

Cable Reliability In Collector System Operations

Failures are not only expensive to repair but can result in millions in lost revenue.

BY BRUCE BROUSSARD & SAMUEL MOSER

Unlike traditional power generating plants built around a few generating units with very high rating in a single location, windfarms derive their power from a multiplicity of small generators spread out over a large area.

The energy generated by each must be collected and channeled to a substation by means of an underground network of cables called a collector system, as illustrated in Figure 1. Owing to the relatively large separation between the generating units and the very large area covered by windfarm installations, typical underground cable collection/home-run feeder networks may measure several tens to well over 100 three-phase circuit miles.

Consequently, the reliability of such plants is strongly impacted by the reliability of their underground cable system. The availability of the units, in turn, is affected not only by the reliability of the cable system, but also by its layout. If a generator or a unit transformer with its associated switchgear fails, a power loss corresponding to the generator rating occurs.

However, when a fault occurs on a collector cable or a home-run feeder system, a large number of generators, depending on cable layout, may no longer be available. Ensuring a

high level of cable reliability is, therefore, essential to the economic operation of windfarms.

This article will discuss how to successfully prepare through system design and conduct commissioning tests for newly installed windfarm cable systems resulting in a more reliable underground cable collector network.

Cable system tests

The two general categories of commissioning tests available are:

- a withstand or high-potential (hipot) test; and
- a partial discharge test.

DC hipot testing is blind to most defects in cables with modern extruded insulation, such as crosslinked polyethylene (XLPE) and ethylene-propylene rubber (EPR), and, therefore, cannot provide a reasonable assessment of the cable system reliability. DC hipot is still mentioned in some standard specifications, but these outdated standards have been revised to exclude it or are in the process of being revised.

An alternative to DC is a hipot using very low frequency, such as 0.1 Hz. This form of hipot testing prescribes the application of a certain voltage for prescribed time duration. If the cable system does not

fail during this test, it is considered fit for service. Experience indicates that certain defective sites do fail during this test, but that other serious defects survive the test and pose a serious reliability issue during subsequent cable operation as they become further aggravated by the test.

A more viable alternative is to conduct a partial discharge (PD) testing. When a PD test is conducted at a reasonably elevated voltage and at a high level of sensitivity, it can detect and locate defects that are likely to cause a subsequent service outage. These can be repaired before placing the plant in service.

All modern extruded cables and their prefabricated accessories are subjected to PD tests at 60 Hz in the factory (refer to Application of IEEE standards section on page 87). A well-conceived and executed field PD test could duplicate the factory test at a reasonable voltage level to ensure that the cable and its accessories have been properly installed at the windfarm and that subsequent service outages are unlikely.

This article will briefly describe a PD test method utilizing 60 Hz, which has been successfully used in commissioning a dozen modern windfarms in North America and Europe. This testing procedure has

proven to be an excellent diagnostic tool to investigate unexpectedly high failure rates in the cable systems of installations which had not been commissioned by means of this PD test technology.

What is partial discharge?

A partial discharge is a small electric spark that occurs in defects in the insulation, or at interfaces or surfaces, or between a conductor and a floating metal component, if the electric field is higher than a certain threshold value.

Typical PD producing defects in new cables include cavities in the insulation or between insulation and shields, sharp protrusions of shield material into the insulation, nascent electrical trees initiated during previous tests that had not been detected and corrected, and

contaminants with sharp edges.

In accessories, PD can be initiated at the sites of voids, tool abrasion marks, cuts into the insulation, incorrect installation and other locations. After installation, the cable system is subjected not only to the normal steady-state operating voltage, but also to transient overvoltages due to switching and lightning. Each PD event associated with a defect can further aggravate the condition of the insulation. As this occurs frequently during service, the threshold voltage at which PD is initiated becomes gradually lower, thus exposing the cable system to the likelihood of more frequent discharges and, ultimately, failure.

