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KNOWING WHEN AND WHERE TO CHOOSE YOUR BATTLES

By Don Horne

The development of new generation is crucial to the viability of the grid, and new generation (pardon the pun), can generate opposition.

The objections to nuclear are the loudest, especially from those who would live closest to any proposed plant fearing that their back yards could turn into another Three Mile Island.

Construction of coal-burning plants has all but been shelved thanks to the air-quality requirements of the Kyoto Accord, despite impressive advances in cleaner burning coal and scrubbing techniques.

Large-scale hydro-electric projects are mostly a thing of the past, only because the majority of potential hydro-electric sites near developed areas have already been exploited.

Natural gas? Clean burning yes, but the potential for a terrorist attack on supply lines does exist.

Really, the very few generation options that seem palatable to everyone seem to be solar and wind.

Or so we thought.

On radio stations in Madison and Fond du Lac Wisconsin, a group called the Advocates for the Horicon Marsh wildlife refuge has been running spots in the hopes of stopping construction of wind turbines for that state's largest wind farm, asking Governor Jim Doyle to personally intervene.

Timed to coincide with the governor's announcement of an environmental and energy policy program - a program that includes a greater state investment in renewable energy (that includes wind power) - the radio spots express concern that development of the Forward Energy Center will result in the destruction of birds at the marsh.

Invenergy is the Chicago-based company that is developing the project - a project that would generate four times the electricity of all of Wisconsin's wind turbines combined. The wind farm aims to sell to Wisconsin Public Power Inc.; Madison Gas & Electric Co.; Wisconsin Power & Light Co.; and Wisconsin Public Service Corp.

Paul Baicich of the National Wildlife Refuge Association has stated that, "Our concern is that you can be for renewable energy and also be responsible. To put (the wind turbines) this close is not responsible."

Along with the Horicon Marsh System Advocates, other groups like the Wisconsin Audubon Council and the National Wildlife Refuge Association want the wind turbines to be built at least four miles from the marsh.

Huh?

Admittedly I am not an expert on ornithology, but surely the winged creatures that inhabit and use the marsh can avoid the slow turning blades of a wind turbine. And the current positioning of the turbines still provides for a buffer from the marsh.

Wisconsin's Public Service Commission has so far approved placing turbines two miles from the edge of the marsh - a buffer based on the recommendations of the U.S. Fish and Wildlife Service, which manages the marsh, and Wisconsin's Department of Natural Resources.

If you buy into what the objectors are saying, it seems that now even the blades of wind turbines need the same distance that nuclear fuel rods and carbon dioxide belching smokestacks do from the homes of living creatures.

It should be noted that the U.S. Fish and Wildlife Service originally sought a buffer of 3 to 4 miles from the marsh but later endorsed the minimum buffer of 2 miles. But it should also be pointed out that they called for more studies to be conducted to document the impact the turbines have on wildlife. Translation: They aren't certain the turbines have any impact whatsoever.

Indeed, previous studies of similar wind turbine sites show that on average there are two bird deaths per turbine per year. Although the deaths are regrettable (and at the risk of being insensitive to avian lovers everywhere), they seem acceptable.

If I really wanted to ruffle some feathers, I could point to the ratio of bird deaths to aircraft propeller blades (both jet turbine and turboprop). I can safely say that those numbers are considerably higher, and no one is eager to put a halt to air travel any time soon.

Ironically, the fiercest debate may be shaping up between environmental groups that advocate for clean energy against groups concerned about wind turbines' impact on birds and bats.

According to the Wisconsin Public Interest Group, the environmental benefits of wind power should be obvious.

A spokesperson for the group says that "if you take a big-picture view of our energy choices, if you care about wildlife and the environment, global warming has to be the top issue, and that is the biggest threat."

Global warming should be a major concern especially in Wisconsin, where more than 70 per cent of that state's energy is derived from coal (with another four or five coal-fired generation plants on the drawing board).

Although global warming concerns should be balanced with future generation concerns, the cries from the advocates for the marsh can be likened to the ludicrous efforts of PETA (People for the Ethical Treatment of Animals).

PETA - an organization that began with the good intentions of protecting and bettering the lives of animals - has become so left-wing that even some vegetarians have begun to question their motives and distance themselves from the group.

So too could the actions of the Advocates for the Horicon Marsh wildlife refuge. The downfall of creating a stir over wind farms harming the wildlife is that when they raise their voice over more serious threats to the marsh, they lose credibility - akin to the story of the boy who cried wolf. **ET**

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NEW ORLEANS TRAGEDY SHUTS DOWN IEEE PES CONFERENCE

A message from the President of IEEE PES, Hans B. Püttgen:

Dear Friends,

As the reports of the devastation in New Orleans come in, our first concerns have been for our many friends in the area and, in particular, for the members of the local organizing committee of the IEEE PES Transmission and Distribution Conference and Exposition. It has now become evident that the recovery process will be prolonged and will require a broad range of resources, including those of our industry. My colleagues from the IEEE Power Engineering Society Governing Board and I have come to the conclusion that the most reasonable course of action, under these dramatic circumstances, is to postpone the event until next spring. We feel that this decision is in the best interest of the industry we serve.

The decision has been reached to postpone the event until spring.

If at all possible, we would like to support the great City of New Orleans and its wonderful team of volunteers by holding the event there next spring.

The venue and dates will be announced within the next few weeks. We are well aware of the conflicts with other events will endeavor to minimize any inconveniences to the exhibitors and participants. Please continue to watch this site for details.

The exact details as to the transition to the new dates are still being worked out. In particular:

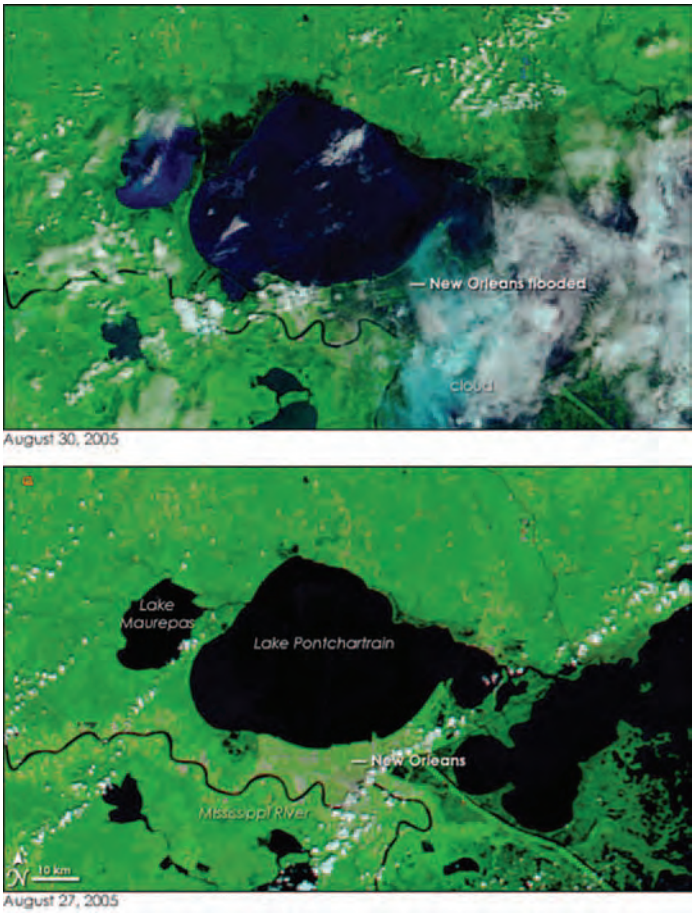
- All contracted exhibiting companies will be contacted shortly by the show management organization to discuss the transition to the new dates.
- We will contact those of you who have already registered as an attendee with information as to the transition of your registration.
- We will shortly have details regarding your housing arrangements if you had already made reservations.

Please check with your airline for conditions regarding refunds for your New Orleans travel arrangements.

In closing, I would like to ask that you keep our friends in the devastated areas in your thoughts as their energies are focused to restore their living conditions. Your support is vital in these difficult times.

We are counting on all of you to attend the event next spring. I am comforted by the strong and broad support we have received from the manufacturers during the decision process; I am confident that we can count on their full support of as exhibitors next spring.

Best regards,
Hans B. (Teddy) Püttgen
President, IEEE Power Engineering Society



Satellite photos before and after the hurricane.

Editor's note:

Our thoughts and best wishes here at Electricity Today go out to the people of New Orleans who are enduring unspeakable hardships in the wake of Hurricane Katrina.

We are confident that the city will bounce back from this tragedy with the resolute pride that everyone in Louisiana has shown throughout the past few weeks, and look forward to participating at next year's IEEE Conference - hopefully down on the bayou.

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600V HIGH RESISTANCE GROUNDING FOR COMMERCIAL AND INSTITUTIONAL BUILDINGS - WHY NOT?

By David Murray, P.Eng., IPC Resistors Inc.

Six-hundred volt and 480V electrical power distribution systems within most commercial and institutional buildings are solidly grounded by tradition.

In solidly grounded systems, ground faults can cause downtime, equipment damage, and in severe cases, arc flash injury to personnel. Many industrial facilities choose high resistance grounding for their 600V distribution systems because they experience more frequent ground faults than commercial and institutional buildings. A high resistance grounded distribution system responds much more safely to ground faults, preventing downtime, damage, and injury.

Why do commercial and institutional buildings continue to have solidly grounded 600V systems when high resistance grounding offers superior protection against ground faults?

- Habit and tradition
- A presumption that solid grounding is safest
- 347V lighting requires a 4-wire solidly grounded source
- A preference for a ground fault to trip a breaker and de-energized immediately
- No maintenance electricians are not available to locate ground faults

Let's examine the principal problem faced in the design of solidly grounded systems – arcing ground faults. High capacity power systems deliver tremendous energy when electrical faults occur. Seventy to 85 per cent of electrical faults begin when an energized phase conductor contacts ground, typically through an insulation failure or human error (dropped tool while working on live equipment). These are known as ground faults. When the resistance at the point of the fault is practically zero, a "bolted" ground fault occurs, causing very high current to flow until interrupted by a circuit breaker or fuse. Such faults usually cause no damage because they are interrupted instantaneously, within 2 – 50 milliseconds (3 cycles or less).

Unfortunately, ground faults caused by insulation failures (typically due to mechanical damage or aging and wear) are not bolted faults; there is an air gap between the energized conductor and ground. In 600V and 480V power systems, there is enough voltage to create a sustained electrical arc across the air gap. Called "low level arcing ground faults" because the arc resistance reduces current flow, they are not quickly detected by circuit breakers or fuses. Without special ground fault protection relays, these arcs can escalate into phase-to-phase and three-phase faults, releasing tremendous heat and mechanical energy [1]. Equipment is damaged and people can be injured or killed if exposed to these faults. Since the early 1970s both the Canadian Electrical Code and National Electrical Code have required ground fault protection on the main breaker on 600 V or 480 V solidly grounded systems where the rated current is 1000 A or higher. The maximum ground fault pick-up setting allowed is 1200A, and the maximum time delay allowed is 1 second. This measure limits, but does not entirely prevent, equipment damage or downtime – arcing faults can do much damage within one second. To avoid tripping the main breaker each time a ground fault occurs, ground fault relays are often specified for branch feeders as well.

Low level arcing ground faults occur more frequently in industrial facilities than in commercial or institutional buildings because there is far more electrical equipment, particularly motors within a relatively confined space. In some industries, the environments are electrically hostile with moisture, dust, contaminants or excessive temperatures. Continuous process industries experienced intolerable equipment damage and downtime due to arcing ground faults in the 1950s and 60s, after they started solidly grounding their 600V and 480V distribution systems. Up to the mid-1950s, most low-voltage industrial distribution systems (600V and 480V) were ungrounded three-wire systems, in which high energy arcing ground faults were rare. However, ungrounded systems were shown to cause high transient overvoltages under certain failure conditions, leading to multiple simultaneous motor failures [2]. Hence 3-wire 600V and 480V systems became solidly grounded in the 1950s to cure this overvoltage problem. Solid grounding solved one problem, but created another.

The probability that phase-to-ground faults on 600V and 480V systems will become sustained and dangerous arcing faults is high. On 208V systems, sustained arcing faults are rare. A safety hazard exists for solidly grounded 600V and 480V systems from the severe flash, arc burning, and blast hazard from a phase-to-ground fault [3]. The phase-to-ground voltage in 208V systems is not high enough to sustain an arc; in most instances the arc self extinguishes in a ?-cycle.

Continuous process industries with hostile electrical environments such as petrochemical, pulp & paper, and steel began high resistance grounding their 600V and 480V distribution systems in the 1970s to prevent low level arcing ground faults. As a result they experienced fewer arc flash injuries, reduced equipment damage and less downtime from ground faults.

Although hospitals and data centres experience fewer ground faults than industrial plants, when they do occur, downtime is just as intolerable when patient care or ATM networks are affected. High resistance grounding eliminates this risk from 600V systems.

High resistance grounding is appropriate for enterprises where:

- downtime due to ground faults

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Our Industrial Electricity Efficiency Forum will also provide background information on current market conditions in Ontario, including federal and provincial government initiatives for promoting energy management and energy conservation and electricity efficiency.

Ontario's electricity market continues to provide significant barriers in taking control of escalating energy costs. The inability to forecast electricity price spikes is just one example. The resulting impact on budgets, cost centres, potential rebates, etc all need to be better understood, communicated and solutions implemented.

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HIGH RESISTANCE

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is intolerable;

- ground faults are located and repaired once they occur, i.e. they are not ignored;
- 347V or 277V lighting is no more than 10 per cent of the total electrical load.

Continuous process industries have successfully used high resistance grounding for over 30 years increase the availability of electrical power from their 600V or 480V distribution systems. Data/telecom centres are now using high resistance grounding to squeeze even more uptime from their backup generators and UPS systems.

Today, 600V and 480V systems are solidly grounded for one of two reasons: (1) either to provide a grounded neutral conductor for 347V or 277V lighting loads, and/or (2) because the solidly grounded system is still perceived to be the safest method of grounding.

347V LIGHTING

Contrary to popular belief, 347V or 277V lighting does not require the entire 600V or 480V distribution system to be solidly grounded, particularly when the 347V lighting load is less than 10 per cent of the total electrical load. Small delta-wye 600V-600/347V isolation transformers can be locally distributed to supply 600/347V lighting panels. This practice (1) improves the safety of the 600V system in the rest of the building by allowing high resistance grounding, (2) saves the cost of distributing a neutral conductor throughout a facility, and (3) provides the added benefit of much lower fault current at the 600V lighting panels, for better coordination.

Three-hundred-and-forty-seven volt, 1-pole, 15A and 20A lighting breakers are available with interrupting ratings of 14-kAIC, 18-kAIC, and 25-kAIC only. Lighting panels connected to 600V systems with higher than 25kA of available fault current cannot be fully rated, but must use series-rated main and branch breakers. Under a bolted ground fault, the series-rated main and branch breakers must trip simultaneously, to dissipate the fault energy across both breakers. In this way a faulty lighting ballast can trip the lighting panel main breaker and plunge all of the other branch lighting circuits into darkness. By inserting a small isolation transformer to supply the lighting panel, the available fault current drops to 2kA or less; a faulty ballast trips the branch breaker only, and a less expensive 14kAIC lighting panel may be used. (See figure 1)

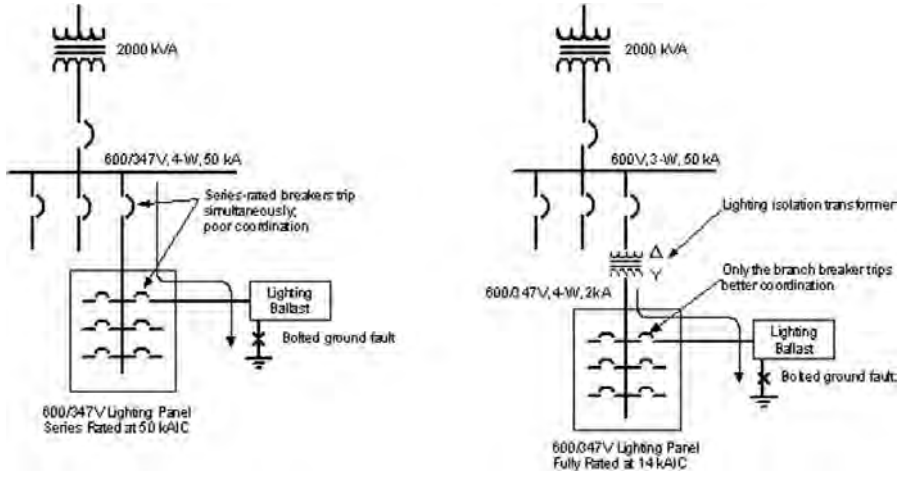

Figure 1 – Improved Co-ordination with Distributed 600V Lighting Transformers

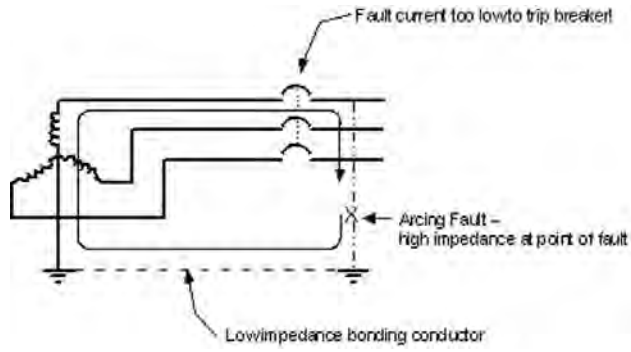

Figure 2 – High Impedance at Point of Fault Fails to Trip Breaker

It is not necessary to solidly ground an entire 600V distribution system just to supply 347V lighting. By limiting the solidly grounded 600V systems to small islands of lighting circuits, the bulk of the 600V distribution system can be high resistance grounded to improve personnel safety, limit downtime, and reduce equipment damage from arcing ground faults.

Also, ground faults cannot travel through a delta winding. Ground faults on a wye secondary winding are converted to phase overcurrents only on the primary circuit when the primary winding is delta configured (the norm). Hence a ground fault on the secondary cannot trip a ground fault relay on the primary, for better coordination.

Are 600V solidly grounded systems really safer? Solidly grounded systems are often perceived to be safest on the mistaken premise that all ground faults will quickly trip the affected feeder fuses or circuit breaker. Unfortunately, no matter how low the impedance of the ground return path is back to the neutral of the transformer, a high impedance at the point of fault itself, such as occurs for arcing ground faults, is enough to reduce the fault current such that the feeder breaker or fuses will not trip without sensitive ground fault relays. (See Figure 2) Only bolted ground faults are guaranteed to trip the feeder breaker or fuses without sensitive ground fault relays.

Contrary to popular belief, most ground faults are not bolted faults and cannot be depended upon to reliably trip the feeder overcurrent protective device each time, unless the feeders have sensitive ground fault relays. Often only the main breaker or fusible disconnect switch has ground fault protection, set to trip at a relatively high level of ground fault (1200A) after a time delay of one second to avoid nuisance trips. A lot of

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arcing damage can occur at the point of branch fault in one second.

To achieve time-current co-ordination between GFP relays, the upstream relays must have longer time delays than downstream relays. The minimum time co-ordination interval between GFP relays 0.2s. F or example three GFP relays in series may ha ve time delays of 100ms, 300ms and 500ms for the branch, feeder and main de vices, respectively. Yet the clearing time of arcing f aults should ideally be less than 12 c ycles or 200ms [3]. Unacceptable damage will still occur for arcing ground f aults located upstream in the distrib ution system, where GFP time delay e xceeds 200ms. Time coordination involves the trade-off between tolerating more damage upstream and achieving better co-ordination.

Co-ordinated GFP relays and branch phase overcurrent devices reduce arcing fault damage, but still do not satisfy the rigid requirements of personnel arc flash hazard protection [4]. This fact makes solidly grounded 600V or 480V systems actually less safe than high resistance grounded systems.

NFPA 70E is a US standard for electrical safety in the w orkplace. It addresses the arc flash hazard pre valent in electrical distribution systems. This standard, or similar v ersion of it, will come to Canada in the future. In order to reduce the arc flash hazard, ground f ault breakers will have to be set with a shorter time delay. This will reduce coordination, b ut increase safety in the presence of ground faults.

High resistance grounding prevents a feeder from tripping on a ground fault by limiting the ground fault current to 5A. It also prevents an arc flash upon a ground fault. There is less disruption and increased safety. (See Figure 3)

The neutral point of the LV system is grounded through a resistor which limits ground fault current to a relati vely low value of 5A or less. When a bolted ground fault occurs, the line-to-neutral voltage of the f aulted phase is fully impressed across the neutral grounding resistor, injecting a controlled current into the fault, in this case 347V÷69 Ω = 5A. At such low fault current, the affected feeder need not be de-ener gized until a more convenient time; hence a formerly un-scheduled outage on solidly grounded systems is con verted to a scheduled one on high resistance grounded systems.

