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Partial Discharge Testing of Medium Voltage Cables: On-line or Off-line?

1. Introduction

Medium voltage (MV) cables are the backbones of power distribution systems. Strictly speaking, MV cables are rated from 2kV to 35kV (phase-to-phase); the cables rated above 35kV are referred as sub-transmission and cables over 69kV are in transmission class. Although there are still some paper insulated lead covered (PILC) cables underground, most of the newly installed MV cables are insulated with cross linked polyethylene (XLPE), water tree retardant cross-linked polyethylene (TR-XLPE), or ethylene propylene rubber (EPR). All the cables above 5kV nowadays are constructed with metallic shields, which have significantly improved the performance and safety of MV cables. The metallic shield drains leakage and capacitive currents generated during the operation of the cable confining the electric field to the insulation.

Numerous ways of testing MV cable systems are now available to the asset managers to determine the conditions of medium voltage cable systems. Partial discharge (PD) test is considered as a more effective tool due to its advantages of differentiating various types of defects and locating the sites of the defects. PD in cable insulation is generated by the breakdown of the gas filled cavities and/or gaps within the cable insulation. The breakdown results as the gas inside the cavity, initially non-conductive, is ionized by hot electron impact to a conductive state. The breach of small cavities by field accelerated electrons is a very fast event that generates short lived disturbances in the electric and magnetic fields. These events observed as pulses have raise times in the range of a few nanoseconds. The generated pulses propagate along the cable between the conductor and metallic shield of the cable. Those PD pulses suffer attenuation as they propagate in both directions along the cable, with which the pulse magnitude and bandwidth decrease with the propagation distance.

The PD generated pulses can be captured by connecting a capacitive voltage divider between the conductor and the metallic shield as performed during both offline and on-line testing. However, this approach requires the equipment being tested to be removed from the system and grounded. On-line testing can be carried out with over the shield coupling capacitors or inductor sensors that are capable of capturing the pulses generated by PD events. Coupling inductors (high frequency current transformers, or HFCT, with open core design) can also be placed over the cable grounding lead. Open metallic shields such as in concentric neutrals and flat straps allow a small fraction of the electric field to escape through the open metallic shield to be coupled with proper sensors. Close metallic shields like non-corroded copper tape neutral and cables with solid corrugated metal sheaths (corrugated aluminum, corrugated steel or lead) can only be tested from the cable ends since the electric fields have no chance of penetrating the metallic barrier.

As with the case of any offline test, this be dc/ac voltage withstand, damped AC, tan delta, polarization/ depolarization or PD measurement, an external power source must be employed to energize the totally isolated cable. In the case of on-line testing, the cable system is energized with power from the electric network as it is exposed to normal current load conditions. In off-line procedures the testing voltages and frequencies can be varied but in the case of on-line testing both voltages and frequencies are fixed by the electric power network. Moreover, on-line testing does not require shutdowns. The pros and cons of on-line and offline testing approaches will be discussed in detail below.

2. Testing Procedures

2.1 On-line PD test procedures

By definition, an on-line test is carried out during normal operation of the cable system. The cable remains in service during the test. No planned outage or isolation of the cable is needed. The on-line test is non-destructive. It uses the system voltage as the test voltage. No extra stress is introduced to the cable. There is no associated switch-in and switch-out which could induce switching surges to the cable system and cause potential damage to already weakened cable insulation.

To acquire PD data, a coupling device, capacitive or inductive, is attached to the energized shielded cable, and is connected to the data acquisition system. The data acquisition system is self-contained and portable so that it can easily be adapted to various indoor and outdoor cable system configurations, such as underground distribution and transmission, substations, industrials and off-shore platforms. When confronting with long cable runs, additional test points can be added in the middle of the cable run when it is accessible. The productivity of on-line cable assessment is also achieved by eliminating power outage arrangement and HV safety arrangement in exposed area otherwise required for off-line test.

2.2 Off-line PD test procedures

In an off-line PD test, the cable is disconnected at both ends and isolated from the network. Arrangements have to be made in advance due to power interruption from the cable under test. An external voltage source is required to energize the cable at the time of the test. The voltage source for an off-line test could be power frequency (50/60 Hz), VLF (0.1 Hz), damped AC, etc. Depending on the frequency of the voltage source, the required capacity of the source to energize the cable increases proportionally to the applied frequency. For the instance of power frequency (50/60 Hz) off-line test, the power supply can be sizable and heavy to transport, e.g. mounted in a truck. When there is limited accessibility, arrangement for the HV connections, which could be in someone's backyard, arises additional operational challenge and safety concern.

Off-line test voltage is normally higher than the cable's operating voltage. Because partial discharges that are active at operating voltage may extinguish after removal of the operating voltage for subsequent off-line test. Since the PD inception voltage (PDIV) is higher than the extinguish voltage (PDEV) due to space charge accumulation, to excite the discharges present at its operating voltage that extinguished from voltage removal, a higher voltage (higher than PDIV) has to be impressed. In IEEE std 400-2012, it states that ***"…monitored withstand test…the test voltage is generally higher than the rated voltage…typical testing voltages range from 1.5 U0 to 3.0 U0…The test can weaken regions of the cable system insulation without causing failure during the test and possibly leading to failure in service at a later time…."*** (page 13/6.1.1) It demonstrates the disadvantage of an overvoltage test. This is especially applicable to aged cables which are most fragile in the cable system. The risk is known but there is no choice for off-line test simply because voltage must be significantly elevated to excite the same discharges present at operating voltage.

