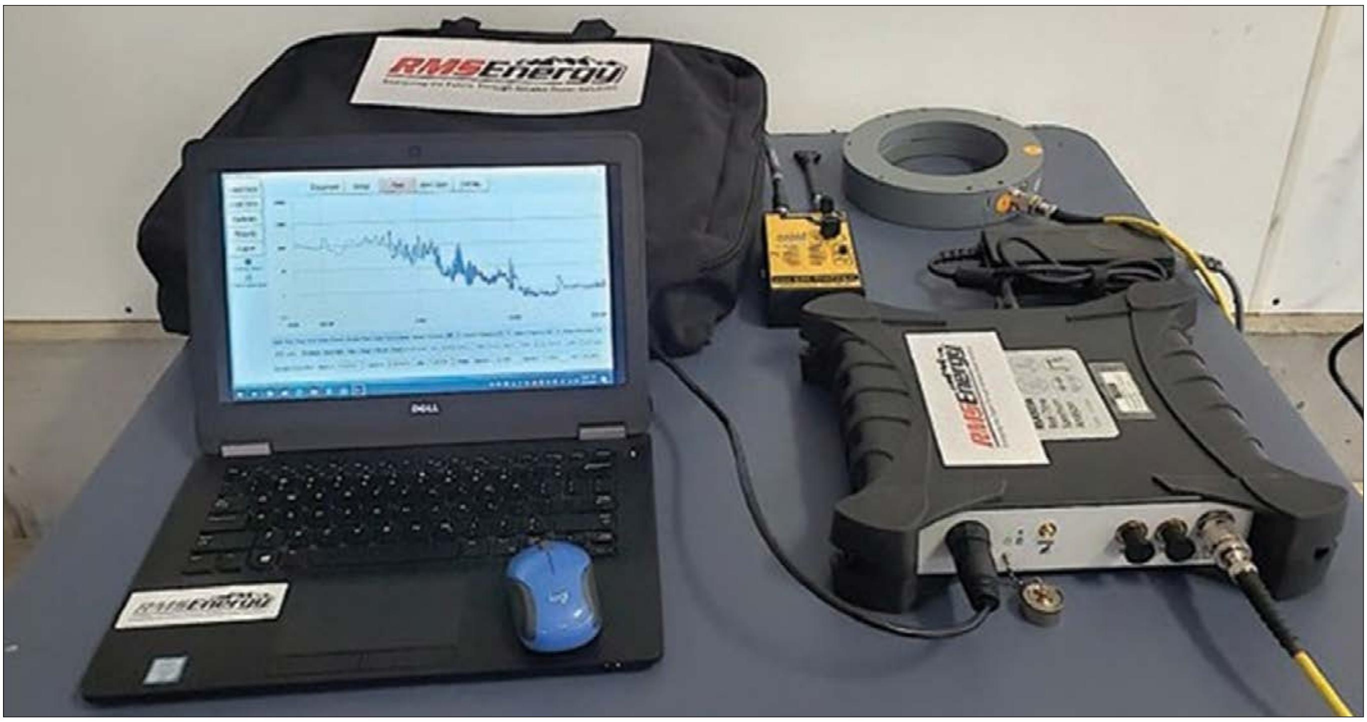

Figure C: Example EMSA testing set up configuration


Figure D: Handheld receiver

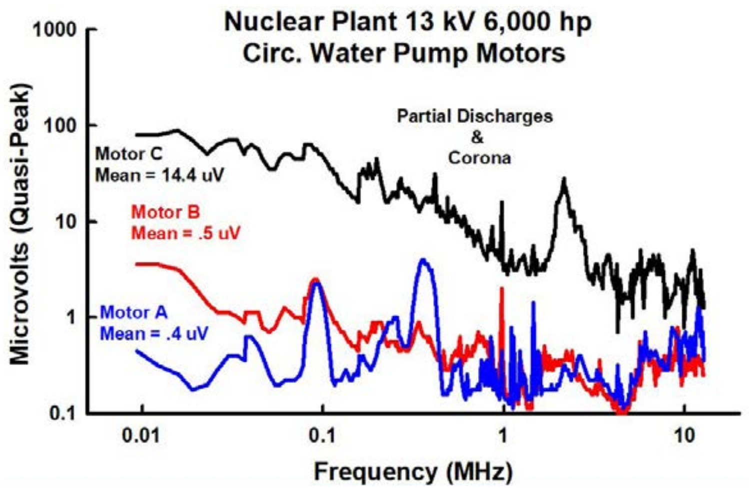


Figure E: Example of typical signal plot chart

high-voltage system testing, operations, and maintenance for electrical systems. The benefits of this advanced technology are very powerful and extremely cost-effective. These benefits can easily offset the associated cost of the monitoring systems, resulting in a zero-balance investment. Other benefits include the following:

**The fees associated with the constant, around-the-clock monitoring of critical energy assets represent a vast difference from any failure and are negligible in comparison**

### Safety

High voltage electrical systems are the backbone of virtually every facet of modern society. Mankind's harnessing of this awe-inspiring technology is an incredible feat, and it has allowed society to make giant strides in virtually millions of modern technologies. Yet it also brings challenges, and the most critical challenge is keeping electrical system employees safe. Any facility that contains and utilizes electrical equipment also carries with it an inherent risk. Small problems can become big problems if they go undetected, and the list of catastrophic electrical failures is a long one. A full-time monitoring system can detect very small problems long before they become a serious issues that can harm or kill plant personnel.

### Failure avoidance

This is the obvious but critical advantage of a constant full-time monitoring system. Electrical faults in large power apparatus are incredibly expensive. Stators, rotors, isophase bus, transformers, circuit breakers, cables, terminations, insulators, bearings, and a vast number of other components degrade over time. Sometimes these components fail prematurely due to manufacturing flaws or because of vibration, thermal stress, loading, insulation failure, dirt, grease, moisture, and a wide assortment of other related issues.