During a ground f ault on a high resistance grounded system, the tw o unfaulted phases rise in v oltage above ground by 73 per cent to 600V . See Figure 4. The neutral point between the three phases rises to 347V abo ve ground during a bolted ground fault. If this were a wye winding, the neutral terminal would become ener gized to this v oltage during ground faults. It is for this reason that the neutral of ungrounded or high resistance grounded systems cannot be distributed throughout a facility and used

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HIGH RESISTANCE

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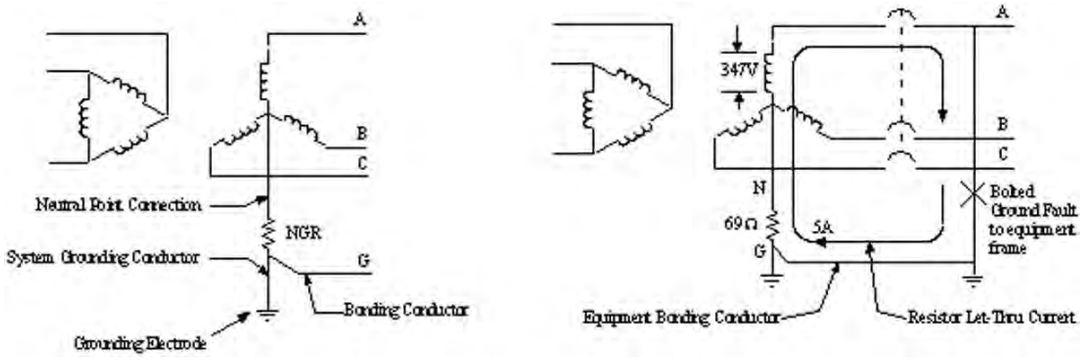

Figure 3 – High Resistance Grounded Power System

to supply line-to-neutral loads – because it becomes energized during ground f aults. To supply 347/600V 4-wire loads, small locally distributed isolation transformers are used, as explained above.

This voltage rise on the tw o unfaulted phases while a ground f ault is presence does not hurt the insulation of cables, transformers or motors. These insulation systems are designed to withstand this voltage with no problem.

Two items that must not be used on high resistance grounded systems: (1) 347/600V "slash-rated" lighting breakers, and (2) 347V/600V wye-rated transient voltage surge suppressors (TVSS). Lighting breakers are designed to be used only on solidly grounded systems, b ut then so is 347V lighting. Only "600V" rated breakers (no "slash", as in "347/600V") may be used on high resistance grounded systems. Ho wever most power panelboards and all switchboard with molded case circuit break ers routinely use 600V-rated breakers anyway.

TVSS must be 600V "delta-rated", which means that they can withstand the increased voltage of the tw o unfaulted phases to 600V. These TVSS are readily available from TVSS manufacturers.

It is a common misconception that a high resistance grounded system is not really a grounded system. Nothing could be further from the truth. First, the grounding and bonding of all non-current carrying exposed metal parts (cable trays, conduits, enclosures, racks, etc.) is absolutely unaffected by the method of system grounding. All such components are still bonded directly to ground in a high resistance grounded system. Second, the neutral is grounded, e xcept through a resistor instead of through a solid conductor. The IEEE Green Book treats high resistance grounded systems as grounded systems:

IEEE 142-1991 (GREEN BOOK)

Recommended Practice for Grounding of Industrial and Commercial Power Systems

1.4.1

Grounded systems emplo y some method of grounding the system neutral.... These methods can be divided into two general cate gories: Solid grounding and impedance grounding.

1.4.2

Numerous advantages are attributed to grounded systems, including greater safety, freedom from e xcessive system over-voltages that can occur on ungrounded systems during arcing… and easier detection and location of ground faults when they do occur.

When a ground f ault occurs on a high resistance grounded system, you fix it just as you would on a solidly grounded system. The difference is that the fault will not ha ve caused an y damage or unscheduled downtime. What's not to like?

Many data centres and hospitals now use high resistance grounding on their 600V distribution systems for increased service continuity and safety in the presence of ground f aults. As the trend for increased electrical safety in the w ork-place continues, more commercial and institutional buildings will begin to realize the benef its of high resistance grounding that industrial plants disco v-ered over thirty years ago. **ET**

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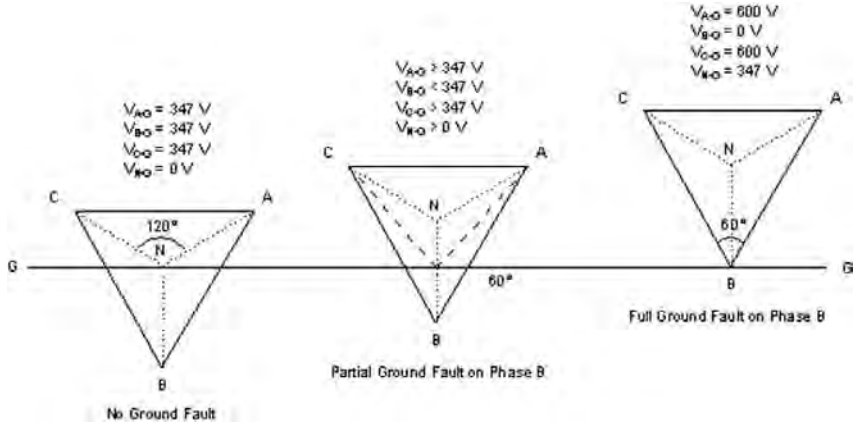

Figure 4 - Voltage Rise of the Neutral and Two Unfaulted Phases

ADVANCED CONDITION-BASED ASSESSMENT OF MEDIUM AND HIGH VOLTAGE ELECTRICAL SYSTEMS WITHOUT REQUIRING AN OUTAGE

By R.R. Mackinlay, High Voltage Solutions Ltd., and Don Genutis, Hampton Tedder Technical Services

INTRODUCTION

Partial discharge (PD) is becoming increasingly vie wed as the best diagnostic for insulation, particularly for on-line measurements. Clearly this applies to insulation, which e xhibits and is degraded by PD acti vity. However, even for insulation, which is designed to be PD free, the kno wledge that the system is actually PD free is still a vital part of the diagnostic process. Hence PD measurements, which are accurate and reliable, al ways contain important information about the high v oltage (HV) equipment to which they apply.

With the development of on-line PD methods, se veral problems still exist to be solv ed to yield the optimum diagnostic for insulation. These are:

- Noise interference from RF radio broadcasts
- Noise interference from pulses other than PD pulses

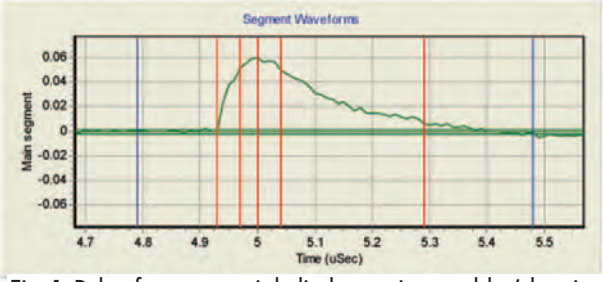

Fig 1 Pulse from a partial discharge in a cable (showing computer generated cursors)

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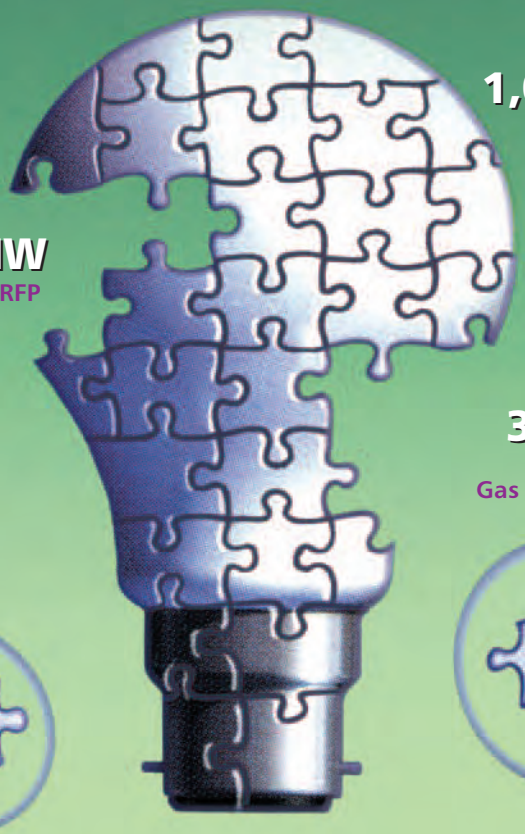

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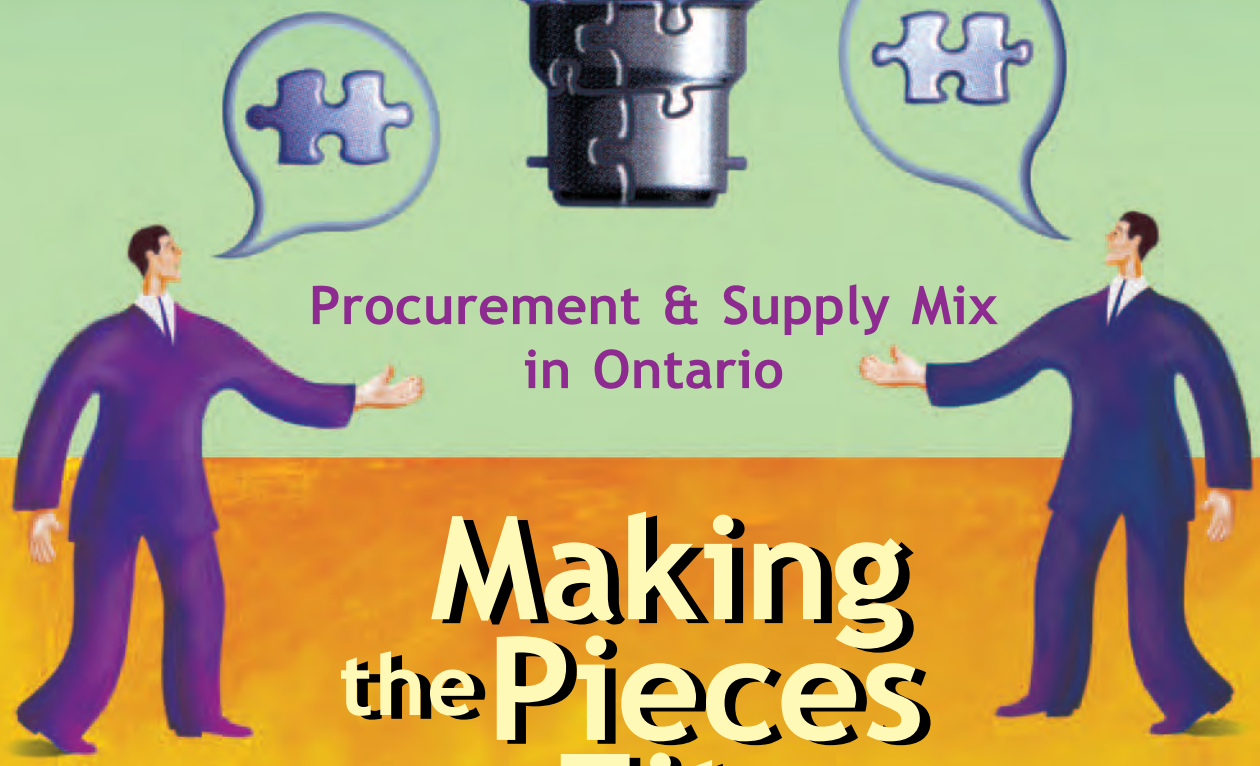

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• Location of PD pulses on cables and static equipment (e.g. switchgear, transformers etc)

• Estimation of remaining service life for the PD activity measured in the HV equipment under test

The remaining service life of equipment exhibiting PD activity is briefly dealt with for restricted types of equipment, otherwise this is left for a future paper. This paper addresses the main issue of making reliable PD measurements, namely the identification and removal of noise sources, and the location of PD events. To be able to do this allows the identification of discharging equipment, and hence the assessment of the risk to reliable service performance.

This paper describes the development of methods to distinguish between noise and PD activity, and to distinguish between several different types of PD. The recognition is done using simple algorithms, which use the waveform shape of the PD (and noise) pulses, to discriminate between the different types.

Partial discharges (PD) in voids and cavities in general produce very similar pulse shapes with very fast pulse widths. Values of a few tens or hundreds of picoseconds are typical. The pulse times are closely related to the breakdown time across the cavity. However, at the terminals of the high voltage equipment (or using an electromagnetic pickup if these are used) the pulse shape is dependant on the parameters of the detection circuit. Often these are determined by the equivalent circuit of the power equipment at the detection point. The observer may not have much control over the detection circuit in these cases. Hence it might appear that using the wave shapes of the pulses to distinguish between noise and PD (and between different types of PD) does not have a bright future.

However, there are two classes of PD pulses, which do retain a reasonable consistency of behaviour, for both on-line and off-line testing. These are cable PD's and PD's from local equipment (switchgear etc). In this case, local equipment means equipment within a few metres of the measurement point. The algorithm used in the development described in this paper, essentially makes three categories of pulsed signals. These are cable PD's, local equipment PD's, and all others are regarded as noise. This simple algorithm gives remarkably good results in a wide variety of circumstances, and has now been successfully incorporated into several commercially available products.

Fig 2 High frequency current transformers (CT's) around cores of 33kV cable for PD measurement (CT's are arrowed)

PD EVENTS FROM HIGH VOLTAGE CABLES

In the special case of partial discharge in cables, the cavity responsible for the PD discharges into a real impedance. This is the surge impedance of the cable and is purely resistive at the point of launch. The resulting pulse is virtually monopolar (see Ref 1) with fast rise times and very short pulse width. This pulse travels outward from the originating site, and arrives at the detection point wider and smaller due to attenuation and dispersion on its travel down the cable. The pulse is in general well defined by the time it is detected, and in practice retains much of the same characteristics as a consequence of originating in the cable. Figure 1 shows a typical cable pulse, with computer-generated cursors to measure the rise times and pulse properties.

Providing the rise times and widths fit into sensible values for a PD pulse, then the event is categorized as a cable event. The rise times are typically between 50nSec and 1?Sec, with pulse widths in general being less than 2?Sec. Actually for XLPE cables these values are generally shorter than this, as the loss and dispersion are considerably less for XLPE cables. The pulse rise time and width are dependent on both the pulse shape at the cable end, and the detection circuit. Hence the neat method of using the risetime (or pulse width) as a measure of the location of the pulse cannot be rigorously used, as the detection circuit is not known, and for example, may contain a large inductance and always then give slow rise times and longer pulses. However, the rise time is nevertheless a valuable tool in the initial localization of the pulses, as for on-line PD detection using high frequency current transformers (CT's) the detection circuits generally have large bandwidth (>20MHz) and simple localization works reasonably well.

Figure 2 shows the current transformer arrangements for a 33kV XLPE cable, where the CT's can be placed around each of the single cores, above the ground strap take off point.

Normally the current transformers are placed around the ground strap. The PD pulses traveling down the cable to the termination, have an equal and opposite polarity on the conductor and screen respectively. Hence it does not matter whether the CT's are placed in the earth strap, or the conductor. The important criterion is that only one of the ground or conductor currents is intercepted. In practice the two signals are very similar, but often the noise content can vary between the two detection points.

Figure 3 shows a cable with a spread of rise time events, where there are clear bands to the rise times recorded. In principle, a graph could be constructed from figure 3, with the ordinate calibrated in metres. This would assume a relationship between the rise time and the distance travelled for PD pulses in cables. This is actually reasonably well established (depending on the cable type), but the main problem is the unknown detection impedance at the termination. For example, if the detecting impedance contained a large inductance, then the rise times of the pulses would be dominated by the detection impedance, and not the distance travelled by the PD pulses.

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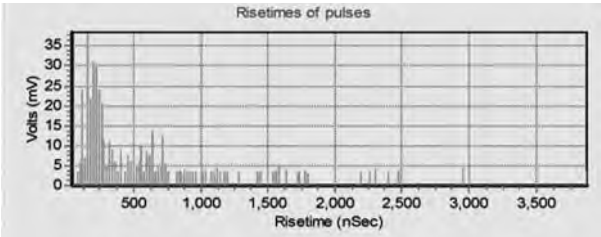

Fig 3 Distribution of pulse rise times from a cable

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In cases like this, a relationship between rise time and distance cannot be made. The response of the detection circuit could be measured, and if possible, the relationship could be correctly established. This will be the subject of a future paper.

The results in figure 3 were taken from a 33kV paper insulated cable tested on-line. Notice that the risetime of the PD events for this cable are around 200nSec. The cable was around 2km in length, and the locations were all from a single splice located at 1600m.

The huge advantage of carrying out PD detection using the waveforms of the PD pulses is that it allows for correction of the magnitude of the discharge almost irrespective of the distance down the cable the pulse has travelled. Particularly for paper-insulated cables where the attenuation is large, making magnitude only measurements of PD pulses leads to poor conclusions about the peak magnitudes. A PD of the same size can easily look a factor of 10 or 20 smaller when seen at some distance down the cable. Hence a very severe event remote to the measurement site can be observed as quite a modest PD if the attenuation has reduced the peak magnitude by a factor of say 20 or so. Using the waveform to measure the area under the curve of the PD current, a measure of magnitude can be made which is much less sensitive to attenuation. The measurement of charge is made by simply integrating the charge under the current curve:

$$Charge = \int_{start_of_pulse}^{end_of_pulse} I * dt = \int_{start_of_pulse}^{end_of_pulse} const * V * dt$$

where 'const' is the multiplier which converts the current to voltage. This will include the transfer impedance of the current transformer and such factors as the cable impedance and amplifier gain. Hence using this method for calculating charge, the values of PD magnitudes can be measured in Pico Coulombs, provided that the detection impedance may be assumed to be the cable surge impedance, or a correction factor used. In practice the variation in the change of surge impedance at the ends tends to be less than 20% or so, when compared to measurements made in the ground straps of splices in the middle of the cable, where the surge impedance will be close to the surge impedance.

As an example of measuring the charge in this way, at 3km on an 11kV paper insulated mass impregnated non-draining (MIND) cable, the area measure had only reduced by a factor 3.

However, the amplitude measurement had reduced by factor of 15.

This means that for on-line PD tests, without the need for any calibration, the cable events can all be expressed in pico coulombs.

PRECISE LOCALIZATION OF PD EVENTS ON CABLES USING A TRANSPONDER

In the special case of testing high voltage cables, the usefulness of measuring PD activity is vastly increased if a localization of the PD origin can be made. For short cables, a double-ended method of timing the arrival of the PD pulses is the most effective. This requires a sensor at both ends of the cable, and a calibration of the cable travel time for both legs. For longer cables, getting a radio frequency cable to the far end sensor is not usually possible. Several methods have been attempted to overcome this problem. GPS sensors can be used to tie two PD recorders to the same absolute time. This method takes a lot of care is setting up, and requires a great deal of marrying up signals after the data is recorded.

Alternatively, the timing information from the remote end of the cable can be directed back down the cable cores themselves. A simple method has been adopted to achieve this. A transponder consists of a detector and trigger level for PD pulses, linked to a large voltage pulse generator, which launches pulses back onto the cable under test. Figure 4 shows a photograph of the two battery operated devices. The trigger levels for the input device spans the range 1mV – 1V . The linked pulse generator is capable of generating 1?Sec pulses at 200V into an open circuit. If high frequency current transformers are used as the detection and launching sensors, the system can be used successfully with cables of 2 or 3 km or more. The accuracy of the device is dependant on the rise time of the PD pulses, as the trigger must occur somewhere on the rising edge.

Figure 5 shows the results of carrying out the locations of a cable PD with and without the help of a transponder. In this case the location of the PD event is very close to the measurement substation, and the very large transponded pulse is clear. The total cable length was around 750m.

The transponder developed for localization of cable PD's is battery powered, allowing remote substation location measurements to be made, even if no local test power is available (a circumstance which is actually quite common). This method for localization has proved very successful largely as a result of its simple and direct application. If the PD pulses are clear, then the transponder method is very robust, and locations are always clear and unambiguous.

Figure 4 the trigger unit and large pulse generator of the transponder unit

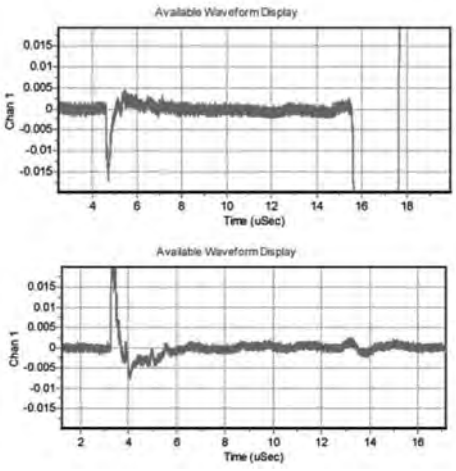

Fig 5 Location of PD pulses with and without transponder location pulses

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PD EVENTS FROM LOCAL EQUIPMENT

For on-line testing local equipment (switchgear, transformers, bushings etc) for PD activity, the most effective sensor is an electromagnetic pickup, placed on the outside of the grounded metal clad surface. Figure 6 shows a typical TEV probe.