3. Comparisons Between On-line and Off-line PD Tests

3.1 Is PD test really non-destructive?

Partial discharge testing is normally considered as a nondestructive approach for cable insulation system diagnosis, as all the PD testing technologies, including both on-line and off-line tests, are aimed to assess the insulation condition while not damaging the object under test. This nondestructive character differs from PD testing by other destructive approaches such as withstand testing, breakdown strength measurement, etc.

On-line PD testing measures PD signals when the cable system is in service, which does not "intrude" into the cable system in any way. Therefore nondestructive is the inherent characteristic and advantage for on-line PD testing, as stated in IEEE 400.3 standard (Chapter 6.1, Page 20),

> ***"On-line measurements do not cause any damage to the cable system during the partial discharge measurements"***

How about off-line PD testing? Is off-line PD testing a real nondestructive for cable insulation system? Let's examine this issue following the off-line testing procedure.

3.1.1 Switching off the cable for testing

Off-line PD testing requires the cable system been removed from service. The switching operation generates surge voltage in the cable system, and the magnitude of the surge voltage depends on the load and the switching mechanism. For a light loaded circuit with slow switching device, for instance pulling out an elbow connector of a unloaded URD cable from pad-mounted transformer, the switching surge is not obvious and can be negligible in terms of cable insulation deterioration; however, the switching surge for a heavily loaded circuit with fast switching mechanism, i.e., switching off a loaded feeder cable with vacuum circuit breaker, **the surge impulse could be three**

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times as high as the operating voltage with a relative narrow pulse width in the range of hundreds of nano-second (ns) to few micro-second (us) [1].

The direct effect of this intensive switching surge for the aged cable insulation is, it increases the probability of converting water tree in the cable insulation into electrical tree, as stated in [2]

> "***The impulse voltage ...... is yielding of the XLPE, generation of a cavity which can sustain partial discharge, and initiation of an electrical tree.*** "

Water treeing is very common in cables with PE or XLPE insulation, but cables do not fail because of water tree. Cables with water tree in the insulation, more or less and larger or smaller, could survive as long as the water trees do not convert into electrical trees. The surge voltage caused by the switching operation increases the probability of converting the water tree in an aged cable insulation into electrical tree, and therefore could fail those cables that would survive otherwise. This is proved by the experiences and the field observations that a large number of the cable failure occurs in a very short time when the cables are re-energized after off-line testing or maintenance.

3.1.2 Over-voltage in off-line PD testing

Like nondestructive is an inherent characteristic of on-line PD testing, over-voltage is the inherent characteristic of off-line PD testing. Since the applied voltage in off-line PD testing can vary, the principles of selecting off-line PD testing voltage is recommended in the IEEE 400.3 standard (Chapter 6, Page 20) as

> ***" The applied voltage should cause partial discharges in the cable, terminations, and splices that have characteristics close, if not identical, to those that occur when the cable system is in service."***

PDs that are active at operating voltage extinct after removing the system out of service for subsequent off-line testing. Because PD inception voltage (PDIV) is higher than PD extinction voltage (PDEV) due to space charge accumulation, to excite the PDs present at its operating voltage, a higher voltage (higher than PDIV) has to be impressed. IEEE 400.3 has detailed explanation about the necessary of using over-voltage in off-line PD testing (Chapter 4.3, Page 13)

> *" When a cable circuit is taken out of service for off-line PD testing, the PD activity is extinguished when the voltage is removed. To re-initiate PD that can continue at normal operating voltage, a voltage of up to ~1.5Vo may have to be applied for some minutes, as the PD inception voltage (PDIV) may be greater than the voltage required to maintain PD (PDEV) once it is initiated. A test duration of some minutes is required to ensure that there is an electron to initiate the discharge. Although in theory the PDIV may be two times the PDEV, in practice it is usually about 1.3 to 1.5 times. Thus,* ***in off-line PD testing, the test voltage should be raised above normal operating voltage to initiate PD that was probably already active before the cable was taken out of service****. If the cable is tested on-line without removing the voltage prior to testing, then those PD sources that are likely to be active during normal service are probably already in PD at the time of the test, although intermittent PD can occur if the PDEV is close to the service voltage."*

That is to say, over-voltage has to be applied in off-line PD testing to re-create what one can already measure from on-line testing. This over-voltage during the off-line PD testing has two effects on degrading cable insulation

1. Over-voltage can create defects that would not be activated in service, as stated in the IEEE 400-2012 standard (Chapter 6.3.1.3, Page 28),

> ***"Test (over) voltage can activate PD defects that can be dormant (indefinitely) under operating voltage."***

Again, the conversion from water tree to electrical tree is still a good example. In operating voltage, the chance that a water tree converting into electrical tree is trivial so that cables can survive a long period of time and eventually fail by other reasons with water trees in the insulation; the over-voltage (as well as switching surge voltage) in off-line testing has much higher probability to trigger PD activity by converting water tree into electrical tree, and fails cable during test or very short time after test.