The vast majority of power plants around the world are insured through the market and carry a relatively high deductible, or conversely, are self-insured and carry the entire burden without market backing. In either case, a failure in a high-voltage asset generally costs anywhere from several hundred thousand dollars to hundreds of millions of dollars, depending on the asset, the degree of damages, and the duration of the outage. The fees associated with the constant, around-the-clock monitoring of these key assets represent a vast difference from any failure and pale in comparison. In fact, there really is no comparison. The development of constant monitoring technology has been designed to reduce costs and virtually pay for itself in many applications. The first and most recognizable of these cost-saving or cost-avoiding measures is the elimination of tremendously costly failures.

### Maintenance planning

All electrical power plants and substations require maintenance. But most maintenance conducted at these facilities is based upon outdated methods and data. The original maintenance recommended practices for electrical power apparatus were generated by electrical equipment manufacturers based on estimates, calculations, or equipment testing in a laboratory setting. This type of maintenance is known as Time Based Maintenance, or TBM. TBM represented the first generation of maintenance procedures for the electric power industry. However, TBM practices were found to be very subjective, quite costly, and often produced exactly the opposite results sought by the asset owners and operators. Faulty maintenance practices, mistakes made by technicians, and various other activities have caused problems where no problem previously existed. In addition, activities such as pulling a rotor out of a stator based on an estimated number can cost upwards of several million dollars, when often there was no need to perform such an expensive outage because nothing was wrong, or no maintenance was needed at that time. Without advanced technology such as EMSA and full-time monitoring, owners and operators of these expensive assets had little choice but to follow the original equipment manufacturers' recommendations.

