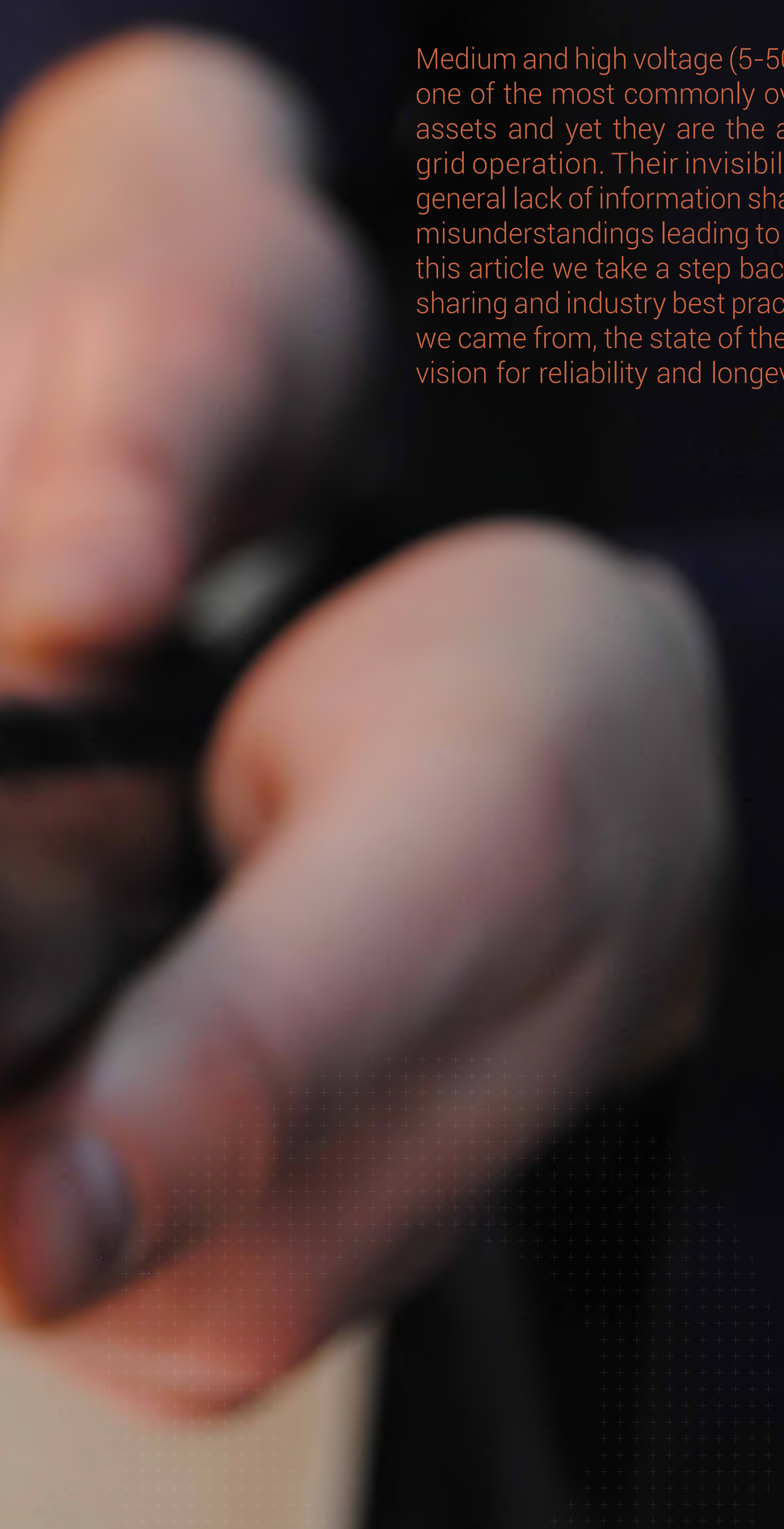
Power Cable Systems Reliability and Longevity: Past, Present and the Future

by **Ben Lanz**

Photo: IMCORP



Medium and high voltage (5-500 kV) cable systems are one of the most commonly overlooked power system assets and yet they are the arteries enabling reliable grid operation. Their invisibility has led to mystery, a general lack of information sharing, and in some cases, misunderstandings leading to suboptimal operation. In this article we take a step back to promote knowledge sharing and industry best practices by reviewing where we came from, the state of the art, and finally provide a vision for reliability and longevity beyond 100 years of service life.