Identifying and correcting these defect sites during a PD commissioning test is the best means available

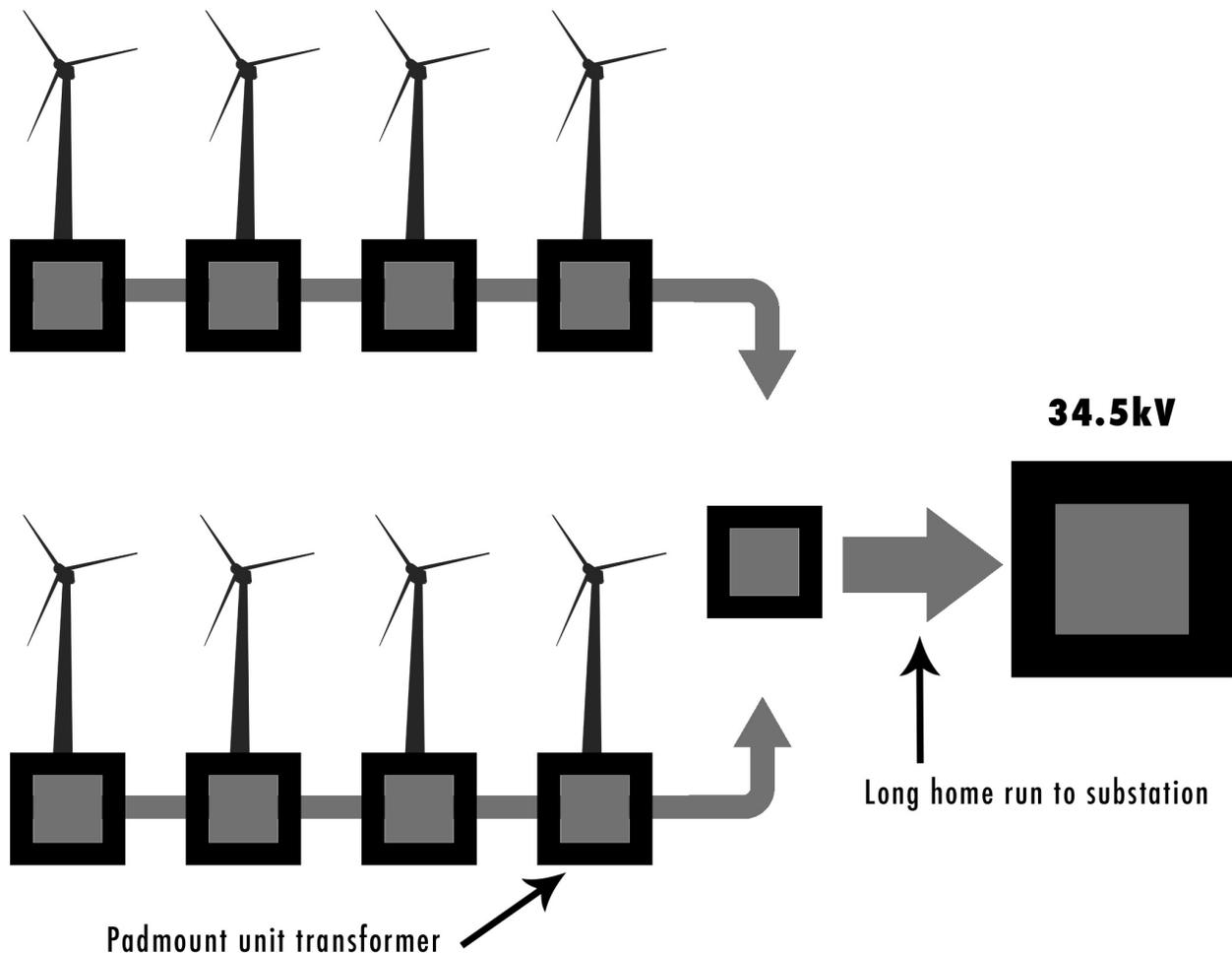
nowadays for ensuring high service reliability.

The anatomy of a PD test

The 60 Hz PD diagnostic method recommended for conducting commissioning tests on windfarm cable systems consists of the following major steps:

- Low voltage time-domain reflectometry (TDR) to characterize the cable system (length, location of splices, continuity and condition of screens and neutrals). A nominal 10 V, short duration pulse (20 to 500 nanosecond) is applied between conductor and neutral at one cable end while the remote cable end is left open. A reflectogram, such is obtained, where splice and any other shield anomalies are recorded as small reflected pulses.
- PD measurement calibration

Figure 1



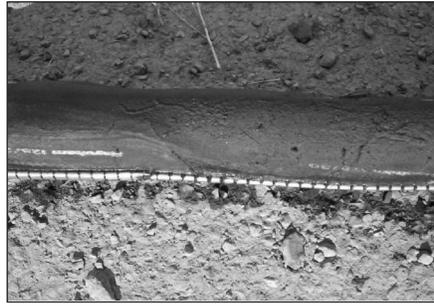


Figure 2. Partial discharge typically produces defects in the insulation of new cables and between a conductor and a floating metal component, if the electric field is higher than a certain threshold value.