2. Over-voltage degrades cable insulation, accelerates the failure process, and reduces the cable life, with or without causing immediate or short term fault.

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Over-voltage tests adopted in manufacture tests, installation tests and commissioning tests for new cables are not likely to cause significant reduction of cable life, as those new cables are defect-free and the insulation have enough redundancy [3][5]. However, in maintenance tests for cables that had been in service for some time and the insulation has been aged to various degree, adopting the same testing voltage for new cables is not appropriate. Over-stress those fragile insulation in an aged cable worsens the situation by accelerating the insulation aging process, as demonstrated in IEEE 400-2012 (Chapter 5.2, Page 8):

> ***"There is a possibility that the insulation system cannot withstand the same levels and durations of voltage as those designed for factory tests, which are intended for newly manufactured cables. Testing aged cable systems or cable systems with defects at elevated test voltage levels can accelerate the failure process."***

Some utilities using over-voltage off-line PD testing have the experience that a portion of the cables (~1%) failed during the over-voltage testing, a portion (~1%) failed right after putting the cable back to service, and a large portion of the cables had higher failure rate within the first two years after testing than the cables without suffering over-voltage testing.

In general, is off-line PD testing really nondestructive? Maybe, if the switching surge voltage can be mitigated, and over-voltage can be avoided.

3.2 Issues Regarding Testing Time

The essential of selecting testing time period for PD measurement, including both on-line and off-line testing, is to ensure sufficient data sampling for meaningful and accurate analysis; while does not damage/degrade the dielectrics of the cable system. Since PD is a sophisticated and random physical process which follows statistical theorem, PD analysis and diagnosis heavily rely on statistical methodologies, with which a long enough data is necessary for meaningful diagnostic analysis to tested cable system.

In on-line PD testing, since all the PD defects in operating voltage are active and on-line testing is a real non-destructive approach as mentioned previously, theoretically one can collect indefinite data with on-line PD testing technology without any limitation. Actually indefinite data acquisition has been put in practice in "on-line PD monitoring" technology.

Off-line PD testing has some other story. First, off-line testing requires a sufficient time to re-produce the PD activities. The discharge is not initiated immediately when the applied voltage reaches PDIV. Instead the initiation of PD is random as there has to be a "free electron" available to initiate breakdown, in which the appearing of this "free electron" is a random event, which requires a long enough time of applying voltage over PDIV to ensure the available of this "free electron". When the PD is initiated, off-line PD testing has the same requirement as on-line testing to acquire long enough data for analysis. As suggested in the IEEE 400.3, Chapter 7.4 on Page 24,

> ***" The voltage in power frequency tests may be applied for up to a maximum of 15 min to ensure that electrons are available in cavities to initiate PD. However, once PDs are detected, the voltage should be applied long enough to collect sufficient data up to a maximum of 15 s."***

The problem is, off-line PD testing is an over-voltage testing. In order to avoid irreversible damage/degradation to cable insulation, the time period of applying over-voltage has to be as short as possible; in contrast, off-line PD testing requires long enough time, in the range of minutes to tens of minutes, of applying over-voltage to cable insulation to ensure the PD activities are re-produced and enough data is acquired for analysis. This conflict between longer testing time for better diagnosis and shorter over-voltage time to protect cable insulation is inherent for off-line PD testing, which needs to be examined very carefully if it is not impossible to have a solution.

3.3 Discovering All Defects?

As the on-line PD testing is performed when the cable system is in service, all the PD defects that are active in operating voltage can be discovered. When performing off-line testing, the cable system needs to be removed from service, and energized by external power supply. The consequences of this "de-energizing, re-energizing without load" procedure in off-line testing are:

1. Cable system in off-line PD testing does not have load. Any load dependent defects, for example the problems in cable grounding system, cannot be reproduced in off-line testing. In IEEE 400.3 standard, this circumference is described in Chapter 4.3, Page 13 as

> *"In a complex cable system such as network feeders, the network can consist of a mixture of cables with different insulations, constructions, and load capabilities. Discharge can occur at the locations where the ground system of two cable sections operates at different ground potentials. In three-conductor cables, discharge can also occur between the shields of the individual phases and the overall cable shield when the shield is not connected properly. This often occurs when two cable sections with different constructions are spliced together.* ***The voltage build up in the ground system is induced by the current being conducted and is therefore a strong function of the cable loading****. In some cases, if an inadequate grounding is employed, the ground potential difference is caused by imbalance between the cable phases. The imbalance between the currents carried by the cable phases is more pronounced as the cable loading increases.* ***For this type of discharge, testing under heavily loaded conditions is essential."***

2. Conductor temperature is much lower in off-line PD testing than that in operating condition. The temperature of cable conductor, depending on load, can reach up to 90 °C (194 °F) in service; while in the off-line testing the temperature of the cable system is equivalent to the ambient temperature which is normally much lower than 40 °C (104 °F). The lower temperature in off-line testing allows the cable system to cool down, which cause voids to disappear or liquids to solidify.