**The next generation of maintenance that became an industry accepted practice is called Condition Based Maintenance**

The next generation of maintenance that became an industry accepted practice is called Condition Based Maintenance (CBM). CBM became popular due to many of the abovementioned issues, especially concerning unnecessary activities that ultimately caused failures. The industry has experienced countless failures caused by errors made during outages. CBM relies upon periodic testing, such as annual maintenance outages when equipment is taken offline and de-energized, while testing is performed in an attempt to learn if there are any degraded or failing conditions or on sensors that only provide an indication when something is significantly wrong and requires immediate attention. While condition-based maintenance is an improvement over time-based maintenance, it still has significant drawbacks. Annual testing leaves a large window of opportunity for serious problems to develop and go undetected, often resulting in costly, avoidable failures. CBM is also quite expensive because it requires costly outages in order to perform testing on equipment while it is de-energized. The cost of shutting down can dwarf the annual cost of installing full-time monitoring systems very easily. The cost of the offline testing can also easily cost more than the annual cost of the installed constant monitoring technology, which is there 24 hours per day, 365 days per year.

The most recent advancement and most valuable maintenance practice prior to the advent of full-time monitoring systems is called Predictive-Based Maintenance (PBM). The PBM form of advanced maintenance practices started to become a reality as advancements in computers, computer software, and sensors became available. The use of EMSA, partial discharge testing, acoustic diagnostics, thermography, dissolved gas analysis, and other similar technologies are good examples of predictive-based maintenance. EMSA is the best technology of any of these test methods because it is performed online and during powered operations. EMSA can detect trouble and problems that none of the other technologies are remotely capable of.

The development of an EMSA based full-time monitoring system is the fourth generation of maintenance practice which is termed "Knowledge-Based Maintenance" (KBM) to describe it. There are two critically important aspects of EMSA based full-time monitoring that also set it apart from all other forms of electrical testing currently available. These two aspects are conducted simultaneously, and they are as follows:

Performing constant monitoring and analysis of electrical anomalies, including arcing, partial discharge, corona, and insulation breakdown in real time, while the equipment and systems under test are fully energized during powered operation.

The importance of this methodology cannot be understated. The system detects even the most minute of anomalies as soon as they initiate. Electrical faults generally form and increase in severity over relatively long periods of time before an actual fault occurs. The system ensures that these anomalies are identified and addressed long before a dangerous and expensive fault develops.

The utilization of an EMSA based full-time monitoring system provides the basis for knowledge-based maintenance applications and critical decision making by providing "actionable intelligence" to asset owners and operators.

**The development of an EMSA based full-time monitoring system is the fourth generation of maintenance practice which is termed "Knowledge-Based Maintenance"**

The system allows for strategic planning to ensure the most cost-effective management of operation and maintenance activities. The cost savings realized through the use of strategic planning can be used to offset the cost of installed monitoring systems.

## Maintenance offsetting and deferment

The use of an EMSA based full-time monitoring system can be used to effectively offset or defer maintenance activities. For example, a power plant may have previously operated with a time-based maintenance cycle of shutting down annually in order to perform electrical system testing. A plant can make the decision to offset this maintenance to the next year based on the results of the real-time online testing provided by the monitoring system, and critical decisions such as plant shutdowns and maintenance should be developed in conjunction with a full suite of tests such as oil dissolved gas analysis in transformers, power factor, winding resistance and many other well-known tests. The savings gained from offsetting or deferring a maintenance outage can easily pay for the installation of a monitoring system. Conversely, suppose the same plant was scheduled for an upcoming maintenance outage and a significant problem developed beforehand. In that case, the monitoring system can provide the critical information necessary for plant management to evaluate the issue and make an informed decision to move the outage up to a convenient date or take an outage immediately if the detected incipient fault is severe and requires immediate attention.

## Operations

The safe and successful operation of an industrial or commercial facility is always a complex mission. The implementation of an EMSA-based monitoring system can provide the critical data needed to make important operational decisions. For example, a power plant may be called upon to significantly increase loading during a heat wave when the system demand dramatically increases. Constant monitoring and testing systems provide real-time data that can be evaluated by experts prior to making any large bulk operation actions. The overall goal is to serve as a client's expert consultant, partnering with them to provide real answers in real time for real-world applications.