Photos courtesy of IMCORP Partial Discharge Diagnostics.

and assessment of sensitivity after noise mitigation precautions are implemented. The magnitude of a PD pulse is measured in picocoulombs (pC). When measuring PD, pC is the amount of charge the PD emits during a discharge or spark. Injecting a pulse of a known pC value at the far end of the cable, the response is measured at the near end and a calibration constant is applied to make the reading equal the value of the injected signal. Next, from the near end, a 5 pC signal is injected.

If the reflection of this signal from the remote end is visible, after application of noise mitigation filters, the test sensitivity is said to be 5 pC or better. Otherwise, a 10 pC or higher pulse is applied until the reflection becomes discernible. This establishes the sensitivity threshold of the test.

- Continuous PD recording at several prescribed voltage levels up to twice the operating level. The duration of the test at a voltage level above normal operation is kept below 10 seconds. During this time, PD information spanning several cycles of the applied voltage are recorded. The short duration time of the test also reduces the amount of stress on the cable.

- Data analysis and recommendations. Appropriate noise mitigation means are applied to the raw data to minimize noise and enhance PD detection and location accuracies. Location, like in radar technology, is based on the principle of reflectometry, whereby the time elapsed between the arrival of

a PD signal and those of its reflections from cable ends determine the PD site location with an accuracy of better than ± 2 ft on a 1,000-ft-long cable section.

The analysis of the results are presented in the following forms, as illustrated in Figure 2:

- For each phase, a graph showing the cable position, including splice positions, and the voltage at which PD was detected;

- A histogram (with a superimposed TDR reflectogram) showing horizontally the cable position and vertically the number of times PD signals were detected at each site during an entire 60 Hz cycle; and

- A phase diagram showing the pC value of each PD pulse versus the phase angle of the 60 Hz voltage at which PD was generated. The information contained in these data, especially the phase diagram, allow the type (void or electrical tree) and severity of the PD activity to be assessed.

Design considerations

The cable system design impacts the ability to perform sensitive and meaningful PD tests. It also influences the reliability and availability of the generating plant.

As a PD pulse travels along the cable from its source to the cable ends, it gets attenuated – its height becoming shorter and its base wider. The PD signal is made up of a summation of signals with various frequencies.

One of the cable properties is that it attenuates these frequencies unequally, the highest frequencies dis-

appearing within a very short travel distance along the cable. The overall result is that small PD signals, after attenuation, may become smaller than the ambient noise and, therefore, impossible to detect. This directly impacts the PD test sensitivity.

The degree of attenuation caused by a cable depends on several factors, the most important among them, for XLPE cable, is the nature and configuration of the semiconducting screens, the type and size of concentric neutral conductors (if copper tape is utilized, the presence of corrosion between overlapping layers), the cable length, the number and characteristics of joints and the grounding (and cross-bonding method, if any).

Assuming that the semiconducting screen materials and thicknesses are standard, one would then concentrate on the other most important parameters, such as neutral type/size and cable length.

For instance, in order to achieve a sensitivity of 20 pC or better, the maximum cable section length may be in the order of 5,000 to 6,000 ft for a cable with 1/6 neutral, while a cable with full neutral may provide, under the same conditions, a sensitivity in the order of 10 pC for a cable in the range of 10,000 ft.

In a windfarm, cable segments between adjacent unit transformers may be, in general, less than 5,000 ft, but home-run feeders are known to be generally much longer. In order to reduce electromagnetically induced current in the neutrals, there may be a tendency to specify feeder cables of large conductor size with reduced neutral.

This condition exacerbates the sensitivity problem, unless the feeders are sectionalized. If such is the case, above-ground junction boxes provide easy access to the ends of cable sections for conducting sensitive PD testing and fault

location. The additional cost is more than justified for the added reliability and availability of the generating units.

Cable layout should be designed to allow isolating opening cable sections for testing or fault finding

with the minimum of loss of generation. If cross-bonding is utilized, care must be exercised not to cut into or leave a poorly shielded gap in the cable semiconducting screens.

Cross-bonding at junction points with dead-front terminations may cir-

Application Of IEEE Standards

The 1960s brought about the transition from PILC cables to extruded power cables. Although the cable changed, the traditional DC hipot testing procedure continued as the acceptance test of choice.