This temperature dependant defect is demonstrated in both IEEE 400-2012 and IEEE.400.3 standards. For example in IEEE 400-2012, Chapter 6.3.1.3, Page 28, it says

> ***"Removing the system from service prior to applying the overvoltage test can allow the system to cool down, which can cause voids to disappear or liquids to solidify."***

And in IEEE 400.3, this condition is explained in details in Chapter 4.3, Page 12 as

> *"Another operating environment affecting the relative severity of a PD causing defect is the cable loading during service. If an XLPE insulated cable is operated at very high temperatures, significantly higher than the crystalline melting temperature, mechanical and structural changes could occur in the insulation. These, in turn,* ***may affect the PD characteristics. The size of some defects varies with cable loading so that the PD magnitude varies with the cable loading****. PD in some cases might disappear (extinguish) as load conditions change. For a laminated cable, long-term operation at high temperatures may cause the insulating fluid to migrate. The extent of this depends on the viscosity of the impregnating fluid. This can affect the PD producing defect."*

It should be aware that the over-voltage gives the possibility for off-line PD testing to discover more dormant defects in a cable system (although the time period to activate those defects are indefinite in operating voltage), however the margin of finding all the other defects except those load/temperature dependant defects with on-line and off-line PD testing is small. Some publication stated that the percentage of defects' PDIV lower than operating voltage is very small (i.e., less than 5%) [1], and concluded that on-line PD testing can only find those small percentage of defects. This conclusion is wrong. On-line PD testing can find all the defects with PDEV lower than operating voltage, since PDIV is not the requirement to sustain a PD activity, instead PDEV is. As stated in the IEEE 400.3 standard (Page 6), "***PDEV can be significantly less than PDIV***". Even if PDIV is higher than operating voltage, the PD defects can be triggered by any temporary over-voltage such as surge voltage caused by switching operation or lightning, or simply temporary system over-voltage. As long as the PDEV is lower than operating voltage, the PD activity can be sustained and discovered by on-line testing once it is initiated. In terms of the relation between PDEV and system operating voltage (SOV), the IEEE 400.3 standard summarized that

> *"****Defects that have both the PDIV and the PDEV below the system operating voltage (SOV)*** *will produce PD once the cable system is energized. The PD will be maintained during operation of the cable.* ***Both on-line and off-line methods will detect these defects*** *provided the PD detection system has the required sensitivity."*

> *"****Defects that have their PDIV > SOV and their PDEV < SOV*** *will not produce PDs at normal operating voltage unless they are triggered by transient over-voltages. However, once triggered, they*

may be self sustaining until the voltage is removed,... ***Both on-line and off-line methods will pick up these defects"***

*"**Defects that have both their PDIV and their PDEV above the SOV** can initiate PD by transient over-voltages, but the PD will usually extinguish quickly after some cycles of the AC voltage. PD could also be generated by off-line tests, particularly if the test voltage is >2 Vo. These defects **are normally harmless during normal system operation**, but there is a possibility that an electrical tree could be initiated having PD that could persist below the SOV, i.e., PDEV < SOV due to the high electric field at the tips of the trees."*

Overall, on-line PD testing has the advantage over off-line testing in discovering all the load and temperature dependant defects. Off-line testing has benefit of finding defects with PDEV higher than operating voltage. What is the percentage for this circumstance? Unfortunately, it is not reported in [1]. Moreover, based on the IEEE standards, although the defects with PDEV above operating voltage are normally harmless, once the electrical tree is initiated from those defects, the PD caused by electrical tree has PDEV lower than operating voltage and can be discovered by both on-line and off-line testing.

3.4 Productivity, Safety, and Miscellaneous

Compared with off-line PD testing, on-line testing does not require additional power supply, which brings a number of advantages for on-line PD testing.

1. On-line testing has higher productivity than off-line testing. Since on-line testing does not need to remove the cable system from service, setup high voltage power supply, and wait for a steady PD to be re-produced, on-line testing normally has higher productivity, i.e., can test more footage per day than off-line testing.
2. On-line testing is more convenient for trending analysis. Since on-line testing does not require additional service from customer except for the permission to entering, the object under test (cables, motors, transformers, etc.) can be retested many times in a certain time frame, which monitors the trending and obtains better prediction of remaining life.
3. On-line testing has no safety concern about using extra high voltage power supply.

Table 1 is the summary of the comparison between on-line and off-line PD testing technology.

4. Benefits of Techimp On-line Approach

On-line testing of cable systems involves the testing of an interconnected piece of equipment that is part of the power distribution network. This approach presents serious difficulties when pulses are not confined just to the cable system but can be entering the cable under test from interconnected equipment. This additional difficulty also provides an important benefit that other equipment can be diagnosed and/or faulty equipment can be spotted without being part of the original scope of the test. The range of equipment outside the scope of the test depends on the strength of the propagating signals. During a regular visit it is possible to spot bad insulators, faulty arresters, floating grounds, corona in switchgears, discharging transformers, motors, lack of clearance between phases and phase to ground, tracking in broken insulators and standoff insulators, etc. Most if not all the equipment and situations listed above will not be detected during an offline test whereby the cable in question is extracted from the regular installation and isolated from the power network.

Although most of the maintenance related cable testing is performed on older and aged cable population, the average failure rates are low and even among aged groups of cables only a small percentage is in danger of immediate failure. However, a large number of pad mounted transformers, arresters and overhead line hardware are interconnected with the underground cables and faulty units are easily spotted while screening the cables. Situations also rise where other than the cables under the planned test have been spotted as presenting problem of concern.