With over 25 years in the power and energy industry, **Ben Lanz** is currently responsible for IMCORP's technical education and outreach efforts and is the Chairmen of the Board for the Power Delivery Intelligence Initiative (PDI2.org), a nonprofit organization dedicated to disseminating T&D best practices. He is a Senior Member of IEEE PES and ICC, and an active or voting member of IEEE DEIS and IAS, American Clean Power, CIGRE, NETA, and a founding member of Electric Power Reliability Alliance. He has served as Chair of IEEE technical committees associated with power system reliability, protection, and testing. He has published dozens of peer reviewed papers and technical conference contributions on the subjects of power system reliability, asset management and diagnostics and is frequently a guest speaker at numerous conferences and seminars.

The Past

Early power cable systems were made of oil impregnated paper insulation incased in a metal moisture barrier. The first cables date back to the early 1900s. Paper insulated lead covered (PILC) cable was a highly successful technology that enabled cable systems to reliably operate at medium and high voltage stress levels for more than 60 years. These cable systems had the benefit of a liquid dielectric (oil) that can move to void areas and provide a "self-healing" mechanism and paper tape layers that allowed technicians to create terminations and splices onsite.

Unfortunately, much of the knowledge and skill to install and maintain paper insulated systems has been lost to retirement and with environmental concerns with oil and lead, they are rapidly being replaced with modern plastic and rubber insulation systems. Operation and maintenance of paper insulated systems was largely based on material limitations and failure mechanisms. Many of the old systems had a maximum operating temperature in the range of 70°C and extreme temperatures could damage the paper irreparably. The most common failure mechanism was associated with conduction through either moisture ingress and ionic conduction or carbonized papers due to a localized lack of oil and partial discharge (PD, described in more detail below). Not surprisingly, the factory and field tests typically recommended were largely based on measurement techniques sensitive to conduction and insulation losses such as DC high potential (HIPOT) with leakage current or AC or very low frequency (VLF, 0.1 Hz) tangent delta (tan delta (TD)).

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PILC cable cross section

In the 1960s and 70s medium and high voltage solid dielectric (SD) insulation systems were developed including materials such as polyethylene (PE), ethylene propylene rubber (EPR), ethylene propylene diene monomer rubber (EPDM), and silicone rubber. These cable systems were expected to be cheaper and easier to install with less skilled labor; resistant to moisture, and have a 40-year life. The history of what actually happened with these early vintage SD cable systems is one of the major reasons underground is still a mystery to many, and the thought of mass adoption can generate fear of the unknown.

SD insulation fails due to an erosion process associated with a phenomenon called partial discharge (PD). PD is an electrical discharge (or "micro arcing") that does not completely bridge the insulation. In SD insulation, PD can arise from an extreme focus of electric stress, a lack of the appropriate solid insulation, or a combination of both. Early manufacturing and testing standards were inadequate to prevent subtle and often gross defects from leaving the factory.

The primary cause of cable system failure is human induced damage exacerbated by extreme transient voltage conditions.

In one case in the 1970s, Dr. Matthew Mashikian working for Detroit Edison research lab asked thirteen manufacturers to supply SD cable. Using a modified World War II radio, he performed 60 Hz PD tests and disqualified eleven of the thirteen suppliers. Clearly, cable 100% PD tested in the factory was insufficient for service in the early 1970s. It wasn't until manufacturers learned to improve materials, material handling and the extrusion process that SD cable system reliability started to dramatically improve. Manufacturers learned that even variations as small as a tenth of a millimeter in cable layer interfaces over decades of time can yield electrical stress concentrations, and in some rare circumstances, under transient voltage conditions yield local stresses 10 kV/mm or higher causing irreparable damage. 40 years later, we now know the problem with aged cable systems has its genesis with manufacturing or installation anomalies that, in some rare cases, can be exacerbated by secondary moisture concentration effects (e.g. water trees and halos).

However, until the early 2000s when the technology to reliably locate defects in the field could illuminate the physics behind cable failure mechanisms, many in the industry missed the origin story and were misdirected to focus on the secondary effects of moisture and conduction – primary issues with PILC cable! There were many efforts to develop tests to detect moisture and chemical solutions to react with it and dry the cable. While tests like tangent delta, dielectric spectroscopy and power factor could detect elevated moisture or conduction levels, they could not detect most defects or locate issues and often produced erroneous values. Chemical injection processes could help dry the cable insulation but could not fix any existing manufacturing or installation defects that still went on to fail cable. While some manufacturers solved their product quality issues sooner than others, by 1990 most of the improvements included in today's cable systems had been implemented and adopted by utility standards. For this reason, the industry typically sees a significant reliability improvement in cable systems installed after 1990.