These so-called transient earth voltage (TEV) pickups detect the electromagnetic pulses from inside the local equipment. They are essentially a capacitive coupling with the metal surface.

This type of sensor is only suitable for local PD pickup, as the sensors do not pass low frequencies. Typical cutoff frequencies are in the region of 2MHz - 5MHz, and signals must be above this frequency to be detected.

Figure 6 transient earth voltage probes (TEV's or capacitive pickups)

Hence for local PD, if the frequency content is typically above this cutoff value, the chances are extremely high that the pulses are from PD's originating in local equipment. The argument also applies to testing equipment with a high frequency current transformer as the pickup; as long as the upper frequency cutoff is above say 20MHz, so that the larger frequency content of the local PD pulses is observable. Figure 7 shows a typical resonant response from a local PD event.

Notice the fast oscillations denoting the large frequency content.

The algorithm for recognizing a local PD event is therefore very simple. If the frequency content of the event is above a critical cutoff, (somewhere in the region of 2MHz to 5MHz) then the event can be counted as a local event. This method cannot

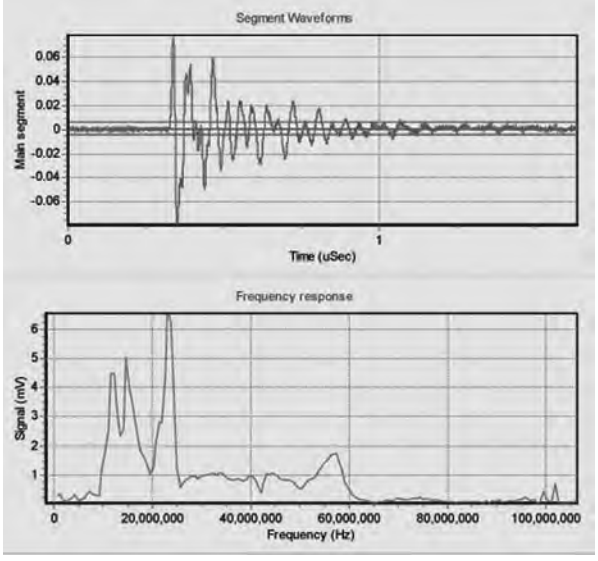

Fig 7 Waveform of local equipment event using a capacitive sensor

apply to ultrasonic signals and sensors, all of which have much smaller frequency content. Other methods apply for the ultrasonic case.

It is reasonably surprising that such a simple algorithm for recognizing local PD events is effective. However, pulses with larger frequency content which are not PD related, are in practice quite rare. The authors have seen some local processing equipment (intelligent switchgear monitors) which produced similar high frequency pulses, but with this exception, the vast majority of pulses with larger frequency content tend to originate from PD's within switchgear or similar equipment.

NOISE REDUCTION FROM CONTINUOUS WAVE INTERFERENCE

A large problem in PD detection comes in the form of radio broadcast interference. This is particularly the case for on-line measurements made on cables attached to switchgear which is not metal clad, although it can sometimes be a problem for metal clad switchgear.

To overcome this major problem, a spectral subtraction method was developed. Again the ideas for this were simple, and are shown schematically in figure 8.

Essentially the largest frequency in the waveform is calculated, and this frequency is subtracted from the waveform, leaving all the pulse data unchanged, but without the interfering RF noise. As the RF radio broadcast noise is in general in the medium or short waveband, the carrier is in general ampli-

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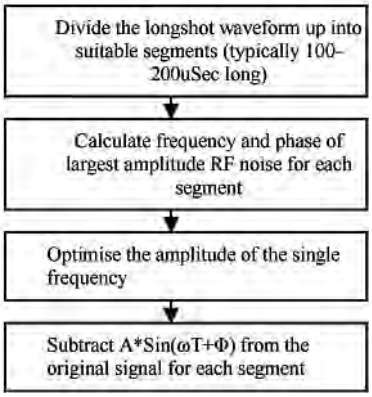

Fig 8 Method for reduction of RF interference from waveforms

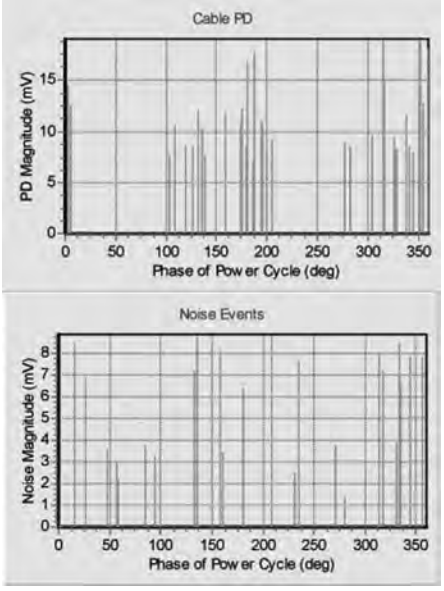

Fig 10 PD distributions across the power cycle in separate categories of cable PD and noise

tude modulated. Hence the best results are achieved if the length of the waveform is made over a time in which the modulation does not change much.

In practice for noise reduction of a waveform spanning the whole power cycle, the length of the segments which are noise reduced are typically 100?Sec - 200?Sec. Figure 9 shows waveforms before and after the noise reduction process.

In figure 9 the reduction in the standard deviation is around 7.6 between the two cases. The waveform interference is reasonably sinusoidal, and the results would be expected to be good in this case, but similar practical cases also yield similar reduction ratios. The double pulse in figure 9 is now clear and can be used for location purposes, whereas before the noise reduction, the second pulse is not evident.

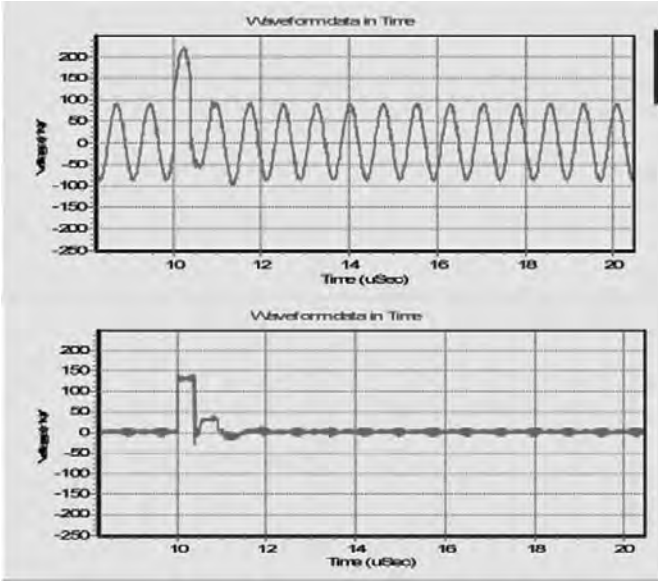

Fig 9 Waveforms from before and after the application of the noise reduction process

OPERATION OF EVENT RECOGNIZER METHOD

The implementation of the event recogniser algorithms starts with recording the complete waveform of a single power cycle of data. This is recorded at full sample rate (normally at least 100MSamples/sec). This 'longshot' recording is now RF noise reduced if required.

The resulting waveform is then analyzed for all the pulse data, and separated into populations of cable, local equipment and noise events. These categories can now be treated separately if required.

The pulsed data is now really a list of PD events with properties such as position in the cycle, channel number (if this applies), category of pulse, and all the pulse data from the curve fitting and frequency analysis. This per-cycle analysis provides for very powerful techniques for continuous monitoring and spot testing. The traditional data resulting from

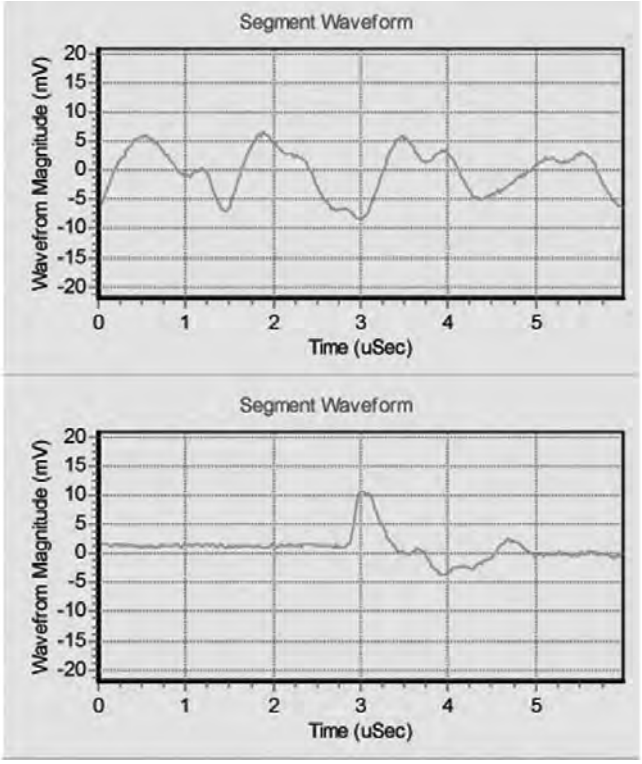

Figure 11 Waveforms of noise and cable PD respectively from the data in figure 10

PD measurements was a record of the peak and count values. In the new method, the peak and count data can be carried out for each category of pulses, and hence in essence for each type of high voltage equipment.

Figure 10 shows the results of 2 minutes of data recording,

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which recorded around 6 power cycles of complete waveform data. In this case, the PD pulses were mixed with a large number of different noise sources. The event recognizer has separated out the good data from the PD recordings, so that all the cable PD events are correctly identified. This was verified by manual inspection of the individual waveforms. Figure 11 shows two typical waveforms representing noise and cable PD respectively. If only peak and count methods had been used, all of these pulses would count as valid data. Using the event recognizer technique, noise can now be distinguished from the cable PD events. The recordings were made on an oscilloscope with an open PC, so the event recognizer software can be run internally on the device which records the data.

This improves data transfer rate between waveform recorder and the PC by a factor of between 2 and 5 times.

Hence by using this method, a large part of the classic difficulties of making PD measurements can be transformed by classifying the pulses into useable categories. This means that less experienced operators can have much more confidence in PD measurements, and that more experienced operators can carry out diagnostics very much more reliably from one set of data.

CONCLUSIONS

The paper has described several new tools which can help to make PD (partial discharge) detection for high voltage equipment much more robust and reliable, by removing two of the largest obstacles to making good PD measurements on high voltage equipment, namely:

- Noise reduction of radio Interference from broadcasts and power line carrier signals
- Separation of noise pulses from cable PD pulses and local equipment PD pulses

The methods described follow simple algorithms, and produce reliable results in practice. All the older traditional methods of measuring peak, counts and distributions for PD activity have all been retained. The new event recognizer tools essentially sit as an add-on to the original data.

However, the clarity and discrimination given by the new event recognizer methods will allow huge improvements in the quality of the PD data recorded. This especially applies to on-line PD measurements.

For the case of high voltage power cables, a location method based on a transponder placed at the remote end of the cable is described, which allows localization of PD events on cables to be made. This is particularly useful for on-line PD measurements where it is notoriously difficult to interpret waveforms to give good location data.

The tools have been developed into several commercial products, where the results from the users (not the authors) have been very encouraging. **ET**

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INTEGRATION OF PROTECTION, CONTROL, MONITORING AND REMOTE COMMUNICATION INTO ONE INTELLIGENT ELECTRONIC DEVICE FOR SMALL HYDRO-POWER PLANTS

By Gunnar STRANNE, Urban NYGREN and Lars MESSING, ABB Power Technologies; Magnus CALLAVIK, Lennart BALGÅRD, Bengt ROTHMAN and Per Erik MODÉN of ABB Corporate Research; and Lennart WIKTORSSON and Mats LINDBERG

ABSTRACT

This paper will briefly describe a new Intelligent Electronic Device (IED) containing integrated control, protection and communication elements for small hydro power plant. This joint project aims to setup two small hydro pilot installations at two Swedish utilities. The concept requirements and project results will be discussed along with results from a Simulink model of the turbine, generator and station control strategies.

(Editor's note: all references to Swedish monetary units - Krona - are abbreviated as SEK. The exchange rate is approximately seven Krona to 1 US dollar)

I. BACKGROUND AND REQUIREMENTS

Sweden has 1000 - 1500 small hydro power stations in operation erected during the last century. Due to low electricity prices and withdrawn subsidies during the 1990s small hydro suffered from low profitability. Consequently about 145 power stations were closed down or paused during a 10-year period from 1989 to 1999 [1]. During this period no or little investment was taking place. This trend was unwanted, since small hydro is both an excellent distributed renewable energy source as well as a part of the cultural and industrial heritage. However, in recent years electricity prices have risen substantially and electricity certificates have been introduced to support hydro power units below 1500kW at an additional price level of circa 250 SEK/MWh. Hence the profit of, and interest in running, small hydro has increased and the interest to renovate power stations in operation and starting up new ones has grown.

Still the relative value of electricity produced from a 1 MW station is relatively low, e.g. an annual production of 4000MWh a 500 SEK equals to 2 MSEK or 5000 SEK per day . Therefore profitable operation of a small station requires a stable system that is autonomous to a certain extent and runs with few unscheduled maintenance and support visits. Furthermore, the systems should have a long life-time with a availability of spare parts, rather than a tailor-made system. A change to a standardized solution that is easy to service is preferable.

Even for small hydro-power plants (< 2 MW) a relatively large number of functionalities must be included for efficient control and protection as compared to larger power stations. Functionalities such as voltage control, generator supervision, turbine control, water management, start/stop, excitation equipment and an interface to the operator control central or access via a remote PC are necessary. Generally the requirements to control all these functionalities set a demand for several building blocks to be included in the hydro-power plant control system. These requirements drive the complexities and costs almost to the level of larger hydro-power stations.

Although optimized production is important, the most vital requirement of the station is safe water management and a safe protection system. Moreover, if the proportion of distributed versus centralized generation unit connected to the grid will grow in the future. Also the role of the distributed hydro power station as a source for robust grid operation is likely to be further strengthened,, which will increase the requirements for protection and interface with the grid. Additionally ,the storage capacity of small hydro will be an asset for the grid operator when balancing other renewable sources such as wind which, in turn, will increase the demand for flexible operation of the power station.

I.1 OBJECTIVE OF THIS PROJECT

The objective of this project is to show how a standardized Intelligent Electronic Device (IED) can provide autonomous operation and prioritize safe water management. The IED should be compact and integrated with the control of electrical and mechanical elements including the flow of water, communication, monitoring and protection system for small hydro-power plants. The IED including all of the stated functionalities above are therefore provided in one compact unit that easily may be carried by just one single person.

I.2 PROJECT SET-UP

The project is realized together with one equipment supplier, two electric utilities and the Swedish Energy Authority to focus on (1) a solution with the minimum functionalities necessary to operate the station and (2) the most important re-

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quirements for reliable and cost-effective operation with the highest possible availability. Prototypes from ABB are planned to be installed in two hydro-power plants owned by participant utilities Mälarenergi AB and Tekniska Verken i Linköping AB.

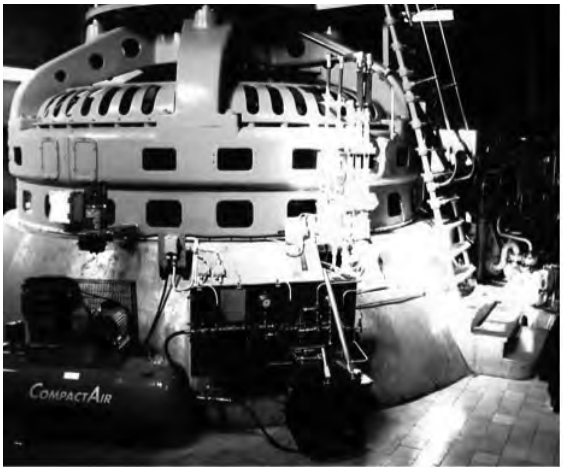

Figure 1 A and B: (A LEFT) Mälarenergi's generator at Surahammar power station. (B RIGHT) Tekniska Verken's Slattefors power station building.

I.3 DESCRIPTION OF THE POWER STATIONS FOR PILOT INSTALLATION

The final prototype concept will be installed in two power stations. One pilot is going to be installed at the Surahammar power station owned by Mälarenergi AB. This power station was erected in 1927 and is rated at 1.0MW, cf. the turbine in A. The second pilot installation is aimed at Slattefors power station owned and operated by Tekniska Verken i Linköping AB. Slattefors was erected in 1962 rated at 0.9MW (see B). Both stations have one Kaplan turbine with a synchronous generator.

II. THE MICROHYDROTM CONCEPTUAL APPROACH

The approach is to integrate station monitoring, turbine and generator control functionality into one commercial high performance protection and control IED. Voltage and current signals that are used by the protection unit are also made available to the control system without additional wiring. Integration of functionality into one unit is considered as a key to improve the cost performance.

Communication, on the other hand, is a technology field with fast development. Therefore the communication module is a separate unit, which can be replaced more often than the control and protection device. It is suggested to use a communication block, based on the IEC 61850 standard, with optional remote communication techniques to a remote PC or the operator control room. In the future it is anticipated that several hydro-power stations in a common watercourse would have the installed IEDs to provide an optimized electricity production by regulating an optimum flow of water through the system.

It is anticipated that using modern control and power electronic equipment will decrease the size of the installation of the control, protection and communication equipment substantially.

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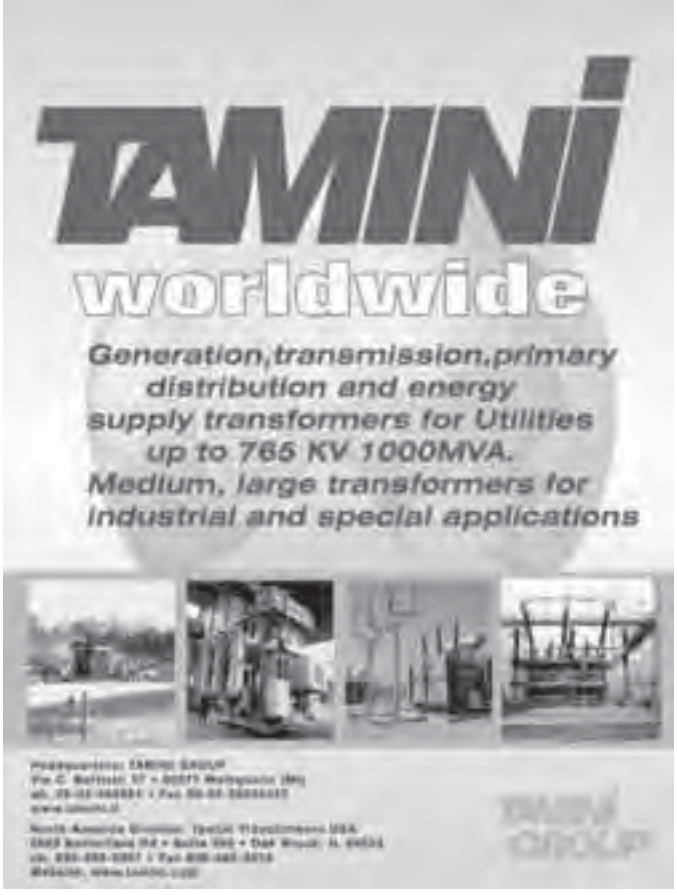
Figure 2 A and B. (A, LEFT) Example of front panel of existing control and protection system at Surahammar hydro power station (B, RIGHT) Example of new station control and protection system.



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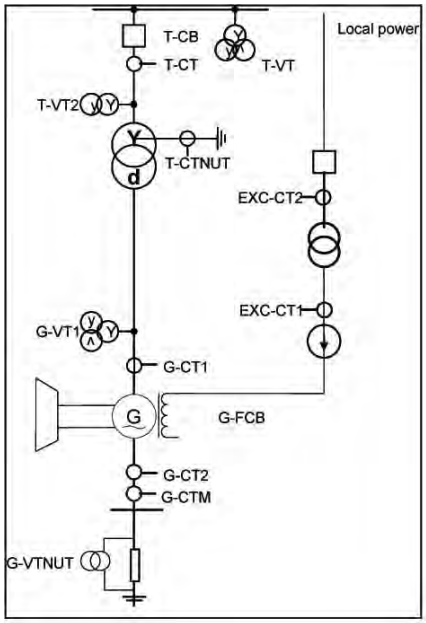
II.1 THE FLEXIBLE CONTROL AND PROTECTION PACKAGE

The configuration flexibility of the relay terminals enables protection of any generator and in particular systems according to the Microhydro concept where even more functions are required to be integrated into one common platform. A Generator Protection Guide describes the applications of individual protection functions and how they are implemented in the ABB 500-series of relay protection terminals [2]. Typical setting guidelines for each protection function are included.