The figures that follow show a series of cases found throughout regular on-line testing by placing the sensor over cables. In most cases equipment being powered by cables cannot be easily tested directly as access to them is

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dangerous or not possible. Figure 1 shows the case where this 35kV transformer bushing connects directly to a long run of a metal clad busbar feeding switchgear. To find this source it was necessary to test from the cables being fed from the nearest switchgear. After the likely spot was located, it was necessary to wait for an outage before the metal clad busbar could be opened. Meanwhile the discharges were monitored from a nearby cable connected to the busbar through the permanent sensors. The sensor installation is shown in Figure 2 and the data pertaining to the measurements are shown in Figure 3.

Table 1. Comparison between on-line and off-line PD testing for power cables.

	PROs	CONs
ON-LINE	1. No power outage 2. Real non-destructive 3. Discover all defects that presenting in operational condition 4. Extended data acquisition time improves the chance to capture PD and adequate data for diagnostic analysis. 5. Multiple data point pickup location 6. Convenient for trending analysis 7. High production rate (footage per day)	1. Cannot express result in pC unit 2. Cannot detect possible defects that would be active above normal operating voltage
OFF-LINE	1. Over-voltage excites defects that only appear above normal operating voltage 2. Can measure PDIV and PDEV 3. Measuring at single point 4. Convenient for calibration and sensitivity assessment	1. Over-voltage is required to simulate the operating condition, which is necessary to trigger PD that discharges in operational voltage 2. Over-voltage damages cable insulation 2.1. Insulation degradation caused by switching operation 2.2. Insulation degradation caused by over-voltage during testing 3. Conflict between longer testing time for better diagnosis and shorter over-voltage time to protect cable insulation 4. Cannot measure load and temperature dependant defects. 5. Severe attenuation issue for long cables.

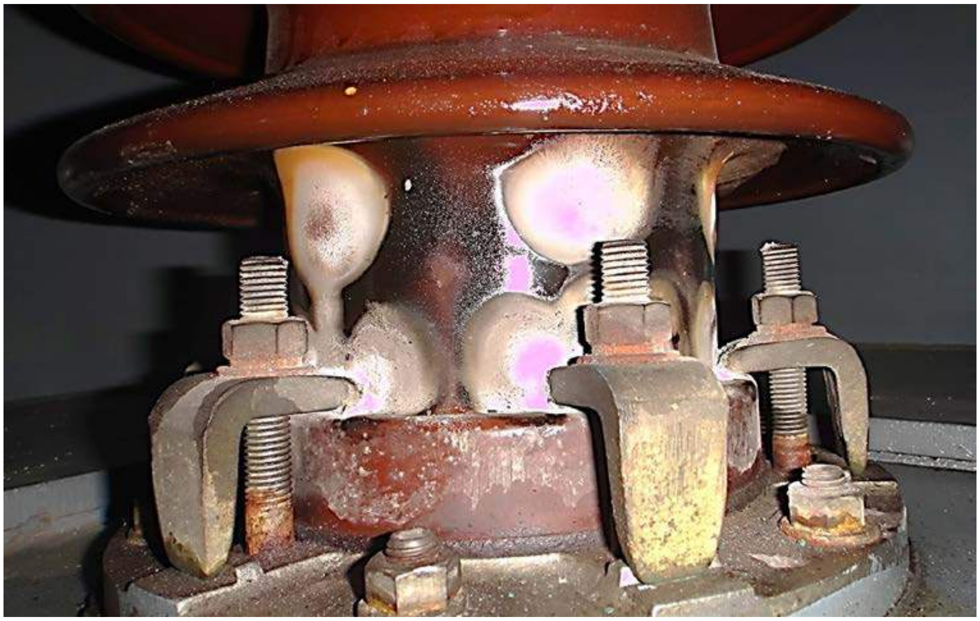

Figure 1 Discharging transformer bushing connected to a metal clad busbar with no direct access for testing.

Figure 2 View of permanent sensors installed over the three phases of a cable connecting to the metal clad busbar. This was the closest point to the source.

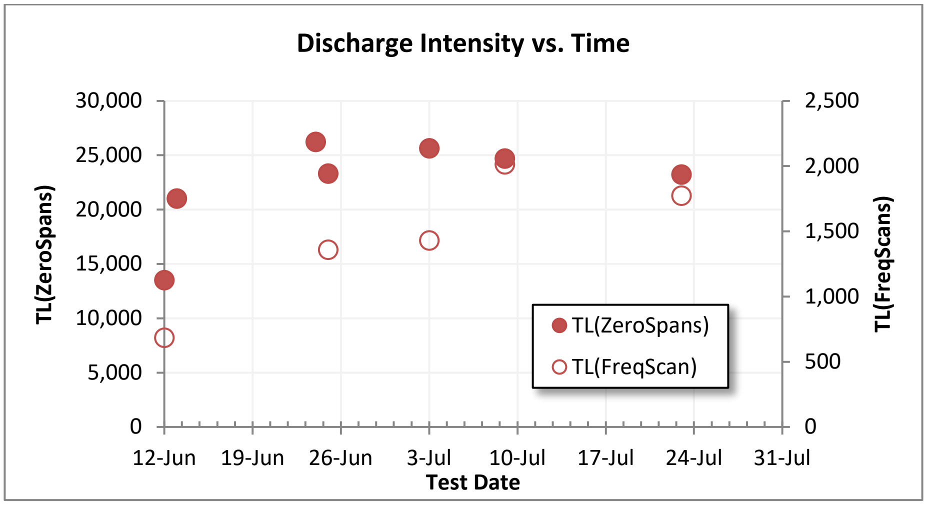

Figure 3 Plot showing the discharge trend of the red phase of the 35kV transformer bushing.