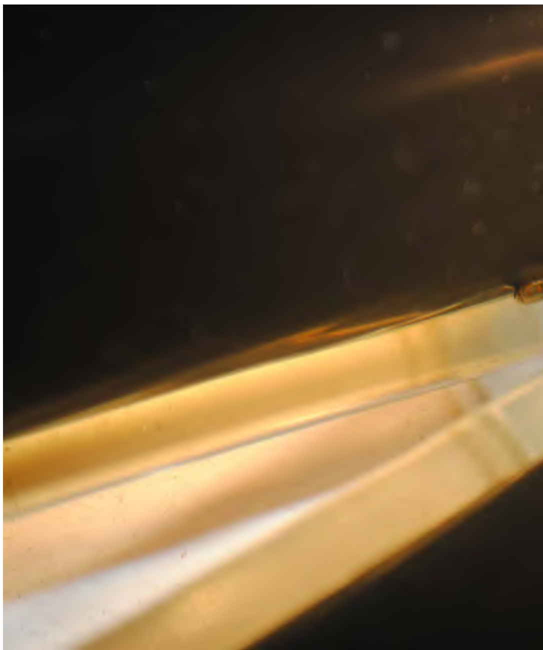

Photo: IMCORP

Common manufacturing defect:
Protrusion on the inner semiconducting layer of MV cable as seen through transparent insulation during a hot oil analysis

Today

According to one recent study, manufacturing issues constitute a minimum of 5% of cable insulation defects detected in new systems. This means approximately 95% of problems are caused by human intervention during installation. What have we learned and what can we do to avoid the issues of the past and enable cable systems to last longer? Studies show that the SD materials can perform reliably for over 100 years.

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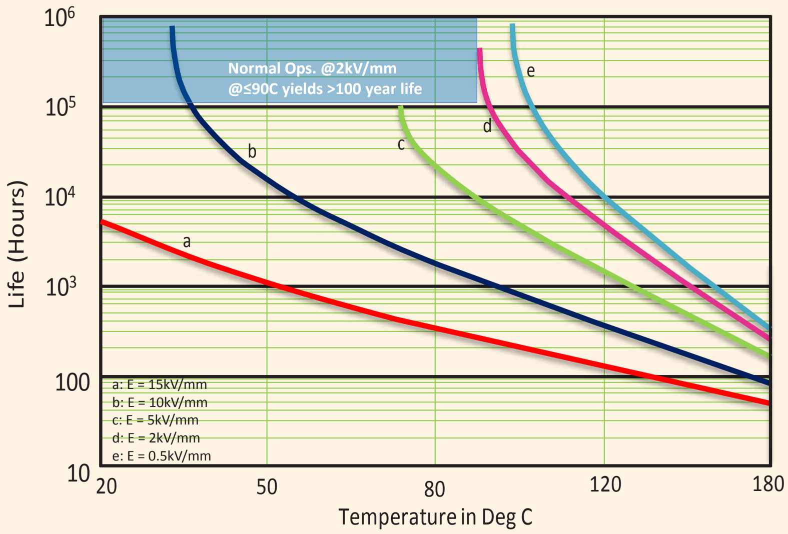
So why are cable systems failing today? On the basis of a study including field assessed meter-by-meter profiles of over 200,000 new and aged cable systems rated 5 to 500 kV and thousands of field and laboratory dissections, the primary cause of cable system failure is human induced damage exacerbated by extreme transient voltage conditions. Successive transients initialize PD in defects intermittently until the associated erosion process causes failure.