The terminals can be ordered for different mounting arrangements (i.e. 19" rack, flush, semi-flush, wall mounting etc.). The 500 series terminals use a microprocessor-based modular platform hardware. More than 25000 such terminals have been delivered worldwide and installed in power networks with rated voltage up to and including 750kV. The main properties of the modular protection and control terminals are:

- The protection and control terminal is fully numerical device (i.e. based on micro-processor technology) with low power consumption in the measuring circuits;
- Great flexibility which easily adapts to user's practice;
- Protection functions to be included;
- Number of current and voltage inputs required (i.e. 10 or 20 analog inputs);
- Number of binary optocoupler inputs required;
- Number of contact outputs needed.

Customer requirements for tripping and external signaling, as well as needs for light emitting diodes (LEDs) to locally indicate status of the unit, starting with protection function and tripping etc. are easily met. Protection and control functions are available as standard/optional software modules and presented to the user as functional blocks. Each individual protective terminal can be provided with built-in, multicolor 18-LED panel module for visual indicators. Additional 40 seconds, integrated disturbance and event recorder can be provided for monitoring/recording up to 10 analogue and 48 binary signals per terminal. Alarms



Protection functions available (ANSI Device No)

- Generator differential (87G)
- Generator restricted EF (87GN)
- 2-stages, 80% stator EF (59N), 3Uo internally calculated
- CB failure protection for generator breaker
- Loss of excitation (40)
- Reverse power (32) with minimum setting of 3%
- Stator thermal overload (49S)
- 4-stages, 3ph over and under voltage protection (59 & 27)
- 2-stages, over and under frequency protection (81O & 81U)
- Overexcitation (V/Hz) protection (24)
- Negative sequence overcurrent protection (46)
- Undervoltage with overcurrent seal-in (27/51)
- Turn-to-turn (generator split star point overcurrent) protection
- Generator 3Ph overcurrent protection

Optional protection functions available

- Rotor EF, AC 50/60Hz injection via RXTTE 4
- 95% stator EF (59N) connected to generator neutral point VT
- 80% stator EF (59N) connected to generator open delta VT1 winding
- Rotor thermal overload for static excitation (49R)
- 3ph overcurrent protection (50/51) for excitation transformer
- 3ph overcurrent protection (50/51) and earth-fault protection (50N/51N) for auxiliary transformer

Figure 3. Typical single line diagram for generator-transformer unit and list of available protection functions.

for the following operating conditions can be provided as voltage free contacts, local LED indication or remote via communication:

- Generator frequency deviation (frequency outside pre-set band around rated i.e. ±0,5Hz);
- Generator voltage deviation (voltage outside pre-set band around rated i.e. ±5%);
- Generator loaded/not-loaded;
- Generator negative sequence overcurrent or over-voltage alarm;
- Generator over-excitation alarm;
- Generator loss-of-field alarm;
- Generator reverse power alarm;
- VT fuse failure alarm;
- Loss of injection voltage for rotor earth fault protection.

II.2 PROTECTION METHOD

Generators are designed to run for a large number of years at a high load factor and also to permit certain incidences of abnormal operating conditions. The synchronous machine and its auxiliaries are continuously supervised by monitoring devices to reduce the exposure to abnormal operating conditions to an absolute minimum. Despite monitoring, electrical and mechanical faults sometimes occur, and the generators must be provided with protective relays that quickly initiate disconnection of the machine from the system in case of a fault and when necessary initiate the complete shutdown of the generator.

No international standard exist regarding the needed configuration of the protective schemes for different types and sizes of generators. Manufacturers provide recommendations and there are guides given by various organization Standards. The protective scheme configurations may vary from country to country and also between power companies in the same country. There are also different needs to consider depending on the specific machine construction. For these reasons the generator protective schemes are flexible.

In the Microhydro concept the generator and the step-up transformer are protected by common equipment. There are also back-up protections for faults outside the protected zone. In practice, there are many mechanical and thermal protection devices that help avoid damage to the power-generating unit. Their output signals typically come to the protection panel as potential-free contacts or mA or voltage signals and incorporated in the overall tripping and alarming scheme via inputs to the terminal.

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II.3 CONTROL AND MONITORING

The functionality required for the control of a small hydropower station is provided by function blocks as illustrated in the block scheme in. The scope includes:

• control of the water level – with various modes of operation;

• normal operation at specified power, water flow, or guide vane opening;

• logic for the timing of start and stop sequences;

• synchronization including required speed control as well as the actual closing of the breaker;

• control of a gate, the guide vanes, and the runner blades by means of binary increase/decrease signals for each actuator (normally acting on hydraulic valves).

It does not include the direct control of the exciter, but it does include provision of the orders to the excitation control to perform voltage control (during synchronization, until the breaker is closed) or control of either reactive power or power factor (during normal operation). Concerning the water level, the following modes of operation are provided:

• Continuous level control – The level is controlled by varying the flow through the gate as well as the turbine, but using the gate only when the required flow is higher than the turbine can accept at the moment;

• Intermittent operation – When the water level approaches the upper and lower limits, the turbine is automatically started and stopped, respectively;

• Level control to within limits - Normally the turbine runs at the preferred operating point. When the water level reaches a limit, level control becomes active in order to get it back inside by means of varying the turbine flow and if necessary also the flow through the bypass gate.

The function blocks have a number of parameter settings that allow adaptation to the particular power station. In addition to that, one can configure the exact conditions to be included in the start sequence by adding simple logic function blocks as required. Apart from automatic start and stop as in intermittent operation, it is of course possible to manually give start or stop orders, and to adjust set point values and limits that govern operation.

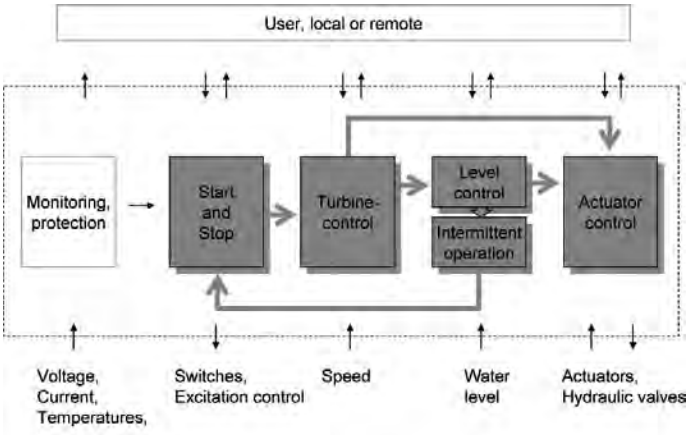

Figure 4. Microhydro interfaces

II.4 COMMUNICATION HIERARCHY

The communication box is intended to work as a gateway between the station networks and a WAN to enable secure remote control. Some extra server functionality must be added to enable a local graphical HMI using just a standard web browser as display. The Web browser could be installed in a permanently mounted touch screen or alternatively on a laptop that the user has when visiting the station. For electrical protection reason this network is based on optical Ethernet to provide galvanic insulation. The communication solution uses three networks for three purposes:

i. A station network that can be designed as standard office network to enable easy connection to miscellaneous devices, e.g. local HMI panel, web cameras and other types of Ethernet connected devices. The station network is based on Ethernet (CAT5 RJ45) and TCP/IP.

ii. WAN based on Ethernet and TCP/IP to enable connection to an as wide as possible range of communication ways between the station and control center. This network is used to connect the station to remote control center through a public or private network, e.g. GSM or rented phone lines. This network serves as protection firewall and is VPN built.

iii. IEC61850 network. Real-time network used for connection to and between IEDs to the remote control center or the local HMI.

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II.5 EXCITATION

The Microhydro concept should be applicable independent of the turbine and generator equipment used, e.g. both for asynchronous generators without excitation as well as for synchronous generators with excitation. Since small hydro stations have been installed over a period of more than 100 years, many various types of excitation equipment exist in the stations today. Old synchronous generators usually have a rotation device for excitation driven by the mains shaft, a separate turbine or motor. Brushes and other equipment in these solutions may demand extensive maintenance and could discontinue operation. More recent installations usually have static power electronic excitation equipment. The rotating converter has sometimes been kept and sometimes been bypassed in recent overhaul. Brushless systems are uncommon in small hydro applications in Sweden, although these systems would be welcomed to limit maintenance.

The vast number of different solutions that exist today does not make it possible to set one standard excitation solution. The conceptual aim is to provide one solution with an integrated approach and one solution with a clean interface to the excitation hard and software.

II.6. MODEL OF THE STATION AND TURBINE CONTROL

As a means to verify the intended control solution and illustrate its behavior, an

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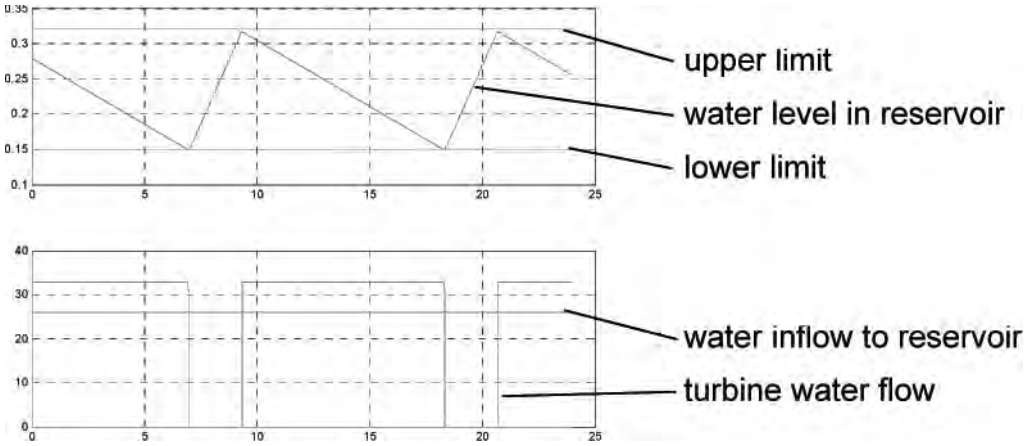

Figure 5. Intermittent operation – turbine at preferred operating level, or closed – the switching governed by the water level reaching its upper or lower limits

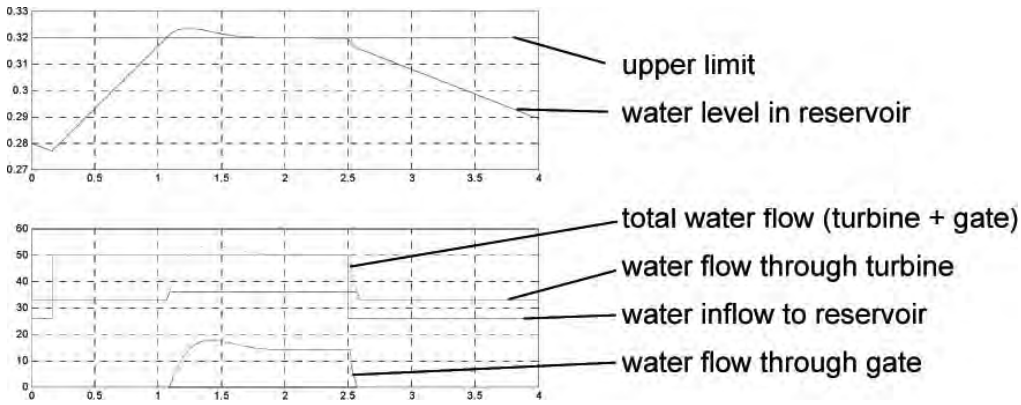

Figure 6. Level control to within limits – turbine at preferred operating level as long as water level is within limits – combined flow through turbine and bypass gate is varied to control the level when so required in order to keep it within limits.

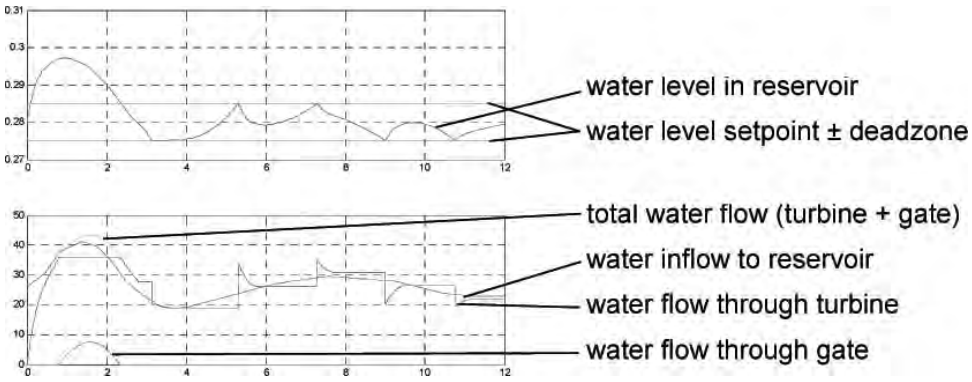

Figure 7. Continuous level control – the flow is varied continuously to control the level to within a small dead zone around the set point, the dead zone enabling the control to come to rest for certain periods of time

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implementation was made in terms of a Simulink model. A reservoir model was added, and simulations were run according to the different modes of operation – continuous level control, level control to within limits, and intermittent operation. Some of these simulations are shown below. They show a case of intermittent operation when the inflow of water to the reservoir remains constant.

Figure 6 shows a case of level control to within limits, where an artificial step is disturbing the reservoir inflow. In fact, there is first a step up and then a step back down, and during this period the inflow is larger than the maximum flow through the turbine, so the bypass gate has to be opened as well in order to keep the water level at the limit.

The continuous level control case (Figure 7), is applied when there is no reservoir or a very small one. Here, the inflow gets high enough for a short period of time to require opening of the bypass gate. The simulation model was also extended to allow simulation of start and stop of the turbine.

II.7 BENEFITS

With a standardized integrated concept it is foreseen that significant cost savings and benefits can be achieved. An attempt to quantify this is given in Figure 8. **ET**

	Installation	Operation	Maintenance	Analysis
Completely integrated	50%	20%	20%	10%
Autonomous	10%	10%	10%	5%
New functions	5%	10%	10%	10%
Communication	-	10%	-	50%

Figure 8. Benefits with a standardized integrated concept

III. ACKNOWLEDGEMENT

Funding for part of this project by the Swedish Energy Agency is greatly acknowledged.

IV. REFERENCES

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[2] ABB Product Guide for RET521 at www.abb.com/substationautomation

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INTERNAL INSULATION FAILURE MECHANISMS OF HV EQUIPMENT UNDER SERVICE CONDITIONS

By A.K. LOKHANIN, T.I. MOROZOVA of the All-Russian Electrotechnical Institute; G.Y. SHNEIDER, Electrozavod Holding Company; V.V. SOKOLOV, Scientific and Engineering Centre ZTZ-Service Research Institute and V.M. CHORNOGOTSKY of the Ukrainian Transformer Research Institute

SUMMARY

This article presents some considerations in failure mechanisms of oil-barrier transformer insulation and oil-paper condenser type insulation of instrument transformers and HV bushings on the basis of service experience and special studies.

1. TYPICAL FAILURE MODES OF EQUIPMENT

Table 1 summarizes some typical defects and failure modes of oil-barrier insulation of transformer, shunt reactor, condenser type bushings and instrument current transformer that were suggested on the basis of service experience [1,2,3] considering a wide range of equipment design and operation conditions. However actual failure-modes and failure cause can be substantially different for different insulation design. Analysis of operation experience with transformer and other equipment in CIS countries for the last 10 years has shown the following picture.

Power Transformers

Insulation problems involve predominantly impairment of insulation condition in service.

Excessive moisture in the cellulose insulation is inherent basically to the transformers with open-breathing preservation system or to those which have an insufficient sealing. Distribution of the moisture in the course of the transformer life is kept quite non-uniform. Most of the water is stored in so-called "cold thin structures", namely in the thin pressboard barriers that operate at bulk oil temperature.

General "aging" problem is accumulation of conductive and polar particles in oil and depositing them on the service. Insulation surface contamination has been observed in the forms of the adsorption of oil aging products with cellulose or deposits of conducting particles and insoluble aging products in areas of high electrical stresses. The surface contamination can cause a distortion of electrical field and a reduction in the electrical strength of the insulation system.

Relative failure rate of power transformers 100 MVA and above in CIS countries is about 1%. The rate of major failures of insulation is about 0.5%. About 25-30% of major failures are associated with breakdown of major and minor insulation being in service over 20-25 years due to accumulation of manifold agents of degradation.

The most likely failure modes are the following:

– occurrence of critical PD in oil due to penetration of free water through bad sealing that results in breakdown between coils typically of HV winding and breakdown of oil gap between HV winding and tank;

– flashing over HV winding under effect of switching surge and lighting impulses due to contamination surface likely with conductive particles and polar oil aging products;

– progressing creeping discharges between phases and between winding – to ground. This type of failure mode has been observed only with some old design as a result of severe contamination of insulation with metal particles and distortion of insulation structure due to winding buckling.

Type of equipment/ Insulation	Typical defects and faults	Failure mode
Power Transformers and Shunt reactors: Oil-barrier insulation	Moisture contamination; Particles contamination; Bubbles evolution; Surface contamination; PD of low energy	Distractive PD; breakdown of oil; surface discharge; creeping discharge
Bushings and Instrument Transformers: Oil-paper Condenser type Insulation	Residual Moisture; Poor Impregnation Overstressing; Ingress of Moisture Ingress of Air; Oversaturation with gas; Aging of oil and Oi Paper Body; Thermal Instability of oil; Gas Unstable Oil; Copper Migration; Dielectric Overheating; Incipient Ionisation X-wax deposit	Critical Ionisation→ Puncture→ Explosion Thermal instability of the oil/paper dielectric→ exponential increase of dielectric losses and temperature→ critical ionisation→ Explosion
Bushings: Oil and Internal Porcelain Surface	Ageing of oil; Formation of metal-contained colloids and particles; Semi conductive deposit; Migration of bound water	Critical ionisation in oil; Surface discharges; Flashing over porcelain
Bushings: External porcelain surface	Transformer oil contamination; Picking up particles by porcelain surface; Semi conductive deposit; PD activity	Critical PD; Flashing over porcelain

Table 1. Typical defects and failure modes in insulation of oil-immersed transformer equipment.

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Shunt Reactors 400-750 kV

The relative rate of major failures is about 1%, and about 40% of forced outages are associated with insulation problems. The following failure modes were involved:

– flashover along the winding and traces of discharges on the barrier facing to the winding;

– flashover between pair or several coils;

– flashover along the inner surface of low porcelain of the bushing.

In many cases severe contamination of insulation with metallic-dust view particles was found. Wear of the pumps bearings, aluminium shield attrition and localized oil heating were recognized in some cases as sources of particles generation.

HV Bushings

Bushings cause about 45% of transformers major failures.

Aged mode failure occurs predominantly. About 80% of failures take place after 10-12 years of service and over 30% after 20-25 years. Core failures happen practically only with unsealed design. Two failure modes have been suggested: ingress of free water resulting in occurrence of critical ionization at the bottom part of the core, and aging of oil paper bulk, occurrence of excessive dielectric losses, that results in thermal instability.

Experience has shown a very low rate of core failure of bushing designed with sealed preservation system incorporating overpressure bellows (about 10 cases per about 100 000 bushings population since 1971). However experience has shown also that hermetically sealed preservation system is more sensitive to residual contaminants, and occurrence of aging by-products. Special requirements shall be specified regarding to selection the proper oil, compatibility tests, processing procedures.

Unusual failures of condenser core have been observed with circuit breaker's bushings of free breading design.

The problem is associated with X-wax formation at low temperature.

The main failure mode of hermetically sealed bushings involves overflashing along internal lower porcelain due to predominantly oil aging and deposit of semiconductive stain on the porcelain surface.

Current Transformers 220-750 kV

The failure rate of 220-500 kV CTs accounts for more than 60 % of the total instrument transformers failures.

The rate of major failures of insulation is about 0.35%.

Two failure-modes have been typically observed:

1. Ionisation-mode failures that occur predominantly in wintertime. These are referred to as "cold failures." They typically happen on the "toroid shape" designs and are caused by de-impregnation of the condenser core, ingress of air during storage, and over-saturation with air that results in bubbles evolution after fast cooling in service.

2. Aging –mode failures that have occurred after 15-25 years of service in the summer are referred to as hot failures. Those involved are typically openbreathing CTs and with hermetically sealed units filled with oil having some elevated (14-18%) aromatic content, and are caused by increased dielectric losses, followed by thermal run a way and subsequent ionisation process. Aging of oil, oil/paper bulk, and in some cases localized moisture contamination have been observed as the most probable life-limiting factors.

