The first of three articles by IMCORP presenting a new technology that will redefine underground cable life-cycle management.

PREDICTIVE MAINTENANCE AND REMAINING USEFUL LIFE FOR UNDERGROUND CABLE SYSTEMS

When it comes to electric power distribution, the fundamental goals of today's electric utilities have not changed much in fifty years. They comprise a safer distribution system that poses minimal risks to the public and to utility workers, the reliable and stable delivery of power to critical, commercial, and residential customers, and economically sound business operations that meet both shareholder and ratepayer expectations.

The challenges to these goals, however, have grown significantly over the past decade. Increasingly intense and frequent weather events raise the threat of outages and environmental risks; the process of shifting from a centralized to decentralized grid to meet decarbonization mandates creates complexities; and the integration of renewable energy sources and the proliferation of electric vehicles are escalating the demands on an aging distribution grid. The resulting economic impacts to utilities range from high O&M costs to loss of revenue, the need for new investments in infrastructure, and, sometimes, class action lawsuits.

The replacement of overhead lines with underground power cable inherently mitigates some of these challenges by increasing the reliability, stability, safety, and, ultimately, resiliency of the grid. Underground power cable systems are less susceptible to windstorms, lightning, wildfires, ice and snowstorms, vehicle collisions, and other environmental hazards. This results in lower life cycle costs compared to overhead lines, where costly O&M restorations and preventive maintenance programs, such as pole inspections and vegetation management, drive long-term costs. Overall, an investment in underground systems pays off in improved safety, reliability, and economic return.

Although underground cable systems are much more reliable, they do occasionally fail. When they do, they can be more expensive than overhead lines to repair, as the failures can be more difficult to pinpoint and to remediate. Replacing failed underground cables can cost even more, as it can be time consuming. The replacement of direct buried cables, for example, can involve directional boring, a slow process that comes with costly risks of hitting other underground infrastructure. Underground cable replacement can take months or even years, depending on circuit mileage, design, and construction work. Hence, the potential for cable defects can certainly not be ignored. Left undetected, they will lead to power outages, and to health and safety risks to the public.

Photo: IMCORP

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Predictive tools combine innovative data analytics and IoT technologies to significantly improve maintenance efficiency, asset availability, reliability and lifetime value.

Cross-section of a typical solid dielectric cable

The Problem

The essential problem is that there is no visual inspection of underground cables. Although manufacturers' quality control standards for cable and accessory performance assume a life expectancy of approximately 40 years, that presumed reliability diminishes from factory to installation through shipping and handling and installation workmanship. Of the new cable systems IMCORP has commissioned, only around 60 percent met the manufacturers' quality standards. Approximately 23 percent had deficiencies primarily due to workmanship-related issues that were easy to remediate before the cables were put into service, while 17 percent had deficiencies involving underground issues, such as damaged cable or splices, that required additional rework to meet standards. As we look further down the life cycle at the aged cable systems (30+ years old) that IMCORP has tested, 43 percent on average met the factory-grade quality standards. Again, approximately 23 percent had deficiencies that were easily remediated, leaving 34 percent involving cable or splice rework. The testing and subsequent repair effectively reset the "life cycle clock," demonstrating that cables can last well beyond the 40-year life expectancy.

In sum, these results mean that a large percentage of cables—new and old—are perfectly fine. An additional percentage do not meet standards, but they may not all be at risk of failure anytime soon. In the millions of miles of cable already present in an evolving power grid, how do we know which cables meet manufacturers' specifications—or come close to meeting them—and can be safely left alone? How do we identify the cables not meeting the standards that can be locally repaired or, in some cases, require replacement? How do we ascertain what defects they have developed or how much longer they may last?

Underground cable system components are highly engineered and adhere to significant quality control standards during manufacturing. After shipping and installation, approximately only 60% of cable systems meet those quality control standards.

Although underground power cable systems are less susceptible to windstorms, lightning, wildfires, ice and snowstorms, vehicle collisions, and other environmental hazards, the ongoing health assessment is completely different than overhead lines.

The replacement of underground cable just because it is old is an expensive undertaking, costing as much as hundreds of dollars per foot and taking perhaps a day or more for a single cable to be replaced. Testing a foot of cable to find out whether it really needs to be replaced, on the other hand, carries a small fraction of that cost and can reach five to seven times the amount of cable that wholesale replacement does in the same amount of time. But repeating cable diagnostics or resetting the "life cycle clock" every so many years is not always economically or operationally efficient.

So, with only these options available to them—wholesale replacement or recurrent testing—how can utilities prioritize risks, establish budgets and financial forecasts, and maintain the safety and reliability of their underground systems? The answer is a technology that makes it possible to locate defects, diagnose them, and predict the remaining useful life in the relatively small percentage of cable that does not meet the manufacturers' quality control requirements.

To that end, IMCORP's objective has been to develop a proactive and predictive maintenance model for underground cable systems that provides visibility for future reliability and, ultimately, lower life cycle costs—a technology that costs less, takes less time, and is more accurate than training and using human analysts to analyze and interpret results from measurements taken in the field.