The data indicated a fairly constant discharge intensity that went on until the metal clad busbar was opened and the problem spotted.

Another case shown in Figure 4 depicts a severe lack of clearance between phases in a switchgear cubicle with two cables per phase. The cubicle was closed during the testing and opened only after diagnosing the problem. It was requested to de-energize the entire switchgear and cables so that the switchgear could be opened.

Another common case of discharges is the unshielded jumper between the cable and arresters that in the case shown in Figure 5, passes through the metallic side of the panel. A phase-to-ground fault would occur if the insulation of the unshielded jumper were sufficiently breached. The case of unshielded cables touching the steel rail inside an 8kV cubicle is shown in Figure 6. It should be pointed out that all these problems were diagnosed when screening cables at the bottom or on the top of the switchgear. Other similar cases are shown in Figures 7 and 8. Switchgears can no longer be opened when testing cables.

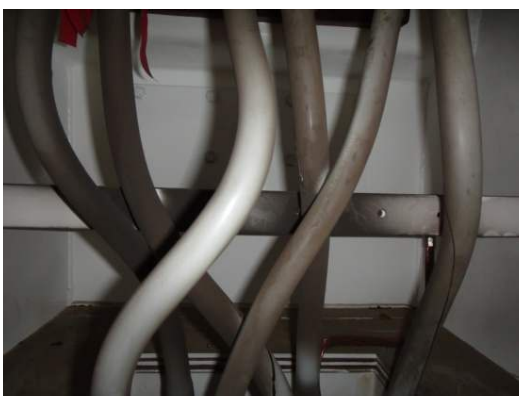

Figure 4 Lack of clearance between phases.

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Figure 5 Discharge between unshielded jumper cable and metallic compartment wall.

Figure 6 Lack of clearance between unshielded portion of cable and panel support beam.

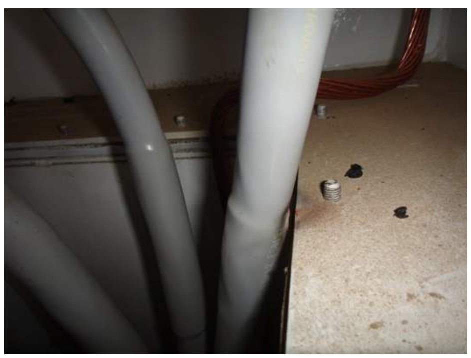

Figure 7 Another case of lack of clearance between unshielded phase and ground.

Figure 8 Discharges in one phase of the trifurcator.

Testing over cables feeding motors can also indicate the presence of discharges in the stator of the motor. Discharges in the end windings and also at the end of the stress grading coating (semicon layers) over the form coil bar are shown in Figure 9. Since sources of PD in motor winding insulation cannot be fixed without rewinding the entire motor, discharges are monitored and checked for drastic changes. At some point the motor has to be removed and repaired.

Figure 9 Discharges between phases in the form coil bars and PD from the grading coating.

Another cause of concern is faulty arresters. Discharging arresters can be localized during on-line testing by the high intensity of their discharges. A faulty gap arrester is shown in Figure 10 after dissection. The arrester was detected through on-line testing. After de-energizing the feeder cables, the arrester was removed and checked by energizing it from a variable power source. Leakage current and PD were determined to verify its condition. The arrester was later dissected and physical evidence of discharges at operation voltage were found across some of the gaps as shown in Figure 10.