2. FAILURE MECHANISMS OF OIL-BARRIER INSULATION

2.1 Summary of transformer models investigation

Short-term and long-term tests of aged oil-barrier insulation on the basis of life models studies have revealed the following aging-mode problems:

Reduction of switching surge breakdown voltage due to a deposit of insoluble aging products in areas of high electrical stress and stimulation of surface discharge occurrence [4].

The minimum breakdown voltage at switching surges may decrease approximately by 15% after aging. Increasing the concentration of particles in oil (from 50 cm-3 up to 160 cm-3) may decrease switching surge breakdown voltage additionally by 10%.

Long-term dielectric strength tests revealed two mechanisms of insulation breakdown:

- "accidental" breakdown was observed during the first period of aging due to the influence of particles and moisture;

- "wearing mode" breakdown due to degradation of materials appeared at the last stage of the calculated term of aging. The latter results in decreasing the initial dielectric strength by 30-40%

Probable cause for the reduction of electrical insulation

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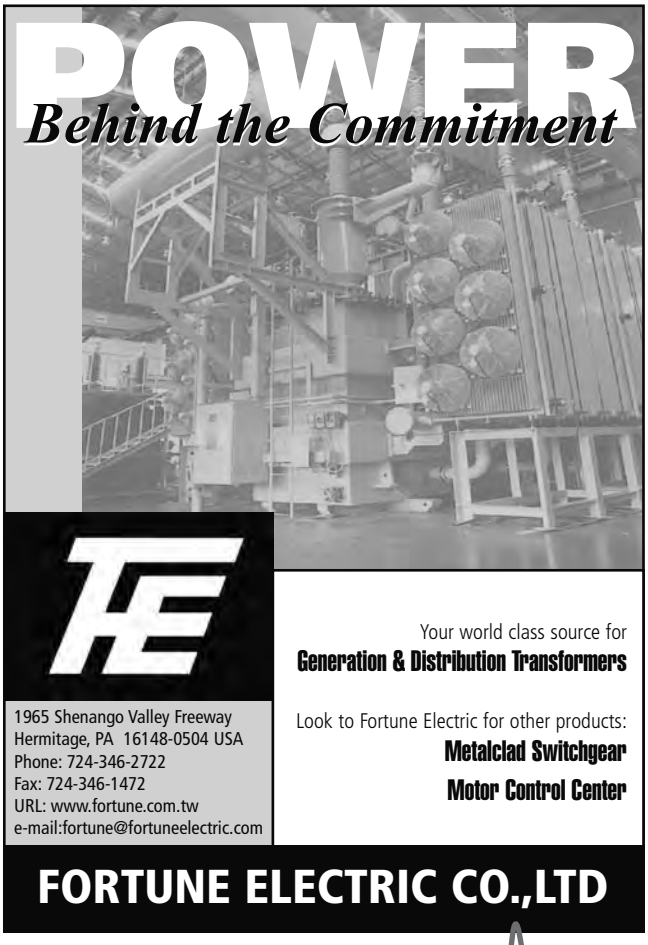

INSULATION

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strength is the formation of aging products, specifically, of anionic surf actants and bound w ater, which is not determined by the typical methods.

2.2 Mechanism of the incipient irreversible failure in oil-barrier insulation:

The first stage if incipient f ailure is associated with critical PD occurrence.

Mechanism of PD occurrence and progressing depends substantially of the configuration of electrical field. Presence of significant magnitude of tangential component of electric f ield intensity is critical to stimulate surface and creeping discharges.

Typically the f ailure is initiated by the breakdown of oil gap, which is registered as an apparent char ge in excess of 10-8 C that rises rapidly to 10-7-10-6 C. It progresses in surf ace discharge in oil across the barrier with PD magnitude over 10–6 C.

"White marks" appear on the surface due to forcing oil and water out of the pressboard pores followed with carbonised "black marks" on the barrier. PDs of 10-7-10-6 C may cause an irre versible damage during tens of hours.

Minimum energy required to cause incipient carbonizing in the cellulose (heating o ver 300 0C) is estimated as 0.1 J, which corresponds to se veral charge pulses of 10-7-10-6 C

Stable discharge in oil associated with PD po wer is P>0.4 W.

An average rate of gas generation under the ef fect of stable PDs in oil is 50 ?l/J

Further steps progress either in the breakdo wn of the insulation space or in the occurrence of creeping discharge.

Possible source of critical ionisation	Gas (air) bubbles (pumps cavitations; residual air after refilling with oil; intensive local oil heating); Penetration of free water; Metal particles contamination; Local overstressing the oil gap; High tangential field component across pressboard surface related with direction of insulation rolling (along the fibbers)
Insulation design configuration stimulating creeping discharge progressing	Creeping path along pressboard between electrodes; Winding disk-to-disk transient touch to adjacent barrier; Touch of barrier to bushing or grounded details
Conditions for creeping discharge occurrence	Magnitude of tangential component of electric field stress ≥1.0 kV/mm

Table 2. Conditions for creeping discharge occurrence (service experience and experiments)

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2.2.1 Creeping discharge

This is, likely, the most dangerous failure mode that typically results in catastrophic failures at normal operating conditions. The phenomenon occurs in the composite oil-barrier insulation and progresses in several steps (table2):

- partial breakdown of oil gap;
- surface discharge in oil across a barrier (an appearance of black carbonised marks on the barrier);
- microscopic sparking within the pressboard or between layers of pressboard sheets where gas evacuation is limited. The presence of some excessive moisture stimulates vapour bubbles forming and degradation of material;
- splitting oil molecules under the effect of sparking.

The formation of hydrocarbons followed with the formation of carbonised traces in the pressboard. This process is resulted in lowering magnitudes of PD apparent charges to 5·10-10-10-9 C however PD energy is still high enough to destruct cellulose.

Creeping process can continue from minutes to months or even years, until the treeing conductive path causes shunting of an essential part of transformer insulation resulting in a powerful arc.

The cellulose destruction while discharge progressing within the pressboard is associated with PD q ≈ 10-9 C; PD power P=0.1-1 W, average rate of gas generation of 40-50 ?l/J.

Three critical factors could be advised to evaluate probability of creeping discharge occurrence:

- Source of initial critical ionisation of high energy to cause carbonised marks of the barrier;
- Specific insulation design configuration;
- High enough dielectric stresses.

2.2.2 Surface discharge

Occurrence of surface discharge is associated with increased voltage (transit overvoltage). Two mechanisms could be suggested on the basis of studies (table 3):

1) Oil breakdown progressing into insulation destruction;

2) Surface discharge as self-firing phenomenon.

A magnitude of tangential component of electric field stress that can result in PD occurrence and forcing oil out of pressboard (reversible–mode "white marks») could be suggested as criterion of dielectric strength across insulation surface. Investigation of models of unaged, dry and clean insulation has shown that surface discharge can occur under action of electric field stress 6.5-12.5 kV/mm on condition if ratio of average and maximum field intensity in oil gap is 0.4-0.5 or less.

Apparently, contamination of surface with conductive particles reduces the value of critical field intensity.

Specimen: shape of electrode; Dielectric material	Incipient Failure	Development of failure
Aluminium cylinder ϕ 150 mm, sharp edge- pressboard	Occurrence of PD≈10^{-10} C; visible luminescence; small bubbles	1st phase (tens seconds): unstable surface discharge of $5\cdot10^{-8}$ C; intensive gassing; intensive luminescence. 2nd phase: Discharges penetrate deep into the pressboard; PD intensity reduces to $5\cdot10^{-10}$ C though intensive destruction of material goes on
Aluminium cylinder ϕ 150 mm, rounding edge radius 1 mm - pressboard	Oil breakdown: PD of 10^{-9} –10^{-8} C; increase of PD repetition rate	Discharge progresses within pressboard; PD intensity <10^{-9} C
Aluminium toroid insulated with craft paper, rounding edge radius 9 mm - pressboard	Surface discharges PD of 10^{-7} C	Intensive gas evolution; Intensive PD> 10^{-7} C; breakdown after 30 s

Table3 Mechanisms of surface discharge origin and progressing; HV Power frequency tests of models

3.FAILURES OF BUSHINGS CAUSED BY STAINING OFF THE LOWER PORCELAIN

3.1 Failure mode induced by peculiar oil aging and staining of internal porcelain

Discharges across the inner part of the transformer end porcelain are outcome of a typical aging-mode phenomenon in the bushing [3]. The failure process is initiated and developing within the oil channel between the core and lower porcelain.

Electric field intensity in the oil channel and across the surfaces of core-end components and inner porcelain is established both by the bushing insulation design and by disposition of the bushing end relative to the grounded parts and the winding.

Formation of semi-conductive residue on the inner surface of the lower porcelain has been followed and known to reduce the dielectric safety margin of the insulation space, causing a flash over across the inner surface.

The failure process may be introduced as the following:

- degradation of the oil and formation of oil decay products, particularly colloids containing atoms of metals; evolution of anionic surfactants and hydrate (bound) water;
- deposits of semi-conductive sediment on the surfaces under effect of electrical field;
- distortion of electrical field, change in the distribution of the voltage along the porcelain; reducing the dielectric strength of the oil due to transfer of bound water in dissolved state and particles [5];

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- surface discharges, gas evolution, and flashover.

Electrical Effect of Bushing Installation

Approach the bushing end to the grounded components can increase field intensity by 20-25% and essentially distort the inner field picture.

In some cases (e.g. some design of shunt reactors) a large stressed volume of oil is set up, which is very sensitive to oil contamination. Spare margin of dielectric strength of the bushing integrity determines by dielectric strength of the oil channel between the core and porcelain.

Reducing dielectric strength of oil can critically reduce the margin and cause partial discharge activity

Electrical field impacts on chemical reactions in oil and favours coagulation of colloid.

Electrical field across the stained bushing surface attracts and picks up the conductive –mode particles out of the transformer oil.

Thermal Effect of Transformer

Heat, which is radiated from transformer tank, determines air temperature around the air-end of the bushing.

Transformer oil is the main source of bushing heating.

Another two sources are dielectric losses in the core and resistance losses in the central conductor. The latter does not effect essentially on temperature distribution if bushings current is less than 50% of rated.

The basic heat exchange is expected to be in the oil channel between the core and porcelain, specifically close to the bottom of the mounting tube approximately on the level of top oil of transformer, where principal mass exchange takes place. Here convection flow turns down close to the surface of the core. The maximal temperature of bushing oil in some place can be equal to the top oil temperature or even above that.

Peculiar process of bushing oil cooling favours formation of colloids.

Effect of oil type and compatibility of the oil with other materials

Field experience and laboratory tests of numerous bushing models have shown that significant impairment of bushings condition have been occurred practically only with acid treated oil containing relatively high aromatic carbon-hydrogen content (CA=17%), that has shown the following properties: high hygroscopic, an elevated content of bound water; aniline point 710C that promotes interaction with rubber gaskets and especially with plasticizer, inclination to form polar aging products and sludge [6].

It was shown also that oil-proof gaskets have shown different effect of oil aging acceleration. Particularly, a gasket with plasticizer can contribute to oil deterioration and promote the formation of semi-conductive sediment on the porcelain.

3.2 Failure mode induced by staining the outer surface of bottom porcelain

Experience has shown that dielectric withstand strength of the oil part of HV bushing could be very sensitive to contamination of transformer oil with conductive particles.

There have been several documented cases associated with a deposit of carbon on the lower porcelain, which originated from the localized overheating of the core, and with deposits of iron particles on the porcelain surface, which originated from pump bearing wear.

Formation of metal-contained colloids resulting from aging of oil with rubber and transformer metals has been observed also as a typical origin of porcelain contamination

Electrical field around the bushing stimulates picking up the particles by the porcelain (a trap effect).

Uneven distribution of voltage along the porcelain close to the gasket joint and presence of electrical field in this area is a typical phenomenon for condenser type bushings.

Maximum field intensity is located just in the vicinity of the gasket joint.

Increasing the field intensity may strengthen "a trap"- effect and result in further extension of the staining area.

The following mechanism of bushing deterioration could be suggested: forming of conductive-mode residue because of complex aging of the transformer oil in the presence of a leaching substance of rubber gasket and transformer metals. This is in combination with dissolved and suspended metals in the transformer oil could cause adherence under influence of an electrical field formed by the bushing and the grounded parts of transformer.

The difference in quality of the oil in the transformer and that used in the bushings and also some difference in oil temperature could be the main factors to explain occurrence of the formation of the stain on the outer surface only.

A local increase of the electrical field intensity in the "Bushing-Tank Wall" space could cause a concentration of conductive substances in this region. Accordingly, that could explain the formation of the semi-conductive streaks along the porcelain.

The following dangerous factors of effect of the stain should be considered:

- reduction of the porcelain leakage path (or insulating distance) and accordingly reduction of the incipient voltage of surface discharge appearance;
- mitigation of the shielding effect of the grounded shield (grounding layer) and accordingly strengthening the electrical field across the surface close to the grounding sleeve and particularly near to gasket location;
- strengthening the "trap"-effect of the stained porcelain to attract conductive-mode particles out of transformer oil.

Presence of the conductive stain on the porcelain may be introduced as "extension" of the grounding sleeve, which results in diminishing the shielding effect of the grounding layer of the core. This phenomenon may cause significant increase maximal field intensity. Accordingly, it could explain substantial reduction of the dielectric withstand strength of the bushing and possible occurrence of PD in the area close to gasket joint location of the stained bushing.

3.3 Failure of oil-filed paper insulation of non-sealed bushings of HV circuit breaker.

When disassembling a bushing of 220 kV oil-filled circuit breaker, failed during operation, mere has been found plenty of X-wax. The failure occurred after operation for three years approximately. DGA analysis of oil samples from sister-type bushings (more than 20 pieces) has shown high concentrations of hydrogen (up to 3.5%), lower but exceeding permissible values of methane (up to 0.5%), ethane (up to 0.2%), carbon monoxide (about 0.5%). The bushings were put out of operation, and delivered to the manufacturer for investigations.

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The later tests on a part of these bushings showed an essential increase in tan ? for the main insulation depending on voltage, and high level of partial discharges (up to some hundreds pC). When doing so, even at low- voltage (10 kV), the value of tan? exceeded the nameplates values as large as 1.5 - 2 times.

All the bushings considered above, have been filled with oil of type GK. In bushings filled with oil of type T-750, having a non-sealed construction, with an insulation construction with is quite identical to that of the bushings considered, at the same operational electric field strength, wax formation has never been detected. Therefore the cause of PD occurrence in the bushings considered shall be searched in difference in properties of oils GK and ?-750. The difference in consequences of PD action on oils GK and ?-750 are caused by the fact that oil of type GK has the more ability of gas emission (its relevant factor is greater by 2.5 fold than that of oil T-75O, therefore creation of conditions for wax formation process ^formation of gas-oil mixture) is easier in oil GK than in oil T-750. Since the value of solubility of atmospheric gases for oil GK is practically equal to that for oil T-750, there are no reasons to suppose that the cause of PD occurrence in the bushing insulation is bound up with formation of gas bubbles when changing the oil temperature.

Experimental investigations of insulation specimens

The specimens (two little sheets of cable-insulating paper, each of them is 0.12 mm thick) were the combinations of paper and oil GK, having the different moisture content:

- 'dry' paper (Wp = 0.5% - 1.0%) and 'dry' oil (W0 - 5 g/t.-9 g/t);
- 'dry' paper and 'wet' oil (WQ = 20 g/t - 40 g/t);
- 'wet' paper (Wp > 4%) and 'wet' oil.

The specimens were tested in sealed and non-sealed vessels.

A part of specimens was at the room temperature (+20°C) all the time. The other part of them was being cooled to +5°C, -10°C, -15°C and -20°C. After cooling and exposure at this temperature, a voltage was being applied to the specimens, and they were warming within 1.5 to 2 hours. A voltage was being applied for 6 to 8 hours every day. The total time of the voltage action was equal to 50-55 hours. The voltage value corresponded to that for the occurrence of steady PD (50 - 100 pC). At the voltage application, the apparent charge and the number of PD pulses were registered.

Some specimens of 'dry' paper and 'dry' oil were being naturally moistened within 1,5 month, this increased the moisture content of the oil to 25 g/t. Some other specimens were made of paper of a failed bushing, which contained moisture (about 20 g/t), wax and oil.

It was revealed that the PD inception voltage varied little for all the specimens, and was equal to 11 - 13 kV . However PD development character essentially depends on the moisture content of specimens, temperature conditions and hermetic sealing of the device.

In the sealed vessel, irrespectively of moisture content of specimens, at cooling-warming cycles for oil: +20°C, -20°C, +20°C> the PD development process, the location of their occurrence (the sharp edges of electrode), the number of PD pulses (about 10-14 pulses/minute) and their apparent charge (900 - 1300 pC) are the same as at the room temperature (+20 °C).

In the non-sealed vessels, when testing specimens of paper- oil insulation which were artificially moistened, at cooling- warming cycles for oil: +20°C> -20°C> +20°C, the number of PD pulses increased to 20-25 pulses/minute but me values of their apparent charges were equal to 100-300 pC. In these specimens, carbonised traces of PD took place in the area of uniform field. There were no traces of wax formation.

When testing the specimens, who were naturally moistened, the character of PD was the same as at tests of the specimens moistened artificially. However when disassembling them, X-was was detected between layers of paper.

Therefore the supposition that moistening of oil in a non-sealed equipment followed by X-wax tonnation can be the cause of PD occurrence in paper -oil insulation in uniform field, has been confirmed. **ET**

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SWITCH MODE POWER SUPPLIES FOR ELECTROSTATIC PRECIPITATORS

By David Seitz and Helmut Herder, NWL Inc.

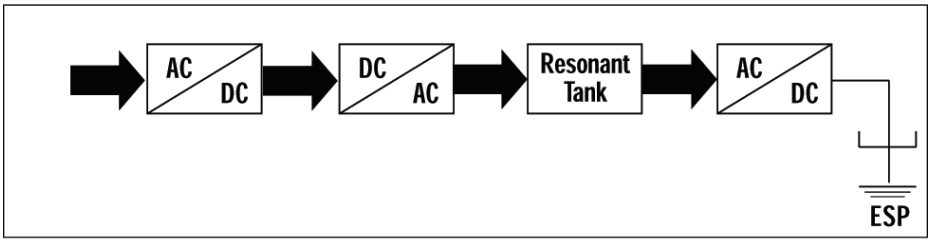
I. INTRODUCTION

Switch Mode Power Supplies (SMPS) are being introduced to the electrostatic precipitator market at price points that are very competitive with linear transformer/rectifier sets and SCR-based controls that have been used in the industry for many years. The new switch mode power supplies have dramatically different performance and physical characteristics than the linear power supplies they will be replacing. As applied to the ESP application, the new power supplies will have a major impact on many aspects of precipitator design, construction, operation, and maintenance.

Suppliers and users of ESPs need to become familiar with this new power supply technology, in order to assess the specific effect that its introduction will have on their businesses. This paper provides an overview of the changes that can be anticipated as SMPS are applied to ESP applications.

II. DESCRIPTION OF SWITCH MODE POWER SUPPLIES

A functional block diagram of a typical switch mode power supply is shown below:



The AC/DC block takes the three-phase input and rectifies and filters it to create a fairly smooth DC bus of approximately 650 volts DC. The DC/AC block consists of an integrated gate bipolar transistor (IGBT) full bridge circuit which converts the DC bus into a high frequency AC waveform. The Resonant Tank block, combined with the last AC/DC block, steps up the high frequency AC, rectifies it, and thus delivers high voltage DC to the ESP load. This block, which is oil-filled, is the high frequency equivalent to a conventional 60hz. T/R set.

Difference in Circuit Toplogy Over Linear Power Supplies

Due to the fact that the step-up transformer operates at high frequency, it can be approximately 1/10 the size and weight of an equivalent 60hz. transformer. It will also use significantly less cooling fluid. The circuit design requires that the AC/DC and DC/AC modules be located very close to the step-up transformer. Therefore it is both practical and necessary for the switch mode power supply system to consist of one physically integrated package, unlike current systems in which the control cabinet and transformer/rectifier set are separate units, often located a considerable distance from each other.

Since the IGBTs can be quickly turned off on command and do not wait for the line current to decay to zero, the circuit can turn on and off over 250 times faster than a linear power supply. This will allow new control algorithms with particular benefits for intermittent energization.

Because the AC input voltage is rectified, filtered, and then switched very fast (25 kHz) in small packets of energy, the ripple voltage is only 3-5% of the DC voltage level as compared to 35-45% for linear 60 hz. power supplies.

The three-phase input results in a much higher power factor (.94 vs. .63), and lower power consumed per kilowatt of power delivered to the precipitator load.