The Problem of Partial Discharge

According to the Institute of Electrical and Electronics Engineers (IEEE), over 90 percent of failures in underground cable systems are associated with partial discharge (PD), a phenomenon in which an electrical discharge does not completely bridge the gap between two electrodes. Underground cable and accessory manufacturers go to great lengths, from design to manufacturing and quality control, to eliminate any potential for PD in their products. Once these products get installed, however, PD inevitably is introduced into these cable systems. In these cases, PD slowly erodes the insulating material at the point of the defect until the cable eventually fails. The challenge to the utility is to find the instances in which PD is occurring and to determine the severity of the PD and the potential time to failure.

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Photo: IMCORP

When activated, PD produces high-frequency signals that are symptomatic of dielectric deterioration and, eventually, fault. At the factory, manufacturers are able to test cables and accessories for PD to high standards because they typically perform their measurements in multimillion-dollar electrically shielded rooms with metallic walls that block all electromagnetic interference from radio waves and other high-frequency signals that can obscure PD defect signals. These tests are performed on all new components at the manufacturing plant prior to shipping and installation, with results that must meet Insulated Cable Engineers Association (ICEA) standards for power cable and IEEE standards for separable connectors, joints, and terminations.

Detecting PD becomes more complicated once the cable is installed and then assembled with other cable system components. The only way to achieve a factory-comparable result in the field is to use a factory-grade technology, using 50/60Hz excitation voltage, high-efficiency sensors, and advanced digital signal processing capable of achieving a measuring sensitivity of at least 5 pico Coulomb. This allows identification of potential PD signals by human analysts, who "characterize" the signals—that is, they assign labels to the PD signals, including location, magnitude, and PD type, and determine how far they deviate from the manufacturers' standards and, therefore, how likely they are to lead to cable failure and how soon.

The interpretation of PD signals by human analysts is subjective and can vary from person to person, which makes the process time consuming, expensive, and difficult to scale. With the tremendous expansion of underground transmission and distribution cable systems in recent years, automation of this task has become of paramount necessity. To accomplish it, IMCORP has set out to develop a technology that uses deep learning to do what the human analysts do, faster, more reliably, and on a much larger scale.

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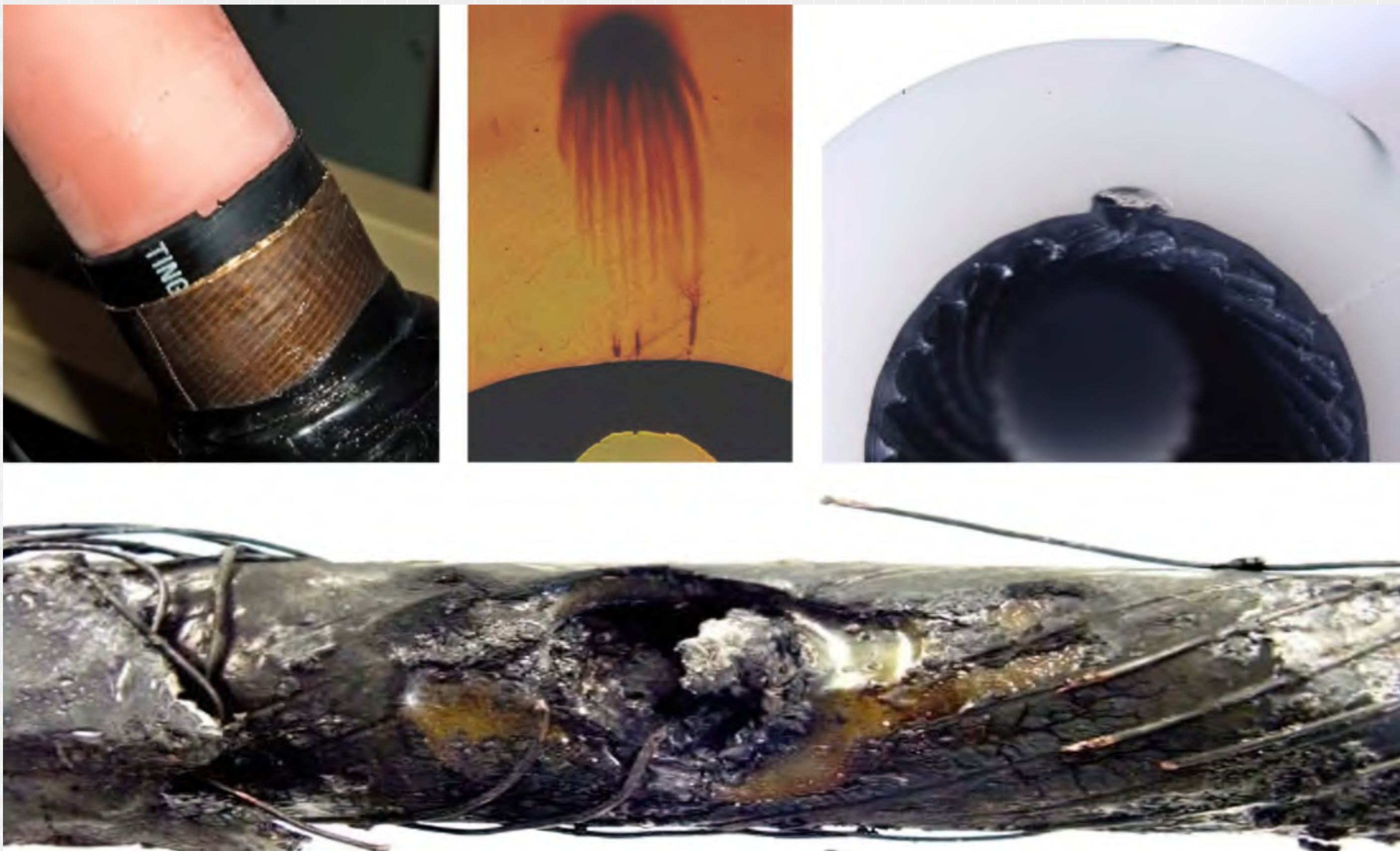