### Insurance premium reduction

The installation of any system designed to increase the system's reliability while avoiding potential personnel injury is a valued technology. Applying the same technology to prevent other negative factors such as costly equipment failures, lengthy business interruptions, and lost business opportunities is always viewed as a very positive application of technology, and as such, demands consideration for insurance premium reductions. A successful reduction of insurance premiums can also help to offset the cost associated with system full-time monitoring.

### Artificial intelligence – 5th generation maintenance

The 5th generation of electrical apparatus testing and maintenance methodology incorporates Artificial Intelligence (AI) into the overall analysis. Much like the 5th generation of advanced military fighter aircraft that delivers capabilities far beyond anything ever seen in the skies before, the 5th generation of electrical apparatus and systems testing goes far beyond any previous technology available to the industry. The adaptation of AI to real-time systems analysis is made possible by major advancements in massive data set processing capabilities.

The use of AI for electrical monitoring, testing, and analysis represent a huge step forward in the advancement of the state-of-the-art in this field. Signals are analyzed in real time, and threshold setpoints are fine-tuned. The system learns about itself and its own operations. Deviations from the norm are evaluated, and the operational software is adjusted to incorporate the "rules" and operational characteristics of the system. In this manner, the system learns and becomes more accurate and more precise. This efficient operation allows for real-time data processing; "right now" system status; and critical "actionable intelligence" needed for strategic operations and maintenance decision making.

**The 5th generation of electrical apparatus testing and maintenance methodology incorporates Artificial Intelligence into the overall analysis**

**The use of an EMSA based full-time monitoring system can be used to effectively offset or defer maintenance activities**

An additional benefit of the use of AI is the supplementation of critical yet significantly unavailable skilled and technically qualified human resources. An unusual and unfortunate side effect of the computer technology rise in society that it has lured many promising students over to hardware and software studies, leaving a huge gap in qualified electrical power systems expertise. The application of AI into the complexities of electrical monitoring, testing, and analysis can greatly supplement these unavailable resources and can actually outperform them in many cases. AI-based machines and systems do not need to take breaks or days off, neither do they require sleep or take vacations. They are immune to fatigue, such as experienced in the field by an engineer who has been listening to audio signals all day. Machines do not get tired and remain accurate regardless of the circumstances. AI-based constant monitoring and testing in real time is the pinnacle of electrical system testing, and that day has finally arrived. The future of electrical systems monitoring, testing, operations, maintenance, safety, and profitability will most assuredly look markedly different in the very near future. It's an exciting time to be alive!


### Author

**Richard K. Ladroga**, P.E., is the Chief Technical Officer at RMS Energy. Richard is a licensed Professional Electrical Power Engineer with over 35 years of experience in the industry. He is a Senior Member of the IEEE; Member of the IEEE Power Engineering Society, IEEE Transformers Committee; IEEE Standards Association; Board Certified Diplomat of the National Academy of Forensic Engineers; and a Member of the National Society of Professional Engineers. He is the past Chairman of ANSI/IEEE Working Group C57.104, active on numerous other working groups and standards, and past Chairman of the Insulating Fluids Subcommittee. Prior to joining RMS Energy, Richard served as Chief Technical Officer at Charles Taylor Engineering Technical Services, where he provided technical expertise and leadership in performing complex forensic investigations and analyses. Richard's extensive engineering background also includes serving as Vice President, Global Strategic Development for Doble Engineering Corporation. Richard has published numerous papers and articles and has testified as an expert witness in state and federal courts. The breadth of the technical areas and sectors Richard has served include electric utilities, oil & gas (onshore & offshore), petrochemical, mining & ore production, pulp & paper, industrial, commercial, hospitals, universities, and all other large bulk users of electrical power. Richard has also served as a technical expert on numerous disaster events, including Hurricanes Katrina, Harvey, Irma, Maria, and human contact events (electrocutions), explosions, and fires. Richard earned his Bachelor of Science, Electrical Engineering, and Power Systems from Worcester Polytechnic Institute and also completed studies in Artificial Intelligence at Massachusetts Institute of Technology.