In summary the major differences in electrical characteristics for a switch mode power supply are:

- Small integrated control and T/R package
- Faster control response
- Higher average output voltage
- Less power consumed

Each of the improvements listed above has a potentially large impact on ESP construction, operation, and maintenance. The changes in control response and output voltage seem likely to enhance the actual collection efficiency, and hence the overall performance of many precipitators. For a detailed comparison of switch mode and conventional 60-hertz precipitator power supplies, refer to the table in Appendix A which compares 19 performance and physical parameters.

The smaller integrated packages can change the way ESP power systems are designed, installed, and serviced. The following section of this paper examines each of these issues in more detail.

III. ENHANCED COLLECTION EFFICIENCY DUE TO SWITCH MODE

Power Supplies

There is a growing body of evidence supporting the fact that the new switch mode power supplies provide improved collection for many precipitator applications. This seems to be primarily due to their ability to deliver a higher average voltage and current to the ESP load, while operating just below the sparking level and/or the back corona level for higher resistivity ashes. This benefit is likely for all ashes: low, medium and high resistivity.

An EPRI-funded study did field tests using a prototype NWL SMPS on a slipstream precipitator at Alabama Power-Plant Miller. The results were very

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encouraging in that depending on the test conditions approximately 30% improvement in percentage penetration was achieved. A conventional linear T/R set and SCR control was also tested to provide a base reference level.

The table shown in Appendix B details the test conditions and results. It may be of interest to note that this study also tested a SMPS combined with a narrow width (1-3 micro-sec) pulsed power supply. This combined unit provided the most improvement.

This is also detailed in the results table.

Testing conducted at the Lansing Board of Water and Light Moores Park facility in Lansing, MI is also of interest. This was a steam generation plant burning low sulfur (1%) coal. Powerspan Corp. (formerly Zero Emissions Technology) conducted tests of a three-phase linear power supply system, the output of which is similar to what SMPS units will provide. The testing showed a higher average power and voltage delivered to the ESP load, as well as reduced sparking and improved collection. The results were documented in a paper presented at the American Power Conference Proceedings, "Performance Improvements From the Use of Low Ripple Three Phase Power Supply for Electrostatic Precipitators."1

A paper presented at the September 1998 proceedings of the ICESP, "A Novel and Versatile Switched Mode Power Supply for ESPs, "2 documented precipitator performance improvements due to the use of SMPS. The testing was done on a cement kiln ESP under various operating conditions. In the conclusions the authors stated that "the prototype test has indicated that this SMPS can improve collecting efficiency, both in cases of low and moderate dust resistivity. The improvement is higher in case of occurrence of back corona."

A second paper presented at the same ICESP conference also discussed ESP performance improvements achieved by the use of SMPS. This paper, "The HVDC Current Source For ESP,"3 concluded that SMPS units provided higher average voltage, reduced sparking, and hence improvements to precipitator efficiency.

An early adopter of the first NWL-built SMPS units has shown promising results. PPC installed an SMPS unit as a replacement for a 60 hz. power supply on a paper mill ESP. The following is an excerpt from the field engineer's report to NWL:

"The existing power supply was operating in the low 30kv range and was sparking heavily. When we installed the SMPS we were able to increase the secondary kv to approximately 40kv — a dramatic improvement. The SMPS now runs current limited at or near 40kv with a clear stack. " PPC has installed SMPS units at other sites, and continues to report improved collection versus 60 hz. units.

The testing done to date on the use of SMPS can not yet be considered to be conclusive proof of enhanced precipitator collection under all conditions. The industry is still in the early stage of understanding the total effects of these new power supplies on ESP performance. However, at this point in time it is reasonable to assume that for many applications, performance improvements can be achieved through the use of SMPS units. As more units are field installed, further data will be accumulated and analyzed. NWL will continue to publish such information as it becomes available.

IV. IMPACTS OF A SMALL INTEGRATED PACKAGE

The different physical configuration of an SMPS unit will have an affect on at least three major aspects of precipitator design, construction, and operation:

1. Physical arrangement of ESP rooftops, control houses, bus ducts, etc.
2. Maintenance and servicing
3. Sourcing of the power supply and other related components

Physical Arrangement

A switch mode power supply is the electrical equivalent of the control cabinet, T/R set, and current limiting reactor used in a linear 60 hz. ESP power supply. The SMPS is contained in one outdoor enclosure, while the conventional unit consists of separate indoor and outdoor enclosures. A quick comparison of the key physical characteristics for a 1000 mili-amp ESP power supply shows the following:

Characteristic	SMPS	Linear 60 hz.
Footprint (square feet)	8	18
Weight (lb.)	750	3900
Fluid Volume (gallons)	25	140

The size and weight reductions from using SMPS units offer new approaches to ESP design. There is no longer a need for a large climate-controlled space for control cabinets, and the power and control wiring to the units will be simpler and easi-

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er to install than with conventional power supplies—resulting in significant anticipated cost savings for new ESP construction.

Another major change with SMPS units is that their size and weight allow the possibility of mounting them directly onto entrance flanges, thus eliminating a significant amount of duct work and offering another opportunity for cost reduction on new precipitator construction.

The reduction in fluid volume may decrease the need for expensive high-flash-point fluid, or if such fluid is still desired, there will be a much lower cost premium than for current systems. The fluid containment issue is now much easier to manage due to the large volume reduction.

Maintenance and Service

History has shown that for a number of reasons the high voltage step-up transformer contained within the T/R set is one of the more likely components to fail within an ESP power supply system.

When such a failure occurs, the T/R set must be removed from the ESP for a time-consuming repair or replacement process. Furthermore, the T/R set is the most expensive component within the system, thus preventing many ESP users from stocking complete spare units, thereby creating a difficult problem when a transformer failure does occur.

The situation is dramatically different with an SMPS unit. The T/R set component of a 1000 ma SMPS unit will weigh roughly 300 lbs. and cost significantly less than a 60 hz. T/R. This makes it more affordable for the ESP user to keep spare T/R sets, as well as making it much easier to get them on and off the ESP.

SMPS T/Rs will also have far less variation in electrical ratings and physical arrangements than 60 hz. units. One key reason for this is that the input to the T/R comes from the inverter, and is always the same voltage and frequency, and thus a major T/R set rating variable is eliminated. Less variation in ratings will

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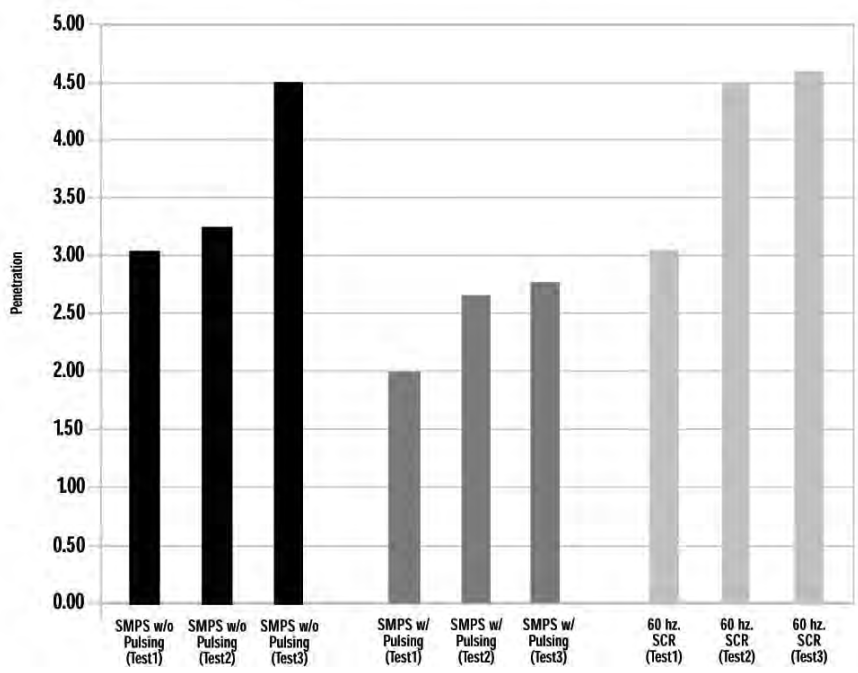
Appendix A
Comparison of SMPS to 60hz. Power Supplies
1000ma Unit

Parameter	SMPS	60hz. T/R
Output Voltage kVdc Average	70	65
Output current mAdc	1000	1000
Output Power kW	70	65
Peak Output Voltage kV	71.8	109.2
% Ripple kVp-p	3-5	35-45
Input Voltage (VAC)	460	460
Input phases	3	1
Input line current line (AAC)	98.8	237
Losses (kW)	4.0	3.5
Power factor	.94	.63
Input kVA	32.2	109
Operating frequency	25 kHz	60 Hz
Arc shutdown time	30 micro-seconds	8.33 mili-seconds
Cooling	Forced Air (1/2 HP fan)	Natural Convection
Volume envelope (cubic feet)	22	60
Plan envelope (square feet)	8	18
Weight (lb.)	750	3860
Gallons of fluid	27	135
Wiring from T/R to control	Factory	Field

Appendix B
Chart 1
Summary of Okant Miller Test Results
High Frequency Pulsing Power Supply



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make it practical for the SMPS supplier to maintain an inventory of replacement T/R sets for quick shipment to a job site.

Furthermore, in emergency situations, air-freight shipment will no longer be prohibitively expensive due to the relatively light weight of the T/R set. When an ESP user knows that replacement T/Rs are readily and quickly available, it may then be practical to forego the expense of carrying spares on site. In summary, the user now has several better options for servicing T/Rs than presently available with linear systems.

SMPS units will also be inherently easier to troubleshoot, since all measurement points are located in an integrated unit and are not split between a control cabinet and T/R set, which are often located a considerable distance apart.

Overall, there can be a much different approach to servicing and supporting SMPS units on precipitators. This will result in significant operational benefits for ESP suppliers and users.

Sourcing of Power Supplies

Current ESP power systems consist of three major components:

1. Voltage control and associated communications hardware and software.
2. Control cabinet including SCR, firing circuit, switchgear, metering, etc.
3. T/R set

The engineering and manufacturing expertise required for each of these components is somewhat diverse, and few suppliers excel in all three. Therefore, many ESP suppliers have chosen to acquire these parts from different vendors. Furthermore, in order to offer exclusive content in their products, many ESP OEMs have developed their own proprietary voltage controls and communications products.

As a result of these factors, ESP suppliers have had to perform as the overall electrical systems integrator, and resolve incompatibilities between the various vendors' products. Due to the maturing of these technologies, however, the systems integration problems are not as difficult as they were in the past, but some still exist today, causing delays and increased project costs.

The introduction of SMPS to the ESP market will change the options available to ESP suppliers and users for buying power supplies and communications software. The SMPS units introduced to the market to date are offered only as a complete package, including the voltage control.

Those ESP OEMs that now have their own proprietary voltage control and communications products will soon have a choice to make. It is technically feasible to modify a 60 hz. Voltage control to work with SMPS units. NWL has already performed the effort to adapt the NWL 60 hz. control for SMPS use.

However, there will be a significant development effort required to design an interface and ensure compatibility between an alternate voltage control and the rest of the power supply system.

Due to other industry trends, there seems to be a move by the major ESP OEMs away from having their own proprietary voltage control and communications systems. The introduction of SMPS units may accelerate such moves, due to the effort required to adapt to SMPS.

More importantly, the use of SMPS units will mandate single point of contact for both the purchase and maintenance of the ESP power supply system, thus offering obvious benefits to ESP OEMs and users.

CONCLUSIONS

The introduction of switch mode power supplies for use on electrostatic precipitators will have a number of impacts on the industry:

- Improved collection performance
- New options for locating and installing power supplies
- Different approaches to maintenance and service
- Changes to power supply purchasing strategies

Each of these factors offers potential cost savings for both new and retrofit installations. Lower power consumption due to the improved power factor will result in direct cost savings. The full impact of all the potential savings has not yet been defined.

We are still in the early stages of understanding how to best apply SMPS units to ESP applications.

The systems commercially available today are relatively unproven and offer limited power and voltage options. But as with all new technology, the systems will continue to improve. Higher power and voltage ratings and more features and options will soon be available. There is little doubt that switch

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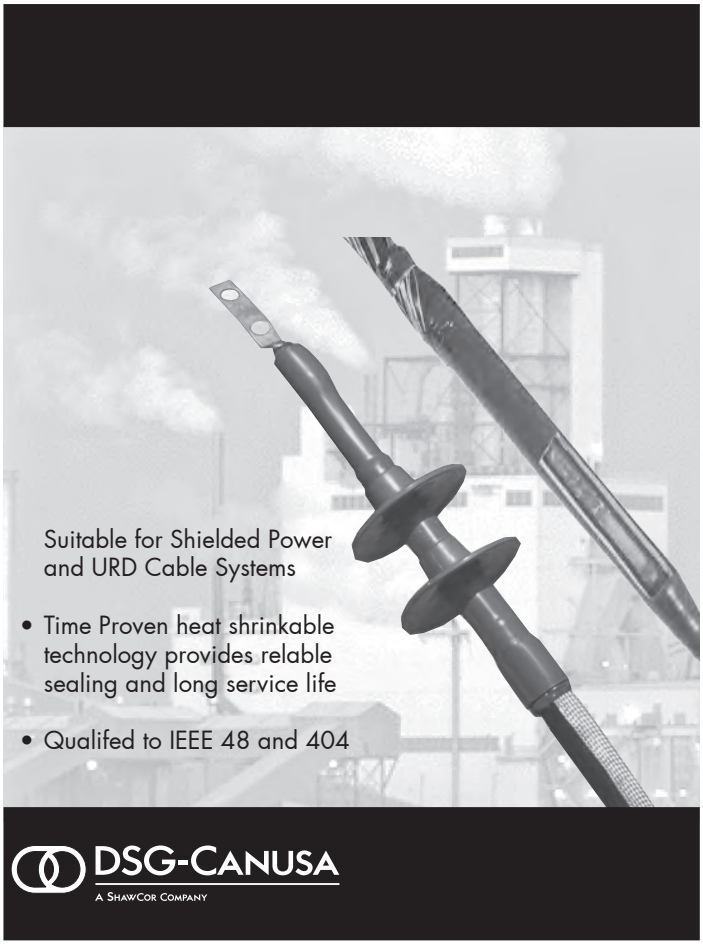

A SUCCESS STORY FROM DEREGULATION: WORLD ENERGY

By Don Horne

After deregulation of the electricity market in the mid 1990s, a number of companies mushroomed into existence trying their hand at matching buyers and suppliers of electricity.

However, by 1999 many had gone under, and those few that survived have learned that gathering timely information is key to not only their success, but that of their customers.

"People want the best price for electricity," says Phil Adams, Chief Operating Officer of World Energy. "We are the product of deregulation."

What began originally as Oceanside in 1996, they metamorphosed into World Energy in 1999, with a goal of leveraging the power of the Internet to streamline and simplify the complexities of buying and selling power in deregulated markets.

"We avoid the uncertainty of the paper process," says Mr. Adams, "by using the reverse auction platform, we are able to provide the lowest price discovery engine for energy procurement."

One example of the cost savings that have been achieved using the World Energy auction platform is the General Services Administration's Energy Center of Excellence, which saved approximately $24 million over a three-year period when suppliers competed to meet the center's energy needs.

"By using the online system, the bidding is quicker and more certain. By doing a lot of up-front work, it is efficient, and the polling of the utility data is formatted in such a way so the information is readily available."

In areas where retail competition is now a reality, consumers have the potential to save large sums of money in energy costs through open choice. Large commercial and industrial companies and government agencies spend anywhere from a few hundred thousand to several million dollars each year on energy, and when purchased in such large quantities, a small change in price can have a tremendous impact on annual profit margins, often making the difference between profit and loss.

"Automated stop times and time stamps ensure the integrity of auction events and create audit trails and a self-documenting capability," points out Mr. Adams. "The new thing we are starting to see is that big companies have to prove they are responsible to their shareholders. With these features, we can provide that integrity."

Another advantage of using the Internet is the level of accountability and transparency for those using it, as they are able to see the entire process in action from start to finish as it happens.

"Automated stop times and time stamps ensure the integrity of auction events and create audit trails and a self-documenting capability," points out Mr. Adams. "The new thing we are starting to see is that big companies have to prove they are responsible to their shareholders. With these features, we can provide that integrity."

Using World Energy's exchange, qualified electricity and gas suppliers compete against one another to secure the buyer's business using a structured and transparent reverse auction platform. Throughout the auction, natural marketplace competition push prices progressively lower, with winning bidders agreeing to provide the power needed at the price determined by the auction's results.

The flexibility of the exchange is such that 9, 12 or 18 contracts can be on auction at any one time, and they can be offered collectively or individually.

"For example, we have had Massachusetts and Texas loads together and separately, with various term lengths and bundles," says Mr. Adams.

World Energy is one of the few nationwide energy procurement companies, boasting a more than 65 per cent market share in the United States. Running almost 800 auctions in the past 18 months, some 11 billion kWh of electricity and 34 billion cubic feet of natural gas have been procured for some of North America's largest and most sophisticated commercial, industrial and government customers, like Costco, Ford Motor Company and the United Nations.

The typical customer savings in the 5-30 per cent range.

"We don't have a crystal ball, but we can tell the customer when the prices are below the industry's benchmark," says Mr. Adams. "If our client has a contract that expires in May and the price is favourable in October, we will encourage them to renew immediately. It is all a matter of anticipating the trends."

With the ever increasing price of oil, the cost of energy has come to the forefront of everyone's minds.

"It looks like $70 and over for a barrel of oil - that's a 61 per cent increase," says Mr. Adams. "That has got everyone's attention, and the restaurants, hotels and big box retailers are all noticing that their electricity bills have gone up 40 per cent.

"People are just beginning to understand that deregulation is good, and they want the best price. The real nuance is how to do it? That's where we come in."

ET

Appendix B
Table 1
Test Conditions and Data
Plant Miller Tests
High Frequency Pulsing Power Supply

Power Supply Mode	Date	Test No.	Inlet Temp. (F)	Boiler Load (MWe)	Flow Rate (acfm)	Sec. Voltage (kV)	Sec. Amp. (mA)	Inlet Loading (gr/dscf)	Outlet Loading (gr/dscf)	BHA Response (Outlet)	Penetration (%)
SMPS w/o Pulsing (Test1)	3/3/00	1	380	702	3,602	42	10	2.05	0.062	0.175	3.02
SMPS w/o Pulsing (Test2)		2	392	702	3,678	42	10	1.95	0.063	0.163	3.23
SMPS w/o Pulsing (Test3)		3	393	700	3,738	42	10	1.71	0.077	0.174	4.50
SMPS w/ Pulsing (Test1)	3/6/00	1	390	691	3,286	30	10 - 15	2.09	0.042	0.062	2.01
SMPS w/ Pulsing (Test2)		2	393	692	3,358	30	10 - 15	1.65	0.043	0.057	2.61
SMPS w/ Pulsing (Test3)		3	392	691	3,283	30	10 - 15	1.72	0.047	0.056	2.73
60hz. SCR (Test1)	8/25/00	1	400	701	3,112	28.7	3.89	2.28	0.069	0.085	3.03
60hz. SCR (Test2)		2	394	701	3,141	29.1	3.85	1.51	0.068	0.092	4.50
60hz. SCR (Test3)		3	391	701	3,309	29.7	3.49	2.18	0.100	0.117	4.59

INSULATION

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mode power supply technology will eventually become the standard solution for ESP power supplies.