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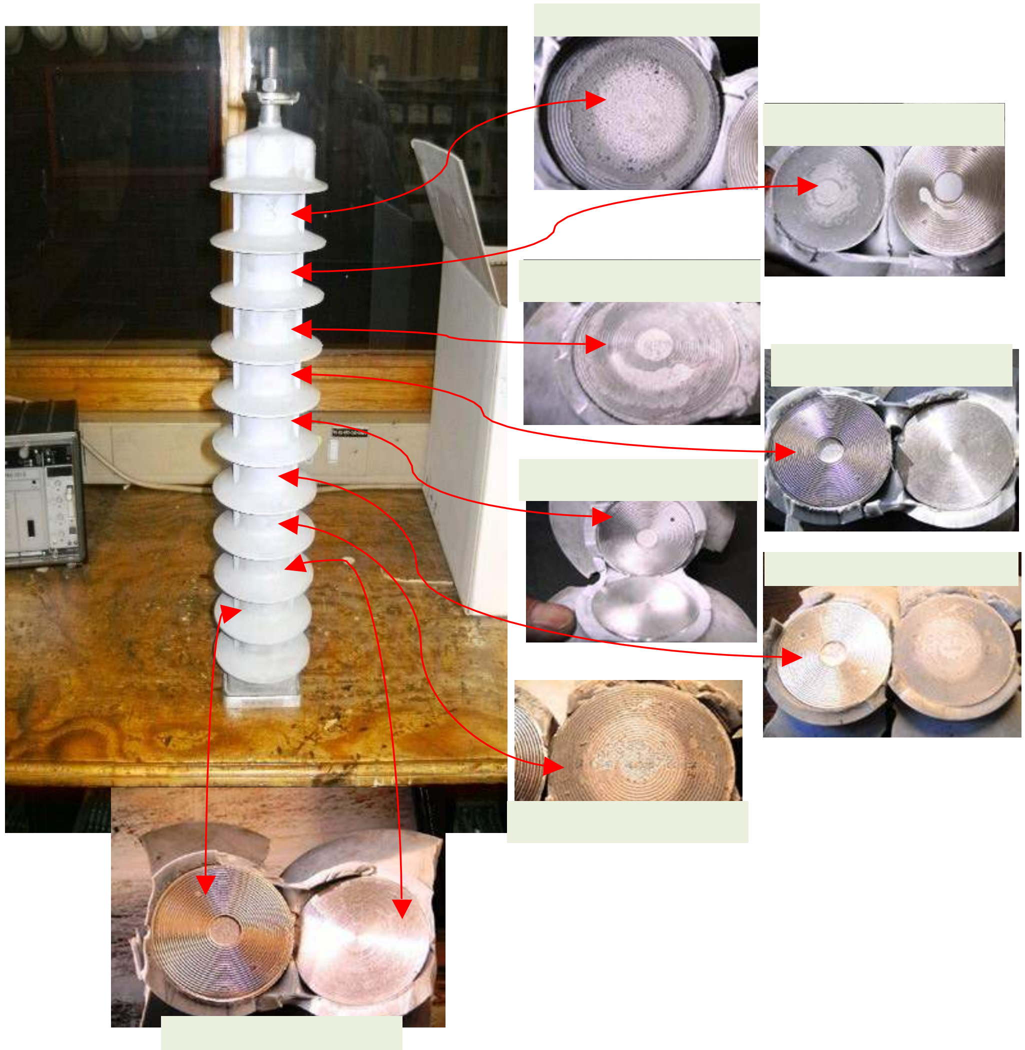

Figure 10. Discharges in a faulty gap arrester.

5. Independent Studies on On-Line Diagnostics Outcome

The diagnosis scale used in Techimp ranges from Level 1 through Level 5, where Level 5 represents the highest probability of failure in two years. From an independent study performed by Neetrac, the distribution of levels in accessories and cables are given in Figure 11. The data results in this study as in any other case of testing is usually biased to contain a large percentage of older cable, as people usually do not spend limited maintenance budget to test newer cables, resulted in about 80% of cables in the low probability of short term failure compared to 4% of levels 4 and 5 that have the highest probability of short term failure.

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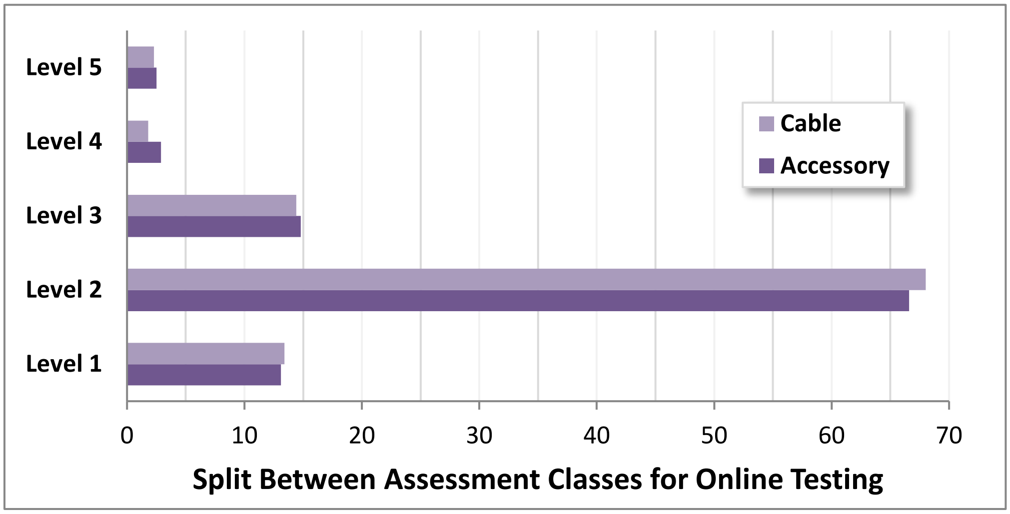

Figure 11. Distribution of levels in accessories and cables, provided by NEETRAC, a third party study.

In this study the cables and accessories were left in place even when diagnosed with high probability of short-term failure. As the cables and accessory failed after the test, the utility kept track of the time to failure, location and compared to the on-line diagnosis report. A third party lab (Neetrac) calculated the performance curves for concern levels 3 to 5. The results are shown in Figure 12. This figure indicates that the probability of failure of a Level 5 in 2 years is 89%, while that of a Level 4 is only 18%. Cables or accessories with Level 3 are already showing signs of discharges and have a probability of failure of 3% in 2 years.