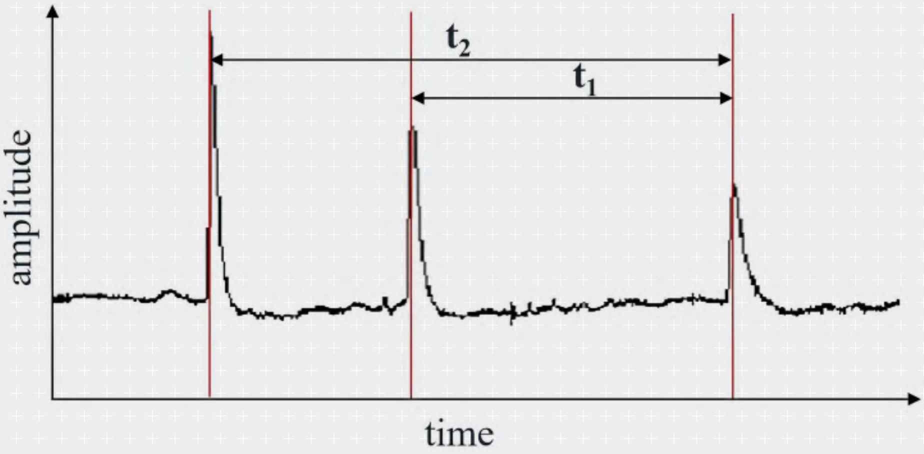
Typical PD-producing defects in underground power cables.
Top row: nonradial cut (left), electrical tree (center), and insulation void (right).
Bottom: cable failure (Photo courtesy of General Cable)

Deep Learning and PD Diagnosis

Machine learning is a branch of artificial intelligence (AI). It involves developing algorithms that allow computers to identify and learn from patterns in sample (training) data, based on which they can make predictions whose accuracy increases as they learn. The larger the base of training data, the greater the potential for the computer to find patterns and successfully learn from them. Two general types of machine learning exist: supervised and unsupervised learning. Supervised learning means the training data fed into the machine learning algorithms are supplemented by the correct outputs—called "labels"—from the analysis of those data. In IMCORP's case, the inputted data are the PD signals, and the labels are those that have been generated by the human experts analyzing them. With deep learning—a subset of machine learning—neural networks are created by IMCORP that simulate the behavior of the human brain doing PD characterization.

Over the past 25 years, IMCORP has tested over 250,000 cable systems and more than 300 million miles of underground cable, amassing a database comprising tens of millions of instances of PD labelled by human analysts. Using this database as sample data, the deep learning networks we are developing are learning to identify and characterize signals by "partial discharge" or "nonpartial discharge," PD location of origin, and PD defect type with ever greater precision and accuracy. Already, they are providing results that rival the accuracy of the human analysts in finding and diagnosing defects in underground cable systems—to date, an accuracy rate of 97 percent. They also provide a more consistent level of quality and a time savings of up to 500 percent in the analysis and interpretation of complex data sets.

The end goal is to be able to predict faults before they occur, rank all defects by severity and the risk they present, and determine what this means in terms of the remaining useful life of the cable.



Signal waveform of a positively identified PD

A Proactive, Predictive Maintenance Model

Locating and characterizing PD signals through automation is helpful for preventing cable failure, but it is only a first step toward developing a predictive maintenance system for underground asset management. Already, the neural network has learned so much about finding and assessing defects that we can rank them according to how severe they are and how likely they are to lead to cable failure. Eventually, it will be able to indicate how soon failure will happen—that is, it will predict the cable's remaining useful life. With this information, utilities will be able to prioritize preventive maintenance, cable repair, and cable replacement and will know exactly where, along the millions of miles of cables in their systems, to make available the materials, equipment, and human resources needed to carry out the work.

Ultimately, we want our deep learning networks to perform classifications in near-real-time so that technicians in the field can see the results soon after data are captured, with the benefit that cables already very close to failing may not get switched back into service. The end goal is to be able to predict faults before they occur, rank all defects by severity and the risk they present, and determine what this means in terms of the remaining useful life of the cable.

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Part 2 of the series will describe the underlying data IMCORP is using and how deep learning is being applied to develop its predictive models.