Participants at all le vels of the ESP market—new system suppliers, reb uild and repair firms, consultants, and users—should begin the process of understanding the impact these ne w power supplies will have on their businesses. **ET**

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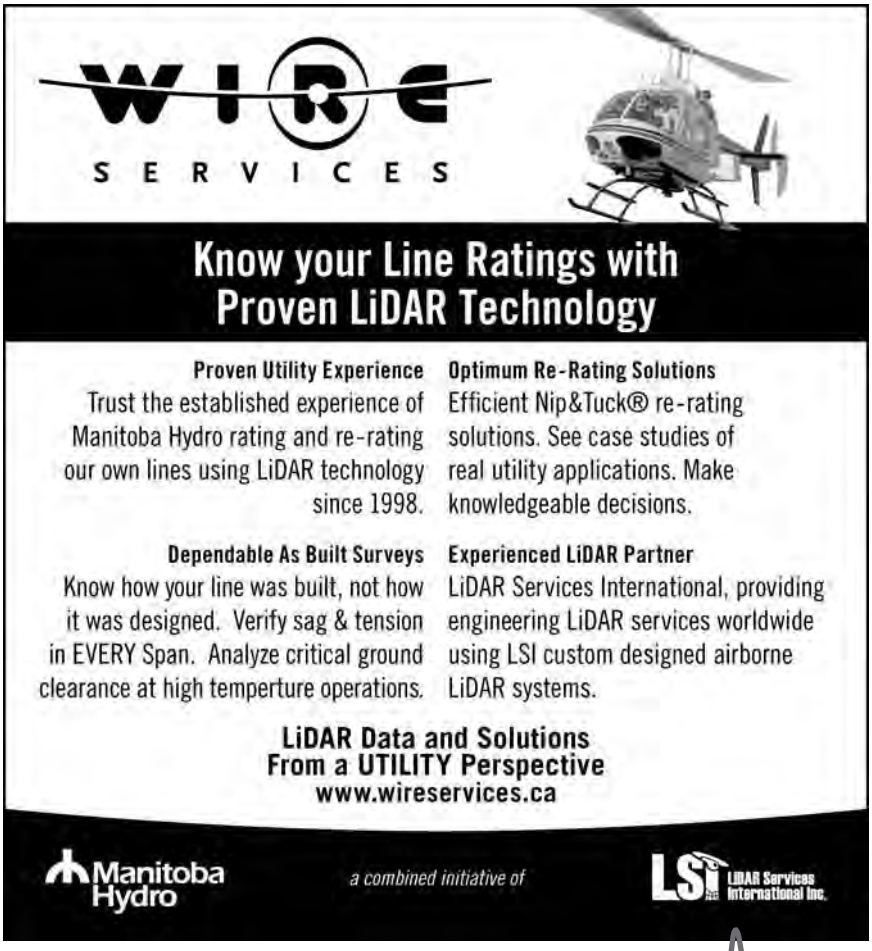

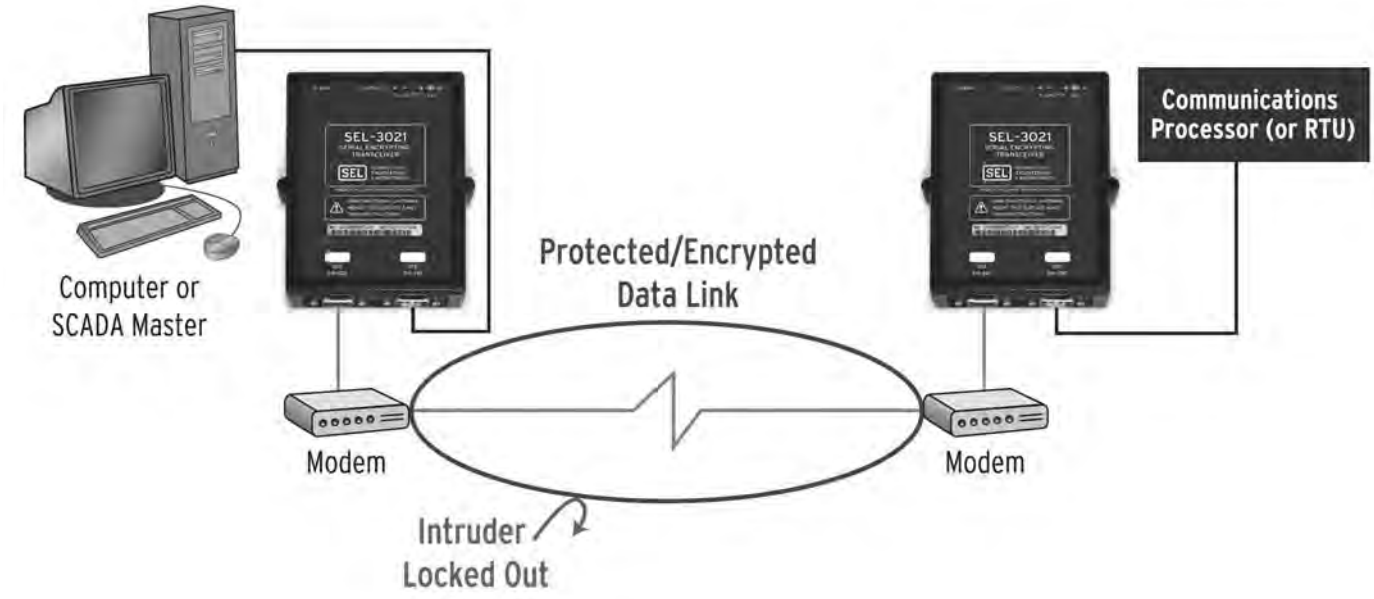

SERIAL ENCRYPTING TRANSCEIVERS SECURE VITAL COMMUNICATIONS TO PROTECT AGAINST CYBER ATTACKS

Protecting existing and new communications links between control centers, substations, and generating plants from cyber attacks is crucial to maintaining service.

Instrumentation and control systems operate and monitor critical infrastructure components. Today there are real threats of malicious physical and cyber attacks on these systems, making their protection and security more important than ever.

An attacker, for example, can secretly monitor sensitive information on data links, or send messages to operate equipment or change settings. Attackers could steal data that would identify biggest customers, usage patterns, delivered power quality, and production rates, or to identify physical targets. Worse yet, imagine the problems they could cause by commanding breakers to open or close, machines to stop or start, and gates or valves to open or close.

Transceivers like these keep intruders locked out of a secure system.

The Federal Energy Regulatory Commission and electric utilities are concerned about attacks on the systems that monitor and control the electrical power grid. Schweitzer Engineering Laboratories SEL-3021 Serial Encrypting Transceiver is one such device that protects critical infrastructure from attack, using encryption and session authentication, and locking out unauthorized control.

The transceiver has low latency, making it ideal for systems that require time-critical communication, such as SCADA, metering, and protection. This "bump-in-the-wire" solution allows easy installation in existing links.

The SEL-3021 is designed to meet Federal Information Processing Standard (FIPS) 140-2 security requirements, meeting or surpassing utility and industrial environmental requirements. In fact, the United Telecom Council selected the SEL-3021 as the UTC Telecom 2004 Product of the Year. **ET**

NERC PREPARES FOR FERC RULE ON ELECTRIC RELIABILITY ORGANIZATION

NERC is moving quickly to transition to become the Electric Reliability Organization (ERO) envisioned by The Energy Policy Act of 2005, culminating nearly 10 years of work toward this goal. Many tasks, such as the formation of an independent board and inclusive stakeholder representation, have already been accomplished.

NERC plans to file comments in response to the notice of proposed rulemaking (NOPR) the Federal Energy Regulatory Commission (FERC) issued on September 1, which proposes criteria for the establishment of the ERO and the procedures under which it will operate (Docket No. RM05-30). Comments are due 30 days after the NOPR is published in The Federal Register.

As soon as FERC establishes the final requirements of the ERO, NERC will file an application to become the ERO. Under the legislation, FERC must finalize a rulemaking by early February, within 180 days of the date the president signed the bill into law.

In preparing its application to become the ERO, NERC must address several key issues, such as membership, funding, governance, functions and responsibilities, relationships with Canadian regulatory authorities, and the role of the NERC regions. NERC is seeking the active involvement and support of stakeholders, and is working with a stakeholder group called the Post-Legislation Steering Committee (PLSC) to assist in coordinating the transition.

The PLSC has been in existence for two years in anticipation of legislation and is being reactivated to continue the work now that legislation has become a reality.

ABB establishes Katrina hotline

The ABB North America Hurricane Katrina Task Force announced today that ABB has established a special toll-free phone number exclusively for customers dealing with the storm's aftermath.

ABB customers should call 1-877-511-4222. ABB Help Desk employees are available from 8:00 a.m. to 6:00 p.m. EDT to direct customers to the appropriate ABB function or contact for assistance. After-hour calls will be handled by an outside service, which will use the same contact sheet and call procedures as the Help Desk employees.

ABB customers in Mexico, or anywhere outside the United States, dealing with the storm's fallout can call 1-440-585-8810 and receive the same support.

Quesnelle appoint to OEB

Ken Quesnelle has become a full-time member of the Ontario Energy Board.

"Ken's extensive insight and experience in the electricity distribution sector will be of great value to the OEB," says Board Chair, Howard I. Wetston.

Mr. Quesnelle most recently served as Vice-President of Woodstock Hydro Services and is the past-chair of the Electricity Distributors Association (EDA). He has also served as Vice-President of Info Energy, member of the Industry Advisory Council to the Electrical Safety Authority and as a member of many electricity industry restructuring task forces.

Mr. Quesnelle has served on the EDA's Western District Board of Directors since 1995, filling the role of Chair since 2001. His appointment is for a two-year term.

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POWER CABLE DIAGNOSTICS FIELD APPLICATION AND CASE STUDIES

By Benjamin T. Lanz, Senior Application Engineer, IMCORP, USA

INTRODUCTION

Power cable diagnostics are the most advanced 'tool' in the 'toolbox' of shielded power cable tests. One of the most common questions regarding cable testing tools is how the test will predict the remaining life of the cable. To be clear, a test that will predict remaining cable life does not exist. However, there are cable tests which can help fulfill testing requirements, dramatically improve reliability, and save the cable owner significant cable replacement costs.

Although standards have offered guidance, cable owners and test providers are largely on their own to determine the best cable test tool for the application. One of the foremost impediments to the decision making process is the lack of clear, credible information. This short paper attempts to provide objective guidance on how to best use the power cable testing toolbox.

The paper then gives recommendations on which test is the most effective for different applications and supports this assertion with case studies.

THE TOOLBOX(4)

There are 3 major categories of cable tests: high potential withstand, general condition assessment, and partial discharge (PD).

Each of these tests serves a different application. By comparing the strengths and weaknesses of each type of test in practical field application, decision makers can quickly determine the test method best suited for their application. In the following section this paper lists the positive and negative attributes for each of the three categories in light of recently published IEEE standards and exclusive large scale field studies and comparison tests.

Although these tests are fundamentally different and cannot be readily compared, some clear distinctions can be made on the basis of practical field application. A table summarizing the comparison can be found at the end of the following attribute lists.

High Potential Withstand (HIPOT)

The HIPOT withstand test is the simplest tool in the toolbox. The HIPOT withstand test can be divided by voltage source into three categories: Direct Voltage (DC), Very Low Frequency (VLF), and Power Frequency. There are positive and negative attributes which pertain to all three types of voltage.

HIPOT (IN GENERAL)

Pros:

- requires simple and relatively inexpensive equipment
- uses very simple procedures
- does not require a trained analyst to interpret results

Cons:

- does not monitor the effect of the test on the cable during the voltage application
- relies on 'pass or fail', thus exposing it to the 'destructive test' label
- is blind to certain types of defects
- weakens all defects simultaneously, but fails only one at a time
- can initiate test/fail/repair/test cycles which are costly and onerous

DC HIPOT

Pros:

- has a long history of use
- uses the most portable, with the lowest power requirements
- is a good HIPOT for conductive type defects (water in laminar cables)

Cons:

- has been demonstrated to induce space charge which aggravates defects in aged extruded cable long after the test's conclusion
- is blind to high impedance defects such as voids and cuts
- does not replicate service conditions and cannot be compared to factory tests

VLF HIPOT

Pros:

- is a portable source with relatively low power requirement
- is a good HIPOT for conductive type defect and high impedance defects

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• does not induce as much space charge as DC which lessens the aggravation of defects in aged extruded cable

• causes some defects to grow rapidly resulting in shorter test time

Cons:

• has been demonstrated to aggravate defects in aged cable without failing

• does not replicate service conditions and cannot be directly compared to factory tests

• is not recommended for aged cable with multiple defects

• does not replicate normal stress distribution in insulation with wet regions

POWER FREQUENCY HIPOT

Pros:

• is good for conductive and high impedance defects

• does not induce space charge which minimizes the aggravation of defects in aged extruded cable

• replicates steady state service conditions and factory HIPOT tests

Cons:

• uses the largest source, is the most expensive, and has the highest power requirement of all the HIPOT tests

• grows certain defects slower than VLF HIPOT test

General Condition Assessment (GCA)

General Condition Assessment is a term which includes a long list of cable diagnostic test methods and technologies, all of which determine the overall health of the cable insulation.

These tests are one of the more sophisticated diagnostic tools in the cable testing toolbox. To name a few of these testing techniques, the following list is provided:

• Dissipation Factor/Tangent Delta/Power Factor

o 50/60 Hz

o 0.1Hz (VLF)

• Dielectric Spectroscopy (Time and Frequency Domain)

• Depolarization -Return Voltage (Recovery Voltage)

• Depolarization -Relaxation Current (Isothermal Relaxation Current)

• Leakage Current

• Total Harmonic Distortion

Each of the technologies has its own advantages and disadvantages which are beyond the scope of this paper. There are, however, generalizations which can be made so reasonable comparison to other cable testing techniques can be made.

GCA DIAGNOSTIC TESTS

Pros:

• are considered to be nondestructive because most tests are conducted at modest voltage levels with a short dwell time

• monitor the overall condition of the cable insulation

• are effective in detecting and assessing conduction type defects

• provide information in the form of three categories- critically aged, moderately aged and like new

Cons:

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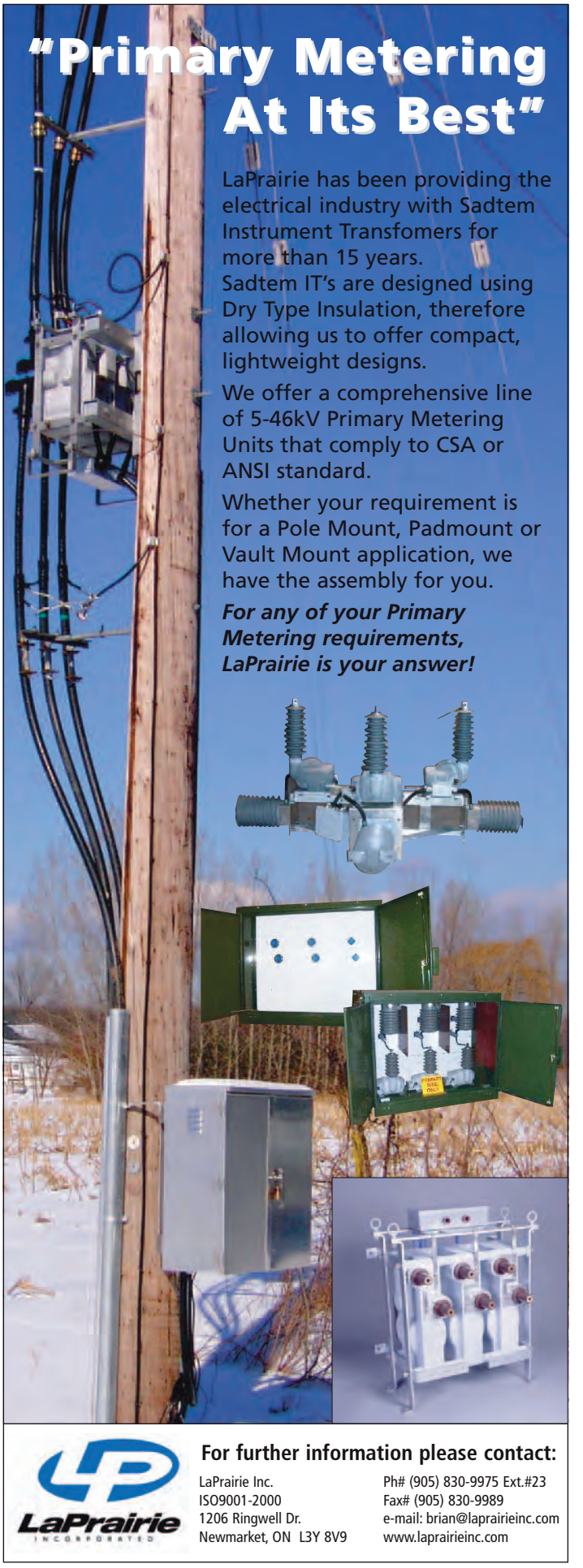

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• require that prior signature files of various cable types be recorded and compared

• have a poor economic trade-off in that there is no defect location (a cable found to be 'bad' needs to be entirely replaced)

• have only been shown to be 50 to 69% accurate in large scale studies

• have results which are highly temperature dependent in extruded cables

• are blind to high impedance defects such as cuts, voids, and partial discharge with less than 10,000pC

• cannot detect singular defects in extruded insulation and require hundreds of large water trees to be present to cause the smallest indication

• are not an effective test for mixed dielectric or newly installed cable

• are not comparable to factory test standards

• require a trained analyst to interpret measurement

• require equipment that is costly when compared to HIPOT equipment

PARTIAL DISCHARGE DIAGNOSTIC TESTS

PD diagnostics are the most effective tool but also the most sophisticated tool in the cable testing toolbox. There are 3 types of PD diagnostics: on-line PD testing, on-line PD monitoring, and off-line PD testing. Continuous on-line PD monitoring technology for cables, although promising, requires further development to make it attractive. For this reason, this paper focuses on on-line and off-line PD testing. PD diagnostics are the only cable tests which can locate defects in shielded power cable.

PD Diagnostic Test (in general)

Pros:

• is a nondestructive test

• is the only testing technology which can detect and locate high impedance defects such as void, cuts, electrical trees, and tracking

• can be performed on-line in limited applications

• is effective at locating defects in mixed dielectric systems

Cons:

• is limited to cables with a continuous metallic shield (time or frequency domain tests)

• requires a trained analyst to interpret measurements

• cannot detect or locate conduction type defects

• becomes complex, onerous, and loses accuracy in branched network applications

ON-LINE PD DIAGNOSTIC TEST

Pros:

• can be performed without switching the circuit out of service

• can detect and locate some accessory defects and a few cable defects

• does not require an external voltage source

Cons:

• will only detect 3% or less of cable insulation defects in extruded cable

• is not a calibrated test; therefore, the test results are not objective

• cannot be compared to factory tests or IEEE standards

• has not been determined to be effective by statistically significant data correlating results to actual cable system defects or failures

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• requires access to the cable e very few hundred feet depending on the cable construction

• requires that manholes be pumped to access cable

• is only of fered as a service and equipment cannot be purchased

• do not pro vide an onsite report of the test results

• cannot be applied to long directly buried cables

OFF-LINE PD DIAGNOSTIC TEST

Pros:

• replicates calibrated f actory baseline tests and can be readily compared

• replicates steady state and transient operating conditions

• can indirectly locate lar ge water trees associated with electrical trees

• locates all defect sites in one test from one end of the cable

• is pro ven to be highly accurate with statistically signif icant correlation studies (85-95%)

• detects and locates defects in the cable system during voltage application

• is ef fective with mix ed dielectric cables

• can test up to 1 to 3 miles of cable depending on the cable construction

• is backed by IEEE 400 as the most effective test

• offers equipment that can be purchased and used by utility personnel

• provides onsite report of the test results

Cons:

• requires that the cable be switched out of service for test to be performed

• requires equipment that is e xpensive when compared to HIPO T equipment

Table –Summary of Comparisons
Key
GCA =General Condition Assessment
PD = Partial Discharge
HIPOT= High Potential Withstand
VLF = Very Low Frequency voltage source (0.1Hz)
PWRFRQ = Power Frequency (20-80Hz)

Which is the right test? - An example

Which test is the 'right test' completely depends on the application at hand. Take an example from the medical world. One could use a blood pressure test to assess the cardiovascular health of a patient or use a specialized stress test with an Electrocardiogram (EKG). Both tests will pro vide information about the patient's cardiovascular health but either test could be the wrong test in dif ferent applications. The stress test, as it is commonly known, will pro vide a much better understanding of the cardio vascular system's health and expected future performance than the blood pressure test. However, the stress test requires the purchase of specialized equipment and the training of a skilled technician. If the measurement is out of the norm, the blood pressure test clearly indicates a disposition to cardio vascular problems, yet the simple test lacks the ability to be as predictive as the stress test. Although the blood pressure test has its limitations, it is a useful test because it uses widely available inexpensive equipment and does not require a highly skilled technician. The moral of this e xample is that the selection of the right 'tool' from the cable testing 'toolbox' depends on the:

Continued on Page 46

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- expectation of the test results
- operator's skill level
- availability of equipment

The table above uses these three attributes to compare all the tests in the cable testing toolbox.

Discussion of Comparisons

Each of the tests in the cable testing toolbox has strengths and weaknesses. Each test must be selected according to the application. The following paragraphs are some typical scenarios which utilities and test providers face while trying to select the right test.

If a utility or a test provider is looking for a direct replacement for the DC HIPOT withstand test that their line crew can operate without significant training, the VLF HIPOT is a good choice. However, the user of such equipment should not expect to perform predictive diagnostics with an instrument which is designed to perform a simple 'go, no go' test.

If a utility or a test provider would like to detect conductive type defects and predict future performance in paper oil insulated cable, a GCA type test would be appropriate.

However, if the cable has a lack of oil, an off-line PD test would be more appropriate. Both paper oil and extruded insulation cables that tests 'good' with a GCA test can still fail due to a high impedance defect such as a crack, void, or electrical tree associated with PD. In this case, an appropriate, all compassing test would be a combination of the GCA and off-line PD diagnostics.