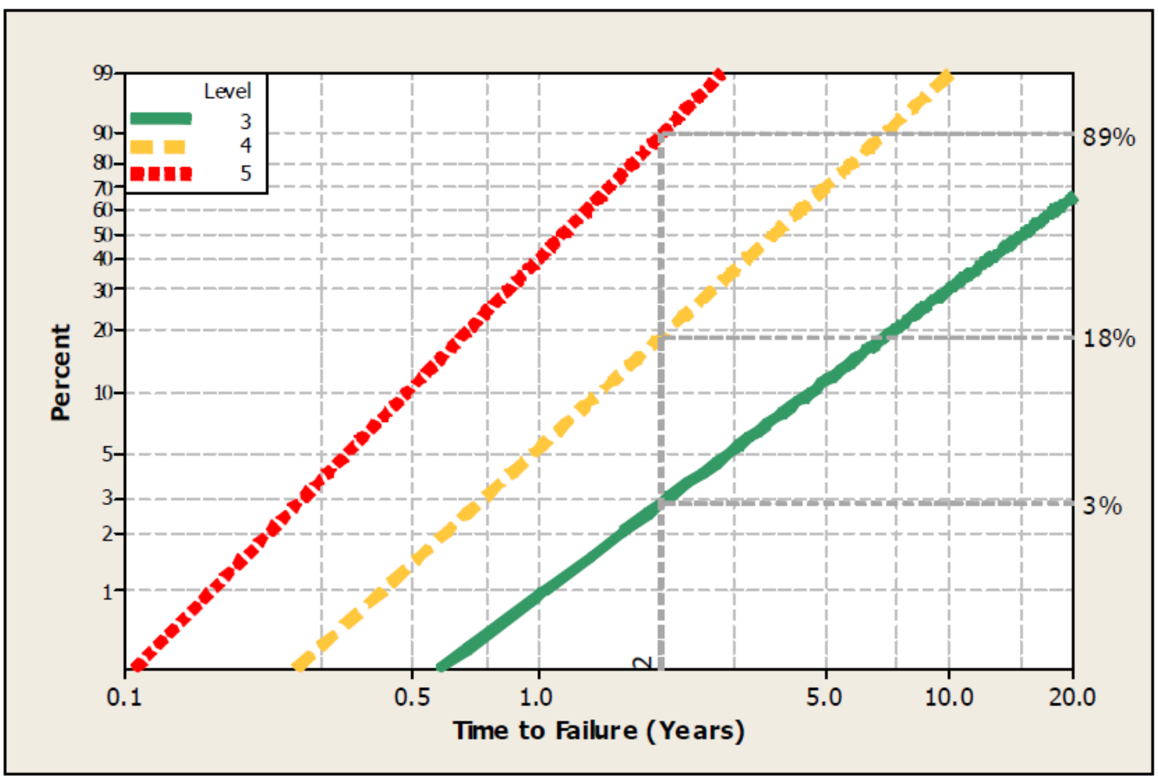

Figure 12. Diagnostic performance curves for one on-line PD test technique.

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6. Summary

Before choosing testing service, let's take a look at what the IEEE standards say.

In IEEE std 400.3-2006, it states that ***"…The applied voltage should cause partial discharges in the cable, terminations, and splices that have characteristics close, if not identical, to those that occur when the cable system is in service…."*** (page 20/6) The ***QUESTION*** is if you are to create a situation that simulates the cable system at its operating condition for PD measurement, why not making measurements on-line at its operating condition.

As depicted in IEEE std 400.3-2006, ***"…this temporary extinction of partial discharges to prepare for off-line measurements generally is not a problem if the off-line test voltage is significantly higher than rated cable system voltage…"*** (page 20/6.1) That is to say, overvoltage is applied to recreate what one can already measure from on-line test without taking the cable from service. The risk of overvoltage an aged cable is known but there is no choice for off-line test simply because voltage has to be elevated significantly to excite the same discharges present at operating voltage. So ***2nd QUESTION*** is why taking cables out of service for off-line test when you can assess the cable on-line, and why overvoltage the cable if you don't have to.

An off-line PD test fails ~1% of the cables that are most degraded within the system by bringing the test voltage to a significantly elevated level. It is not that bad an idea to fail those cables EXCEPT that the overvoltage test also accelerates degradation of the rest 99% of the tested cables to differing degree. The consequence of the overly stressing the already degraded cable insulation is that some of the 99% overvoltage tested cables fail shortly after returning to service, and some fail in months up to two years after the test. The delay is because defects were created during the test but did not fail the cable at the time of the test. This portion of cables should not fail but do fail in a later time after the test as a result of the overvoltage from the test. Now here comes the ***3rd QUESTION***, what is the original goal of testing. If one looks at the 1% cables that failed during the test, it is satisfactory because it is desired to flunk out the 1% bad cables if they can't be saved by other alternatives, and would think it increases the system reliability. However, the overvoltage was applied to cables beyond the 1% that failed. The overvoltage applies to a larger population, the 99% of which has a reduced reliability because of the defects introduced by the overvoltage test. Saving 1% by degrading 99%, good deal?

In all, the maintenance goal is to increase the system reliability, not to decrease the reliability. The way to improve system reliability is to improve aged cables, and at least not to destroy the cables. An on-line PD test examines the cable's insulation health at its operating condition, e.g. voltage and load. It is non-destructive, no shutdown, short set-up time and absolutely NO overvoltage!

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7. References

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