With the advancements in technology including digital signal processing (DSP), cable manufacturers utilized the PD lab tests to determine the quality of their product, it is possible for this technology to be applied to field applications.

This test will not only assess the cable insulation but also the accessories simultaneously. The new standards will show that the PD factory test for cable and components, which can be applied in the field after installation, is the most effective testing method to prevent services outages that are so costly in the wind generation industry.

The definition of a shielded power cable acceptance test according to IEEE 400, the IEEE Standard Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems, is the following:

- A field test made after cable system installation, including terminations (see IEEE 48) and joints (see IEEE 404), but before the cable system is placed in normal service. The test is intended to further detect installation damage and to show any gross defects or errors in installation of other system components.

Referring to the DC hipot testing, this test no longer fulfills IEEE 400's definition of an acceptance test for extruded cables. IEEE 400, Section 4.2, states:

Furthermore, from Bach's work in 1993, we know that even massive insulation defects in extruded dielectric insulation cannot be detected with DC at the recommended voltage levels.

As the experience and knowledge of extruded cables has grown and the old DC hipot is being replaced, the IEEE 400 guide covers many of the AC and VLF hipot techniques that are more effective than the DC test, but Section 7.4 also states the following:

- If the cable system can be tested in the field to show that its partial discharge level is comparable with that obtained in the factory tests on the cable and accessories, it is the most convincing evidence that the cable system is in excellent condition.

According to this statement, "the most convincing evidence that the cable system is in excellent condition" is a test that can best replicate the factory test. If you consider again that all of the cable and accessories have to pass IEEE standards for acceptable PD levels, this same test should be applied to the cables in the field where workmanship is the crucial factor in having a reliable cable and needs to be checked.

Each component of the collector system has acceptable PD levels that the manufacturer must achieve. These standards are stated at the end of this article. The standards can give you the baseline and confidence that, if your system after installation meets these acceptable PD levels, you will have the

most reliable collector system. It is important to indicate the pass/fail qualifications based on the IEEE standards for the components and cable that the contractor will have to achieve the high quality workmanship. A contractor generally offers a one year warranty on a system that should last 30 to 40 years.

This gap between the warranty and life expectancy is somewhat ludicrous, but can be reduced by performing factory comparable PD testing in the field to know or correct issues before there are major problems. This holds the parties responsible accountable. Generally, the contractor performs its own quality control test (most of the time a DC hipot) but with that comes a conflict-of-interest. Independent qualification and testing is still a problem in the industry today.

General Standards for MV Installations

IEEE 48 Terminations

No PD > or = 5 pC up to 1.5 U_o

IEEE 404 Joints

No PD > or = 3 pC up to 1.5 U_o

IEEE 386 Separable Connectors

No PD > or = 3 pC up to 1.3 U_o

ICEA S-94-649 MV Extruded Cable

No PD > or = 5 pC at < 4 U_o

If the cable system's PD levels after installation are comparable to the factory IEEE and ICEA standards, you can be confident that you have the most reliable collector system that is so crucial in wind power generation. 

cumvent this need. These cross-bonding areas could be temporarily bypassed during PD tests. In order to minimize the risk of poor heat transfer and cable overheating, it is imperative to perform thorough measurements of soil resistivity and a good balancing of the load on the various feeders. Installation of accessories, such as joints and terminations, may be less than ideal. A sensitive PD acceptance test should be able to identify any defective accessory before the plant is placed into service.

A case study

A large wind generation facility in the U.S. was averaging three failures

a month in 2003, with more than 40 collector system failures on its essential cable sections since the system went online in 2001.

The failures were costing the operations between \$30,000 to \$50,000 per failure, which resulted in millions of dollars in lost revenue. Offline, nondestructive 60 Hz partial discharge test were performed, which pinpointed defective joints and cables.

If left uncorrected, these would have resulted in short-term service failure. After the recommended repairs, the wind facility had zero failures in 2004 and only one failure up to September 2005 on all cable sections subjected to partial

discharge diagnostics. The preventive maintenance program success was found to have saved over \$5 million by preventing the service outages. **SVP**

Bruce Broussard is vice president of operations and Samuel Moser is an application engineer at Storrs, Conn.-based IMCORP Partial Discharge Diagnostics, which performs a partial discharge location test, which is used as a commissioning test on newly installed cable systems as well as on aged cables with low reliability. Both can be reached at (860) 427-7620.