R. Gorur, M. Dyer, Saint, A Novel Approach for Prioritizing Maintenance of Underground Cables PSERC Report 2006

Cable under typical 2 kV/mm stress operated under 90°C lasts longer than 10^6 or 114 years

Common termination defect:
Jagged outer semiconducting layer cutback

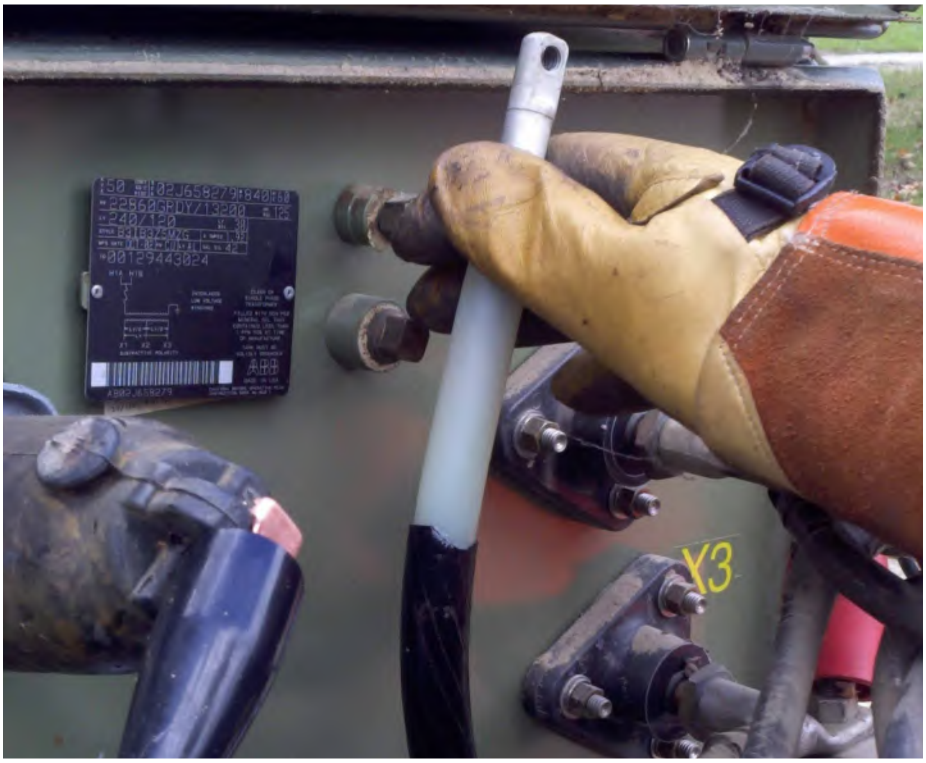


Photo: Wolv via Getting Images

Repeated field tests pinpointing the same defects over multiple years and subsequent laboratory dissections show manufacturing and installation defects often take years and sometimes decades to go to failure.

However, once an aged cable fails, studies show the fault location process, often including intentional voltage transients, creates new defects, thus fulfilling the commonly held belief that cables have a life shorter than 100 years.

So, how can we avoid this cycle of damaging cable systems and drive longevity? We need to avoid introducing defects and extreme voltage stress. How? Consider the following short list of current industry best practices:

- Specify accessory products that are easy to install with large tolerance for installer error
- Train installers to know what a defect looks like and how to fix when a defect is identified
- Commission cable systems with a test comparable to the cable and accessory manufacturers' standards (Overvoltage 50/60 Hz PD test with 5 pC sensitivity)
- Avoid overvoltage tests that do not measure the failure mechanism (PD)
- Ensure proper overvoltage protect (surge arresters) are installed at impedance transitions (overhead to underground transition, branch points, and end points)
- For critical or high ampacity circuits also consider using shear bolt connectors, inspect connector IR signatures under high load conditions, and use ultrasound to detect any significant arcing due to open air termination clearance issues.


General Cable

The Future

What will cable systems look like in the future? While we cannot predict the future, we can observe trends and extrapolate. Cable system technology has not dramatically changed in the last three decades and will not likely change much in the next decade. However, more and more power system owners are looking at the lifecycle costs of transmission and distribution systems and are choosing underground over overhead. Compared to overhead, underground is on the order of ten times safer and ten times more reliable, can last two to three times longer than wood supported systems, is far more resilient in the face of natural disasters, and the operating and maintenance costs are typically more than three times lower. In the future, where the upfront costs are reasonable, cable systems are likely to be selected as the "ultimate sustainability solution" for power delivery networks. Where feasible, cable systems will likely be directly buried to enable the best ampacity performance and the lowest upfront and operating and maintenance costs. High-cost duct and vaults systems have some of the highest maintenance costs and yet show no significant reliability improvement over directly buried systems.