CASE STUDIES

Case 1: VLF HIPOT Withstand Test on Aged XPLE Cable

THE WRONG TOOL FOR THE JOB

According to the IEEE 400.2 standard "Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF)" Table 2: Usefulness of VLF testing methods for selected cable and/or insulation conditions, the VLF HIPOT withstand test should not be used on aged extruded cable systems with multiple defects. This of course presents a problem to the cable owner. Who knows which aged cables have multiple defects? The following case study demonstrates why the VLF HIPOT withstand test is a poor choice for testing aged extruded cable systems.

In February of 2004 a utility had some doubt whether a simple VLF HIPOT withstand test would be an effective test for sorting out 'good' and 'bad' aged extruded cables. The utility requested a 60Hz, off-line PD diagnostic test to be performed on a 3 phase, 1400ft long, 25kV, XPLE cable. This test is a superior base-line test for comparisons because it is directly comparable to a cable factory test. According to the PD test results, multiple defects in the cable insulation were present in the cable. The cable was condemned for replacement on the basis of the utility's criteria. There were too many defects to repair, and it would be more economical to replace the cable. The utility requested a VLF HIPOT withstand test to be performed on the cable. If

Continued on Page 47

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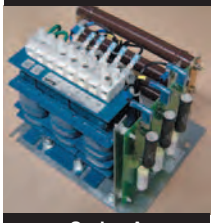

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any of the condemned phases survi ved, the PD test w ould be repeated on those phases to pro vide comparison data. The VLF test was performed according to the IEEE 400.2 guidelines for a 25kV class cable, 23kVrms with 0.1Hz VLF for 30 minutes. According to the standard, if the cable fails within the 30 minutes HIPO T test the cable is 'bad' and if it survi ves the cable is 'good.' If the cable f ails the standard recommends the repair be made and the 30 minute test repeated. Each phase was VLF HIPOT withstand tested independently. The results were:

- A phase survived 31 minutes.
- B phase failed after 20 minutes.
- C phase f ailed after a prolonged dwell time of 37 minutes. (The operator of the test lost track of time and forgot to stop the HIPOT at 30 minutes.)

In this case study , B phase w as the only phase that w as found to be 'bad' according to the IEEE standards. A phase passed and C phase would have passed if the test did not accidentally run past the 30 minute time limit.

Immediately after the VLF HIPOT withstand test w as concluded, the PD diagnostic test w as repeated. The only cable which could be retested w as A phase, since the other tw o phases failed during the test. A phase w as known to have 3 cable PD (defect) sites (see Figure

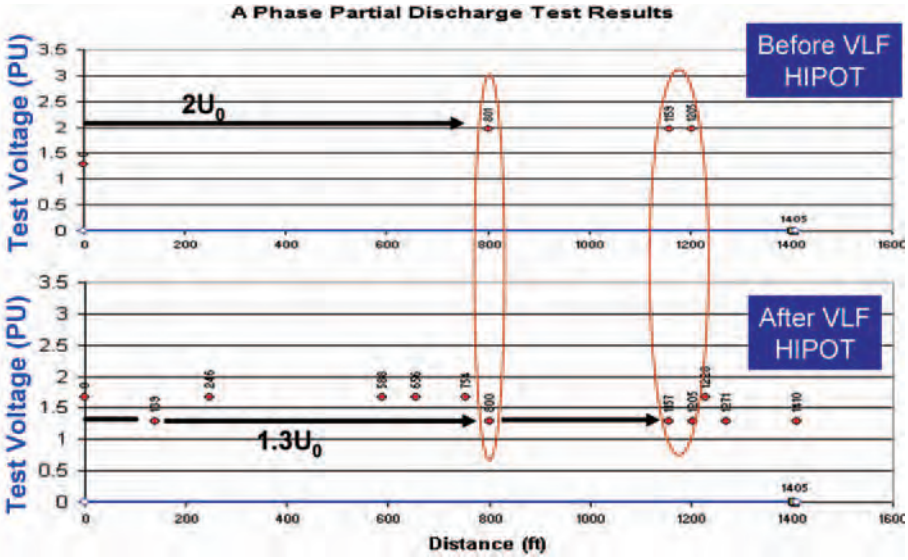

Figure 1
A Phase Off-line 60Hz Partial Discharge Test Results Before and After VLF HIPOT Withstand Test

Continued on Page 48

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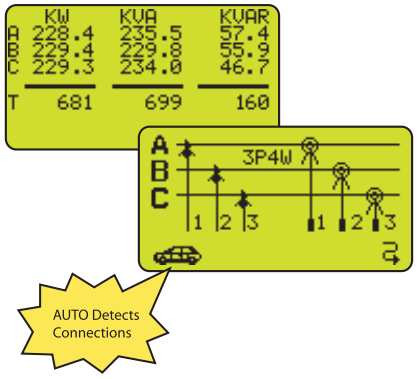

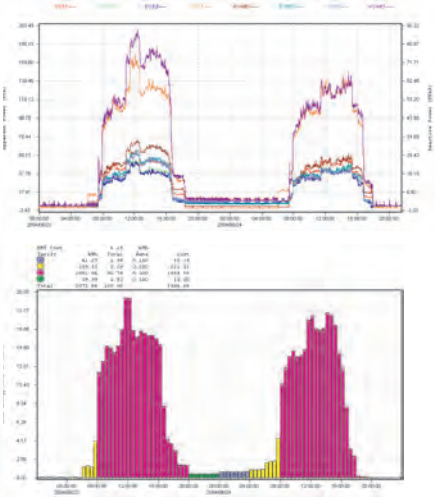

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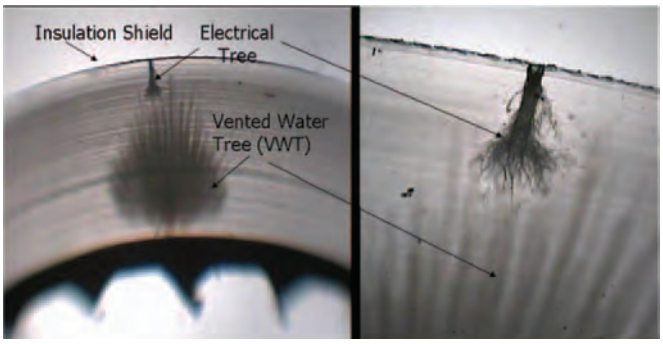

Figure 2
Typical Defect (PD Site) from the Utility's Cable System

2 for an example) from the previous test (top graph of Figure 1). In addition to these 3 sites, the second PD test showed 7 new sites after the 30 minute VLF HIPOT test (lower graph of Figure 1). The three original PD sites, circled, appeared at lower test voltage after the VLF HIPOT. This is indicative that the defects have worsened without failing. Both PD tests were highly sensitive despite high levels of ambient noise and were calibrated to be accurate to 10 picoCoulombs (pC) according to IEC and AEIC calibration standards.

This case study demonstrates how using the wrong tool for the job can make a poor situation worse, unbeknownst to the test operator. In this case, according to the IEEE 400.2 standard, the operator would have to go through the cycle of test, fault locate, repair, and retest several times before the cable could be declared defect free. This is a time consuming, expensive and onerous proposition on aged cables with multiple defects. The VLF HIPOT withstand might be a great replacement for the DC HIPOT withstand test, which can be operated by line crews, but, users of this test should not expect to diagnose aged extruded cables and predict their future performance.

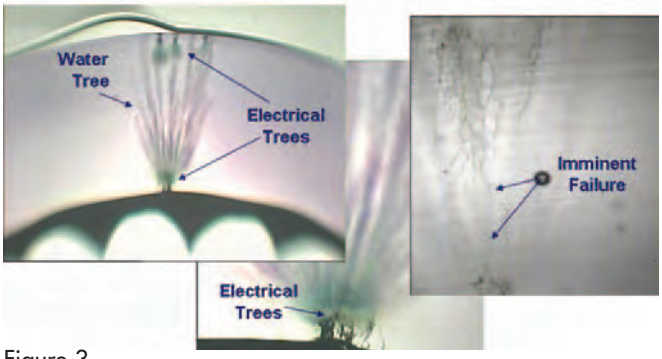

Figure 3
Typical Defect (PD Site) from the Utility's Cable System

Case 2: On-line PD Diagnostic Test Applied to Aged Extruded Cable.

THE WRONG TOOL FOR THE JOB

In January of 2005, a utility was interested in comparing Off-line PD Diagnostics with On-line PD Diagnostics. The on-line test had the obvious advantage of not having to take the line out of service. The utility first requested a 60Hz, Off-line PD Diagnostic test performed on a 1200ft long, 15kV class, extruded cable. The test was calibrated to 5pC sensitivity according to AEIC and IEC standards. The results of the test showed that there were several defects in the cable insulation and one defect in a joint. The defect in the joint was found to have PD at only 80% of the operating voltage stress level. After the off-line PD test, the cable was put back in service.

The On-line PD Diagnostic test technician applied the sensors at the terminations of the cable. Using custom designed sensors, a spectrum analyzer, and a special noise filtering process the mobile on-line testing unit was not able to detect even the largest levels of PD in the cable. A report stated that the cable was free from defect and should be left in service.

This case study demonstrates how using the wrong 'tool' can give an inaccurate reading on a potentially imminent failure. Although the on-line PD Diagnostic test is very convenient, it has a number of limitations. These limitations are listed in the comparison section (above) of this paper. This case study suggests that the on-line test did not have enough sensitivity to detect the defects in this cable. Since on-line tests are not calibrated in the field, as the off-line tests are, they are inherently susceptible to missing defects. Some of the serious cable insulation defects found by the off-line test was not detected by the on-line test because the PD sites were not active at the operating voltage stress level. According to Figure 4, 3% or less of all defects in extruded cable associated with PD are active at operating voltage. One plausible reason that

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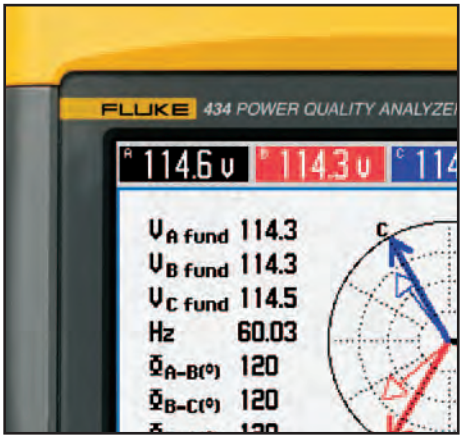

MORE THAN JUST...

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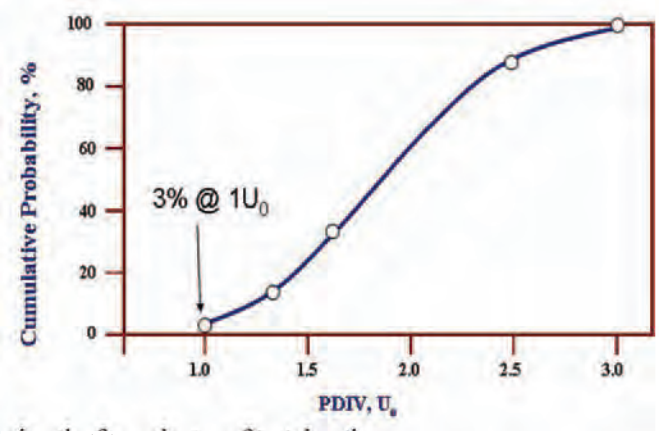

Figure 4(5)
Cumulative Probability of pC Magnitude vs. PD Inception Voltage

online test do not typically detect defects in extruded cable insulation is that insulation defects typically last only minutes to hours under continuous PD conditions. This means the window of opportunity for observing these defects with PD at operation voltage is very short and not likely to be active during the few minutes of test duration.

The graph in Figure 4 is derived from 1,555 miles of extruded cable and 960 PD sites located in the cable extruded cable insulation.

On-line PD Diagnostic tests are useful if there is no way to take the cable system out of service. They are useful at detecting some cable accessory (joints and terminations) defects; especially in short cables where the PD signals are not greatly attenuated. As the case study implies an On-line PD Diagnostic test should not be expected to perform a comprehensive test on a cable system.

Case 3: 60Hz PD Diagnostic Test Applied to Aged XPLE Cable

THE RIGHT TOOL FOR THE JOB

IEEE 400 standard "Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems" states the most effective test is the off-line PD diagnostic test which replicated factory test conditions. Section 7.4 states that "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." The following case study demonstrates how off-line PD diagnostic testing is the right tool for testing an aged XLPE cable system.

During the period from January 2001 to December 2004, a large utility in southern United States used 60Hz, Off-line PD diagnostic testing to direct their cable replacement program. This program uses the results of the tests to determine whether to repair, replace, or defer action on the utility's directly buried feeder cable. The worst performing cables were 430 miles of directly buried cable ranging in age from 20 to 35 years old. Prior to utilizing cable diagnostics, the utility was using the common practice of replacing these cables on the basis of failure history and vintage. Although millions of dollars were budgeted for cable replacement, the failure rate of the cables was steadily rising at an average rate of 4% per year. By incorporating off-line PD testing to their replacement program the utility has been able to maintain the same cable replacement budget but dramatically improve the reliability of their worst performing cables.

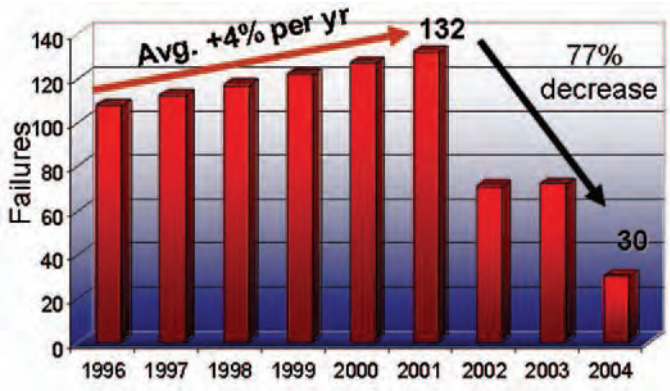

Figure 5
Number of Failures vs. Year

Since the utility has taken action on the basis of the off-line PD cable diagnostics, the utility has not only reversed the increasing failure rate trend, the failure rates have dropped

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COAL-BASED FUEL CELLS: A GIANT LEAP FOR FUEL CELL TECHNOLOGY

By David Anna, DOE National Energy Technology

The Department of Energy recently announced the first two projects selected under the Department's new Fuel Cell Coal-Based Systems program. The projects will be conducted by two research teams — one led by General Electric Hybrid Power Generations Systems and the other by Siemens Westinghouse Power Corporation — and they share the same goal: to develop the fuel cell technology required for central power stations to produce affordable, efficient, environmentally friendly electricity from coal.

The new program leverages knowledge gained in DOE's Solid State Energy Conversion Alliance (SECA), extending coal-based solid oxide fuel cell technology to large central power generation stations.

The benefits of developing coal-based fuel cell systems are significant. Coal is a cost-effective energy source and, with approximately 250 years of reserves, it is America's most abundant fossil fuel. Our improved ability to use this domestic energy supply reduces our dependence on foreign markets and increases our energy security. In addition, fuel cells are one of the most attractive power generating technologies for the future. Fuel cell systems do not rely upon combustion; consequently, they produce nearly none of the air pollutants associated with conventional power systems.

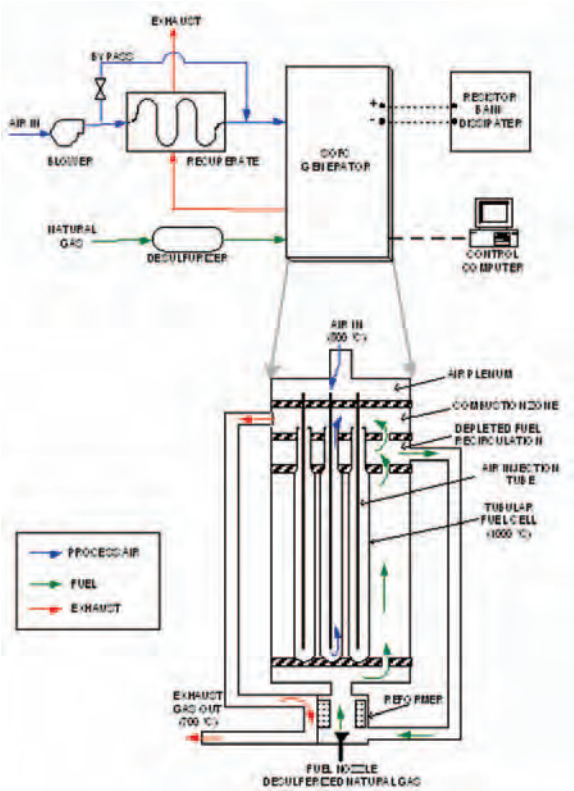
Given these advantages, advances made under the Fuel Cell Coal-Based Systems program are expected to become key enabling technologies for FutureGen, a DOE demonstration of advanced power systems that emit near-zero emissions, have double-today's electric generating efficiency, co-produce hydrogen, and capture and sequester carbon dioxide.

The two teams will research, develop, and demonstrate fuel cell technologies that can support power generation systems larger than 100 megawatts capacity. Key system requirements to be achieved include:

- At least 50 per cent overall efficiency in converting the energy contained in coal to grid electrical power.
- Capture of 90 percent or more of the system's carbon dioxide emissions.
- Cost of $400 per kilowatt, exclusive of the coal gasification unit and carbon dioxide separation subsystems.

Projects will be conducted in three phases. During Phase I, the teams will focus on the design, cost analysis, fabrication, and testing of large-scale fuel cell stacks fueled by coal synthesis gas. Central to the Phase I effort will be the resolution of technical barriers with respect to the manufacture and performance of larger-sized fuel cells.

Phases II and III will focus on the fabrication of aggregate fuel cell systems and will culminate in proof-of-concept systems to be field tested for a minimum of 25,000 hours. These systems will be sited at existing or planned coal gasification units, potentially at DOE's FutureGen facility.



A diagram of Siemens-Westinghouse 25 KW tubular solid oxide fuel cell.

The Office of Fossil Energy's National Energy Technology Laboratory will manage the Fuel Cell Coal-Based Systems program and projects. The new projects are described below:

• Solid Oxide Fuel Cell Coal Based Power Systems — General Electric Hybrid Power Generation Systems will partner with GE Energy, GE Global Research, the Pacific Northwest National Laboratory, and the University of South Carolina to develop an integrated gasification fuel cell system that merges GE's SECA-based solid oxide fuel cell, gas turbine, and coal gasification technologies. The system design incorporates a fuel cell/turbine hybrid as the main power generation unit. (DOE Phase I award: $7.5 million; Phase I duration: 36 months).

• Coal Gas Fueled Solid Oxide Fuel Cell/Gas Turbine Hybrid Power System with CO2 Separation — Siemens Westinghouse Power Corporation is partnering with ConocoPhillips and Air Products and Chemicals Inc. to develop large-scale fuel cell systems based on their in-house gas turbine and SECA-modified tubular solid oxide fuel cell technology. ConocoPhillips will provide gasifier expertise, while the baseline design will incorporate an ion transport membrane (ITM) oxygen separation unit from Air Products. (DOE Phase I award: $7.5 million; Phase I duration: 36 months).

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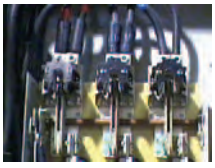

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DIAGNOSTICS

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from 132 in 2001 to 30 in 2004 (a 77% reduction in failures). Figure 5 shows the dramatic change in failure rate after off-line PD diagnostic tests were used to direct the cable replacement program.

This successful reduction in failure rate was enabled by using the right tool for the application. The utility also reports that during this 3 year period there have been no failures in cables which had defects located, were repaired, and put back in service. With a 5 year deferment on the cost of replacement capital alone, the cost benefit of this project is up to 4 times the initial cable testing and cable repair expense. Whether this case study is viewed from the aspect of reliability or economics, the 60Hz, Off-line PD Diagnostics test is clearly the right tool for the job.

CONCLUSION

Throughout this paper the tools from the 'toolbox' of shielded power cable tests have been compared using IEEE standards and exclusive field case studies. These studies are a sample of the case studies that are available but were not included in this paper for the sake of brevity. The IEEE standards quoted and the field studies presented provide evidence that making an informed decision is imperative to achieving the expected reliability results with cable testing.

Throughout this paper the Off-line PD Diagnostic test is shown to be the most effective test in the field and highly recommended by IEEE specifications. The VLF HIPOT withstand test, although a good replacement for the DC HIPOT and is simple to use, needs to be used with caution because its limitations could be detrimental to the reliability of field aged cable. While the on-line PD diagnostic test is convenient, the test is only recommended if a cable cannot be taken out of service, and cable owner can accept the risk of the test missing cable insulation defects. When the right test is used in the correct application and the expectations are inline with reality, the results are predictable.

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Benjamin Lanz received a BS in Electrical Engineering from the University of Connecticut in 1999. Since 1997 he has worked with IMCORP in Storrs, Connecticut and now holds the position of Senior Application Engineer. He supported the development of the IMCORP Cable Diagnostic Technology and has extensive field testing experience in North America and Europe.

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