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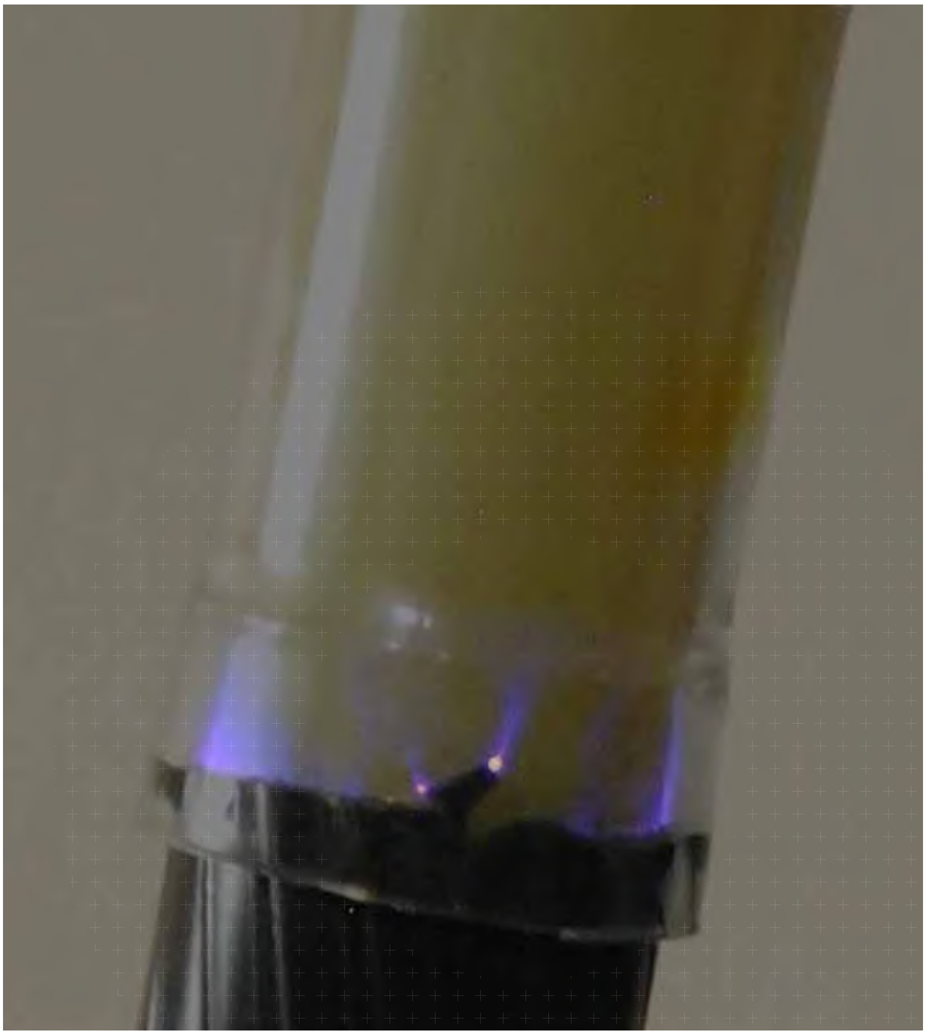
Where the industry will likely see great improvement is in grid reliability performance such as when cable owners take advantage of installer training coupled with effective commissioning tests (as mentioned above) to provide a feedback loop to improve craftwork and drive out operating and maintenance costs during the capital investment period (installation). Once a cable system is installed, the cable owner will only need to apply maintenance when an extreme event is detected. In the future, data analytics will utilize input from distributed sensors detecting extreme voltage and current events, and data from work orders which indicate potentially damaging mechanical events (such as repairs, relocations, and support structure failures) to drive work orders and direct technicians to re-baseline the cable system using the commissioning test and repair accordingly (see best practices mentioned above).



With modern cable systems properly specified, installed, commissioned, and protected from extreme operational events, the physics indicates we can expect them to last longer than 100 years.

Conclusion

The industry has come a long way from the days of the intensive skill needed to install PILC cable and the poor performance of early vintage solid dielectric systems. Systems are easier to install correctly and more reliable than ever before. We have learned the physics behind cable reliability and longevity, and we no longer need to guess at the failure mechanism. This means we can be much more efficient and precise with specifications avoiding costly partial solutions or risky, ineffective procedures. With modern cable systems properly specified, installed, commissioned, and protected from extreme operational events, the physics indicates we can expect them to last longer than 100 years.